الجمهورية الجزائرية الديمقراطية الشعبية

**REPUBLIQUE ALGERIENNE DEMOCRATIQUE ET POPULAIRE**

وزارة التعليم العالي و البحث العلمي

**Ministère de l’Enseignement Supérieur et de la Recherche Scientifique**

جامعة أبي بكر بلقايد – تلمسان –

Université Aboubakr Belkaïd – Tlemcen –
Faculté de TECHNOLOGIE

# THESE

Présentée pour l’obtention du **grade** de **DOCTORAT 3$^{\text{ème}}$ Cycle**

**En** : Génie Mécanique

**Spécialité** : Energies Renouvelables

**Par** : TERFA Hani

**Sujet**

# Study of distributed smart renewable-energy microplants

Soutenue publiquement, le 16/03/2023, devant le jury composé de :

| | | | |
|---|---|---|---|
| Mr Abdelhalim BENMANSOUR | Professeur | Univ. Tlemcen | Président |
| Mr Abdelatif ZERGA | Professeur | Univ. Tlemcen | Examinateur 1 |
| Mr Fouad BOUKLI HACENE | Professeur | ESSAT | Examinateur 2 |
| Mr Lotfi BAGHLI | Professeur | Univ. Tlemcen | Directeur de thèse |
| Mr Ramchandra BHANDARI | Professeur | TH KOLN Allemagne | Co- Directeur de thèse |

# Table of content

# Dedication

*Above all, I thank* ***Allah*** *for giving me the strength and the patience to complete this work and to go through with the dream.*

*As a sign of love, gratitude and respect, I dedicate this modest work:*

*To my dear* ***mother****, my soul, the light of my eyes, whom I love more than anything in the world, the one who made me who I am.*

*To my dear* ***father*** *who enlightened my way and who encouraged and supported me in the difficult moments of my career.*

*To my* ***wife,*** *to my second half who stands beside me till the end of my success.*

*To all my* ***brothers*** *and* ***sisters*** *who helped me and encouraged me to move forward in this PhD research, and to all my family;*

*To all my best* ***friends*** *that I have known;*

*To all my* ***teachers*** *from the primary school to the university*

*Hani TERFA*

# Acknowledgment

First and foremost, all Praises and Thanks be to ALLAH for providing me with the health and the courage to carry out this work.

Then, I would like to express my sincere gratitude to my thesis supervisor, Professor **Lotfi BAGHLI**, for his continuous support during my doctoral studies and my research, for his patience, his motivation, his enthusiasm, his immense knowledge, and his human qualities. His advices helped me in all phases of this research work.

I extend my warm thanks to my thesis co-supervisor, Professor **Ramchandra BHANDARI** for his support, precious directives, fruitful advices, and his human qualities. He continually encouraged me and was always ready and enthusiastic to help me in any way throughout the research project.

My thanks also go to the members of the jury who were kind enough to judge my work and honor me with their participation: Professor **Abdelatif ZERGA**, and Professor **Fouad BOUKLI HACENE**, for agreeing to be the rapporteurs for this dissertation.

I warmly thank Professor **Halim BENMANSOUR** for having approved to chair this jury.

I also thank all the LAT members and colleagues for their generous help and support. Working with them during this time has been a very fruitful experience.

Finally, I thank from the deep of my heart my family for encouraging me throughout my research, in particular **my parents, my wife, my brothers and sisters** for all their support.

The research works presented in this PhD thesis was carried out within the **Laboratoire d'Automatique de Tlemcen (LAT)**, at the Faculty of Technology of the University Aboubakr Belkaïd -Tlemcen.

This PhD thesis is financially supported by the German Federal Ministry of Education and Research (BMBF) via its project management agency DLR, under the project "Water and Energy Security in Africa (WESA-ITT)". It is also supported by the Direction Generale de la Recherche Scientifique et du Developpement Technologique (DG RSDT) of Algeria through the Laboratoire d'Automatique de Tlemcen (LAT) project.

# Abbreviations and symbols

## Abbreviations

**5G**: The Fifth-Generation technology standard for broadband cellular networks
**ABC**: Artificial Bee Colony
**AC**: Alternative Current
**AFC**: Alkaline Fuel Cells
**AfDB**: African Development Bank
**AI**: Artificial Intelligence
**ANFIS**: Adaptive Neuro-Fuzzy Inference System
**ANN**: Artificial Neural Networks
**ARMA**: Autoregressive Moving Averages
**AVCs**: Automatic Voltage Controllers
**AVR**: Automatic Voltage Regulator
**BESS**: Battery Energy Storage Systems
**BIPV**: Building-Integrated Photovoltaic
**BMBF**: German Federal Ministry of Education And Research
**CdTe**: Cadmium Telluride
**CERTS**: Consortium for Electric Reliability Technology Solutions
**CHP**: Combined Heat and Power
**CNNs**: Conventional Neural Networks
**COE**: Cost of Energy
CIGS: Copper–indium–allium–diselenide
**CPF**: Continuous Power Flow
**DB**: Database
**DBN**: Deep Belief Network
**DC** : Direct Curent
**DCPT**: Deliverable Capacity Probability Table
**DER**: Distributed Energy Resources
**DFIG**: Double Fed Induction Generator
**DG RSDT**: Direction Generale de la Recherche Scientifique et du Developpement Technologique
**DG** : Distributed Generation
**DL**: Deep Learning
**DN**: Distribution Network
**DNNs**: Deep Neural Networks
**DR**: Demand Response
**DREMP**: Distributed Renewable Energy Micro Plant
**DRL**: Reinforcement Learning
**DSM**: Demand side management
**D-STATCOM**: Distribution Static Compensators
**DT**: Decision Tree
**ECU**: Energy Communication Unit
**EDLC**: Electric Double Layer Capacitor
**EE**: Energy Efficiency
**EISA**: Energy Independence and Security Act
**EMSs**: Energy Management Systems
**EMTP**: Equivalent Multistate Transmission Provider
**EPS**: Ensemble Prediction Systems
**ESS**: Energy Storage Systems
**ETAP**: Electrical Transient Analysis Program
**EU**: European Union
**EVs**: Electric Vehicles

**FC**: Fuel Cell
**FD**: Firebase Database
**FW**: flywheel
**G2V**: Grid to Vehicle
**GA**: Genetic Algorithm
**GHE** : Greenhouse Gas Emissions
**GSA**: Gravitational Search Algorithm
**GSC**: Grid Side Converter
**GTI**: Grid Tie Inverter
**$G_T$:** Solar irradiance
**HANs**: Home Area Networks
**HAT**: Horizontal Axis Turbines
**HCC**: Hybrid Charge Controller
**HEMS**: Home Energy Management System
**HMI**: Human Machine Interfaces
**HOMER**: Hybrid Optimization of Multiple Energy Resources
**HPS**: Hybrid Power Systems
**HSA**: Harmony Search Algorithm
**HV** : High Voltage
**ICE**: Internal Combustion Engine
**ICT**: Information and Communication Technologies
**IEC**: International Electrotechnical Commission
**IEEE**: Institute of Electrical and Electronics Engineering
**IEEE-RTS**: IEEE Reliability Test System
**IGA**: Immune-Genetic Algorithm
**IPMs**: Interior-Point Methods
**IPP**: Independent Power Producers
**KPIs**: Key Performance Indicators
**kW**: kilowatts
**LAT**: Laboratoire d’Automatique de Tlemcen
**LF**: Load Flow
**LV**: Low Voltage
**M2M**: Machine to Machine
**MCFC**: Molten Carbonate Fuel Cells
**MHP**: Micro-Hydropower
**MicroCHP**: Micro Combined Heat and Power
**MILP**: Mixed-Integer Linear Programming
**MIP**: Mixed-Integer Programming
**ML**: Machine Learning
**MLP**: Multilayer Perceptron
**mMTC**: massive machine type communication
**MPPT**: Maximum Power Point Tracking
**MPs**: Micro Plants
**MSC**: Motor Side Converter
**MSW**: Municipal Solid Waste
**MTG**: Micro-Turbine Generator
**MTLBO**: Modified Teaching-Learning Based Optimization
**MV**: Medium-Voltage
**MW**: Megawatts
**NANs**: Neighborhood Area Networks
**NLP**: Nonlinear Programming
**O&M**: Operation And Maintenance

**OPF**: Optimal Power Flow
**PAUWES**: Pan African University Institute for Water and Energy Sciences
**PCC**: Point Of Common Coupling
**PDF:** Probability Density Function
**PEM**: Proton Exchange Membrane
**PENREE**: Algerian Renewable Energy Development and Energy Efficiency Program
**PEVs**: Plug-in Electric Vehicles
**PF**: Power Factor
**PHEV**: Plug-in Hybrid Electric Vehicle
**PHS**: Pumped Hydroelectric Storage
**PLC**: Power Line Communication
**PSO**: Particle Swarm Optimization
**PSO-GSA**: Combination of the Particle Swarm Optimization with The Gravitational Search Algorithm
**PSSs**: Power System Stabilizers
**Pu**: Per-Unit
**PV**: Photovoltaic
**PWM** : Pulse Width Modulation
**QP**: Quadratic Programming
**RES**: Renewable Energy Sources
**RNNs**: Recurrent Neural Networks
**Rpi3**: Raspberry Pi3
**RTP**: Real Time Pricing
**SA**: Simulated Annealing
**SCADA**: Supervisory Control and Data Acquisition
**SDKs**: Software Development Kits
**SG**: Synchronous Generator
**SMCS**: Sequential Monte Carlo Simulation
**SMES**: Superconducting Magnetic Energy Storage
**SoC**: State of Charge
**SSM**: Supply Side Management
**SVM**: Support Vector Machines
**TS**: Transient Stability
**UPS**: Unit Power Supply
**URLLC**: Ultra-Reliable Low-Latency Communication
**V2G**: Vehicle-to-Grid
**VAT**: Vertical Axis Turbines
**VSI**: Voltage Source Inverter
**WANs**: Wide Area Networks
**WECS**: Wind Energy Conversion Systems
**WESA-ITT**: Water and Energy Security in Africa
**Wi-Fi**: Wireless Fidelity
**WiMAX**: Worldwide Interoperability for Microwave Access
**WLANs**: Wireless Local Area Networks
**WNN**: Wavelet Neural Network
**WP:** Wind Power
**WTE**: Wind Turbine Emulator
**ZCD**: Zero Cross Detection

## Symbols

$f_s$**:** Stator frequency
$\mathcal{V}_a$**:** Annual average wind speed

**$\varphi_k$**: Phase angle of the network impedance
**$\omega_s$** : Synchronous speed
**$\Delta H$**: Transferred heat from the electric cable to the outside environment
***a***: Quality factor
***C***: Speed of light ($C = 3\times10^8$ m/s)
**Cp**: Power coefficient
***D***: Damping for each generator (p.u.)
**e.m.f**: Electromotive Force
***e***: Controller input error (voltage / speed)
**$E_{\mathrm{avail}}$**: Energy available to the grid
**$E_{\mathrm{del}}$**: Energy delivered to the grid
**$E_g$**: e.m.f of the SG
**$E_{g.max}$**: Maximum electromotive force (e.m.f) of the generators
**$E_{g.ref}$**: Reference values for the e.m.f
**$E_{g0}$**: Nominal values of e.m.f
**$E_{\mathrm{p}}$**: Energy in a photon (J)
**$E_{\mathrm{PV}}$**: Energy output from the PV module
***F***: Faraday’s constant (96,485.33 C/mole)
***G***: Gearbox ratio
**$G_T$**: Solar irradiance
***H***: Inertia moment (p.u.)
***h***: Constant of Planck ($h = 6.625 \times 10^{-34}$ J.s)
***I**:* Current
***I***: RMS (root mean square) current of the power line
**$I_{\mathrm{d}}$**: Current of the diode that flows when there is no irradiance and the diode is forward-biased
**$I_{dr}$**: Rotor direct current
**$I_{drref}$**: Reference of the rotor direct current
**$I_g$**: Generated current of the SG
**$I_L$**: Current of the overhead transmission line
**$I_{\mathrm{M}}$**:  Total generated current by the connected PV modules (parallel and series PV modules)
**$I_o$**: Diode saturation current
**$I_{ph}$**: Photon current
**$I_{pv}$**: Output current of a PV panel
**$I_{qr}$**: Rotor quadrature current
**$I_{qrref}$**: Reference of rotor quadrature current
***k***: Constant of Boltzmann
**$K_i$**: Integral coefficient of the AVR or the speed governor
**$K_p$**: Proportional coefficient of the AVR or the speed governor
***lambda_opt***: Optimal relative speed ratio
**Li ion**: Lithium ion
**Li–CuO**: Lithium–copper oxide
**LiFe S2**: Lithium–iron disulfide
**LiMn O2**: Lithium–manganese dioxide
**$L_r$**: Rotor inductance
**$L_s$**: Stator inductance
***M***: Mutual inductance
***n**:* Number of electrons released during the chemical reaction
**$\eta_{\mathrm{ab}}$**: Absorption rate of the grid
**NaS**: Sodium-sulfur
**$\eta_{\mathrm{dist}}$**: Efficiency of the distribution system
**Ni-Cd**: Nickel-cadmium

***NiMH***: Nickel-metal hydride
**$\eta_{inv}$**: Efficiency of the inverter
***NOX***: Nitrogen oxide
**$N_{PM}$:** Number of parallel-connected PV modules
**$N_{SM}$:** Number of series-connected PV modules
**$P_g$**: Total generated power
**$P_L$**: Total consumed power (total load)
**$P_{Loss}$**: Power losses
**$P_m$**:  Mechanical power of the turbine
**$P_{m.max}$**: Maximum mechanical power
**$P_{m.ref}$**: Reference value of the mechanical power
**$P_{m0}$** : Nominal value of the mechanical power
**$P_s$**: Stator active power of the DFIG
**$P_{sref}$**: Stator active power reference
**$P_{st}$**: Flicker indices
***q***: Electron’s charge
***Q***: Flow rate of the fluid (m3/s)
**$Q_L$**: Line load's reactive power
**$Q_S$**: Stator reactive power of the DFIG
**$P_g$**: DREMP's active power
**$Q_g$**: DREMP's reactive power
**$Q_{sref}$**: Reference of reactive power
***R***: Radius of the turbine (m)
**$R_L$**: Resistance of the power line
**$R_p$**: Parallel resistance
**$R_r$**: Rotor resistance
**$R_s$**: Serial resistance
**$S''_k$**: Power of the short-circuit at the point of common coupling (PCC)
***Sigma***: leakage coefficient, scatter coefficient, or Blondel coefficient.
**$S_n$**: The rated power of wind system
***SOX***: Sulfur dioxide
***T***: Temperature
***Tm***: Torque of the turbine (Nm)
***V***: Voltage
**$V_b$**: Nominal value of the bus voltage
**$V_{dr}$**: Rotor direct voltage
**$V_{qr}$**: Rotor quadrature voltage
**$V_{drref}$**: Reference rotor direct voltage
**$V_M$**: the DC voltage throughout the entire array
**$V_{qrref}$** : Reference rotor quadrature voltage
**$V_s$**: Stator voltage
**$W_m$**: Mechanical speed of the DFIG
**$W_{m.ref}$**: Reference of the DFIG mechanical speed $W_m$
**$W_{m\_opt}$**: Optimum mechanical speed of the DFIG
**$W_r$**: Slip pulsation
**$W_s$**: Stator pulsation ($2\pi f_S$)
**$W_{sp}$**: Wind speed
***X***: Reactance of the line connecting the DREMP and the substation
**$X_d$**: Transient reactance
**$Y_g$**: Admittance of the SG
**$\Delta G$**: Gibbs free energy

$\Delta U_0$: Voltage of the cell to sustain thermodynamic equilibrium when there is no current flow through the cell (V = J/C)
$\lambda$: Wavelength (m)
$\rho$: Density of the fluid (kg/m$^3$)
$\omega$: Rotational speed of the turbine (rad/s).
$\Omega_m$: Mechanical speed of the DFIG (rpm)
$C\ (\varphi_k, \mathcal{V}_a)$: Coefficient of wind flicker determined through several tests on wind turbines
$\nu$: Frequency (Hz)
$\delta$ : Internal angle of the synchronous generator (rad)
$\omega$ : Rotor speed of the synchronous generator (p.u.)

## List of figures

## List of tables

## Abstract

In an increasingly pressing ecological context, this thesis contributes to the field of renewable energy and especially in the control of distributed smart renewable-energy microplants and smart micro-grids to manage electricity production from small-scale intermittent renewable sources to support the development of small-scale communities in on-grid and off-grid areas. It consists in the study, design, and implementation of experimental test benches for the control of renewable-energy microplants (Photovoltaic and wind). These benches drive real production systems:

- Photovoltaic panels, MPPT controlled chopper, Grid Tie Inverter (single-phase inverter),

- Wind-based DFIG (Double Fed Induction Generator) driven by a DC motor emulating the wind turbine.

- Wind-based SG (Synchronous Generator) driven by a DC motor emulating the wind turbine.

These developed prototypes of renewable microplants are also emulated by their equivalent models running on computer-based systems or embedded processors in clusters such as Raspberry Pi3. Thus, the assembly represents a swarm of microplants, could be named as a micro-grid, connected to the distribution network, which is connected to the high voltage power grid. The communication of these systems can be done between them, or via a central supervisor, thanks to a real-time Firebase Database and a 4G LTE communication network.

In addition to mastering the sizing and control-command methods of these microplants, the study of their insertion in a distribution network as well as in grid-connected / islanded micro-grid is carried out. This will in the sense of the change undergone by the electrical power networks, since we are moving slowly but surely towards low-power distributed generation by compared to traditional centralized high-power generation. The stability of the network and its distributed control set new problems that will be carried out in this thesis. The intelligent control of the whole as well as the elements of regulation of the microplants themselves is the subject of particular attention in this study.

**KEYWORDS**

Distributed renewable-energy microplants, microgrid, smart grid, distributed generation, Firebase Database, Information and Communication Technology (ICT), decentralized control.

## Résumé :

Dans un contexte écologique de plus en plus pressant, cette thèse apporte une contribution dans le domaine des énergies renouvelables et plus particulièrement dans le contrôle des microcentrales à énergies renouvelables intelligentes distribuées et des micro-réseaux intelligents pour gérer la production d'électricité à partir de sources renouvelables intermittentes à petite échelle pour soutenir le développement de communautés à petite échelle dans les zones connectées au réseau et hors réseau. Il consiste en l'étude, la conception et la réalisation de bancs d'essais expérimentaux pour le contrôle de microcentrales à énergies renouvelables (Photovoltaïque et éolien). Ces bancs pilotent de véritables systèmes de production :

- Panneaux photovoltaïques, hacheur contrôlé par MPPT, onduleur monophasé connecté au réseau,

- Éolien à base du GADA (Génératrice Asynchrone à Double Alimentation) entraîné par un moteur à courant continu émulant l'éolienne.

- Éolien à base du GS (Génératrice Synchrone) entraîné par un moteur à courant continu émulant l'éolienne.

Ces prototypes développés de microcentrales renouvelables sont également émulés par leurs modèles équivalents fonctionnant sur des systèmes informatiques ou des processeurs intégrés dans des clusters tels que le Raspberry Pi3. Ainsi, l'ensemble représente un essaim de microcentrales, pourrait être nommé comme un micro-réseau, connecté au réseau de distribution, qui est connecté au réseau électrique à haute tension. La communication de ces systèmes peut se faire entre eux, ou via un superviseur central, grâce à une base de données Firebase Database en temps réel et un réseau de communication 4G LTE.

Outre la maîtrise des méthodes de dimensionnement et de contrôle-commande de ces microcentrales, l'étude de leur insertion dans un réseau de distribution ainsi qu'en micro-réseau connecté ou isolé est réalisée. Cela va dans le sens de l'évolution que subissent les réseaux électriques, puisque l'on évolue lentement mais sûrement vers une production décentralisée de faible puissance par rapport à la production centralisée traditionnelle de forte puissance. La stabilité du réseau et son contrôle distribué posent de nouveaux problèmes qui seront traités dans cette thèse. Le contrôle intelligent de l'ensemble ainsi que les éléments de régulation des microcentrales elles-mêmes font l'objet d'une attention particulière dans cette étude.

## MOTS CLÉS

Microcentrales d'énergie renouvelable distribuée, micro réseau, réseau intelligent, production distribuée, base de données Firebase, technologies de l'information et de la communication (TIC), contrôle décentralisé.

## ملخص:

في سياق بيئي أكثر إلحاحًا، تساهم هذه الأطروحة في مجال الطاقات المتجددة وخاصة في التحكم في المحطات الصغيرة لتوليد الطاقة المتجددة الذكية الموزعة وكذا التحكم في الشبكات الصغيرة الذكية لتسيير إنتاج الكهرباء النقية من مصادر متجددة متقطعة صغيرة الحجم لدعم التنمية للمجتمعات الصغيرة في المناطق المتصلة بالشبكة وغير المتصلة. وهي تتألف من دراسة، تصميم، وتنفيذ مناضد الاختبار التجريبية للتحكم في المحطات الصغيرة للطاقة المتجددة (الكهروضوئية والرياح). تقود هذه المناضد أنظمة إنتاج حقيقية:

- الألواح الكهروضوئية، محول (مستمر / مستمر) الذي يتم التحكم فيه بواسطة MPPT، محول ربط الشبكة (مستمر / متناوب) أحادي الطور،

- مولد لا متزامن ذو التغذية المزدوجة (DFIG) الذي يتم دفعه بواسطة محرك مستمر (DC) يحاكي توربينات الرياح.

- مولد متزامن (SG) الذي يتم دفعه بواسطة محرك مستمر (DC) يحاكي توربينات الرياح.

يتم أيضًا محاكاة هذه النماذج الأولية المطورة للمحطات الصغيرة لتوليد الطاقة المتجددة من خلال نماذجها المكافئة التي تعمل على أنظمة الكمبيوتر أو معالجات مدمجة في مجموعات مثل Raspberry Pi3. وبالتالي، يمثل التجمع سربًا من المحطات الصغيرة، يمكن تسميته بالشبكة الصغيرة، المتصلة بشبكة التوزيع المنخفضة الجهد، المتصلة بشبكة الطاقة عالية الجهد. هذه المحطات الصغيرة يمكنها الاتصال فيما بينها مباشرة من دون وساطة، أو عبر مشرف مركزي، بفضل قاعدة بيانات Firebase Database في الوقت الفعلي وشبكة اتصالات 4G LTE.

بالإضافة إلى إتقان طرق التحكم في الحجم والتحكم في هذه المحطات الصغيرة، يتم إجراء دراسة إدخالها في شبكة التوزيع التقليدية وكذلك في الشبكة الصغيرة المتصلة أو المنفصلة عن الشبكة الرئيسية التقليدية. سيكون هذا بمعنى التغيير الذي تمر به شبكات الطاقة الكهربائية، لأننا نتحرك ببطء ولكن حتما نحو توليد طاقات بأحجام مصغرة وموزعة مقارنةً بتوليد الطاقة العالية المركزية التقليدية. يطرح استقرار الشبكة والتحكم الموزع فيها مشاكل جديدة سيتم التطرق إليها في هذه الأطروحة. إن التحكم الذكي في الكل وكذلك عناصر التنظيم للمحطات الصغيرة نفسها هو موضوع اهتمام خاص في هذه الدراسة.

الكلمات المفتاحية:

المحطات الصغيرة المتوزعة لتوليد الطاقة المتجددة، الشبكة الصغيرة، الشبكة الذكية، التوليد الموزع، قاعدة بيانات Firebase، تكنولوجيا المعلومات والاتصالات (ICT)، التحكم اللامركزي.

# Chapter 1 General Introduction

In this first chapter, we will give an overview about the WESA project and its goals. In addition, we will present our motivation to this study besides the thesis objectives and methodology. Moreover, the thesis outlines will be thoroughly discussed.

## 1.1 Presentation of the project Water and Energy Security for Africa (WESA Project)

The Project of Water and Energy Security for Africa, WESA project, was officially launched at Tlemcen (North-western of Algeria) in a special kick-off event; To welcome the initiative that supports the development of the Pan African University Institute for Water and Energy Sciences – Including climate change (PAUWES) (PAUWES, 2017; UNU-EHS, 2017). The project aims to improve PAUWES' research programs and activities in the disciplines of water and energy sciences by developing and establishing innovative scientific research methodologies that are applicable in the areas of water and energy security for Africa (PAUWES, 2017).

The WESA project represents a first step towards the establishment, realization and implementation of the following objectives (ZEF, 2017):

1- Developing research activities and capacities in order to successfully implement a research agenda at PAUWES;

2- Offering the first Master graduates the opportunity to conduct PhD studies

3- Establishing PAUWES as a center for a Pan-African research network (and even outside) through its fundamental contribution to the development of a "Reach-Out" program in the topics of Energy, Water and Climate Change.

4- Strengthening and enhancing the partnership between PAUWES and the host institution, the University of Tlemcen.

The WESA project involves eight PhD research studies in the fields of Water and Energy policy & engineering (PAUWES, 2017):

***Water Policy and Engineering***

- Impact of land use change and climate change on water balance and sediment yield.
- Integrated water resource management in transboundary river basins.
- Integrated water resources management and improvement of basin functionalities.

***Energy Policy and Engineering***

- Design of hybrid power plant with policy and regulatory frameworks formulation for renewable energy intervention in Africa.
- Analysis of standards for energy distribution systems and disaster risk reduction.
- Managing the dynamics of electricity supply based renewable-energy microplants and of demand in the perspective of control, protection and stability of current and future power grids.
- Energy transition, technological and regulatory strategies for the deployment of renewable energies.
- Exploring the feasibility and potentialities of hydrogen production coupled with solar energy.

## 1.2 Motivation to this research work

The United Nations estimates that the current population of Africa is more than 1.41 billion with more than 56 % of people living in non-urban areas ("Population of Africa (2022) - Worldometer," 2022). Although Africa is rich by renewable and non-renewable energy sources (A Photovoltaic panel produces twice energy in Africa than it will produce in Central Europe on average), the generation of electricity is not yet satisfied, making a mismatch between the generation and the consumption, which lead to a low power service and many blackouts and outages. This affects directly the economic growth of African countries. The conventional solution of extending the power grid face many constraints, among them; distributed population, difficult terrains, long distances between the utility grid and the loads and the expensive cost. However, with the development of renewable energy technologies, and with the increase of fuel prices, many countries on Africa continent are enabling high investments in solar and wind energies. For example, Algeria, the biggest country in Africa, has launched an ambitious program (the Algerian Renewable Energy Development and Energy Efficiency Program-PENREE) which consist of installing up to 22000 MW of power generating capacity from renewable energy sources by 2030 (Bouznit et al., 2020). These important capacities open the doors to study the impact of installing many distributed renewable-energy microplants and to analyze their mutual interaction not only in islanded mode, but also in grid-connected mode. Moreover, due to the lower rating capacity of distributed renewable-energy micro-plants and due to their intermittent nature, many and various types of these MPs need to operate together in the preexisting distribution networks of the radial power grid or in new grid-connected / islanded micro-grids, making the controlling process and coordination between them a difficult task. These systems necessitate a deep understanding due to the different behaviors of each MP.

In this thesis, we are paying a lot of attention to the study and development of distributed renewable energy-based smart micro-grid solutions to develop effective ways to control the MPs and coordinate between them and optimally much the supply with the demand in grid-connected / islanded micro-grids without the intervention of conventional fuel-based distributed generators.

In addition to mastering the sizing and control-command methods of these microplants, the study of their integration in a distribution network as well as in a grid-connected / islanded micro-grid will be carried out. This will go in the sense of the change undergone by the electrical power networks, since we are moving slowly but surely towards low-power distributed generation by compared to traditional centralized high-power generation. The stability of the network and its distributed control pose new problems.

Information and Communication Technologies (ICT) is one of the most important technologies that could solve these issues. ICT have made the smart grid / micro-grid a particularly effective tool for addressing a number of problems with the conventional grid, including numerous blackouts, failures, and system stability issues. Smart micro-grid uses two-way communications to optimally manage its resources including power outputs from renewable MPs, loads, and ESSs.

The intelligent control of the whole as well as the elements of regulation of the microplants themselves is the subject of particular attention in this study. This goes in the direction of intelligent power networks (smart grids / smart micro-grids) which are being developed.

## 1.3 Thesis objectives and methodology

The concept of integration or interconnection of distributed renewable-energy microplants in power grids will be most significant in near future (Berrada et al., 2021; Iweh et al., 2021; Terfa et al., 2020). This PhD thesis goes in the direction of the prospecting and the control of the production of electricity from renewable-energy sources started in Algeria whose government has set the objective of installing up to 22 000 MW of power generating capacity from renewable energy sources by 2030, which represents 40% of the total production (Ouedraogo, 2017; Terfa et al., 2022). It deals especially with the control of renewable energy micro plants (MPs) such as PV and wind in order to manage electricity produced from different types of renewable energy MP to match the supply with the demand instantaneously and conserve the stability of the power grid. To achieve this goal, the overall project is divided into many parts: 1- Mastering the active and reactive power produced from all the MP (both experimental and simulated ones). 2- Mastering the data flow between all the MP, the emulated power grid, the external supervisor (android application or PC) and the firebase database. 3- Studying the impacts of integrating renewable energy MP on power grids in term of frequency and voltage stability. 4- Develop strategies (centralized or decentralized control) to drive the swarm of MPs in a way that each one produces an amount of power proportional to its installed capacity and to other producers to respect the load/production equilibrium, to conserve the stability of the power grid, and to enhance the quality of service.

The experimental work of this PhD thesis consists in the study, design and implementation of smart distributed renewable-energy microplants. Four prototypes of renewable MP are being developed at the laboratoire d'automatique de Tlemcen (LAT); a 1.5 kW Wind Turbine Emulator based on a Double Fed Induction Generator, a 1.5 kW Wind Turbine Emulator based on a Synchronous Generator, a 1.5 kW Photovoltaic system with Grid Tie Inverters and finally, a 250 W Photovoltaic micro-power plant connected through a self-made single-phase Grid Tie Inverter.

In addition to the experimental prototypes, a simulated power grid with conventional power plants, power system stabilizers and automatic voltage controllers and other modelled power plants running in real time on embedded processors (Raspberry PI3) are developed. To ensure the data flow between all these micro-power plants and the simulated power grid, we use a Firebase Database; the experimental benches send data and receive orders to/from the database thanks to Wi-Fi connected microcontrollers ESP8266. Load Flow and Transient Stability studies are considered.

## 1.4 Thesis outlines

In the first chapter of this thesis, we will give an overview about the WESA project and its goals. In addition, we will present our motivation to this study besides the thesis objectives and methodology. Moreover, the thesis outlines will be thoroughly discussed.

The second chapter discusses the latest technologies and developments of distributed energy micro-plants, their concept and their classification. We focused extensively in renewable ones such as PV, wind, hydroelectric, geothermal, and biomass micro-plants. The commonly found criteria to classify whither a generation unit is DG or not are thoroughly presented. Moreover, we have briefly discussed the comparison between DREMPs using different key performance indicators (KPIs) such as efficiency, various GHG emissions, installation cost/kW, operational & maintenance cost, and other KPIs. The various ESS technologies and their power electronic interface are also highlighted in the first chapter. We gave an extensive focus on BESS because this type of ESS is the most frequently employed with distributed renewable micro-plants. We gave an overview about the WESA project and its goals. We finalize the first chapter by presenting the thesis objectives and methodology, thesis outlines and conclusion.

In the third chapter, we tackle the topic of integrating DREMPs in power systems. We have shed the light on grid integration studies and power system planning to accommodate high DREMPs penetration levels while addressing numerous technical, economic, and environmental challenges. A key job in the grid integration process is determining the best connecting point for DREMPs in the grid as well as its maximum capacity that could be supported by the power network. The latest approaches and methods for determining these two important points were extensively discussed in this chapter. We have shed the light on various factors found in the literature that influence the determination of the optimal location and size of DREMPs. In addition, several practical applications and solutions used by utilities and system operators to boost the deployment of DREMPs as well as motivated factors for the increase use of DREMPs in power systems are detailed in this chapter. In this context, it is necessary to think about the challenges and the implications of integrating DREMP into the power grids (specially the distribution network). According to the literature, many researchers have investigated the issues of integrating DREMPs in power systems. Technical, economic, environment and regulatory concerns arisen as a result of the increasing integration of DREMPs are discussed in this chapter, including power quality issues (ex. voltage level fluctuations (over/under voltage), transient voltage changes, voltage flickers, frequency variation, harmonics distortion (both current and voltage)), grid instability, increase in the fault level and more. These issues may have a great influence on supply security and reliability, equipment control and protection, islanding, and safety. Research studies to solve these challenges so that DREMPs can be successfully integrated are also tackled in this chapter. Another approach that does not demand grid integration is stand-alone (off-grid) hybrid power system based DREMPs. In this second chapter, we have presented the literature review about off-grid HPSs based DREMPs. In HPSs based DREMPs, controlling process and coordination is a difficult task. Many research works and studies found in the literature about how to best optimize and coordinate between DREMPs in a HPS are discussed. We finalized the second chapter by presenting the drawbacks of HPS based DREMPs and a general conclusion of the chapter.

In the fourth chapter, we tackle the topic of smart grids and micro-grids. The Energy Management Systems (EMS) used in smart grids and micro-grids are well presented. The Quantification methods that should be considered for the EMS are also considered such as Supply Side Management (SSM), Demand side management (DSM), demand response (DR), and pricing policy. Machine Learning (ML) methods and its models as well as Artificial Intelligence for smart grids and micro-grids such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), Tree-based models (Decision trees), Ensemble Prediction Systems (EPS), Adaptive Neuro-Fuzzy Inference System (ANFIS), Wavelet Neural Network (WNN), Multilayer Perceptron (MLP), and Deep Learning are also discussed.

In the fifth chapter, we have presented a background on communication technologies for smart grid applications. We emphasize in this chapter in presenting the different types of communication networks that may be used for smart grid communications including Home Area Networks (HANs), Neighborhood Area Networks (NANs), and Wide Area Networks (WANs). Moreover, some kinds of communication technologies applicable for smart grids and micro-grids have been thoroughly presented in this chapter. Both wired and wireless technologies have been taken into consideration. In wired communication technologies, we have presented Power Line Communication (PLC) and fiber optic communication technologies. In the other hand, in wireless communication technologies, we have presented the ZigBee, Worldwide Interoperability for Microwave Access (WiMAX), Wireless Technologies – Wireless Fidelity (Wi-Fi), and Satellite communication technologies. Finally, we end the fourth chapter by presenting an overview about 5G communication networks and a conclusion.

In the sixth chapter, we present the results and discussions. We have divided this chapter into many parts:

In the first part, we present the experimental works and the research studies conducted at our laboratory, LAT-Tlemcen, to achieve building prototypes of smart distributed renewable energy micro-plants. Four types of renewable micro-plants that are developed at the LAT-Tlemcen have been fully presented in this chapter; a 1.5 kW Wind Turbine Emulator based on a Double Fed Induction Generator, a 1.5 kW Wind Turbine Emulator based on a Synchronous Generator, a 1.5 kW Photovoltaic system with Grid Tie Inverters (YC500) and finally, a 250 W Photovoltaic micro-power plant connected through a self-made single-phase Grid Tie Inverter.

In the second part, we present the modeling and controlling of renewable-energy MPs, especially wind and PV. The micro-plants models must have the same behavior as the experimental ones presented in the first part. We have used a simplified model of a DFIG expressed in a ($d$-$q$) axis with flux vector control to simulate the wind MP based DFIG. We have also implemented an MPPT algorithm to extract the maximum power available. In addition, we have used pitch regulation strategy to extract exactly the needed power from the maximum available power. Concerning the PV MP, we have used the single diode equivalent model due to its simplicity. We have took the weather data including solar irradiance and temperature as input variables. The output variables are the current, voltage, and the PV power. Moreover, we have implemented an MPPT algorithm to extract the maximum available power from the PV modules. Furthermore, we have implemented another algorithm that extract exactly the needed power the maximum available power. In parallel to the modeling of DREMPs, a simulated power grid with conventional power plants running in real time are also presented. All these models (PV, wind, and conventional power grid) can run on both computer-based systems or on embedded processors (Raspberry PI3).

In the third part, the power grids' stability in the presence of DREMPs is presented. We emphasize in presenting the impact of renewable energy MPs integration in utility power grids in term of frequency and voltage stability. The simulation results are well presented and discussed. Developed programs that compute the load flow (LF), the transient stability (TS), the power system stabilizers (PSSs), automatic voltage controllers (AVCs), and the power injection from renewable energy MPs at the grid buses are also considered. To study the impact of integrating renewable-energy MP on the stability of power grids and to analyze their mutual interaction in grid-connected mode, four cases are presented. The first is when the 5-buses power grid functions without injecting the power of the DREMPs. The second is when we inject only the power of the PV micro-plant at ELM bus. The third is when we inject only the power of the WTE based on a DFIG MP at LAKE bus. The last case is when we inject the power of both PV and WTE micro-plants in the corresponding buses. In the cases 1, 2, 3 and 4, the installed capacity from DREMPs is 0%, 20%, 35% and 55% of the total production respectively. The results and discussions are well presented.

In the fourth part of this chapter, Information and communication (ICT) technologies: A way to explore the potential benefit of DREMPs in smart grids are well presented. We have developed a micro-grid based DREMPs, especially wind and PV, and a battery bank ESS to feed a small-scale communities with many consumers. Two computer-based systems have been used. The first is for emulating the DREMPs with their local controller. The second is for emulating the loads with their local controller. A decentralized control strategy has been performed to control the power production from DREMPs as well as to control the consumers' devices in both grid-connected and islanded mode. In addition, we have used a real-time control strategy instead of the conventional load/dispatch forecasting methods. The intelligent DREMPs' local controller (SSM-LC) performs the energy production management and the demand-side local controller (DSM-LC) performs the DSM. The micro-grid central controller (can be emulated by a third computer-based system) can receive all the information about the MPs and loads and send orders (power references for all the MPs, switch on/off loads, RTP …etc.) to the local controllers when operating in centralized control. However, in this thesis, we have choose to perform the decentralized control instead of the centralized control. To ensure the data flow between the distributed systems, we have developed a Firebase Database (DB); the intelligent swarm of renewable-energy MPs can send information about their real-time power production and receive consumers' data to produce the exact quantity of power and follows the load profile or operate in MPPT mode. The demand-side local controller can send information about the real time power consumption and receive data about the real-time power production to manage its local loads such as switching on/off its connected appliances or reduce flexible loads such as cooling or heating systems and adapt the load profile to the supply profile and skip the weather limitations. The tow computer-based systems (or three in case of centralized control) are connected to the DB via a Wi-Fi WLAN of the home router. The home router is connected to the 4G LTE network. We have also developed an Android application to check for any updates in the DB and displays data. The experimental prototypes of renewable-energy micro-plants can also be connected to the DB to send data and receive orders to/from the DB thanks to Wi-Fi connected microcontrollers ESP8266. We emphasize in this part in presenting the communication interactions results between the supply-side and demand-side local controllers. The first computer-based system which emulate the smart DREMPs sends real time data about their generated power to the DB. We suppose that the generated power vary each 1 second. The second computer-based system which emulate the demands-side resources receives the data about the real-time generated power to perform the DSM in distributed control. In this part, we are not going to present the DSM nor the SSM, but we are going to present only the communication interactions between the various systems and highlight the communication issues such as communication delay time and failures that may occur during the communication system operation. Thus, four scenarios are presented, the first is when both SSM-LC and DSM-LC send / receive data from the DB each 10s. The second is when both SSM-LC and DSM-LC send / receive data from the DB each 5s. The third is when both SSM-LC and DSM-LC send / receive data from the DB each 1s. The last is when a failure occurred in the communication system. The objective is to compare the data profile received from the DB with the real-time true values and to see the effect of the communication delay on giving correct real-time information and on conserving the real profile variations.

The fifth part of this chapter is a continuity of the previous part where some practical applications of smart micro-grids based renewable energy micro-plants for powering small-scale residential communities are developed. The idea concerns the development of renewable energy-based smart micro-grid solutions to support the development of small-scale communities in off-grid and on-grid areas and serve their typical energy needs such as cooling, heating, pumping, lightening, and other electricity usages. The main objective in this part consists in managing electricity production from renewable energy micro-plants as well as managing the loads of consumers to develop effective solutions for achieving the self-sufficiency of micro-grids in both grid-connected and islanded modes. We have replaced the traditional dispatch based forecasting methods by iterative real-time control. A decentralized control strategy is developed to control the micro-grid in both grid-connected and islanded modes in a way that each micro-plant produces an exact quantity of energy in real time to follow the consumption variation. For the wind micro-plant, we have used a pitch regulation strategy to control the blades angle of the wind turbine and produce an exact quantity of energy and maintain a constant power supply, less than the MPPT available power, even with a variable wind speed. Concerning the PV micro-plant, we have implemented another algorithm besides the MPPT algorithm that searches for the appropriate PV-GTI DC voltage to produce a precise amount of power from the PV micro-plant and maintain a constant power supply, less than the MPPT available power, even with a variable solar irradiance. Concerning the demand-side resources, two strategies are proposed to manage consumers' appliances and skip the weather limitations: load shifting and load conservation strategies. Their effect on the power mismatch between the generation and the consumption in the micro-grid is also presented.

At the end of this chapter, we present the conclusion.

Finally, we end this PhD thesis by a general conclusion and perspectives.

# Chapter 2 From centralized generation to distributed renewable-energy microplants

This chapter discusses the latest technologies and developments of distributed-energy micro-plants, their concept and their classification. We will focus extensively in renewable ones such as PV, wind, hydroelectric, geothermal, and biomass micro-plants. The commonly found criteria to classify whither a generation unit is DG or not will be thoroughly presented. Moreover, we will briefly discuss the comparison between DREMPs using different key performance indicators (KPIs) such as efficiency, various GHG emissions, installation cost/kW, operational & maintenance cost, and other KPIs. The various ESS technologies and their power electronic interface will be also highlighted in this chapter. We will give an extensive focus on BESS because this type of ESS is the most frequently employed with distributed renewable-energy micro-plants.

## 2.1 Introduction

Electricity demand is increasing exponentially over time (Ahmed et al., 2017; Funabashi, 2016). According to (Moodley, 2021), Global electricity demand is predicted to climb by around 48% in the next 20 years, after a decrease of about 1% in 2020 owing to the Covid-19 epidemic (IEA, 2021). Meeting this increased demand on electricity across all sectors in the past century were leading by installing new centralized generations, increasing the scale of existing power plants (Martin, 2009) and grid extensions (Terfa et al., 2022).

The term centralized generation is referred to large-scale electricity generation facilities. These lasts are usually located far from end-users and connected to high voltage (HV) power grid (US EPA, 2015a). The produced electricity follows the traditional path from generation to transmission to distribution to multiple end-users (i.e. buildings, industries, offices, hospitals …etc.) (Martin, 2009). Centralized generations include power plants based fossil fuels, hydraulic power stations, nuclear power plants, solar utility-scale farms, wind turbine farms, and more (US EPA, 2015a).

Centralized generations based fossil fuels are influenced by reliability, economic, and environmental regulations of governments (US EPA, 2015a). However, the recent quests and investigations for reducing greenhouse gas emissions (GHG), energy efficiency and reliability led to explore possibilities to modify the current centralized paradigm and to enhance its global performance as much as possible (Martin, 2009). In addition, centralized generation paradigm is characterized by a unique direction of power flow (from centralized power plants to end consumers) and by many significant power losses in the long transmission lines (Copper losses, Magnetic Losses, Corona effect, and skin effect) (Alumona et al., 2014; Terfa et al., 2022). These losses generate additional economic and environmental impacts by consuming fuels to generate electricity that is not consumed by end-users. Moreover, 30 % of the cost for delivering electricity is due to the transmission system (Dalwadi et al., 2011; Terfa et al., 2022). Another important drawback of current electric infrastructures based centralized generation is that 70% of the transmission systems including large power transformers are more than 25 years old and some other parts of the power grids are more than a century old (EIA, 2018; US EPA, 2015a). Thereby, High investments are needed to sustain grid reliability as the assets age (US EPA, 2015a). Looking also to the high percentage of distributed population of many countries (ex. The United Nations estimates that the current population of Africa is more than 1.32 billion with more than 56% of people living in nonurban areas (“Population of Africa (2020) - Worldometer,” 2020)), it is often difficult to electrify them by centralized generations (Terfa et al., 2022). Along with all these drawbacks, there is an urgent need to modify, complement or even replace the current centralized paradigm. One of the best solutions is to turn from centralization to distributed generations (DG).

## 2.2 The Concept of Distributed Generation (DG)

There is no commonly agreed-upon definition of DG, and the literature on this topic is inconsistent as the concept covers multiple applications and technologies (Iweh et al., 2021; Pepermans et al., 2005). However, DG is described, according to the US Department of Energy, as the use of integrated or standalone small production units (electricity or thermal energy) that are installed near load centers. It includes PV systems, solar thermal, micro-hydro turbines, wind turbines, combustion turbines, fuel cells, biomass systems and generating sets.

According to the IEEE (Institute of Electrical and Electronics Engineering) (IEEE SA Working Groups, 2021), DGs are power generation facilities that are far smaller in capacity than centralized power plants, typically 10 MW or less, in order to permit interconnection at practically any point within the power grid. The authors in (Dondi et al., 2002) described DGs as a small source of power generation for storage, often between a few kilowatts and tens of megawatts, which is not part of the large, centralized power grid and is positioned close to end-users. (Chambers, 2001) Characterizes DGs as power pockets that have a capacity of 30 MW or less and are often positioned near consumers, allowing them to economically support the distribution network. As per (Ackermann et al., 2001a), DG refers to a type of power generation technology, renewable or non-renewable energy technologies, within distribution network or on the end-user side. In addition, it should be able to deliver active power to the network to which it is linked, as well as provide reactive power and/or other auxiliary services on occasion. Moreover, DGs could operate in either stand-alone mode or grid-connected mode. (Iweh et al., 2021) used the definition of DG as small- or medium-sized, integrated, electricity-producing machineries that are not centrally managed by the main grid and are typically connected close to load centers to increase power supply. Their electricity management techniques is normally independent of the main grid, and they are mostly connected to power-demanding sites. (Tazvinga et al., 2017) defined DG as small-to-medium power plants that are placed at or near energy users, such as in off-grid, rural, or peri-urban areas. Distributed resources also include distributed generation technologies, which are located within the distribution system or on the customer side of the meter. As well as demand-side resources, such as load management systems, which shift electricity use from peak to off-peak periods. In addition to energy efficiency options, such as reducing peak electricity demand, increasing the efficiency of buildings or drives for industrial applications, or lowering overall electricity demand. (Tazvinga et al., 2017) stated that DGs are unquestionably the way forward considering the deregulated electric energy paradigm embraced by most countries. It is feasible, has long-term cost savings, and promotes the use of renewable energy sources in the energy mix. (Helman, 2019) uses the broadest definition of DG, which includes small-scale (generally less than 20 MW) facilities connected to the distribution or even to the transmission networks, as well as customer-sited resources (including load management) of all size. This definition aids in capturing the general trend toward smaller-scale resources, which is being led by photovoltaics, which may be put at various scales throughout the grid as well as at the client site. According to this author, integrating aggregations of various sorts of DG give more flexibility to the state regulators as well as wholesale markets. As per (Basak et al., 2012), The primary feature of DG is that they are active devices that are put at the distribution system level rather than at the transmission level. Photovoltaic systems, wind energy systems, fuel cells, and CHP-based micro-turbines are examples of DGs, as are storage technologies such as batteries, flywheels, ultra-capacitors, and super conducting magnetic energy storages.

In general, Distributed Generation is an approach that employs various and numerous of small-scale (micro) power generation, mostly are based  renewable energy sources (RES) (Fathabad et al., 2021; Sayed and Gabbar, 2017), or storage technologies to produce electricity at or near where it will be consumed (Funabashi, 2016; Yerasimou et al., 2021) (US EPA, 2015b). DG, on-site generation, local generation, distributed energy resources (DER), decentralized generation, embedded generation or dispersed generation are all terms that have been used interchangeably with distributed generation (Iweh et al., 2021).

## 2.3 Some Criterions and benchmarks for considering a generation unit as DG

Assessing DG as it travels between countries and specialized institutions, and establishing a clear benchmark for DG capacity and location assessment is a challenge. Many institutions and countries have different point of views on the connection points of DG. Some authors define DGs as power sources that directly feed consumer loads, whereas others regard DG in terms of the voltage level at which the DG is connected (Iweh et al., 2021). Most scientists argue that the proper location for DG plants should be on a low voltage (LV) distribution network where consumers can easily use energy with minimal losses (Colmenar-Santos et al., 2016). However, some claim that high voltage (HV) transmission network can also accommodate DG facilities (Ackermann et al., 2001a). According to (Ackermann et al., 2001b; Brahma and Girgis, 2004; Lopes et al., 2007a; Manditereza and Bansal, 2016a), DGs are connected to the grid through low- to medium-voltage power networks. However, DGs with capacities more than 50MW are usually connected at the transmission or sub-transmission level (Roy and Pota, 2015a).

In another view, scientists use ownership of a power generation unit as a criterion for determining whether it should be classified as a DG or not. In which some have claimed that only power off-taker or Independent Power Producers (IPP) should own a DG unit. Where others have refused this criteria (Ackermann et al., 2001a) and show that Independent Power Producers (IPPs), consumers, and governments can all own DG micro-plants.

The maximum allowed capacity of a DG that can be hosted by the main grid is also a debated topic among different institutions and countries, because each connection point has a maximum quantity of power it can handle, above which the system may become unstable (Iweh et al., 2021). *Table 2.1* indicates commonly found criteria used by several governments and entities to classify whither a generation unit is DG or not (Ackermann et al., 2001a; Iweh et al., 2021; Pepermans et al., 2005):

*Table 2.1 Some criteria to classify whither a generation unit is DG or not by some institutions/countries.*

| Institution / Country | Capacity of DG | Connection point of DG | Operation Mode |
|---|---|---|---|
| Sweden | ≤ 1500 kW | - | - |
| New Zealand | < 5 MW | - | - |
| Australian Energy Market Operator | ≤ 30MW | - | - |
| International Council on Large Electricity Systems | < 100 MW | Most often coupled to the distribution network | Not managed/ dispatched centrally |

| | | | |
|---|---|---|---|
| Bulgarian Energy Holding Company | < 10MW | Connected to the distribution network | Not managed centrally |
| Electric Power Research Institute | ≤ 50 MW | Most often installed near load centers or distribution and medium-voltage (MV) substations | - |
| Gas Research Institute | 25 kW ≤ X ≤ 25 MW | - | - |
| England and Wales Electricity Markets | < 100 MW | - | Not dispatched at a central point |
| Estonian Power Markets | < 10 MW | Connected to the distribution network | - |
| Institute of Electrical and Electronics Engineering | ≤ 10 MW | Connected to any point within the power grid | - |

## 2.4 Classification of DGs and their technologies

It is possible to classify the technologies of DGs into three broad categories: non-renewable technologies (e.g. gas and diesel), renewable energy sources technologies (Hung, 2014; Puttgen et al., 2003) and energy storage systems technologies (Terfa et al., 2022). Typically, their capacities vary in the range of kilowatts to several Megawatts. They have a set of technical, economic and environmental advantages such as reduced electricity losses and cost, increased reliability and efficiency, higher security with less greenhouse gas emissions (US EPA, 2015b; Virginia Tech, 2018). In addition, DG are allowing end-users to have some flexibility in energy use (Basak et al., 2012).

DG may involve the following devices and technologies (Funabashi, 2016; Hung, 2014; US EPA, 2015b):

***Nonrenewable DG:***

- Reciprocating engines including emergency backup generators (usually fueled by diesel or gas);
- Micro-turbine generators (fueled by gas);
- Combustion gas turbines
- Micro combined heat and power (MicroCHP) systems;
- Fuel cells (usually fueled by natural gas or hydrogen)

***Small-scale Renewable energy sources:***

These technologies are also known as Renewable DG, distributed RES, or DREMP. These technologies include all types of small-scale RES such as Micro wind turbines, Photovoltaic systems (ex. Rooftop PV system), solar hybrid or wind hybrid systems, biomass, geothermal, small hydropower, tide micro-plants and more.

***Energy Storage Systems (ESS):***

Such as Battery Energy Storage Systems (BESS), flywheel, Lion-battery, Fuel cells (when hydrogen is used as storage fuel) and more.

***The combination of the above devices could also be considered as DG.***

*Figure 2.1* Summaries the classification of DG systems (Khetrapal, 2020):

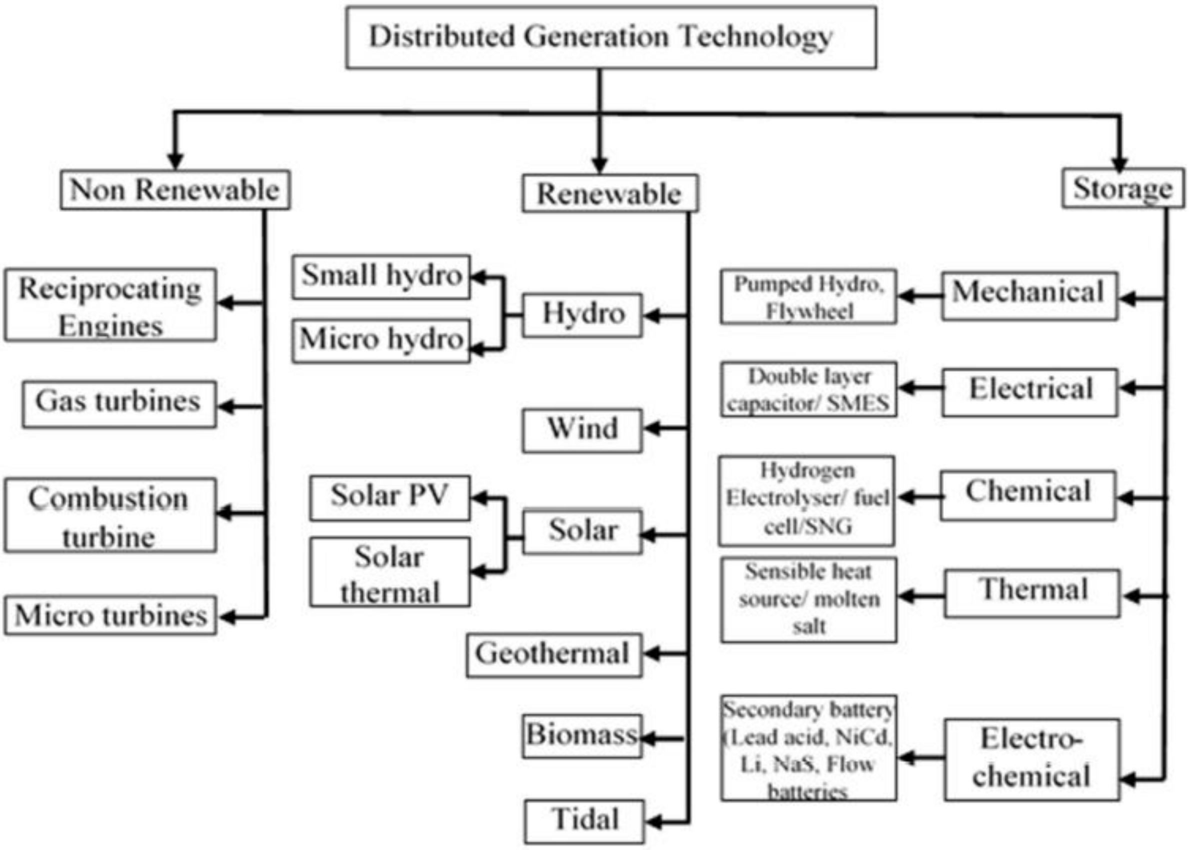


*Figure 2.1 Classification of DG systems*

A detailed presentation of distributed generation technologies, especially DREMPs is considered in the next section.

## 2.4.1 Non-renewable distributed generation technologies

### *2.4.1.1 Reciprocating engines*

The reciprocating engine, often known as the piston engine. It is an internal combustion engine (ICE) that can burn a several types of fuels such as diesel, natural gas, biofuels, biodiesel and more. The reciprocating engine is an ideal prime mover for powering electricity generating sets used to offer primary power in remote places or, more broadly, for delivering mobile and emergency or stand-by electrical power due to its compact size, wide range of power outputs, and fuel preferences. The reciprocating engines' power generation scales range from 1 kVA (small scale) to several tens of MVA (large scale) (Akorede et al., 2010a; Funabashi, 2016).

The reciprocating engine delivers the lowest cost of all combined heat and power (CHP) systems, high efficiencies, short start-up times to full loads (10–15 s), and great reliability in the case of the DG application. However, these engines emit pollutants (e.g.,CO, NOX, SOX, etc.) that are potentially detrimental to the environment (Funabashi, 2016).

### 2.4.1.2 Micro-turbine generator system (MTG)

One of the best distributed generation technologies is the micro-turbine generator (MTG). It has many advantages such as being multi-fueled, lightweight, reliable as well as it has low initial cost. Furthermore, the MTG provides a cogeneration system that produces both electricity and heat. This function is appropriate for energy systems in hospitals, hotels, supermarkets, and other similar establishments. Despite the fact that the MTG uses natural gas to produce electricity, it provides environmental savings in terms of minimal nitrogen dioxide emissions. However, the MTG has a poorer energy efficiency (EE) than reciprocating engines (Funabashi, 2016; Urasaki et al., 2011).

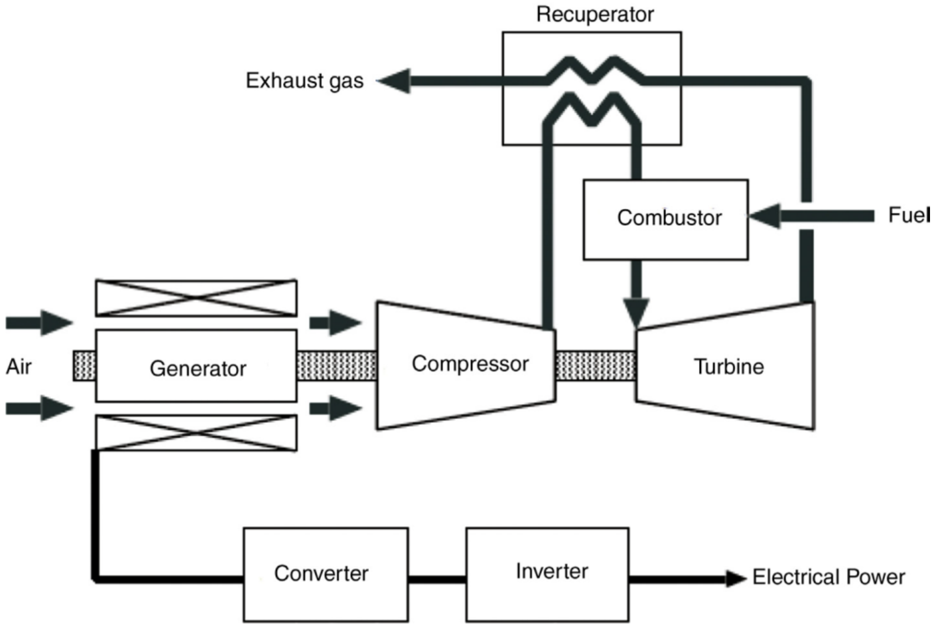


*Figure 2.2 The system configuration of the Micro-turbine generator.*

The system configuration of the micro-turbine generator is depicted in *Figure 2.2*. The following is a brief summary of how these systems operate (Funabashi, 2016):

- The Exterior air is compressed by the compressor.
- The exhausted gas in the recuperated heats the compressed air.
- The natural gas and heated air are mixed together. The combustor then burns the combined gas.
- The kinetic energy is generated by the combustion gas flowing to the turbine. Both the generator and the compressor are driven by the turbine's power.
- An AC/DC converter is used to convert the high frequency voltage of the generator to DC voltage. The DC voltage then converted to AC voltage to feed consumers (Funabashi, 2016).

### 2.4.1.3 Fuel cells

#### 2.4.1.3.1 History

Sir William Grove and Christian Friedrich Schœnbein (Grove, 1838; Schœnbein, 1839) were the first to investigate and study fuel cell technology as a potential type of power generation in the 19th century. Fuel cells, on the other hand, started to acquire traction around the beginning of the century. In 1939, Francis Thomas Bacon built the first fuel cell with a 5 kW capacity. Since then, fuel cells have been employed for vehicles run by fuel cells, space travel applications, stationary power applications, and electronic devices based portable fuel cells (Barnett and Teagan, 1992; Bills, 1964). Fuel cells are suitable candidate for the role of a reliable DREMPs due to their enormous benefits such as having a high energy efficiency (EE), emit no harmful pollutants, and have a small number of moving parts, which reduces maintenance and operation costs (Huang et al., 2006; Tazvinga et al., 2017).

#### *2.4.1.3.2 Working principle of a fuel cell*

There are many types of fuel cells. However, a fuel cell is generally composed of an anode, a cathode, and an electrolyte. Using a chemical reaction, the electrolyte allows charges to circulate between the anode and cathode. An external circuit is used to drain electrons from the anode to the cathode, resulting in DC electrical energy (Funabashi, 2016).

In this section, a hydrogen–oxygen ($H_2$–$O_2$) fuel cell is used to demonstrate the operating concept of a fuel cell. *Figure 2.3* depicts a schematic illustration of such a fuel cell. (Tazvinga et al., 2017).

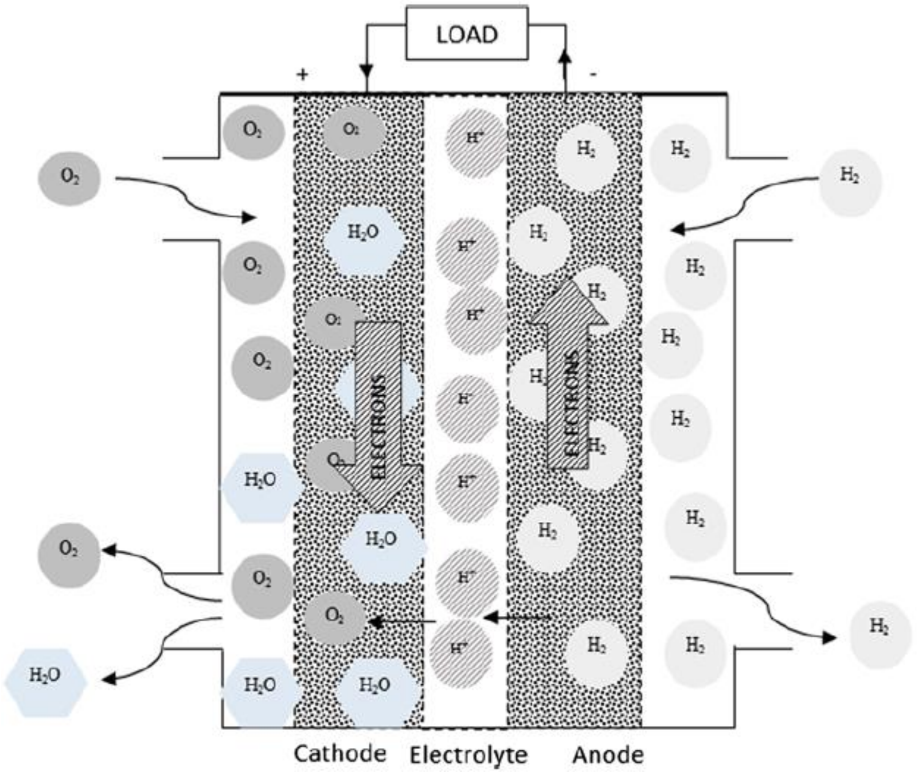


*Figure 2.3 A hydrogen–oxygen* ($H_2$–$O_2$) *fuel cell schematic illustration* (Carrette et al., 2001)

As illustrated in *Figure 2.3*, Both $H_2$ and $O_2$ are delivered to the cell from vents on either sides. $H_2$ is the fuel in this example, and $O_2$ is the oxidant. The electrodes are permeable enough allowing them to absorb these gases quickly. The anode oxidizes every $H_2$ molecule that enters, producing two free electrons and two $H^+$ ions. The ions of $H^+$ move to the cathode, in which they interact with $O_2^-$ ions produced by the reduction of $O_2$ with the cathode to generate water ($H_2O$). The Gibbs free energy, indicated in Eq. 2.1, defines the free energy created during this chemical reaction of two $H^+$ ions and one $O_2^-$ ion (1.39) (Tazvinga et al., 2017):

*Eq. 2.1:*

$$\Delta G = -nF\Delta U_0$$

Where $\Delta G$ is the Gibbs free energy (kJ/mole), $n$ is the number of electrons released during the chemical reaction, $F$ is Faraday's constant (96,485.33 C/mole), and $\Delta U_0$ is the voltage of the cell to sustain thermodynamic equilibrium when there is no current flow through the cell (V = J/C).

The Gibbs free energy for the $H_2O$ reaction is -237 kJ/mole, which specifies how much energy per mole of $H_2$ will be transformed into electricity and used to power a load connected to the fuel cell. Theoretically, the voltage level of a fuel cell is estimated to be around 1.2 VDC. This value can only be produced in open-circuit cases. This phenomenon is termed as polarization, and it is depicted by the electrical characteristic curve (*Figure 2.4*), usually known as the static polarization curve. The fuel cell voltage is represented on the y-axis, and the current density is represented on the x-axis. Polarization occurs as a result of physical and chemical losses in a cell. Fuel cells operate optimally when just ohmic (resistive) losses occur. It can be seen that when the current density increases, the fuel cell voltage decreases (Tazvinga et al., 2017).

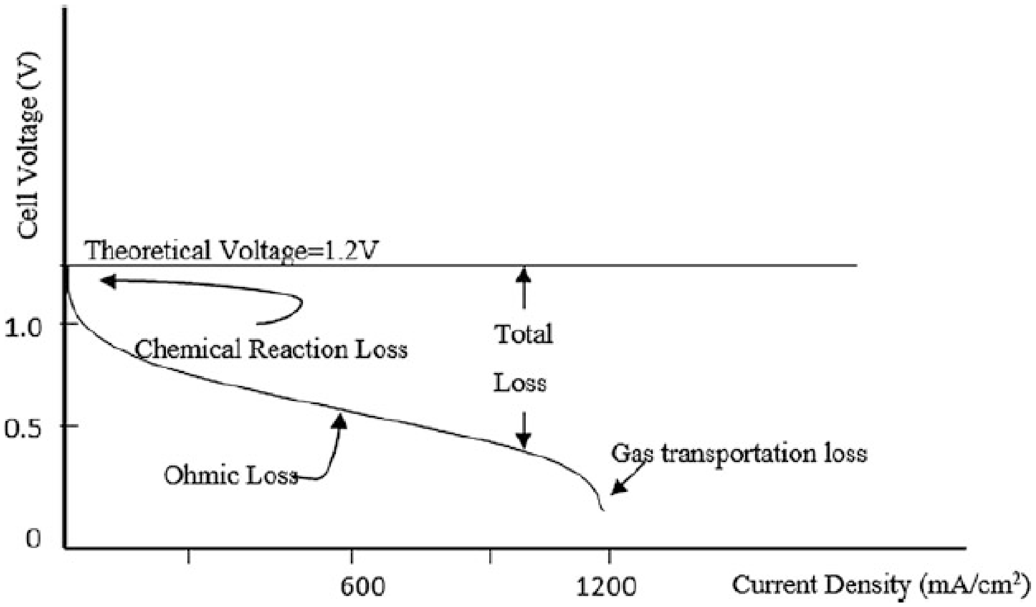


*Figure 2.4 A fuel cell's polarization curve (Huang et al., 2006; Tazvinga et al., 2017).*

### 2.4.1.3.3 Types of Fuel Cells

A fundamental and simple fuel cell is the $H_2$–$O_2$ fuel cell. There are several more types of fuel cells (NFCRC, 2022) which vary from one another in terms of characteristics, electrolyte utilized, and fuel type as shown in *Table 2.2* and *Table 2.3* (Funabashi, 2016; Tazvinga et al., 2017).

*Table 2.2 Characteristics of various fuel cells* (Huang et al., 2006; NFCRC, 2022)

| Type of fuel cell (FC) | Proton exchange membrane (PEM) FC | Direct methanol FC | Phosphoric acid FC |
|---|---|---|---|
| Electrolyte | Solid polymer membrane (Nafion) | Solid polymer membrane (Nafion) | Liquid phosphoric acid ($H_3PO_4$) in silicon carbide |
| Fuels | Pure $H_2$ (allows $CO_2$) | Methanol in water solution | Pure $H_2$ (allows $CO_2$ and 1% $CO$) |
| Catalyst | Platinum | Platinum | Carbon-supported platinum |
| Operating temperatures (°C) | 60 to 80 (°C) | Up to 110 (°C) | 160 to 220 (°C) |

| | | | |
|---|---|---|---|
| Energy efficiency (%) | 40 to 60 (%) | $\leq 40$ (%) | 36 to 42 (%) |
| Primary chemical reaction | $H_2 + 1/2O_2 \rightarrow H_2O$ | $CH_3OH + 3/2O_2 \rightarrow 2H_2O + CO_2$ | $2H_2 + O_2 \rightarrow 2H_2O$ |

*Table 2.3 Characteristics of various fuel cells* (Huang et al., 2006; NFCRC, 2022)

| Type of FC | Solid oxide FC | Alkaline FC | Molten carbon FC |
|---|---|---|---|
| Electrolyte | Solid ceramic or metal oxide | Potassium hydroxide in water solution | Alkali carbonates |
| Fuels | $H_2$ and other hydrocarbons (allows $CO_2$) | Pure $H_2$ | $H_2$ and other hydrocarbons (allows $CO_2$) |
| Catalyst | Non-platinum group catalysts | Non-precious metal crystals | Non-platinum group catalysts |
| Operating temperatures (°C) | 800 to 1000 (°C) | Up to 230 (°C) | 600 to 700 (°C) |
| Energy efficiency (%) | 50 to 60 % | 60 to 70 % | 50 to 60 % |
| Principle chemical reaction | $H_2 + 1/2O_2 \rightarrow H_2O$ | $H_2 + 1/2O_2 \rightarrow H_2O$ | $H_2 + 1/2O_2 + CO_2 \rightarrow H_2O + CO_2$ |

Fuel cells are designed to produce electricity ranging from 300 kW to 20 MW for large-scale uses, 10 to 300 kW for medium-scale uses, and up to 10 kW for small-scale uses. (Tazvinga et al., 2017). Fuel cells use $H_2$ gas as a fuel. As a result, sulfur dioxide ($SOX$), nitrogen oxide ($NOX$), and particulate matter are virtually entirely absent from power generation. Moreover, fuel cells are extremely efficient, appropriate for combined heat and power (CHP) and fuel-flexible. There are various drawbacks to fuel cells, including the fact that alkaline fuel cells (AFC) are sensitive to $CO_2$ in both the fuel and the air; and molten carbonate fuel cells (MCFC) have a low power density and take a long start-up time. (Funabashi, 2016).

#### 2.4.1.3.4 Fuel cells for distributed generation

A complete fuel cell system includes a fuel extractor that provides $H_2$ to the cell, which further generates DC electricity (*Figure 2.5*). The DC output voltage of the fuel cell goes through a number of steps before being converted into high-quality AC power (Akorede et al., 2010b; Funabashi, 2016; Tazvinga et al., 2017). The DC boosting converter will increase the fuel cell's output voltage, while the DC-DC controller will help to keep the output voltage at a fixed value. This last is converted to AC voltage by a voltage source inverter (VSI). A LC filter is used to reduce harmonics and ensure high quality AC power. The AC power is then injected to the power grid via a transformer, and a percentage of it can be supplied back to an active / reactive power controller which ensures the quality of power injected to the network (Candusso et al., 2002; Tazvinga et al., 2017; Tomal and Gabbar, 2015).

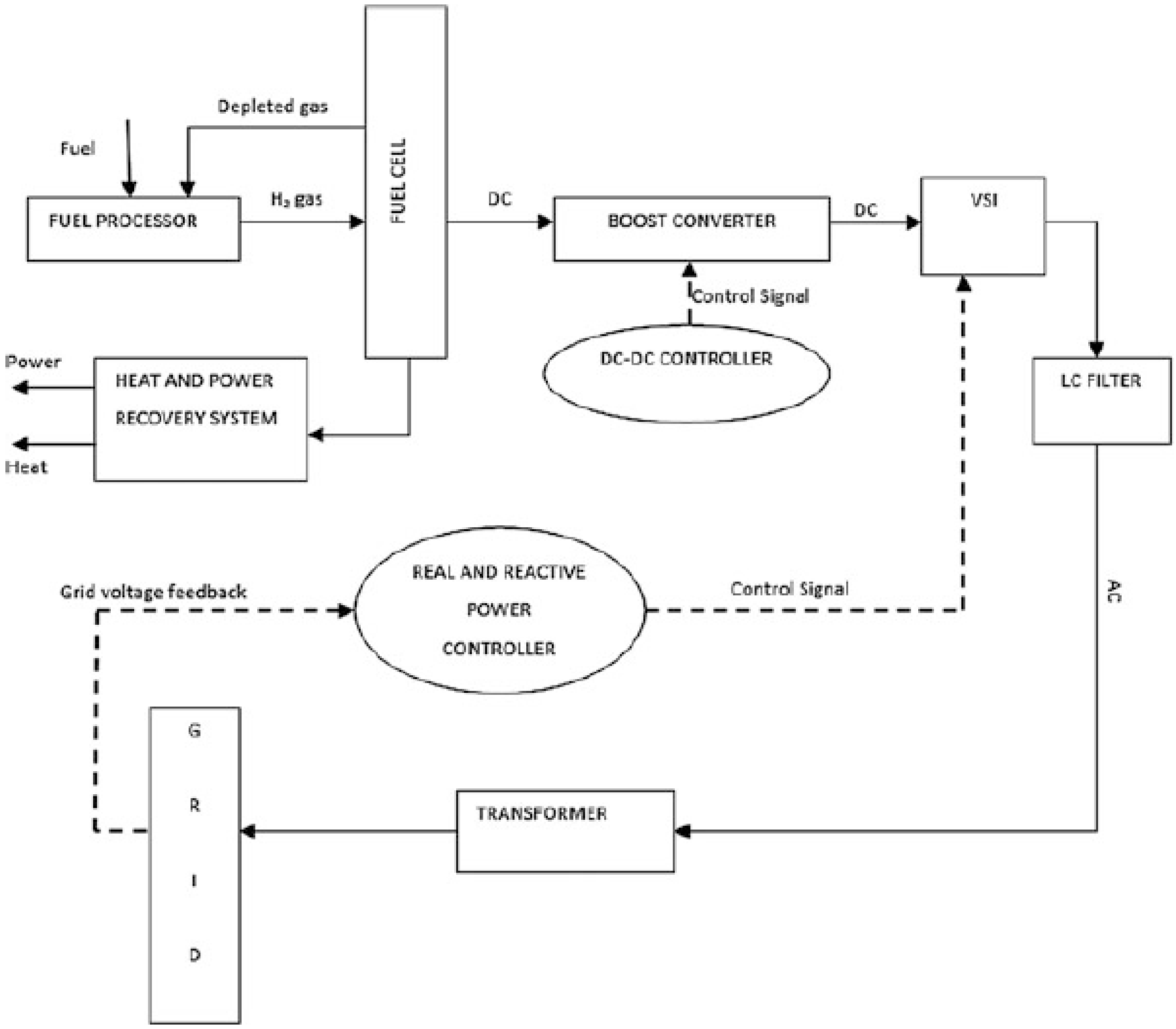


*Figure 2.5 Schematic representation of a fuel cell micro-plant (Huang et al., 2006; Tazvinga et al., 2017; Tomal and Gabbar, 2015)*

In general, before choosing any DG technology, it is critical to examine if whether it is reliable, inexpensive, and robust. Therefore, despite fuel cells have great efficiency as well as they are environmentally friendly and could support many start-and-stop cycles, the fuel cells are not a popular option for DG because the capital cost of a fuel cell is extremely high due to the high costs of the components required for manufacturing a high-quality fuel cell. Furthermore, the lack of real fuel cell applications data contributes to limited researches for lowering their high costs. Minimizing the system's overall cost including the cost of the materials used for installing fuel cells as well as the payback period of installing such a systems could be a potential topic of research in the future (Tazvinga et al., 2017).

### 2.4.2 Distributed renewable energy micro-plants

In distributed generation technologies, renewable energy is a primary source of energy (Sayed and Gabbar, 2017). According to (Masoum and Fuchs, 2015), the power generation composition of existing energy systems (coal, natural gas, nuclear power, hydropower plants, etc.) in the future will be mainly natural gas-fired power plants, distributed renewable energy micro-plants (Fuchs and Fuchs, 2007) and storage facilities. Grid capacity expansion through the integration of distributed renewable energy systems has emerged as a global trend, with the cost of renewable energy system accessories such as PV, biomass, and wind energy projected to reduce significantly as a result of lower costs (Iweh et al., 2021; REN21, 2017). In general, RES are those energy sources that are continuously replenished by natural phenomena. RES can be found in any area of the planet. However, access to such resources is limited by their availability and their operation cost.

DREMPs are distributed generation technologies that use RES as the main source of energy. DREMP are often scattered, small-scale generating units, thus the term micro-plants is used in this thesis. According to (Masoum and Fuchs, 2015), DREMPs are smaller than 100 MW, whereas conventional power plants use units ranging from 100 MW to 600 MW or even 1200 MW. Most DREMPs are considered as non-dispatchable sources that are highly intermittent. This means that their energy output varies over time due to natural factors that cannot be controlled such as solar irradiance or wind speed (Afework et al., 2021; Leisch and Cochran, 2015).

DREMPs become more and more attractive and highly important for many countries (Alsokhiry and Lo, 2013; Masoum and Fuchs, 2015; Shamseldein and Abdelaziz, 2019; Tazvinga et al., 2017). They have been developed to reduce the constraints of conventional power systems and reduce the reliance on producing electric energy from fossil fuels (Tazvinga et al., 2017; Yerasimou et al., 2021). In addition, DREMPs demonstrated many technical, economic and environmental advantages such as reducing electricity losses along transmission and distribution lines (US EPA, 2015b), strengthening energy security, enhancing power systems stability, reducing the electricity-price and its fluctuations, increasing the reliability and energy efficiency, minimizing the GHG emissions and decreasing the dependency on fossil fuels (Tazvinga et al., 2017). In addition, they are easy to install (Tazvinga et al., 2017) and faster to implement due to their small size and no need for large terrain compared to large conventional facilities and their associated transmission infrastructure. Furthermore, concerns about global warming and sustainability have prompted many countries to boost their use of DREMPs, such as solar cells and wind micro-turbines, to generate electricity (Shamseldein and Abdelaziz, 2019). Moreover, Electric vehicles (EVs) and Battery Energy Storage Systems (BESS) connected to the power network are likely to become increasingly widespread in the next few years allowing high penetration levels of DREMPs (Shamseldein and Abdelaziz, 2019). By 2030, RES in both distributed micro-plants and centralized macro-plants (utility-scale) are assumed to account for 34% of global energy (Adefarati and Bansal, 2016). As per (Howlader et al., 2013), DREMPs are entering the world energy market at a similar rate as nuclear energy did in the 1970s and 1980s. Due to the vast benefits of DREMPs, they will be an important component of the future smart grid system (Funabashi, 2016).

In this thesis, the term DREMPs refers to small-scale power plants located at or near electricity consumers. DREMPs operates in both grid-connected or standalone modes such as in off-grid or rural or peri-urban locations. Solar PV, wind micro-turbines, fuel cells, small hydropower, biomass, geothermal, waste-to-energy, biofuels, and ocean (waves and tidal) energy systems are all examples of distributed renewable energy micro-plants (Funabashi, 2016; Tazvinga et al., 2017). These small production units can be used to meet heating, cooling, remote power, baseload power, peaking power, backup power, and power quality requirements.

### 2.4.2.1 Solar Photovoltaic (PV) technology

#### 2.4.2.1.1 Introduction

The photovoltaic effect, which occurs when semiconductor materials come into contact with solar irradiance and generate an electric current, can be successfully applied to produce electricity thanks to the technology of solar cells based semiconductors. The first-generation of solar cells are primarily silicon-based semiconductor. This technology was first developed and used for space applications, later on, this technology has been utilized on the earth as a viable method of generating power since the mid-1970s, and it is becoming increasingly appealing as the cost of PV modules has decreased in latest years. As progress was made to improve the energy efficiency of first-generation solar cells, market has grown, allowing for large-scale fabrication and intensive researches which lead to further lowering investment costs. The first-generation solar cells are mostly employed in residential rooftop installations. They have a poor energy efficiency and, but they are extremely durable and are quite expensive to manufacture. In the presence of solar irradiation, each silicon cell may produce a maximum of 0.6 V, and a module efficiency of up to 15% can be achieved under normal conditions of 25 °C and 1000 W/m2 of solar irradiation. (Pastuszak and Węgierek, 2022; Tazvinga et al., 2017).

The second-generation solar cells is based of thin-film technology, lowering the expensive costs associated with first-generation solar cells. They do not surpass the first-generation in terms of energy efficiency that is below 20%, and they frequently employ cadmium telluride (CdTe), hydrogenated amorphous thin-film silicon, or copper–indium–allium–diselenide (CIGS). It is frequently utilized for building-integrated photovoltaic (BIPV) projects as well as solar power plants due to its thin design. PV modules based CIGS and CdTe have lesser efficiency than silicon-based PV modules, but they have a longer-term stability and lower cost (Pastuszak and Węgierek, 2022; Tazvinga et al., 2017).

Third-generation solar cells are the most efficient among others, but they are also the costliest, as they incorporate a range of materials such as silicon wires and nanotubes. This generation of solar cells may include copper–zinc–tin–sulphide solar cells, quantum dot solar cells, and perovskite solar cells. Several laboratories and institutions are working on making this generation of solar cells more cost-effective to help PV technologies gaining acceptance as a cost-effective and efficient source of power (Pastuszak and Węgierek, 2022; Tazvinga et al., 2017).

The fourth generation solar cells involves the low cost or low flexibility of thin film polymers together with the endurance of “modern inorganic nanostructures" like metal nanoparticles and metal oxides or "organic nanomaterials" like carbon nanotubes, graphene, and graphene derivatives (Pastuszak and Węgierek, 2022).

###### *2.4.2.1.2 Working Principle of Solar Cells*

The solar cell is made by utilizing the photoelectric feature of semiconductors, which produces electrons and holes in the semiconductor when a high-energy photons hit its surface. The flow of electric charges created by electron mobility can be captured as DC current. Semiconductor materials have a broad variety of physical characteristics, including thermal energy conversion and light emission, making them a viable choice for a variety of applications. They can be doped to produce n-type and p-type semiconductors. When these two types combined, form a *p*–*n* junction, which is the fundamental component of all electronic devices-based semiconductor, such as solar cells. The most widely utilized semiconductor is silicon which is part to group IV of the periodic table. There are various types of semiconductors that can be utilized to make a solar cell, such as organic semiconductors, but silicon-based solar cells are the most common (Tazvinga et al., 2017). *Figure 2.6* and Figure 2.7 show the fundamental working principle of a solar cell.

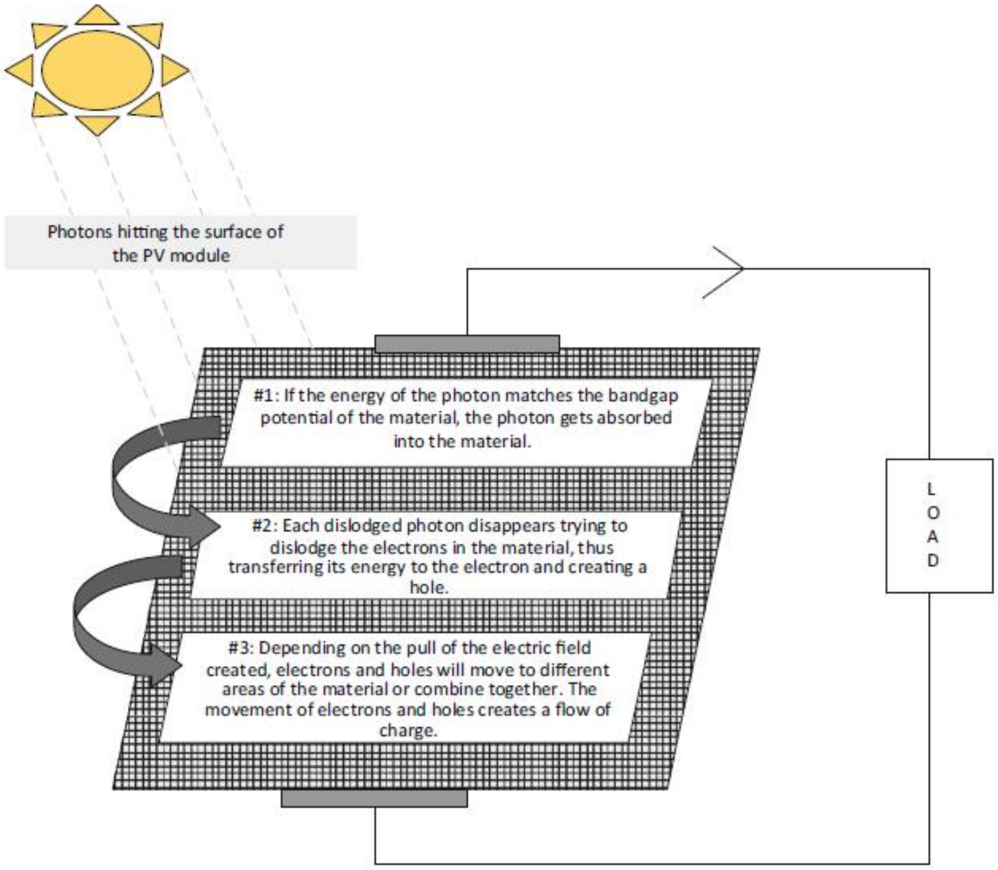


*Figure 2.6 The fundamental working principle of a solar cell*

#1: If the energy of the photon matches the bandgap potential of the material, the photon gets absorbed into the material.
#2: Each dislodged photon disappears trying to dislodge the electrons in the material, thus transferring its energy to the electron and creating a hole.
#3: Depending on the pull of the electric field created, electrons and holes will move to different areas of the material or combine together. The movement of electrons and holes creates a flow of charge.

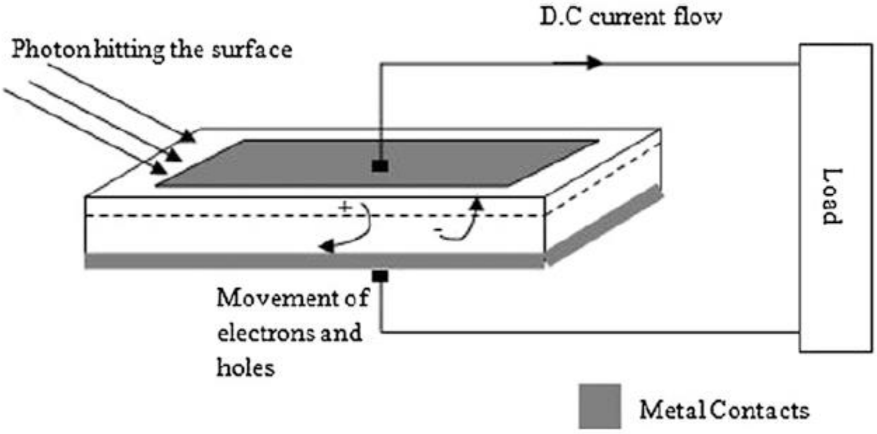


*Figure 2.7 Schematic representation of a solar cell showing the working principle a solar cell (Tazvinga et al., 2017).*

The photon energy required to dislodge electrons from a semiconductor material is seen to be dependent on the semiconductor material's bandgap. To dislodge electrons, photon energy must surpass the bandgap potential of the semiconductor. Silicon-based semiconductor, for example, has a bandgap of 1.17 eV (Balkanski and Wallis, 2012). A single photon's energy is transmitted to the semiconductor, resulting in a movement of charges in the form of DC electric energy. This energy can be quantitatively expressed as *Eq. 2.2* (Tazvinga et al., 2017):

*Eq. 2.2:* $$E_p = hv$$

Where $h$ represents the constant of Planck ($h = 6.625 \times 10^{-34}$ J.s), $E_p$ is the energy in a photon (J), $v$ is the frequency (Hz), and:

*Eq. 2.3:* $$v = c/\lambda$$

Where $C$ is the speed of light ($C = 3\times10^8$ m/s), and λ is the wavelength (m).

This photon energy ($E_p$) is transformed, in the semiconductor, to current source produced by photon ($I_{ph}$). A PV panel is modelled as a current source in parallel to a diode (due to the p–n junction of the semiconductor) and a parallel resistance $R_p$ (representing the resistance of the cell). All are in series with a resistance $R_s$ (representing the internal resistance of the diode). *Figure 2.8* shows the PV panel equivalent circuit. The difference between $I_{ph}$ and $I_d$ (current of the diode that flows when there is no irradiance and the diode is forward-biased) determine the output current $I$ of the PV panel that reaches the load. V represents the DC output voltage across the load (Kalogirou, 2013).

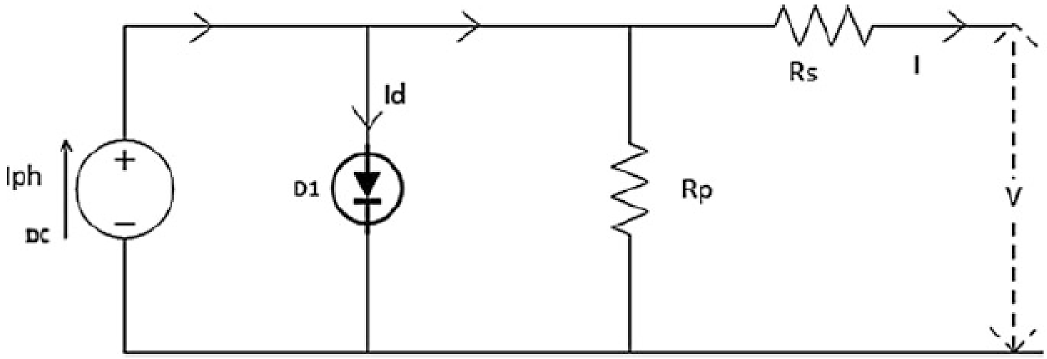


*Figure 2.8 The equivalent circuit of a PV cell (Kalogirou, 2013)*

### *2.4.2.1.3 Arrangement of solar cells to form a PV module*

Because the maximum achievable potential difference along a solar cell based monocrystalline silicon is only about 0.6 V, its structure and design must be altered for practical usage. A PV module is made up of several solar cells coupled together with additional protective components. To boost the energy output, many of these modules can be placed in rows to form an array. Depending on the application, PV cells can be coupled in series, parallel, or series–parallel configurations. The current output is increased by parallel connections, while the voltage output is increased by series connections. *Figure 2.9* shows a schematic illustration of $N_{SM} = 3$ (number of series-connected PV modules) and $N_{PM} = 5$ (number of parallel-connected PV modules) where $I_M$

is the total generated current by all these modules and $V_M$ is the DC voltage throughout the entire array (Tazvinga et al., 2017).

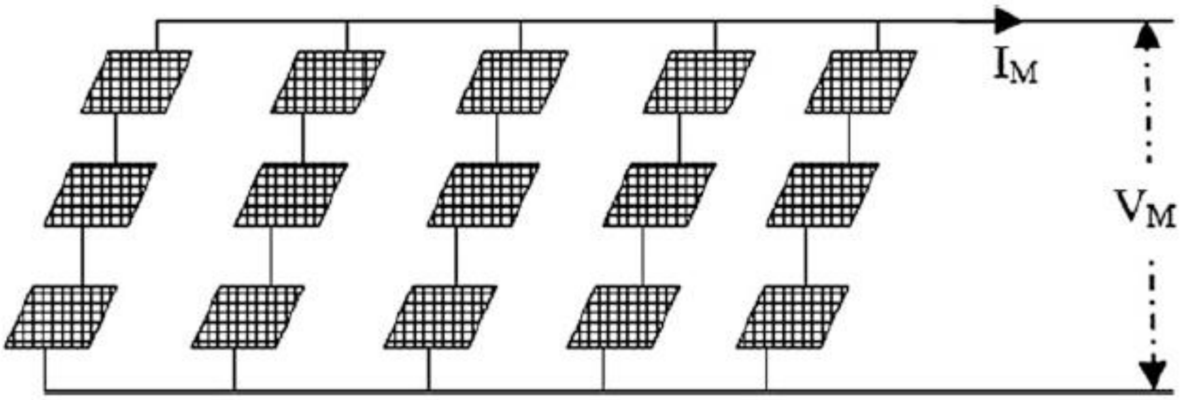


*Figure 2.9 A PV array formed by three series modules and five parallel modules*

### *2.4.2.1.4 Factors that affect the operation of a PV cell*

Solar energy is essential to the operation of Photovoltaic modules, thus it is crucial to learn more about how it affects the power output of a PV module. *Figure 2.10* illustrates the *I–V* curve under various levels of solar irradiation falling on a first-generation silicon solar cell. It is clear that the output power of the PV cell is directly proportional to the levels of solar irradiation (Chaibi et al., 2019; Labouret and Villoz, 2010).

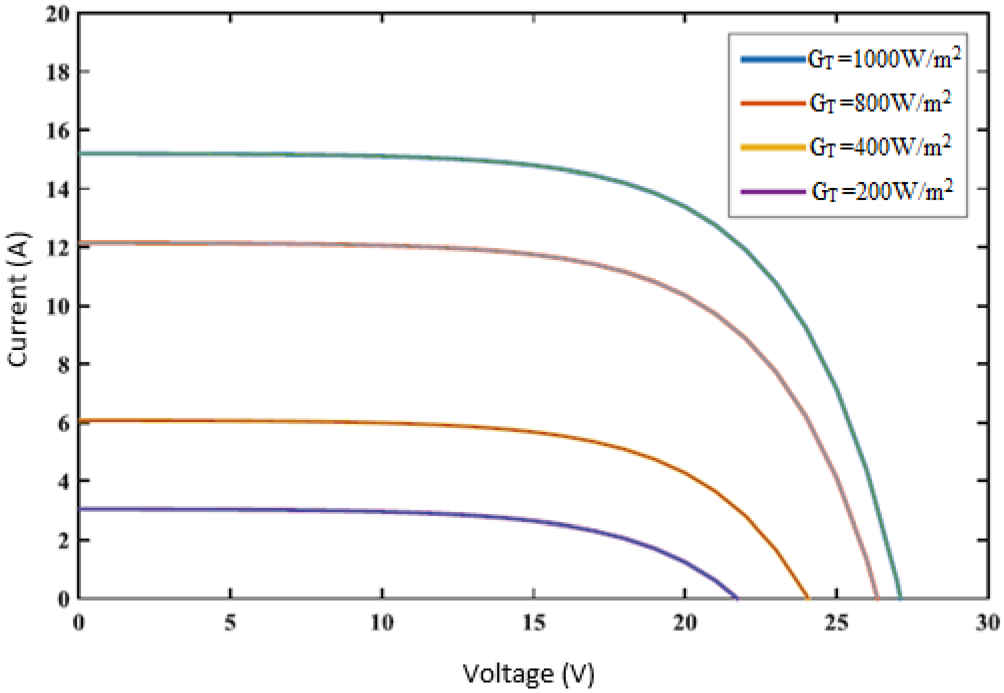


*Figure 2.10 I–V curves with various solar irradiance ($G_T$) (Labouret and Villoz, 2010).*

Aside from solar irradiation, there are many other factors that influence the operation and efficiency of a PV cell, which are listed in *Table 2.4*. To maximize the modules' efficiency, all of these factors must be considered before constructing a PV module arrangement (Tazvinga et al., 2017).

*Table 2.4 Impact of various parameters on PV module performance (Blazev, 2012).*

| **Factors** | **Impact on the performance of the PV cell** |
|---|---|
| Ambient temperature | Even at optimal operating point, only about 10 to 15 % of solar irradiance is transformed to electrical energy; the remainder is converted to thermal energy, therefore high ambient temperatures do not always signify high power production. |
| Moisture interference | The PV modules can degrade as a result of moisture that enters the PV modules through the degradation of protective layers. The use of bad-quality materials, extreme temperature conditions, physical handling, and more are all reasons for the fast degradation of protective layers. |
| The presence of reflective materials | Any reflecting materials present on the module's surface work against the conversion of solar energy into electricity since they will cause some light energy to be reflected and lost. Due to this, PV modules must have antireflective coating. |
| The quality of the used materials | Since PV system is used in locations with extremely high levels of solar irradiance and is thus vulnerable to harsh environmental conditions, low-quality materials would hasten the degradation of the PV cell. The materials used for the modules must be able to sustain natural disasters like hail and lightning because they are exposed to them. |
| Dimensions of the PV module | The PV module output is influenced by its surface area. However larger dimensions also mean more expensive initial investments. |
| Operating point | The PV cell can operate efficiently if its operating point is kept within a few degrees of its optimum operating point. Employing trackers will help to make sure that the PV cell is functioning as closely as possible to its optimum operating point. |
| Tilt angle of the PV module | The angle that the module forms with the horizontal plane on which it is installed is known as the tilt angle. When this angle is changed according to the seasons, the PV modules will produce more electricity. Despite their cost, tracking systems can increase energy output but will use part of the energy produced for the motion. |

#### 2.4.2.1.5 Photovoltaic Systems for DREMP

Regarding the deregulated electric paradigm embraced by most countries, DREMPs are unquestionably the way forward. PV technology, which was discussed extensively in the preceding subsections of this thesis, is one of the most popular form of DREMPs that can be utilized. PV systems use the solar irradiance, a resource that is widely available in most regions around the globe and specially in MENA region. PV micro-plants do not necessitate as much maintenance as other DREMPs do. The PV micro-plants are robust and undergo extensive testing prior to use to guarantee that they can resist under bad weather situations (Tazvinga et al., 2017). It is also important to mention that PV micro-plants are one of the few types of renewable technologies that can be easily implemented in residential, commercial, or office buildings. Nevertheless, shading effect, even by a tiny bird flying over the PV panels might influence the generated power to drop resulting in technical concerns like voltage fluctuations on the power network. The output power of PV micro-plant is highly intermittent, which implies that it may not be continuously accessible when needed, lowering its reliability as a satisfactory form of energy (Tazvinga et al., 2017).

Despite the fact that PV modules are the basic building blocks of a PV micro-plants, additional devices are required for the system to find practical uses. *Figure 2.11* shows the several components of a complete PV micro-plant connected to the grid with a battery backup as ESS. The PV micro-plant collects energy from the sunlight and transforms it to a DC electricity, which is then converted into a desired level by a DC–DC converter. A battery energy storage system (BESS) connected in the DC-bus stores excess electricity in the battery and provides it back when needed. A DC/AC inverter transforms the DC-bus voltage to AC voltage to satisfy the AC load requirements (Funabashi, 2016).

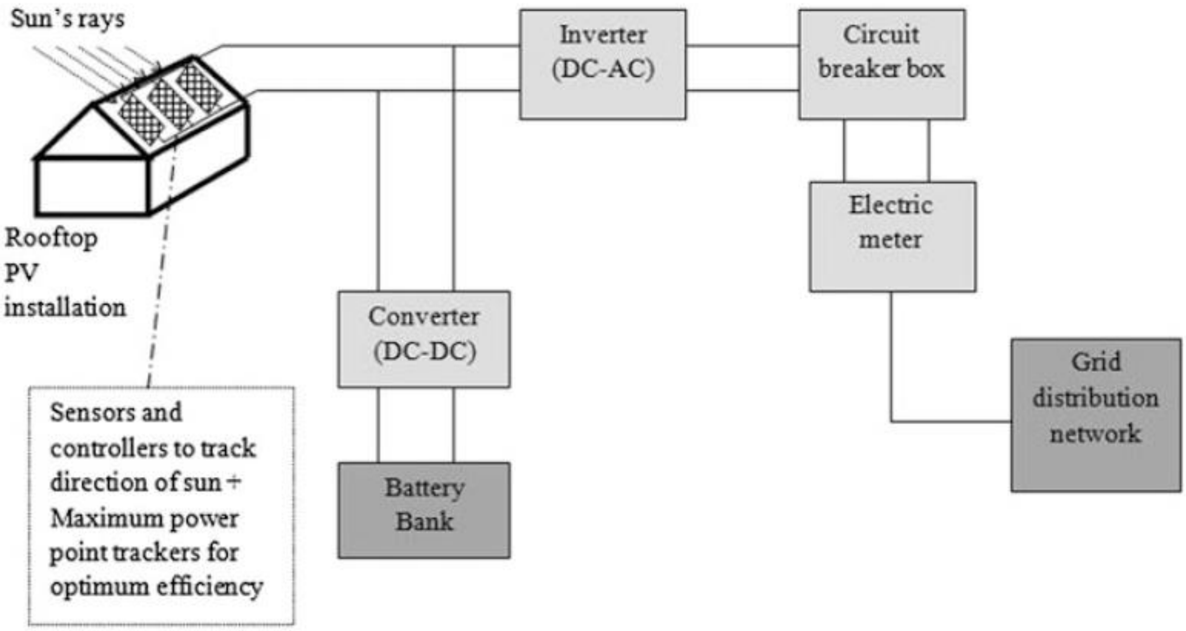


*Figure 2.11 A block diagram representation of a various elements of a grid-connected PV micro-plant with battery ESS (Khaligh and Onar, 2011).*

When the PV micro-plant operate in grid-connected mode, the inverter synchronizes its AC voltage output with the distribution network voltage. The energy is then transported to the network through a circuit breaker and an energy meter. Bidirectional energy meter will be required in countries that adopt feed-in tariffs, in which the utility pays the prosumer for supplying power. The entire amount of energy sent to the distribution network is given in Eq. 2.4 (Kalogirou, 2013; Tazvinga et al., 2017).

*Eq. 2.4:*
$$E_{del} = E_{avail}\,\eta_{ab}\eta_{dist}$$

*Eq. 2.5:*
$$E_{avail} = \eta_{inv}\,E_{PV}$$

Where $E_{\text{del}}$ is the energy delivered to the grid, $E_{\text{avail}}$ is the energy available to the grid, $\eta_{\text{ab}}$ is the absorption rate of the grid, $\eta_{\text{dist}}$ is the efficiency of the distribution system, $\eta_{\text{inv}}$ is the efficiency of the inverter, and $E_{\text{PV}}$ is the energy output from the PV module.

During faults, the circuit breaker will be tripped to disconnect the PV micro-plant from power network. This action help protecting the PV micro-plant from any grid faults and avoid unnecessary maintenances. The PV micro-plant could then operate in off-grid mode to feed the small community such as houses, offices, and so on. Battery-based ESS is charged via DC/DC converter, which prevent them from overcharging caused by high-voltages of the PV micro-plant.

To boost ESS capacity, multiple batteries can be linked in parallel and series connection to form a battery bank. Lead–acid batteries are the most popular, but many other types can also be utilized such as lithium ion batteries and nickel–cadmium batteries (Catherine, 2021; Tazvinga et al., 2017).

#### *2.4.2.2 Wind Energy Conversion Systems (WECS)*

In this subsection, an overview of wind power (WP) generation and system evolution is briefly introduced. Thus, it presents a definition of the system with its fundamental principles, the construction of wind turbines, and the future trends of wind energy and its contribution to the world energy system.

##### *2.4.2.2.1 History*

Before the industrial revolution of the 19th century, almost all energy was used from renewable energy sources (RES). Wind was one of the first energy resources discovered, it was used in the transport by navigation more than 4000 years ago by the Egyptians. Later on it was developed to be used in daily life as in mills for grinding grain (Dekali, 2021; Mechter et al., 2015). The first windmills were designed by the Persians 2000 years ago, for the transport of water (Ashglaf, 2019). Between the years [1846- 1908], the Danish meteorologist “Paul La COUR” experimented using a wind turbine to rotate a direct current generator to produce electricity. In [1887-1888], the American “Charles Francis Brush” built the first wind turbine to drive a 12kW electric generator to feed his house with electricity using a battery as energy storage system (*Figure 2.12*) (Ashglaf, 2019; Dekali, 2021).

.

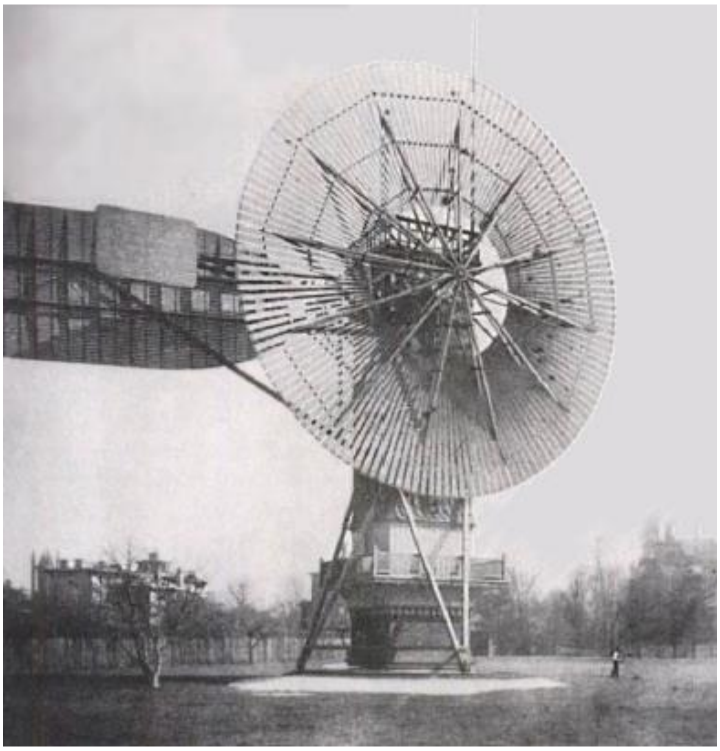


*Figure 2.12 First aerodynamic generator built by Charles F. Bruch (Camille, 2010).*

In 1957, one of La COUR's students, Johannes JUUL, invented the first wind turbine, the Gedser Turbine (*Figure 2.13*), which generates 200 kW of alternative current (Ashglaf, 2019).

*Figure 2.13 The Gedser Turbine.*

#### *2.4.2.2.2 Turbines Classification*

Wind turbines are classified according to the viewpoint of research areas; for instance, they are divided into two primary categories in terms of control (Ashglaf, 2019):

1- Fixed-speed controlled wind turbines
2- Variable-speed controlled wind turbines

In addition, based on the generated mechanical power, wind turbines are divided into three categories:
1- Small scale: less than 40 kW nominal power.
2- Medium scale: nominal power ranges from 40 kW to hundreds of kW.
3- Large-scale: more than 1MW nominal power (Adaramola, 2014).

In contrast, turbines can be divided into two categories according to their rotational axis:
1- Turbines with a horizontal axis
2- Turbines with a vertical axis

##### ***2.4.2.2.2.1 Horizontal Axis Turbines (HAT)***

Horizontal axis turbines (*Figure 2.14*) are the most widely used in WECS; they are made up of three blades, a shaft, an electrical generator, and a gearbox, which are all placed at the top of the tower in a nacelle (Ashglaf, 2019).

*Figure 2.14 Horizontal axis wind turbine.*

### *2.4.2.2.2.2 Vertical Axis Turbines (VAWT)*

Darrieus and Savonius turbines are the most widely used vertical axis turbines.

#### *2.4.2.2.2.2.1 Darrieus Wind Turbine*

Darrieus Wind Turbine (Figure 2.15) is one of the most popular vertical-axis wind turbines on the market. Its generator and transmission components are positioned at ground level, which seems to be the most attractive characteristic of this type. It can also capture winds coming from any direction. Unfortunately, these merits are offset by a reduction in mechanical energy capture since the winds received by the rotor have less energy. Furthermore, even though the generator and transmission are both positioned at ground level, maintenance is not simple since the rotor must be removed. Because of these factors, vertical axis wind turbines have been less popular in latest years (Ashglaf, 2019; Dekali, 2021) .

*Figure 2.15 Darrieus Wind Turbine.*

#### *2.4.2.2.2.2.2 Savonius Wind Turbine*

Savonius wind turbine type (*Figure 2.16*) works on the idea of differential drag force, which means that the wind's force on each blade is different. As a result, produces a torque that causes the turbine to rotate (Ashglaf, 2019; Casini, 2015).

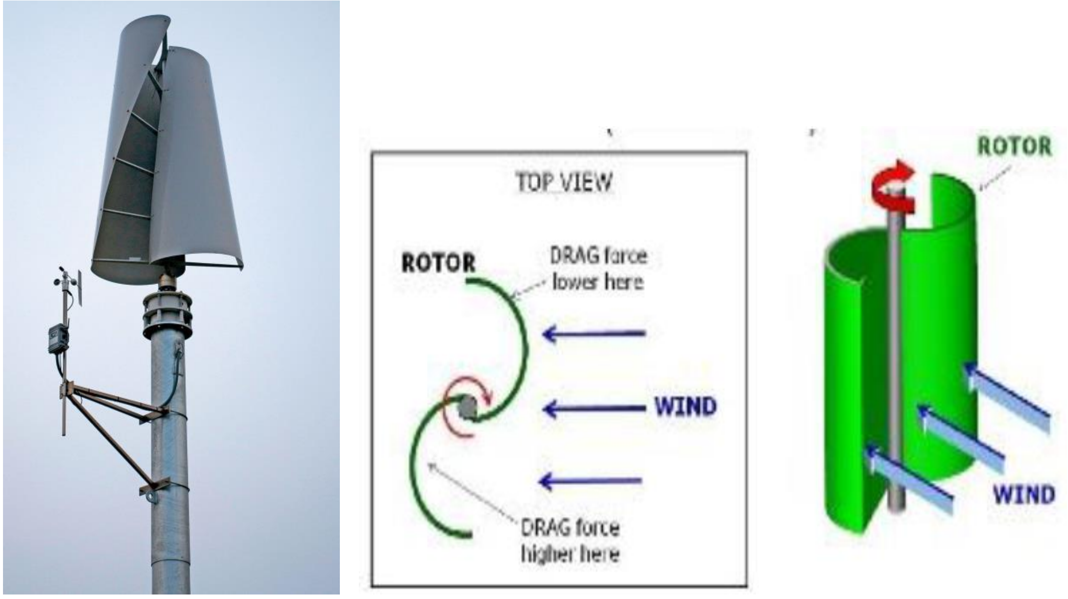


*Figure 2.16 Savonius vertical wind turbine.*

### *2.4.2.2.3 Operation Types of wind turbines*

Wind turbines with a horizontal axis are older and more common compared to wind turbines with vertical axis. Models with a vertical axis generate less power and are less widely recognized (Horch, 2018).

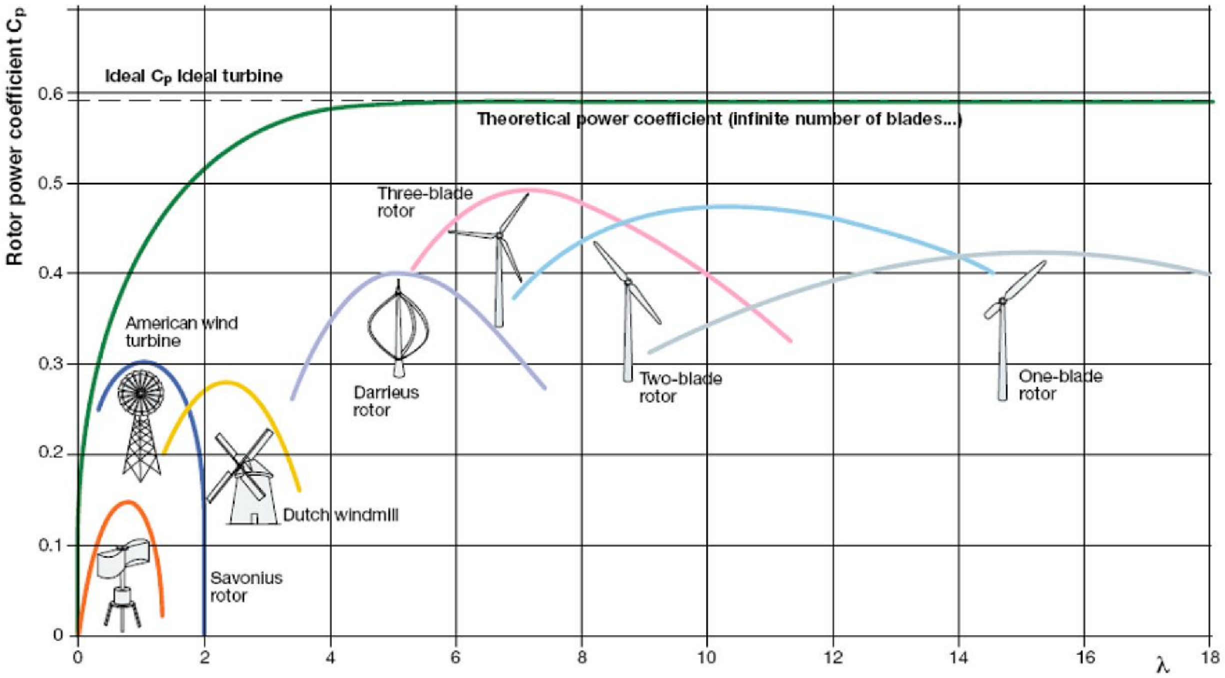


*Figure 2.17 The power coefficient Cp evolution according to the type of wind turbine.*

*Figure 2.17* illustrates why most modern wind turbines have three blades. In fact, it is with the number of blades that the power coefficient *Cp*, which is an important part of the wind turbine's energy formula, reaches its maximum value [1.5]. *Figure 2.17* also shows that in order to operate at a maximum power coefficient *Cp*, then $\lambda$ must be kept at a constant value (Dekali, 2021). Because blade radius after construction and wind speed are both out of control and cannot be changed, thus the rotational speed $\Omega$ must be adapted in real time. This adaptation is called variable speed control of wind turbine that allows working constantly at the maximum power point (Dendouga, 2020; Horch et al., 2019).

### 2.4.2.3 Hydroelectric micro-plants

The autonomous water falling from a higher level to the bottom level has a high gravitational force that may be successfully transformed to electricity. This form of electricity is called as hydropower or hydroelectricity. Hydropower is a renewable energy source that may be utilized for distributed generating thanks to its small-scale applications. This technology of generating electricity was first used in the nineteenth century. In 1878, William George Armstrong at England constructed the first successful hydropower system, and the Schoellkopf Power Station in Niagara Falls commenced its operation in 1881 (NiagaraFallsInfo, 2017).

#### 2.4.2.3.1 Overview

The accessibility to water bodies restricts the construction of a hydropower plant. A huge river is frequently necessary to produce considerable amounts of electricity. Nevertheless, many smaller water bodies exist in many regions over the world, commonly near communities, in the form of backwaters, river distributaries, and lakes that can be used for micro-hydropower applications to generate electricity for local residential or commercial load centers. As a result, it becomes a suitable option for DG. Besides the small water sources, the flow of water from any existing reservoirs or dams, as well as the water treatment facilities, can all be used to create a hydropower micro-plant. According to (Tazvinga et al., 2017), a micro-hydropower plant must generate less than 50 MW of a maximum power production to be classified as a small hydropower plant. However, this depend on the cut-off imposed by different governments and intuitions as discussed in second section of this chapter. In the situation of water flowing from a high head, an illustration of the places where hydroelectric micro-plants can be constructed is given in *Figure 2.18*.

The first potential location of hydroelectric micro-plant is right adjacent to the dam, allowing direct water passage from the dam to the turbines without significant head loss. The second location is close to water treatment stations. In this case, the water supply from a sufficiently high head may also be useful for hydroelectric micro-plant to generate electricity (Van Dijk et al., 2014). In these treatment stations, the water stored in reservoirs before sending it to nearby users can be used to generate small amounts of electricity. Very close to the users, it is feasible to build hydroelectric micro-plants at pressure-reducing stations that have the role of reducing the water high-pressure to protect the users' pipelines system. This water would be at very high pressure before entering the station and can supply significant amount of electricity for local loads. Hydroelectric micro-plants can also be constructed even if the water pressure is not enough in the case of small heads. In such cases, the two or more extremities of the dam can be used to supply water in sufficient pressure to produce electricity (Tazvinga et al., 2017). In this case, the hydroelectric micro-plant will be equivalent to the one constructed next to rivers.

It is also possible to use the water from irrigation systems to generate electricity in areas that use flow dams for agriculture. Although there may be several places suitable for the construction of a hydroelectric micro-plant, the water flow and pressure must be determined prior to any construction. The project's economic feasibility, as well as other potential societal consequences, notably environmental consequences, must be assessed (Van Dijk et al., 2014).

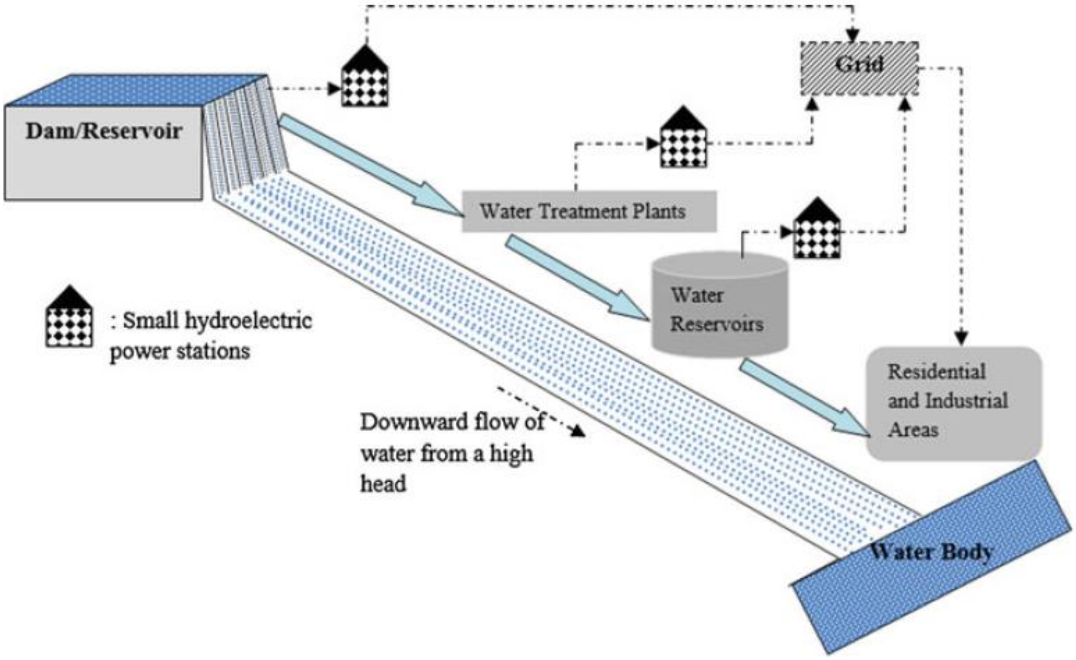


*Figure 2.18 Illustration of the different places where hydroelectric micro-plants can be constructed (Van Dijk et al., 2014).*

### 2.4.2.3.2 Components of hydroelectric micro-plants

The primary components of hydroelectric micro-plant include in general an electric generator, a transformer, and a turbine. Table 2.5 summarizes the various kinds of turbines that can be utilized for micro-hydropower generator (Van Dijk et al., 2014). Turbines work by converting the potential energy of water in a high altitude into kinetic energy of water flowing through a penstock and nozzle for hitting a series of blades mounted on a rotor with a shaft linked to its center generating a rotational mechanical energy (Tazvinga et al., 2017). The *Eq. 2.6* defines the torque of the turbine, where is the *Eq. 2.7* defines its mechanical power (Tazvinga et al., 2017).

*Eq. 2.6:*
$$T = \rho Q \left(R_{in} V_{in} - R_{out} V_{out}\right)$$

*Eq. 2.7:*
$$P = \omega T$$

Where $T$ is the Torque of the turbine (Nm), $P$ is the output power of the turbine (W), $\rho$ is the density of the fluid (kg/m$^3$), $Q$ is the flow rate of the fluid (m3/s), $R$ is the radius of the turbine (m), $V$ is the velocity of the fluid hitting the blades tangentially (m/s), and $\omega$ is the rotational speed of the turbine (rad/s).

The turbine's shaft is coupled to an asynchronous or synchronous generator (SG). The essential working concept is the same regardless of the type of generator employed (Mishra et al., 2012). Voltage regulator, turbine controller, gearbox, switchgear, backup power supply, sensors, and more are complimentary components that help in improving the quality of power. However, electronic or electromechanical voltage regulators can be utilized to maintain a good quality of voltage profile. In addition, speed governor, which regulate the water flow, and load governor, which keep the turbine operating at maximum load, are used to regulate the turbines' speed. When there are problems or anomalies, breakers are utilized to separate the hydroelectric micro-plant from the grid. For the transformer's protection against faults, switches and relays are utilized. For the seamless connection of the energy produced by a hydroelectric micro-plant to the grid, switchgear and protection are also crucial components. To control voltage and current levels, respectively, voltage and current transformers are utilized. Reverse power relays are employed in the cases of induction generators to stop them from operating in motor mode. For measuring the amount of electricity (injected to / or received from) the grid, bidirectional power flow meters are necessary (Tazvinga et al., 2017).

*Table 2.5 Types of turbines used for hydroelectric micro-plants (Van Dijk et al., 2014).*

| Turbine type | Description | Altitude of head | Efficiency |
|---|---|---|---|
| Kaplan turbines | Rotor is positioned axially in opposition to the flow of water, which, when it strikes the rotor, causes its blades to rotate. | 2-40 m | 91 % |
| Cross-flow turbine | utilizes curved blades that are connected to a rotor; water then impacts a different blade from the interior of the rotor and exits toward the tailarce. | 2-200 m | 86 % |
| Turgo turbine | Numerous split-cured buckets are simultaneously hit by angled jets of water. | 50-250 m | 85 % |
| Francis turbine | Rotor is positioned radially in relation to the direction of the water flow, allowing water to enter inside to turn the blades before exiting axially. Additionally, it can let axial water flow into the rotor, in which case the turbine is known as a Francis mixed-flow turbine. | 25-350 m | 94 % |
| Pelton turbine | A wheel turns by being blasted with tangential jets of water through nozzles onto split, curved buckets that have been positioned on its rim. | 50-1300 m | 90 % |

### 2.4.2.3.3 Hydroelectric micro-plants for Distributed Generation

Hydroelectric micro-plant is viable source of electricity in distributed generation technologies for the renewable energy mix. It is feasible to make use of many preexisting systems such as dams, water reservoirs, water treatment plants, irrigation systems, pressure-reducing stations, and wastewater systems with low capital costs to construct several hydroelectric micro-plants in different regions. However, maintenance should be conducted regularly to guarantee the plant's smooth functioning, particularly before and after severe weather conditions such as severe storms and rain (Tazvinga et al., 2017).

The efficiency of a hydroelectric micro-plant depends on the height of head in the location where it will be constructed and the type of flow. One of the previous methods to test hydroelectric micro-plants was to build a turbine model prototype and test it on site or use a historical data and modify it to the environment and situation. Computational flow dynamics studies have aided researchers and engineers in using simulations to avoid the costly process of prototype model while also improving turbine efficiency (Ardizzon et al., 2014). Because the turbine is such an important part of a hydropower micro-plant, studies are being conducted to improve the characteristics and design of existing models by analyzing the impact of selecting the right turbines for different levels of head, turbine erosion, turbine propeller variation, and speed control of the turbine. This last is also an important research area in the case of hydroelectric micro-plants, since it provides more flexibility during variations in head or flow. In addition, Diverse generators' behavior may be investigated and monitored in various operational situations, including remote electrification and grid-connected operations , as well as during natural disasters like landslides and floods (Tazvinga et al., 2017).

Hydroelectric micro-plants make advantage of using an accessible and reliable resource that produces no pollutants or emissions while being in service. Because of their capability to adjust under fluctuating demand, these micro-plants frequently enhance the stability of the power grid and they could be considered as efficient energy source. Nevertheless, more research is needed to examine its economic and financial consequences, the social impact on remote communities, the impact on the biosystem close to the site, improving the design of electromechanical materials, and conducting detailed investigations into the multiple disciplines of science that forms the basic working principles of a hydroelectric micro-plant (Tazvinga et al., 2017).

### 2.4.2.4 Geothermal Technology

#### 2.4.2.4.1 Introduction

The exploitation of geothermal energy for electricity generation, heat pumps, and other direct applications has expanded dramatically in the 30 years as a result of government regulations to exploit geothermal resources and growing public awareness of using environmentally friendly resources of energy. Geothermal energy total installed capacity has increased from about 6832 MW to about 15,854 MW in 1995 and 2022 respectively (ThinkGeoEnergy, 2022). Where is geothermal electricity generation has jumped from about 38,038 GWh to about 73,549 GWh in 1995 and 2015 respectively (REN21, 2015). Geothermal energy technologies for electricity generation is deployed in 21 countries throughout the world (Fridleifsson, 2001). This demonstrates that power system operators and utilities have adopted geothermal energy because of its low environmental effects, high energy efficiency, reliability, reduced maintenance and operational costs, and its independence from weather conditions. However, with current technologies, just 6% of the geothermal energy has been used for various applications. Moreover, the electricity generated by geothermal resources accounts only for 0.3 % of the total worldwide electricity generated by all resources. Geothermal energy plays a vital role generally in countries that already adopted geothermal resources for their energy mix (Tazvinga et al., 2017).

Around 1800 miles below the earth’s surface, molten rock that have melted into liquid may be found deep inside the earth’s crust due to the high temperatures under the earth surface. Geothermal energy is generated by taking use of the hot enough temperatures near the Earth's surface. In hotter close to the earth surface places, deep wells can be dug and cold water can be injected deep down. The water gets heated as it passes through shards in the rocks. It returns as steam and hot water, releasing energy that may be utilized to rotate turbines and produces electric power. Because the heat is continually created by the Earth and the water is replenished by rains, geothermal power is considered as a RES. Geothermal energy may sometimes produce certain gases from inside the Earth that might be slightly dangerous, however these gases can be easily handled. Thus, geothermal energy is considered highly environmentally friendly. In addition, the terrains for constructing geothermal energy plants are generally cheaper than the terrains of constructing gas, nuclear, oil, or coal power plants (Funabashi, 2016). Furthermore, when compared to traditional power plants, it is a clean and sustainable energy resource that helps to reduce the dependency of fossil fuels and GHG emissions (Tazvinga et al., 2017).

### 2.4.2.4.2 Advantages and disadvantages of geothermal energy

*Table 2.6* summarizes the benefits and drawbacks of geothermal energy.

*Table 2.6 Advantages and disadvantages of geothermal energy (Gupta and Roy, 2007; Kömürcü and Akpınar, 2009; Kose, 2007).*

| Advantages | Disadvantages |
|---|---|
| ✓ Low GHG emissions<br>✓ Reliable resource<br>✓ Reduced operating and maintenance costs<br>✓ Potential of long-term resource<br>✓ Long lifespans<br>✓ Highly available<br>✓ Considerable cost savings<br>✓ Adaptability and variety of applications<br>✓ Less reliance on fossil fuels<br>✓ Does not require as much area as conventional production<br>✓ High to medium efficiency<br>✓ Not intermittent nature (independent from weather conditions)<br>✓ No pollutant products | ✓ There are few naturally occurring vents and they may not always be appropriate in a specific place.<br>✓ Disturbance to both humans and animals<br>✓ High cost of construction<br>✓ Loss of vegetation<br>✓ A lack of specialists since geothermal energy sources are not widely available<br>✓ Impaired hearing<br>✓ Degradation and erosion of the soil.<br>✓ Influence on the watershed<br>✓ The total generating capacity of geothermal is very low.<br>✓ The risk of a volcano erupting is always possible.<br>✓ Long payback period<br>✓ Long period of construction |

### 2.4.2.4.3 Applications of Geothermal Technology

Geothermal technology has many applications such as electricity production, heat pumps as well as direct usage. However, these primary applications are dependent to the temperature of geothermal fluid and steam. Ground heat (10–20 °C), low-to-medium temperature geothermal resources (below 200 °C), and high-temperature geothermal resources (200–350 °C) are the three primary temperature groups (Tazvinga et al., 2017).

***The direct-use applications*** of geothermal energy make use of both high and low geothermal resource temperatures (Tazvinga et al., 2017). The direct applications of geothermal technologies may include the use of hot water to heat the buildings, industrial operations, cool, bath, pasteurize milk, fish farms, wash, fruit and vegetable drying, lumber drying, aquaculture, greenhouses, and so on.

***Geothermal heat pumps applications*** are renewable technologies that take advantage of the features of geothermal energy to generate cool in the summer and / or heat in the winter. Both domestic and industrial space cooling and heating may benefit from geothermal heat pumps application. The water after receiving heat from a residence in the summer is cooled by passing through a closed-loop system that includes a condenser and evaporator. The cooled water is returned to the residence, where it absorbs additional heat and cools it further (Tazvinga et al., 2017).

***Geothermal electricity generation applications*** are generally achieved by rotating turbine blades using geothermal steam generated in geothermal reservoirs under the surface of the earth. Direct dry steam, binary cycle, and flash steam are three geothermal power systems that make use of the geothermal steam to produce electricity. The most simple and cost-effective technique is a direct dry steam power plant, which enables steam to circulate continuously between the production and discharge wells. It rotates the turbine blades with high-temperature steam. Thus, the turbine rotates a shaft that is connected to an electrical generator to produce electricity as shown in *Figure 2.19*. The injection well is used to return the condensed water after leaving the condenser to the geothermal reservoir. This technology take advantage of the geothermal steam for eliminating the needs of installing further boilers based fossil fuels to operate the turbine. The direct dry steam power generation emit very low levels of GHG emissions into the environment. Additionally, these installations remove the requirement for fuel storage and transportation at the power station. Contrarily to the direct dry steam power plants, the flash steam power plants transform high-pressure hot water that is extracted from deep inside the ground into steam that rotates the turbine blades.

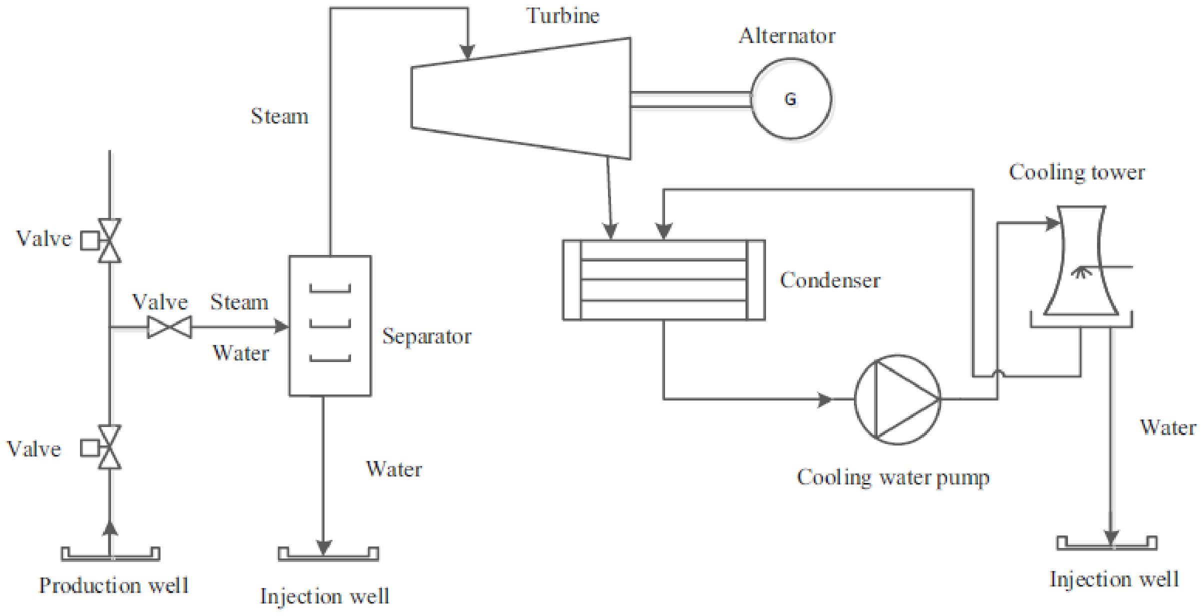


*Figure 2.19 Schematic representation of a direct dry steam power plant (UWEC, 2004).*

In comparison to flash steam and direct dry steam power plants, binary cycle geothermal technology operates in a different way since the geothermal steam does not come into direct contact with the turbines. From the pipes of the production well, the hot fluid drawn from the geothermal reservoir transported first to the heat exchanger where it exchange the temperature with a second lower boiling point fluid in the exchanger. The second fluid is evaporated to change its state to steam. This last is then used to rotate the turbine blades (*Figure 2.20*). Thus, the binary cycle power plant is the most economical method of generating electricity from low-temperature geothermal resources (Tazvinga et al., 2017).

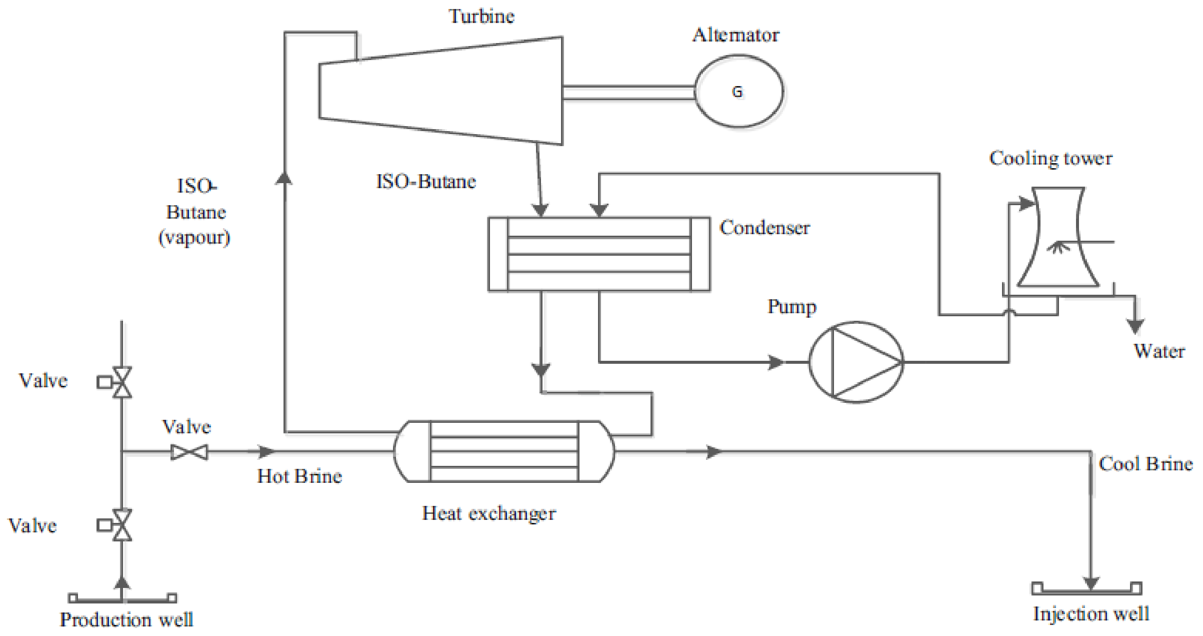


*Figure 2.20 Schematic representation of a binary cycle power plant (UWEC, 2004).*

#### 2.4.2.4.4 Issues related to Geothermal Technologies

Due to its high capital costs, lengthy building times, lengthy payback periods, difficulties modularizing, and difficulties accessing geothermal resources, geothermal power technologies are falling behind other RESs and traditional power plants in terms of installed capacity and yearly growth rate. In addition, several government and financial institution incentives for the advancement of geothermal energy technologies have lately decreased. Moreover, the adoption of geothermal energy is seriously hampered by the lack of competent personnel that can manage the maintenance and operation of geothermal power facilities throughout the world (Tazvinga et al., 2017). Furthermore, Direct Dry Steam and Binary Cycle geothermal technologies have some GHG emissions. Nevertheless, when compared to other RESs with variable production (i.e. solar and wind), geothermal energy technologies have a stable energy output. Furthermore, when compared to conventional power plants, geothermal has commercial advantage over them due to its independence from the crude oil price fluctuations (Tazvinga et al., 2017).

### 2.4.2.5 Biomass Technology

Thermochemical and Biological process are the two major categories used to classify energy generation from biomass. Concerning the biological processes, there are several technologies may be used, such as biological water–gas shift reaction, dark fermentation, direct and indirect bio-photolysis, and photofermentation. Combustion, gasification, liquefaction, and pyrolysis are the primary thermochemical processes. Combustion processes is direct burning of biomass fuel in the air to convert the chemical energy of biomass into heat, electricity or mechanical power by the employment of devices such as furnaces and stoves, steam turbines or boilers, respectively. However, this process is not suited for producing hydrogen for sustainable development since combustion has a low efficiency (10–30%) and produces by-products that are linked to pollution emissions. In the process of liquefaction, biomass is heated to temperatures between 525 and 600 K in water without the presence of air and at pressures between 5 and 20 MPa (Ni et al., 2006). In the liquefaction process, solvents or catalysts could be introduced. Nonetheless, it is challenging to obtain the aforementioned operational conditions, and hydrogen generation is low, making this process unfavorable for hydrogen generation. The hydrogen generation research institutions are paying close attention to other possible thermochemical methods including pyrolysis and gasification as well as biological methods like fermentation, biological water gas shift reaction, and bio-photolysis (Ni et al., 2006).

The following categories apply to the biomass resources (Ni et al., 2006):

(I) Municipal and industrial wastes including sewage sludge, municipal solid waste (MSW), and industry waste.

(II) Crops used for energy production, such as woody, aquatic, herbaceous, industrial, and agricultural crops.

(III) Agricultural waste and residues, including animal and crop waste.

(IV) Waste and residues from the forestry, such as trees, shrub, and logging residues, and the wastes of mill wood.

One of the most attractive biomass and bioenergy technologies, which tackles the present global concerns of global warming and energy poverty, is distributed biogas micro-plant. Studies first appeared in the middle of the nineteenth century, while naturally generated biogas has been known about since the seventeenth century. The combustible gas produced during biogas production may be utilized for a variety of purposes, such as lighting, cooking, heat production, and electricity generation, among many others (Tazvinga et al., 2017).

Because it is inexpensive and naturally occurring, biomass is commonly used as a source of energy, making up nearly 6.9% of the global energy production around the world (Funabashi, 2016).

#### *2.4.2.6 Comparison between Distributed Renewable Energy Micro-Plants*

RESs offer enormous potential for use in producing electricity or for other direct applications. *Table 2.7* presents a comparison between various DREMPs such as solar, wind, hydropower and geothermal micro-plants using different key performance indicators (KPIs) (Tazvinga et al., 2017).

*Table 2.7 A comparison between different DREMPs (Borbely et al., 2001; Hung and Mithulananthan, 2011; Narbel et al., 2014; Strachan and Farrell, 2006)*

| KPIs | Wind MP | PV MP | Hydroelectric MP | Geothermal MP |
|---|---|---|---|---|
| Energy efficiency (%) | 35 to 45 | 8 to 35 | 60 to 90 | 10 to 17 |
| Fuel | Wind | Sun | Water | Nil |
| $CO_2$ emissions (g/kWh) | No direct emission | No direct emission | 10 to 20 | ~ 120 |
| $SO_2$ emissions (g/kWh) | No direct emission | No direct emission | 0.024 to 0.046 | ~ 0.0031 |
| $NO_x$ emissions (g/kWh) | No direct emission | No direct emission | 0.046 to 0.086 | ~ 0.01 |
| Installation cost/kW, (US$/kW) | 900 to 1400 | 1550 to 3830 | 30 to 250 | 800 to 3000 |
| Energy cost (US cent/kWh) | 5 to 13 | 25 to 125 | 2 to 10 | 2 to 10 |
| Capital factor (%) | 20 to 30 | 8 to 20 | 20 to 70 | 45 to 90 |

| | | | | |
|---|---|---|---|---|
| Operation & Maintenance cost (US$/MWh) | ~ 10 | 1 to 4 | 0.045 to 0.09 | 10 to 30 |
| Payback time (year) | 0.4 to 1.4 | 1 to 2.7 | ~ 11.8 (small)<br>~ 0.5 (large) | ~ 5.7 |

## 2.4.3 Energy storage systems

### 2.4.3.1 *Introduction*

Energy storage systems (ESSs) are the set of technologies and methods utilized to store energy for later useful operations. ESSs are a vital component of the distributed renewable energy micro-plants. Wind, solar, and hydroelectric micro-plants are intermittent in supply. To provide a continues supply of electricity for consumers, ESSs are generally installed with renewable energy micro-plants as backup generators. RESs are unreliable; for example, wind energy might occasionally experience wind velocity that are insufficient to produce electricity. Similarly, sunlight may be accessible only for 6 or 8 hours a day. The ESSs can provide electricity to the users when there is no longer any energy production from RESs or when there is a significant demand for energy. This feature makes the ESSs a crucial part for the future green smart grid systems. There are many different kinds of ESSs, including electric double layer capacitors (EDLC), Battery energy storage systems (BESS), flywheels (FW), superconducting magnetic energy storage (SMES), plug-in electric vehicles (PEV), and more (Funabashi, 2016). In this subsection of the thesis, we provide a brief summary of the various ESS technologies.

### 2.4.3.2 *Battery energy storage system (BESS)*

#### 2.4.3.2.1 *Introduction*

One of the best technologies for storing electricity are the battery energy storage systems (BESS). This type of ESSs is the most frequently employed for distributed applications such in the case of distributed renewable micro-plants (Abdi et al., 2017).

Studies of the technical and financial performances of batteries have been conducted by many researchers such as (Huskinson et al., 2014; Wang et al., 2014). The materials used throughout the batteries have advanced significantly in recent years, making a variety of battery-based applications more favorable. Among the various types of batteries, lead acid are the widely utilized type. Nevertheless, Li-ion batteries are becoming quite popular, mostly because they have higher energy density, longer lifetimes, and high energy capabilities than batteries-based lead acid. Despite Li-ion batteries have a lower maintenance costs than lead acid batteries, they are limited in use because of their very high capital cost (Abdi et al., 2017).

Lead-acid, nickel-cadmium (Ni-Cd), sodium-sulfur (NaS), and lithium ion (Li ion) capital power prices can range from 50 to 100, 400 to 2400, 210 to 250, and 900 to 1300 $/kWh, respectively (Díaz-González et al., 2012; Rabiee et al., 2013). Nevertheless, a lot of work is being done to make Li-ion, NaS, and Ni-Cd batteries cheaper alternatives for greater power applications (Funabashi, 2016).

#### 2.4.3.2.2 *The working principle of batteries*

Typically, batteries are made up of one or more internal cells that are connected in parallel to boost the current and in series to obtain a high voltage level. The working principle of batteries is shown in *Figure 2.21*. Each battery is made up of two half-cells that are joined together in series by an electrolyte that contains both negative and positive ions. The negative ions are introduced to the user through the electric wires when the battery is connected to the load. Once the negative ions have created energy, they are then transferred to the positive ions and progressively neutralize them (Kousksou et al., 2014). The energy of the battery decreases as time goes on, and its internal resistance grows as much more positive ions are neutralized. In this condition, the battery is fully discharged after a certain period of time that depends on the capacity of the battery (Abdi et al., 2017).

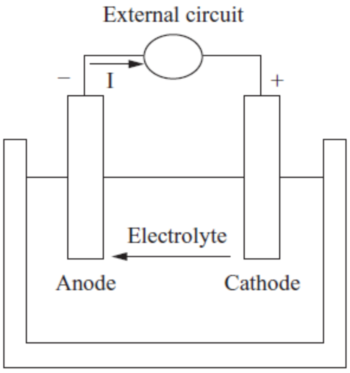


*Figure 2.21 Working principle of an electrochemical cell (Abdi et al., 2017).*

### *2.4.3.2.3 Classification of Cells*

The following factors can be used to classify batteries (Abdi et al., 2017):

- The materials used for electrolytes and electrodes
- The level of power
- Recharge and use

A battery is termed as a primary battery if it is only used once (one charge/discharge cycle) and cannot be recharged again for further usages. As opposed to this, a secondary battery is the one that can be recharged (more than one charge / discharge cycle) and used again (Abdi et al., 2017).

### *2.4.3.2.4 The Self-Discharge Rate*

Because of specific chemical reactions occurring inside the cell, a small current leaks between the anode and cathode of the battery cell. This phenomenon is called self-discharge of the cell. The cell might discharge to a certain extent even when it is not being used because of internal chemical reactions. The chemistry of the cell and the operating temperature have an impact on how quickly the cell discharges itself (Abdi et al., 2017).

### *2.4.3.2.5 The Discharge Rate*

The performance of the cell is significantly influenced by its rate of discharge. Experimental tests have demonstrated that increasing the discharge duration reduces the cell's capacity (Abdi et al., 2017).

### *2.4.3.2.6 State of Charge (SOC)*

The available capacity as a ratio of the rated capacity of a battery is indicated by a cell's state of charge (SOC). This last ranges from 0% (completely discharged) to 100% (fully charged). For a better usage of a battery, its SOC might not go beyond 50%. Thus, the battery is charged again when its SOC reached that value. Once the battery starts aging, its maximum SOC gradually drops with time. This implies that a 100% SOC for an aged battery would be similar to a 75% to 80% SOC for a newer battery (Abdi et al., 2017).

### 2.4.3.2.7 Designing Batteries: Important Factors

As was previously discussed, a battery is made up of a collection of cells that are linked together in series or in parallel to increase the voltage or current respectively. The operational requirements of the electrical system, which are described below (Ellabban et al., 2014), will, nevertheless, have an impact on how a cluster of battery (Battery bank) is designed (Abdi et al., 2017):

#### 2.4.3.2.7.1 Bank voltage

In order to achieve greater voltage levels, cells are connected in series as shown in *Figure 2.22*. It is seen that to obtain a battery bank voltage equal to 2X (V), simply we connect two cells with a voltage equal to X (V) for each. By wiring the cells in series, the bank's overall voltage is achieved (Abdi et al., 2017).

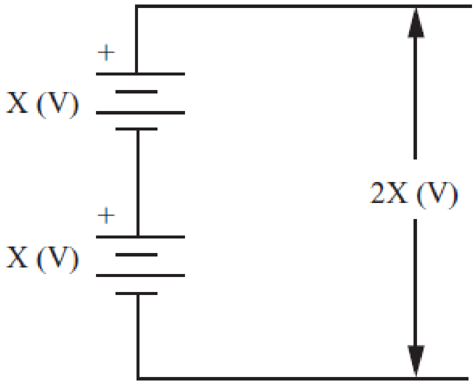


*Figure 2.22 Schematic representation of a series connection of cells (Abdi et al., 2017).*

#### 2.4.3.2.7.2 Bank capacity

By determining the required capacity of consumer and the output current, the cells might connected in series as shown in *Figure 2.23* to achieve that capacity (Abdi et al., 2017).

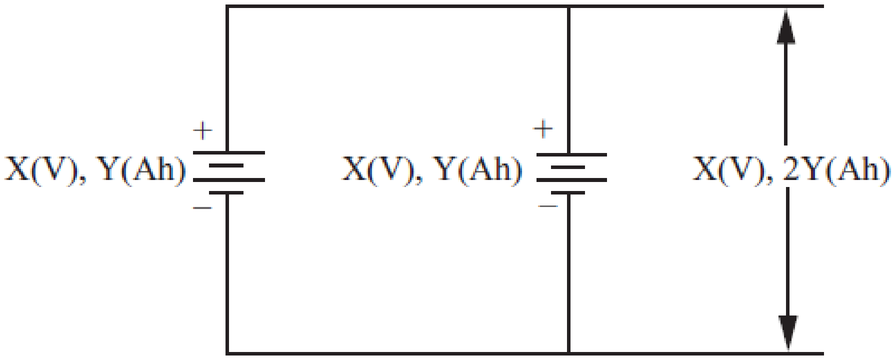


*Figure 2.23 Schematic representation of a parallel connection of cells (Abdi et al., 2017).*

### 2.4.3.2.8 Common types of batteries

The following is a list of some typical cell types (Abdi et al., 2017):

- Lead acid battery

- Alkaline (zinc–manganese dioxide) battery
- Nickel Cadmium (Ni-Cd) battery
- Nickel-metal hydride (NiMH) battery
- Lithium (lithium–copper oxide) Li–CuO battery
- Lithium (lithium–iron disulfide) LiFe S2 battery
- Lithium-ion polymer battery
- Lithium-ion (Li-Ion) battery
- Lithium (lithium–manganese dioxide) LiMn O2 battery
- Nickel oxyhydroxide (zinc–manganese dioxide/nickel oxyhydroxide) battery
- Zinc–Chloride battery
- Zinc–Air battery
- Zinc–Carbon battery
- Mercury Oxide battery
- Silver-oxide (Silver–Zinc) battery

#### 2.4.3.3 Super capacitor or Electric double layer capacitor (EDLC)

Electric double layer capacitor (EDLC) is often referred to as an ultra or super capacitor. This system can be defined as an electrochemical capacitor with electrodes made of conducting polymers (Dhand and Pullen, 2015; Dutta, 2014). The fundamental composition of the EDLC (super capacitor) cell is depicted in *Figure 2.24*. It has two electrodes that are submerged in an electrolyte, just like a battery. The distinction, however, is in the materials utilized to make the electrodes and the electrolyte (Abdi et al., 2017).

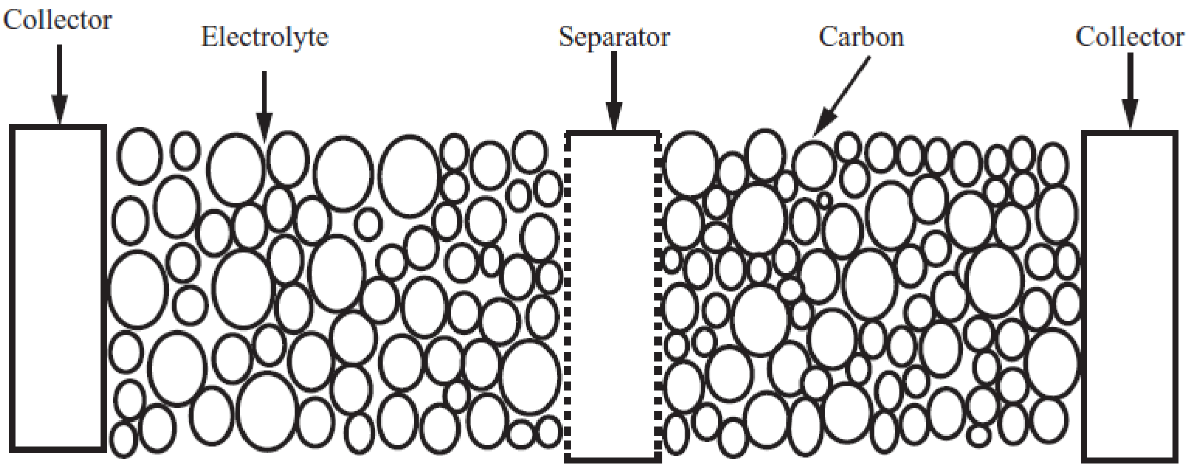


*Figure 2.24 An EDLC (ultra capacitor) cell construction (Abdi et al., 2017).*

The super capacitor has a small storage capacity of about 10 Wh/kg but it may provide a high-power impacts per weight with a value up to 10 kW/kg. It is characterized by a very short storage duration, often between 30 and 60 seconds (Abdi et al., 2017). In the future, a 1m$^3$ super capacitor may achieve a power pulse of about 1 to 5 MW with a weight of about 100 to 500 kg (Schneuwly et al., 2006). The primary disadvantage of EDLCs is their expensive cost (Funabashi, 2016; Kusko and DeDad, 2005). In the next five to ten years, a price level of 10-15 €/Wh is expected. Currently, the cost is around 200–600 €/kWh and 50–150 €/Wh (Funabashi, 2016).

Super capacitors are used to provide a buffer of electrical energy for short transients. They can be combined to fuel cells to complete their relatively slow reaction time, hence providing an effective ESS.

### 2.4.3.4 Hydrogen Energy Storage

One of the most common and basic natural components that potentially replace fossil fuels is hydrogen. Hydrogen energy storage technology uses the excess of energy generated by RES at times when there is little demand for energy to power electrolysis, which separates hydrogen from a chemical solution by passing an electrical current through it (*Figure 2.25*). Once hydrogen has been produced via electrolysis, it may be utilized to generate electricity in stationary fuel cells (FCHEA, 2019).

The working principle of hydrogen fuel cells for generating electricity is well described in the subsection "Fuel cells" in this chapter of the thesis.

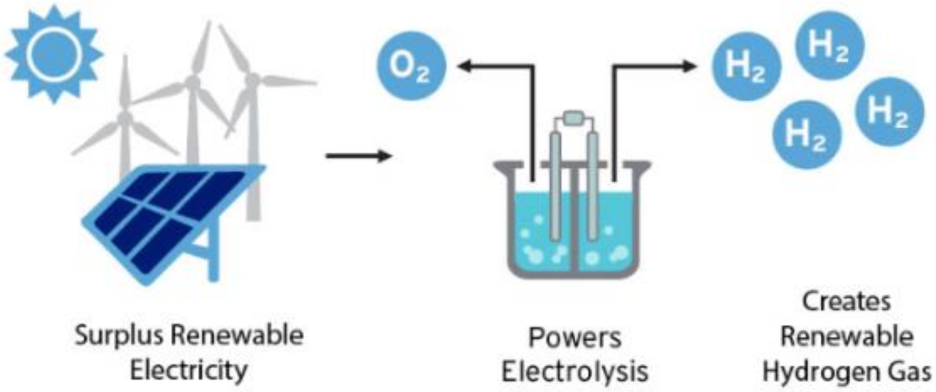


*Figure 2.25 Schematic representation showing the hydrogen production process (FCHEA, 2019).*

Produced hydrogen can physically be stored in either a liquid or a gas (EERE, n.d.). Hydrogen combustion in fuel cells produces water vapor, which is released into the atmosphere and aids in cleaning the environment. With statistics from the International Energy Agency indicating that hydrogen generated from wind would be less expensive than natural gas by 2030, hydrogen is demonstrating significant potential as a financially viable fuel option in the future. Although BESS may meet the same energy demands, hydrogen energy storage has advantages over it. Batteries degrade over time and have a limited capacity, but hydrogen may be stored for a long time and in large quantities, with the only restriction being the size of the storage facilities (FCHEA, 2019). Nevertheless, hydrogen fuel cells have not yet been extensively used due to their greater manufacturing costs than those of fossil fuels (Abdi et al., 2017).

### 2.4.3.5 Superconducting magnetic energy storage (SMES)

The superconducting magnetic energy storage (SMES) is comparatively a new technology. It works by storing energy in a magnetic field that is produced by a DC current flowing through a huge superconducting coil that is kept at a low temperature. The amount of energy that is stored is computed as the product of the coil's self-inductance and the square of current that is passing through it. SMES is characterized by a very short response time. Although the SMES system has been proven, the cost is still quite expensive. The capital cost of electricity may range from $1,000 to $10,000 per kW (Nielsen and Molinas, 2010).

### 2.4.3.6 Flywheel (FW)

A flywheel (FW) technology is a simple mechanical energy storage device. The FW is a large spinning disk that used for storing angular momentum. In the charging period (also known as the motor mode), the electrical energy is transformed to a kinetic energy and used to charge the FW.

Conversely, during the discharging period (also known as the generator mode), the stored mechanical energy in the FW will be converted back into electrical energy and the FW discharges. A FW energy storage system with an AC/DC converter is shown in *Figure 2.26* (Abdi et al., 2017).

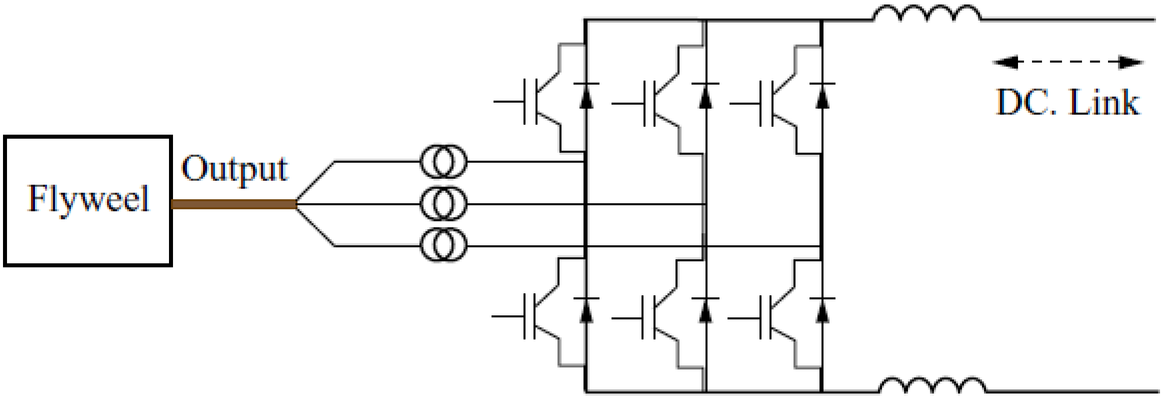


*Figure 2.26 A FW energy storage system with an AC/DC converter.*

FW energy storage systems have a significant maximum output power, a long lifetime, and a high energy density. A FW can have usually capacities varying from 3 to 133 kWh and an energy efficiency of up to 90% (Funabashi, 2016).

### *2.4.3.7 Pumped Hydroelectric Storage (PHS)*

In pumped hydroelectric storage (PHS), water is pumped from a lower altitude to a higher altitude when RE is in excess, and when demand rises, water is released from the higher altitudes to produce electricity. An illustration of a common PHS system is shown in *Figure 2.27* (Abdi et al., 2017). The process of producing electricity using a hydroelectric power system is extensively discussed in the "hydroelectric micro-plant" subsection in this thesis.

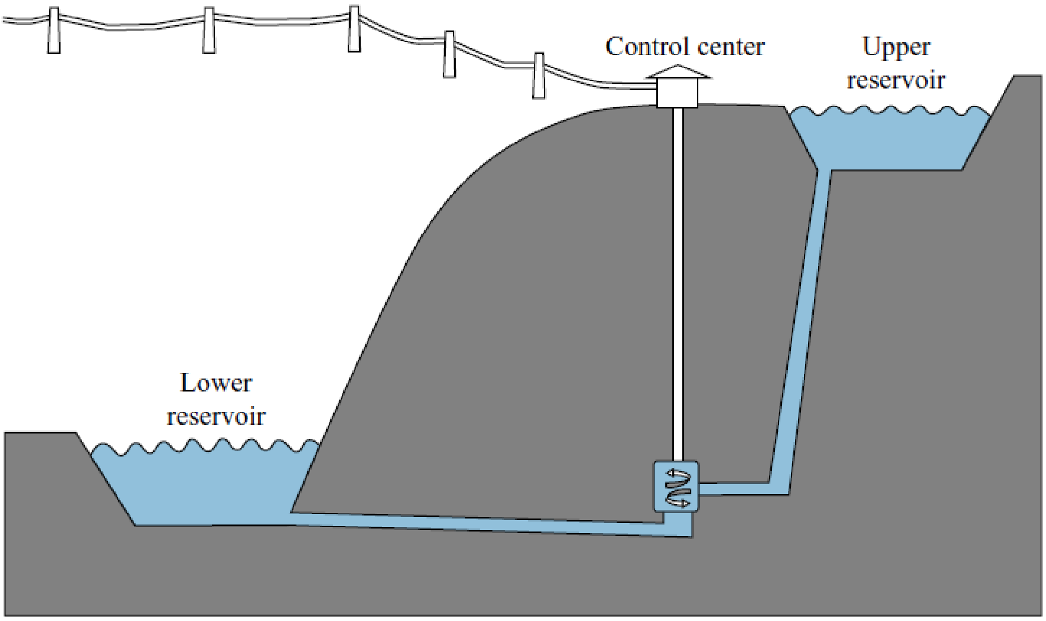


*Figure 2.27 Pumped hydro-storage system (Abdi et al., 2017).*

#### 2.4.3.8 Plug-in electric vehicles (PEVs)

In the recent years, electric vehicles (EVs) have seen a widespread usage around the world. The term plug-in electric vehicles (PEVs) refers to any road vehicle that can store electricity within its onboard BESS using an external power source. This last could be a wall socket that is connected to the power network. The BESS in turn feed the electric motor and aids to propel the wheels (*Plug-In Electric Vehicles*, 2009). Through their use as distributed generation, PEVs might significantly contribute to the grid's energy balancing measures. This concept is also known as Vehicle-to-Grid (V2G). A utility may be able to inject extra power from PEVs into the grid during critical peak periods, preventing power failures and power outages, by drawing on a significant number of batteries linked into the SG. As a result, they can significantly contribute to enhancing the SG's power quality and reliability. PEVs have the potential to significantly reduce reliance on oil and they produce no air pollution when operated entirely on electricity. Nevertheless, PEVs rely on power plants to recharge their batteries, and traditional power plants based fossil fuels produce GHG emissions. Generally, a PEV should be charged early in the morning when electricity consumption is at its lowest while wind energy is often at its highest in order to operate as cleanly as feasible. However, the future energy management systems (EMSs) and SG technologies can take all these parameters into account to charge the EVs at the most appropriate time (US Department of Energy, 2019).

#### 2.4.3.9 ESS: Power Electronic Interface

All ESSs produce DC power as their electrical output, which must be transformed to AC using power electronic converters before being connected to the grid. (Abdi et al., 2017). The connecting of an ESS to the power network via bidirectional and unidirectional converters is briefly depicted in *Figure 2.28*. Considering the cost of installation, bidirectional converters are recommended since utilizing two unidirectional converters is much more expensive than using a one bidirectional converter. During the charging phase, a bidirectional converter function as a rectifier, as shown in *Figure 2.29* (Nick et al., 2014). While during the discharging phase, when the batteries are charged, this function will be switched to an inverter.

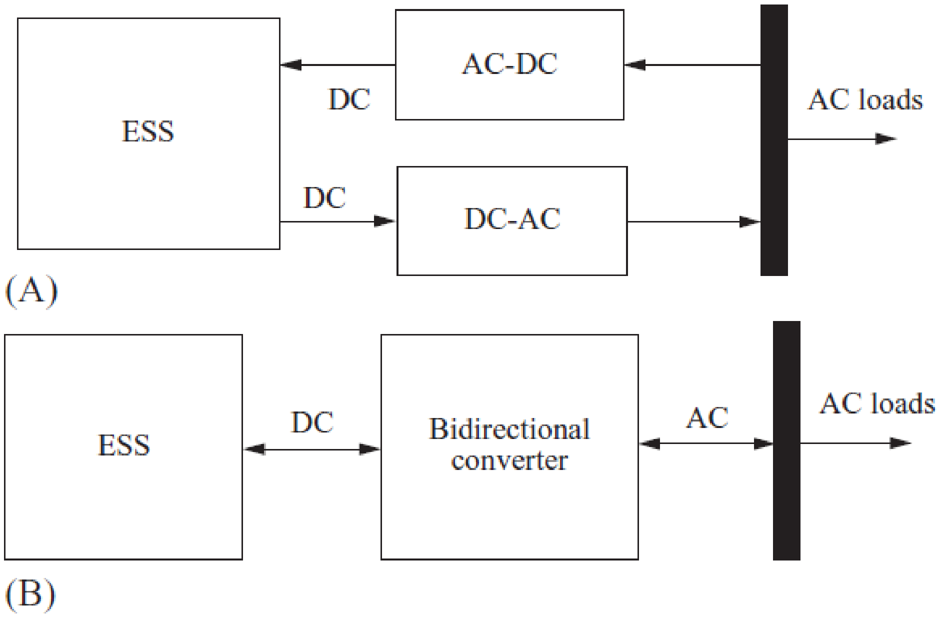


*Figure 2.28 (A): Unidirectional converter, (B): bidirectional converter.*

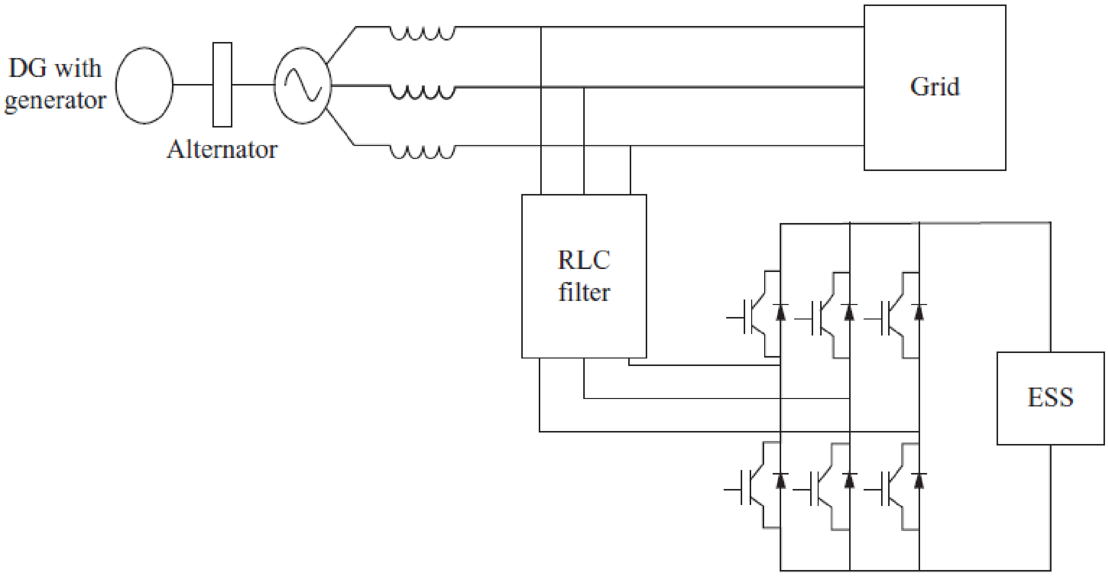


*Figure 2.29 ESS tied to the grid with power electronic interface*

## 2.5 Conclusion

Advancement technologies in Renewable Energy Sources (RES) have permitted their widespread usage in small-scale capacities ranging from kilowatts (kW) to few megawatts (MW), such as PV micro-plants, micro wind turbines and small hydropower in residential, commercial and industrial areas.

In this thesis, a comprehensive literature review about the latest researches and developments of distributed renewable energy micro-plants as a promising technologies for the future smart power grids and micro-grids is presented. It provides a description of the global research trend on DREMPs, which is currently one of the most important topics.

There is no commonly agreed-upon definition of DG, and the literature on this topic is inconsistent as the concept of DG covers multiple applications and technologies. However, most authors agreed that DG is an approach that employs various and numerous of small-scale (micro) power generators, mostly are based RES, or storage technologies to produce electricity at or near where it will be consumed. DG, on-site generation, local generation, distributed energy resources (DER), decentralized generation, embedded generation or dispersed generation are all terms that have been found in the literature and used interchangeably with DG. RESs offer enormous potential for use in producing electricity or for other direct or indirect applications.

ESSs are a vital component of the distributed renewable energy micro-plants. To provide a continue supply of electricity for consumers, ESSs are generally installed with renewable energy micro-plants as backup generators. The ESSs can provide electricity to the users when there is no longer any energy production from RESs or when there is a significant demand for energy. This feature makes the ESSs a crucial part for the future green smart grid systems.

One of the best technologies for storing electricity are the battery energy storage systems (BESS). This type of ESSs is the most frequently employed with distributed renewable micro-plants. The materials used throughout the batteries have advanced significantly in recent years, making a variety of battery-based applications more favorable. Among the various types of batteries, lead acid ones are the widely utilized. Nevertheless, Li-ion batteries are becoming quite popular, mostly because they have higher energy density, longer lifetimes, and high energy capabilities than batteries-based lead acid and also because the technology is more mature due to the massive use in electric cars. Despite Li-ion batteries have a lower maintenance costs than lead acid batteries, they are limited in use because of their very high capital cost.

Hydrogen ESS has some advantages over BESS. Batteries degrade over time and have a limited capacity, but hydrogen may be stored for a long time and in large quantities, with the only restriction being the size of the storage facilities. Nevertheless, hydrogen fuel cells have not yet been extensively used due to their greater manufacturing costs.

Another important resource of ESS that is assumed to be widely utilized all over the world in the near future is PEVs. Through their use as distributed generation (V2G / G2V), PEVs might significantly contribute to the grid's energy balancing measures. A utility may be able to inject extra power from PEVs into the grid (i.e. V2G) during critical peak periods, preventing power failures and power outages, by drawing on a significant number of EVs linked into the SG. As a result, they can significantly contribute to enhancing the SG's power quality and reliability. PEVs have the potential to significantly reduce reliance on oil and they produce no air pollution when operated entirely on electricity. Nevertheless, PEVs rely on power plants to recharge their batteries, and traditional power plants based fossil fuels produce GHG emissions. Generally, a PEV should be charged early in the morning when electricity consumption is at its lowest while wind energy is often at its highest in order to operate as cleanly as feasible. However, the future energy management systems (EMSs) and SG technologies can take all these parameters into account to charge the EVs at the most appropriate time. All ESSs produce DC power as their electrical output, which must be transformed to AC using power electronic converters before being connected to the grid.

According to the literature, the main barriers to a widespread adoption of DREMPs are the financial investment needed to build such infrastructures. In addition, the intermittent nature of RES necessitates the use of ESSs and advanced local control to manage the local grid optimally.

# Chapter 3 Integration of distributed renewable energy micro-plants in power systems

In this chapter, we will tackle the topic of integrating DREMPs in power systems. We will shed the light on grid integration studies and power system planning to accommodate high DREMPs penetration levels while addressing numerous technical, economic, and environmental challenges. The latest approaches and methods for determining the best connecting point for DREMPs in the grid as well as its maximum capacity that could be supported by the power network will be extensively discussed in this chapter. We will also shed the light on various factors found in the literature that influence the determination of the optimal location and size of DREMPs. In addition, several practical applications and solutions used by utilities and system operators to boost the deployment of DREMPs as well as motivated factors for the increase use of DREMPs in power systems will be detailed. Technical, economic, environment and regulatory concerns arisen as a result of the increasing integration of DREMPs will be discussed, including power quality issues, grid instability, increase in the fault level and more. Research studies to solve these challenges so that DREMPs can be successfully integrated will be also tackled in this chapter. Another approach that does not demand grid integration which is stand-alone (off-grid) hybrid power system based DREMPs will be thoroughly presented.

## 3.1 Introduction

The interconnected electricity system was not widely used before the 1940 (Basak et al., 2012). The power exchange between nearby power providers and the decrease of reserve capacity are two major benefits of interconnection. However, if proper safety and reliability safeguards are not in place, Interconnected electricity systems are more susceptible to cascading failures than standalone electricity systems (Krishna and Daniel, 2009).

Distributed renewable energy micro-plants (DREMPs) such as solar PV, wind micro-turbines, micro-hydro, biomass, geothermal heat, and ocean are considered as green resources due to their low greenhouse gas emissions (Hung, 2014). The notion of integrating DREMPs in power systems was first proposed after the first oil crisis in 1970s as an alternative power solution to reduce reliance on fossil fuels (Basak et al., 2012; Hung, 2014; MARNAY et al., 2003; Rahman, 2003). DREMPs, on the other hand, remained relatively dormant throughout this time because of its high energy costs, as well as government and utility disincentives, till the 1999, when the subject of climate change and global warming reached to the frontline of concerns in several regions around the globe (Mozina, 2010). This renewed interest was also aided by the introduction of feed-in tariffs in 1990s (IRENA, 2017). Moreover, Advances in renewable energy technologies and lower renewable energy costs (Iweh et al., 2021) have permitted widespread usage of distributed renewable energy micro-plants in the electricity mix with capacities ranging from a few kilowatts (kW) to megawatts (MW), such as PV panels and micro wind turbines (Yang et al., 2019) in combination with various ESS facilities. The notion of DREMPs and their grid connections is depicted in Figure 3.1.

In 1999, the Consortium for Electric Reliability Technology Solutions (CERTS) has been actively reviewing and assessing DREMPs test facilities in order to demonstrate the concept of advanced integration of DREMPs in power systems (MARNAY et al., 2003). According to (Basak et al., 2012), It would be impossible to fulfill future power demand growth at an acceptable cost due to limits on the expansion of existing centralized generation and distribution systems in industrialized countries. Meanwhile, advancements in distributed energy resources, especially renewables, together with the deployment of power electronic-based devices, will shift the power generation economy to smaller scales. Furthermore, integrating several numbers of dispersed types of distributed renewable energy micro-plants with capacities ranging from kilowatts (kW) to megawatts (MW), such as PV micro-plants, micro wind turbines, and small hydroelectric power on the distribution network side in a pattern that is quite different from today's conventional power grids may offers significant engineering and research challenges (Marnay et al., 2001). In this case, interconnected electricity system must have the ability to support two ways power flow direction (Berrada et al., 2021; Iweh et al., 2021; Terfa et al., 2022).

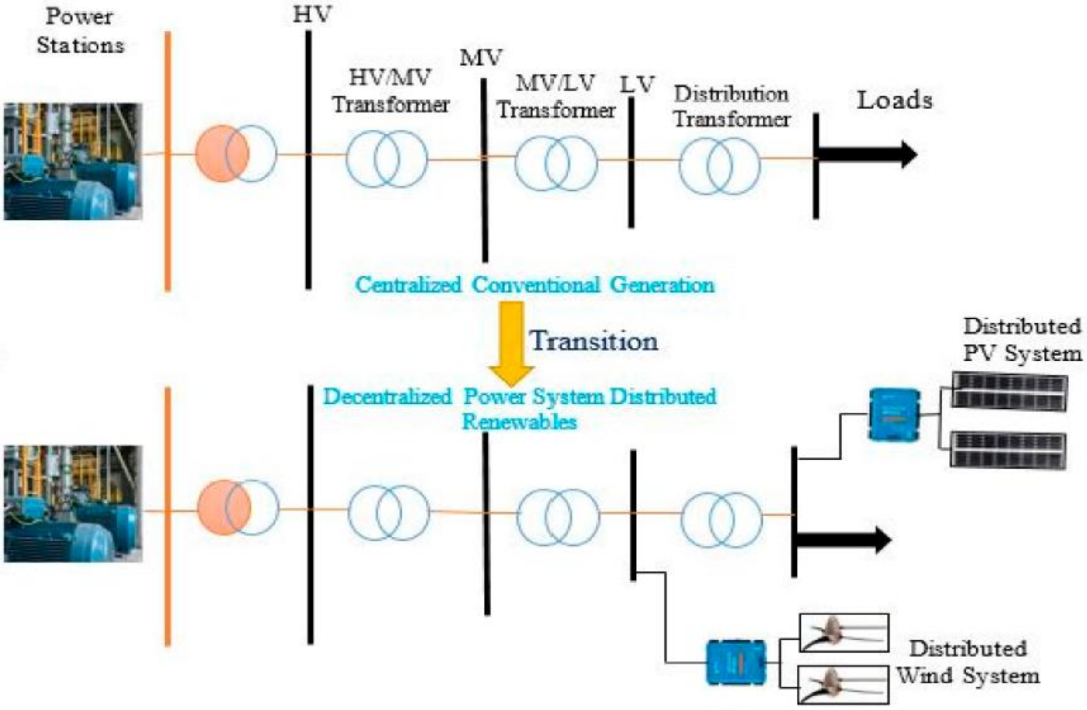


*Figure 3.1 The integrating DREMPs in power systems (Iweh et al., 2021).*

Between 1999 and 2000, an initial survey was conducted to identify the facilities and resources where DREMPs and other non-renewables with storage systems could be tested. Photovoltaic systems, wind, micro-turbines, fuel cells, battery storage systems, and power electronic converter systems were among the technological devices covered in this study. (MARNAY et al., 2003) summarizes the compendium of data gathered by the CERTS team on the test facilities for integrated DREMPs during that period. In and around the year 2000, the DREMP technology was transitioning from the laboratory to the marketplace (Basak et al., 2012). In this year, (Marnay et al., 2000) describes an integrated model toward DREMP adoption in the surrounding of the Distribution Network (DN) which may called as a micro-grid. The goal of this project is to develop an integrated, comprehensive, and iterative approach. It was a first step toward developing a micro-grid adoption model for customer sites centered on a feeder or the neighborhoods of the DN. (Bailey et al., 2003) provides information about the benefits and drawbacks of integrating DREMPs in various sites such as education, agriculture, health care, manufacturing facilities and airports.

It was about the year 2006 when the integration of DREMPs began to gain traction and growing in popularity (Strunz, 2006). Furthermore, government incentives, economic and technical benefits, and technological advancements have considerably raised interests in the usage of DREMPs around the world (Hung, 2014). For instance, RES contributed around 16.7% of the world's energy consumption in 2010 (REN21, 2020a). PV technology expanded the quickest among all renewable energy technologies, with an average annual growth rate of 58 % throughout the globe from 2006 to 2011, and it reached in 2012 around 102 GW of the world's total installed capacity (Eco-Business, 2012). In the other hand, wind energy accounted for just about 282 GW of the world's installed capacity at the late of 2012, expanding with an annual growth rate of 30% (REN21, 2020a). This energy generation technology is frequently employed in Asia, united states, and Europe (Hung, 2014). As a result, the grid codes in several governments, including Germany, Denmark, the UK, Spain, Australia, and the US have been changed to accommodate high-levels penetration of such technologies as well as modernizing the power system to fulfill the needs for greater energy efficiency, security, and reliability of the power grid system (Hung, 2014). In the Meanwhile, the smart grid concept has been introduced as a vital component of this grid codes modification in order to promote a high integration levels of DREMPs (Simoes et al., 2012). The SG is a complex electrical infrastructure that combines power systems with information and communication technologies (ICT). A smart DREMPs integration strategy has been proposed as a crucial component of the SG in (Hung, 2014). The major goal of smart integration was to strategically incorporate and operate DREMPs and related BESSs in DN while considering a number of economic, technical, and environmental concerns.

In 2019, initiatives about market structure, demand-side management (DSM), and transmission and distribution network improvements were the focus to promote distributed renewable energy micro-plants integration into the grid. In these latest years, many countries are making significant success in increasing the share of DREMPs in their total energy generation mix (Iweh et al., 2021). For example, in 2020, RESs went up by 2% while all other demands for fuels decreased due to the Covid 19 pandemic. The continuous implementation of new plants, priority access to the grid, and long-term agreements supported the growth of RESs despite the lower demand for electricity, construction delays in many regions over the world, and supply chain issues. As a result, the share of RESs in the world's power generation increased from 26.5% in 2019 to 28.2% in 2020 (IEA, 2021).

In 2021, RES integration records another new capacity level to reach 8300 TWh, despite the ongoing supply chain issues and delays brought on by the Covid 19 pandemic (IEA, 2022a). However, the invasion of Ukraine by the Russian Federation is leading to an unprecedented energy catastrophe for European countries. Thus, many governments are putting forth initiatives to hasten the switch to sustainable energy technology, minimize reliance on Russian supply, and shield consumers from rising energy prices.

According to the (IEA, 2022b), nearly 70% of worldwide power generation in 2030 will come from renewables in the Net Zero Scenario, 2010-2030. As per (Shamseldein and Abdelaziz, 2019), the introduction of high-speed, low-cost, and efficient power electronics and computing has enabled new techniques of electrical power generation and consumption. EVs are also likely to become increasingly common in the near future, resulting in a considerable rise in DC loads connected to DNs. In addition, the number of distributed BESSs will grow, allowing for the integration of high levels of DREMPs and EVs penetration. Moreover, the limitations of expanding transmission and distribution networks as well as the deregulation of the power industry and the

Ukraine-Russia war are all subject to the current trends in the development and integration of DREMPs for power generation (Adefarati and Bansal, 2016; IEA, 2022a). Figure 3.2 depicts the evolution of RESs and other non-renewable sources in world electricity-generation from 1971 to 2021 (IEA, 2021).

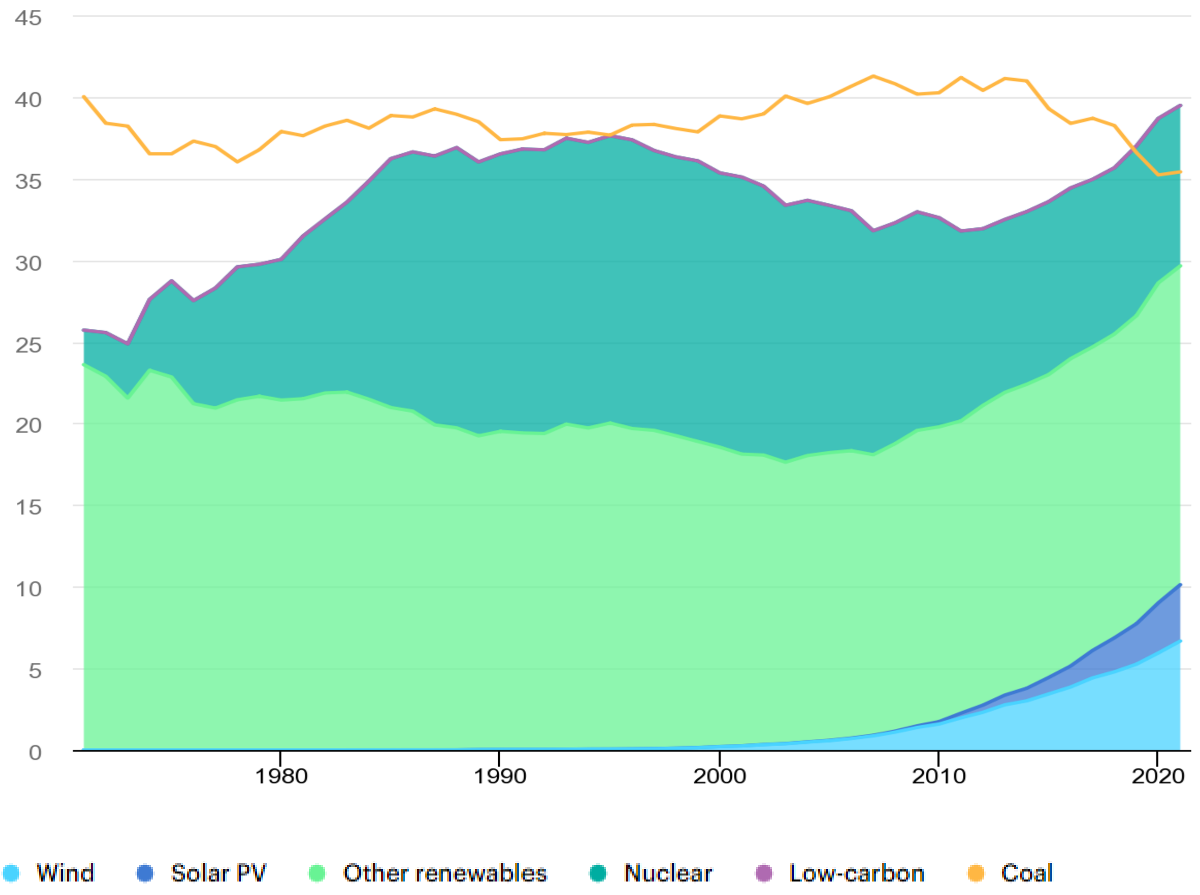


*Figure 3.2 The evolution of RESs and other non-renewable sources in world electricity-generation from 1971 to 2021*

Although DREMPs offer potential benefits, there are obstacles to their seamless integration into the grid, which frustrates efforts to implement a new power system transition (Adil and Ko, 2016). According to (Hung, 2014; Katiraei and Agüero, 2011), the significant penetration levels of DREMPs, together with demand fluctuations have introduced many issues and challenges to the distribution systems such as voltage instability, voltage rise, and power fluctuations. Moreover, intermittent nature of DREMPs (e.g., solar and wind) connected to the distribution networks can also create various issues and stability concerns in distribution network (DN). Many technical, economic, environment and regulatory concerns have arisen as a result of the increasing integration of DREMPs. As per (Fathabad et al., 2021), the trend toward increased DREMPs penetration in distribution networks is providing new problems to DN operation, as well as the overall operation of the power system. In this context, it is necessary to think about the challenges and the implications of integrating DREMP into the power grids (specially the distribution network). More studies are needed to solve these challenges so that DREMPs can be successfully integrated (Berrada et al., 2021) in order to obtain optimal grid performance (Iweh et al., 2021).

(Bhandari et al., 2014) suggested that before implementing a full-phase DREMPs, several issues must be considered before making any judgments about the implementation of such systems.

In the next sections, grid integration studies and power system planning to accommodate high DREMPs penetration levels while addressing numerous technical, economic, and environmental challenges are treated extensively.

## 3.2 Grid integration studies and power system planning

Integration of DREMP in power systems refers to the process of power system planning, interconnection, and operation that allows for efficient as well as cost-effective use of renewable energy sources while preserving or increasing the reliability and stability of electricity delivery to the power grids (Leisch and Cochran, 2015). According to (Iweh et al., 2021), high penetration levels of DREMP in power systems necessitates careful considerations of the type, devices, installation, and operation of DREMP to allow the pre-existing power network to absorb acceptable levels of RES such as solar, wind, biomass, hydro, and more.

Electricity access has increased rapidly in countries that have adopted an integrated planning strategy, an electrification method that includes grid extension, solar residential micro-plants, and mini-grids (REN21, 2020b) . Tanzania, Cambodia, Nepal, Rwanda, Myanmar, Kenya, India and Bangladesh have recently had the most significant increases in electrification (Iweh et al., 2021).

When discussing grid integration of renewable energy sources, regulators, policymakers, planners and system operators address a number of challenges that can be divided into four categories (Leisch and Cochran, 2015):

- New renewable energy sources
- New transmission infrastructure
- Increase the flexibility of power system
- Planning for a high-level penetration of RES in the future.

### 3.2.1 New renewable energy sources

When compared to utility-scale renewable energy sources such as centralized wind and solar farms, integrating distributed renewable energy micro-plants has its own set of benefits and obstacles. Significant localized DREMP expansion can cause issues in low-voltage distribution systems, including as voltage fluctuations and reverse power flow. Nevertheless, several researches demonstrated that distributed renewable energy MPs can have favorable effects such as decreased line losses and minimized production costs.

As planners explore increasing DREMP capacity, the inherent features of uncertainty of RES affects assessments of whether a grid with considerable DREMP has reliable supply to meet long-term energy needs. There are several methods for evaluating the capacity value of DREMPs, as well as approaches that enable system operators and utility companies to meet electricity demand reliably with DREMPs. By aligning incentives and goals with grid integration requirements, planners of power system may secure and sustain investment in new DREMPs. Furthermore, ambitious, long-term renewable energy goals provide a roadmap that can inspire development in clean renewable energy policies and system operations. Also important are "Grid-aware" motivations (for example, boosting wind and solar producers who employ innovations and technologies that help maintaining or increasing grid stability), as they simultaneously encourage renewables investment and offset the negative consequences of integrating these sources into the power systems.

Upgrading grid integration standards, protocols, and distribution planning approaches to properly reflect the features of distributed renewable energy micro-plants can assist in realizing these advantages and postpone or perhaps eliminate the need for grid reinforcement.

### 3.2.2 New transmission infrastructure

Integration of centralized RES, that are located outside of the current transmission system needs grid extension and upgrades, so that power systems and stockholders can access high-quality, reliable and sustain RES power supply. These actions are not necessary in the case of integrating DREMPs where most of them are located near load centers in the existing distribution networks.

### 3.2.3 Power system flexibility

In power systems with significant grid-connected DREMPs, accessing various types of sources of significant operational flexibility become extremely crucial. Market practices and system operating procedures, particularly rapid scheduling, implementing real-time predictions, and ancillary services, are frequently among the most cost-effective ways to gain significant flexibility without investing in new physical facilities. Moreover, Operational coordination for balancing utility zones is also another institutional flexibility solution, since it allows for resource cooperation via coordinated scheduling, reserve sharing, or unified operations. Furthermore, flexible traditional generators and transmission facilities are other sources of flexibility. Storage technologies and demand response are also evolving as options for boosting flexibility at very significant levels of DREMP adoption.

The regulation context influences the flexibility available options. Policy procedures or contractual are the fundamental basis for pushing vertically integrated companies to adopt flexibility solutions. On the other hand, ancillary services markets, sub-hourly dispatch, and price-responsive demand, encourage flexibility via subsidies and market design strategies.

### 3.2.4 Planning for a high-level penetration of DREMPs in the future

With the penetration of considerable levels of DREMPs in power grids, appropriate system planning is becoming increasingly important (Vallem et al., 2006). Power system planners and researchers are placing greater emphasis on exploring possibilities *for maximizing system flexibility*. Planning initiatives and activities involve assessing long-term demand and investigating possibilities for improving capacity of power grid and distribution system. The grid assessment, also known as a compatibility check, considers two essential scenarios (Bayer and Marian, 2020): the highest possible power produced with the smallest possible energy consumption, and the lowest possible power produced with the highest possible power demand**.** Hence, long-term data such as solar irradiance and wind speed data in the case of PV and wind micro-plants are needed in order to improve energy output projections. Because of the energy gap between PV and wind systems, battery banks with sufficient capacity are required to meet the demand for electricity (Adzic et al., 2009; Bhandari et al., 2014; Soetedjo et al., 2011).

However, the inappropriate power system planning and operations of these facilities will lead to voltage rise, significant power losses, and system instability because of reverse power flow (Eftekharnejad et al., 2013; Katiraei and Agüero, 2011). Thus, a proper methodologies and effective approaches for accommodating DREMPs must be developed. Over the last two decades, there has been many discussions on DREMPs planning grid integration studies in terms of different economic, technical, and environmental issues (Viral and Khatod, 2012). A grid integration studies analyze and simulate power system operation under various scenarios and sensitivities, assesses the cost of interventions and identifies potential reliability limits to remove such limitations. These studies aim to inform investors and participants about a power system's capabilities and requirements for functioning with large amounts of DREMPs. Robust grid integration studies are built based on a comprehensive range of basic data as well as stakeholders input (Leisch and Cochran, 2015). According to (Bhandari et al., 2014), long-term data (i.e. irradiation, wind speed, ambient temperature …etc.) should be collected at least once a year.

Despite grid integration studies commonly use production cost to model optimized dispatch and unit commitment, estimating the system full costs of integrating DREMPs is significantly more difficult. The overall costs of integrating DREMPs in power systems depend on complex and dynamic interactions between these generation units and the loads, thermal generators, reserves, and transmission and distribution networks.

## 3.3 Best connecting point and Capacity of DREMP on a Power Network:

Utility companies, power system operators, and electricity customers may all benefit from the integration of DREMPs into the distribution network (Iweh et al., 2021). The integration of renewable distributed MPs benefit society and has the ability to improve the functioning of distribution networks (Atwa et al., 2010; Franco et al., 2021; Lopes et al., 2007b).

A key job in the grid integration process is determining the best connecting point for DREMPs in the grid as well as its maximum capacity that could be supported by the power network. If such important aspects of the network are not properly specified, the network's performance may suffer (i.e. increased power losses, voltage fluctuations, power quality issues, system stability and more); consequently DREMPs could be considered geographically localized voltage control points (Iyer et al., 2005; Misra and Singh, 2007; Thong et al., 2005). As a result, optimal power system planning, selection of an ideal connection point, and determination of optimum hosting capacity as well as the type of DREMP technology would be required for DREMP coupling to the grid, particularly the distribution network (Jain et al., 2017; Zahedi, 2011). The appropriate selection of the previous aspects may increase the system's reliability and security while also expanding the level of DREMPs penetration and lowering generation costs. Furthermore, when the capacity of DREMP is adequately sized, it lowers the capital cost of purchasing equipment in a presumably enormous system, increasing the network's efficiency (Roy and Pota, 2015b).

Many scholars have focused on the location and capacity of DREMP into the grid. For example, (Al Talaq and Belhaj, 2020) used the Electrical Transient Analysis Program (ETAP) to investigate the best location and penetration levels of photovoltaic (PV) systems on an IEEE 30-bus system and found that a 50 percent penetration level was satisfactory (Iweh et al., 2021). (Luhmann et al., 2015) proposed employing low-cost methods to manage growing solar–wind–biomass capacity in distribution networks in Northern Germany. They created a medium-voltage (MV) grid model that was used to test and analyze numerous scenarios utilizing a 5% load flow-dependent energy curtailment approach. They concluded that the 5% strategy was a potential structure for lowering the costs of integrating DREMPs into distribution systems. A dynamic approach of the TS was used by (Newman et al., 2011) to examine the effects of the integration of DREMPs on the robustness of the TS. The ratio of the DREMPs' variability to the generation capacity margin is discovered to be a crucial factor. In certain of these situations, increasing the integration of DREMPs if not handled appropriately may raise the probability of major failures as well as reducing the robustness of the TS.

In the next subsections, we present various factors found in the literature that influence the determination of the optimal location and size of DREMPs.

### 3.3.1 Factors that influence location and capacity of DREMPs

The goal of engineers and power system planners when determining the optimal location and size of DREMPs is to deliver a number of potential benefits to the distribution network while respecting technical limits like the maximum grid’s energy-hosting capability, penetration levels, feeder thermal capacity and bus voltages (Hung, 2014). The grid impact assessment essentially ensures that grid voltage and current restrictions are obeyed, as these are crucial characteristics in determining the grid's energy-hosting capability. To avoid equipment damage, the current restrictions of equipment, also known as ampacity, must not be exceeded (Iweh et al., 2021). As per (Bayer and Marian, 2020; Iweh et al., 2021), A connection request from an energy project developer is followed by a rigorous grid compatibility check by the utility operator to determine which node or bus on the grid could be the most cost-effective site to inject power.

The following subsections present some of the relevant factors available in the literature.

#### *3.3.1.1 Technical factors*

##### *3.3.1.1.1 Power Losses*

The distribution network is known by its high R/X ratio and considerable voltage drops, which can result in significant power losses throughout feeders (Hung, 2014). It is also important to note that the power losses along the distribution network is typically higher than the losses in the transmission network. According to the research published in (Nourai et al., 2008) , an American distribution network experienced a loss of 6-8 %, compared to 2.5-7.5 % in the transmission network. In radial DNs with a high R/X ratio, this value would be higher. (Hung, 2014). As a result, one of the most difficult tasks facing electricity distribution operators around the world is reducing distribution losses. Thus, losses reduction along the distribution network level must be investigated. Because of the influence on operators' incomes, loss reduction along the distribution network level might be one of the key benefits. Loss reduction can also have a favorable effect on system capacity delivery, voltage stability, and voltage profiles as a crucial concern for DREMP planning (Atwa and El-Saadany, 2011).

In recent years, the appropriate DREMP location and capacity concerns for minimizing power losses in the DN level have gotten a lot of attention. The majority of previous solutions presume that DREMPs can be dispatched and installed at maximum load (Georgilakis and Hatziargyriou, 2013). We state as an example: numerical methods (Atwa et al., 2010; Atwa and El-Saadany, 2011; Ochoa and Harrison, 2011), analytical solutions (Acharya et al., 2006; Gözel and Hocaoglu, 2009; Hung et al., 2010; Hung and Mithulananthan, 2013; Wang and Nehrir, 2004), as well as a large number of heuristic algorithms including Genetic Algorithm (GA) (Singh et al., 2009), Simulated Annealing (SA) (Injeti and Prema Kumar, 2013), Artificial Bee Colony (ABC) algorithm (Abu-Mouti and El-Hawary, 2011), Particle Swarm Optimization (PSO) (AlRashidi and AlHajri, 2011; Kansal et al., 2013), Harmony Search Algorithm (HSA) (Rao et al., 2013), and Modified Teaching-Learning Based Optimization (MTLBO) (Martín García and Gil Mena, 2013). Conventional approaches, on the other hand, may not handle a real example of intermittent renewable energy generation (e.g., nondispatchable PV and wind generation) and time-varying consumption as the appropriate size of DREMP during peak load may not be the same at other loading levels. As a result, reducing energy loss is not really optimum (Hung, 2014).

In the literature, there have recently been two different tools and techniques based on time-series and probabilistic approaches to predict energy losses in the presence of DREMP. For the first approach, some researches have proposed DREMP integration for reducing energy losses which takes into account the time-varying features of production and consumption. For instance, an Optimal Power Flow (OPF)-based method (Ochoa and Harrison, 2011) and a GA-based model (Ugranlı and Karatepe, 2013) were used to size wind MP, but the optimum connection points were not taken into account. Concerning the second approach, a probabilistic planning strategy was used to handle DREMP (i.e. biomass, wind, and solar) mix while taking into account time-varying consumption and probabilistic production (Atwa et al., 2010). The demand was expected to follow the IEEE-RTS system's hourly load curve (Pinheiro et al., 1998).

The Beta Probability Density Function (PDF) and Weibull methods were used to represent the stochastic nature of solar irradiation and wind speed, respectively (Boyle, 2004; Salameh et al., 1995). The rated production of biomass distributed micro-plants were considered to be constant with no related uncertainty. A mixed production-consumption approach was presented to accommodate the output powers of DREMP as multistate variables in the problem of power system planning. Furthermore, (Atwa and El-Saadany, 2011; Khatod et al., 2013) described a planning strategies for finding optimum location and size of PV and wind-based DREMP that takes production and consumption probabilities into account. However, the probabilistic or time-series planning strategies can produce more appropriate outcomes than the conventional ones (Hung, 2014). Furthermore, according to the related literature survey and due to the IEEE 1547 standard, the majority of existing researches have supposed that DREMP function at unity power factor. In these studies, only the connecting point and capacity of DREMP were examined, whereas the appropriate power factor for each DREMP, which is critical for minimizing energy losses, was overlooked and neglected. Based on the requirements of loads, DREMP that can produce simultaneously active and reactive power at appropriate power factor may have a favorable influence on energy loss minimization (Hung, 2014).

#### *3.3.1.1.2 Voltage Stability*

At the transmission network level, the voltage stability has been extensively researched and studied during the last four decades (Ajjarapu and Lee, 1998). Voltage instability usually appears when power systems are heavily loaded with insufficient reactive power support resulting in voltage instability.

Concerning the distribution network level, voltage instability was not recognised only after the previous two decades. In 1997, a significant outage in the S/SE Brazilian power system was triggered by a voltage failure in a power distribution network that propagated to the connected power transmission network (Prada and Souza, 1998). A further investigation found that the distribution network in a specific industrial zone encountered voltage failure under severe loading conditions (Chakravorty and Das, 2001).

Voltage stability at the distribution network level took a great attention of power system operators and researchers, in the recent years, due to the significant increase of distributed renewable energy micro-plants, dramatically growing demands, and the requirement for improved system security. Some recent studies and researches have focused on the location and capacity of DREMPs for improving voltage stability in the distribution network.

Concerning the location, several methods have considered that distributed generation micro-plants are dispatchable and installed at the peak load for improving voltage stability. These methods are generally iterative based on Continuous Power Flow (CPF) (Hedayati et al., 2008; Hemdan and Kurrat, 2009), a mix of model analysis and CPF (Ettehadi et al., 2013), PSO (M. M. Aman et al., 2013; Hien et al., 2013; Kayal and Chanda, 2013), heuristic algorithms like SA (Injeti and Prema Kumar, 2013), a numerical approach (Esmaili, 2013), and a power stability index-based method (M. M. Aman et al., 2013). However, these methodologies are well-suited for dispatchable distributed micro-plants such as gas micro-turbine. Nevertheless, they may not handle a realistic situation that involves the time-varying characteristics of nondispatchable distributed renewable energy micro-plants and fluctuating demand. Lately, a methodology based *probabilistic* planning for the placement of DREMP (i.e., solar, biomass, and wind micro-plants) that takes into account probabilistic generation and time- varying demand was effectively developed (Al Abri et al., 2013).

Similar approach was previously introduced in (Atwa et al., 2010) in order to integrate DREMP for reducing energy losses. A sensitivity method was employed in (Al Abri et al., 2013) to find the candidate nodes to efficiently minimize the search area (Hung, 2014).

According to the researches presented in (Acharya et al., 2006; Esmaili, 2013; Kollu et al., 2014), sensitivity methods may not be helpful in capturing the candidate nodes for the placement of DREMP on radial distribution feeders with the purpose of improving voltage stability and reducing energy losses. In addition, using these strategies may also dramatically reduce DREMP penetration rate in feeders (Al Abri et al., 2013; Ettehadi et al., 2013; Hedayati et al., 2008; Hemdan and Kurrat, 2009; Hung et al., 2010; Kollu et al., 2014; Rao et al., 2013). Because the most sensitive nodes are usually situated near the end of feeders. Another drawback of these methods reported in (Al Abri et al., 2013; M. M. Aman et al., 2013; Esmaili, 2013; Ettehadi et al., 2013; Hedayati et al., 2008; Hemdan and Kurrat, 2009; Hien et al., 2013; Injeti and Prema Kumar, 2013; Kayal and Chanda, 2013) is that the appropriate power factor for each DREMP was not taken into account (Hung, 2014).

Knowing that DREMP functioning at optimal power factor that is suited with the type of loads may have favorable effects on voltage stability (Hung, 2014).

##### 3.3.1.1.3 Voltage Profiles

From the standpoint of utilities, the voltage profile aspect in distribution networks, which is related to power quality, is usually less critical than energy losses. However, due to significant DREMP penetration in DN level, it seems that there has been a growing interest of researchers and utilities in the voltage profile problems at the distribution network level in latest years (Hung, 2014; Tan et al., 2013).

For selecting the best connecting point and determining the size of DREMP, the voltage profile is usually considered with system restrictions and technical measures, which can be expressed as a multiobjective approach. For instance, detailed load flow calculations have been used in (Ochoa et al., 2008, 2006) to address multiobjective index. This index is constituted by multiple impact indices, each one of them is given a weight  (Hung, 2014). Moreover, these impact indicators are related to voltage drops, active and reactive power losses, short-circuit currents and capacity of conductor. Likewise, another research work (Tan et al., 2013) presented a combination of the PSO with the Gravitational Search Algorithm (PSO-GSA). The goal of the study is to reduce the multiobjective index, which is made up by a various indices related to the number of DG units, voltage profiles, power losses, MVA capacity, and emissions. In general, the studies mentioned previously considered a constant load approach. Therefore, the voltage-dependent load models should also be considered  (Hung, 2014).

When comparing voltage-dependent load approach to the constant load approach, a new research studies (El-Zonkoly, 2011; Misra and Singh, 2007; Singh et al., 2009) have shown that voltage-dependent load models (i.e. commercial, residential , and industrial) have a significant impact on DREMP integration planning. (Misra and Singh, 2007) proposed a multiobjective optimization planning approach utilizing GA with various load approaches to determine the location of DREMP in distribution networks. It was observed that using various types of load models can result in different outcomes in terms of location and capacity of DREMP in power networks. Similarly, PSO was used to construct a multiobjective planning model for various DREMP placement in distribution systems with multiple load models (El-Zonkoly, 2011).

The influence of time-varying load approaches on energy loss analysis in a distribution networks with wind distributed MP was reported in (Qian et al., 2011), but the optimal placement and capacity were not discussed in this paper. According to another study (Ebrahimi et al., 2013), time-varying voltage-dependent load approaches have a significant impact on the placement and capacity of distributed energy micro-plants. Nevertheless, this study did not include nondispatchable renewable MP that that are characterized by uncertainty of generation  (Hung, 2014).

#### 3.3.1.1.4 Deferral of power network upgrade

The capability to defer and postpone the required investment in strengthening transformers and feeders thanks to DREMP integration is known as power network upgrade deferral. It has been noted in the latest years that network upgrade deferral is an interesting solution for DREMP planning to meet the increase of load in power networks (Favuzza et al., 2007; Gil and Joos, 2006; Méndez et al., 2006).

According to (Méndez et al., 2006), DREMPs have varying effects on power network upgrade deferral depending on the technology used. Wind micro-plants, for example, are less capable than CHP generation units to reduce power network overloads due to their intermittent nature. Furthermore, according to (Gil and Joos, 2006), DREMPs functioning at non-unity power factor, where it provides both active and reactive power, offers a greater benefit than DREMP functioning at unity power factor. However, the importance of DREMP placement and capacity and their effects on power network upgrade deferral should be considered  (Hung, 2014).

The determination of optimal placement and scale of DREMPs for postponing distribution network upgrading is typically analyzed with other factors like economic and technical benefits, as well as system limitations. For instance, various methods have been reported in the literature for determining the best location of DREMP in order to maximize the benefits of power network upgrade deferral and minimize energy losses : ordinal optimization (Jabr and Pal, 2009), hybrid GA-OPF (Harrison et al., 2008), and Immune-Genetic Algorithm (IGA) (Soroudi and Ehsan, 2011). Furthermore, for distribution network planning in the presence of DREMP over a specified planning period, an OPF-based approach was presented in (Naderi et al., 2012). The goal is to reduce the expenses for operation, feeder reinforcement, and energy losses as much as possible. Likewise, a strategy based multiyear multiperiod OPF was effectively improved in (Piccolo and Siano, 2009; Siano et al., 2009) for DREMP planning taking into account the deferral of power network investment. One other research reported in (Celli et al., 2005) established a multiobjective framework based GA to find the best location and optimum size of DREMP in order to identify the optimal compromise between network upgrade deferral and the costs related to: imported energy, energy losses as well as unserved energy. Furthermore, a recent research published in (Shaaban et al., 2013) suggested a GA-based model for locating and sizing DREMP, such as biomass, solar, and wind, to maximize the benefits of postponing network upgrades while lowering interruption and energy losses costs.

This model also consider the intermittent nature of DREMP and consumption fluctuation. Aside from the benefits listed previously, another technical benefit that DG may provide to distribution networks is reliability.

#### 3.3.1.2 Environmental factors

The worldwide climate change initiatives (such as Kyoto Protocol) seek to reduce greenhouse gas (GHG) emissions. Carbon dioxide ($CO_2$), sulphur dioxide ($SO_2$), and nitrogen oxide ($NOX$) are the three major components of GHG emissions from power generation. These emissions are mainly resulted from the combustion of fossil fuels in centralized power facilities. Thus, increasing the quantity of clean energy produced by DREMP in power networks to reduce the use of electricity provided by centralized power plants will help reducing GHG emissions (Tsikalakis and Hatziargyriou, 2007). According to a British research published in (Viral and Khatod, 2012), CHP-based power plants decreased $CO_2$ emissions approximately 41% in 1999. Likewise, another research work on the Danish electricity system reported that using distributed energy micro-plants resulted in a 30% reduction in emissions from 1998 to 2001 (Hung, 2014). In general, the widespread deployment of distributed energy micro-plants may have a significant effect on the amount of GHG emission reduction depends on the technology used. For example, when compared to non-renewable MP technologies that utilize fossil fuels such as reciprocating engines, natural gas micro-turbines, and fuel cells based natural gas, DREMP technologies such as wind, biomass, and solar PV provide minimal or zero emissions. However, system constraints, as well as economic and technical boundaries, may limit their adoption (Hung, 2014).

Various approaches and methods have been used in the literature for siting and scaling DREMP to maximize emission reduction related to economic and technical benefits while satisfying the constraints of power systems. For instance, an optimization strategy based honey bee mating was presented in (Niknam et al., 2011) to lower emissions while minimizing distributed energy MP construction and operation costs, energy losses, and voltage deviations. Likewise, a multiobjective planning approach based on an IGA strategy was also provided in (Soroudi et al., 2011b) to minimize GHG emissions while lowering costs associated with distributed energy MP installation and operation, imported power and system reinforcement. A similar research presented in (Vahidinasab, 2014) suggested a multiobjective planning approach to perform a trade-off between GHG emissions and cost savings. In this study, the cost is associated to distributed energy

MP installation and operation, imported energy and energy losses. The limitations of these research works (Niknam et al., 2011; Soroudi et al., 2011b; Vahidinasab, 2014) is that DREMP were considered to function as a dispatchable source with no related uncertainty.

In contrast to previous studies, a multiobjective approach based GA for wind DREMP planning was proposed in (Jin et al., 2013) that takes into account production uncertainty. The purpose of this study is to reduce the costs of DREMP installation and operation, as well as the GHG emission penalties while enhancing system reliability.

#### *3.3.1.3 Economic factors*

Along with the environmental and technical factors that influence the location and size of DREMPs already covered above, a complete examination of their costs and benefits including energy sales as well as the monetary gains derived from the environmental and technical benefits of DREMPs must be also taken into account (Hung, 2014).

The preceding mentioned literature reveals that DREMP planning has been discussed extensively. Nevertheless, the majority of the studies have only addressed cost analyses such as DREMP installation and operation costs and GHG emissions penalties. However, a research work presented in (Kumar and Gao, 2010) proposed a method for determining the position and number of DREMPs. The goal is to reduce electricity losses and fuel costs to a minimum. A planning framework for PV micro-plant integration was also proposed by minimizing fossil fuel imported electricity and PV investment & operation costs (Kucuksari et al., 2014). Furthermore, heuristic models for locating and sizing DREMPs were presented in (El-Khattam et al., 2005; Porkar et al., 2010) with the goal of reducing installation, operation, energy losses, and imported electricity costs. A study presented in (Mistry and Roy, 2014) offered a PSO-based DREMP planning strategy with the same goals. However, the cost-benefit of DREMPs also must be considered in the assessment.

Through a cost-benefit analysis, a dynamic programming algorithm was developed in (Khalesi et al., 2011) to locate and scale DREMPs. The entire cost includes the costs of DREMPs installation, operation, and maintenance, whereas the entire benefit includes savings from reduced energy losses, imported electricity, and unserved energy. However, including DREMP electricity exports in the assessment appears to give a much more precise results and conclusions (Hung, 2014). However, some researches works have presented comprehensive frameworks for investment planning of DREMP based on cost-benefit analyses that include DREMP electricity sales. For example, a report published in (El-Khattam et al., 2004) proposed a heuristic model for locating and scaling distributed energy micro-plants based on increasing the profit of utilities as a function of costs and benefits. The costs are associated with DG installation, operation, unserved energy, imported energy from the utility grid, and energy losses, while the benefit is associated with energy exports (sales). Similarly, A cost and benefit strategy based GA for accommodating DREMP was presented in (Akorede et al., 2011). In this study, electricity sales are the benefit, whereas DREMP installation and energy losses charges are the cost. Moreover, through a cost-benefit analysis, a heuristic technique for locating and scaling DREMPs was also presented (Humayd and Bhattacharya, 2013). Installation and operation of DREMPs, feeder and substation investments, imported electricity, and unserved energy, all constitute costs, whereas electricity sales constitute the benefit (Hung, 2014).

Finally, the above literature research demonstrates that multiple approaches for DREMP integration in distribution systems have been established, taking into account various factors including technical, environmental and economic benefits. However, the majority of these studies consider that DREMPs operate at a unity power factor, which is not really the case. Because with the development of power electronic converters, the modern DREMPs can produce both, active and reactive power simultaneously. DREMPs functioning at optimized power factor, depending on the type of loads, have favorable effects on voltage stability, energy losses, and system capacity release.

## 3.4 Practical applications and solutions for boosting DREMPs integration

To boost the deployment of DREMP, utilities and system operators have used several practical applications and solutions. In the following subsection, some of these practical applications are presented.

### 3.4.1 Voltage Regulation at the Level of Substations

HV/MV transformers with voltage regulation option are employed at the substation level to regulate the voltages in the transition between the HV/MV networks (Bayer and Marian, 2020; Iweh et al., 2021). Voltage regulators were primarily utilized by most utilities in the past to correct for voltage fluctuations on the HV network and stabilize the MV to a reasonably consistent level. Power system operators in Germany (Bayer and Marian, 2020) have incorporated power electronics and software programs to modify MV levels in relation to the proportion of renewable energy penetration and the load flow situation at the substation since the introduction of renewable energy integration in the grid. This is done to keep the MV network's voltage from rising when renewables are injected. However, there are a number of drawbacks to this strategy (Iweh et al., 2021). Voltage variations, for example, could have a severe impact on commercial manufacturing units connected to the power grid at the medium-voltage (MV) level, limiting the use of dynamic voltage regulation. Furthermore, the ability to lower the voltage in a network will be determined by the physical distribution of renewable energy systems in a specific MV grid area, with energy systems located far from the substation posing challenges when lowering the voltage. Nonetheless, German Distributed System operators consider the use of this technology to be one of the most cost-effective ways to improve the grid's hosting capacity (Bayer and Marian, 2020; Iweh et al., 2021).

### 3.4.2 Modified Grid Configuration

Grid growth with the addition of distributed renewable energy micro-plants necessitates optimizing the existing grid's structure in such a way that power losses are reduced, fault detection and rectification is aided, and physically accessible switching stations are created (Bayer and Marian, 2020; Iweh et al., 2021).

With increased DREMPs penetration and the need for grid expansion, a techno-economic dilemma arises, prompting system operators to set additional goals: avoid building new transmission lines or power substations as much as feasible. This extra purpose of limiting power network expansion, which is also named as *power network upgrade deferral*, clashes with the previously mentioned optimization approach (Iweh et al., 2021).

Actions aimed at lowering grid impedance would increase the capacity of renewables to be hosted in the electrical grid. The closed-loop application in MV networks (Bayer and Marian, 2020) , in which a radial MV grid topology is turned into closed rings with each substation connected to multiple energy supply lines, is a feasible solution widely utilized by German system operators to minimize grid impedance. This method creates a closed loop by connecting previously autonomous transmission lines that were fed by a common distribution transformer to a switching station. However, this strategy makes failure detection and recovery extremely difficult, and it is still contentious among power system operators (Iweh et al., 2021). As a result, in order to maximize the use of existing grid capacity, grid integration studies, sustainable solutions and optimal planning for equitably distributing injected DREMPs electricity over the whole grid must be developed (Iweh et al., 2021).

### 3.4.3 Reactive Power Control:

Power network operators leverage the capabilities of distributed renewable energy micro-plants to create reactive power to control voltage quality (voltage profile) since injecting active power into the grid causes a voltage rise. The infusion of reactive power balances out the voltage spike, boosting the network's ability to support DREMPs (Bayer and Marian, 2020). At the HV level, system operators have adopted advanced approaches such as automatic supervisory control systems to govern reactive power injection. Reactive power control can also be used to reduce reactive power imbalances in the MV network, which is typically provided by generators.

### 3.4.4 Creation of Express Feeders in the MV Network

Some system operators have chosen to build express feeders that connect HV/MV substations to DREMPs for better current carrying capacity energy evacuation. The express feeders are large-cross-section transmission lines (500–800 mm2) capable of transporting significant volumes of electricity to consumers. Because of the huge cross-section, the voltage drop on these lines is low, and as a result, the reduced voltage drop can considerably boost the MV network's hosting capacity (Bayer et al., 2018). This method has proven to be cost-effective in locations where strong DREMP penetration has caused voltage issues (Iweh et al., 2021).

### 3.4.5 Providing ancillary services

Ancillary services are those that guarantee the quality of electricity supply through the electric grid. The system operator may assess the need for these services and control it in a specific place using qualitative and quantitative controls. These services are delivered by a range of devices in power grid, which use their capability to meet certain technical needs like voltage regulation and frequency control (Alsokhiry and Lo, 2013). However, in modern power grids, DREMPs are one of these devices that have the capability to work in parallel with the conventional power plants and other grid equipment to ensure the reliability, security and stability of the power system by delivering necessary ancillary services. In several cases, delivering ancillary services using DREMPs instead of traditional power plants has become more practical since the opportunity cost of DREMPs is significantly lower due to their small electricity production, and the DREMPs are typically placed near the load center. This results in a significant drop of electricity costs due to the long transmission lines of centralized power plants (Alsokhiry and Lo, 2013).

DREMPs such as PV and wind could deliver power system ancillary services such as frequency response and voltage support ancillary services, by using controllable BESS. In addition, the owners of wind-based DREMP may need to change fixed-speed induction generators with variable-speed wind generators, like synchronous or double fed induction generators with fully rated converters, for a much more reliable power operation, since they can assist to AC voltage regulation (Alsokhiry and Lo, 2013).

### 3.4.6 Power off-grid areas and sensitive loads

In addition to the previous mentioned applications, DREMPs deployment has been steadily increasing in underdeveloped countries mostly to power off-grid areas (Iweh et al., 2021).

In general, DREMPs can be used to assist utilities in resolving issues related to distribution system performance. The basic requirement is that DREMPs run in parallel with the utility at all times and provide sensitive loads that risk to be turned off due to distribution system failures, such as when power system disturbances occur owing to line faults producing brief voltage sag (Basak et al., 2012; Lasseter and Kevin, 2000).

## 3.5 Motivated Factors for the increase use of DREMPs in power grids:

Distributed renewable energy micro-plants play a crucial role in modern power systems (Iweh et al., 2021) and the vast range of its expected uses besides its potential benefits toward producing clean and reliable energy open the doors for more research and development of these technologies that will contribute significantly to future generation (Berrada et al., 2021).

The conventional electric grid system would not easily be replaced by distributed renewables, maybe because the latter is a well-established technology that should not be abandoned, and the new distributed renewable energy technologies are generally not matured enough to handle the complete demand. As a result, sustainable options such as incorporating DREMPs into the current power infrastructure are becoming increasingly important. However, Power system operators are looking for cost-effective ways to increase the penetration of distributed renewable energy MPs in the grid. Many scholars investigated the driving factors for the increase use of DREMPs in power systems. For example, (Zahedi, 2011) examined the push factors, benefits, and problems of integrating distributed renewable energy MPs into the grid, with end user perception issues being the most prominent. However, Global climate concerns, increasing power consumption, the need for increased flexibility, aging grid infrastructure, and the need to diversify energy sources are all driving this transformation (Iweh et al., 2021).

Economic, environmental, technical and regulatory factors all play a role in the widespread of DREMPs and its current role in grid integration (Hung, 2014; Paliwal et al., 2014; Iweh et al., 2021).

### 3.5.1 Economic factors

DREMP require less capital investment and risk because their capacity is small compared to centralized generation. As a result, this could encourage investors to enter power generation market via DREMPs (Iweh et al., 2021). Moreover, the cost of operation and maintenance (O&M) for DREMPs is lower, mainly due to the fact that they are generally positioned near load centers, where losses are minimal. Furthermore, the liberalization of the electricity market with minimal and limited restrictions would entice investors for the use of DREMPs to reap the benefits (Paliwal et al., 2014). A decrease in the cost of RESs like solar PV is also pushing DREMPs deployment forward.

### 3.5.2 Environmental factors

One of the key driving factors for distributed renewable energy micro-plants is the need to minimize greenhouse gas (GHG) emissions and decarbonize power systems. Because DREMPs deployment does not necessitate the building of huge power plants or new power lines, it eliminates the environmental challenges associated with their construction as well as public opposition (Iweh et al., 2021). As per (Adil and Ko, 2016), environmental protection institutions have expressed concerns about the development of onshore wind farms, citing noise and aesthetic issues. As a result, a compromise must be reached between the need to preserve the beauty of the environment and the need for sustainable energy supply. Some authors (Adil and Ko, 2016; Iweh et al., 2021) suggest that renewable energy technologies, such as wind, should be promoted because they have no waste management difficulties and produce nearly no GHG emissions. These environmental issues, however, must be supported by rules and regulations that require those involved in the energy sector to adhere to environmental sustainability norms.

### 3.5.3 Technical factors

DREMPs can provide ancillary services including voltage and frequency regulation, spinning reserve, and  reactive power support (Mashhour and Moghaddas-Tafreshi, 2011; Rueda-Medina and Padilha-Feltrin, 2013; Yuen et al., 2011).

### 3.5.4 Regulatory factors

The majority of countries are increasingly adopting and implementing policies aimed at promoting the deployment of DGs, particularly DREMPs. This is due to the fact that modern societies are so reliant on electricity that any disruption in supply might have disastrous economic, political, and social effects. As a result, DREMPs, are a viable source of long-term energy supply and security. Furthermore, a fully competitive electricity market will result in lower electricity prices and better service. This market framework will incentivize power sector investors to deploy a large number of DREMPs (Adil and Ko, 2016). Moreover, rising electricity demand in countries as well as the need to reduce fossil fuel-based generation are major driving factors behind the deployment of DREMP to fulfill load requirements with clean, secure and sustainable sources. According to the REN21 Global Status Report (REN21, 2020b), the global policy push for renewable energy integration and related technologies like ESSs continues to emphasize the need to increase grid flexibility, control, and grid resilience. This confirms the study's premise as a current problem that requires additional investigation.

## 3.6 Issues resulting from the integration of DREMP in power grids

### 3.6.1 Introduction

Distributed renewable energy micro-plants play a crucial role in modern power systems. The conventional generation, transmission and distribution power systems could all benefit and suffer from the widespread deployment of DREMPs in power grids. However, because DREMPs with intermittent outputs are largely connected at the distribution network, their effects on the distribution network are likely to be greater (Iweh et al., 2021).

Many technical, economic, environment and regulatory concerns have arisen as a result of the increasing integration of DREMPs, including power quality issues (ex. voltage level fluctuations (over/under voltage), transient voltage changes, voltage flickers, frequency variation, harmonics distortion (both current and voltage)), grid instability, increase in the fault level and more. These issues may have a great influence on supply security and reliability, equipment control and protection, islanding, and safety (Hamlyn et al., 2008; Iweh et al., 2021; Manditereza and Bansal, 2016a; Millar et al., 2013; Roy and Pota, 2015b; Xyngi and Popov, 2013). In addition, the integration of a large number of DREMPs in power network cause fundamental changes to the power network topology, particularly at the distribution level, which may eventually shift the power system architecture from vertical to a horizontal one (Manditereza and Bansal, 2016b). With

AC and DC high-voltage transmission lines, centralized renewable energy plants (e.g., large hydro plants, off-shore wind farms) may be transported from high-energy density generation locations to high-energy density consumption areas (e.g., cities, manufacturing sites). This vertical topology is not anymore valid in power systems where residential, commercial and industrial consumers could also have their own distributed renewable energy micro-plants. According to (Soroudi et al., 2011a), DNs are elaborated in such a way that they can only regulate power flow in one direction. As a result, the grid's connectivity of DREMPs could cause voltage fluctuations, challenges with protective device coordination, and reactive power control concerns. When solar and wind systems are connected to the grid as dispersed micro-plants, their stochastic nature might compromise power reliability. Furthermore, the capital cost of distributed renewables, particularly in Sub-Saharan Africa, is quite high, making large-scale deployment difficult (Iweh et al., 2021).

The impact of DREMPs on power networks significantly depends on the type of DREMPs as well as the type of the network. DREMPs can be connected directly to the DN, as in the case of constant speed wind micro-plant based asynchronous or SGs, or through power electronic converters. However, in all cases, the voltage regulation, network losses, and power flow in the DN are impacted. SGs generate a significant short-circuit current that affects the fault level and the protection system. In the other hand, the effect of DREMPs linked via power electronic converters on the protection system and fault level is minimal since they barely contribute to the fault current (Coster et al., 2011; Morren and Haan, 2008). Nevertheless, they may generate harmonics. The operation mode and the architecture of the converter determine the order and amplitude of the harmonic currents (Ackermann and Knyazkin, 2002). These harmonic currents can distort the profile of the voltage that propagate across the DN. Moreover, it is clear that small voltage distortions, at a series resonance conditions of the supply inductance (cable inductance and transformer leakage) and cable capacitance, can result in significant harmonic currents that must be avoided. Parallel resonance of the supply inductance and the parallel network capacitance (cable capacitance and output capacitance of the inverter), particularly for inverter interfaced DREMP, can result in significant voltage distortions at the point of interconnection (Enslin et al., 2003). These forms of resonances have been studied by several researchers, including (Enslin et al., 2003; Heskes et al., 2005) who carried out real measurements on DNs and residential areas that had numerous PV micro-plants. The results, in particular, demonstrated that parallel resonances can trip inverters because of a distorted voltage profile (Coster et al., 2011).

In this context, it is necessary to think about the challenges and the implications of integrating DREMPs into the power grids (specially the distribution network). More studies are needed to solve these challenges so that DREMPs can be successfully integrated (Berrada et al., 2021) in order to obtain optimal grid performance (Iweh et al., 2021). According to the literature, many researchers have investigated the issues of integrating DREMPs in power systems. We cite for instance:

A research in (Lopes and Borges, 2015) divides the challenges of interconnecting DREMPs into three categories, namely economic, technical, and regulatory. The authors focused only on technical issues. The two other issues were ignored because they are related to government policy and decisions. However, increasing the share of DREMPs in the energy mix will be successful only if these concerns are addressed. When undertaking grid planning and operational studies, the problems of RE integration to the grid, such as the choice of technology and a suitable connection point, should be taken into account (Colmenar-Santos et al., 2016). The goal of the work in (Meyer et al., 2006) is to provide a quick overview of the circumstances and the regularity environment around development in France and Europe in general. In this paper, the technical challenges for DREMP integration are briefly reviewed, demonstrating that the introduction of DREMPs on the distribution network raises a number of issues. Power quality, voltage profile, active and reactive power, including voltage control contribution to ancillary services, stability and capability of DREMPs to tolerate disturbances, protective aspects, islanding and islanded operation, and system safety are among the challenges. These concerns can differ depending on a country's laws and regulations, power sector economy, voltage and frequency levels, and so on (Basak et al., 2012). Other authors (Al Talaq and Belhaj, 2020; Archana and subramaniya, 2018; Bank et al., 2013; Belcher et al., 2017; Kumar and Selvan, 2017) used ideal test grids to investigate specific challenges such as voltage level fluctuations, power losses, and reverse power flow influencing power injection into the grid. The authors give also some considerations of how these issues could alter in a real-world grid system. Similarly, (Cobben, 2007) provides a summary and classification of all power quality issues, as well as the impact of the DREMPs on power quality. Likewise, (Coster et al., 2011) discussed the effects of grid connected DREMPs on power quality concerns. In this paper, three major aspects are considered: voltage flicker, dips and steady-state voltage rise, and harmonics. (Rohouma et al., 2020) investigated the power quality issues and the usage of capacitor-less distribution static compensators (D-STATCOM) in advanced DNs for power quality compensation. (Laaksonen and Kauhaniemi, 2008) investigated voltage and current THD (total harmonic distortion) with various DREMPs and load configurations, and simulations are run using negative sequence filtering in the converter's control system to reduce voltage and current THD for unsymmetrical loads. Voltage dips are frequently responsible for compromising the operation of sensitive electronic components in DREMPs and micro-grid (Macken et al., 2004). (Papadimitriou and Vovos, 2010) discusses specific challenges related with the islanding of grid-tie inverters used to inject power generated from wind micro-plants into the grid. The authors proposed, a simple, cost-efficient, and practical solution to minimize grid-connected inverter islanding by utilizing a fuzzy based local controller that exploit the inertia of a DFIG-based wind turbine. (Hamzeh et al., 2012) discusses the power quality issues in an islanded micro-grid related with the addition of a single-phase load in presence of DREMPs. To dual with the unbalanced state of the micro-grid based DREMPs and to improve its power quality, the paper proposes a new control method that involves employing a proportional resonance controller, a droop control scheme, and a negative sequences impedance controller, which minimizes the negative sequences current in an imbalanced condition. (Ipakchi and Albuyeh, 2009) discussed the difficulties associated with widespread use of DREMPs, especially intermittent ones like solar PV and wind. The obstacles in this context are based on the following issues: integration standards, transmission network issues, distribution network issues, forecasting, scheduling, and operational issues. Several problems about demand response and distribution circuit congestion were raised as part of the transition from a load following to a load shaping strategy. Also emphasized was the vital role of information and automation technology in smart grid concerns. (Nagy and Körmendi, 2012) provides an analysis of issues related to new energy strategies from 2011 to 2020, examining the impact of the strategy on the use of DREMPs. The analytical study states that future energy demand and the use of DREMPs will require a balance between efforts to increase renewable energy use and the way energy demand develops. The authors of this paper recognized that this research approach is essential for the sustainable development of micro-grid technology to meet future energy needs.

In the next sections, we present more details and most common challenges and implications of integrating DREMPs into the power grids.

### 3.6.2 Technical issues

#### *3.6.2.1 Power Quality issues related to the widespread of DREMP:*

Continuity of electricity supply was previously for a long time the biggest concern for energy users, but currently this is not the case. A rise in non-linear loads caused by modern technologies including DREMPs, EV chargers, power electronic inverters, and micro-grids, pose problems for power quality and stability. As demand increases, power quality deteriorates, which leads to increased utility expenses, poor electrical system performance, supply continuity concerns, shorter equipment lifespan, more unscheduled maintenances, and non-compliance to grid codes (ABB, 2021).

Power quality may be assessed using standard defined limits and several key performance indicators (KPI) that let electrical components of the power grid function as intended without noticeably reducing lifetime or performance. When adequate power quality is in place, the whole electrical network would have a stable, reliable and continuous power supply with a pure sinusoidal noise-free wave form and is always within frequency and voltage tolerances (ABB, 2021).

The power quality issues can frequently be divided into two categories, short-term and long-term disturbances (ABB, 2021). Short-term disturbances are those that have an immediate and/or observable effect, like voltage variation and transients, unplanned downtime, decreased power systems efficiency, and unexpected equipment damage or failure. Long-term disturbances include harmonics, over- and under- voltages, unbalances, flicker, and low power factor. These disturbances lead to overheating, malfunctions, damages, and failures of electrical equipment (ABB, 2021; Iweh et al., 2021; Zahedi, 2011). In general, low power quality may also lead to automatic resets, data errors, memory losses, software corruptions, circuit board failures, unit power supply (UPS) failures and alarms, and overheating of DNs and power supply problems (ABB, 2021).

The integration of distributed renewable energy micro-plants in the distribution networks can further exacerbate the power quality issues such as harmonics (Rohouma et al., 2020). The use of rectifiers and inverters in PV and WP micro-plants generates harmonics and undesired electrical noise, such as reverse-recovery currents (Fuchs and Masoum, 2011; Masoum and Fuchs, 2015). Moreover, these micro-plants produce high system impedances at the DN, in addition to power-load balancing concerns, because these micro-plants are unable to offer additional transient currents when faults arise due to their operation at peak power (Masoum et al., 2002). Even with acceptable current harmonics, high system impedance can lead to unacceptably high voltage harmonics, single-time events (e.g., spikes due to network switching and synchronization), and non-periodic but repetitive (e.g., flicker) events, all of which can contribute to power quality issues (Arrillaga, 1998; Fuchs et al., 2004; Fuchs and Masoum, 2008; M. Masoum et al., 2004; M. A. S. Masoum et al., 2004; Masoum et al., 2005; Masoum and Fuchs, 2015). The impact on power quality will be determined by the number and capacity of connected DREMPs to the network; uncontrolled power injection from these systems could have a negative effect on power quality (Misra and Singh, 2007; Nabavi et al., 2011).

Power quality is a vital aspect in the power network systems, especially with the influx of new electrical equipment on the market that is extremely sensitive to voltage changes. The amount of voltage variation (over/under voltage), frequency variation, and harmonics are all measured as part of power quality (Zahedi, 2011).

Figure *3.3* gives a simple understanding of common power quality issues that may result from connecting DREMPs in power networks.

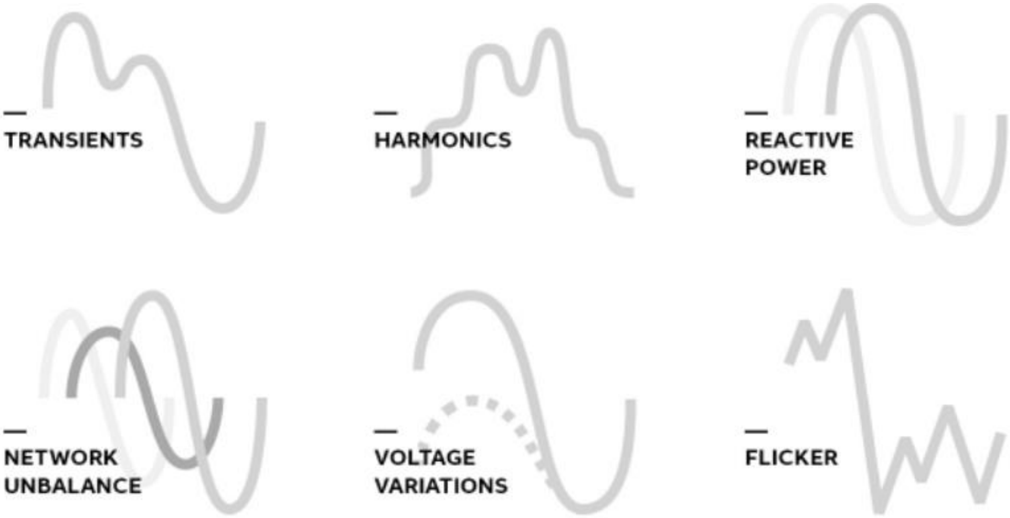


*Figure 3.3 Most common power quality issues (ABB, 2021)*

### 3.6.2.1.1 Power quality based Voltage Level Fluctuations

In virtually all circumstances, the distributed micro-plant is dependent on the power system's voltage, which means that the voltage cannot be changed by a single renewable micro-plant because to its lower capacity rating, and only the current delivered into the grid can be managed. In other words, as soon as the grid voltage falls below or rises over specified thresholds, renewable energy micro-plants must be unplugged from the grid for safety reasons (Masoum and Fuchs, 2015). However, if many DREMPs run on the grid, voltage regulation related with reactive power/load flow and frequency will be more and more complicated (Masoum and Fuchs, 2015). Maintaining a somewhat steady voltage level in a power network is critical for the grid's components to function properly. Because the power flow and voltage are highly influenced by changing demand and generation, most DREMPs are now positioned near load centers, where they distribute electricity to customers. Any significant change in power flow will influence the feeder voltage. The flow of electric current to loads in a radial-configured electricity distribution network is prone to a positive voltage drop as one proceeds along the network, which can create voltage amplitude oscillations at network nodes (Wasiak and Hanzelka, 2009). The addition of a distributed renewable energy micro-plants to the electricity network has the same effect on power quality as disruptive loads since they can generate long-term and short-term voltage changes, voltage flickers, and harmonic distortions, among other things. Depending on the scenario, voltage increases and voltage decreases can be noticed in a power system network with the presence of DREMPs (Iweh et al., 2021).

The non-dispatchable nature of solar and WP micro-plants (i.e., the production of electricity that cannot be adjusted to match fluctuating power demand) are a possible sources of grid voltage oscillations. Any change in the system voltage must be restored by some voltage controls in the power network (Belcher et al., 2017). The voltage regulation is affected when a distributed renewable energy micro-plant injects power into the grid since it is highly dependent on the power flow in the network. If the DREMP is positioned near the loads in a distribution feeder and the DREMP's power factor is equal to that of the load, there will be no voltage violations. The voltage drop is decreased since the main grid supplies less energy with a lower feeder current. In contrast, as the electricity generated by the DREMP exceeds the feeder load or reaches an extreme power factor, voltage rises. A reverse power flow causes this increase in voltage, which is dependent on the DREMP capacity, power factor, and grid impedance (Khetrapal, 2020).

The power injected into the distribution network system causes an increase in voltage at the connection point of DREMP, and for radial feeders, this change in voltage may be estimated using the Eq. 3.1 (Conti et al., 2003):

*Eq. 3.1:*

$$\Delta V = \frac{(P_S - P_L)R + (Q_S - Q_L)\,X}{V}$$

Where $P_S$ and $Q_S$ are the DREMP's active and reactive powers, respectively, and $P_L$ and $Q_L$ are the line load's active and reactive power, respectively. The resistance and reactance of the line connecting the DREMP and the substation are $R$ and $X$, respectively. $V$ represents the line voltage at the DREMP's connection point. Figure 3.4 depicts this circumstance.

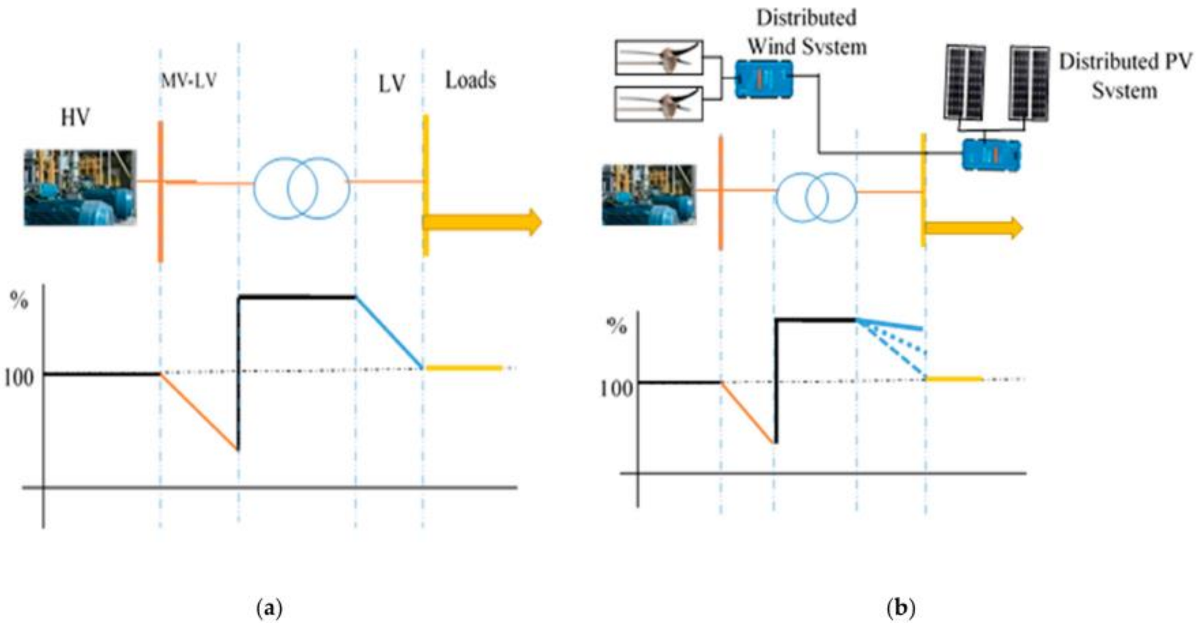


*Figure 3.4 (a) The voltage along the power network without DREMPs; (b) The voltage along the power network with DREMPs (Iweh et al., 2021).*

The voltage variations may result in a voltage violation, in which the power network system encounters voltages that are outside of the acceptable limits. These voltage variations can also cause damages in grid equipment and client electrical appliances (Mahmud et al., 2014; Mahmud and Zahedi, 2016). Another significant requirement is voltage stability, which has been established by several governments, regional blocs (e.g., the European Union), and professional organizations such as the Institute of Electrical and Electronic Engineers (IEEE). The European standard for voltage limitations allows for a 10% tolerance in daily power system operation (Markiewicz and Klajn, 2008), while IEEE standards allow for a 5% tolerance. These voltage limitations should be used to manage the operation of power system components. To regulate voltage in a continually changing load condition, energy utility companies typically use transformer tap changing functionality and capacitor bank switching. These steps help to keep the voltage in the network stable within its standards limits (Iweh et al., 2021). As we proceed throughout the grid, Figure 3.5 illustrates a profile of voltage ranges.

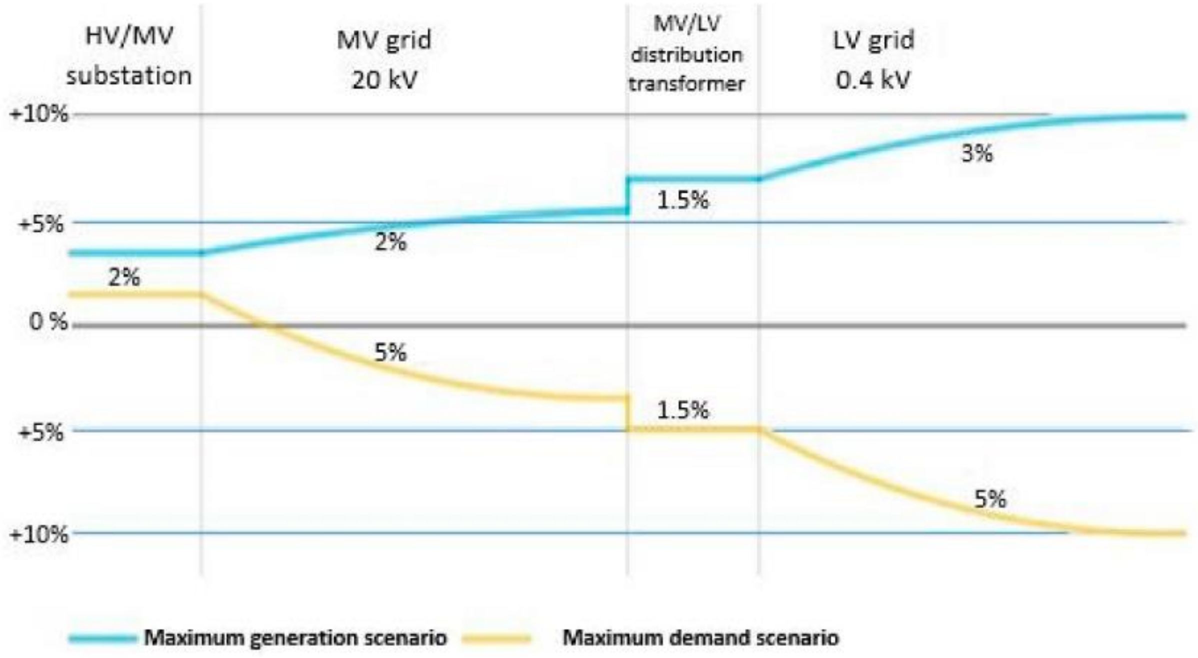


*Figure 3.5 Recommended distribution of voltage ranges along the power network (VDE, 2016).*

The installation of distributed renewable energy MPs near load centers or distribution transformers will generate power flow irregularities, which will affect the network's overall voltage. In a low-voltage (LV) network, power fluctuations produce undesirable voltage variation, which is exacerbated by high renewable penetration levels, which result in a sudden surge in voltage, usually under situations of reduced energy use. As a result, automatic voltage regulators should be installed in the LV network to control the voltage level in that area of the grid (Zahedi, 2011).

### *3.6.2.1.2 Power quality based Harmonics Distortion*

DREMPs such as WP and solar PV micro-plants that have power electronic converters to convert the generated DC power to AC (Eluri and Naik, 2021), may create voltage distortion and current harmonics at some point during the process of energy conversion (Wasiak and Hanzelka, 2009). The type of converter, its characteristics, and its mode of operation all have a significant impact on the amplitude and order of the current harmonics. Even though some of the introduced harmonic currents could distort the voltage form, the majority of modern converters linking distributed renewable energy MPs to the DN can actively shape their output current to a tolerable level (Barghi Latran et al., 2015; Bizon, 2018). At startup times, harmonics may occur in wind micro-plants based induction generators, for a short period of time, due to a power electronic converter. In addition to the DREMPs based power electronic converters, some nonlinear loads may generate harmonics as well, which are frequencies that are multiples of 50/60 Hz. These undesired frequencies injected into the power network can lead to a failure in the power system (Belcher et al., 2017). Most power systems can accept harmonic current up to a certain level, but if it reaches a critical level, it causes communication problems, overheating, excessive line losses, and erroneous circuit breaker tripping, among other things. Many research articles have been written to analyze power quality in low voltage systems based on harmonic problems (Basak et al., 2012; "Harmonics White Paper," 2022).

Harmonic compensation and elimination are more challenging in power networks with the presence of distributed renewable energy micro-plants than in a traditional power network with central power stations, where fewer harmonic sources make voltage management through appropriate capacitor placement easier. Even in systems with distributed renewable energy micro-plants, huge conventional power plants such as natural gas, coal, and nuclear power facilities function as frequency leaders (Masoum and Fuchs, 2015).

In conclusion, the occurrence of harmonics in power grids results in a variety of problems, such as equipment overheating, a decrease in the efficiency and performance of the grid components, a decline in the power factor (PF), communication signal interference, wrong responses of protection systems, malfunction of nearby devices due to resonance, unwanted electrical motors vibration, noise, and so on (Archana and subramaniya, 2018).

#### 3.6.2.1.3 Power quality based Transient Voltage Changes

When some DREMPs types are connected to the DN, voltage changes may occur as a result of switching activities in the DREMP installation, often during the equipment's start/stop cycles or during a capacitor system switch. There is currently no specific definition for the transient voltage changes on a global scale, nor are there any established limit levels for this perturbation. (Iweh et al., 2021; Wasiak and Hanzelka, 2009). When connecting and disconnecting from the grid, the DREMPs can cause transient voltage changes in the power network if quite substantial current fluctuations are permissible. During the design phase of the DREMP, the amplitude of the current transients may be more effectively regulated. When the synchronization is performed properly, the connection of SG in the DN, such in the case of wind micro-plants based SG, results in a negligible disturbance, and the magnetizing current of induction generator-based DREMP is dropped below to its acceptable limit by using anti-parallel soft-start elements. However, removing a generator that is running at its maximum capacity could result in significant voltage drops (Iweh et al., 2021).

#### 3.6.2.1.4 Power quality based Voltage Flickers

The deployment of intermittent DREMPs such as WP and PV micro-plants in the power networks could be a source of voltage flickers. This is due to the fact that their output voltage changes when the wind's direction and speed change for WP micro-plants or when the clouds cover the surface of PV panels for PV micro-plants. The British Standards Institution (BSI, 2008) stated that before wind turbines are linked to power networks, a voltage flicker evaluation should be done. The assessment of flicker indices $P_{st}$ and $P_{st}$ could be done using the Eq. 3.2 (Iweh et al., 2021):

*Eq. 3.2*
$$P_{st} = P_{st} = C\ (\varphi_k, \mathcal{V}_a)\frac{S_n}{S''_k}$$

Where $C\ (\varphi_k, \mathcal{V}_a)$ represents the coefficient of wind flicker determined through several tests on wind turbines, $\varphi_k$ represents the phase angle of the network impedance, $\mathcal{V}_a$ represents the wind speed annual average, $S_n$ represents the rated power of wind system, and $S''_k$ represents the power of the short-circuit at the point of common coupling (PCC).

### 3.6.2.2 Impact on Power Line Losses

Ohm's law may be used to calculate the power losses that occur as a result of the electrical energy flowing through a conductor. However, the equation below can be used to assess the energy losses of power lines (Eq. 3.3):

*Eq. 3.3:* $$P_{loss} = \frac{1}{T}\int_0^T R\, i(t)^2 \, dt$$

In the case of sinusoidal currents and for a full cycle (T = 2π), the average of power losses in the power line $P_{Loss}$ is determined as follows (Eq. 3.4):

*Eq. 3.4:* $$P_{loss} = \frac{1}{2\pi}\int_0^{2\pi} R \times (\, I_{max}^2 \, sin^2 \, \omega t)\, d\omega t$$

This equation could be written after simplification as follow (Eq. 3.5):

*Eq. 3.5:* $$P_{loss} = R\, I^2$$

Where $P_{loss}$ is the average of power losses in the power line, $I$ is the rms (root mean square) current of the power line, and $R$ is the resistance of the power line.

The connection point of a DREMP and the amount of its injected power into the network determine the quantity of energy loss experienced as a result of integrating DREMPs. When a distributed renewable energy MP is connected in a distribution feeder to feet the electrical appliances of users, the power supplied from the DREMP will be directly used by loads, which lowers the feeder losses and the flow of electrical energy. In addition, the danger of grid overloading is decreased because the flow of electrical current from the HV/MV system to the load is minimized. This could be considered as an advantage of DREMP integration (Khetrapal, 2020). Nevertheless, there will be a rise in energy losses in the DN if the energy delivered by DREMPs into the DN is greater than what the distribution lines were originally intended to handle. The cumulative energy losses in DNs can have a considerable impact on network management costs, which are frequently charged to customers in the form of higher tariffs.

#### 3.6.2.3 Intermittent nature of some types of DREMPs

The amount of electricity produced by DREMPs such as wind and solar micro-plants depends on the availability of wind and solar natural resources at a specific area. This fact is due to the continual variations in wind speed and velocity, and solar irradiance that cause the production of these micro-plants to change regularly. These changes in energy production with time and location from various DREMPs might result in grid destabilization and reduced reliability. (Khalesi et al., 2011).

Moreover, these intermittent DREMPs would increase grid losses because of their less correlation with electricity consumption. For instance, if the wind-based DREMP production is at its high owing to strong wind speeds and velocity and the electricity consumption at night is minimal, extra power will be flowed to the main grid, which will increase energy losses. According to (Delfanti et al., 2013), this issue could be overcome by incorporating a local ESSs to prevent energy exports and regulate the energy flow locally. The intermittent aspect of various DREMPs (biomass, solar, and wind) in a specific area is depicted in Figure 3.6. where is Figure 3.7 specifically shows the intermittent aspect of generated power from two PV panels (250W for each) in summer on a cloudy afternoon at Tlemcen, Northwest of Algeria.

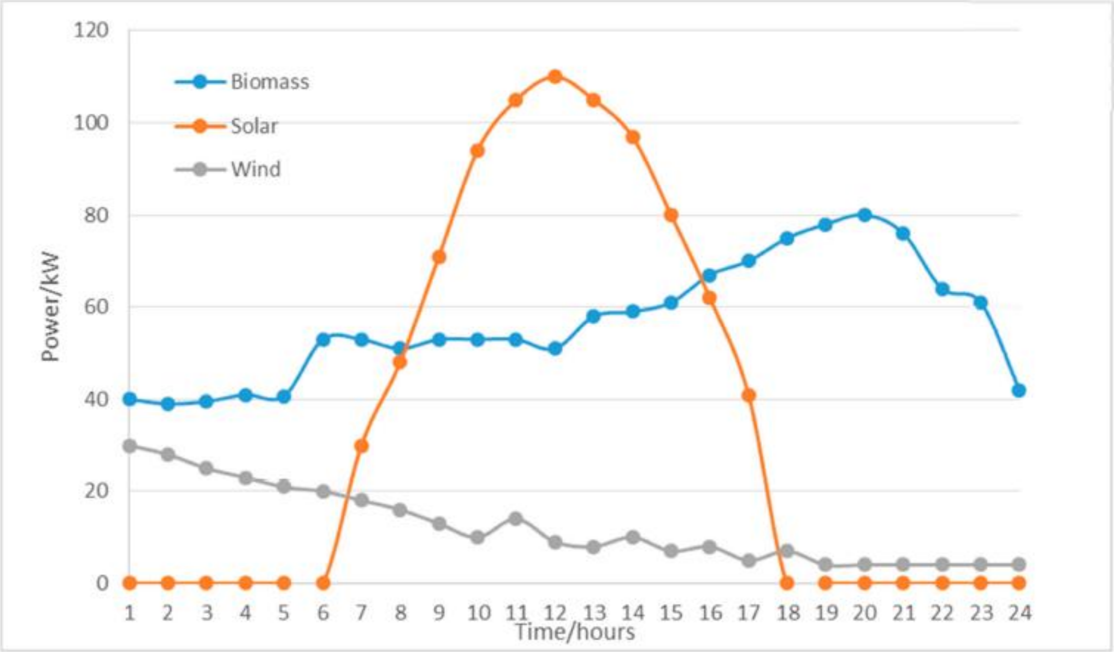


*Figure 3.6 The intermittent aspect of various DREMPs (Zaheeruddin and Manas, 2015).*

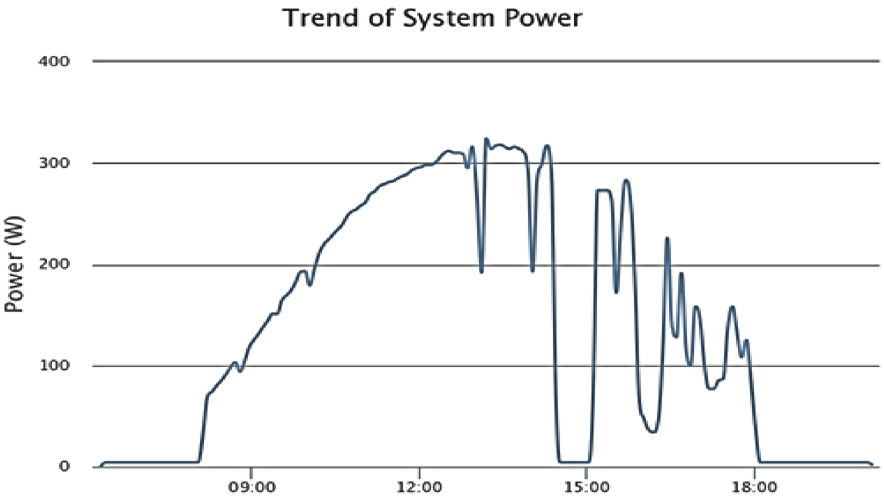


*Figure 3.7 Experimental curve of PV power in the summer at Tlemcen, cloudy afternoon (Terfa et al., 2022).*

### 3.6.2.4 Stability issues of power grid

Previously, electricity networks had a one power flow direction with a radial topology. Thus, power system operators and utilities plugged DREMPs in a "fit and forget" method. Nevertheless, when the penetration of DREMPs grew to high levels, increasing the supplied power from DREPMs started to become a concern. When a high number of DREMPs are plugged into distribution networks, a significant amount of electricity would not be imported from the conventional power pants, which influences the dynamics of the main power grid operation. Generally, the massive mismatch between energy production and consumption that often arises during operation can be stabilized when a power grid has enough spinning inertia (Khetrapal, 2020). But when many DREMPs takes the position of a large conventional plant, the power system inertia decreases, which can increase the mismatch between energy production and consumption, weakening the power grid and create stability issues. (Paliwal et al., 2014) argue that if a significant conventional plants is replaced by DREMPs installed near load centers, the existing inertia in the main power grid would decrease, exposing the main power grid to stability problems, notably for penetration levels of above 30% from DREMPs. However, engineers and power system planners must respect the grid limits during DREMPs integration studies and planning.

In order to address grid instability brought on by DREMPs integration, the "fault ride-through" condition can be utilized, in which standard time periods are imposed for DREMPs to stay connected in the power network throughout voltage increases, decreases, or faults. It becomes essential to define and establish the standard time periods for DREMPs connected to the power grid, mainly at the distribution level, as they are typically defined for big centralized plants. However, depending on the DREMP's capacity, such condition can also help stabilizing frequency and voltage during faults. Nevertheless, the performance of the local protective equipment may be impeded by the fact that DREMPs remain continually connected to the network during local faults, making fault detection and restoration more challenging (Khetrapal, 2020). Consequently, in-depth study is needed to maintain a stable power grid in the presence of DREMPs, and the rising DREMPs deployment throughout the power network necessitates synchronization and coordination between "fault ride-through" criteria and local protective equipment (Iweh et al., 2021).

#### *3.6.2.5 Fragility in the grid protection systems and rise in fault levels*

Because DREMPs may contribute to the fault current, their integration into the DN may have a negative impact on the grid protection system and create some fragility on the DN. The quantity of fault current injected into the DN is strongly influenced by how the DREMP is interfaced with the power grid, which might result in exceeding the limits of electrical equipment. For instance, when compared to DREMPs that are directly interconnected to the power grid, which generate a large amount of fault current, DREMPs interconnected via a power electronic converters rarely increase the fault current (Brearley and Prabu, 2017). Injecting significant amounts of fault current into the DN by DREMPs have a severe impact on the network's protective equipment, degrading their performance and making fault detection more challenging. Consequently, a protection management system with the capability to enable a two way power flow is required for connecting DREMPs into power grid (Ishchenko et al., 2012). When power injected into the DN exceeds the power limits of the system equipment, thermal overload occurs, which causes heating in the DN. One of the most expensive equipment of the electrical grid is the transformer, and any overloading will result in a number of failures and occasionally total damage (Murugan and Ramasamy, 2015). Similarly, transmission and distribution lines are very important in power systems, and any overheating will accelerate their degradation. The resistance and total heat transfer to the cable determine the maximum overhead transmission line current capacity as demonstrated in Eq. 3.6 (Trichakis et al., 2008):

*Eq. 3.6:*

$$I_L = \sqrt{\frac{\Delta H}{R}}$$

Where $I_L$, $\Delta H$, and $R$ represent, respectively, the current of the overhead transmission line, the transferred heat from the electric cable to the outside environment, and the resistance of the line.

When power systems are overloaded, the electric components of power systems must be upgraded to a higher rating. Therefore, the power system, especially DNs, must be capable of handling the implementation of a high number of DREMPs that are active devices installed mostly near consumers (Iweh et al., 2021).

### 3.6.3 Economic issues

When looking from the standpoint of resolving disputes between the utility and users, DREMPs may arise difficulties. Selling electrical power while acting alone in power grid management is the typical business strategy adopted by the majority of utilities, particularly in Africa. If power consumers, for example, implement rooftop PV micro-plants, they will be able to offset some of their imported energy and maybe sell excess power to the grid operator. Evidently, as the deployment of DREMPs from consumers' side becoming more and more popular, there are growing worries about the economic sustainability of the earnings of power system operators. In addition, the lifetime of the grid components might be shortened by the unmanaged injection of electricity from customers' side DREMPs that may cause overheating of the grid equipment. According to (Agah and Abyaneh, 2011; El Batawy and Morsi, 2017; Márk et al., 2017; Mousavi Agah and Askarian Abyaneh, 2011), transformers and electric cables begin to wear down earlier than their expected manufacturing time when the penetration level of DREMPs exceed a specific percentage. As a result, power systems' operation and maintenance (O&M) expenses will rise, which also lead to a rise in electricity tariffs (Iweh et al., 2021).

Concerning the digital economy, which is in fact highly related to the real-time and continuous transmission of information, a continuous electricity supply and increased power quality are essential. Power interruptions are excessively costly and even harmful for several businesses based digital economy and e-commerce. For instance, in Europe only, power quality issues are thought to cost business and industry around €10 billion annually. Although it is predicted that fixing these power quality issues would only cost 5% of this amount (ABB, 2021). The integration of DREMPs in the distribution networks can further exacerbate the power quality issues if not proper actions are done (Rohouma et al., 2020). Businesses and industries that are looking to solve their power quality concerns, increase energy efficiency, maximize their productivity, and boost grid reliability, must start by establishing a strategy for power quality improvement such as choosing the appropriate meters to record events and data, utilizing cutting-edge technology for accurate results, utilizing the appropriate visualization software to perform analysis, and choosing an expert solution provider (ABB, 2021). However, all these actions might be complicated in the presence of DREMPs that lead to additional costs. Moreover, upgrading power system equipment such as currently installed protective devices is essential in the presence of DREMPs, which adds to the total cost of the system (Abdi et al., 2017).

## 3.7 Stand-alone (Off-grid) Hybrid power systems based DREMPs

### 3.7.1 Introduction

Another approach that does not demand grid integration is stand-alone hybrid power system based DREMPs. Standalone or off-grid DREMPs hybrid systems can currently be created by combining several technologies like solar PV micro-plants, wind micro-turbines, micro-hydropower and batteries. In most cases, stand-alone DREMPs hybrid systems have also the ability to operate in grid-connected mode when needed. In this case, many distributed micro-plants need to operate on the grid due to the lower rating of DREMPs, making it difficult to control voltage in relation to reactive power / load flow and frequency. In almost all cases the distributed source depends on the voltage of the power grid, for that reason, we cannot change the voltage with a single renewable energy micro-plant, we can only control the power delivered to the grid. In other words, for safety reasons, low power DREMP should be disconnected from the grid as soon as the voltage on the grid falls below or above a certain limit (Masoum and Fuchs, 2015). For instance, (Meshram et al., 2013) proposed a solar–hydro hybrid system that is grid connected. They proposed a grid-connected solar system to provide power during the summer when solar energy is abundant and the hydro system is turned off. Similarly, when water is plentiful during the rainy season, the grid-connected hydro system is activated and the solar system is turned off (Bhandari et al., 2014).

However, Hybrid power systems (HPS) based DREMPs research is a multi-disciplinary field (Bhandari et al., 2014) that uses a combination of two or more RESs (Sayed and Gabbar, 2017) as a solution to improve the reliability of DNs (Adefarati and Bansal, 2016; Bansal, 2007; Salih et al., 2014) and to benefit from the complementarity between DREMPs to meet energy needs in off-grid areas. The periodic nature of RES is the main stumbling block to their rapid adoption (Adzic et al., 2009; Soetedjo et al., 2011). Energy storage systems and conventional generators such as diesel generator are commonly utilized as backup power systems in parallel with hybrid DREMPs to improve their reliability and power quality, and to meet demand requirements whenever DREMPs are not enough sufficient (Bhandari et al., 2014). DREMPs with several renewable energy sources can greatly improve reliability (Bhandari et al., 2015; Nema et al., 2009) and enhance the performance of electricity network (Adefarati and Bansal, 2016; Bansal, 2002). PV–battery, PV–diesel, wind–battery, wind–diesel, PV–wind–battery, and PV–wind–diesel–battery systems are all commercially feasible hybrid DREMPs. According to recent research (Mundada et al., 2016), these systems have a low levelized cost of power.

Due to the fast development of HPSs and the environmental implications of utilizing fossil fuels as well as their depletion, power system planners and grid operators are given a great attention to HPS technologies and considering them as an alternative to conventional systems in the near future (Gupta et al., 2008; Rajkumar et al., 2011). In terms of global installed capacity, hydro, wind, and solar PV energy are the most popular RES.

Figure 3.8 shows a schematic representation of a HPS based DREMPs. Because an HPS's reliability is largely dependent on the RES's dynamic behavior, it is critical to examine these dynamic characteristics in real time over lengthy periods of time. The development of a real-time control strategy for the HPS is a huge task. A controller must be able to interface with a hardware simulator and process inputs and outputs in real time in order to test HPS controllers. Today, advances in communications systems have pushed the use of a centralized supervisory control platform, often known as a SCADA system, to execute HPS employing PLCs and RTU control methods. In the PLC environment, all of the modules should be simulated. A dedicated protocol that can be delivered through a serial port or Ethernet connects PLCs and SCADA systems (Sayed and Gabbar, 2017).

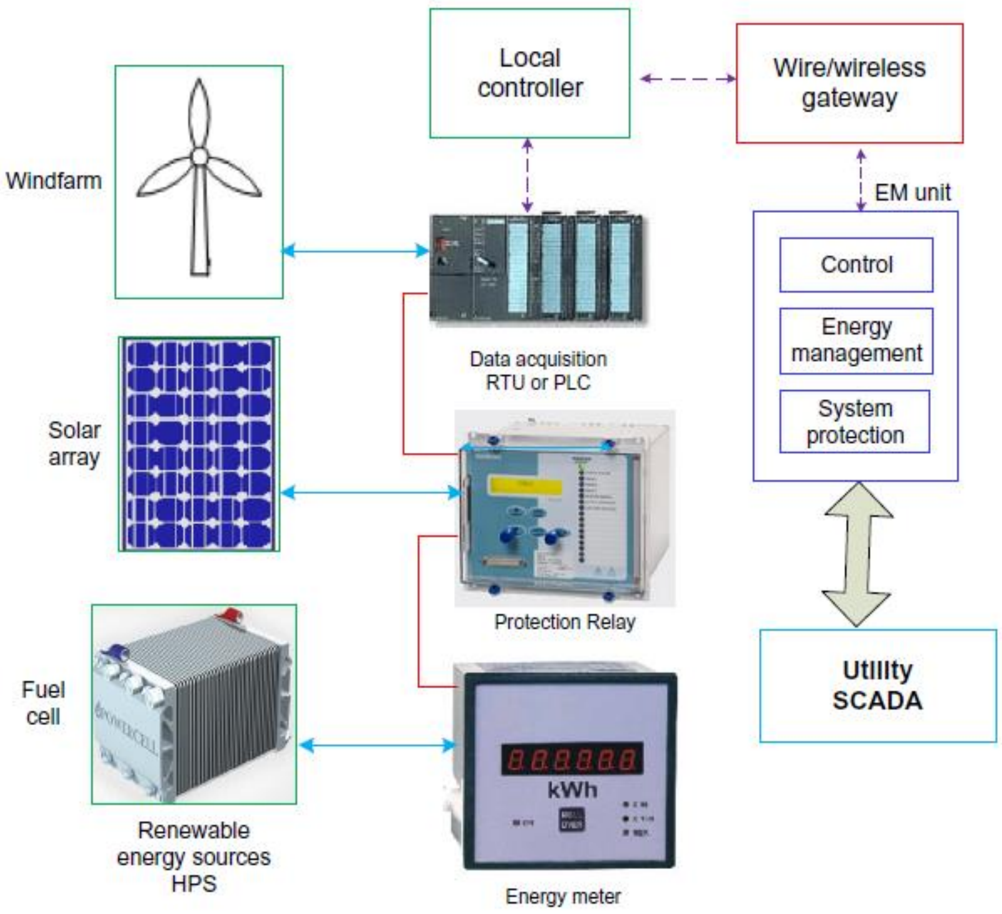


*Figure 3.8 Schematic representation of a HPS based DREMPs*

Figure 3.8 depicts the HPS control hierarchy. PV cells and FCs are monitored using a PLC that is connected to a SCADA/EMS system, allowing the operator to easily view and control the parameters in response to changes in system requirements. The data from the HPS is collected by a PLC and communicated to the control room via a protocol. The PLC is connected to the energy management control unit, which allows it to take control actions based on the micro-grid loads and environmental circumstances. For supervision and control, the complete system is connected to SCADA. Various I/O consoles, such as engineering and operator consoles, are located in the control room. The engineering console is in charge of introducing new IED devices or points to the system.

### 3.7.2 Optimization of Hybrid power Systems based on DREMPs:

A number of researchers have looked into how to best optimize and coordinate between renewable energy HPSs to meet energy needs with and without conventional backup generation systems.

For example, (Safdarian et al., 2012) proposes a mathematical framework for balancing the contribution of various sources of renewable energies with different natures such as wind and solar energy. The goal of the optimization problem is to increase system reliability while maintaining a fixed financial investment in both solar and wind energies. The problem is expressed using a mixed-integer programming (MIP) method, for which the optimized solution is assured or can be traded with the execution time. The number of solar panels and wind turbines to be deployed represent the decision variables. Furthermore, system uncertainties related with wind speed, solar radiation and hourly load are presented based on probability density functions (PDF). The Monte Carlo simulation method is used to generate these scenarios. The proposed methodology's effectiveness is proved by numerical assessments based on real-data. HOMER (Hybrid Optimization of Multiple Energy Resources) software was utilized to optimize the potential of six small hydropower projects in conjunction with wind-PV systems. Ismail et al. (Ismail et al., 2013) conducted a feasibility assessment as well as a techno-economic analysis of a PV system with batteries and a micro turbine as a backup supply. To reduce the cost of energy (COE), component size and optimization were done using an iterative process (Bhandari et al., 2014). (Saha et al., 2013) proposed a hypothetical hybrid system that uses a wind–solar–biogas–micro hydro hybrid as the primary energy source and a diesel generator as a backup. (Menshsari et al., 2013) used the ant colony algorithm to optimize a hydro–wind–solar–fuel cell HPS. With the goal of rural electrification in Malaysia, (Fadaeenejad et al., 2014) investigated PV–wind–battery hybrids and PV–wind–diesel–battery hybrids (Bhandari et al., 2014). (Arabali et al., 2014) provide a stochastic approach for reliability analysis and optimum sizing of HPSs that includes DREMPs and ESSs. In this paper, the authors use autoregressive moving averages (ARMA) to model stochastically photovoltaic (PV), wind and load uncertainties. To minimize system cost and meet reliability criteria, a pattern search-based optimization method is employed in conjunction with a sequential Monte Carlo simulation (SMCS). From a sequence of simulated experiments, the SMCS simulates the system's chronological behavior and determines the reliability indices. In a hybrid power system, load shifting solutions are offered to enhance flexibility and reduce the mismatch between renewable energy and loads such as cooling, heating, ventilation, and air conditioning needs. The results show that the above mentioned techniques help satisfying the reliability requirements and minimize the system costs. Using a compromise-solution strategy, the optimal compromise between cost-effectiveness and reliability requirements is achieved through the integration of hybrid power systems.

Using a battery charger and GTI, (Bhandari et al., 2014) offered two realistic hybridization strategies for combining PV, wind, and hydropower in a single small off-grid system in the villages of Thingan and Kolkhop of Nepal. The PV and wind generators are hybridized using a hybrid charge controller (HCC), and the power output from the HCC is fed into the battery bank to charge the batteries in the former hybridizing technique depicted in Figure 3.9. The micro-hydropower (MHP) is also used to charge the batteries, which is done with a battery charger of sufficient capacity. The DC electricity in the battery bank is subsequently converted to AC power and sent into the grid via an inverter. This design is straightforward and cost-effective to build, but it may be less cost-effective when the generating systems are far apart because two different networks are necessary to charge the batteries and then send power to the user.

The second hybridization method employing GTI is shown in Figure 3.10. PV and wind micro-plants are hybridized using an HCC to charge the battery bank, same like in the previous approach. The second strategy was utilized to hybridize the three micro-plants, but instead of employing a battery charger, this technique employs GTI to directly synchronize the hybrid PV–wind system with the mini-grid to assure a reliable power supply for the towns. *Another technique* was used to connect a hybrid PV–wind system to a hydro-dominant system using a mini-grid connecting the villages of Thingan and Kolkhop in Nepal's Makawanpur District. *The results showed* that the combined demand of the two villages cannot be met by either the hybrid PV-wind system in Thingan or the micro-hydropower (MHP) in Kolkhop. However, combining the two micro-power plants into a single mini-grid improves the power supply's reliability and meets demand. This study can be used as a reference for putting similar systems in different places.

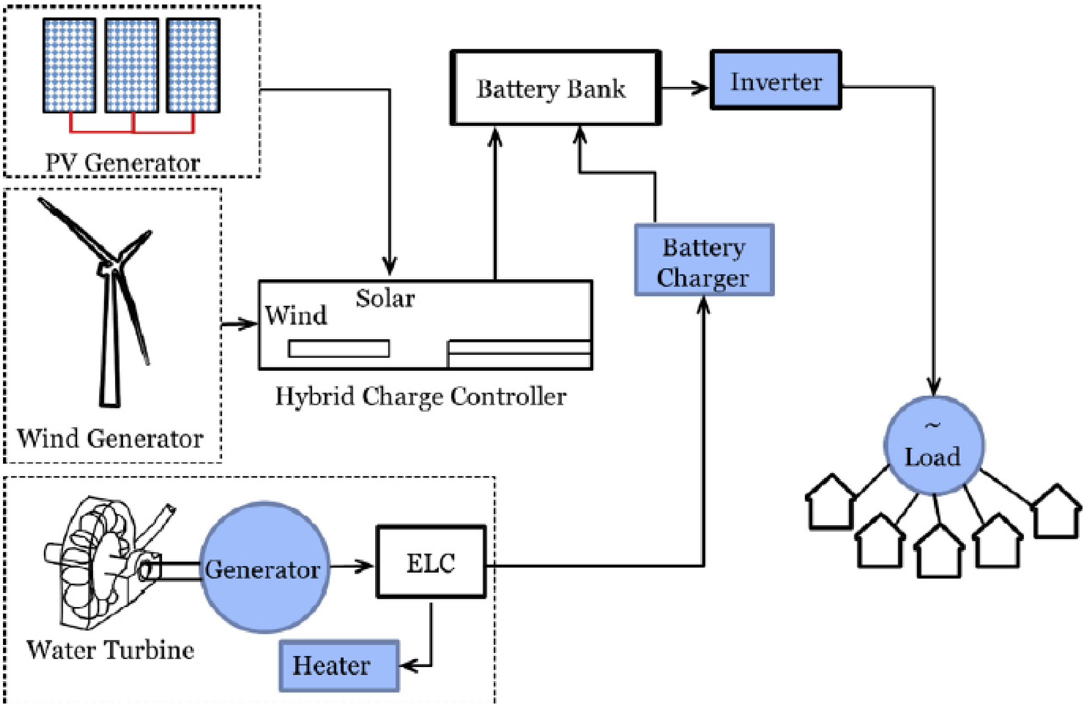


*Figure 3.9 Hybrid wind, PV, and hydro micro-plants, using a HCC and a battery charger.*

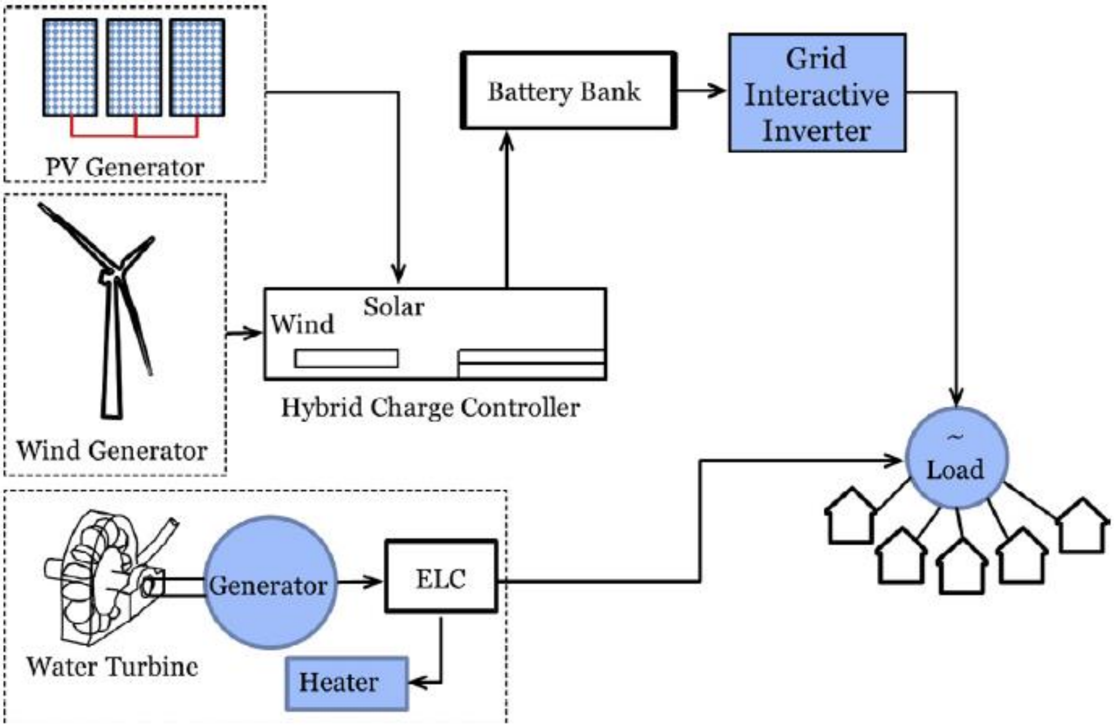


*Figure 3.10 Hybrid wind, PV, and hydro micro-plants, using a HCC and a grid tie inverter.*

In the event of a power outage, (Bakos, 2002) conducted a feasibility assessment of a wind-pumped hydro storage system aided by a diesel generator. The system is set up so that wind farm supplies arrive first to the load. The solar–wind hybrid, solar–hydro hybrid, solar–wind–diesel hybrid, solar–wind–diesel–hydro/biogas hybrid, and solar–wind–diesel–hydro/biogas hybrid were discussed, and the viability and significance of solar energy (both in standalone and hybrid form) in global electrification were demonstrated by (Akikur et al., 2013). (Bekele and Tadesse, 2012) proposed a PV–hydro–wind hybrid system capable of providing continuous electricity to an Ethiopian community. Power management solutions for battery assisted PV–wind–hydro hybrid systems were studied by (Prabhakar and Ragavan, 2013). The energy balancing model, DC-link voltage control, and drop control were used to design a control technique that estimates the load. (Jaramillo et al., 2004) carried out a theoretical analysis of hypothetical wind and hydroelectric facilities. The characteristics of an off-grid hybrid DREMPs and their consequences for the system's reliability were investigated by (Ahn et al., 2012). Similarly, (Margeta and Glasnovic, 2010) investigated a solar-hydro hybrid system capable of providing continuous electric power. (Daud and Ismail, 2012) built and studied a PV–wind–diesel hybrid system for a Palestinian family home, taking into account efficiency and reliability as well as dumped electric power. Almost every publication has a different goal in mind, such as design for off-grid applications, analysis, modeling, optimization, socio-economic study, and so on.

### 3.7.3 Coordination between DREMPs in a hybrid power Systems

There are many authors who investigate the Coordination between DREMPs in hybrid systems. We site for example, Reference (Hu et al., 2009) offers a model based on sequential Monte Carlo simulation that takes into account the chronology of wind, hydraulic flow, and load in order to assess wind and hydro-generation coordination and show the impact on reliability and performance indices. Whereas in (Billinton et al., 1996), the reliability indices are computed considering wind, hydro, and thermal power plants dispatched in a coordinated way. The approach is based on an hourly stochastic simulation to emulate the operation of a generating system, taking into consideration the auto-correlation and variable nature of wind speeds, stochastic outages and failures of renewable sources, and other known dependencies. To demonstrate the suggested approach, a reliability test system of renewable micro-plants is used. It was demonstrated that renewable micro-plants's coordinated operation could bring benefits to the system. (Karki et al., 2010) provides reliability models that include coordination between wind, hydro, and thermal energy sources, and can be used to assess renewable energy usage and hybrid system reliability in the long term. In this study, an IEEE Reliability Test System is used to analyze the influence of coordination on system reliability and the amount of wind and water usage when considering reservoir limitation, variable wind penetration, and different wind regimes. (Mehrtash et al., 2012) propose a novel approach to estimate the deliverable capacity probability table (DCPT) of the equivalent multistate transmission provider (EMTP) which represents the capacity of the transmission system. This strategy dramatically minimizes calculation complexity when both load and supply are subject to change in a power system like in the case of wind and PV MPs.

The research in (Zhang et al., 2010) proposes a probabilistic paradigm of reliability modeling for renewable energy sources integration, such as wind energy conversion systems (WECS). The stochastic features of WECS integration, such as resource availability, facility failures, and transmission availability are investigated. The proposed models and approaches are demonstrated using the IEEE Reliability Test System (IEEE-RTS). It was concluded that the cost of wind energy conversion system integration in the utility power grid for sustaining reliability and system adequacy may be accurately evaluated using the proposed reliability models and methods. These methodologies can be used for the reliability modeling of commercial and industrial infrastructures being serviced by wind micro-plants and transmission lines.

(Lopes and Borges, 2015) focus on adding a new aspect to these studies by the exploitation of various wind location and micro-hydropower plant complementarity, as well as its impact on system reliability. The restrictions of the transmission system in delivering the generated power to the load is considered. By applying chronological simulations including several factors, such as spacial and temporal correlation, complementarity, and others, it was shown that there is complementarity between wind and micro-hydropower plant when in dry seasons when wind speed behavior exhibits its highest and most consistent values. In these seasons, the wind and inflow time series have a negative correlation coefficient (a statistical coefficient that shows the relationship between two stochastic variables. it varies from -1 to +1) showing that they are complimentary. This complementarity could be a solution to reduce the risk of power generating shortages. This research also gives the planner and operator a more accurate picture of how much they may benefit from combining different distributed renewable energy micro-plants while also increasing system reliability. As per (Lopes and Borges, 2015), for high penetration level of intermittent DREMP, it is necessary to consider their time series and variable load in order to exploit both temporal and spatial correlations, as well as any complementarity that may occur between them.

### 3.7.4 Drawbacks of hybrid power systems based DREMPs

In HPSs based DREMPs, controlling process and coordination is a difficult task. The hybrid system necessitate some understanding due to the various sorts of DREMPs used. The operation of many DREMPs, as well as their interaction and coordination, must be controlled, which can be very complicated. For example, synchronizing hybrid DREMPs with a mini-grid differs from synchronizing large hybrid systems with a national utility grid. The fundamental difference is that with a mini-grid, the voltage and current are less reliable and of lesser quality.

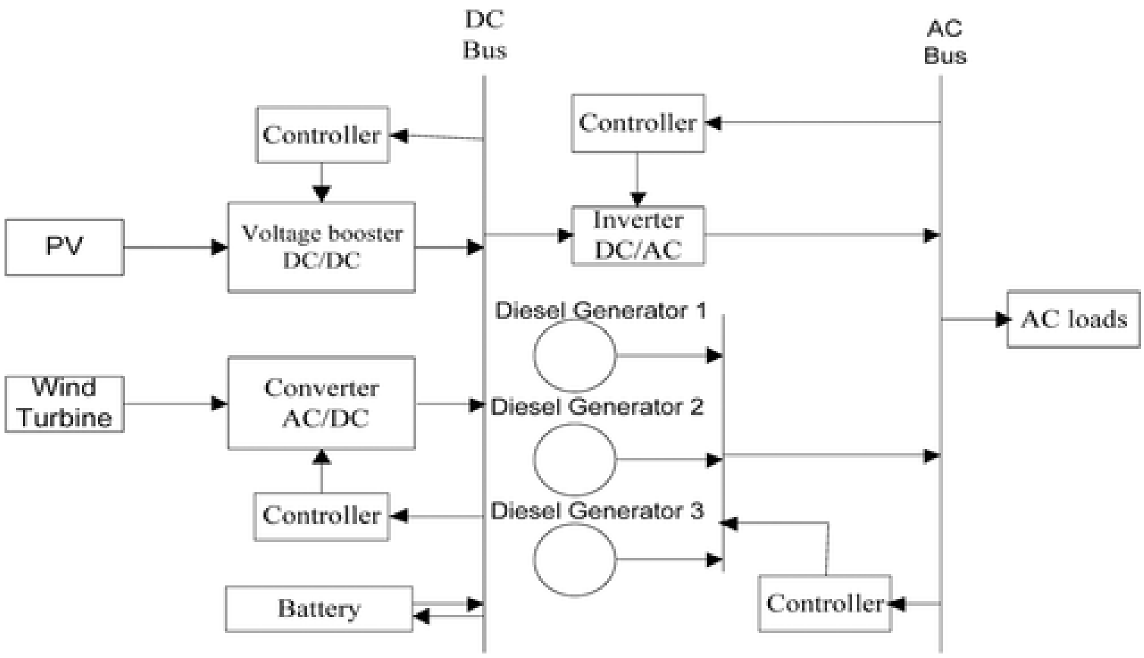


*Figure 3.11 Hybrid power system based wind-PV-diesel micro-plants (Adefarati and Bansal, 2016).*

A mini-grid is prone to fast frequency and voltage fluctuations, whereas a national utility grid maintains a set frequency (50 Hz or 60 Hz) and voltage (Bhandari et al., 2014). In addition, the unpredictable nature of RES is one of the major disadvantages of the off-grid hybrid power systems (Adefarati and Bansal, 2016). This disadvantage can be reduced by incorporating backups into the system such as the energy storage systems and/or diesel generator (Figure 3.11) (Varaiya et al., 2011). Because users can produce electricity utilizing off-grid DREMPs in a HPS, many researchers such as (Kantamneni et al., 2016) think that these off-grid HPSs may enable a large-scale grid defection.

## 3.8 Conclusion

Electricity demand is increasing at a faster rate than it has ever been in the world. This leads to the emergence need of many DGs in the power systems. As a result, the number of distributed renewable energy micro-plants is growing and is expected to grow much faster in the near future. This is not the only incentive to accelerate the adoption of DREMPs in power systems, where is dealing with climate change and global warming, sustainability, reducing reliance on fossil fuels to prepare for future fuel disruptions, lowering operational & maintenance costs, minimizing system overcrowding, and lowering the necessity of new generation and transmission capacity are all reasons for adopting DREMPs. Moreover, Advances in renewable energy technologies and lower renewable energy costs have permitted widespread usage of distributed renewable energy micro-plants in the electricity mix of many countries over the world.

Integration of DREMPs in power systems refers to the process of power system planning, interconnection, and operation that allows for efficient as well as cost-effective use of renewable energy sources while preserving or increasing the reliability and stability of electricity delivery to the power grids.

A grid integration studies analyze and simulate power system operation under various scenarios and sensitivities, assesses the cost of interventions and identifies potential reliability limits to remove such limitations. Robust grid integration studies are built based on a comprehensive range of basic data as well as stakeholders input. Long-term data (i.e. irradiation, wind speed, ambient temperature …etc.) should be collected at least one year. Despite grid integration studies commonly use production cost to model optimized dispatch and unit commitment, estimating the system full costs of integrating DREMPs is significantly more difficult. The overall costs of integrating DREMPs in power systems depend on complex and dynamic interactions between these generation units and the loads, thermal generators, reserves, and transmission and distribution networks.

A key job in the grid integration process is determining the best connecting point for DREMPs in the grid as well as its maximum capacity that could be supported by the power network. A connection request from an energy project developer is followed by a rigorous grid compatibility check by the utility operator to determine which node or bus on the grid could be the most cost-effective site to inject power. If such important aspects of the network are not properly specified, the network's performance may suffer (i.e. increased power losses, voltage fluctuations, power quality issues, system stability and more). The appropriate selection of the previous aspects may increase the system's reliability and security while also expanding the level of DREMPs penetration and lowering generation costs. High penetration levels of DREMPs in power systems necessitates careful considerations of the type, devices, installation, and operation of DREMP to allow the pre-existing power network to absorb acceptable levels of DREMPs.

Nevertheless, the conventional electric grid system would not easily be replaced by distributed renewables, maybe because the latter is a well-established technology that should not be abandoned, and the new distributed renewable energy technologies are generally not matured enough to handle the complete demand. As a result, sustainable options such as incorporating DREMPs into the current power infrastructure are becoming increasingly important.

To boost the deployment of DREMP, utilities and power system operators are looking for efficient, reliable, secure, and cost-effective ways to increase the penetration of DREMPs in the grid. They have used several practical applications and solutions such as utilizing DREMPs for regulating the voltage at the level of substations, controlling the reactive power, providing ancillary services, powering off-grid areas and sensitive loads, and more. Also important are "Grid-aware" motivations (for example, boosting wind and solar producers who employ innovations and technologies that help maintaining or increasing grid stability), as they simultaneously encourage renewables investment and offset the negative consequences of integrating these micro-plants into the power systems.

Upgrading grid integration standards, protocols, and distribution planning approaches to properly reflect the features of DREMPs can assist in the deployment of DREMPs and postpone or perhaps eliminate the need for grid reinforcement.

In power systems with significant grid-connected DREMPs, accessing various types of sources of significant operational flexibility become extremely crucial. Market practices and system operating procedures, particularly rapid scheduling, implementing real-time predictions, and ancillary services, are frequently among the most cost-effective ways to gain significant flexibility without investing in new physical facilities. Moreover, Operational coordination for balancing utility zones is also another institutional flexibility solution, since it allows for resource cooperation via coordinated scheduling, reserve sharing, or unified operations. Furthermore, flexible traditional generators and transmission facilities are other sources of flexibility. Storage technologies and demand response are also evolving as options for boosting flexibility at very significant levels of DREMPs adoption. However, the inappropriate power system planning and operations of these facilities will lead to voltage rise, significant power losses, and system instability because of reverse power flow. Thus, a proper methodologies and effective approaches for accommodating DREMPs must be developed.

Although DREMPs offer potential benefits, there are obstacles to their seamless integration into the grid, which frustrates efforts to implement a new power system transition. In addition, many technical, economic, environment and regulatory concerns have arisen as a result of the increasing integration of DREMPs, including power quality issues (ex. voltage level fluctuations (over/under voltage), transient voltage changes, voltage flickers, frequency variation, harmonics distortion (both current and voltage)), grid instability, increase in the fault level and more. Moreover, intermittent nature of DREMPs (e.g., solar and wind) connected to the distribution networks can also create divers issues and stability concerns in distribution network. Furthermore, the integration of a large number of DREMPs in power network cause fundamental changes to the power network topology, particularly at the distribution level, which may eventually shift the power system architecture from vertical to a horizontal one. These issues may have a great influence on supply security and reliability, equipment control and protection, islanding, and safety. Moreover, the occurrence of harmonics in power grids results in a variety of problems, such as equipment overheating, a decrease in the efficiency and performance of the grid components, a decline in the power factor (PF), communication signal interference, wrong responses of protection systems, malfunction of nearby devices due to resonance, unwanted electrical motors vibration, noise, and so on.

In this context, it is necessary to think about the challenges and the implications of integrating DREMPs into the power grids (specially the distribution network). The presented literature demonstrated that the integration, operation, control and protection of DREMPs and their effects on power grids and micro-grids (i.e. reliability, marketability, power quality and stability concerns) need all to be investigated for the successful implementation of DREMPs and to obtain optimal grid performance. The literature also demonstrated that the impact of DREMPs on power networks significantly depends on the type of DREMPs as well as the type of the network. However, in all cases, the voltage regulation, network losses, and power flow in the DN are impacted.

Another approach that does not demand grid integration is off-grid HPS based DREMPs. The literature demonstrated that in locations where the national utility grid is not accessible due to some financial and technical concerns, an HPS based DREMPs is a comparatively cost-effective alternative, making it suited for power applications in remote communities. Integrating DREMPs into a mini-grid improves electricity quality and reliability. To ensure a reliable, cost-effective, and continues electricity generation, all available DREMPs must be used at optimal locations and sizes. By reducing the need for fossil fuels, and contributing to productive, healthy lifestyles over the world, the use of HPSs based DREMPs would enhance environmental sustainability.

Controlling process and coordination in HPSs based DREMPs is a difficult task. The hybrid system necessitate some understanding due to the various sorts of DREMPs used. The operation of many DREMPs, as well as their interaction and coordination, must be controlled, which can be very complicated. In addition, because users can produce electricity utilizing off-grid DREMPs in a HPS, many researchers think that these off-grid HPSs may enable a large-scale grid defection. Moreover, the unpredictable nature of RES is one of the major disadvantages of the off-grid HPSs. This disadvantage can be reduced by incorporating backups into the system such as the energy storage systems and/or diesel generator. Hybrid power systems based DREMPs with ESSs or diesel generators us backups provide the following advantages: enhanced reliability, reduced operational and maintenance costs, increased operational life of power system components, reduced GHG emissions, low noise pollution, and improved energy services.

Energy demand is steadily increasing, whether in standalone or grid-connected power systems. The challenge is to meet the rising demand for electricity while also acknowledging public concern about global environmental issues such as GHG emissions and global warming, as well as the depletion of fossil fuel resources. Installing HPSs based DREMPs plus ESSs and remaining on the grid is the most cost-effective option for electricity users.

# Chapter 4 Smart grids, micro-grids, and energy management systems

In this chapter, we will tackle the topic of smart grids and micro-grids. The Energy Management Systems (EMS) used in smart grids and micro-grids will be presented. The quantification methods that should be considered for EMS will be also considered such as Supply Side Management (SSM), Demand Side Management (DSM), Demand Response (DR), and pricing policy. Machine Learning (ML) methods and its models as well as Artificial Intelligence for smart grids and micro-grids such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), Tree-based models (Decision trees), Ensemble Prediction Systems (EPS), Adaptive Neuro-Fuzzy Inference System (ANFIS), Wavelet Neural Network (WNN), Multilayer Perceptron (MLP), and Deep Learning will be also discussed.

## 4.1 Smart grids

In 2007, the US Government in their "Energy Independence and Security Act of 2007 (EISA-2007)" was officially defined the Smart Grid by its ten main characteristics which collectively describe a Smart Grid (Sissine, 2007):

(1) Increased utilization of control technology and digitalization in order to improve the efficiency, reliability and security of power grids.
(2) Full cyber-security and flexible optimization of grid functions and resources.
(3) Widespread utilization of DG and resources, including distributed renewable energy micro-plants.
(4) Incorporation and development of demand-side, demand response and energy-efficiency resources.
(5) Use of "intelligent" technologies, such as automated, real-time and interactive technologies that improve the operation of appliances and customer equipment, for metering, grid communications, and distribution automation.
(6) Integration of 'intelligent' appliances and customer equipment.
(7) Deployment and integration of electricity storage and peak-shaving technologies, such as hybrid electric vehicles and plug-in electric, as well as thermal storage air conditioning.
(8) Providing control alternatives and timely information to consumers.
(9) Development of communication and interoperability standards for equipment and appliances connected to the electric grid, as well as grid infrastructure.
(10) Identification and lowering of unreasonable or unnecessary barriers to adoption of smart grid technologies, practices, and services."

Smart grid is also defined by the European Union (EU) Commission Task Force for Smart Grids as follow (Neufeld et al., 2020): "A Smart Grid is an electricity network that can cost-effectively integrate the behavior and actions of all users connected to it – generators, consumers, and those who do both – to ensure an economically efficient, sustainable power system with low losses and high levels of supply quality, security, and safety. A smart grid combines innovative goods and services with sophisticated monitoring, control, communication, and self-healing technology to:

(1) Make it easier to connect and operate generators of all sizes and types.
(2) Allow consumers to contribute to the system's functioning optimization.
(3) Give customers more information and choices on how to use their supply.
(4) Significantly lower the entire electrical delivery system's environmental impact.
(5) Maintain or even increase the system's current high levels of reliability, quality, and supply security.
(6) Effectively maintain and improve existing services."

As per (Abdullah Asuhaimi, 2019; Olivieri et al., 2014), The smart grid combines power systems, communications, and information technology to provide a more efficient power system structure that fulfills loads while allowing for continual application development for end users. Moreover, smart grid enables bidirectional power and information flow. Thereby, electricity consumers can become prosumers (i.e. active participants, or consumers and producers in the same time) (Hansen, 2016; i-SCOOP, 2018).

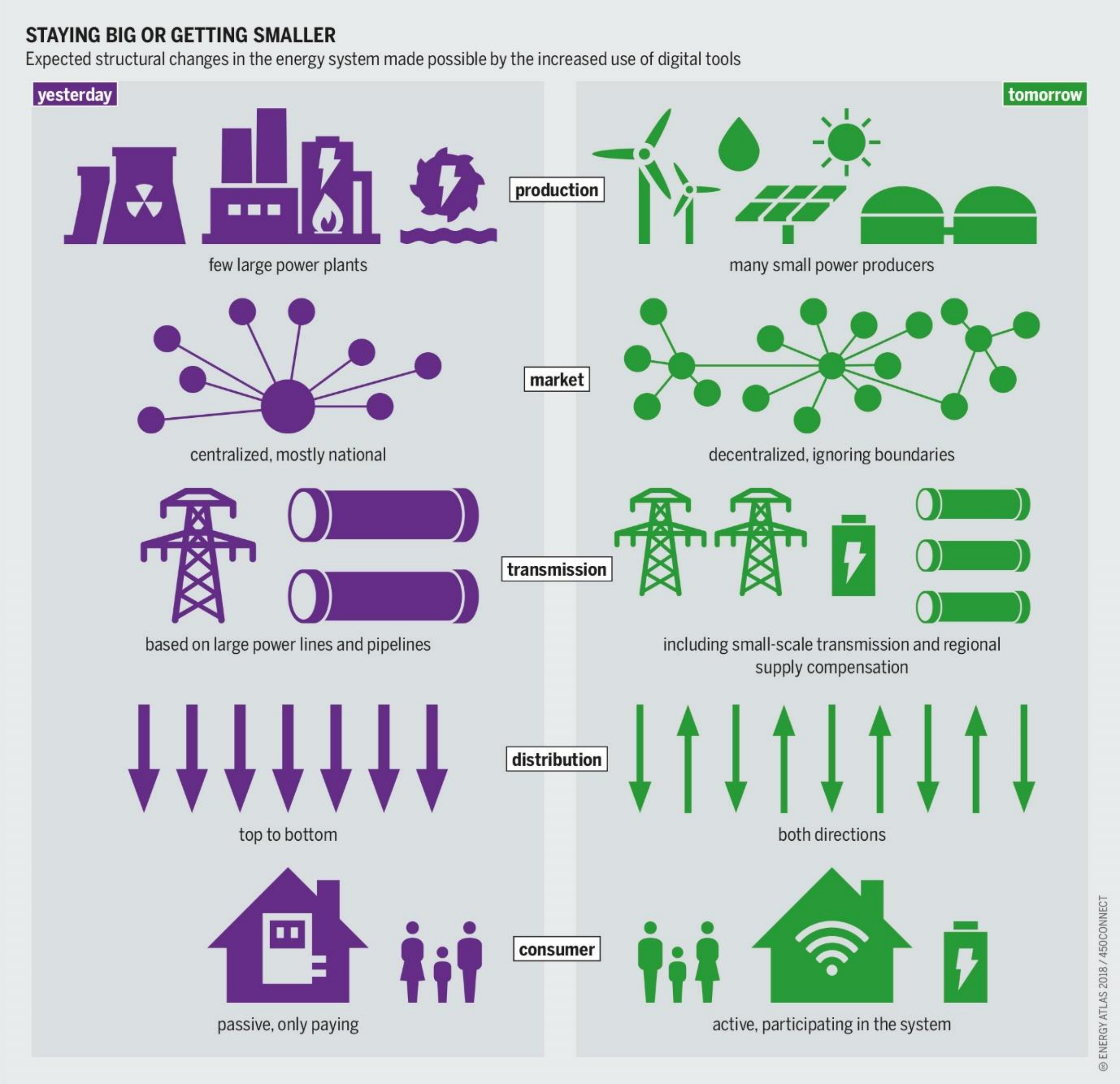


*Figure 4.1* Some aspects of a smart grid that differ from standard power grid *(i-SCOOP, 2018).*

A smart grid's ability to self-healing is one of its most important properties. This is made feasible by the widespread use of smart sensors and other smart devices, as well as automated controls that monitor and analyze the network's status and condition in order to spot anomalies and problems (i-SCOOP, 2018). Multiple factors are driving the transition from traditional power grids to smart grids, including new points where and purposes for which electricity is used (e.g. electrical vehicle charging points), evolutions in metering, deregulation of the energy market, decentralization (i.e. distributed energy), changes in electricity production, and the increase of islanded micro-grids with high penetration of DREMPs. The emergence of distributed micro-generation / micro-grids, or the so-called micro-plants, is one of the most significant shifts in the power business. (i-SCOOP, 2018). Even without the inclusion of ESSs, the smart grid's increased flexibility allows for higher penetration of DREMPs like wind and solar micro-plants. Rapid variations in power produced by DREMPs, such as those caused by cloudy or gusty weather, provide substantial issues for power engineers who must maintain stable power levels by altering the output of more controllable generators like gas turbines and/or hydroelectric generators. For this reason, smart grid technology is a prerequisite for putting many renewable energy micro-plants on the system. (Varaiya et al., 2011) Reported that a smart grid is necessary to manage and control the increasingly complex future grid with large share of RESs, higher capacity ESSs with accurate infrastructure of sensors, smart meters, demand response (DR) and communications. In this context, recent research efforts are aimed at building a link between limited availability of electricity from RESs and demand-side consumption to extract the greatest benefit of RESs for the habitat in remote places (Basak et al., 2012). *Figure 4.1* and Table 4.1 show some aspects of the smart grid that differ from standard power grid (i-SCOOP, 2018; Nassar, 2017).

*Table 4.1: some aspects of the smart grid that differ from conventional power grid (Nassar, 2017).*

| **Conventional grid** | **Smart grid** |
|---|---|
| One-way communication | Two-way communication |
| Electromechanical relays | Digital relays |
| Centralized and fossil fuel generation | Distributed and more green generation |
| Manual restoration | Self-healing |
| Manual monitoring | Self-monitoring |
| Manual check | Remote check |
| Minimum sensors | Widespread sensors |
| Blackouts | Islanding |
| Limited customer choice | Flexible customer choice |
| Limited control | Expanded control |

## 4.2 Micro-grids

### 4.2.1 The concept of micro-grids

Many researchers in the fields of distributed micro-plants, sustainable energy, power systems, and rural area electrification have been and still heavily focusing on micro-grids (Jane, 2020). The integration of DREMPs such as micro-wind turbines, PV systems, fuel cells, biomass with the widespread of information and communication technologies (ICT) has initiated more recent concepts of micro-grid (Basak et al., 2012). This last can be defined as a cluster of interconnected micro-plants, and storage facilities that cooperate with each other to meet the energy needs of small communities such as office buildings, residential buildings, restaurants, small villages, laboratories, hospitals … etc. (Basak et al., 2012; Yerasimou et al., 2021). The whole system can works in both grid-connected and islanded modes (Hatziargyriou et al., 2007; Zia, 2020) and can be either operates in AC, DC or hybrid configurations (Yerasimou et al., 2021). In grid-connected mode, the micro-grid either draws or delivers power from or to the main grid, depending on generation, consumption or market policies. Whenever the main grid has a power quality incident, the micro-grid can disconnect from it (Hatziargyriou et al., 2007). In addition, micro-grid could be treated by the national electricity grid as flexible load or source (Basak et al., 2012; Pedrasa, 2006). (Peng et al., 2009; Pogaku et al., 2007) define the micro-grid as an integrated form of distributed micro-sources that can be connected to the load and to the utility grid thanks to power electronic inverters. As per (SGCG, 2014), a micro-grid is a "low- and/or medium- voltage network equipped with some installations that allow it to autonomously control and manage its own demand-side and supply-side resources, in both grid-connected and islanded modes". According to IEEE 1547.4, a distributed resources system (referred to as micro-grid) must satisfy the following requirements: (1) integrate DGs and loads; (2) consist the local electricity system; (3) be able to be isolated from the main power grid; and (4) be purposefully planned (Kroposki et al., 2008). Additionally, the US Department of Energy defines a smart micro-grid as follows: “a cluster of interconnected DGs (including DREMPs and ESSs) and loads within well-known electrical boundaries that acts as a single, controllable entity with regard to the main grid. Moreover, a micro-grid can operate in both grid-connected or islanded (autonomous) modes when it is coupled to the main grid at the point of common coupling (PCC) or when it is not coupled to the main grid, respectively (*Figure 4.2*)” (Arikiez, 2016; Montoya et al., 2013; Zia, 2020).

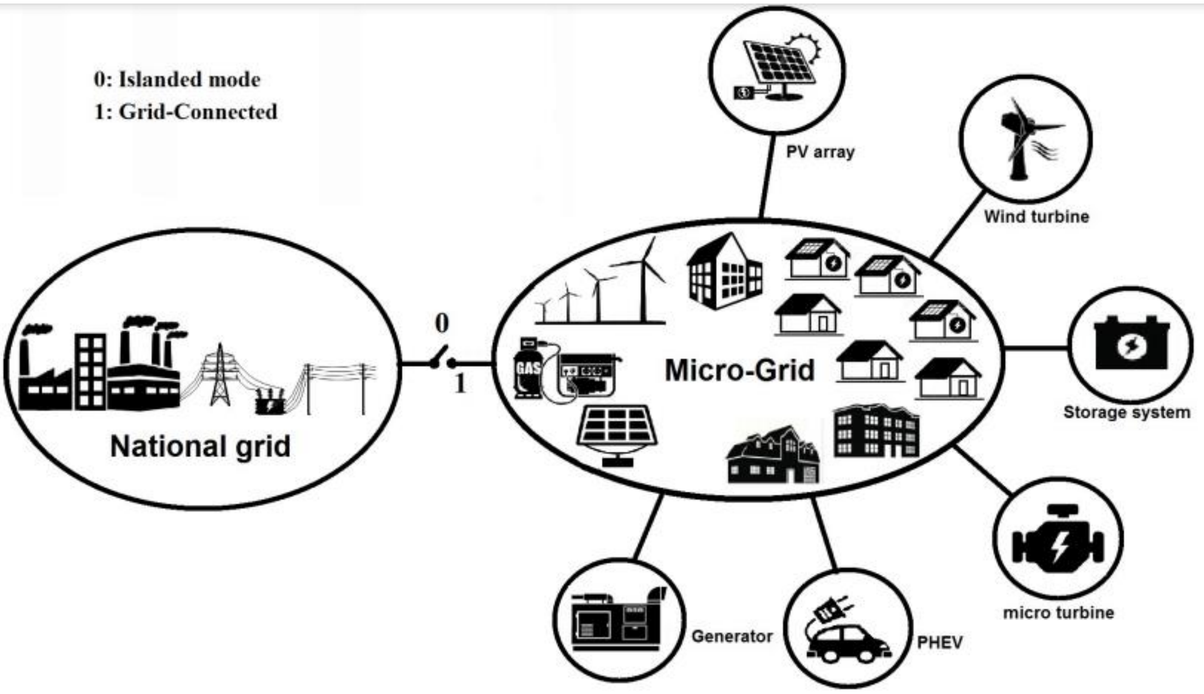


*Figure 4.2 Micro-grid diagram* (S. Aman et al., 2013).

To keep the stability of the micro-grid, this last must continuously manage its resources and variations in demand and generation (Arikiez, 2016). The efficient coordination and management of supply-side and demand-side resources lead to the improvement in system performance as well as sustainable development (Hatziargyriou, 2004).

### 4.2.2 Classifications of micro-grids

As shown in *Figure 4.3*, micro-grids may be divided according to their (1) type of power, (2) mode of operation, and/or (3) control strategy. There are several uses for micro-grids, including: (a) powering isolated, remote, and off-grid locations, such as rural areas, military sites, or mountains; and (b) in grid-connected topologies, powering crucial infrastructures such as universities, industries, and commercial hubs. In general, utilities, independent power producers (IPP), or customers can all own micro-grids. The potential advantage of micro-grid in the energy sector is its ability to isolate itself from the utility grid in the event of main grids failures, blackouts, disturbances, or economic factors (Asmus, 2010).

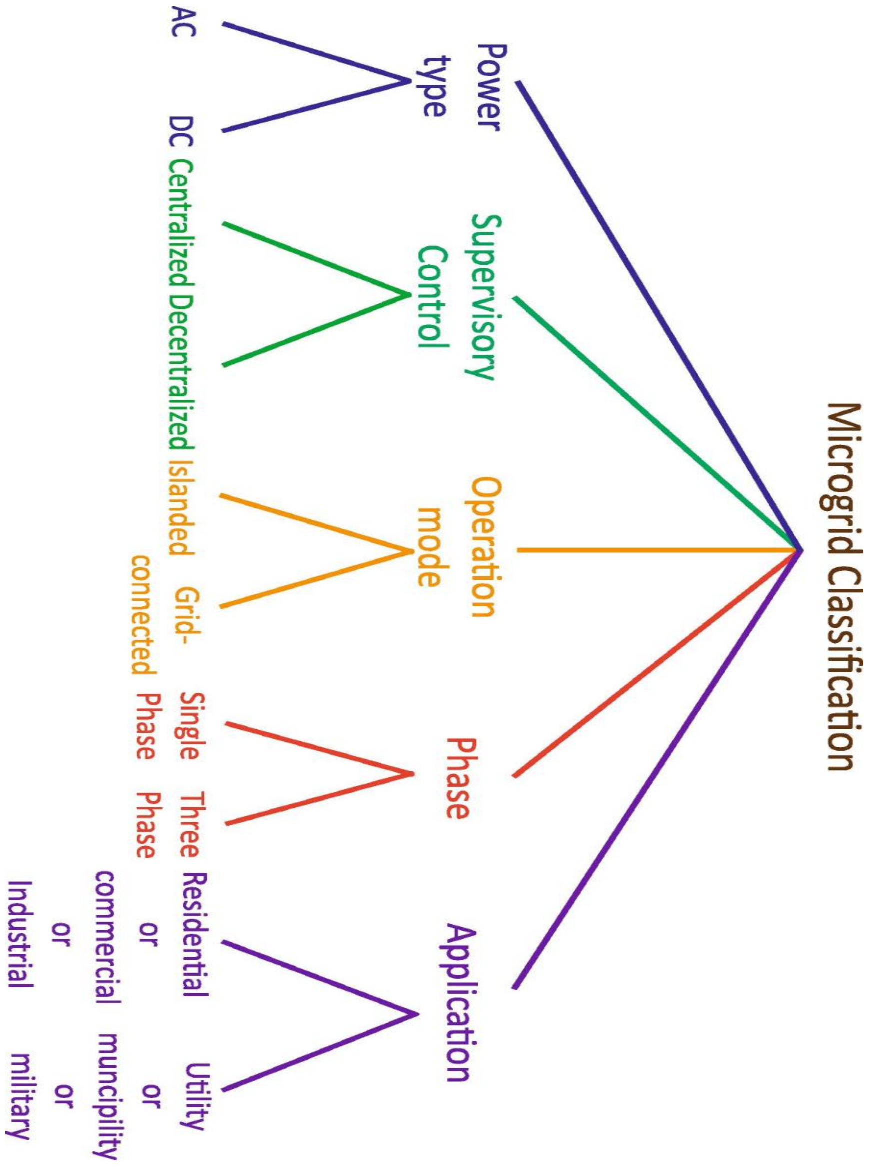


*Figure 4.3 Classification of micro-grids* (Zia et al., 2018).

In the next subsections, we present two types of micro-grids according to their mode of operation: grid-connected micro-grids and isolated micro-grids.

#### 4.2.2.1 Grid-connected micro-grids

The micro-grid in grid-connected mode is coupled to the main grid or a neighbor power network of multi-micro-grids. In this operation mode, micro-grid exports excess power to the main grid or to the neighbor micro-grids for maximizing its electricity trading profit (Zia et al., 2019). Contrarily, micro-grid imports energy when its on-site generations including DREMPs and ESSs are not sufficient to meet the local load requirements. The frequency of grid-connected micro-grid at the PCC is imposed by the main grid (Vergara et al., 2019). Nevertheless, micro-grid can functions as a grid-supporting entity, depending on its condition, by adjusting its energy to deliver ancillary services to the primary grid to prevent instability or other issues (Zia, 2020).

#### *4.2.2.2 Islanded micro-grids*

In islanded (i.e. isolated or off-grid) micro-grids, production and consumption balance, as well as frequency and voltage stability, are all guaranteed by distributed micro-plants. Distributed micro-plants are separated into two main categories: grid-forming and grid-following resources, with the former acts as frequency leader and being in charge of maintaining frequency and voltage stability (Caldognetto and Tenti, 2014; Rocabert et al., 2012). In this operation mode, at least one micro-plant must act as grid-forming for micro-grid stability and control. As a result, micro-grid must be correctly designed and sized in order to limit the risk of load shedding or loss of load (Vergara et al., 2017).

Islanded micro-grids are seen to be the best solution for supplying energy in remote communities (Carvallo et al., 2014; Illindala et al., 2007; Williams et al., 2015). For instance, the writers in (Carvallo et al., 2014) looked at seven examples from around the globe with various criteria to demonstrate the enormous benefits of using the islanded micro-grid strategy for isolated communities. It was found that micro-grids are a potential solution for isolated communities. In such scenarios, hybrid micro-grids combine DREMPs with traditional micro-plants, usually diesel generators, but the fuel costs for these traditional micro-plants are significant (Arriaga et al., 2017; Carvallo et al., 2014).

## 4.3 Energy Management Systems (EMS) for micro-grids

An Energy Management System (EMS) is defined by the International Electrotechnical Commission (IEC) in its standard (IEC 61970-1, 2005) as a computer-aided tools offering basic support services and a collection of applications delivering the functionality needed for the efficient operation of electrical generation and transmission systems so as to guarantee appropriate security of energy delivery at least cost.

An EMS for micro-grid also has similar features and often includes of modules that carry out decision-making tasks. Control modules of distributed micro-plants, demand-side management and load forecasting, supervisory control and data acquisition (SCADA) with human machine interfaces (HMI), among many others, guarantee that EMS decision-making strategies are implemented effectively for the best possible decisions to each micro-plant, load, and storage unit in the micro-grid (Chen et al., 2011). As shown in *Figure 4.4*, a micro-grid EMS carries out a range of tasks, such as decisions making after monitoring, analyzing, and predicting power outputs from DREMPs, consumption variations, meteorological conditions, and electricity and ancillary market prices (Zia, 2020).

The micro-grid EMS may be configured to function as part of a DR program, support self-sufficiency, or take part in the energy market when the micro-grid is in grid-connected mode. In the meanwhile, optimum dispatch, unit commitment, and load management tasks in the island mode may be addressed to the micro-grid EMS (Zia, 2020).

In order to balance energy consumption and production in real time and to meet economic and environmental goals, new opportunities in smart grids and micro-grids must be investigated. These opportunities include supply-side management (SSM), demand-side management (DSM), and adequate price and load forecasting (Khan, 2022). In the next subsections of the thesis, we will present the SSM and DSM of an EMS for micro-grids.

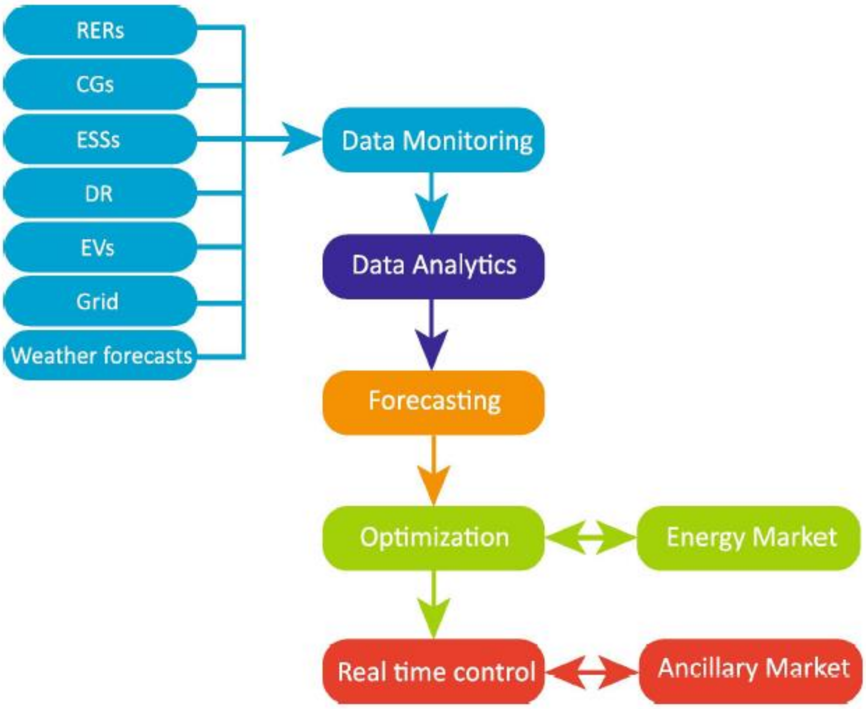


*Figure 4.4 Functions of a micro-grid EMS* (Zia et al., 2018).

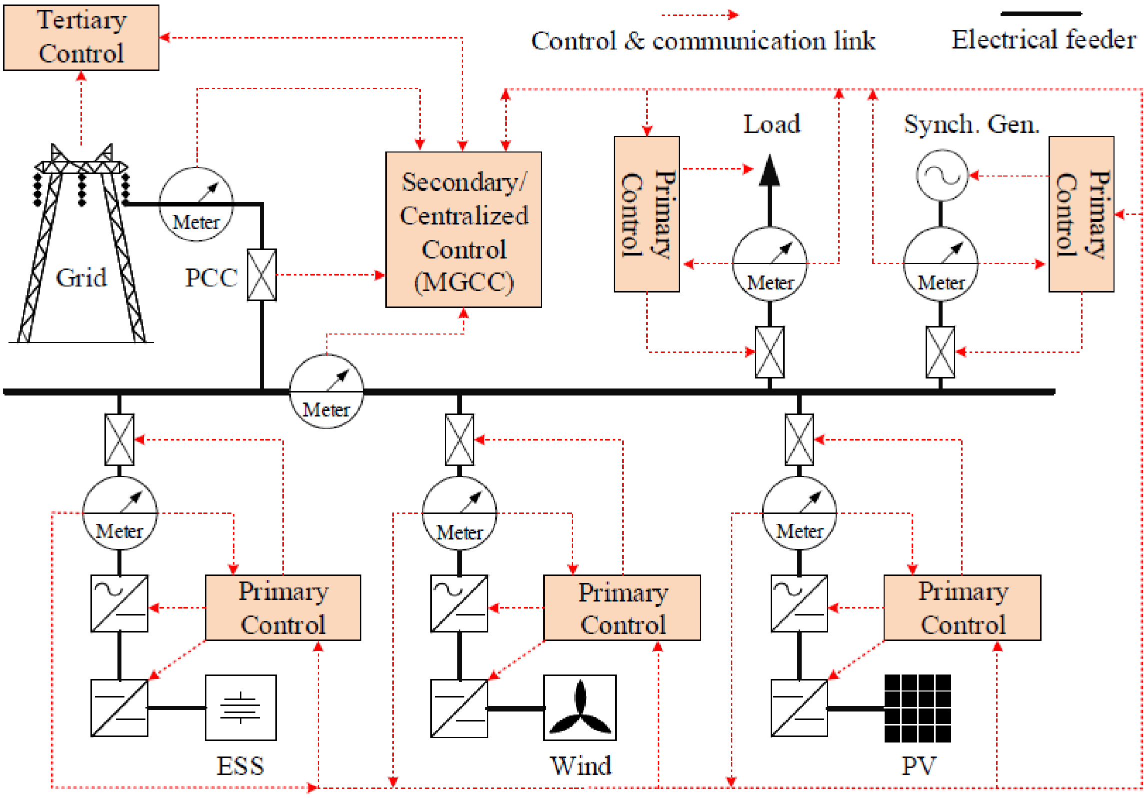


*Figure 4.5 Micro-grid primary, secondary, and tertiary controls architectures (Farrokhabadi et al., 2020).*

### 4.3.1 Supply Side Management (SSM)

Supply side management (SSM) is the term used to describe the steps required to guarantee that the production, transmission, and distribution of electricity are performed optimally. In the past, SSM focused only on improving conventional production and transmission facilities. However, modern SSM systems promote on-site generations options, like as DREMPs, cogeneration, as well as enhancing the operation, maintenance, and modernization of available assets (Khan, 2022). DREMPs has been identified in (Hafez and Bhattacharya, 2012) as an important supply-side management option for micro-grids, suggesting that renewable energy-based micro-grids are the most environmentally friendly and have significantly lower system emissions.

The various micro-plants interconnected in the micro-grid have multiple cost functions as well as multiple limitations. Many conventional mathematical optimization methods, such as mixed-integer linear programming (MILP), nonlinear programming (NLP), quadratic programming (QP), and interior-point methods (IPMs) (Fortenbacher and Demiray, 2019; Gabash and Li, 2012), have been suggested for use in this area since Optimal Power Flow (OPF) was introduced over 50 years ago. The advantage of such methods is their robustness and fast convergence in finding an optimal solution. Nevertheless, the necessity to initially linearize the optimization function is a significant drawback of such optimization approaches (Khan, 2022).

### 4.3.2 Demand-Side Management (DSM)

#### *4.3.2.1 Introduction*

The second important part of an EMS is the demand-side management (DSM). The fundamental goal of DSM is to smooth the demand curve by motivating consumers to shift their energy usage to off-peak hours or to reduce the consumption during peak-hours (Khan, 2022).

The following three factors make consumers adjust their power usage based on DSM (Arikiez, 2016): (1) Dynamic pricing, (2) The ability of consumers to have a control system to monitor and regulate their consumption profiles, as well as (3) the ability of consumers to measure the financial benefits of DSM adoption (Arikiez, 2016). In the next subsections of this thesis, we present the various DSM strategies.

#### *4.3.2.2 Demand-side management strategies*

DSM strategies generally aim to maximize the efficient use of existed production units, as well as postpone or avoid the necessity of installing new production units. There are several strategies of DSM (*Figure 4.6*) such as (Gelazanskas and Gamage, 2014; Logenthiran et al., 2012; Zhu et al., 2012):

##### *4.3.2.2.1 Conservation:*

It is the most well-known and earliest method of reducing overall power usage, not only during peak hours. Energy-saving appliances, for instance, may all time save electricity.

##### *4.3.2.2.2 Load shifting:*

This strategy's main goal is to shift (i.e. move) loads from peak-hours to off-peak hours. Customers can, for instance, heat or cool water at night (during off-peak hours) and utilize it in the morning (during peak hours).

#### *4.3.2.2.3 Peak clipping:*

Reducing demand during peak hours is the main objective of this technique. This reduction can be realized by consumers or energy suppliers managing interruptible devices like heaters and air conditioners.

#### *4.3.2.2.4 Load growth:*

This technique consists of increasing overall sales during both off-peak and peak hours. , it is in opposition to conservation strategy.

#### *4.3.2.2.5 Valley filling:*

The main goal of this method is to increase consumption at off-peak hours to smooth the demand curve. An excellent example of valley filling is a plug-in hybrid electric vehicle (PHEV), which charges its battery bank at nights.

#### *4.3.2.2.6 Flexible load shape:*

With this approach, the grid operator has the authority to stop loads when necessary without informing the customers. Typically, the strategy "flexible load shape" refers to fluctuations in service quality and reliability of energy provider (Arikiez, 2016).

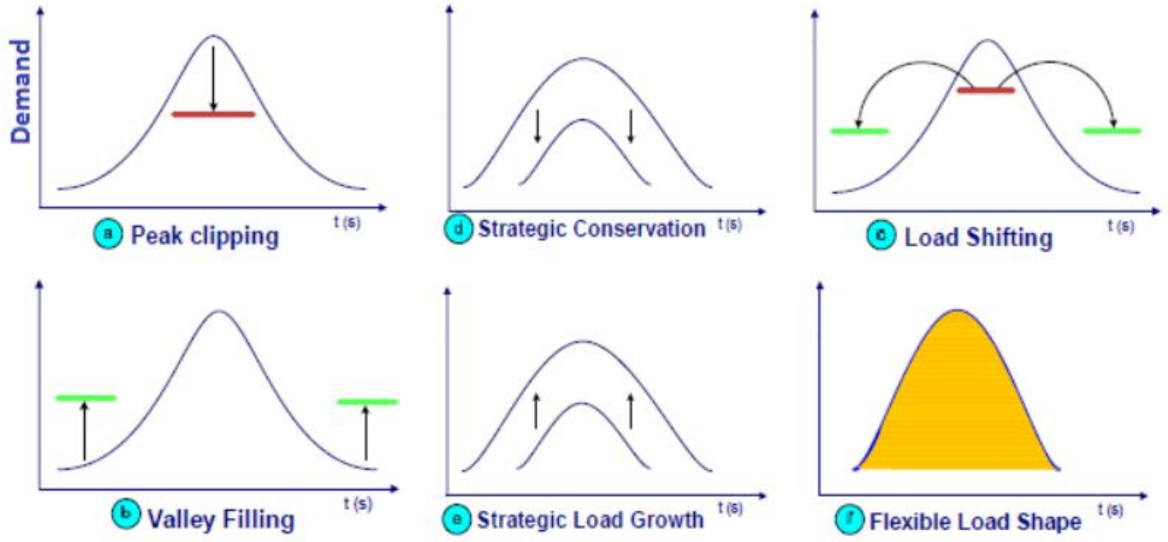


*Figure 4.6 Strategies of DSM and its objectives*

### *4.3.2.3 Demand response (DR)*

DSM is realized through demand response (DR). this last is a mechanism for reducing the demand when the supply of electricity is not sufficient (Ali et al., 2016). The DSM typically targets long-term energy use reductions (Yoldaş et al., 2017), whereas demand response (DR) is the activity that consumers take to decrease energy usage in a specific period of time (peak-hours for example).

The main idea of DR is depicted in *Figure 4.7*, which is implementing appropriate measures to limit the use of power during times when it is most expensive (Zia, 2020). As shown in this curve, during high price hours, the demand is decreased from $Q$ to $Q_{DR}$ in order to decrease the price from $P$ to $P_{DR}$.

In terms of motivation, DR may be classified into two categories: price-based DR and incentive-based DR (Zia, 2020). In price-based DR, consumers change their demand in response to changes in power prices (Wang et al., 2015). In this case, the most typical pricing strategies are flat rate pricing (i.e. constant price for all energy quantities and for all periods), time of use pricing, critical peak pricing, and real time pricing (RTP) (Zia, 2020). Contrarily, in incentive-based DR, micro-grid operator or utility company has remote access to some loads and may indirectly, using control systems implemented at consumers' side, switch certain of them at specific periods (Siano, 2014; Wang et al., 2015).

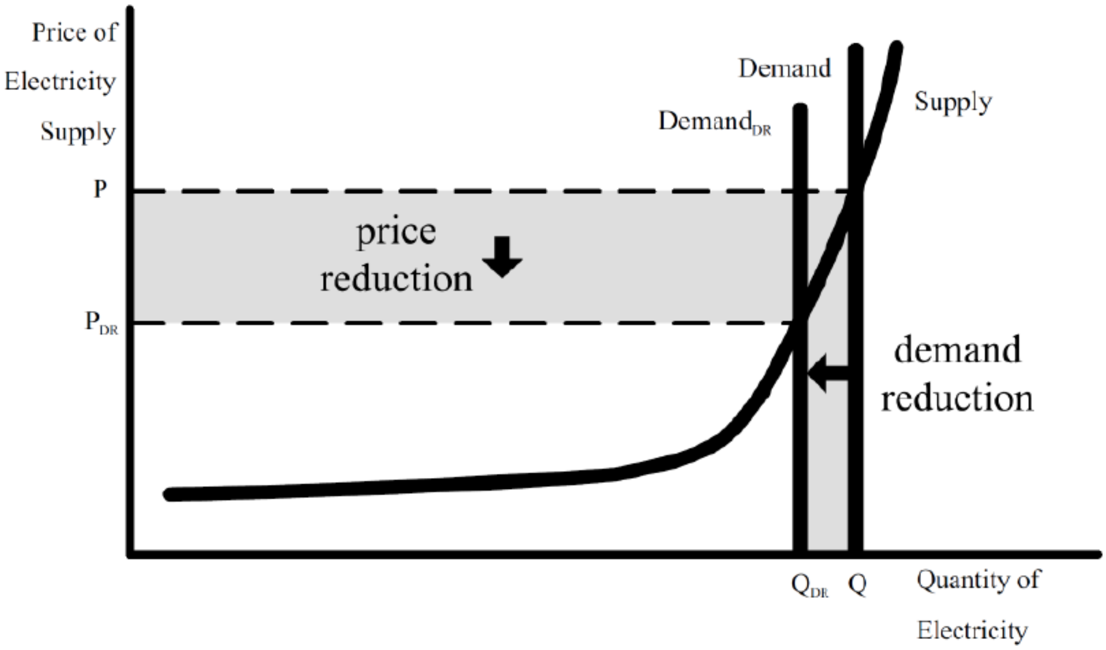


*Figure 4.7 The concept of demand response* (Qdr, 2006).

## 4.4 Machine Learning (ML) and Artificial Intelligence (AI) for EMSs

### 4.4.1 Introduction

In this subsection of the thesis, we present the machine learning (ML) techniques and its various models for EMSs. The ML techniques are an essential key option for the efficient operation of micro-grid EMS.

An EMS strategy's main objective is to maximize or minimize the objective function. This function may include energy quality, energy cost, stability, efficiency, reliability, GHG emissions, and so on. Therefore, ML is becoming more and more popular for the effective operation of micro-grid EMSs. The most common ML algorithms are (Meliani et al., 2021): Artificial neural networks (ANN), Wavelet Neural Network (WNN), Support vector machines (SVM), Adaptive Neuro-Fuzzy Inference System (ANFIS), Tree-based models (Decision trees), Multilayer Perceptron (MLP), Ensemble Prediction Systems (EPS), and Deep learning (DL).

### 4.4.2 Artificial neural networks (ANNs)

Artificial Neural Networks (ANNs) are the platforms for various ML methods to process large amounts of complex data. The computing architecture of ANNs is inspired from the biological neural networks of animal brains. The basic building block of an ANN is a neuron that employs a transfer function to formulate its outputs. The primary advantage of an ANN method is its simplicity for multivariate issues. This method may be applied to a variety of tasks, including regression, curve fitting, and forecasting. ANNs can be adapted for micro-grid and smart city applications, such as energy management, renewable energy forecasting, danger detection, urban transportation, water supply, and so on (Veerapen et al., 2015).

### *4.4.3* Wavelet Neural Network *(WNN)*

Wavelet Neural Network (WNN) is one of ML methods. WNN combine the advantages of neural networks and wavelet theory. One of its goals is to estimate or compute the function of a trend or process. Using a sequence of data, a neural network may create the structure of a function and produce or calculate the predicted output value for a given input value. Compared to other neural networks, WNN provides a number of benefits. For example, it has a faster convergence and needs less training compared to the Multilayer Perceptron (MLP) method (Burger and Moura, 2015; Faizollahzadeh Ardabili et al., 2016).

### 4.4.4 Support vector machines (SVM)

Another ML technique that may be applied for several smart grid applications is Support vector machines (SVM). SVMs are supervised learning models with corresponding learning algorithms (based on statistical learning framework for minimization of risks) that examine data for regression, classification, or other purposes such as outliers detection. Based on a collection of training examples, each one is clearly categorized as belonging to one of two classes; an SVM training algorithm creates a classifier model that categorizes new examples to one of the two classes. SVMs are more robust in model classification, recognition, and regression analysis than other prediction approaches. Due to their ability to make generalizations, SVMs have a wide variety of smart grid applications, including smart and health domains assessment, water and energy supply management, and load forecasting (Ahmad et al., 2018).

### 4.4.5 Adaptive Neuro-Fuzzy Inference System (ANFIS)

Adaptive Neuro-Fuzzy Inference System (ANFIS) is another kind of ML methods that makes use of ANN based on Takagi–Sugeno fuzzy inference system. Because ANFIS incorporates both fuzzy logic and neural network concepts, it has the ability to combine their advantages into a single framework. This method is used to address several real-world problems including energy management issues, smart city assessment issues, and urban governance issues (Mosavi et al., 2019).

### 4.4.6 Decision trees (Tree-based models)

Decision Tree (DT) is a supervised learning method applied in ML, data mining, and statistics. A regression or classification decision tree is employed in this formalism like a predictive approach to make decisions about a set of target variables. Considering their simplicity and intelligibility, DTs are one of the most widely used ML methods in several various power systems (Yang et al., 2016). DTs have been used by engineers and researchers to solve problems related to air pollution, businesses, food, and urban transportation for the development of smart cities (Ozdemir et al., 2016).

### 4.4.7 Ensemble Prediction Systems (EPS)

Ensemble Prediction Systems (EPS) is a ML method which has been employed more and more to solve predictability problems such as energy and weather forecasting issues, and offer estimations for uncertainties (Buizza et al., 2019). EPSs employ numerous statistics and learning algorithms in machine learning to get highest modelling performance (Abdulwahid, 2018; Costa et al., 2016).

### 4.4.8 Multilayer Perceptron (MLP)

The Multilayer Perceptron (MLP) is one of feed-forward ANN classes. It uses a supervised learning for training purposes called backpropagation. MLP is a simple method that is widely used in energy systems and engineering applications for prediction and system modelling, and is frequently referred to as the control model (Liu and Yao, 1999).

### 4.4.9 Deep learning (DL)

Deep learning (DL) is a category of ML methods based ANN that uses cascading layers of processing units to extract higher-level features from the given data and make predictions about the new data. The three types of learning: supervised, semi-supervised, and unsupervised, could all be used in this method (LeCun et al., 2015). The are many architectures of DL including deep neural networks (DNNs), deep reinforcement learning (DRL), deep belief network (DBN), recurrent neural networks (RNNs), and conventional neural networks (CNNs) (Krizhevsky et al., 2017).

The success of DL in recent real-world applications like speech and face recognition, machine translation, natural language processing, and AlphaGo has demonstrated incredible potential of DL methods (Abdullah Asuhaimi, 2019; Krizhevsky et al., 2017). Moreover, DL methods have many other potential applications in different aspects of smart grids and smart city including energy management, smart city management, transportation, and health (Yilmaz et al., 2014).

## 4.5 Conclusion

In this third chapter, we tackled the topic of smart grids and micro-grids. The concept of micro-grid as well as its classifications are presented. We emphasized in grid-connected and islanded micro-grids. Moreover, the EMSs used in smart grids and micro-grids are explained. The quantification methods are also considered such as SSM, DSM, DR, and pricing policy. ML methods and its models as well as Artificial Intelligence for smart grids and micro-grids such as ANNs, SVMs, Tree-based models, EPSs, ANFIS, WNNs, MLP, and DL are also discussed. It was shown that the ML techniques are an essential key option for the efficient operation of micro-grid EMS. An EMS strategy's main objective is to maximize or minimize the objective function. This function may include energy quality, energy cost, stability, efficiency, reliability, GHG emissions, and so on. Therefore, ML is becoming more and more popular for the effective operation of micro-grid EMSs.

# Chapter 5 Background on Communication Technologies for Smart Grids Applications

This chapter presents a background on communication technologies for smart grid applications. We will emphasize in this chapter in presenting the different types of communication networks that may be used for smart grid communications including Home Area Networks (HANs), Neighborhood Area Networks (NANs), and Wide Area Networks (WANs). Moreover, some kinds of communication technologies applicable for smart grids and micro-grids will be thoroughly presented in this chapter. Both wired and wireless technologies will be taken into consideration. In wired communication technologies, we will present Power Line Communication (PLC) and fiber optic communication technologies. In the other hand, in wireless communication technologies, we will present the ZigBee, Worldwide Interoperability for Microwave Access (WiMAX), Wireless Technologies – Wireless Fidelity (Wi-Fi), Satellite communication technologies, and 5G communication networks.

## 5.1 Introduction

Researchers are now paying a lot of attention to smart grids to develop effective ways to much the supply with the demand. Information and communication technologies (ICT) have made the smart grid a particularly effective tool for addressing a number of problems with the conventional grid, including numerous blackouts, failures, and system stability issues (Khan, 2022).

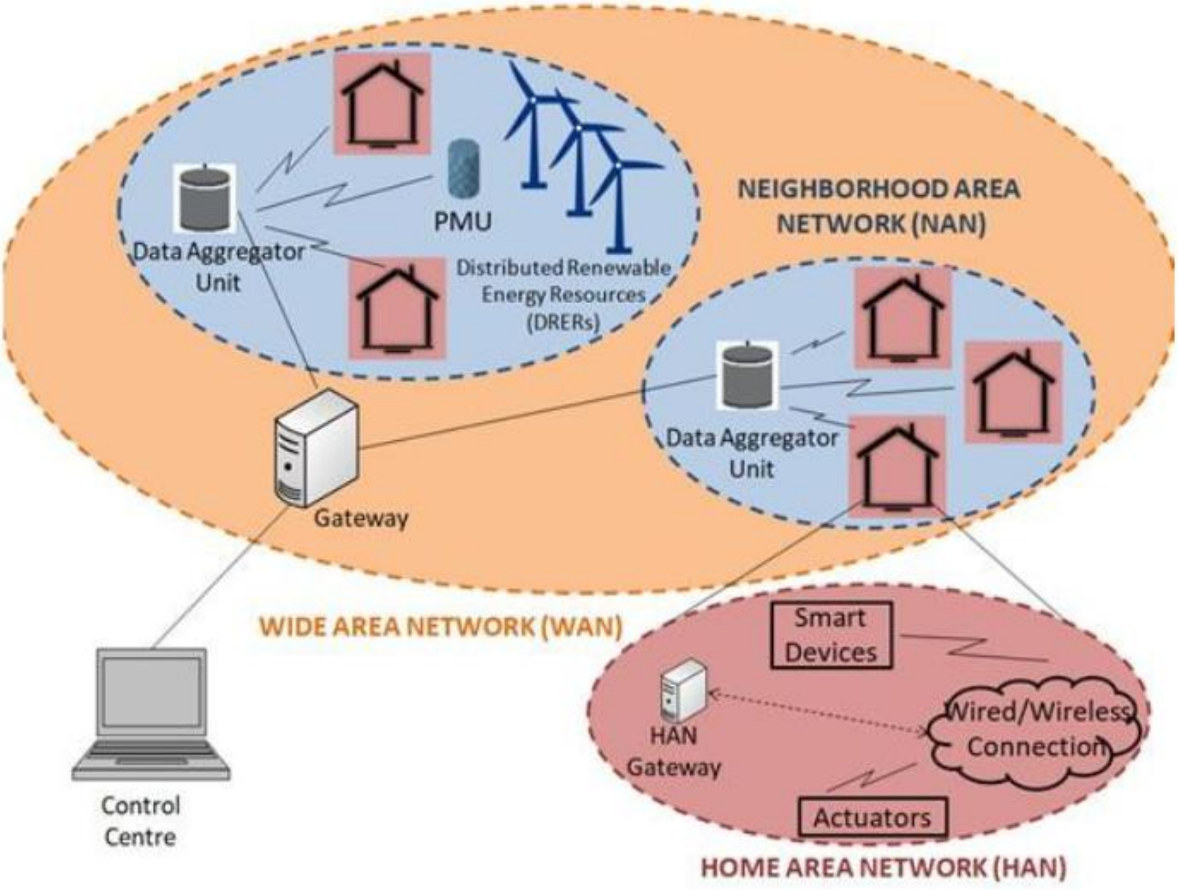


*Figure 5.1 The smart grid communication technologies.*

Smart grid use two-way communications to optimally manage its resources including power outputs from RESs, loads, and ESSs. There are three different types of communication networks that may be used for smart grid communications: Home Area Networks (HANs), Neighborhood Area Networks (NANs), and Wide Area Networks (WANs). Among these, NANs' responsibilities include creating communication infrastructure for smart grid DNs (Meng et al., 2014), such as transmitting meter data to the control center for DSM applications as well as performing the management of various DREMPs in DNs or in micro-grids (Huang et al., 2011). *Figure 5.1* illustrates the hierarchical structure of smart grid communication technologies based on their functionality and coverage area (Kayastha et al., 2014).

## 5.2 Different types of communication networks

### 5.2.1 The Home Area Networks (HANs)

One of the smallest components in smart grids that connects smart meters and electrical devices, such as sensors, Home Energy Management System (HEMS) that assists consumers in controlling their energy usage based on RTP data, and actuators that measure different variables, such as temperature and light intensity, is the Home Area Network (HAN). Since HANs can cover only small areas, low-data-rate, short-distance communication technologies like WiFi and ZigBee are sufficient for such networks (Abdullah Asuhaimi, 2019).

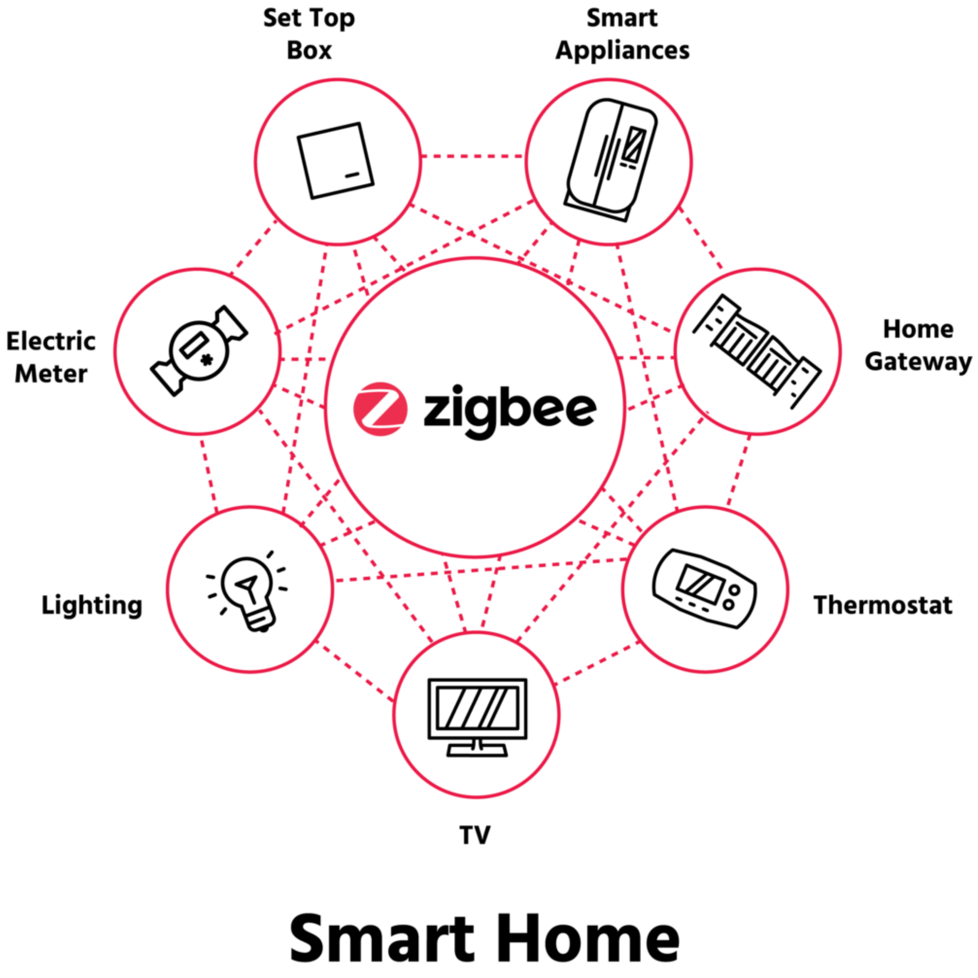


*Figure 5.2 HAN with ZigBee technology*

### 5.2.2 The Neighborhood Area Networks (NANs)

Neighborhood Area Networks (NANs) are an important communication networks for smart grids. The NANs can handle the majority of communications in DNs and micro-grids that contain several HANs and local access point (Meng et al., 2014). In smart grids, NANs deal with a large number of appliances and handle a big heterogeneous data to perform several smart grid applications such as distribution automation, smart metering, DREMPs management, load management, pricing management, as well as outage management and restoration (Lo and Ansari, 2012). NANs can cover areas such as a cluster of buildings, a micro-grid, a small industry, and so on, therefore it necessitate a medium-range communication technology with a large network capacity for connecting many appliances. Worldwide Interoperability for Microwave Access (WiMAX) and Power Line Communication (PLC) technologies are most likely to be sufficient for such networks (Kalalas et al., 2016).

### 5.2.3 The Wide Area Networks (WANs)

Another important type of communication networks in smart grids is the Wide Area Networks (WAN). This type of network provides communications between the control center of the utility main grid and substations. Moreover, the WANs allow data-exchange between the NANs and the electricity provider. WANs gather various sorts of data from various distribution domains, and then send them to the control center (Yan et al., 2013). Due to the size of the area covered by a WAN, which might include a whole village or urban area, very high data rates with long-distance communication technologies are required (Gungor et al., 2013).

## 5.3 Communication Technologies for Smart grid applications

Several communication technologies, including wired and wireless technologies, have been taken into consideration to enable communications in smart grid. In this subsection of the thesis, we present some kinds of communication technologies applicable for smart grids and micro-grids.

### 5.3.1 Wired communication technologies

In terms of security, reliability, and bandwidth, wired communication technologies are seen as preferable to wireless ones since cables are simpler to shield from interference as well as to protect from eavesdroppers. Furthermore, wired communication technologies offer cheaper installations and maintenance costs (Abdullah Asuhaimi, 2019). The next subsections give an overview about some wired communication technologies utilized in smart grids.

#### *5.3.1.1 Power Line Communication (PLC)*

The Power line communication (PLC) was primarily intended to monitor distribution line failures, but it is currently receiving a lot of attention for communications in power grids (Tsado et al., 2017). PLC is a financially advantageous solution for NAN applications in smart grids (ex. load control and DR) due to the use of only a single medium to transmit simultaneously electricity and data, and the widespread of PLC networks. Generally speaking, narrowband PLC may cover communication distances between 300 m to 1 km, and deliver data rates between 10 to 500 Kbps (Abdullah Asuhaimi, 2019).

#### *5.3.1.2 Fiber optic communications*

Alternatively, numerous applications employ fiber optic communications, which convey data using light pulses traveling through optical fibers. Nowadays, Ethernet is being used extensively in power systems to offer real-time control and monitoring in smart grid DNs as well as in micro-grids (IEC 61850, 2004). Without using intermediate amplifications or relays, fiber optic technology enable long-distance communications (up to 100 km) and are secure from electromagnetic interferences (Adamiak et al., 2009). They offer a data rate from about 155 Mbps to about 40 Gbps. Fiber optic technologies, on the other hand, lack the scalability and flexibility to rapidly adjust to topology changes when communication in smart grids, which comprises a significant number of power units (Parikh et al., 2010).

## 5.3.2 Wireless communication technologies

Because of their scalability, flexibility, accessibility, and efficiency, wireless communication technologies are seen as a viable approach to serve smart grid applications (Abdullah Asuhaimi, 2019). In the next subsections of this thesis, we present the relevant wireless communication technologies applicable for smart grids.

### *5.3.2.1 ZigBee*

According to IEEE 802.15.4 standard, ZigBee is a viable option for small-scale, low power, and low cost machine to machine (M2M) and IoT networks (Gezer and Buratti, 2011). ZigBee standard can cover longer range of Advanced Metering Infrastructure (AMI) where a significant number of intelligent devices in remote locations communicate with data aggregator using peer-to-peer multi-hop approach (Meng et al., 2014). Nevertheless, the drawbacks of this technology that limit its adoption for smart grids include its complexity, security, data rate, and functioning in license-free bands. The ZigBee standard can typically transmit data at a rate of 20 to 250 Kbps across distances of about 10m to 1.6 km (Kalalas et al., 2016).

### *5.3.2.2 Worldwide Interoperability for Microwave Access (WiMAX)*

Worldwide Interoperability for Microwave Access (WiMAX) is a group of wireless broadband communication standards based on the IEEE 802.16 set of specifications. This standard is developed to give a broad and sufficient covering for the NANs in smart grids (ex. DNs and micro-grids) (Abdullah Asuhaimi, 2019). In general, WiMAX is distinguished from other wireless technologies by its low latency (below 100 ms round-trip), long-distance communications (tens of kilometers), advanced security protocol, and high data rates (up to tens of Mbps). Nevertheless, the expensive cost of WiMAX installations and the associated maintenance limit its adoption in power grids (Rengaraju et al., 2012).

### *5.3.2.3 Wireless Technologies, Wireless Fidelity (Wi-Fi)*

Wireless Technologies, Wireless Fidelity (Wi-Fi) is a family of wireless network protocols based on the IEEE 802.11 family of standards, which are generally utilized for Wireless Local Area Networks (WLANs) (ex. smart homes, offices, campuses …etc.) enabling nearby digital devices (ex. laptops, smartphones, digital sensors, smart meters …etc.) to exchange data thanks to radio waves. This standard can provide high data rate (up to 6.75 Gbps). Nevertheless, the coverage distance of Wi-Fi standard, which is between 20m to 1 km, limits its usage in smart grids, notably for NANs (Kalalas et al., 2016). Therefore, Wi-Fi standard is only appropriate for smart grid WLANs, such as smart appliances interconnection in homes or offices (Cena et al., 2010), or communication in intra-substation (Parikh et al., 2013).

#### *5.3.2.4 Satellite communications*

Another option for smart grid applications is satellite communications (Yang, 2012; Yang et al., 2011). The benefit of this wireless technology is that it can cover the areas of the electricity distribution systems thanks to its extremely broad coverage areas. Nevertheless, installing big antennas for satellite communications is necessary and highly expensive, and a potential geometric storm might lower the quality of signals. In addition, the energy consumption of this technology is high due to the large-distance communications. Moreover, the widespread use of this technology necessitates international cooperation and adherence to national laws (Abdullah Asuhaimi, 2019).

### 5.3.3 5G communication Networks

The strict communication needs of smart grids (i.e. control services and data collection) were addressed by new important concepts established by 5G communication networks such as the ultra-reliable low-latency communication (URLLC) and the massive machine type communication (mMTC) services. The URLLC service can offer connections lessen than 1ms with ultrahigh reliability, while the mMTC service can enable enormous access of machines with more than 10 million connections/m$^2$, which are suitable for applications with strict communication needs of smart grids (Ismail et al., 2019). Moreover, the notion of network slicing in 5G wireless technology makes it possible to create separate virtual entities and support several operations within the same communication network without interfering with each other. There are other important features in 5G wireless technology such as cloud computing that might more effectively and flexibly manage the massive data generated by the smart grid and quickly produce the best operational decisions (Abdullah Asuhaimi, 2019). Nevertheless, 5G wireless technology is not yet fully adopted for many reasons (Reka et al., 2019). The biggest issue with 5G communication networks is the lack of standardization, which is necessary to ensure that the current technology may be used and upgraded to be in line with the 5G standard. Additionally, as this field of study is still in its early stages, there are still a number of challenges that need to be investigated (Ismail et al., 2019). Table 5.1 provides a comparison between 4G and 5G wireless communication networks (Reka et al., 2019).

*Table 5.1 Comparison between 5G and 4G communication technologies*

| **Features** | **4G** | **5G** |
|---|---|---|
| Deployment (year) | 2010 | 2020 or later |
| Speed (Gbps) | 0.1 | 10 |
| Frequency band (GHz) | 2 to 8 | 3 to 300 |
| Data | Digital broadband packet data | Not yet defined |
| Technology | WiMax, Wi-Fi, LTE | Not yet fully defined |
| Core network | Internet | Internet |
| Multiple access | Orthogonal Frequency division | Orthogonal Frequency division |
| Advantages | High data rate, high throughput, high maturity and availability | High reliability, high speed, and very low latency |
| Disadvantages | Costly, relatively high energy consumption | The complete adoption of the systems is lacking. |

## 5.4 Conclusions

In this chapter of the thesis, we have presented a background on communication technologies for smart grid applications. We emphasized in this chapter in presenting the different types of communication networks that may be used for smart grid communications including Home Area Networks (HANs), Neighborhood Area Networks (NANs), and Wide Area Networks (WANs). Moreover, some kinds of communication technologies applicable for smart grids and micro-grids have been thoroughly presented in this chapter. Both wired and wireless technologies have been taken into consideration. In wired communication technologies, we have presented Power Line Communication (PLC) and fiber optic communication technologies. In the other hand, in wireless communication technologies, we have presented the ZigBee, Worldwide Interoperability for Microwave Access (WiMAX), Wireless Technologies – Wireless Fidelity (Wi-Fi), and Satellite communication technologies. Moreover, an overview about 5G communication networks are also presented.

# Chapter 6 Results and discussions

In this chapter of results and discussions, we shed the light on the prototyping, modeling, and controlling of distributed smart renewable-energy microplants. In addition, the impacts of integrating renewable energy MPs on power grids in term of frequency and voltage stability will be tackled. Moreover, information and communication technologies: a way to explore the potential benefit of DREMPs in smart grids and micro-grids will be highlighted. Furthermore, some practical applications of smart micro-grids based renewable-energy microplants for powering small-scale residential communities will be presented. Effective solutions for achieving the self-sufficiency of micro-grids in both grid-connected and islanded modes will be developed. In all the previous mentioned points, the results will be thoroughly presented and discussed.

## 6.1 Introduction

In this last chapter, we present the results and discussions. We have divided this chapter into many parts:

In the first part, we present the experimental works and the research studies conducted at our laboratory, LAT-Tlemcen, to achieve building prototypes of smart distributed renewable energy micro-plants. Four types of renewable micro-plants that are developed at the LAT-Tlemcen have been fully presented in this chapter; a 1.5 kW Wind Turbine Emulator based on a Double Fed Induction Generator, a 1.5 kW Wind Turbine Emulator based on a Synchronous Generator, a 1.5 kW Photovoltaic system with Grid Tie Inverters (YC500) and finally, a 250 W Photovoltaic micro-power plant connected through a self-made single-phase Grid Tie Inverter.

In the second part, we present the modeling and controlling of renewable-energy MPs, especially wind and PV. The micro-plants models must have the same behavior as the experimental ones presented in the first part. We have used a simplified model of a DFIG expressed in a (*d*-*q*) axis with flux vector control to simulate the wind MP based DFIG. We have also implemented an MPPT algorithm to extract the maximum power available. In addition, we have used pitch regulation strategy to extract exactly the needed power from the maximum available power. Concerning the PV MP, we have used the single diode equivalent model because of its simplicity. We took the weather data including solar irradiance and temperature as input variables. The output variables are the current, voltage, and the PV power. Moreover, we have implemented an MPPT algorithm to extract the maximum available power from the PV modules. Furthermore, we have implemented another algorithm that extract exactly the needed power and not the maximum available power. In parallel to the modeling of DREMPs, a simulated power grid with conventional power plants running in real time are also presented. All these models (PV, wind, and conventional power grid) can run on both computer-based systems or on embedded processors (Raspberry PI3).

In the third part, the power grids' stability in the presence of DREMPs is presented. We emphasize in presenting the impact of renewable energy MPs integration in utility power grids in term of frequency and voltage stability. The simulation results are well presented and discussed. Developed programs that compute the load flow (LF), the transient stability (TS), the power system stabilizers (PSSs), automatic voltage controllers (AVCs), and the power injection from renewable energy MPs at the grid buses are also considered. To study the impact of integrating renewable-energy MP on the stability of power grids and to analyze their mutual interaction in grid-connected mode, four cases are presented. The first is when the 5-buses power grid functions without injecting the power of the DREMPs. The second is when we inject only the power of the PV micro-plant at ELM bus. The third is when we inject only the power of the WTE based on a DFIG MP at LAKE bus. The last case is when we inject the power of both PV and WTE micro-plants in the corresponding buses. In the cases 1, 2, 3 and 4, the installed capacity from DREMPs is 0%, 20%, 35% and 55% of the total production respectively. The results and discussions are well presented.

In the fourth part of this chapter, Information and communication (ICT) technologies: A way to explore the potential benefit of DREMPs in smart grids are well presented. We have developed a micro-grid based DREMPs, especially wind and PV, and a battery bank ESS to feed small-scale communities with many consumers. Two computer-based systems have been used. The first is for emulating the DREMPs with their local controller. The second is for emulating the loads with their local controller. A decentralized control strategy has been performed to control the power production from DREMPs as well as to control the consumers' devices in both grid-connected and islanded mode. In addition, we have used a real-time control strategy instead of the conventional load/dispatch forecasting methods. The intelligent DREMPs' local controller (SSM-LC) performs the energy production management and the demand-side local controller (DSM-LC) performs the DSM. The micro-grid central controller (can be emulated by a third computer-based system) can receive all the information about the MPs and loads and send orders (power references for all the MPs, switch on/off loads, RTP …etc.) to the local controllers when operating in centralized control. However, in this thesis, we choose to perform the decentralized control instead of the centralized control. To ensure the data flow between the distributed systems, we have developed a Firebase Database (DB); the intelligent swarm of renewable-energy MPs can send information about their real-time power production and receive consumers' data to produce the exact quantity of power and follows the load profile or operate in MPPT mode. The demand-side local controller can send information about the real time power consumption and receive data about the real-time power production to manage its local loads such as switching on/off its connected appliances or reduce flexible loads such as cooling or heating systems and adapt the load profile to the supply profile and skip the weather limitations. The tow computer-based systems (or three in case of centralized control) are connected to the DB via a Wi-Fi WLAN of the home router. The home router is connected to the 4G LTE network. We have also developed an Android application to check for any updates in the DB and displays data. The experimental prototypes of renewable-energy micro-plants can also be connected to the DB to send data and receive orders to/from the DB thanks to Wi-Fi connected microcontrollers ESP8266. We emphasize in this part in presenting the communication interactions results between the supply-side and demand-side local controllers. The first computer-based system emulates the smart DREMPs, which send real time data about their generated power to the DB. We suppose that the generated power varies each 1 second. The second computer-based system which emulate the demands-side resources receives the data about the real-time generated power to perform the DSM in distributed control. In this part, we are not going to present the DSM nor the SSM, but we are going to present only the communication interactions between the various systems and highlight the communication issues such as communication delay time and failures that may occur during the communication system operation. Thus, four scenarios are presented, the first is when both SSM-LC and DSM-LC send / receive data from the DB each 10s. The second is when both SSM-LC and DSM-LC send / receive data from the DB each 5s. The third is when both SSM-LC and DSM-LC send / receive data from the DB each 1s. The last is when a failure occurred in the communication system. The objective is to compare the data profile received from the DB with the real-time true values and to see the effect of the communication delay on giving correct real-time information and on conserving the real profile variations.

The fifth part of this chapter is a continuity of the previous part where some practical applications of smart micro-grids based renewable energy micro-plants for powering small-scale residential communities are developed. The idea concerns the development of renewable energy-based smart micro-grid solutions to support the development of small-scale communities in off-grid and on-grid areas and serve their typical energy needs such as cooling, heating, pumping, lightening, and other electricity usages. The main objective in this part consists in managing electricity production from renewable energy micro-plants as well as managing the loads of consumers to develop effective solutions for achieving the self-sufficiency of micro-grids in both grid-connected and islanded modes. We have replaced the traditional dispatch-based forecasting methods by iterative real-time control. A decentralized control strategy is developed to control the micro-grid in both grid-connected and islanded modes in a way that each micro-plant produces an exact quantity of energy in real time to follow the consumption variation. For the wind micro-plant, we have used a pitch regulation strategy to control the blades angle of the wind turbine and produce an exact quantity of energy and maintain a constant power supply, less than the MPPT available power, even with a variable wind speed. Concerning the PV micro-plant, we have implemented another algorithm besides the MPPT algorithm that searches for the appropriate PV-GTI DC voltage to produce a precise amount of power from the PV micro-plant and maintain a constant power supply, less than the MPPT available power, even with a variable solar irradiance. Concerning the demand-side resources, two strategies are proposed to manage consumers' appliances and skip the weather limitations: load shifting  and load conservation strategies. Their effect on the power mismatch between the generation and the consumption in the micro-grid is also presented.

## 6.2 Part 1: Prototyping of distributed renewable energy micro-plants

Experimental prototypes of smart distributed MPs are developed at the Laboratoire d'Automatique de Tlemcen (LAT), Algeria.

### 6.2.1 Wind turbine emulator based on a Double Fed Induction Generator

*Figure 6.1* shows the overall experimental structure of the emulator of the wind energy conversion system (DEKALI et al., 2021a; Dekali et al., 2019).

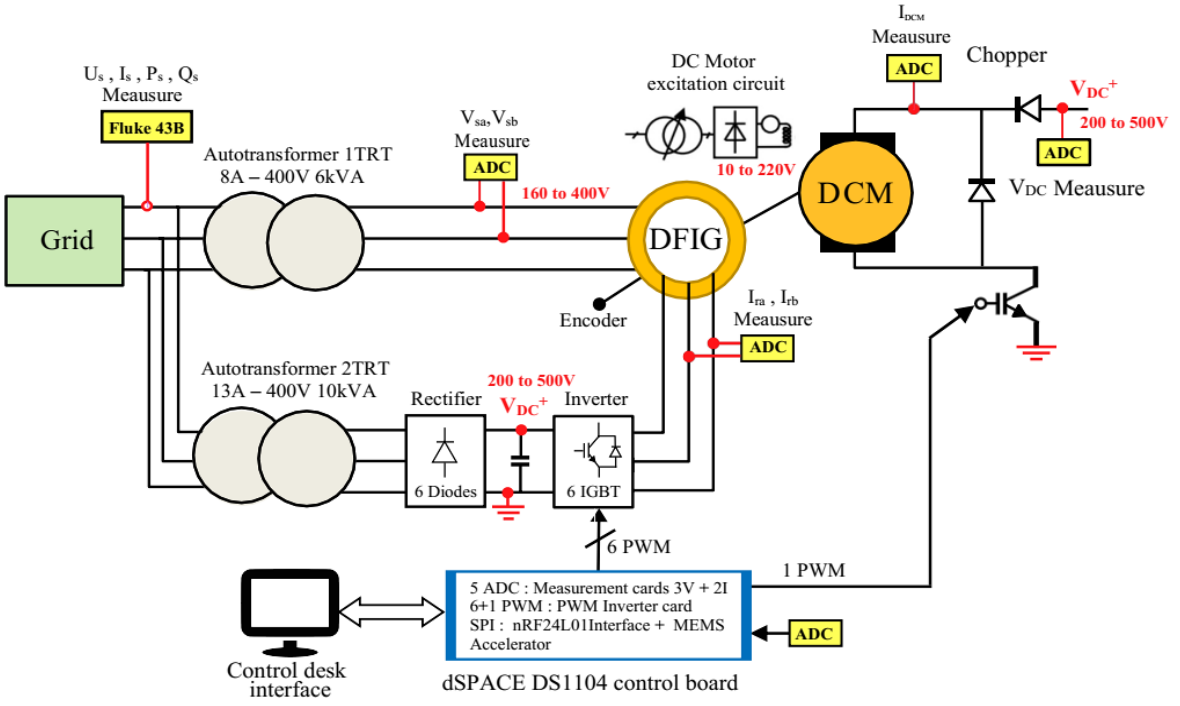


Figure 6.1. Experimental hardware structure of the wind turbine emulator based on a DFIG.

This is a special implementation in order to reduce costs. The DC motor is directly coupled to the Double Fed Induction Generator (DFIG) and is powered by a chopper. The chopper is powered from the same DC bus as the DFIG rotor side inverter. This ensures that the delivered power from the rotor side of the DFIG through the Motor Side Converter (MSC) in hyper-synchronous mode will not increase the DC bus voltage and destroy the capacitors. Hence, we only need a simple three-phase diode-based rectifier as a Grid Side Converter (GSC). We use autotransformers for voltage adaptation as low as the DC machine maximum voltage (250V). The stator of the DFIG is connected to the grid. The main part of the generated power $P_s$ flows from the stator to the grid through the 13A autotransformer. To control both the 3-phases inverter and the DC chopper, we use a dSPACE DS1104 single board control solution with reprogrammed firmware.

Figure 6.2 shows the experimental hardware setup of the WTE based on a DFIG, whereas Table 6.1 details its hardware components.

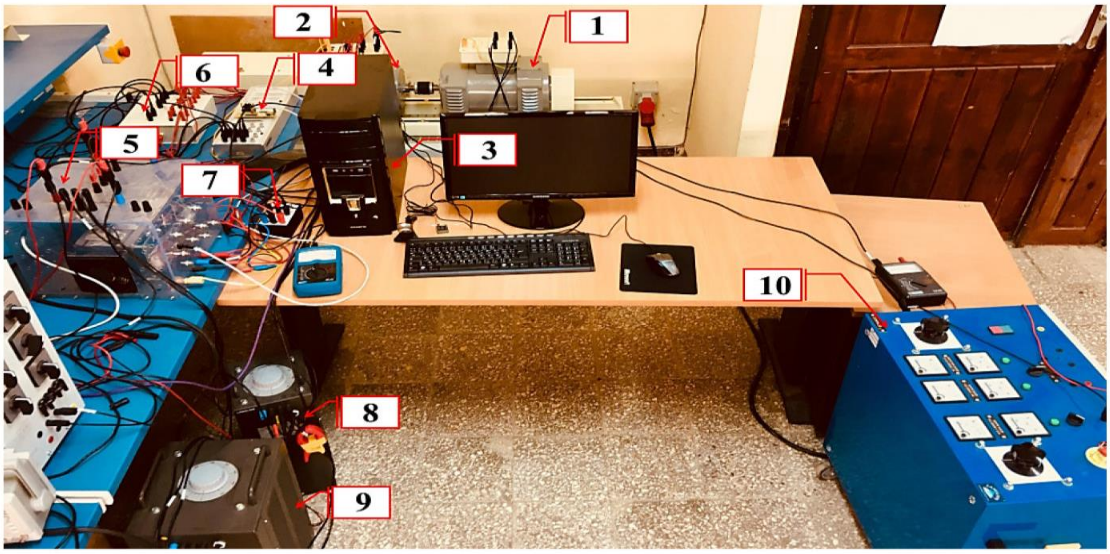


*Figure 6.2 Experimental hardware setup of the WTE based on a DFIG*

*Table 6.1 WTE based on a DFIG hardware components*

| Components | Name | Components | Name |
|---|---|---|---|
| 1 | DFIG | 6 | Measure interfaces for DFIG |
| 2 | DC Motor | 7 | Measure interfaces for DC Motor |
| 3 | PC | 8 | Autotransformer (stator side) |
| 4 | DS1104 interface | 9 | Autotransformer (rotor side) |
| 5 | Inverter and Rectifier | 10 | Power supply (DC excitation) |

Different wind profiles are applied through the control of the DC motor and an MPPT (Maximum Power Point Tracking) extraction algorithm allows the control of the speed of the Wind Turbine Emulator (WTE) in order to get the maximum power generated by the DFIG. In order to get closer to the emulation of the real behavior of a wind power plant, we used a wind speed profile (see Figure 6.3) based on random values around the synchronism speed (7.5 m/s equivalent to 1500 rpm).

The speed control loop shows high dynamics. The speed tracks accurately the reference value found by the MPPT algorithm in respect to the wind speed (Figure 6.4).

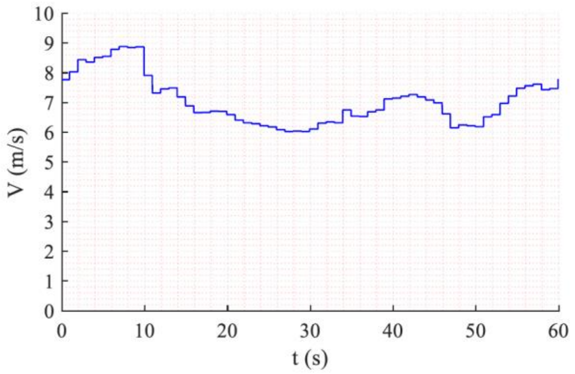


Figure 6.3 Wind profile used for DFIG experiments

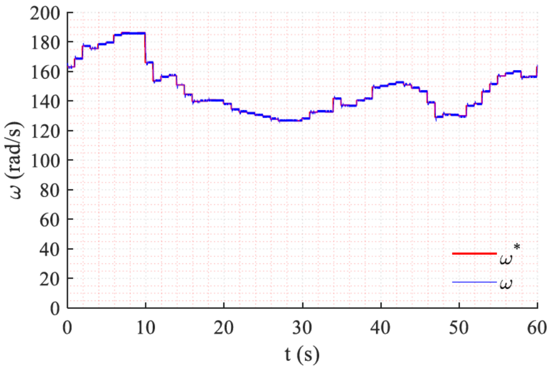


Figure 6.4 Speed control of the DFIG

When the reference wind speed reaches a high value (more than 8 m/s), the DC motor needs a greater e.m.f, thus requiring a supply voltage greater than its limitation at 220VDC. The control limits this voltage at 220VDC (*Figure 6.6*) and therefore no longer regulates the armature current (Figure 6.5) as well as the drive torque of the DC motor. This last lead to a reduction in the electromagnetic torque of the DFIG to guarantee the speed control and therefore an instantaneous cancellation of the energy produced $P_s$ by the DFIG (Figure 6.7). When the speed is lower and the voltage is no more at its limit, the control recover the normal operating and the MPPT is once again guaranteed.

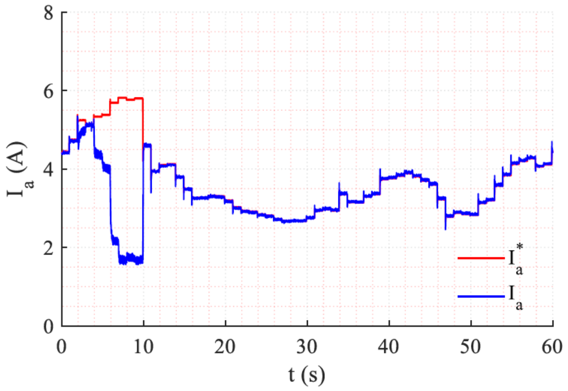


*Figure 6.5 Armature current of the DC Motor*

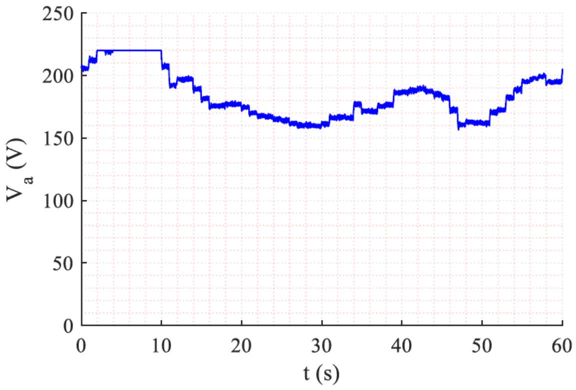


*Figure 6.6 Armature voltage of the DC Motor*

The reactive power $Q_s$ of the stator remains compensated at 0 Var following the reference (Figure 6.9), which explain the consumption of the rotor direct current $I_{dr}$ around 8A (Figure 6.10) for reactive power compensation. The DFIG generates the defined active power by the MPPT loop (Figure 6.7), thanks to the PI controllers of the rotor currents (Figure 6.10 and Figure 6.8).
The pikes on the generated power $P_s$ is due to the sudden change of wind speed and because the controller are chosen to be fast in time response.

The rotor voltages, $V_{dr}$ and $V_{qr}$ (Figure 6.11), which are the outputs of rotor-current controllers, impose the required rotor currents $I_{dr}$ and $I_{qr}$ (Figure 6.10 and Figure 6.8).

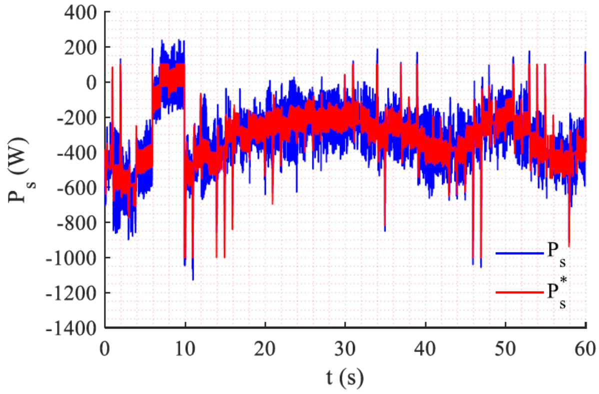


*Figure 6.7 Stator active power of the DFIG.*

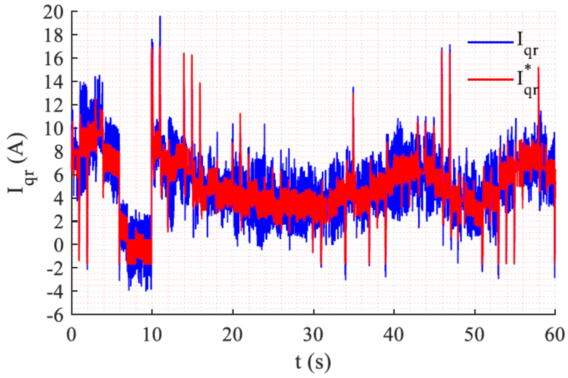


*Figure 6.8 Rotor quadrature current.*

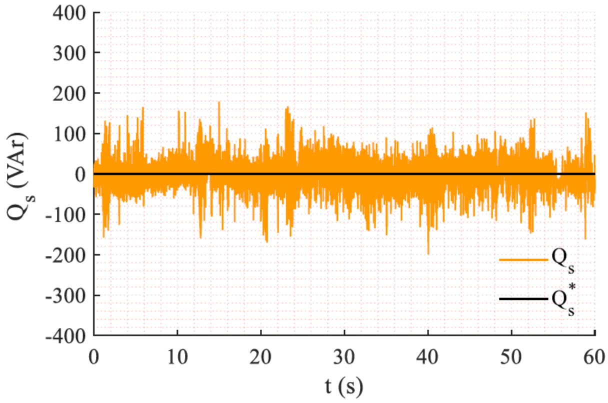


*Figure 6.9 Stator reactive power.*

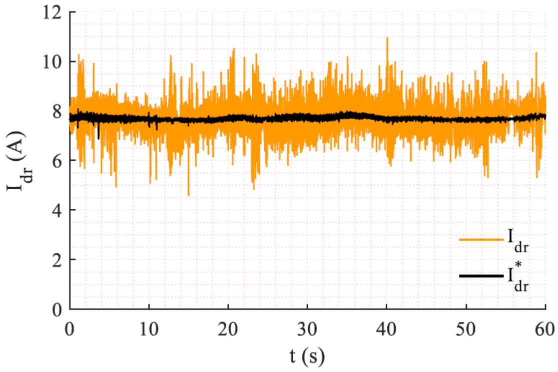


Figure 6.10 Rotor direct current.

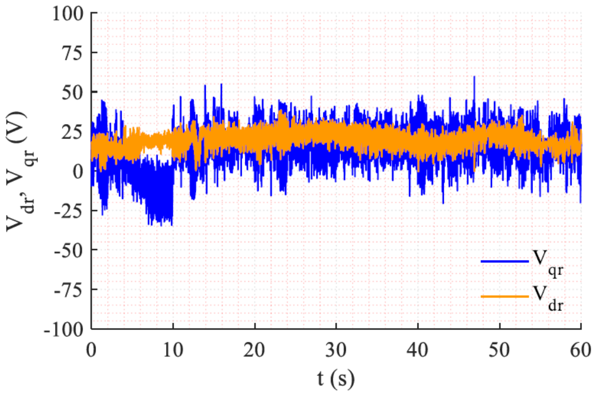


*Figure 6.11 DFIG rotor voltages.*

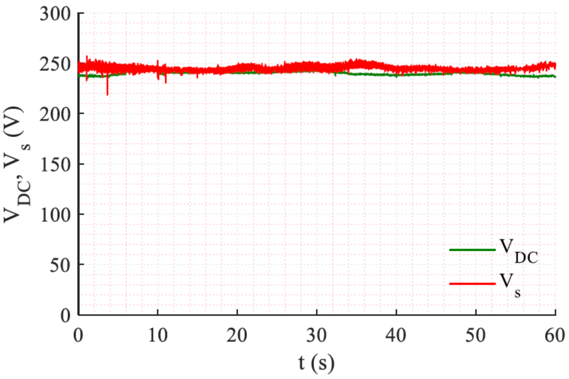


*Figure 6.12 DFIG stator voltage Vs,* DC-Bus voltage $V_{DC}$.

### 6.2.2 Wind turbine emulator based on a Synchronous Generator

A similar structure is used for the WTE based on a Synchronous Generator (SG) (Figure 6.13) (DEKALI et al., 2021b), but we need back-to-back converters (MSC and GSC) between the grid and the stator of the SG. The Control Desk™ running on the host PC of the DS1104 permits the interaction with the embedded control program variables of the system in real time.

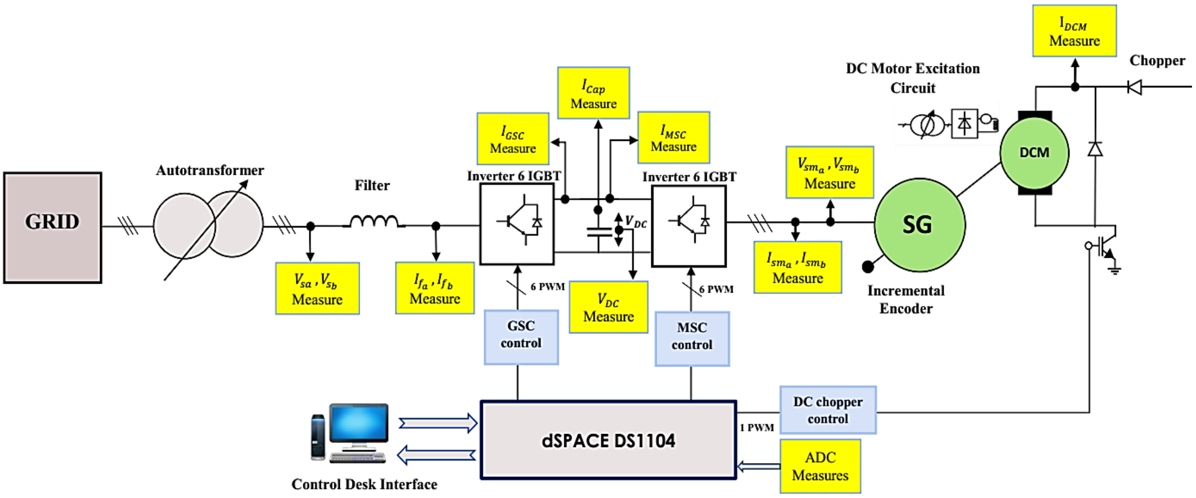


Figure 6.13. Experimental structure of the wind turbine emulator based on a SG

Figure 6.14 shows the experimental hardware setup of the WTE based on a SG, whereas Table 6.2 details its hardware components. However, this system is not yet fully operational; parameters identification and control parameters computation need to be performed.

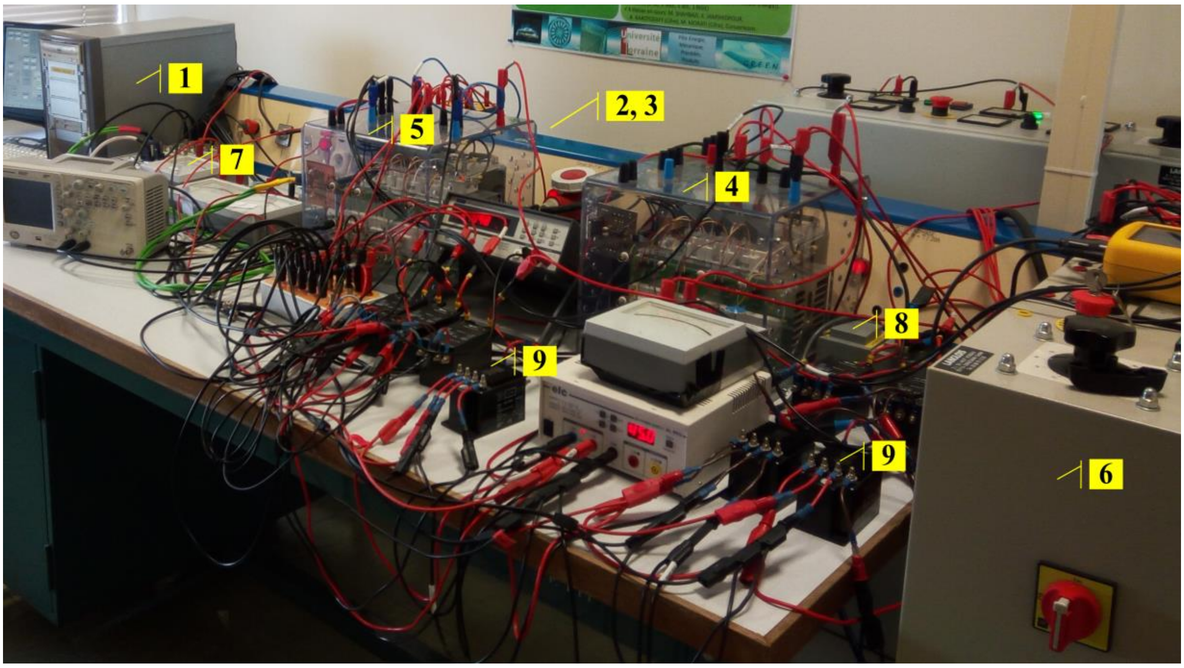


*Figure 6.14 Experimental hardware setup of the WTE based on a SG*

*Table 6.2 WTE based on a SG hardware components*

| Component | Name | Component | Name |
|---|---|---|---|
| 1 | PC | 6 | Autotransformer |
| 2 | DC Motor | 7 | DS1104 interface |
| 3 | SG | 8 | Filter |
| 4 | Grid side converter (GSC) | 9 | Sensors |
| 5 | Machine side converter (MSC) | | |

### 6.2.3 Photovoltaic industrial micro power plant

Six PV panels (250 W for each one) are connected each two with one Grid Tie Inverter (GTI) YC500. Each GTI has two independent DC input with dedicated MPPT per input. The three GTI are connected in parallel to the grid via a circuit breaker. The Energy Communication Unit (ECU) uses PLC to communicate with the GTI and sends data over the Wifi router to an external database (Figure 6.15**)**. The ECU acts also as a local web server. A Raspberry Pi3 (RPi3) that we program connects to the LAN, reads the data of the generated power from the web server of the ECU and sends them to the Firebase Database (DB) each 5 minutes. This time can be adjusted.

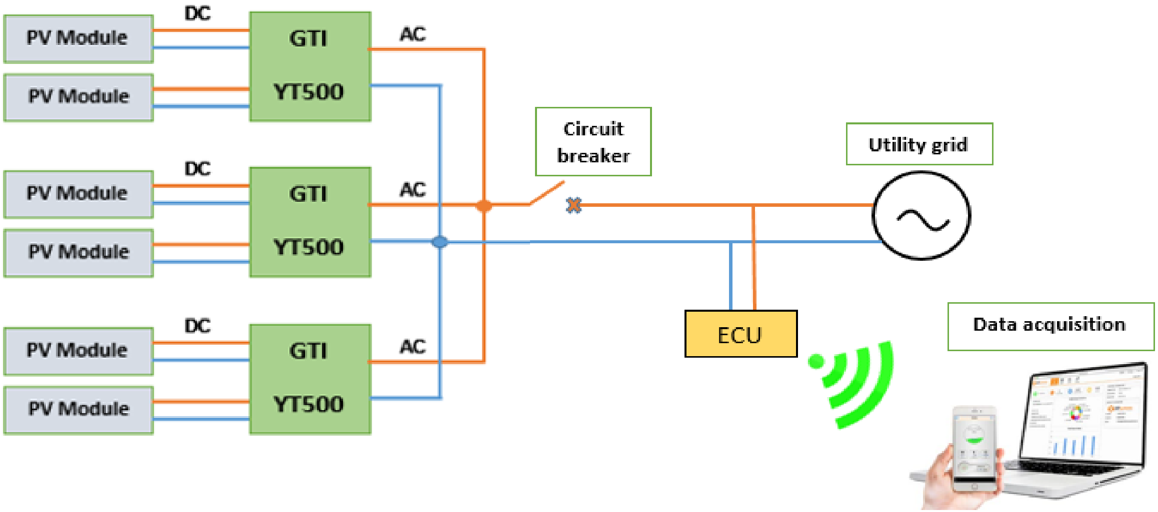


Figure 6.15. Experimental structure of the PV Grid Tie Inverter microplant (Terfa et al., 2019).

Figure 6.16 shows the experimental hardware setup of the PV industrial micro-plant, whereas Table 6.3 details its hardware components. The Figure 6.17 shows the generated power from only two Photovoltaic (PV) panels (250 W for each one) with one GTI YC500 in summer on a cloudy afternoon at Tlemcen, Algeria. In the other hand, Figure 6.18 shows the generated power when the electricity from the grid is cut (off grid). In this case, the industrial GTI stops working.

The GTI extracts the maximum power from the two PV panels thanks to its internal MPPT algorithm. Then, it synchronize to the grid and inject active power at a unity power factor. Because we do not have access to its internal algorithm, it is not possible to adjust the active power of this experimental banc. Moreover, generating the reactive power is also not possible. When looking to this figure, we notice that the generated power of the PV micro-plant is highly intermittent and depends highly by the weather conditions. This is the main problem with renewable energy sources.

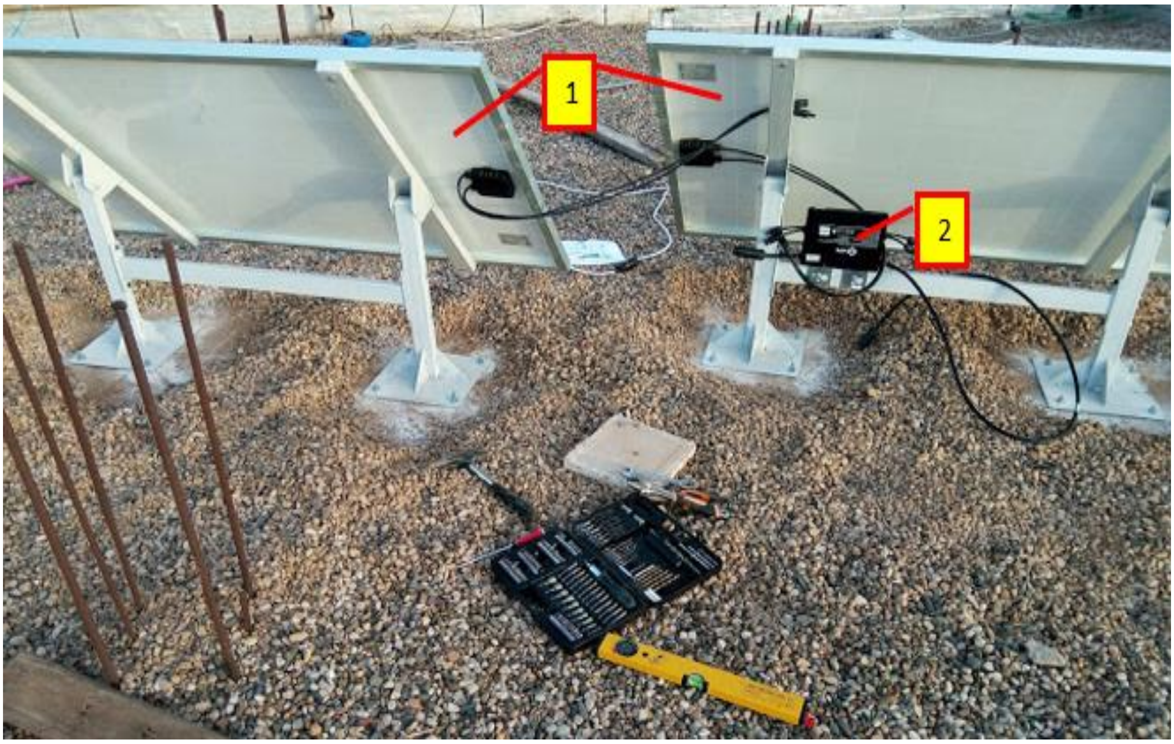


*Figure 6.16 Experimental hardware setup of the PV industrial MP*

*Table 6.3 PV industrial micro-plant hardware components*

| Component | Name |
|---|---|
| 1 | Photovoltaic cells (250 W for each one) |
| 2 | GTI YC500 |

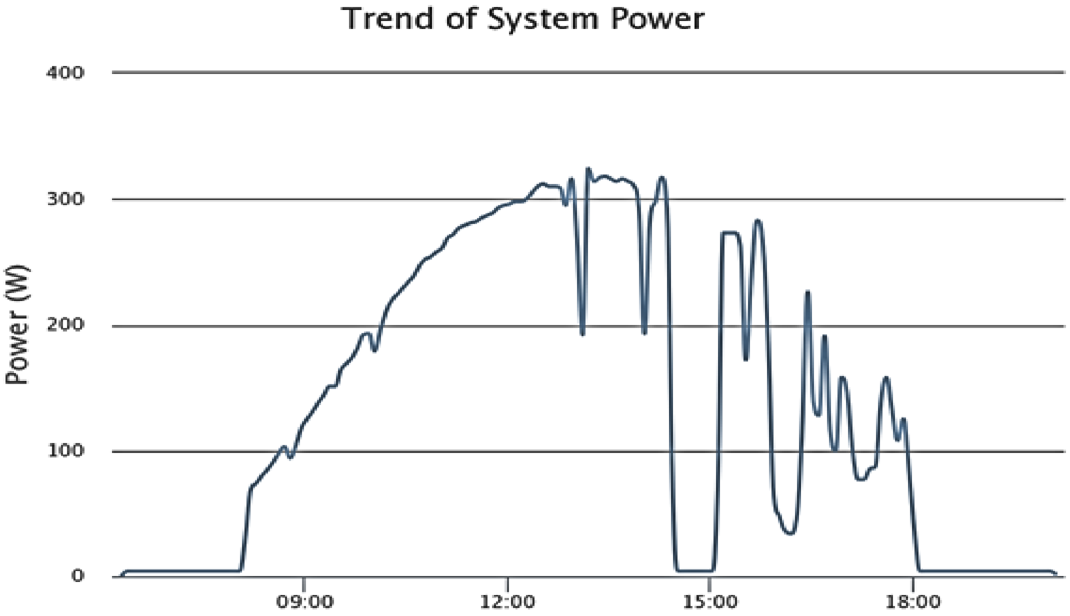


*Figure 6.17 Experimental curve of the PV industrial MP power in the summer at Tlemcen, cloudy afternoon*

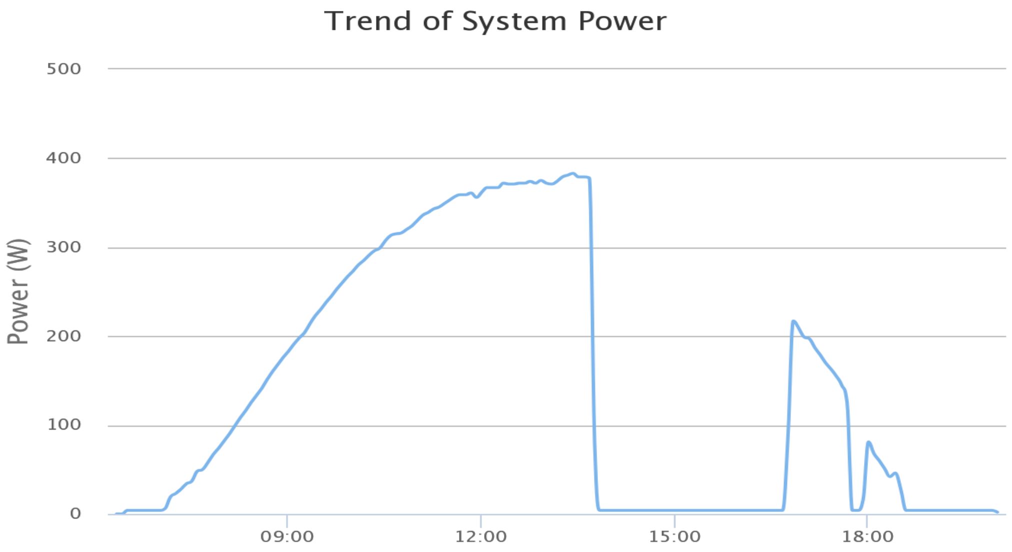


*Figure 6.18 Experimental curve of PV industrial MP power when the grid power is cut (off grid) in the summer at Tlemcen.*

### 6.2.4 Photovoltaic self-made micro power plant

In order to study our own implementation of a GTI, we choose to build it, at the lab, with two interleave step-up DC-DC choppers that extract the power form the PV. Then, the inverter stage synchronizes to the grid using a Zero Cross Detection (ZCD) algorithm and allows the injection of the reference active power. The reactive power can also be absorbed or generated from the grid or work at a unity power factor (Merah et al., 2019). The control is done using TI Launchpad F28069M as shown in Figure 6.19. The communication to the DB is done with a Wemos ESP8266.

In order to produce the maximum power available (MPPT), or the exact amount of needed power or to shut down the power production, the control is taking the reference point from the DB.

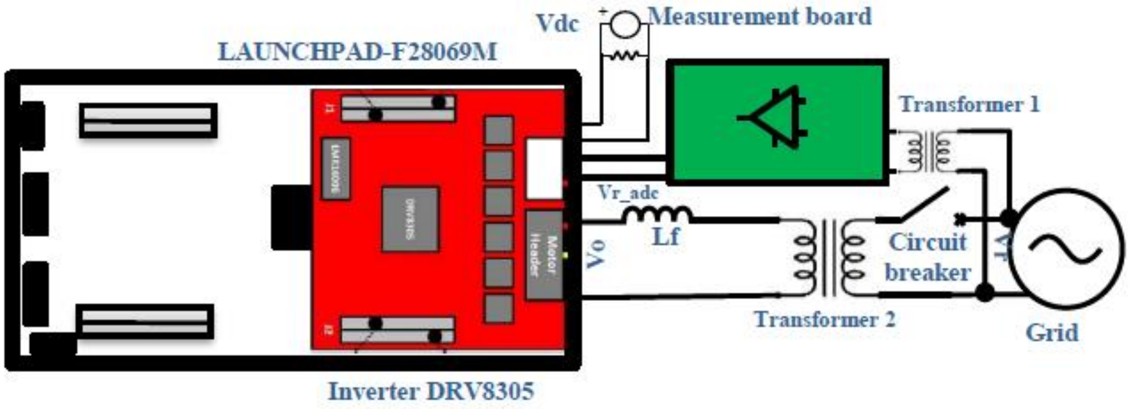


Figure 6.19. Experimental structure of the PV self-made micro power plant

Figure 6.20 shows the experimental hardware setup of the PV self-made micro-plant, whereas Table 6.4 details its hardware components.

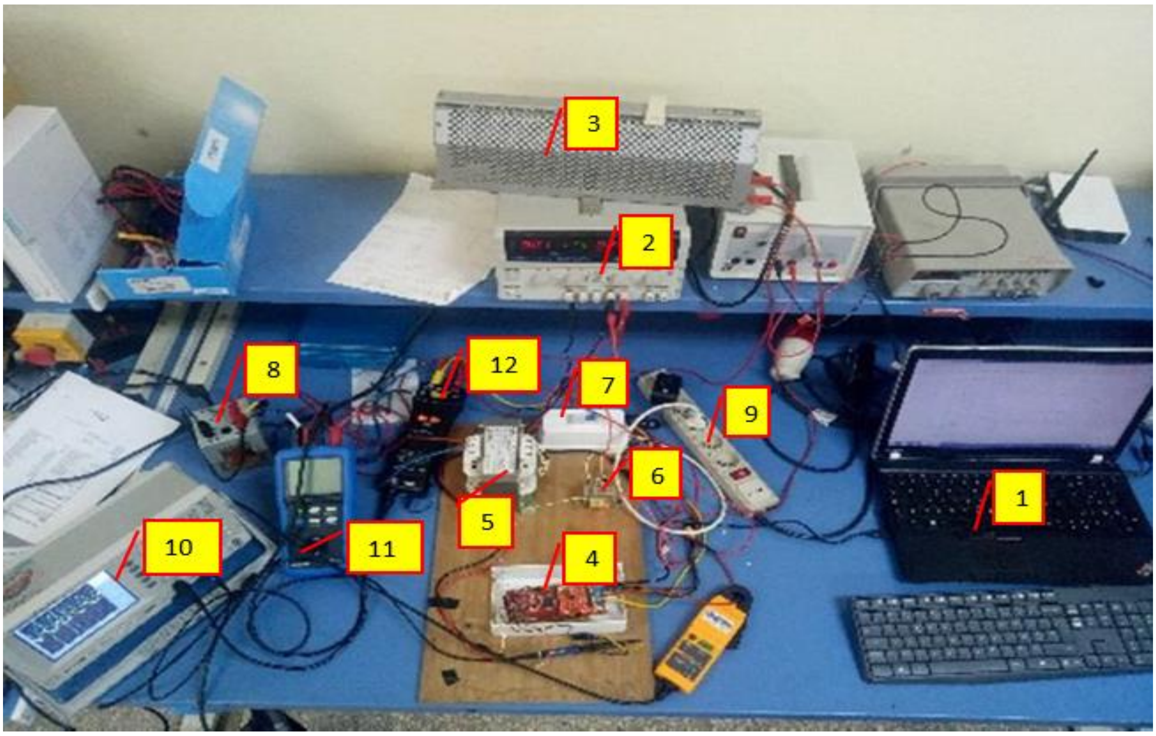


*Figure 6.20 Experimental hardware setup of the PV self-made MP*

*Table 6.4 PV self-made MP hardware components*

| Component | Name | Components | Name |
|---|---|---|---|
| 1 | PC | 7 | Circuit breaker |
| 2 | DC Source | 8 | 5.2mH Inductance coil |
| 3 | Rheostat | 9 | Grid source |
| 4 | Measurement boards | 10 | Oscilloscope |
| 5 | Transformer 1 (250VA) | 11 | Power meter |
| 6 | Transformer 2 (40VA) | 12 | Voltage differential probe |

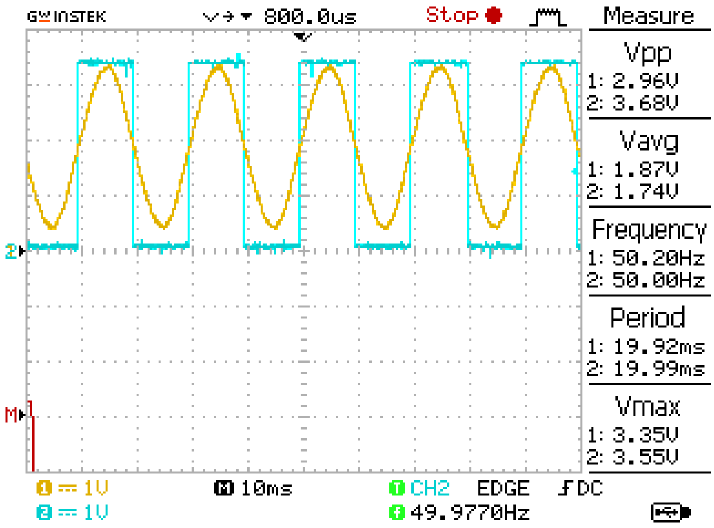


*Figure 6.21* Experimental measurements of the grid voltage in (channel 1, yellow curve) and ZCD algorithm in (channel 2, blue curve)

Figure 6.21 shows the experimental measurements of the grid voltage (channel 1, yellow curve), and the ZCD algorithm of the GTI (channel 2, blue curve). Moreover, Figure 6.22 shows the GTI filtered output voltage (blue curve), and the grid voltage (yellow curve) with ($\delta=-\pi/2$). It must be noted that, when the angle $\delta$ is different from zero, we can inject to the grid or absorb from it the reactive power. These results show that the measurement of the grid voltage, the PWM control of the GTI, and the ZCD algorithm to synchronize the GTI output voltage with the grid voltage are well operating. Nevertheless, this experimental bench is still in progress. More experimental work and research studies must be conducted to well master the injection of the active and reactive power to the grid and succeed the operation of the PV self-made micro-plant.

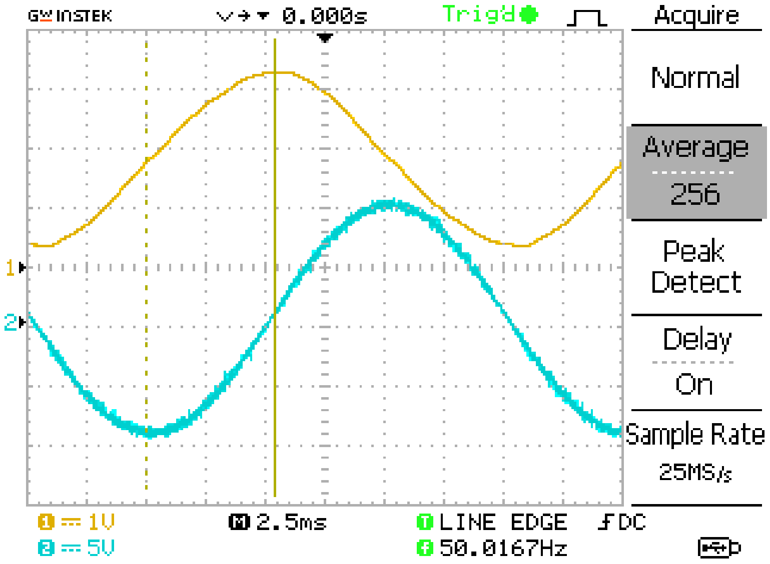


*Figure 6.22 GTI filtered output voltage (blue curve) and grid voltage (yellow curve) with ($\delta=-\pi/2$)*

## 6.3 Part 2: Modelling of distributed renewable energy micro-plants: solar and wind

In parallel to the experimental prototypes conducted in the lab by our project partners, we created models of smart micro-plants.

### 6.3.1 Wind turbine micro-plant model

A simplified model of a DFIG expressed in a ($d$-$q$) axis is used with flux vector control. This strategy allows the linearity between the rotor currents ($I_{qr}$, $I_{dr}$) and the stator powers ($P_s$, $Q_s$) of the DFIG (Dekali et al., 2019).

Figure 6.23 shows the active and reactive power control diagram. Where $P_{sref}$, $Q_{sref}$, $I_{drref}$, $I_{qrref}$, $V_{drref}$ *and* $V_{qrref}$ are the references of active power, reactive power, direct rotor current, quadrature rotor current, direct rotor voltage and quadrature rotor voltage respectively. $P_s$, $Q_s$, $I_{dr}$, $I_{qr}$ *and* $V_s$ are the active power, reactive power, direct rotor current, quadrature rotor current and stator voltage respectively. $L_s$, $L_r$, $M$, $R_r$ and *sigma* are the stator inductance, rotor inductance, mutual inductance, rotor resistance and leakage coefficient respectively. $W_s$ and $W_r$ are the stator pulsation ($2\pi f_s$) and the slip pulsation respectively.

To extract the maximum power available, we used an MPPT algorithm that calculates the optimum mechanical speed $W_{m\_opt}$ of the DFIG and then generates the active power reference $P_{sref}$ thanks to a PI controller as shown in Figure 6.24. Where *lambda_opt* is the optimal relative speed, $G$ is the gearbox ratio, $R$ is the pale radius, $W_{sp}$ is the wind speed and $W_m$ is the mechanical speed of the DFIG.

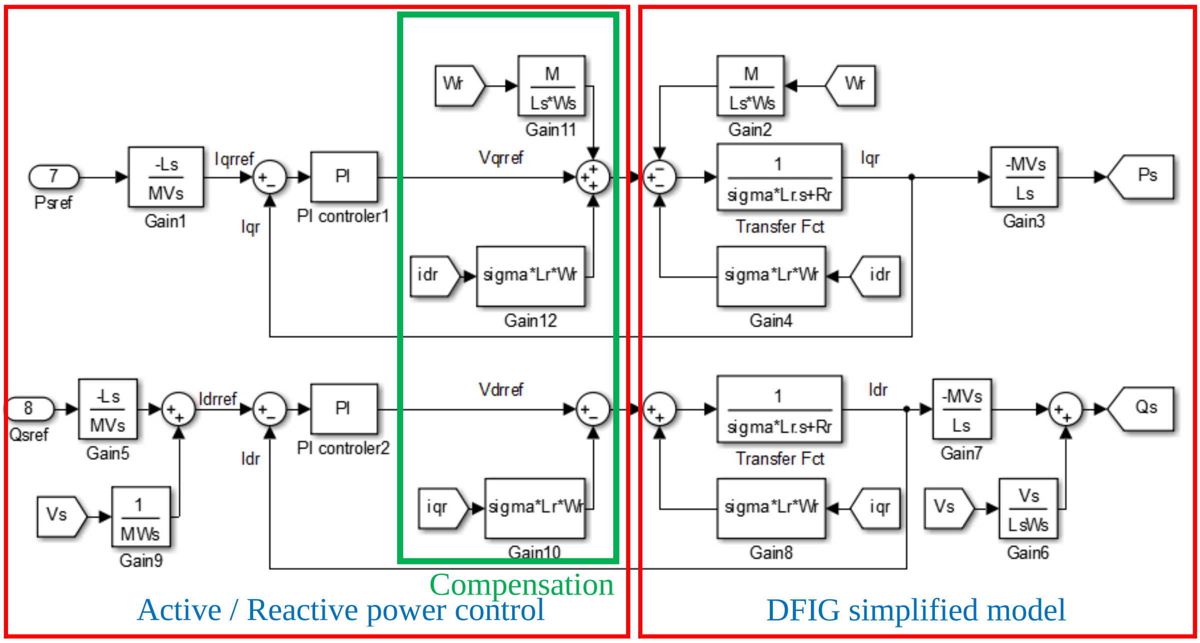


Figure 6.23. DFIG active and reactive power control diagram

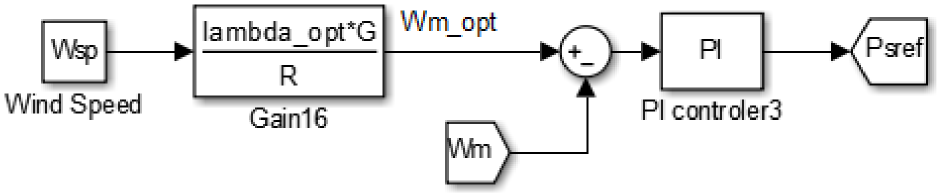


Figure 6.24. MPPT Diagram of the wind turbine generator

Figure 6.25 shows the behavior of the WTE based DFIG micro-plant model when applying a variable wind profile shown in the subplot (A). The subplot (B) shows the DFIG mechanical speed $W_m$ and its reference $W_{m.ref}$. The DFIG mechanical speed $W_m$ gradually increases and decreases to follow its reference value for maximum power extraction (see subplot (E)).

The subplot (F) shows the reactive power $Q_s$ absorbed by the DFIG for its self-magnetizing. In this scenario we have not compensated the reactive power which explain the zero consumption of the direct current ($I_{dr} = 0$ A).

The subplot (C) shows the rotor voltages $V_{dr}$ and $V_{qr}$ of the DFIG that impose the rotor currents $I_{dr}$ and $I_{qr}$ shown in the subplot (D) to guarantee the injection of the active and reactive power into the grid. The output active power $P_s$ of the DFIG follows perfectly its reference value $P_{s.ref}$ calculated by the speed control loop. The sign negative “-” means generated power. It must be noted that in these simulations we have not taken the effect of the PWM control signals which generate more noises in the DFIG variables.

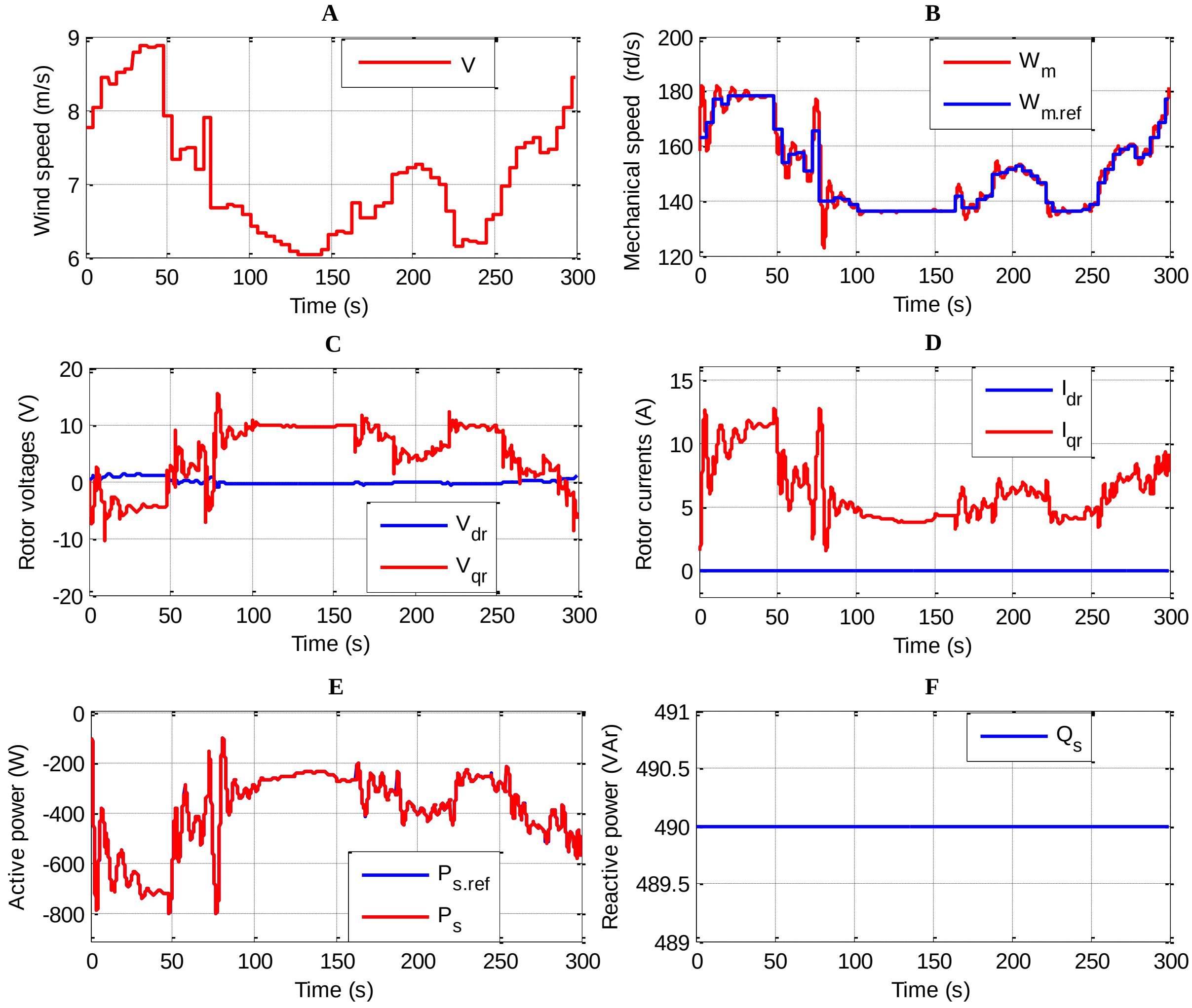


Figure 6.25. The different electrical and mechanical variables of the wind based DFIG micro-plant model

Figure 6.26 shows the different mechanical variables of the wind turbine emulator. The pitch angle $\beta$ of the turbine blades is maintained at its optimal value during this simulation to extract the maximum available power ($beta_{trb}$ = 2º). The power coefficient $C_p$ varies between 0.39 and 0.44. This coefficient represents the ratio between the mechanical power extracted by the wind turbine and the available power in the wind stream. According to the Betz's law, a wind turbine can only extract a maximum of 59.3% ($C_{p.max}$ = 0.593) from the kinetic wind energy that flows to the wind turbine (Jamdade et al., 2013).

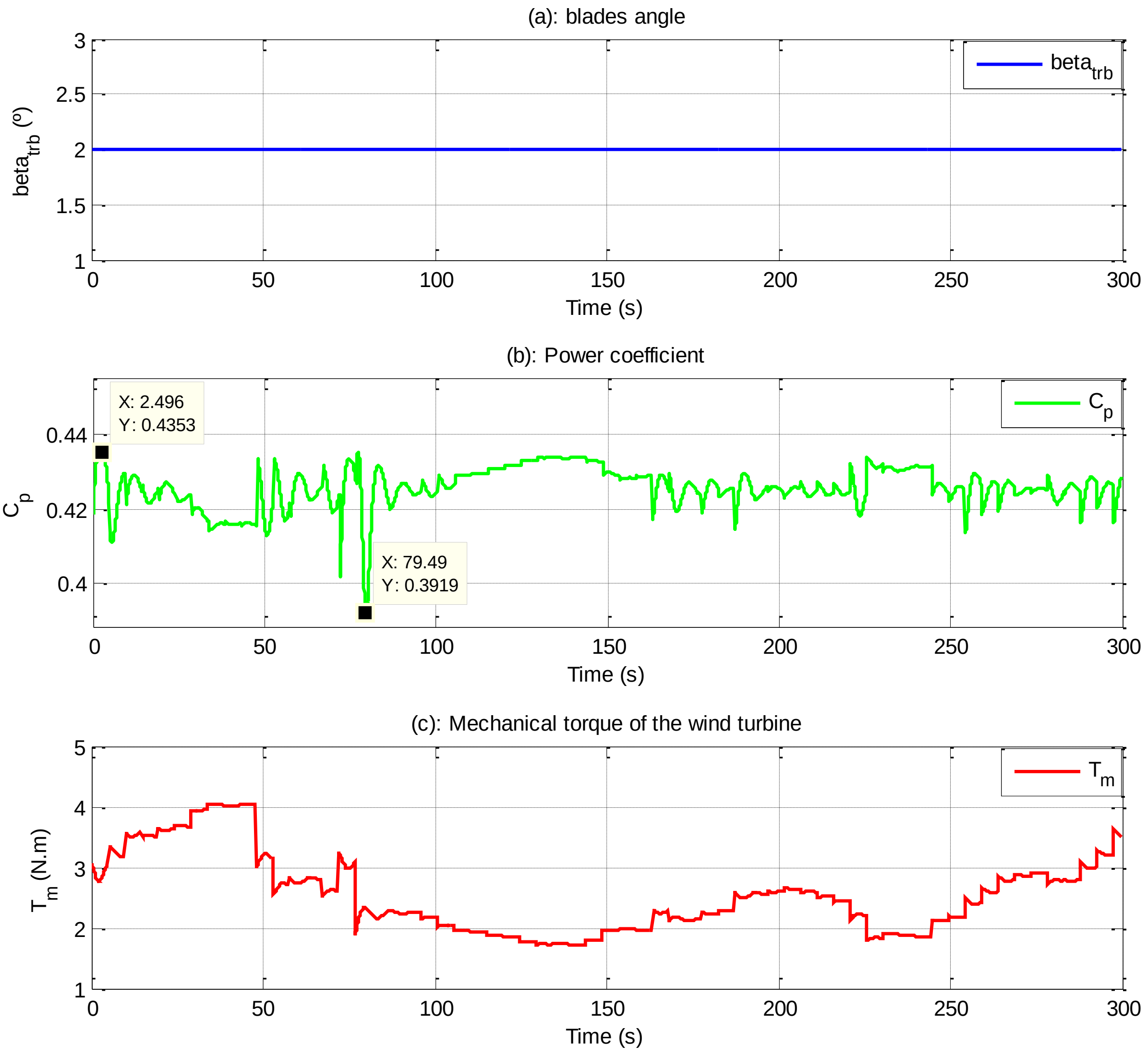


*Figure 6.26 Mechanical variables of the WTE.*

In general, the mechanical power $P_m$ available on the shaft of the wind turbine can be calculated as follow (Gaillard, 2010):

*Eq. 6.1:*
$$P_m = \frac{1}{2}\rho\pi C_p(\lambda,\beta)R^2V^3$$

Where $C_p\ (\beta, \lambda)$ is the power coefficient in function of the relative speed ratio $\lambda$ of the turbine and the pitch angle $\beta$ of the blades, $R$ is the blades radius, and $V$ is the wind speed. The relative speed ratio $\lambda$ can be written as (El Aimani, 2015):

*Eq. 6.2:*
$$\lambda = \frac{R\Omega_{trb}}{V}$$

Where $\Omega_{trb}$ is the rotational speed of the wind turbine rotor. The power coefficient $C_p$ is expressed as a function of the relative speed ratio λ and of the pitch angle β as follows (Loucif, 2016):

*Eq. 6.3:*
$$C_p = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-21/\lambda_i} + 0.0068\lambda$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$$

To produce an exact quantity of energy and maintain a constant power supply, less than the MPPT available power $P_{s.avai}$, even with a variable weather conditions (variable wind speed), we have used a pitch regulation strategy to control the blades angle of the wind micro-plant. We have used a PI controller to regulate the pitch angle $\beta$ in a way that the power coefficient $C_p$ $(\beta, \lambda)$ is modified to achieve and maintain the $P_{sref}$ even with a variable wind speed.

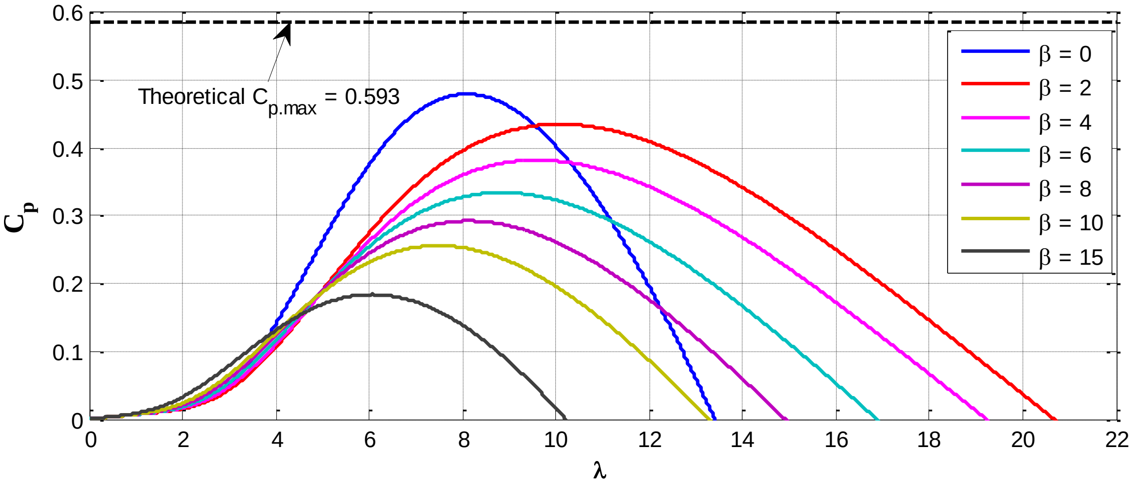


*Figure 6.27 The variation of the power coefficient $C_p$ in function of the pitch angle $\beta$ and relative speed ratio $\lambda$.*

Figure 6.27 shows the variation of the power coefficient $C_p$ in function of the pitch angle β and relative speed ratio λ. According to this figure, for a constant relative speed ratio, the power coefficient decreases when the pitch angle increases. Thus, for regulating the output power of a wind turbine and maintain the rotor rotational speed within its limits, it is sufficient to regulate its pitch angle to extract less power from the total available mechanical power in the wind turbine rotor.

To show the ability of our developed model of the wind micro-plant based DFIG for maintaining a constant power production even with a variable wind speed, we have applied a $P_{s.ref}$ from -1000W to -133W at t = 150s as shown in Figure 6.28. Before t = 150s, the wind MP is operating in the MPPT mode because the power output could not reach the reference value. The PI controller is maintaining the pitch angle $\beta$ at its optimum value ($beta_{opt} = 2^{o}$) to produce the maximum power available in the wind turbine. Thus, the power coefficient $C_p$ reaches its maximum value around 0.43. Just for a comparison, the highest $C_p$ values for modern large-scale wind turbines is around 0.45 and 0.5 (Jamdade et al., 2013).

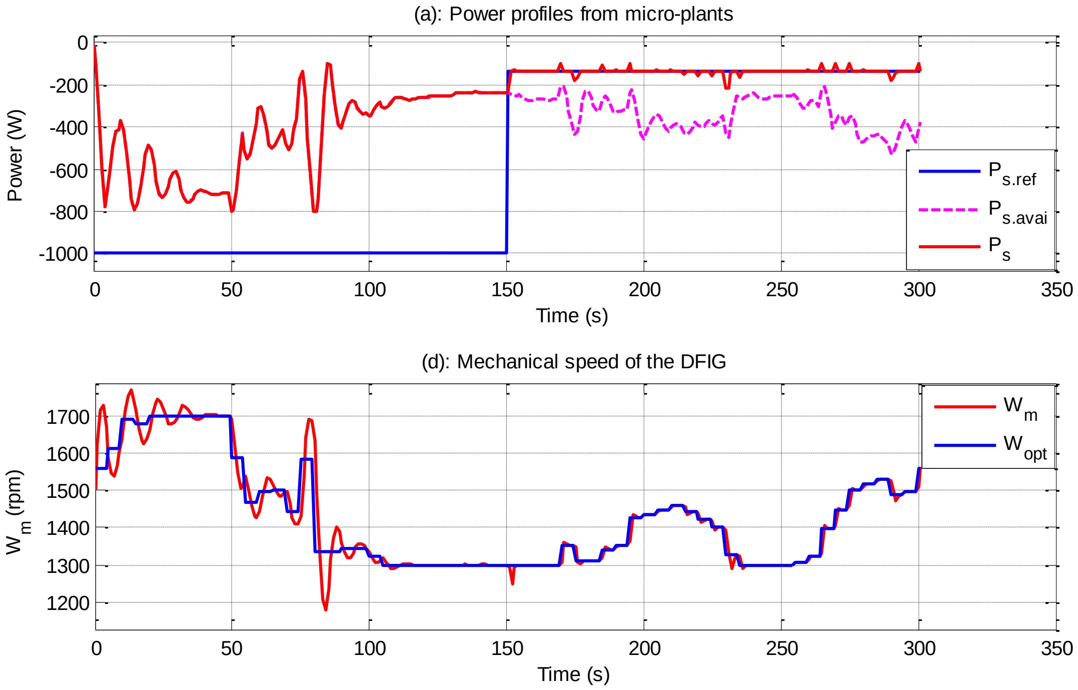


*Figure 6.28 Control of the power production of the WTE based DFIG for a variable wind profile.*

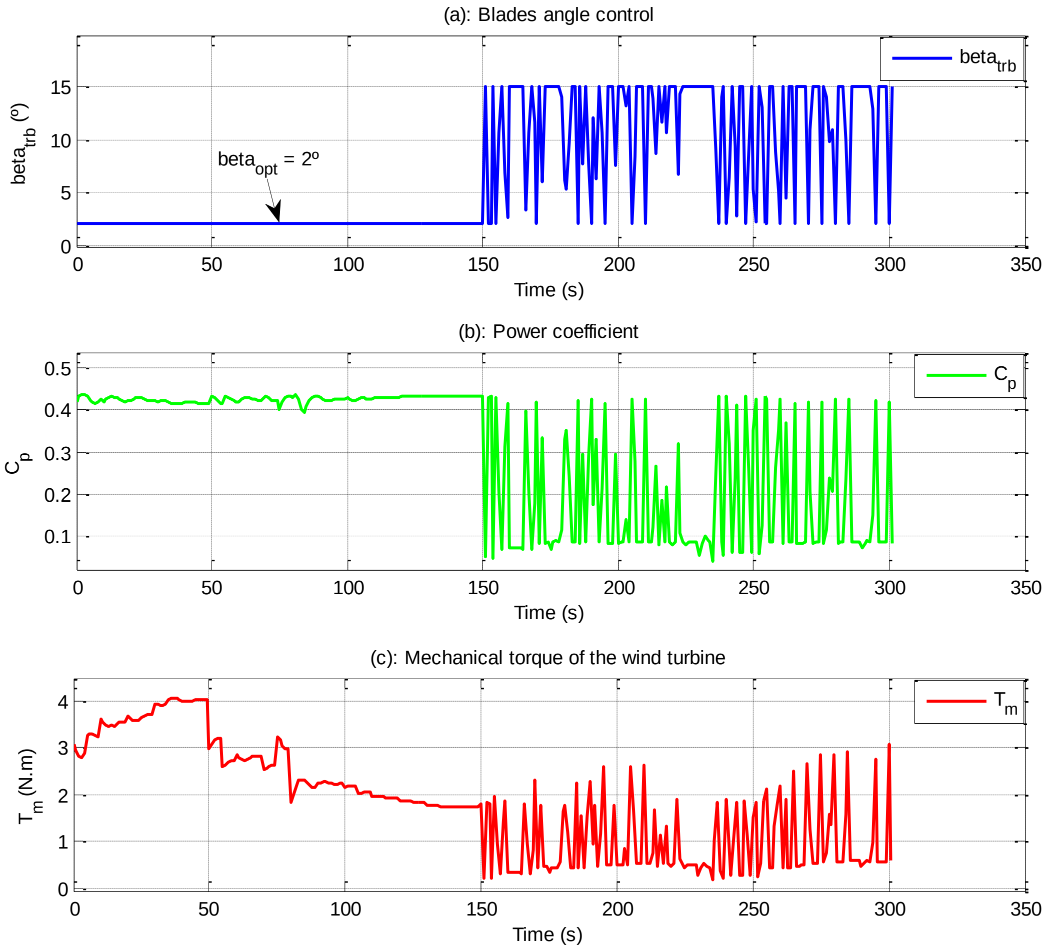


*Figure 6.29 wind micro-plant mechanical variables*

After t = 150s, the power reference $P_{s.ref}$ is less than the available power $P_{s.avai}$. Thus, the PI controller regulates the pitch angle $beta_{trb}$ (i.e. $\beta$) as shown in Figure 6.29, which lead to a regulation of the power coefficient and consequently the mechanical torque of the turbine is regulated in a way that the wind MP follows and maintains its power reference $P_{s.ref}$ perfectly even with a variable wind speed.

### 6.3.2 Photovoltaic micro-plant model

A PV panel is modelled as a current source in parallel to a diode and a parallel resistance $R_p$. All are in series with a resistance $R_s$. The output current $I_{pv}$ of a PV panel is calculated as fallow (Çelik and Meral, 2019; Dekali et al., 2019):

*Eq. 6.4:*

$$I_{pv} = I_{ph} - I_o\left(\frac{e^{q(V+I_{pv}Rs)}}{akT} - 1\right) - \frac{V+I_{pv}R_s}{R_p}$$

Where $I_{ph}$ is the photon current, $I_o$ is the Diode saturation current, $q$ is the electron's charge, $V$ is the PV voltage, $T$ is the temperature, $k$ is the constant of Boltzmann and $a$ is the quality factor.

For a specific temperature and irradiance, the generated power of a PV panel varies in function of the voltage as shown in Figure 6.30. To extract the maximum power available, an MPPT algorithm searches the appropriate voltage that fulfils the equation $dP_{PV} / dV = 0$. Where $P_{PV}$ is the photovoltaic generated power.

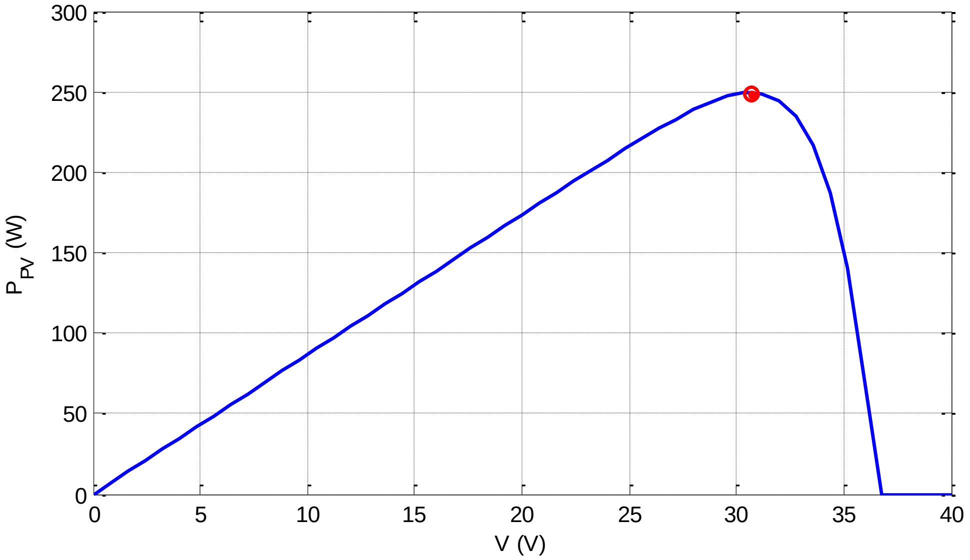


Figure 6.30. The variation of the PV power in function of the voltage

Figure 6.31 shows the maximum active power (blue curve) extracted from the PV micro-plant model when applying irradiance profile shown by the green curve. In this simulation, the temperature supposed constant at 25°C. Figure 6.32 shows the corresponding DC voltage and DC current of the PV-GTI.

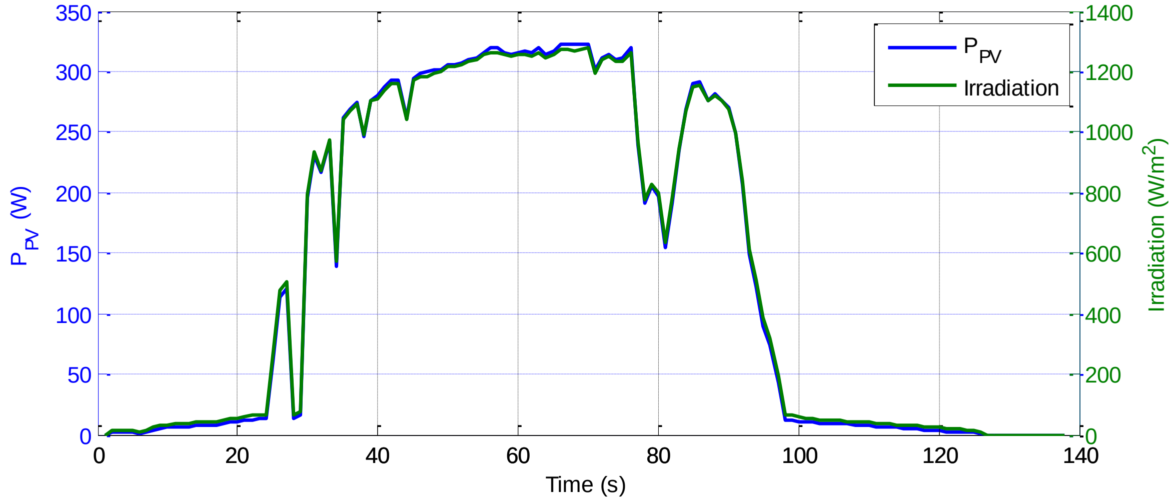


Figure 6.31. Simulated solar power

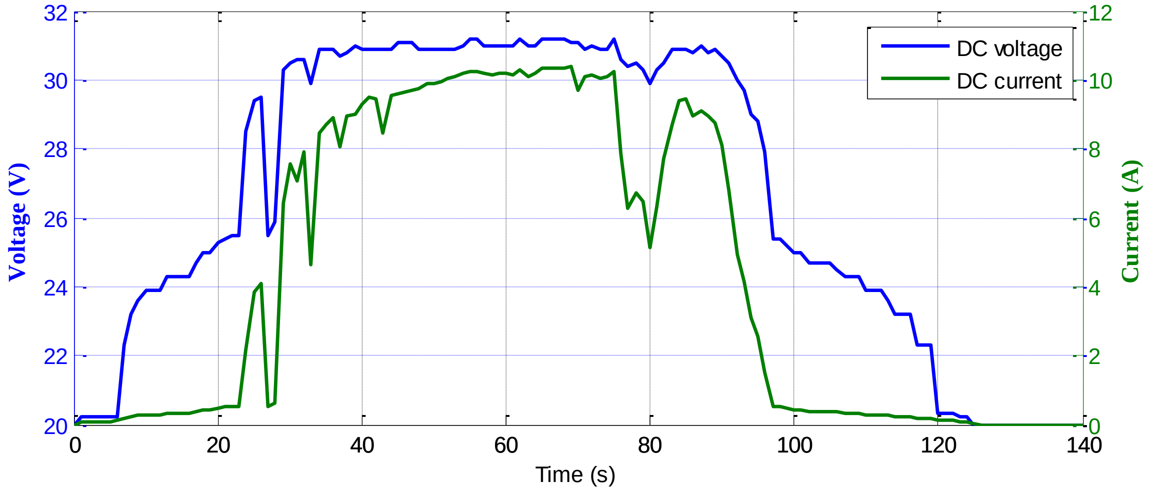


*Figure 6.32 DC voltage and DC current of the PV-GTI*

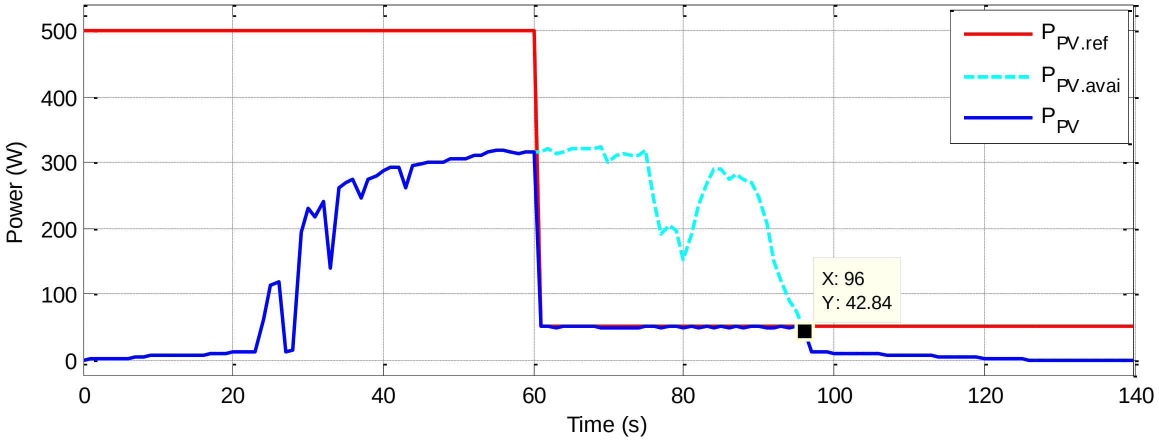


*Figure 6.33 PV micro-plant output power*

To produce a precise amount of power from the PV micro-plant and maintain a constant power supply, less than the MPPT available power $P_{PV.avai}$, even with a variable weather conditions (variable solar irradiance), we have implemented another algorithm besides the MPPT algorithm that searches for the appropriate PV-GTI DC voltage to follow and maintain the reference power value $P_{PV.ref}$. Figure 6.33 shows the output power of the PV-GTI when applying a $P_{PV.ref}$ from 500 W to 50W at t = 60s. Before t = 60s, the PV micro-plant is operating in the MPPT mode because the power output could not reach the reference value. After t = 60s, the power reference $P_{PV.ref}$ is less than the available power $P_{PV.avai}$. Thus, the DC voltage (see Figure 6.34) is reduced and regulated in a way that the power output follows its reference perfectly. After t = 96s, the PV micro-plant is no more following the power reference because the maximum power available is less than the reference value. Thus, the PV micro-plant entered automatically in the MPPT mode.

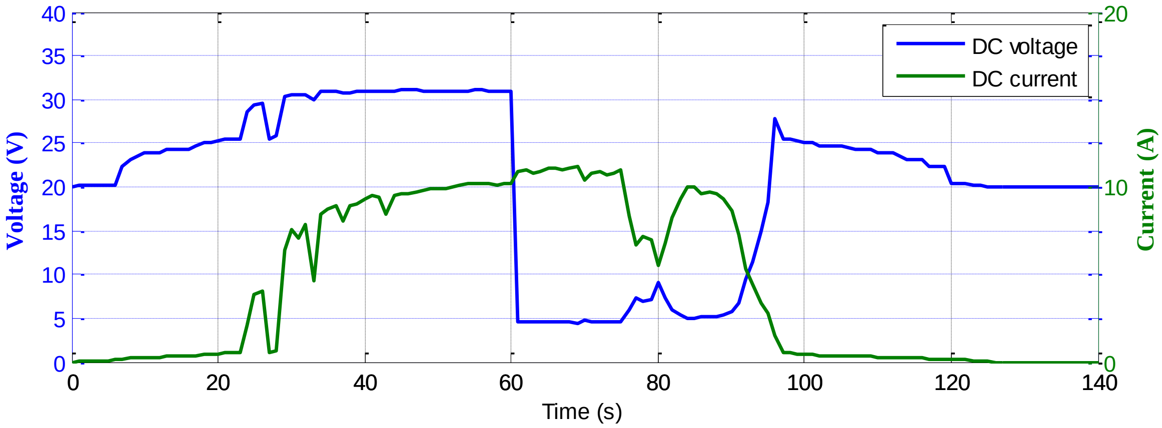


*Figure 6.34 DC voltage and DC current of the PV-GTI*

### 6.3.3 The power grid model

For this step, we emulate the high-voltage utility grid by a 5-buses power grid (Baghli et al., 2010) (Figure 6.35) running in real time on the RPi3. It contains two Generator buses (nodes). SOUTH is a PV bus and NORTH is the Slack bus. There are three consumption nodes (ELM, LAKE, and MAIN). To compute the power flow through the grid and the voltage at all the buses, we implemented the Load Flow (LF) program (see *Figure 6.36*) of a Lab developed program (Baghli et al., 2010) on the RPi3. In addition, the Transient Stability (TS) program (see Figure 6.37) is also implemented and adapted to the RPi3. Moreover, we implemented two power system stabilizers (PSS) to ensure the stability of the system. The first one is an Automatic Voltage Regulator (AVR) to stabilize the magnitude of the voltage and the second one is the speed governor to stabilize the speed of the power plant SG.

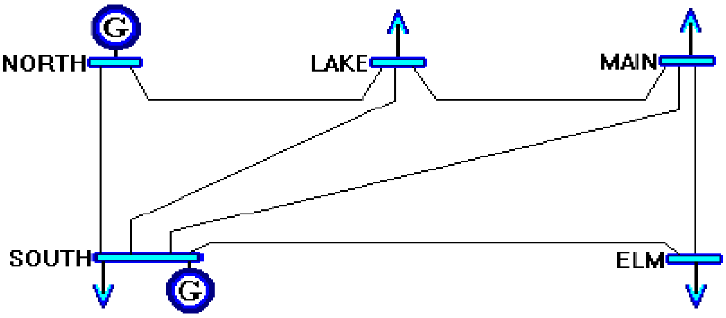


Figure 6.35. 5-buses power system *(Baghli et al., 2010)*

The mathematical equations and the power system modelling for LF and TS studies are found in (Baghli et al., 2010). The Runge–Kutta 4 and Gauss-Seidel are the numerical methods implemented for the iterative calculations of TS and LF respectively. The system of equations to be solved for TS studies to express the dynamic behavior of a SG is (Baghli et al., 2010):

*Eq. 6.5:*

$$\begin{cases} \frac{d\delta}{dt} = \omega - \omega_s \\ \frac{d^2\delta}{dt^2} = \frac{\omega_s}{2\,H}\left(P_m - \; P_e - D\,\frac{d\delta}{dt}\right) \end{cases}$$

Where $\delta$ is the internal angel, $\omega$ is the rotor speed, $\omega_s$ is the synchronous speed, $P_m$ is the mechanical power of the turbine, $P_e$ is the electrical power, $H$ is the inertia moment, and $D$ is the damping for each generator.

The Gauss-Seidal method is easy to implant and is suitable for small-sized networks. For bigger networks, the convergence is attainable after a large number of iterations. The load flow algorithm is iterated until the voltage difference, at each bus, between two successive iterations, falls under a fixed tolerance. The current injected through the $i^{th}$ bus to the network equals

*Eq. 6.6:*

$$I_i = \sum_{k=1}^{N} I_{ik} = \sum_{k=1}^{N} Y_{ik}V_k = Y_{ii}V_i + \sum_{\substack{k=1 \\ k\neq i}}^{N} Y_{ik}V_k$$

Where $Y_{ii}$ represents the admittance at the node $i$ and $Y_{ik}$ represents the admittance between this node and another one. The Y matrix is constituted from all these elements. It is built thanks to the power system elements, prior to power flow calculation. The power at a node is expressed as:

*Eq. 6.7:*

$$S_i = P_i + jQ_i = V_i I_i^*$$

*Eq. 6.8:*

$$I_i = \frac{P_i - jQ_i}{V_i^*} = \sum_{k=1}^{N} Y_{ik}V_k = Y_{ii}V_i + \sum_{\substack{k=1 \\ k\neq i}}^{N} Y_{ik}V_k$$

*Eq. 6.9:*

$$V_i = \underbrace{\frac{P_i - jQ_i}{Y_{ii}}}_{KL_i}\frac{1}{V_i^*} - \sum_{\substack{k=1 \\ k\neq i}}^{N} \underbrace{\frac{Y_{ik}}{Y_{ii}}}_{YL_{ik}} V_k$$

To compute $V_i^{m+1}$, the voltage, at the bus numbered $i$, at iteration $m$+1, we use voltages computed at previous iterations $V_i^{m}$:

*Eq. 6.10:*

$$V_i^{m+1} = KL_i\,\frac{1}{V_i^{*m}} - \sum_{\substack{k=1 \\ k\neq i}}^{N} YL_{ik}V_k^{m}$$

In the algorithm, we use *Vc1* for the new vector $V^{m+1}$ and *Vc* for the vector $V^m$ of the previous iteration.

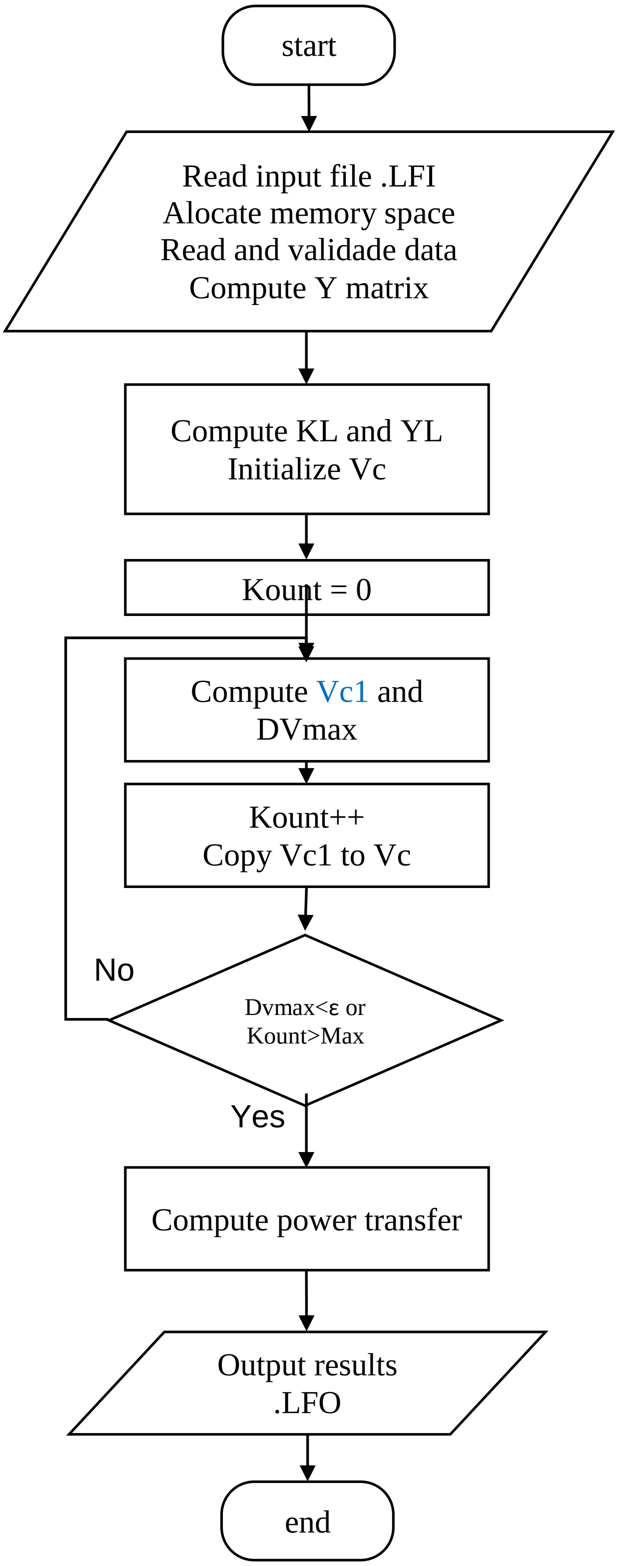


*Figure 6.36 GS Load flow algorithm*

A slightly modified version allows the use of the recently computed voltages at iteration *m*+1; those below the *i* th node to evaluate the voltage of bus *i*.

*Eq. 6.11:*

$$V_i^{m+1} = KL_i \frac{1}{V_i^{*m}} - \sum_{k=1}^{i-1} YL_{ik} V_k^{m+1} - \sum_{k=i+1}^{N} YL_{ik} V_k^{m}$$

This is the Gauss-Seidel algorithm for Load flow. These equations are suitable for PQ buses. For PV buses, the algorithm is adapted, because the voltage magnitude is kept constant to its nominal value and the active power is also fixed, the phase is free to change. The active power produced is fixed to the one of the generator connected to that bus. Only the phase of the voltage vector at a PV bus changes. If the reactive power produced by the generator connected to a PV bus reaches its limit, then the PV bus becomes a PQ bus with a fixed power and with a voltage vector free to change in magnitude and phase (Baghli, 2022, 1994).

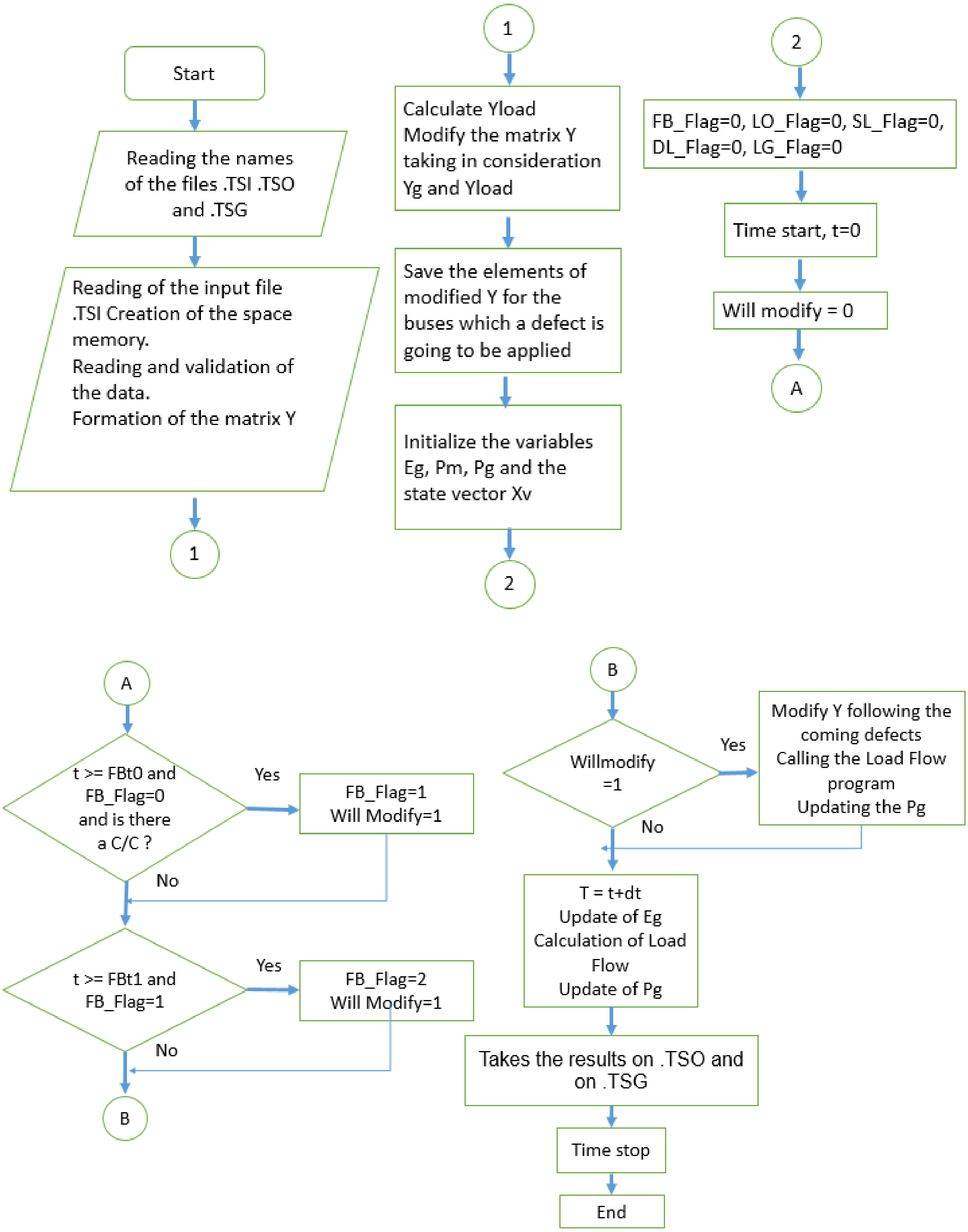


*Figure 6.37 Transient stability algorithm (Terfa et al., 2018)*

The characteristics of the two SG are presented in Table 6.5**.** The TS and LF calculations are performed every 1ms to get the new values of the generated power, bus voltage, speed and internal angles of both SG. The AVR is called every 2 ms whereas the speed governor loop is performed every 10 ms. Table 6.6 shows the initial data for TS calculations. They are obtained from a previous LF simulation, in steady state conditions, before starting the TS simulation.

*Table 6.5 Generators transient characteristics*

| Generators | $H$ (pu) | $D$ (pu) | $R$ (pu) | $X_d$ (pu) | $P_{m.max}$ (pu) | $E_{g.max}$ (pu) |
|---|---|---|---|---|---|---|
| NORTH | 50.0000 | 0.0600 | 0.0000 | 0.2500 | 2.0000 | 2.0000 |
| SOUTH | 01.0000 | 0.1500 | 0.0000 | 1.5000 | 1.0000 | 1.6000 |

Where $H$ represents the inertia moment, $D$ is the damping, $R$ is the resistance, $X_d$ is the transient reactance, $P_{m.max}$ is the maximum mechanical power and $E_{g.max}$ is the maximum electromotive force (e.m.f) of the generators.

*Table 6.6 The initial data for LF and TS programs*

| Bus | $P_g$ (pu) | $P_L$ (pu) | $V_b$ (pu) |
|---|---|---|---|
| NORTH | 1.2957 | 0.0000 | 1.0600 |
| SOUTH | 0.4000 | 0.2000 | 1.0474 |
| LAKE | 0.0000 | 0.4500 | 1.0000 |
| MAIN | 0.0000 | 0.4000 | 1.0000 |
| ELM | 0.0000 | 0.6000 | 1.0000 |
| Total production | 1.6957 | - | - |
| Total consumption | - | 1.6500 | - |
| Total line losses | 0.0457 | - | - |

Where $P_g$ is the generated power, $P_L$ is the consumed power (load) and $V_b$ is the bus voltage.

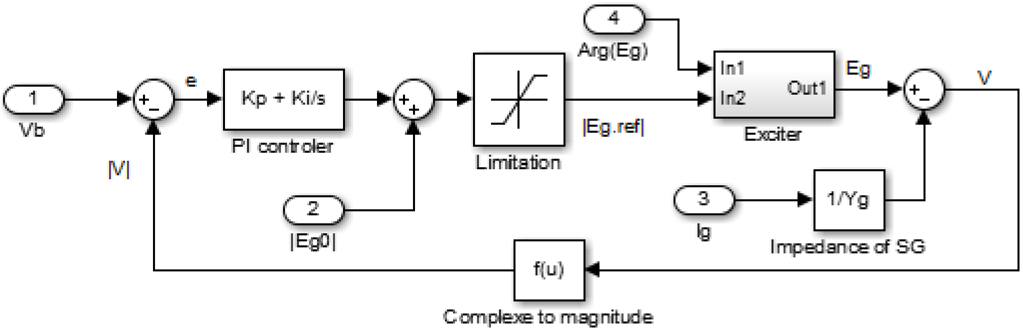


Figure 6.38. AVR loop for both generators (Terfa et al., 2020)

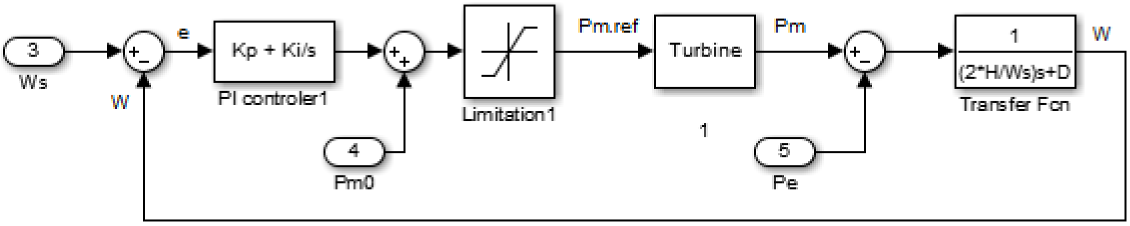


Figure 6.39. Speed Governor loop for both generators (Terfa et al., 2020)

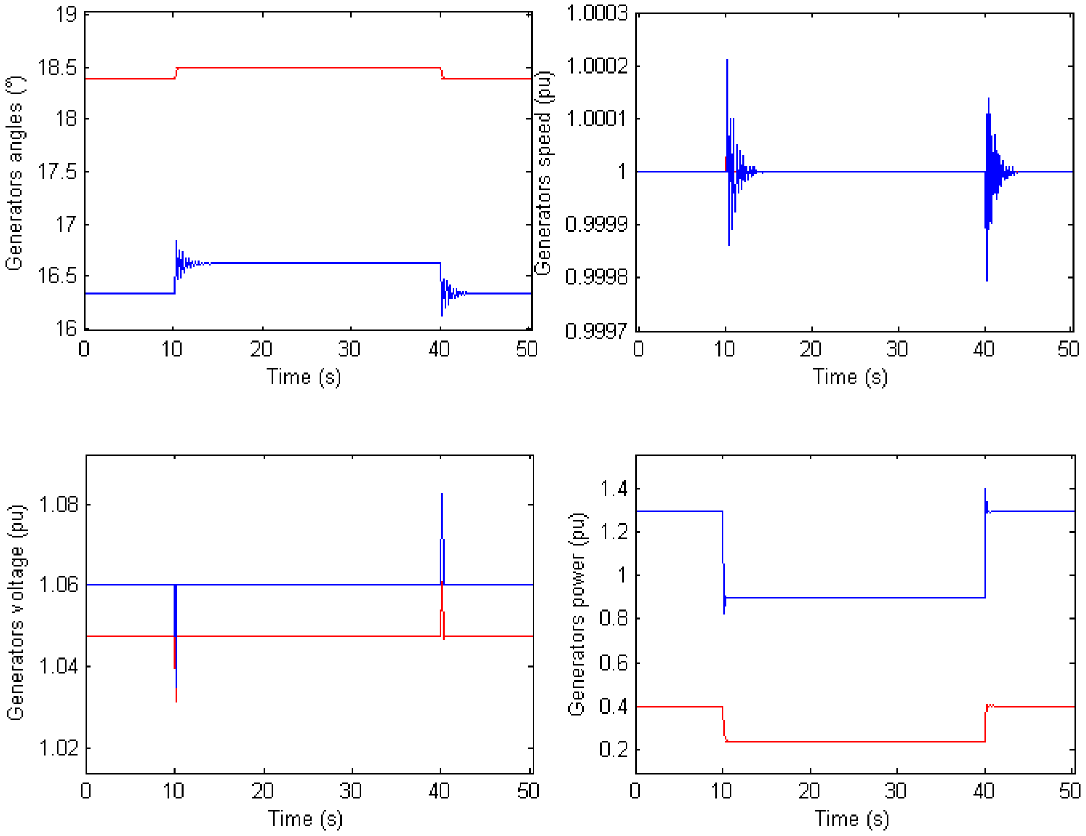


*Figure 6.40 The electrical and mechanical variables of the 5-bus power grid model during load drop event.*

Figure 6.38 and Figure 6.39 show the AVR and the speed governor loops respectively; Where $E_{g0}$ and $P_{m0}$ are the nominal values of e.m.f and mechanical power respectively. $E_{g.ref}$ and $P_{m.ref}$ are the reference values for the e.m.f and the mechanical power respectively. $E_g$, $I_g$, $V$ and $Y_g$ are the e.m.f, current, voltage and admittance of the SG respectively. $K_p$ and $K_i$ are the proportional and integral coefficients of the AVR or the speed governor.

For testing the behavior of the power grid model and the proper operation of the implemented PSSs, we have applied a dropped in load of 0.5 pu in the ELM bus at t=10s. The load return to its initial value after 30s. Figure 6.40 shows the different electrical and mechanical variables of the 5-bus power grid model during this scenario. The NORTH generator curves are represented by the blue color and the SOUTH ones are represented by the red color. It is clear that the disturbances caused by the dropped in load in the ELM bus affects the operation of the SOUTH generator as well as propagate through the whole grid to affect the operation of the NORTH generator also. The generated powers of both generators decrease automatically which lead to an increase on their speeds. The AVR and the speed governor, regulate the voltages and the speeds of the generators during any disturbances in the grid.

## 6.4 Part 3: Power grids' stability in the presence of distributed renewable-energy microplants

### 6.4.1 Introduction

The United Nations estimates that the current population of Africa is more than 1.32 billion with more than 56 % of people living in non-urban areas ("Population of Africa (2020) - Worldometer," 2020). Although Africa is rich by renewable and non-renewable energy sources (A Photovoltaic panel produces twice energy in Africa than it will produce in Central Europe on average), the generation of electricity is not yet satisfied (Ouedraogo, 2017; Szabó et al., 2011); making a mismatch between the generation and the consumption, which lead to a low power service and many blackouts and outages (Cole et al., 2018). This affects directly the economic growth of African countries (Ouedraogo, 2013a, 2013b). The conventional solution of extending the power grid face many constraints, among them; distributed population, difficult terrains, long distances between the utility grid and the loads and the expensive cost (Li et al., 2020). However, with the development of renewable energy technologies, and with the increase of fuel prices (Farmad and Biglar, 2012; Montuori et al., 2014; Park and Hur, 2018), the integration of distributed renewable energy micro-plants is more favorable to enforce the weakness of the power grids in Africa.

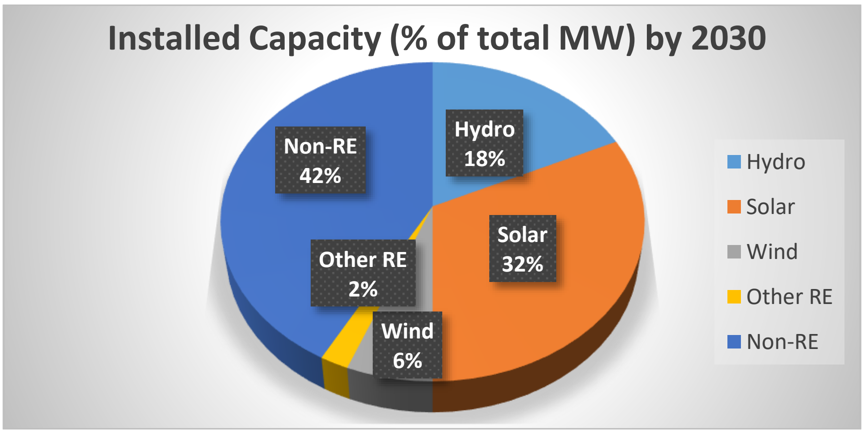


Figure 6.41. The renewable energy transition in Africa, a view towards 2030

Many countries on Africa continent are enabling high investments in solar and wind energies. Figure 6.41 shows the Law-Carbon scenario based on African Development Bank (AfDB) a New Deal on Energy for Africa policy document, Balmorel model ("Roadmap to the New Deal on Energy for Africa: An analysis of optimal expansion and investment requirements," 2018). This model shows the power sector expansion of the 54 African countries by 2030. It is a dynamic approach for the integration of renewable energies. It includes real data for wind and irradiance to match the supply with the demand through the day. It is shown that the installed capacity from renewable energies in Africa will exceed 50% of the total production by 2030. For example, Algeria, the biggest country in Africa, has launched an ambitious program (the Algerian Renewable Energy Development and Energy Efficiency Program-PENREE), in 2011, which consist of installing up to 22000 MW of power generating capacity from renewable energy sources by 2030 (Services of the Algerian Prime Minister, 2022). With the introduction of the feed-in tariffs scheme in 2014, there has been an increase in the installed capacity (Bouznit et al., 2020). Despite the importance given to this program, it did not achieve its objectives. The initial goal of 40% of electricity production from renewable sources by 2030 was revised downwards, in 2015, to 27%. Algeria aims to achieve this objective within the set deadlines (Services of the Algerian Prime Minister, 2022). Since 2015, when Algeria's energy program was updated, there has been the greatest increase in installed capacity. In addition, it coincides with the launch of the renewable energy fund (Bouznit et al., 2020). In order to accelerate the development of renewable energies, a High Commission for Renewable Energies, attached to the Algerian Prime Ministry, and a Ministry for Energy Transition and Renewable Energies were created in 2019 and 2020 respectively. The roadmap of this new ministry plans to achieve a rate of integration in electricity production of 30% by 2030, starting with the implementation of 1,000 MW of renewable electricity (Services of the Algerian Prime Minister, 2022). Figure 6.42 shows the evolution of installed RE capacity and measures adopted by the "Algerian Ministry of Energy and Mines" to promote renewable energies in the electricity sector (Bouznit et al., 2020). 37% of installed capacity by 2030 and 27% of electricity production for national consumption will be of renewable origin (The Algerian Ministry of Energy and Mines, 2019). These important capacities open the doors to study the impact of installing many renewable energy MP and power plants, and to analyze their mutual interaction not only in islanded mode, but also in grid-connected mode.

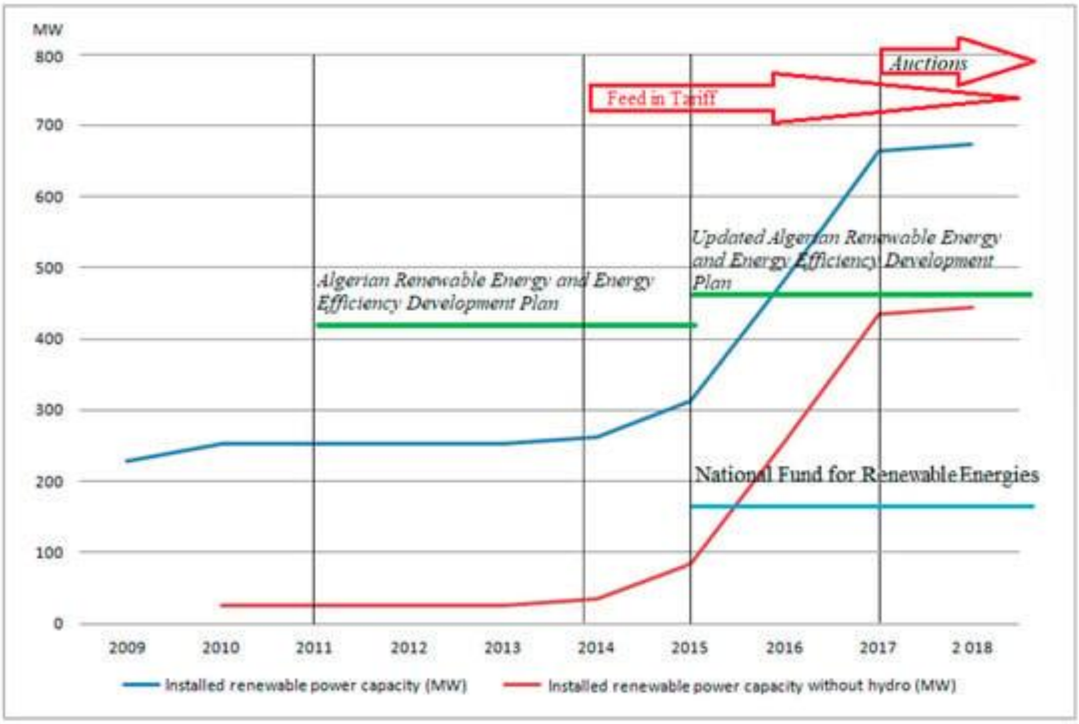


Figure 6.42. Evolution of installed RE capacity and measures adopted by the "Algerian Ministry of Energy and Mines" to promote renewable energies in the electricity sector.

Distributed renewable energy MP give a clean energy and help to reduce the green houses emissions (Ćosić et al., 2012). Nevertheless, as we cannot store as much energy as we want in the batteries, the integration of distributed renewable energy MP brings new challenges for the stability of the power grid and for the quality of service (Zhang and Huang, 2011). It is known that renewable energies have an intermittent generation that directly varies with weather conditions (clouds, sun, wind, etc.), the energy output can go from zero on a cloudy day to the maximum value spontaneously and vice versa (Figure 6.43). Certainly, when its power capacity exceeds certain percentage, the disturbances will be more important (Alves et al., 2019; Lund et al., 2012). To minimize the fast changes in the generated power and improve reliability and service, we need a new approach of power network control, making full use of communication technology. This will result in Smart Distributed Renewable Energy Micro-Plants.

The *Figure* 6.43 shows the intermittent aspect of generated power from two Photovoltaic (PV) panels (500W) in summer on a cloudy afternoon at Tlemcen, Algeria.

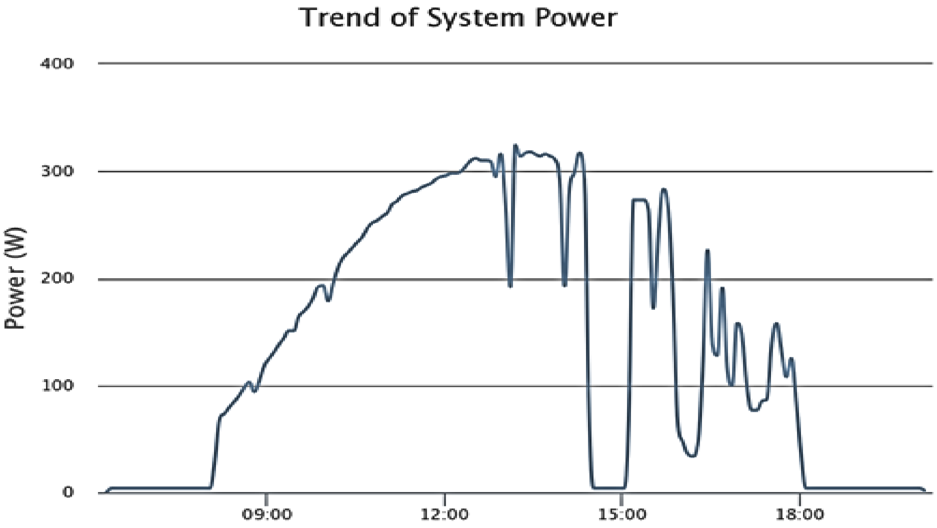


Figure 6.43. Experimental curve of PV power in the summer at Tlemcen, cloudy afternoon

### 6.4.2 Impact of distributed renewable energy micro-plants on power grids

To study the impact of integrating renewable energy MP on the stability of power grids and to analyze their mutual interaction in grid-connected mode, four cases are presented: the first is when the 5-buses power grid operates without injecting the power of the MP, the second is when we inject only the power of the PV micro-plant at ELM bus, the third is when we inject only the power of the WTE based on a DFIG at LAKE bus, and the last case is when we inject the power of both PV and WTE micro-plants in the corresponding buses. In the cases 1, 2, 3 and 4, the installed capacity from renewable energy MP is 0%, 20%, 35% and 55% of the total production respectively. In all these cases, we consider all other loads constant. In addition, the data are received in Watt, and then transformed to per-unit (pu) in order to adapt them with LF and TS calculations that are in pu. The NORTH generator curves are represented by the blue color and the SOUTH ones are represented by the red color in the following figures.

#### *6.4.2.1 Case 1*

In this case, the 5-buses power grid are operating with no power injected from the MP. The Figure 6.44 shows the variation of the electrical and mechanical quantities (Voltage, internal angle, speed and power) of both SG. The total active power production is 1.6957 pu (0.4 pu from SOUTH and 1.2957 pu from NORTH). We see that, all the electrical and mechanical quantities are constant in steady state. This is explained by the non-integration of MP and that there is no modification or faults in the power network.

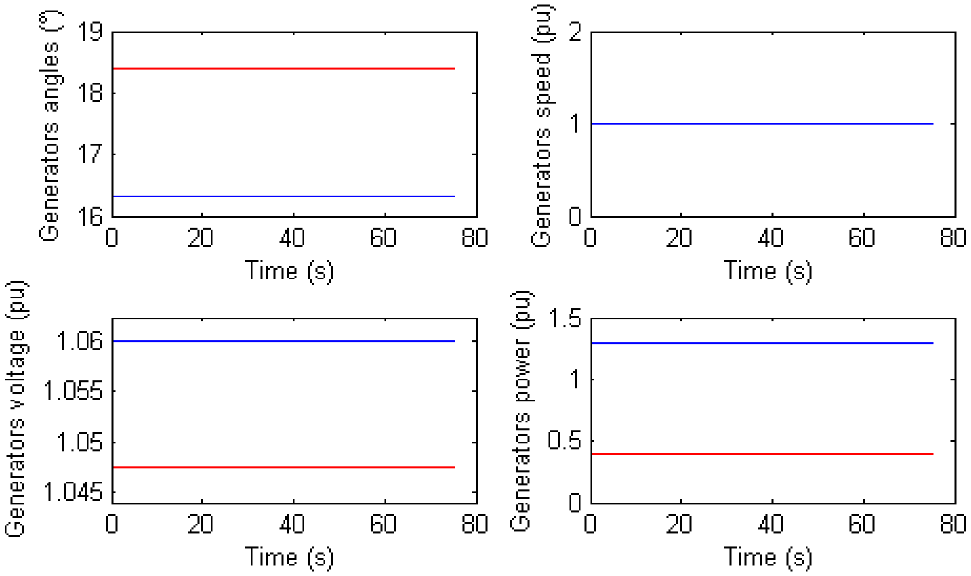


Figure 6.44. Synchronous Generators (SG) electrical and mechanical variables in p.u.

#### 6.4.2.2 Case 2

In this case, the PV MP starts injecting power in the 5-buses power grid at ELM bus after t=10s. Figure 6.45 shows the variation of the PV power. A routine is added to the TS program to read these data from a file and to inject them in the 5-buses power grid as additional negative load that varies with time (negative load values are for generated power).

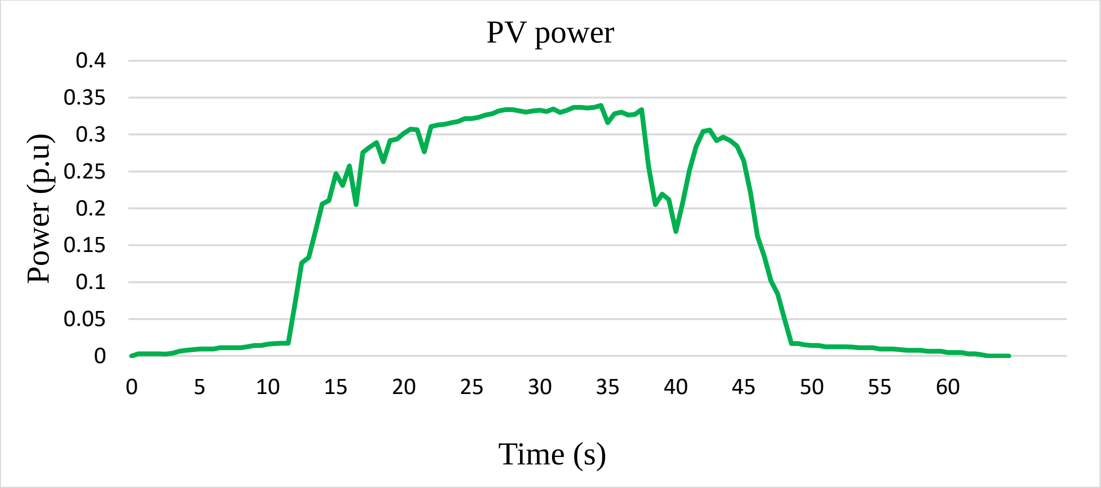


Figure 6.45. The power of the PV prototype

Figure 6.46 shows the variation of the electrical and mechanical quantities of both generators. We see that, when injecting the PV power in ELM bus, both generators will be affected due to the interconnection of the grid. A mismatch between the consumption and the production happened. Thus, both generators accelerate. Thanks to the PSS, the AVR and the speed governor that control respectively the e.m.f and the mechanical power of both SG, the generated power from the non-renewable sources is reduced. This fast acting makes the voltage and the speed come back to their nominal values spontaneously after each increase or decrease in the injected power. In addition, it makes the internal angels of both generators stay in the stability limit (δ < 90°).

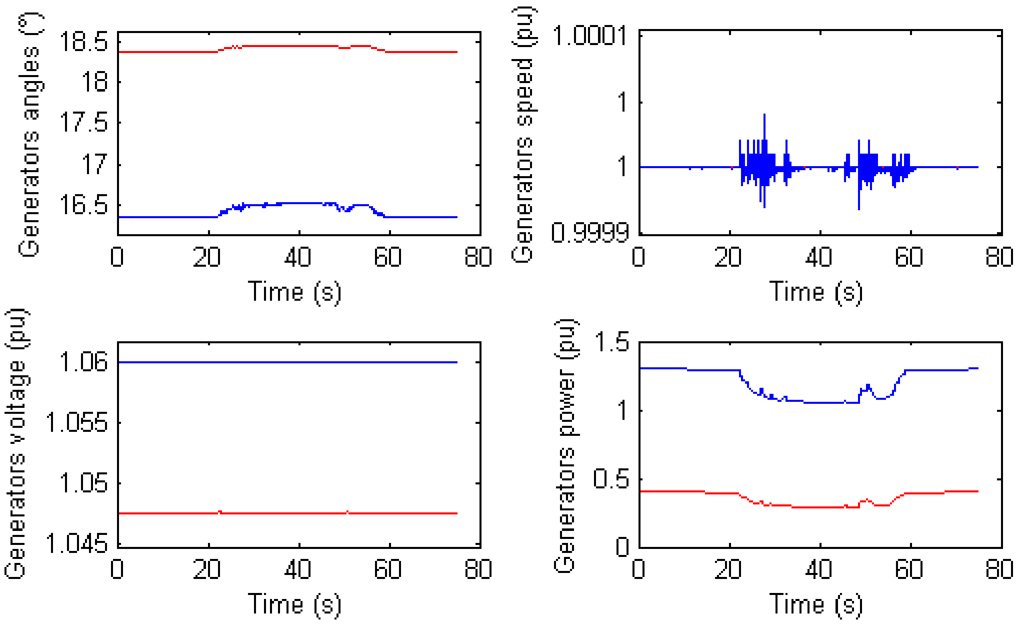


Figure 6.46. SG electrical and mechanical variables, PV power is integrated

### *6.4.2.3 Case 3*

In this case, the DFIG-based WTE microplant starts injecting its power at the LAKE bus.

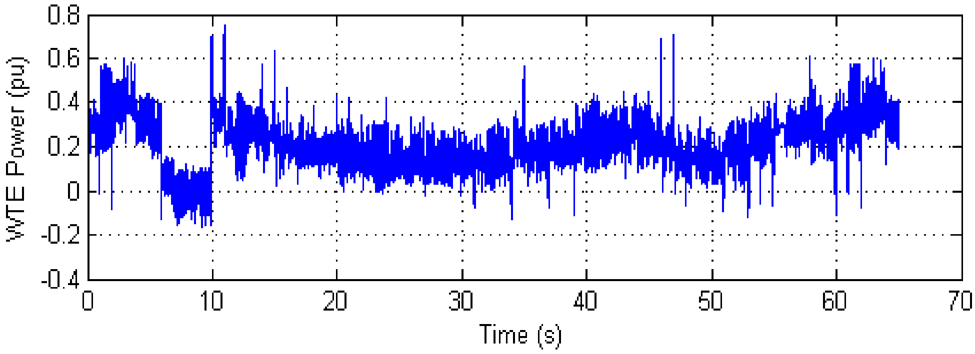


Figure 6.47. The DFIG-based WTE generated power

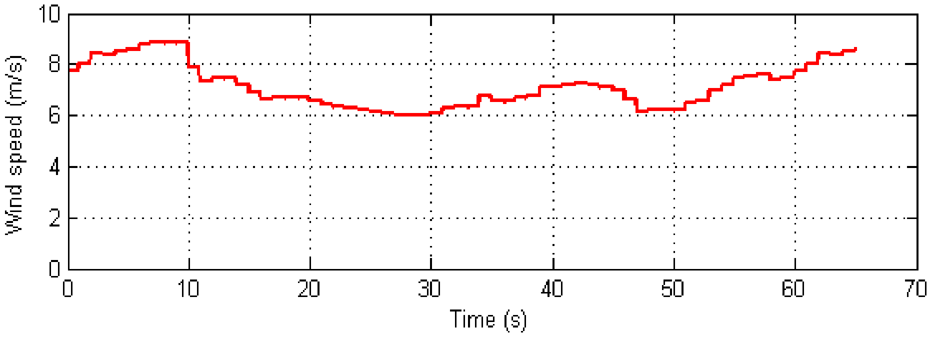


Figure 6.48. Wind profile used for WTE experiments

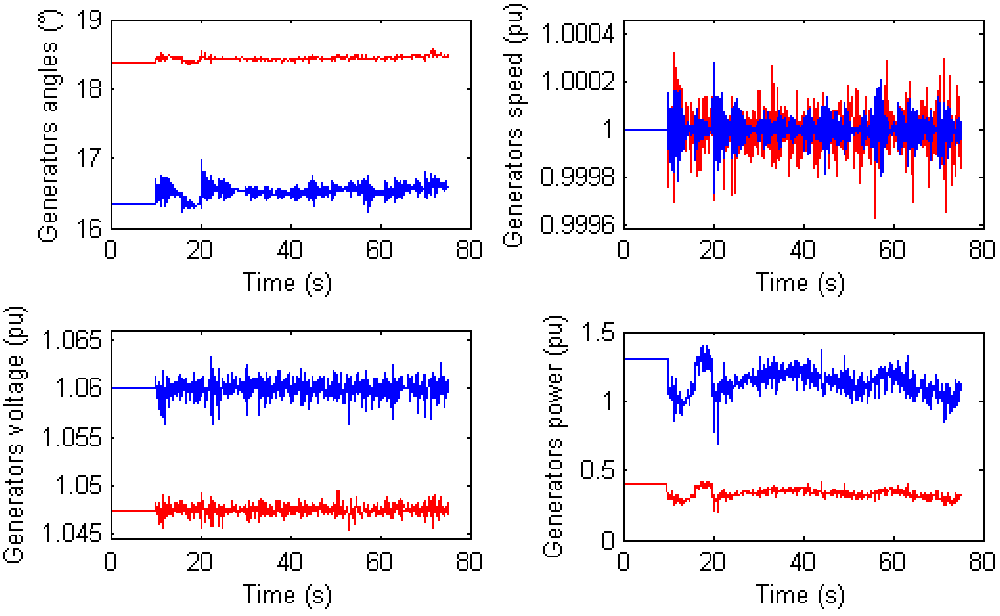


Figure 6.49. SG electrical and mechanical variables, WTE power is injected

Figure 6.47 shows the variation of the injected power in pu which is more fluctuant compared to the injected PV power. This power is obtained with certain conditions: The wind profile (Figure 6.48) should be more than 5 m/s and less than 9 m/s (Dekali et al., 2019). which is equivalent to 1300 rpm and 1800 rpm for the WTE respectively. If, due to the wind profile, the control variable (voltage of the DC motor) exceeds its limits, the driven torque is no more controlled and we stops the power generation. This is shown between 5s and 10s.

In this third case study, the mechanical and the electrical quantities are more affected by the high fluctuation of the WTE power (Figure 6.49) compared to the PV power of case 2 but, once again, the system is well controlled thanks to the PSS.

#### *6.4.2.4 Case 4*

In this last case study, the data of both PV and WTE are used for a power injection at ELM and LAKE buses respectively from t=10s. It is clear that the disturbances generated by the intermittent injected powers propagate rapidly to the grid connected affecting both generators as shown in Figure 6.50. In addition, the PSS present a fast reaction to the power mismatch making voltage and speed remaining to their nominal values for each disturbance.

Comparing case 2, 3 and 4, we conclude that, it is not the quantity of the injected power that makes important disturbances, but its variation rate. We see in case 4 that the disturbances are the same as case 3. Indeed, the generated power from the two SG is reduced much more in the case 4 compared to the case 2 and 3.

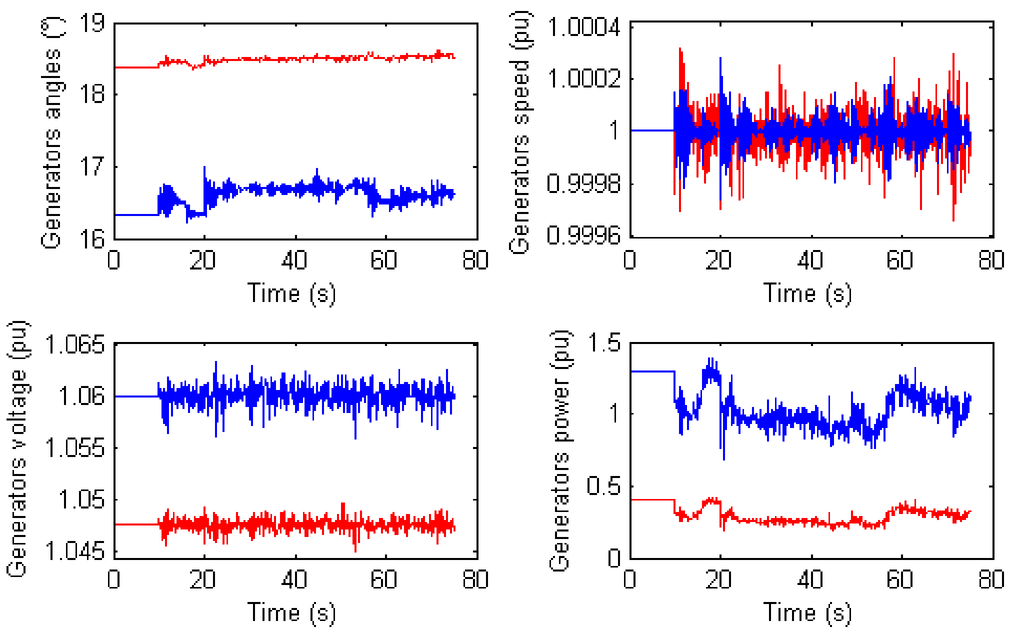
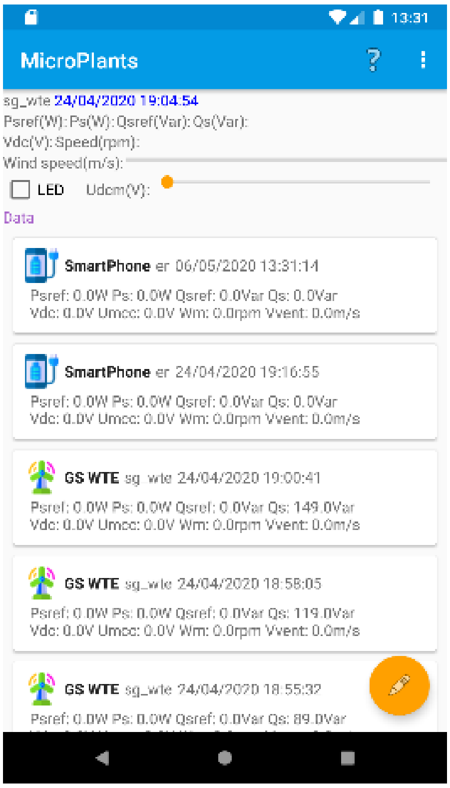


Figure 6.50. SG electrical and mechanical variables when both PV and WTE are considered

## 6.5 Part 4: Information and communication (ICT) technologies: A way to explore the potential benefit of DREMPs in smart grids

### 6.5.1 Introduction

In this part, we have developed a micro-grid based DREMPs, especially wind and PV, and a battery bank ESS to feed a small-scale communities with many consumers. Two computer-based systems have been used. The first is for emulating the DREMPs with their local controller. The second is for emulating the loads with their local controller. A decentralized control strategy has been performed to control the power production from DREMPs as well as to control the consumers' devices in both grid-connected and islanded mode. In addition, we have used a real-time control strategy instead of the conventional load/dispatch forecasting methods. The intelligent DREMPs' local controller (SSM-LC) performs the energy production management and the demand-side local controller (DSM-LC) performs the DSM. The micro-grid central controller (can be emulated by a third computer-based system) can receive all the information about the MPs and loads and send orders (power references for all the MPs, switch on/off loads, RTP …etc.) to the local controllers when operating in centralized control. However, in this thesis, we choose to perform the decentralized control instead of the centralized control.



sg_wte 24/04/2020 19:04:54
Psref(W): Ps(W): Qsref(Var): Qs(Var):
Vdc(V): Speed(rpm):
Wind speed(m/s):
☐ LED Udcm(V):

**SmartPhone** er 06/05/2020 13:31:14
Psref: 0.0W Ps: 0.0W Qsref: 0.0Var Qs: 0.0Var
Vdc: 0.0V Umcc: 0.0V Wm: 0.0rpm Vvent: 0.0m/s

**SmartPhone** er 24/04/2020 19:16:55
Psref: 0.0W Ps: 0.0W Qsref: 0.0Var Qs: 0.0Var
Vdc: 0.0V Umcc: 0.0V Wm: 0.0rpm Vvent: 0.0m/s

**GS WTE** sg_wte 24/04/2020 19:00:41
Psref: 0.0W Ps: 0.0W Qsref: 0.0Var Qs: 149.0Var
Vdc: 0.0V Umcc: 0.0V Wm: 0.0rpm Vvent: 0.0m/s

**GS WTE** sg_wte 24/04/2020 18:58:05
Psref: 0.0W Ps: 0.0W Qsref: 0.0Var Qs: 119.0Var
Vdc: 0.0V Umcc: 0.0V Wm: 0.0rpm Vvent: 0.0m/s

**GS WTE** sg_wte 24/04/2020 18:55:32
Psref: 0.0W Ps: 0.0W Qsref: 0.0Var Qs: 89.0Var

Figure 6.51. MicroPlants Android application

To ensure the data flow between the distributed systems, we have developed a Firebase Database (DB); the intelligent swarm of renewable-energy MPs can send information about their real-time power production and receive consumers' data to produce the exact quantity of power and follows the load profile or operate in MPPT mode. The demand-side local controller can send information about the real time power consumption and receive data about the real-time power production to manage its local loads such as switching on/off its connected appliances or reduce flexible loads such as cooling or heating systems and adapt the load profile to the supply profile and skip the weather limitations.

The two computer-based systems (or three in case of centralized control) are connected to the DB via a Wi-Fi WLAN of the home router. The home router is connected to the 4G LTE network. We also developed an Android application (Figure 6.51) to check for any updates in the DB and displays data; it is available on:
https://play.google.com/store/apps/details?id=com.embesystems.microplants.

### 6.5.2 Firebase Real-time Database (DB)

The Firebase Database is a cloud-hosted database provided by Google in which data are stored as JSON (JSON is a data file format written in text, widely used) and synchronized in real-time to all connected users. It is a NoSQL[1] database. It enables users to cooperate with each other without the need for servers. The connected users receive updates with the latest data in real-time within milliseconds (Figure 6.52), when we develop cross-platform apps with mobile and web SDKs (Software Development Kits).

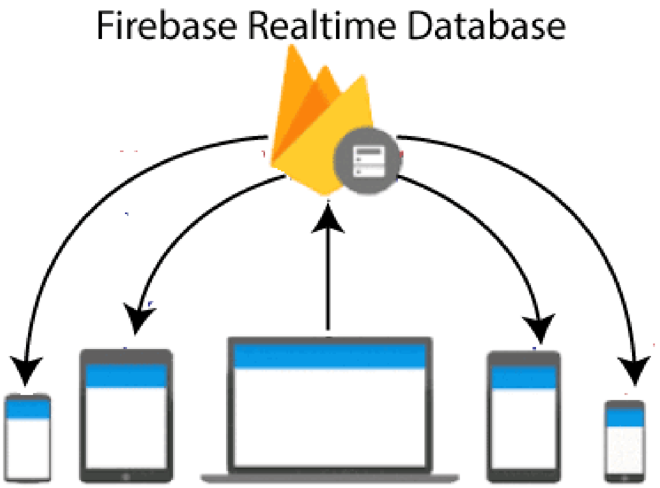


*Figure 6.52 Interactions with connected clients*

### 6.5.3 Communication interactions results

In this subsection of the thesis, we present the communication interactions results between the supply-side and demand-side local controllers. The first computer-based system emulates the smart DREMPs, which send real time data about their generated power to the DB. We suppose

---

[1] SQL means Structured Query Language. It is described as a common programming language used for managing, extracting, organizing, and manipulating data from relational databases. NoSQL means not only SQL.

that the generated power varies each 1 second. The second computer-based system which emulates the demands-side resources receives the data about the real-time generated power to perform the DSM in distributed control. In this part, we are not going to present the DSM nor the SSM, but we are going to present only the communication interactions between the various systems and highlight the communication issues such as communication delay time and failures that may occur during the communication system operation. Thus, four scenarios are presented, the first is when both SSM-LC and DSM-LC send / receive data from the DB each 10s. The second is when both SSM-LC and DSM-LC send / receive data from the DB each 5s. The third is when both SSM-LC and DSM-LC send / receive data from the DB each 1s. The last is when a failure occurred in the communication system. The objective is to compare the data profile received from the DB with the real-time values and to see the effect of the communication delay on giving correct real-time information and on conserving the real profile variations.

#### 6.5.3.1 Scenario 1: 10s communication delay for each supply-side and demand-side LCs

The smart wind based DFIG micro-plant, in this scenario, sends data to the DB each 10 seconds. The demand-side local controller reads these data from the DB each 10s too. *Figure 6.53* shows the DFIG real generated power profile and the profile with communication delay received from the DB. The DFIG micro-plant starts injecting power at t = 0s, the supply-side LC updates these values each 10s, and the demand-side LC received the first value after a total communication delay of 17s. According to this figure, it is clear that the power profile received from the DB with maximum communication delay of 10s for each LC is very different from the real generated power profile. This will lead to very wrong decisions during the energy management.

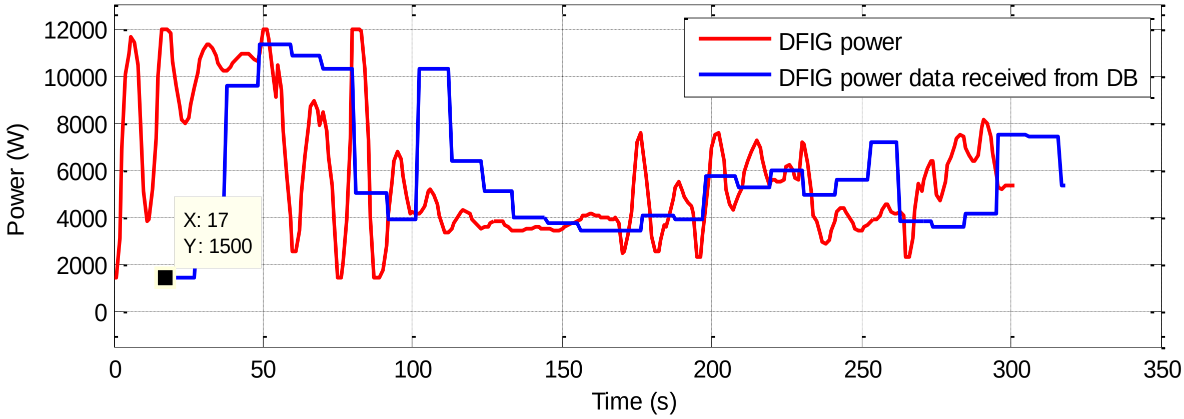


*Figure 6.53 DFIG power profiles with maximum communication delay of 10s for each LC*

#### 6.5.3.2 Scenario 2: 5 s communication delay for each supply-side and demand-side LC

In this scenario, sending and receiving data from the DB is done every 5s for both supply-side and demand-side LC. Figure 6.54 shows the DFIG real generated power profile and the profile received from DB. As the first scenario, the DFIG micro-plant starts injecting power at t = 0s. The demand-side LC received the first value after a total communication delay of 10s. In this scenario, the power profile received from the DB is better compared to the one in the previous scenario. However, this profile is still different from the real one. Which may lead to significant decision-making errors during both SSM and DSM.

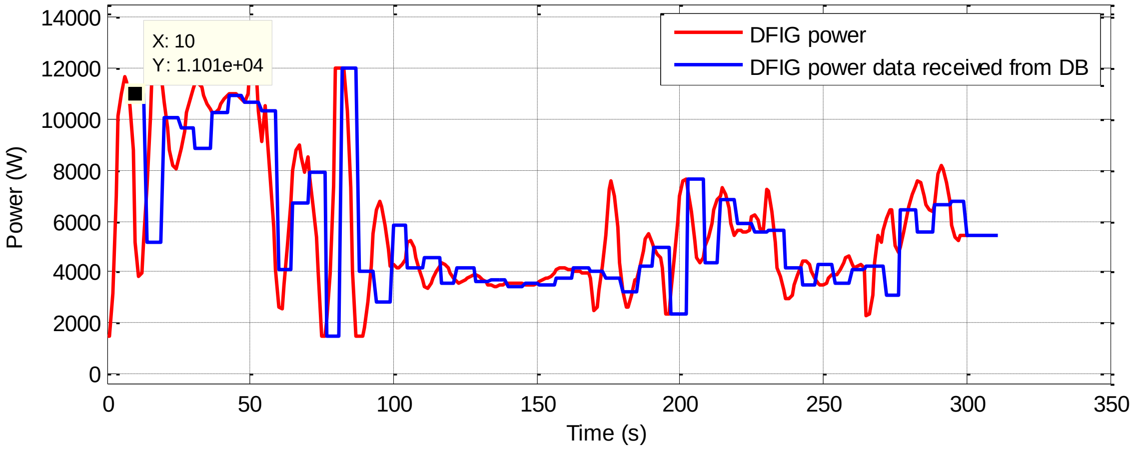


*Figure 6.54 DFIG power profiles with maximum communication delay of 5s for each LC*

### 6.5.3.3 Scenario 3: 1 s communication delay for each supply-side and demand-side LC

In this third scenario, both supply-side and demand-side LCs are making updates to/from the DB each 1s. Figure 6.55 shows the DFIG real generated power profile and the profile received from the DB. The DFIG micro-plant starts injecting power at t = 0s. The demand-side LC received the first value after a total communication delay of 2s. In this scenario, the power profile received from the DB is much much better compared to the previous scenarios. The real and the received profiles are approximately the same. From the previous scenarios, we can conclude that the shorter the communication delay, the higher the data accuracy, and the fewer decision-making errors during both SSM and DSM.

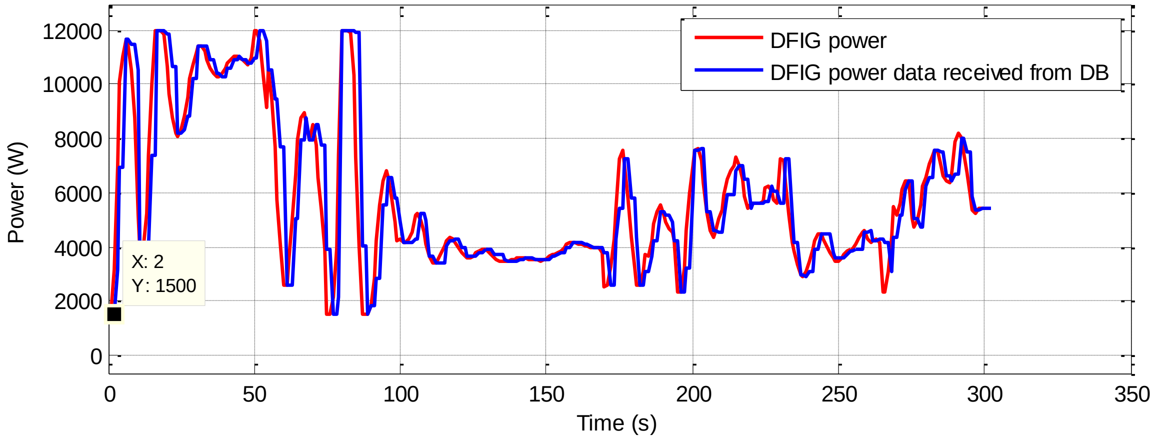


*Figure 6.55 DFIG power profiles with maximum communication delay of 1s for each LC*

### 6.5.3.4 Scenario 4: A failure in the communication system

In this scenario, we simulate a failure in the communication system in the supply-side LC. Reading and sending data to/from the DB are done every 1 second. At t = 179s, a failure in the supply-side communication system occurred. From this moment, there is no updates in the DB and the demand-side LC is no more receiving correct values about the generated power as shown in Figure 6.56. Therefore, a robust and an adequate communication system is necessary to avoid wrong data sharing.

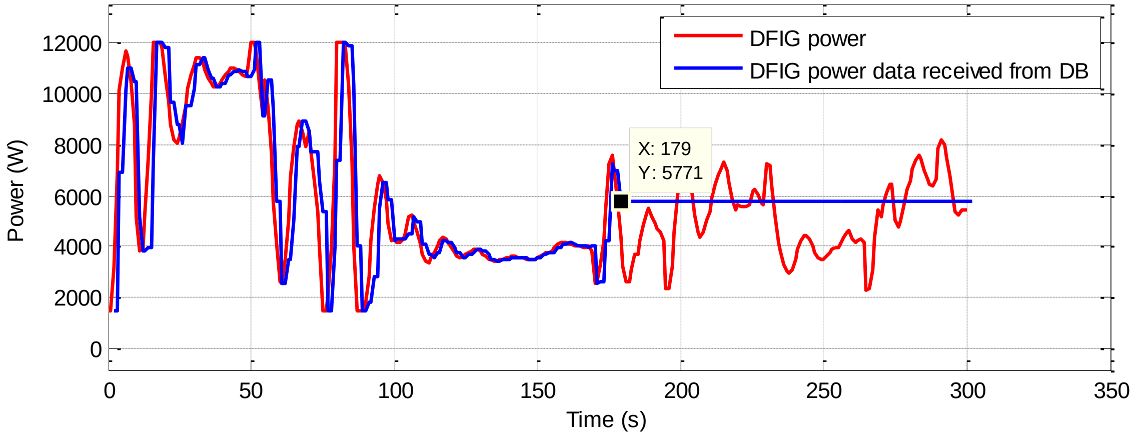


*Figure 6.56 DFIG power profiles during a communication failure in the supply-side LC.*

## 6.6 Part 5: Some micro-grids' practical applications for powering small-scale residential communities: issues and solutions

### 6.6.1 Introduction

We consider here some practical applications of smart micro-grids based renewable energy micro-plants for powering small-scale residential communities. The idea concerns the development of renewable energy-based smart micro-grid solutions to support the development of small-scale communities in off-grid and on-grid areas and serve their typical energy needs such as cooling, heating, pumping, lightening, and other electricity usages. The main objective in this part consists in managing electricity production from renewable energy micro-plants as well as managing the loads of consumers to develop effective solutions for achieving the self-sufficiency of micro-grids in both grid-connected and islanded modes. We replace the traditional dispatch based forecasting methods by iterative real-time control. A decentralized control strategy is developed to control the micro-grid in both grid-connected and islanded modes in a way that each micro-plant produces an exact quantity of energy in real time to follow the consumption variation. For the wind micro-plant, we have used a pitch regulation strategy to control the blades angle of the wind turbine and produce an exact quantity of energy and maintain a constant power supply, less than the MPPT available power, even with a variable wind speed. Concerning the PV micro-plant, we have implemented another algorithm besides the MPPT algorithm that searches for the appropriate PV-GTI DC voltage to produce a precise amount of power from the PV micro-plant and maintain a constant power supply, less than the MPPT available power, even with a variable solar irradiance. Concerning the demand-side resources, two strategies are proposed to manage consumers' appliances and skip the weather limitations: load shifting and load conservation strategies. Their effect on the power mismatch between the generation and the consumption in the micro-grid is also presented.

### 6.6.2 Load assessment

In our proposed scenarios, three consumers (C1, C2, and C3) are connected to the micro-grid where each of them has the following appliances presented in Table 6.7:

*Table 6.7 Consumers' devices*

| **Device** | **Total run-time a day for each device (hours/day)** | | |
|---|---|---|---|
| | **C1** | **C2** | **C3** |
| Three small street LEDs | 11h | 11h | 11h |
| Heating system | 4h | 4h | 3h |
| Air conditioner | 10h | 15h | 12h |
| Cleaning vacuum | 1h | 1h | 1h |
| Electric water pump | 1h | 1h | 1h |
| Washing machine | 1h | 1h | 1h |
| Electric Vehicle | Plugged 8h at night, or 2h at midday | - | - |
| Classic oven | 5h | 4h | 4h |
| Three room LEDs | 9h | 11h | 7h |
| Laptop | 6h | 5h | 4h |
| Smart-phone fast-charger | 3h | 3h | 3h |
| TV Plasma | 3h | 4h | 5h |
| Fridge | 24h | 24h | 24h |
| Wi-Fi Router | 24h | 24h | 24h |
| Aquarium | - | 24h | - |

Table 6.7 and Table 6.8 show the total run-time of each device during the whole day for each consumer and the DSM program for each device, respectively. In all the next scenarios, we have reduced the run-time of each device to shorten the simulation time. Each one hour of the day is equivalent to 12.5s in our simulations so that the demand of the whole 24 hours of the day is represented in only 300s in our real-time simulations.

*Table 6.8 Demand-side management program*

| **Device** | **Power** | **Demand-side management program** |
|---|---|---|
| Three small street LEDs | 3 x 60W | Load conservation up to 75% |
| Heating system | 2000W | Load conservation up to 50% |
| Air conditioner | 2600W | Load conservation up to 60% |
| Cleaning vacuum | 650W | Load shifting from low to high renewable-energy production hours |
| Water pump | 750W | Load shifting from low to high renewable-energy production hours |
| Washing machine | 2500W | Load shifting from low to high renewable-energy production hours |
| Electric Vehicle | 7200W | Load shifting from low to high renewable-energy production hours |
| Classic oven | 2000W | uncontrollable load |
| Three room LEDs | 3 x 20W | uncontrollable load |
| Laptop | 100W | uncontrollable load |
| Smart-phone fast-charger | 30W | uncontrollable load |
| TV Plasma | 260W | uncontrollable load |
| Fridge | 200W | uncontrollable load |
| Wi-Fi Router | 10 W | uncontrollable load |
| Aquarium | 100W | uncontrollable load |

To perform the demand-side management, it is necessary for consumers to have a local controller as well as some flexible loads (controllable loads). The loads are feed through digital relays that can be switched on/off remotely based on the DSM-LC signals. The consumers' loads could be divided into three types:

(1) Interruptible load (schedulable): This term refers to the appliances that can start or stop operating at any set time interval, such as cooling system, heating system, and street LEDs.
(2) Uninterruptible load (schedulable): This term refers to schedulable consumer appliances that must be operated constantly (starting and ending times can be freely set), such as a washing machine. These loads can be moved from low to high renewable energy production hours. EV and electric water pump are interruptible loads (schedulable), but in our simulations we will consider them as uninterruptible loads just to not reduce the comfort of users.
(3) Baseline load (non-schedulable): this is a must-run service that must be provided instantly in response to resident requests, such as room LEDs, refrigerator, TV, and computer. The classic oven is also considered as a baseline load in our simulations. As a result, it is the baseline load and cannot be scheduled.

### 6.6.3 DREMPs assessment

The various distributed renewable-energy micro-plants connected to the micro-grid for feeding the consumers' loads consist of***:***

***(1) A 20kW PV micro-plant:*** 80 PV panels (250W for each panel) are connected each two to one GTI.
***(2) A 15kVA wind micro-plant:*** A 15 kVA wind micro-plant based DFIG is connected to the micro-grid.
***(3) A 10kVA Battery Energy Storage System (BESS):*** The BESS is connected to the micro-grid only in islanded mode to support the renewable energy micro-plants. The BESS stores the surplus power when the production is greater than the demand and discharged to feed the loads when the production is less than the demand. The characteristics of the BESS are presented in Table 6.9.

*Table 6.9 The characteristics of the BESS*

| **Characteristics** | **Rated value** |
|---|---|
| Battery capacity | 65Ah |
| Battery voltage | 12VDC |
| Number of series batteries | 16 |
| Number of parallel batteries | 2 |
| Number of total batteries | 32 |
| BESS DC-bus voltage | 192VDC |
| BESS capacity | 10kVA |
| BESS maximum rated power | 8000W |
| BESS run-time | 1h (12.5s in simulations) |
| BESS capacity | 24960Wh |
| Minimum allowed SoC | 20% |
| Maximum allowed SoC | 100% |

### 6.6.4 Distributed control of the micro-grid in grid-connected mode

In this subsection, the micro-grid is connected to the main utility power grid where it can sell the surplus power or buy the needed power to/from the main utility grid. However, even with the ability of exchanging power with the main grid, the smart energy management is very important to increase the economic benefits of the micro-grid and handle stability issues when they occur. We have used two computer-based systems in this part to emulate the smart swarm of DREMPs and the demand-side resources. The supply-side and demand-side LCs communicate with each other directly through the DB without the need of a central controller of the micro-grid. The supply-side LC performs the SSM and the demand-side LC performs the DSM.

#### *6.6.4.1 Scenario 1: Operation in grid-connected mode without any power management*

In this first scenario, the micro-grid operates without any power management. The DREMPs produce the maximum available power as shown in Figure 6.58. The consumers consume their typical energy needs without any demand response such as load conservation or load shifting (see Figure 6.57).

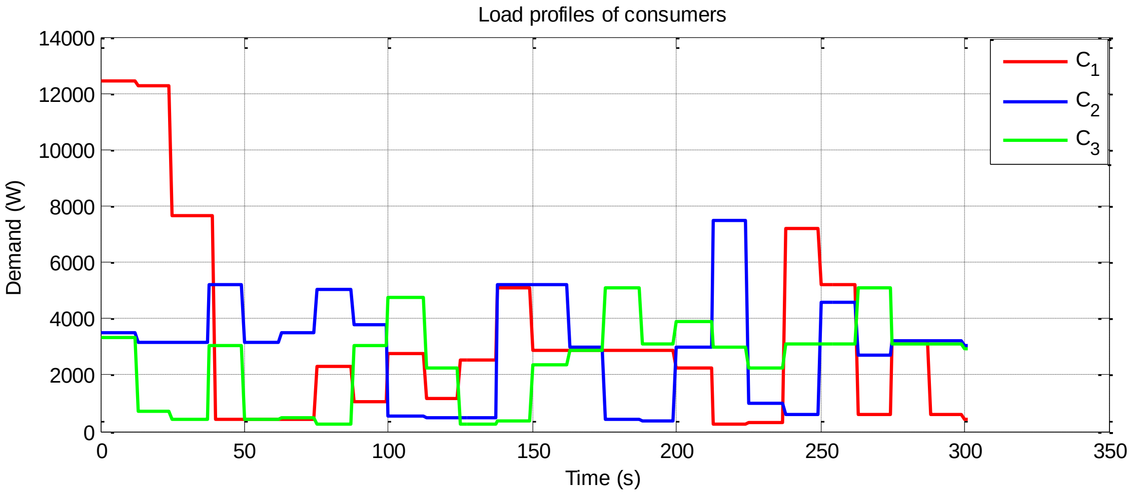


*Figure 6.57 Load profiles of each consumer*

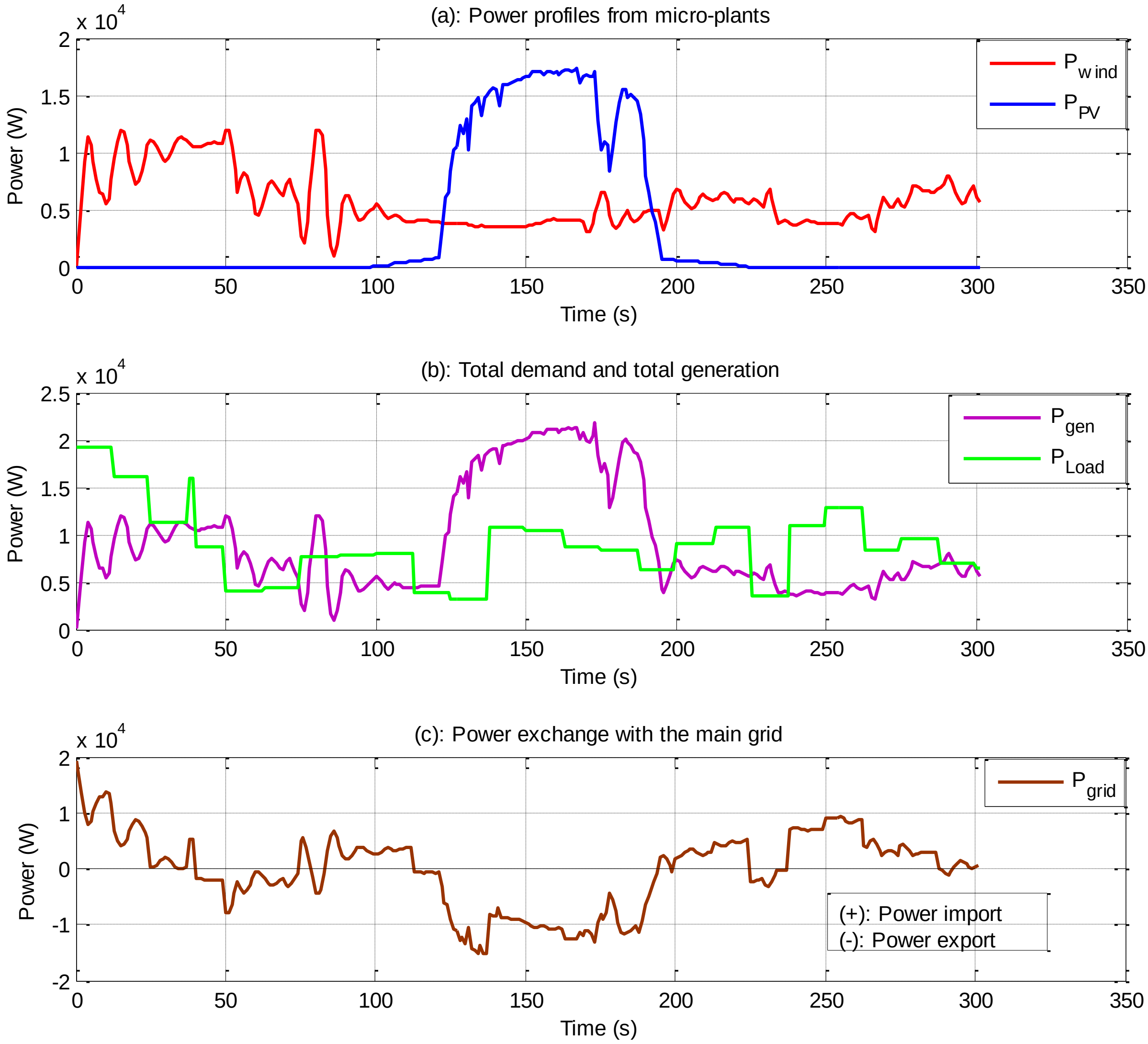


*Figure 6.58 (a) Power profile of each micro-plant, (b) total demand and total generation, (c) power exchange with the main grid.*

The EV consumes a constant electric power in grid-connected mode (7200W) to charge its batteries from 60% at t=0s to 100% at t=40s (see Figure 6.61). As shown in Figure 6.58, the power mismatch between the production and consumption is very high which lead to a high power exchange with the main utility grid. The micro-grid exports the surplus power to the main grid when the local production is higher than the demand and imports the needed power when the demand is higher than the local production. According to this figure we can conclude that, even if the total DREMPs' installed capacity is much than the total demand in the micro-grid, the real-time generated power is still not enough to feed the typical energy needs of consumers due to the intermittent nature of RES and the weather limitations. Thus the micro-grid imports a significant power from the main grid during low renewable power production times to feed the loads. The conventional solutions to develop a self-siffisient micro-grid is to make an extra-over-sizing of DREMPs to feed the load requirements which lead to an extra-expensive cost of installation. However, in the next scenarios, we are going to develop a self-sufficient micro-grid that can operates in both grid-connected and islanded mode by using a various DSM-SSM strategies.

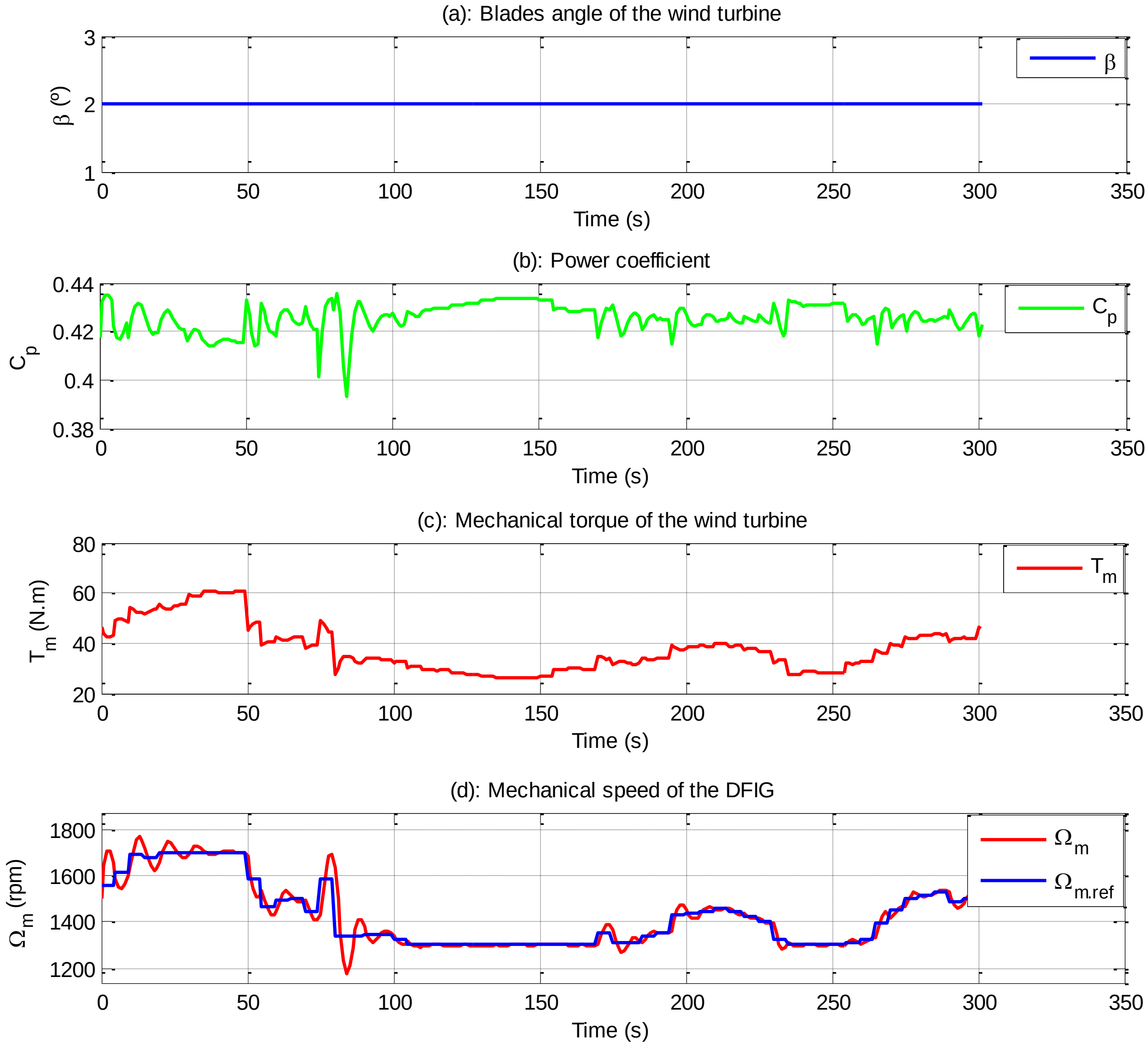


*Figure 6.59 Wind micro-plant mechanical variables*

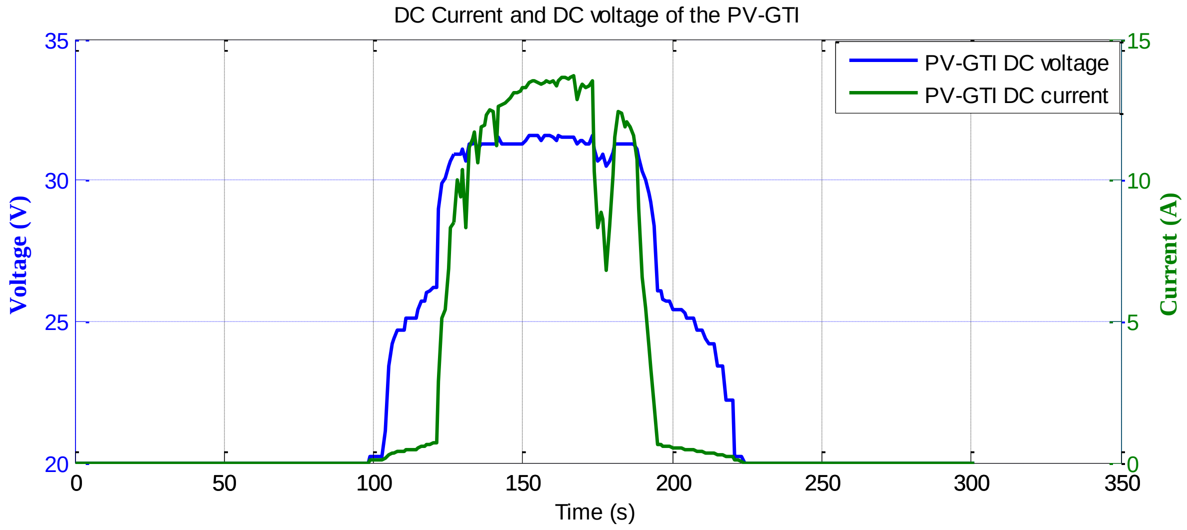


*Figure 6.60 PV micro-plant variables*

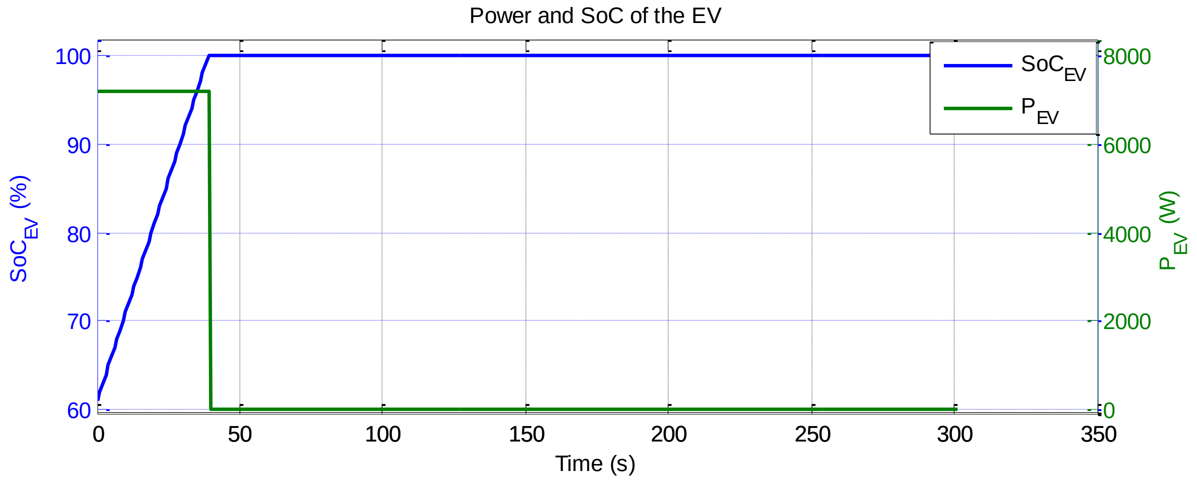


*Figure 6.61 Electric power and SoC of the EV*

### 6.6.4.2 Scenario 2: Operation in grid-connected mode with SSM

In this second scenario, the micro-grid operates in grid-connected mode with managing the power generation from the local renewable micro-plants. The main objective is to adapt the intermittent renewable production to the load profile of small communities and to serve their typical energy needs. It is very important to have the ability of controlling the power production from renewable energy sources, which is highly dependent on the weather conditions, to follow the consumption variations even with a variable weather. Our control strategy is to replace the traditional load forecasting methods by iterative real-time control. To show the benefits of this proposed control strategy, our first computer-based system that emulates the DSM local controller sends data about the consumption variation to the DB every second. The second computer-based system that emulates the SSM local controller reads these data from the DB every second too and performs the SSM. The demand profile of each consumer remains the same as the previous scenario.

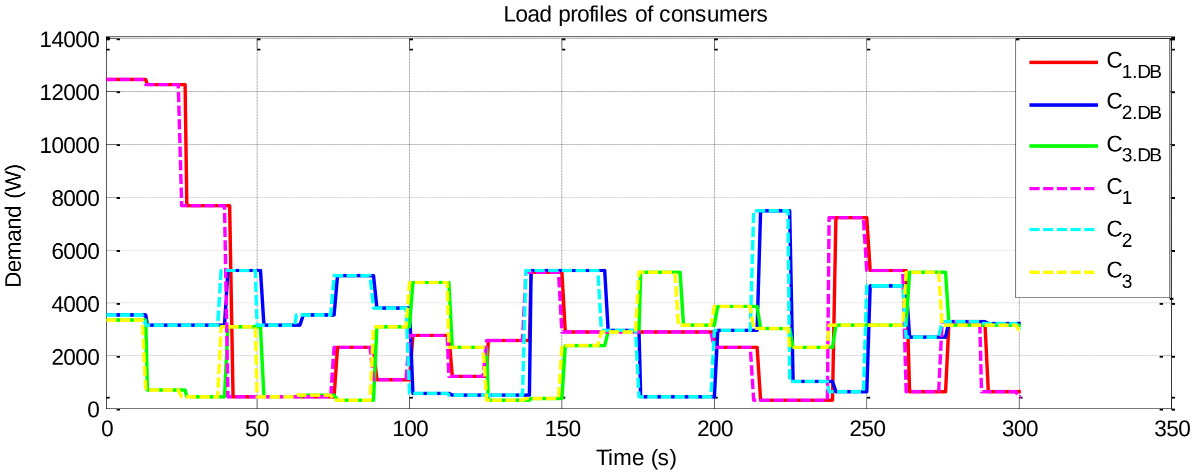


*Figure 6.62 Load profile of each consumer*

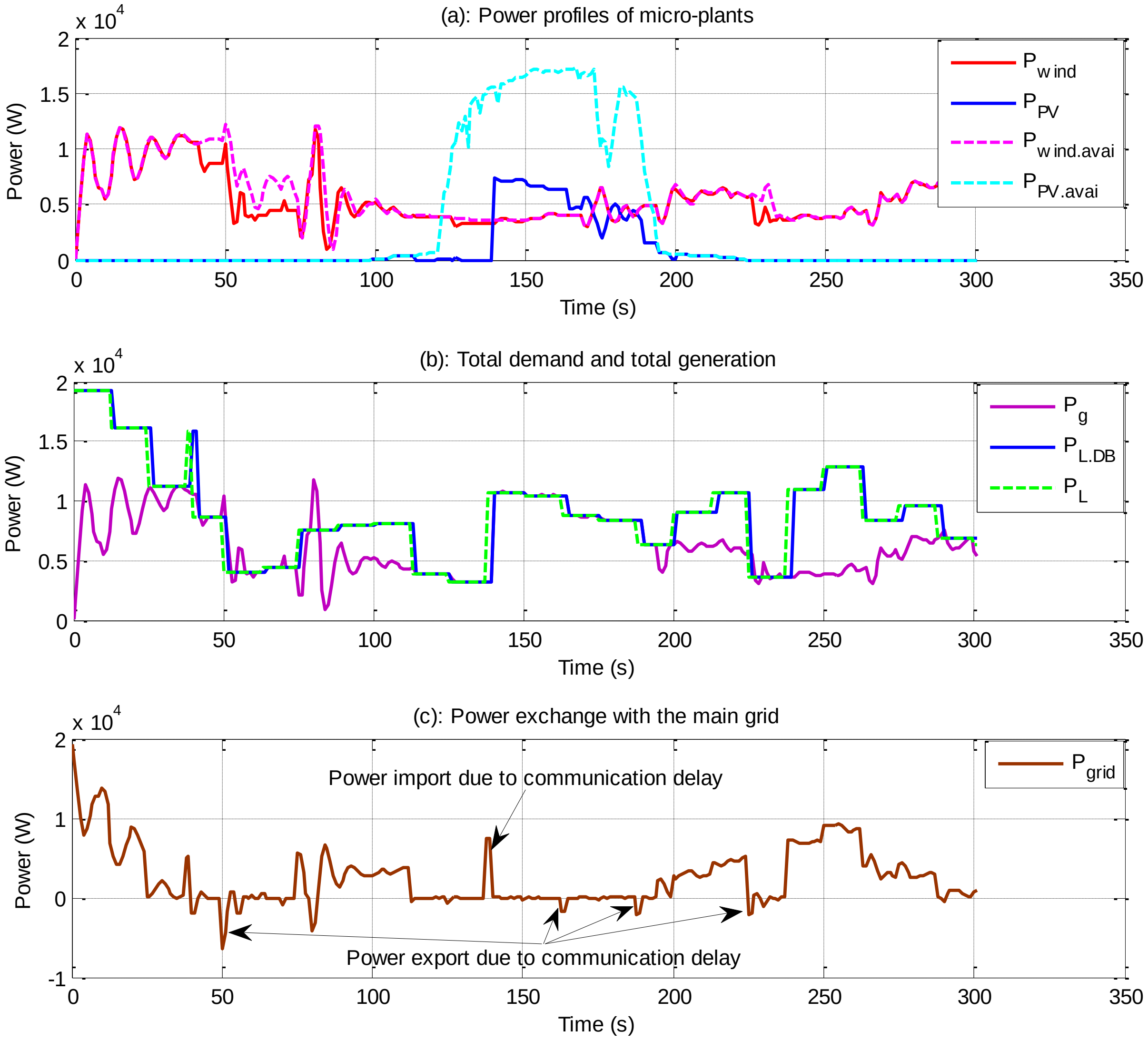
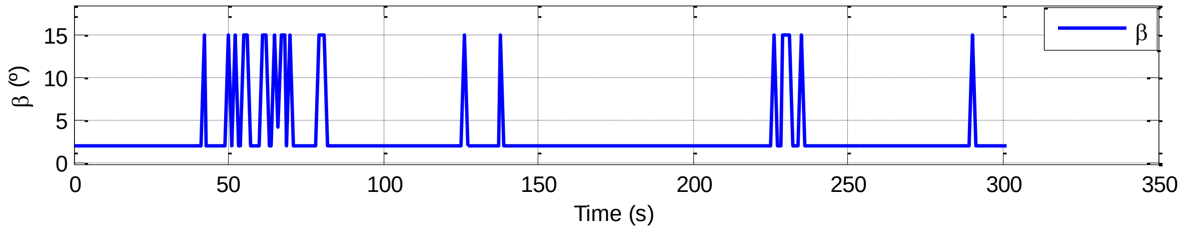


*Figure 6.63 (a) Power profile of each micro-plant, (b) total demand and total generation, (c) power exchange with the main grid.*

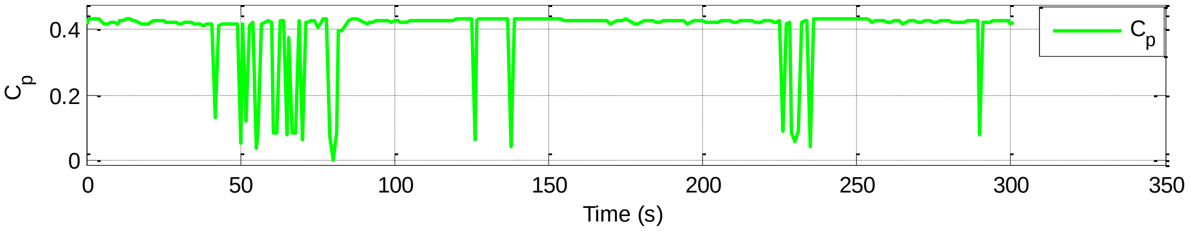
Figure 6.62 shows the load profiles C1, C2, and C3 of consumers 1, 2, and 3 as well as their associated data received from the DB represented by the curves $C_{1.DB}$, $C_{2.DB}$, and $C_{3.DB}$ respectively. For the wind micro-plant, we have used a pitch regulation strategy to extract the needed power $P_{wind}$ from the maximum available wind power $P_{wind.avai}$. Concerning the PV micro-plant, the GTI regulates the DC voltage to extract the needed power from the maximum available solar power $P_{PV.avai}$.

Figure 6.63 shows: (a) the power profile of each micro-plant, (b) the total demand and total generation, and (c) the power exchange with the main grid. According to this figure, when the demand is more than the maximum available power, the micro-plants operate in MPPT mode to extract the maximum available power. However, because the total renewable power is not sufficient to feed the total demand, the micro-grid imports power from the main utility grid to fulfil the load requirements.

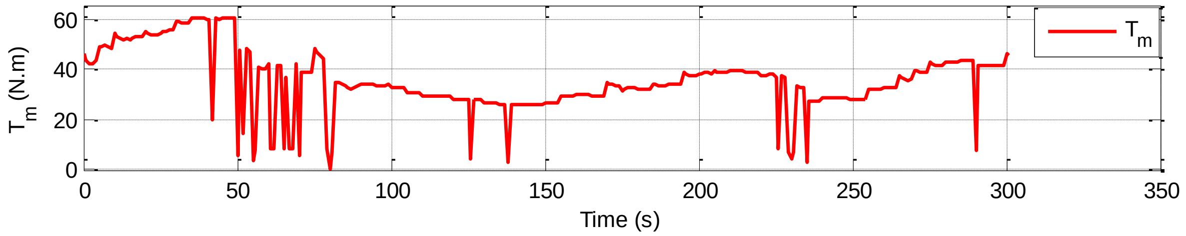
(a): Blades angle of the wind turbine



(b): Power coefficient



(c): Mechanical torque of the wind turbine



(d): Mechanical speed of the DFIG

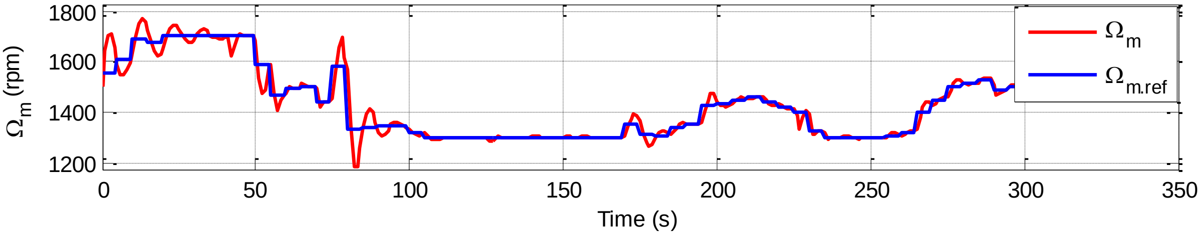


*Figure 6.64 Wind micro-plant's mechanical variables*

Contrarily, when the demand is less than the maximum available power, the PI regulator of the wind micro-plant increases the pitch angle to reduce the power coefficient *Cp* which lead to a reduction in the mechanical torque $T_m$ of the wind turbine (see Figure 6.64) as well as a reduction in the wind power production. In addition, the GTIs of the PV micro-plant reduce the DC voltage (see Figure 6.65) to reduce the PV power production and match the total real-time production with the total load profile data received from the DB. Nevertheless, the communication delay of each local controller with the DB as well as the delay due to the 4G LTE network lead to some decision errors during the SSM as shown in Figure 6.63 where the total generation follows the delayed consumption data received from the DB and the micro-grid imports/exports unnecessary power from/to the main grid.

From this scenario, we conclude that the SSM eliminates the power export to the main utility grid and the power flow is mainly in one direction, which reduces the stability issues presented in part 3 of this chapter, and reduces the voltage rises in load buses.

Although the total installed capacity from DREMPs (45kVA) is greater than the total installed load, the total DREMPs power supply is not enough to feed the typical energy needs of the micro-grid consumers during all the times. Moreover, when the supply is greater than the demand, the micro-plants reduces their power production to match the supply which lead to the loss of too much renewable power that is not consumed nor stored in batteries. Thus, a BESS is very important to store the excess power when operating in islanded mode where there is no possibility to sell the excess power to the neighbour micro-grids nor to the main grid.

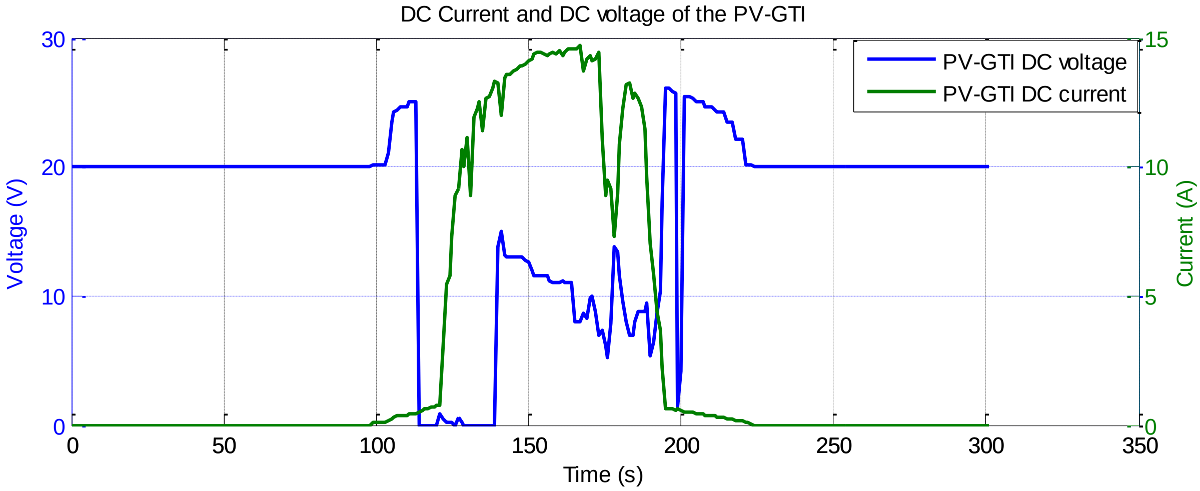


*Figure 6.65 PV micro-plant variables*

### 6.6.4.3 Scenario 3: Operation in grid-connected mode with DSM based load shifting

In this third scenario, the micro-grid operates in grid-connected mode with managing the local consumers' loads in order to skip the weather limitations and match the total demand $P_L$ with the total available supply $P_g$ as well as reducing the imported power from the main utility grid $P_{grid}$. For that, it is necessary for consumers to have a local controller as well as some flexible loads. The loads are feed through digital relays that can be switched on/off remotely based on the DSM-LC signals. We have used an iterative real-time control strategy instead of the traditional renewable generation forecasting methods. The SSM-LC sends the power production data of the renewable micro-plants to the DB every second. The DSM-LC reads these data every second too to manage the consumers' loads. In this scenario, only the load shifting strategy was used to move the possible controllable loads such as electric water pump, washing machine, cleaning vacuum and electric vehicle from low renewable power production times to high renewable power production times in midday (see Table 6.7 and Table 6.8).

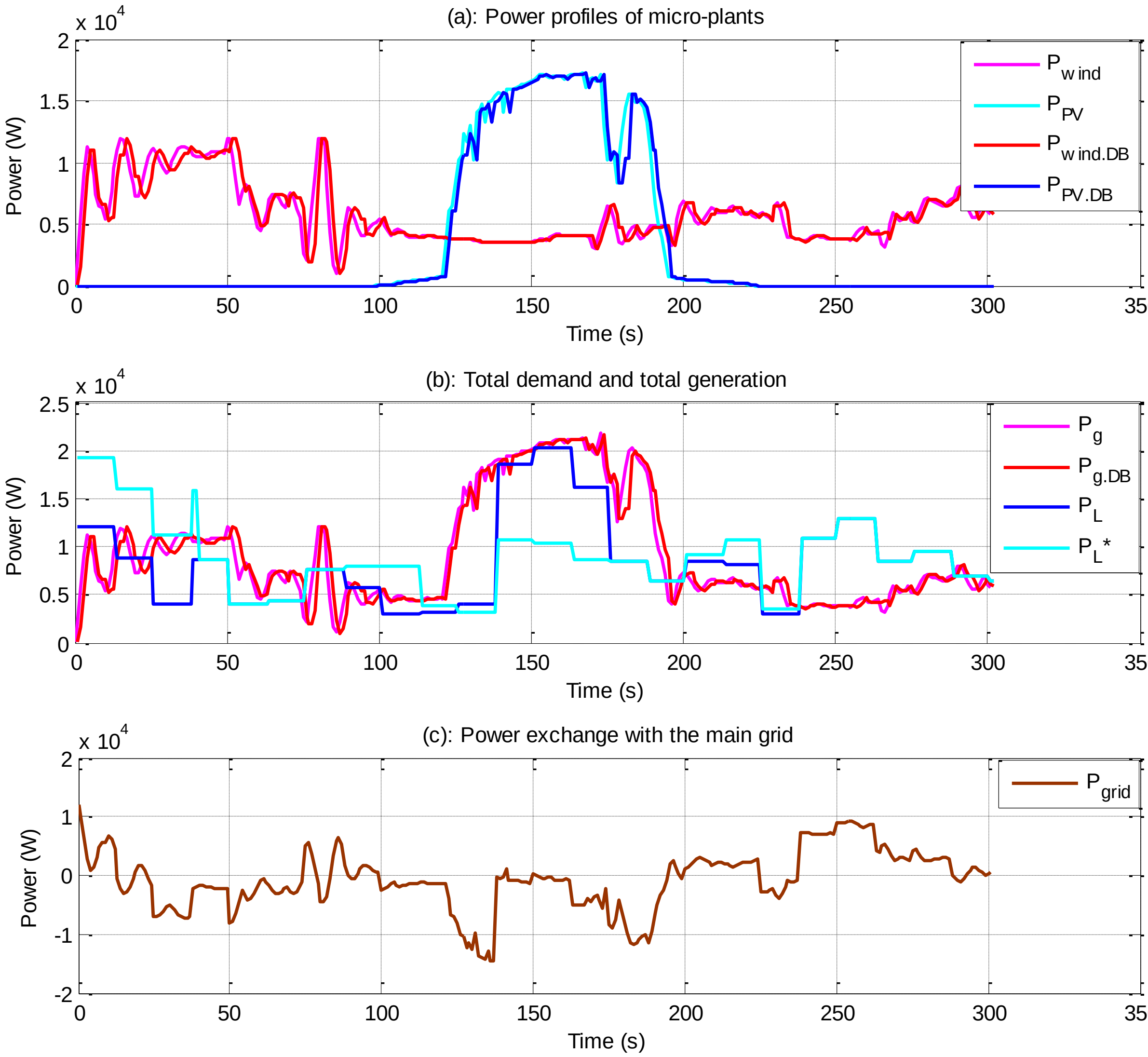


*Figure 6.66 (a) Power profile of each micro-plant, (b) total demand and total generation, (c) power exchange with the main grid.*

Figure 6.66 (a) shows the real-time generated power profiles ($P_{PV}$, $P_{wind}$) of both PV and wind micro-plants as well as their associated data ($P_{PV.DB}$, $P_{wind.DB}$) received from the DB. Based on these received data which are a little bit delayed from the real ones , the DSM-LC performs the load shifting strategy to shift the possible controllable loads (electric water pump, washing machine, cleaning vacuum, and EV charging) from low renewable power production times to high renewable power production times as shown in Figure 6.66 (b) where $P_L$ represents the total demand with DSM program and $P_L$* represents the total demand without any DSM program. It is clear that with DSM program-based load shifting strategy, the imported power from the main grid is lower compared to the first scenario without DSM program. In addition, with the same generated power from renewable micro-plants, the micro-grid is nearer to the self-sufficiency with DSM programs than without DSM programs. Thus, the necessity of extra oversizing of DREMPs is reduced thanks to the load management during critical periods. Moreover, the DSM program-based load shifting will not reduce the total consumed power, thus the comfort of users is generally not affected. Nevertheless, this will reduce the exported energy to the main grid as well because it will be consumed locally by the shifted consumers' loads. However, consume electricity locally or export it to the main grid in a specific time depend on other factors such as RTP.

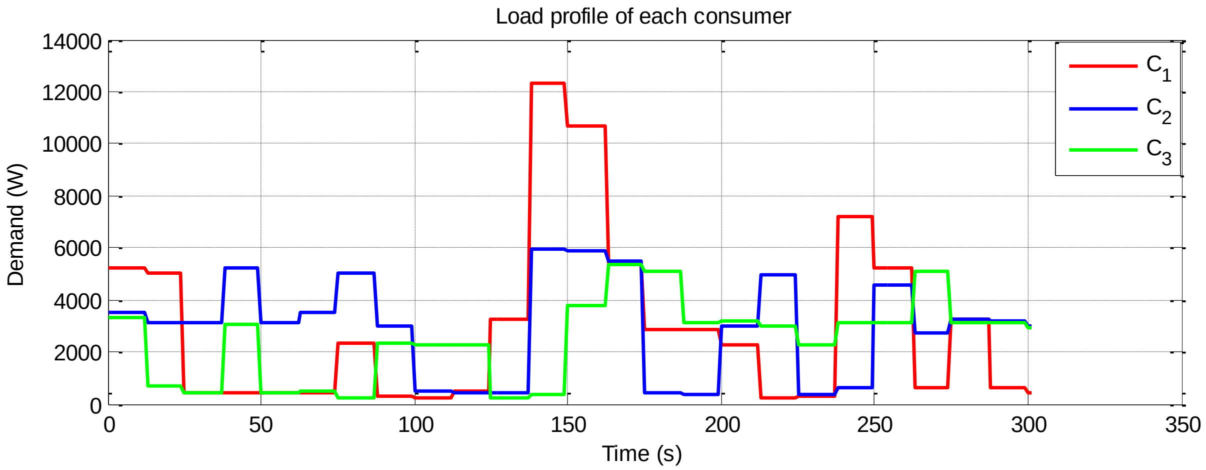


*Figure 6.67 Load profile of each consumer*

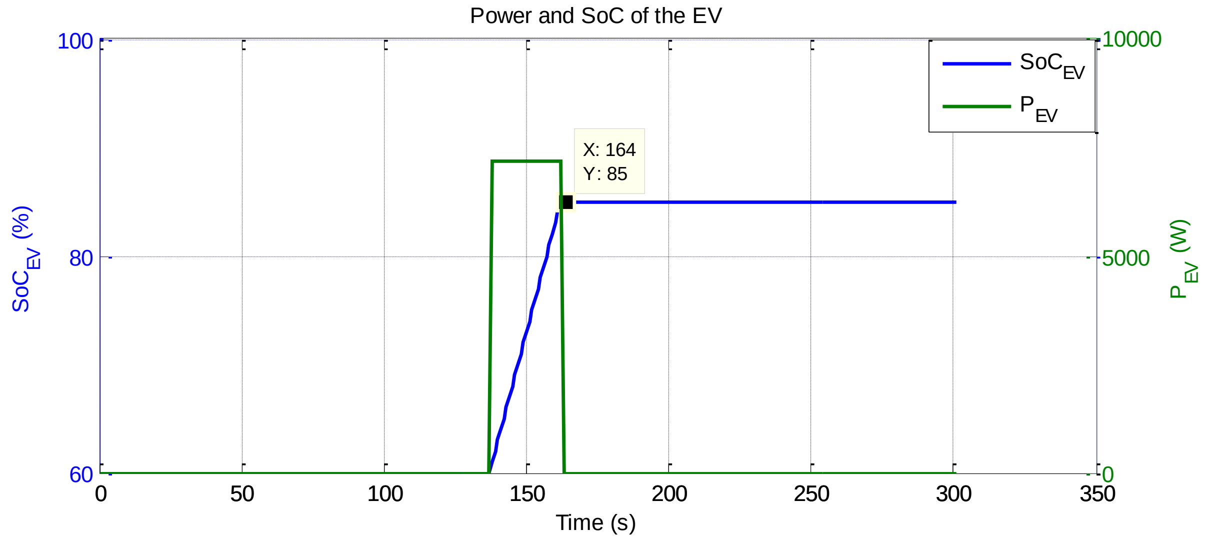


*Figure 6.68 Electric power and SoC of the EV*

#### 6.6.4.4 Scenario 4: Operation in grid-connected mode with DSM based load shifting and load conservation strategies

This fourth scenario is the same as the third one, but in addition to the DSM program based load shifting strategy, we have applied a load conservation strategy as shown in Table 6.8. We understand from the previous scenario that the load shifting conserves the total demand and shift only possible controllable loads from low renewable power production times to high renewable power production times. Contrarily, the load conservation strategy affects the total demand and reduces the consumption of the flexible loads such as street lights, heating system, and cooling system.

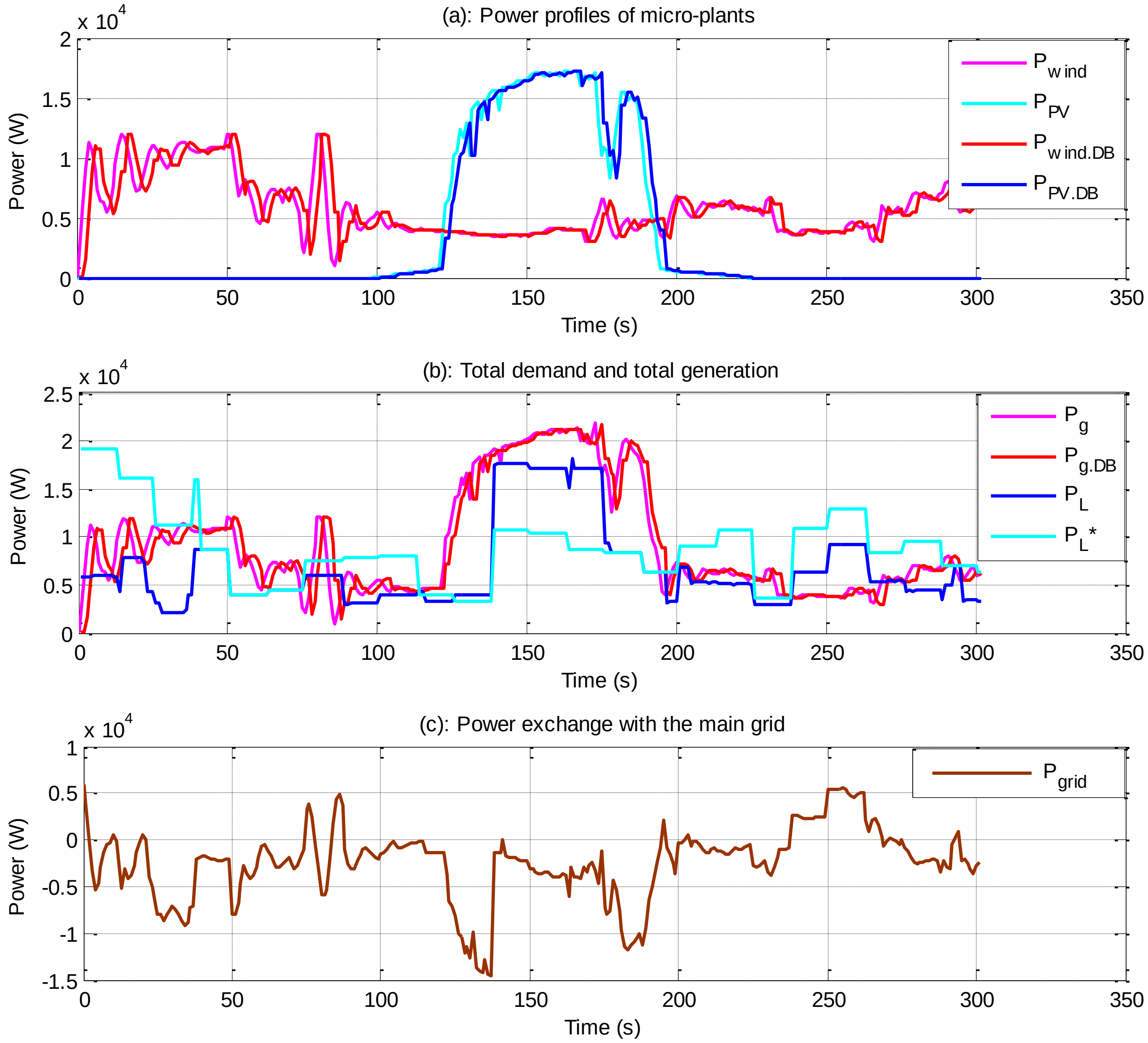


*Figure 6.69 (a) Power profile of each micro-plant, (b) total demand and total generation, (c) power exchange with the main grid.*

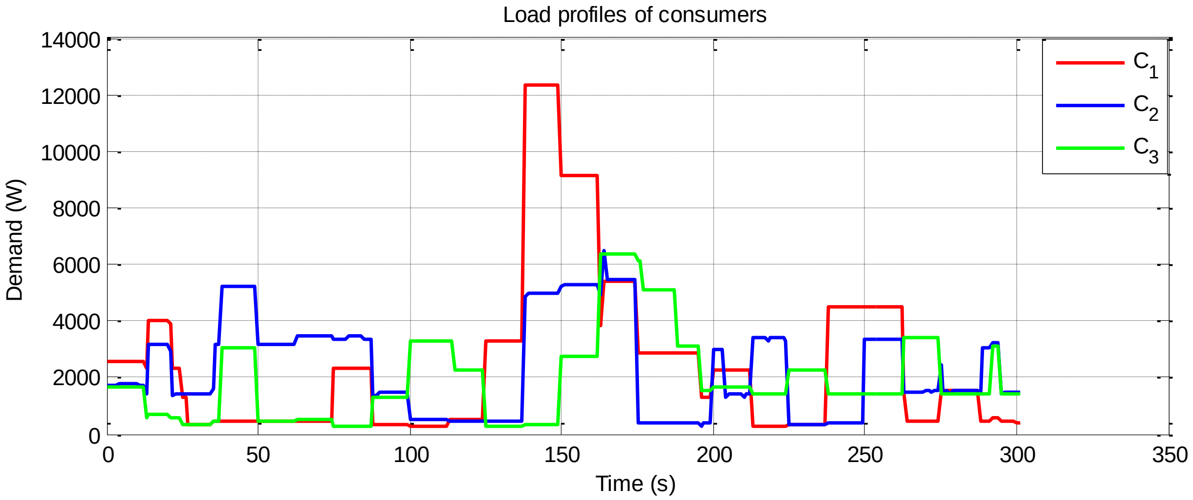


*Figure 6.70 Load profile of each consumer*

Figure 6.69 shows: (a) the power profile of each micro-plant and their associated data received from the DB, (b) the total demand and the total generation, and (c) the power exchange with the main grid. It is clear that with DSM program-based load shifting and load conservation strategies, the imported power from the main utility grid is highly reduced compared to the previous case and the micro-grid is nearer to the self-sufficiency. Moreover, the exported power to the main grid is increased due to the load conservation strategy which lead to the increase of the financial benefits of the micro-grid's users. Nevertheless, the load conservation strategy may reduce the comfort of users depending on the preferences of each one.

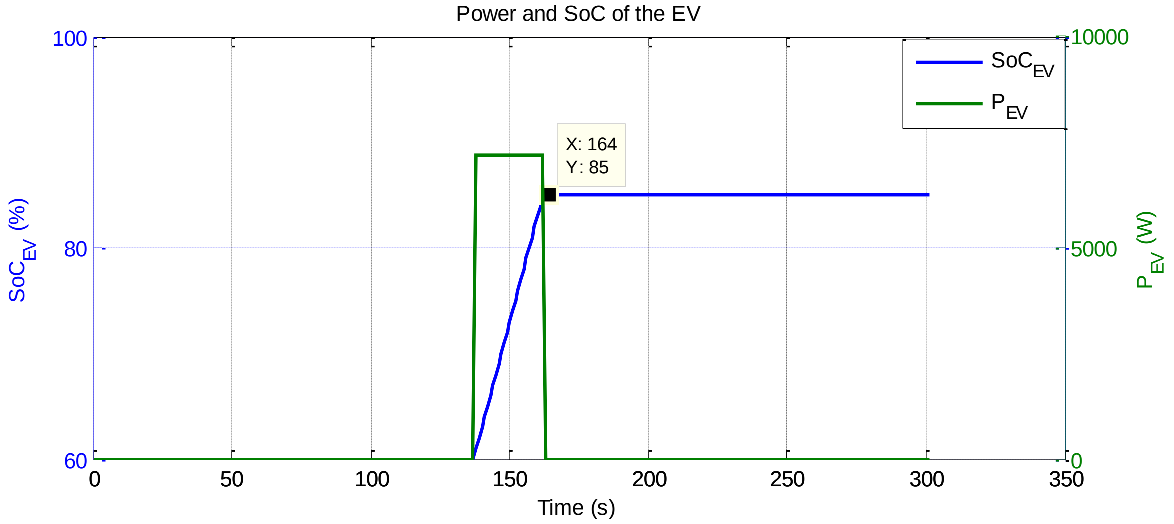


*Figure 6.71 Electric power and SoC of the EV*

### 6.6.4.5 Scenario 5: Operation in grid-connected mode with both SSM and DSM based load shifting strategy

In this fifth scenario, the micro-grid operates in grid-connected mode with managing both supply-side and demand-side resources. The DSM-LC sends the power consumption data of each consumer to the DB and reads the power production data of each micro-plant from the DB every second to manage the flexible loads and match the demand to the available supply. In the same time, the SSM-LC reads the consumers data from the DB to manage the power production of the micro-plants and sends data to the DB every second. For the wind micro-plant, we have used a pitch regulation strategy as shown in Figure 6.74 to extract the needed power $P_{wind}$ from the maximum available wind power $P_{wind.avai}$ as shown in Figure 6.73. Concerning the PV micro-plant, the GTI regulates the DC voltage as shown in Figure 6.75 to extract the needed power from the maximum available solar power $P_{PV.avai}$ as shown in Figure 6.73. Moreover, the DSM-LC performs the load shifting strategy to move the controllable loads from low renewable power production times to high renewable power production times as shown in Figure 6.73.

From this scenario, we conclude that with both SSM and DSM based load shifting strategy, the power mismatch between the local renewable generation and the local demand is reduced. The power flow from the micro-grid to the main utility grid is approximately eliminated except the ones due to communication delay. Thus, the voltage rises in load buses will be reduced and the main grid instability caused by reverse power flow will be reduced as well. Moreover, the DSM based load shifting reduces the imported power from the main grid. Nevertheless, this strategy is not yet enough to achieve the self-sufficiency of the micro-grid. Thus, a load conservation strategy is needed to reduce much more the dependence on the main utility grid.

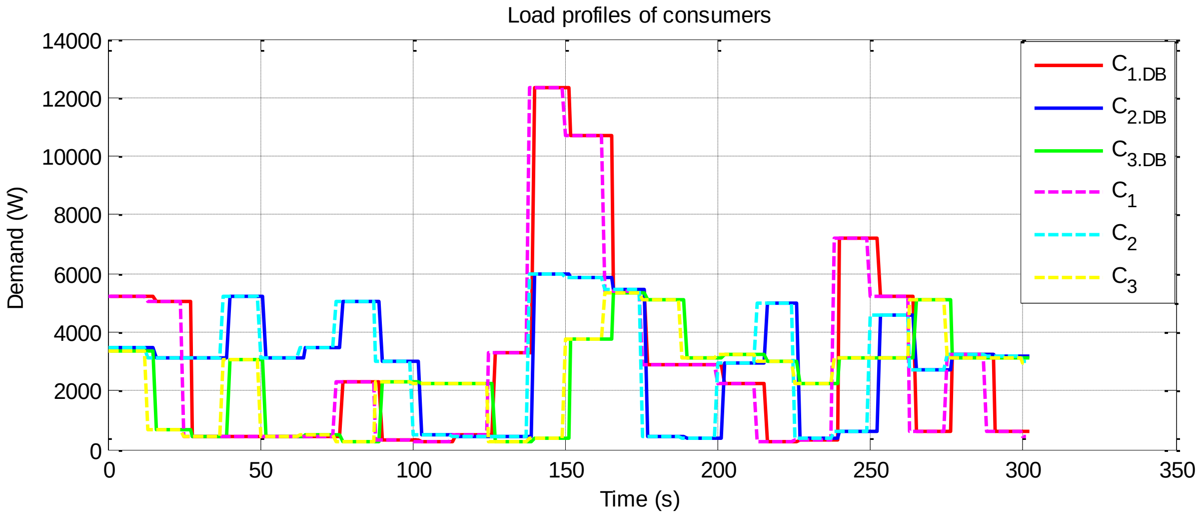


*Figure 6.72 Load profile of each consumer*

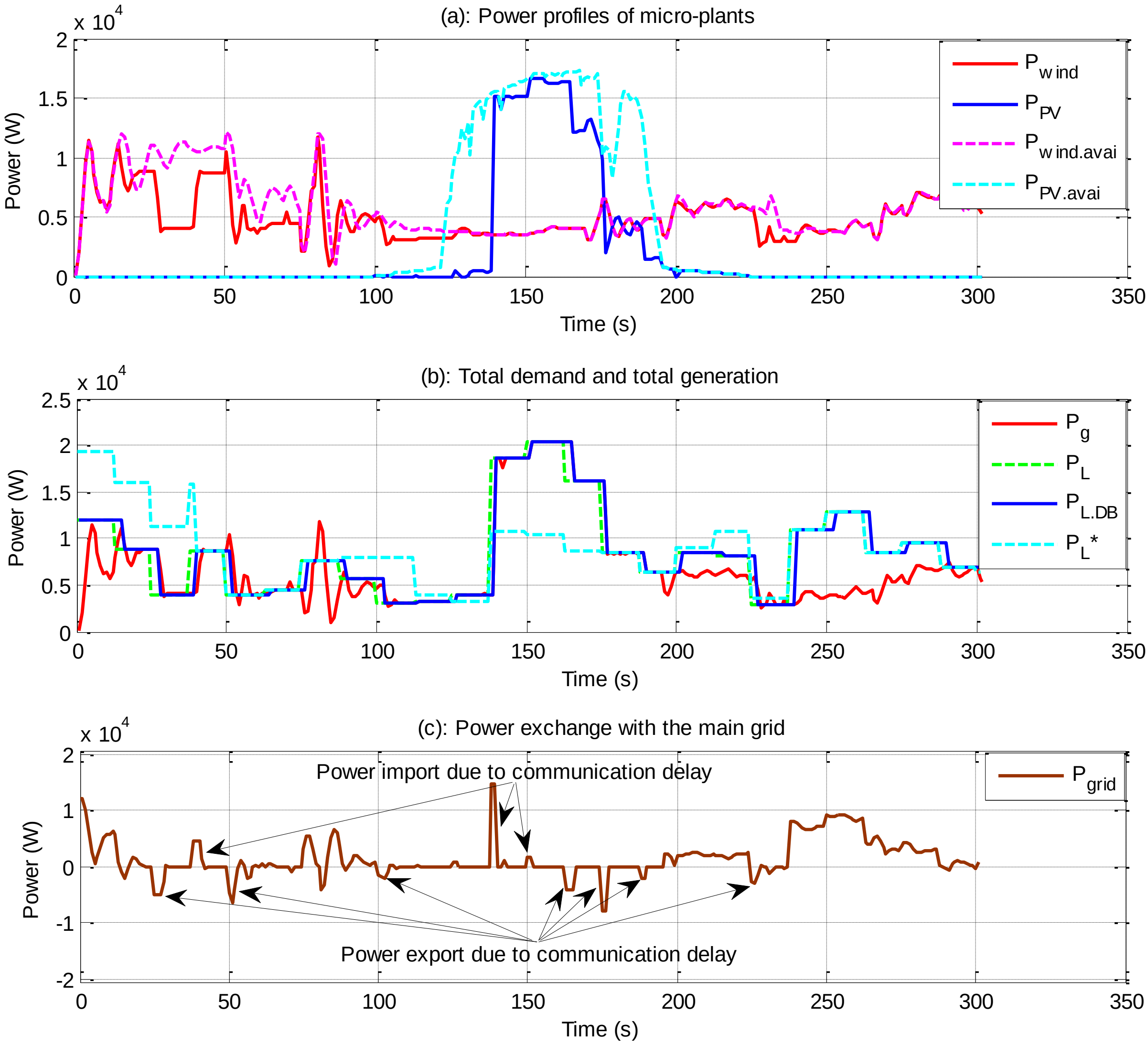


*Figure 6.73 (a) Power profile of each micro-plant, (b) total demand and total generation, (c) power exchange with the main grid.*

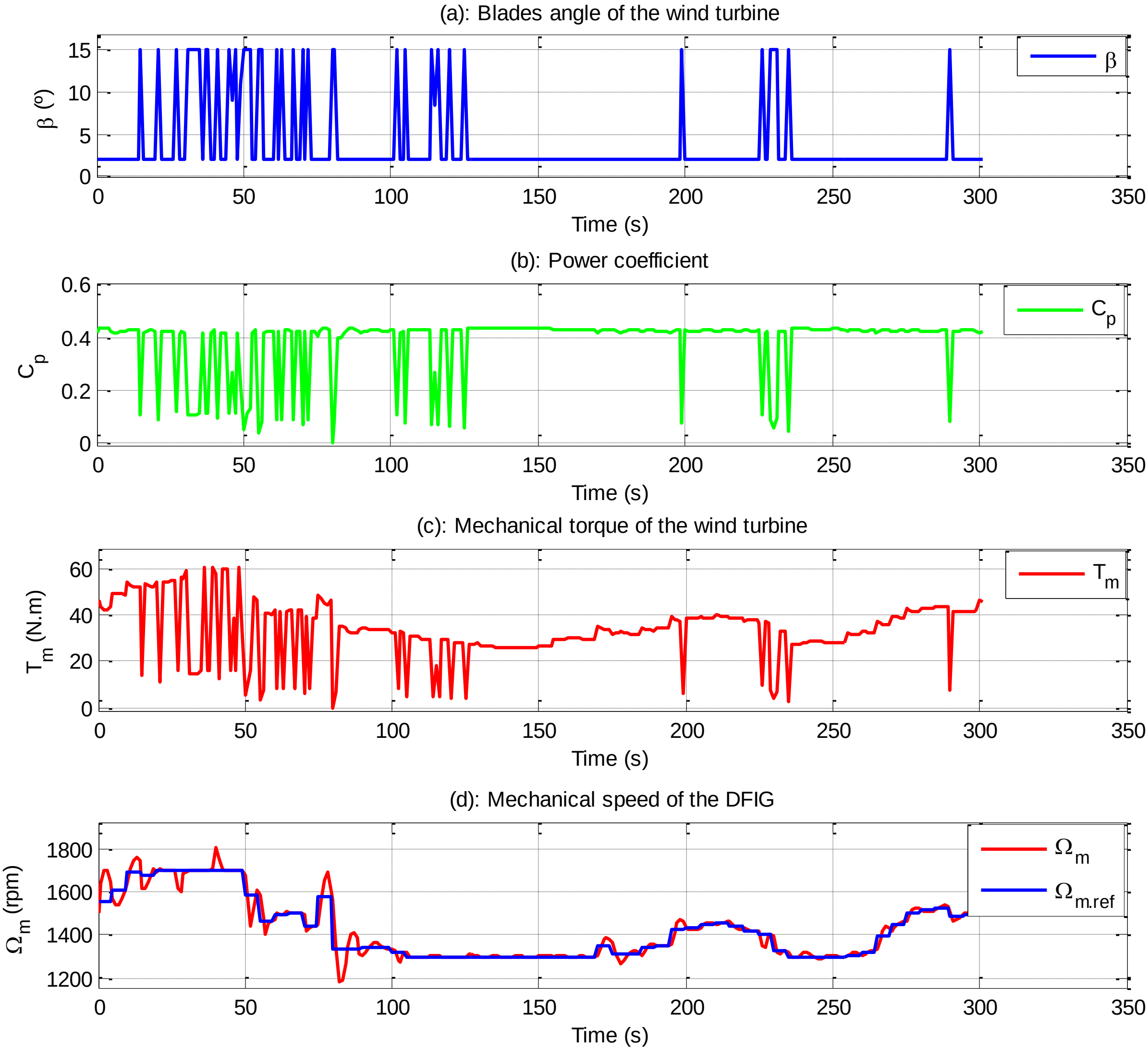


*Figure 6.74 Wind micro-plant mechanical variables*

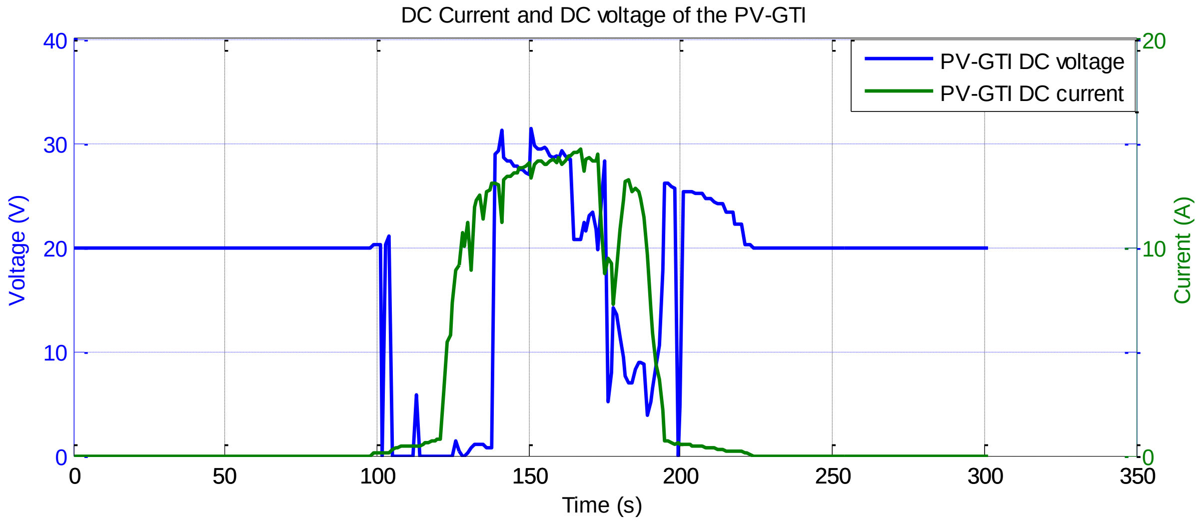


*Figure 6.75 PV micro-plant variables*

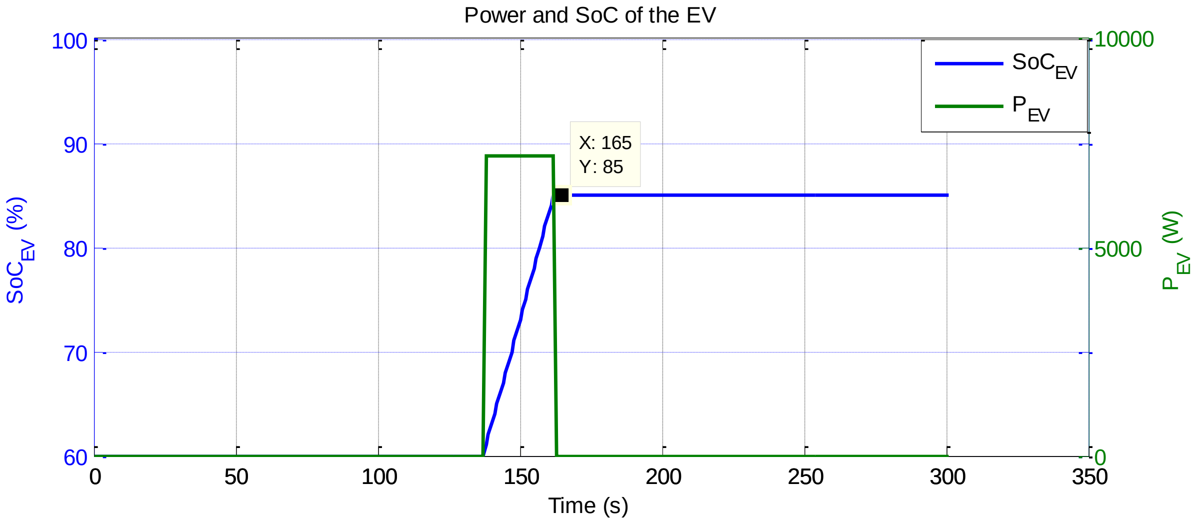


*Figure 6.76 Power and SoC of the EV*

### 6.6.4.6 Scenario 6: Operation in grid-connected mode with both SSM and DSM based load shifting and load conservation strategies

This sixth scenario is the same as the fifth one, but in addition to the DSM based load shifting strategy, the DSM-LC performs also the load conservation as shown in *Table* 6.8. According to Figure 6.78, the power supply from renewable micro-plants follows the total demand of consumers. The power mismatch is reduced much more compared the previous scenario where the DSM-LC performs only the load shifting strategy. In addition, the revers power flow from the micro-grid to the main utility grid is approximately eliminated except the ones due to communication delay. Thus, the voltage rises in load buses will be reduced and the main grid instability caused by reverse power flow will be reduced as well. Nevertheless, an important available renewable power was lost due to the load conservation strategy. In addition, the power generation from the wind and PV micro-plants was not enough to feed the typical energy needs of the consumers even with both DSM strategies (load shifting and load conservation). Thus, a BESS is necessary for the micro-grid to operate in islanded mode.

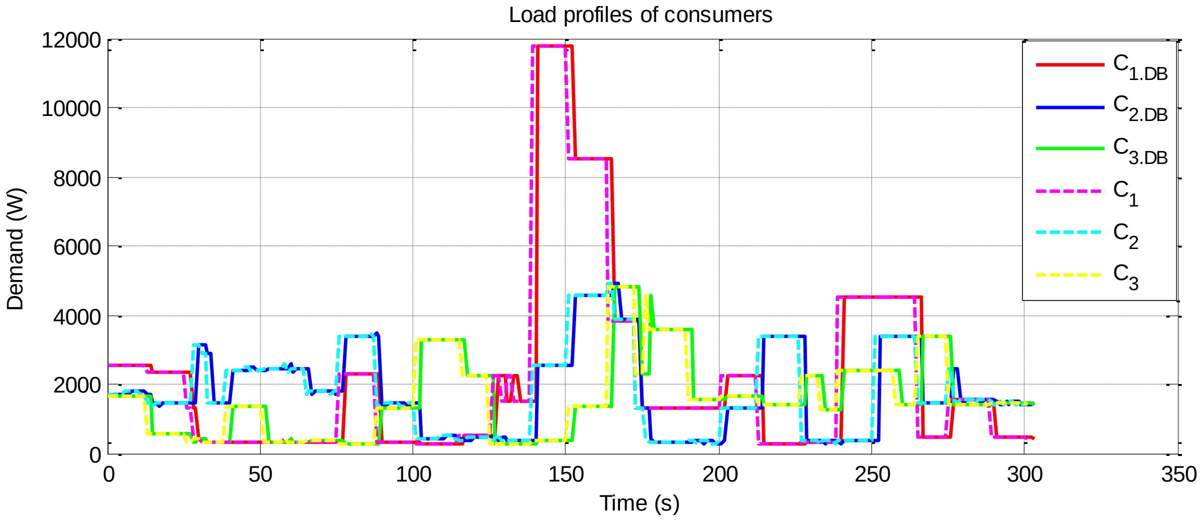


*Figure 6.77 Load profile of each consumer*

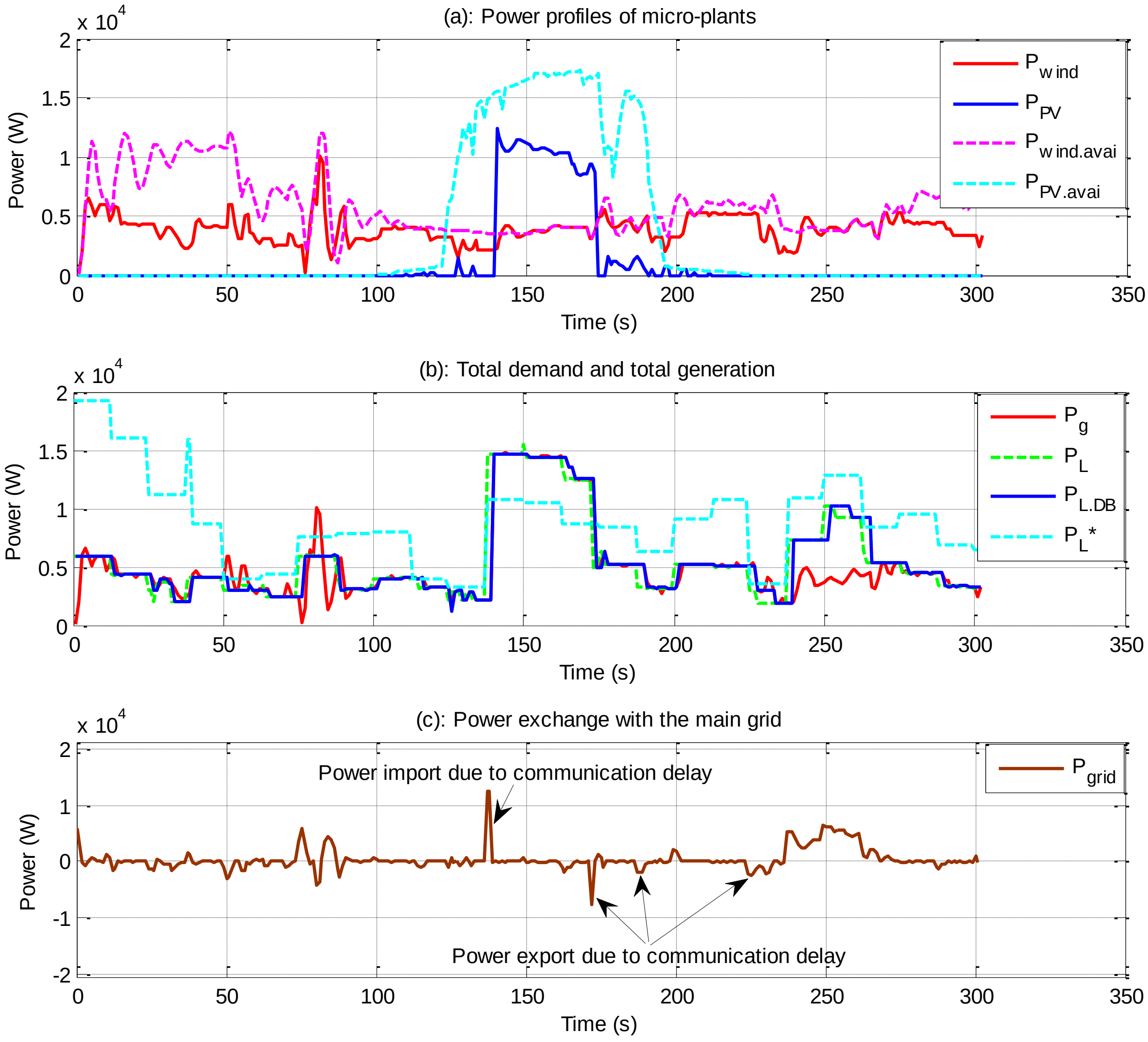


*Figure 6.78 (a) Power profile of each micro-plant, (b) total demand and total generation, (c) power exchange with the main grid.*

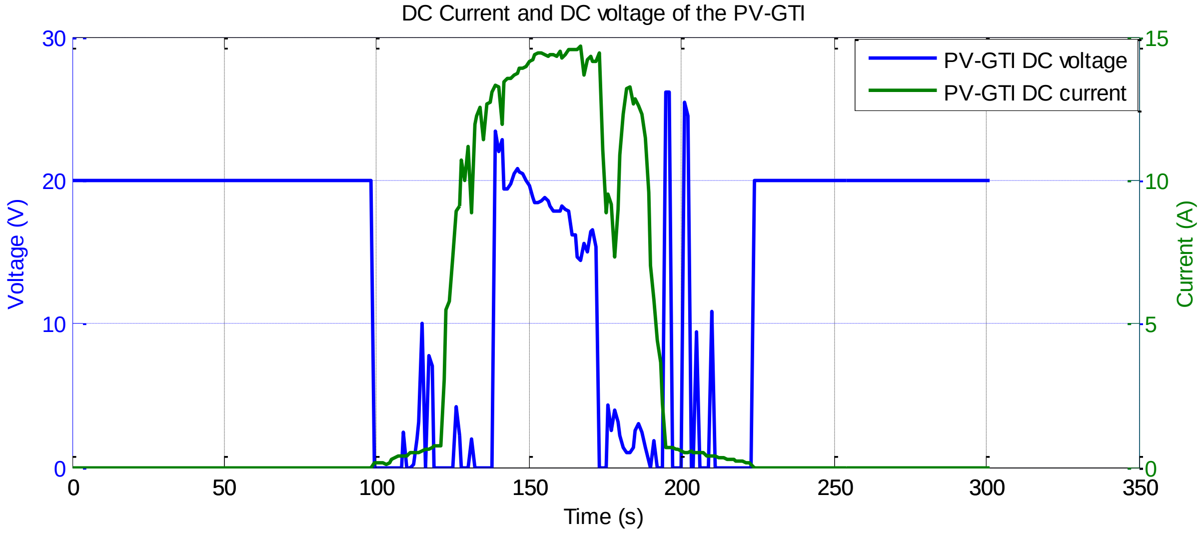


*Figure 6.79 PV microplant electrical variables*

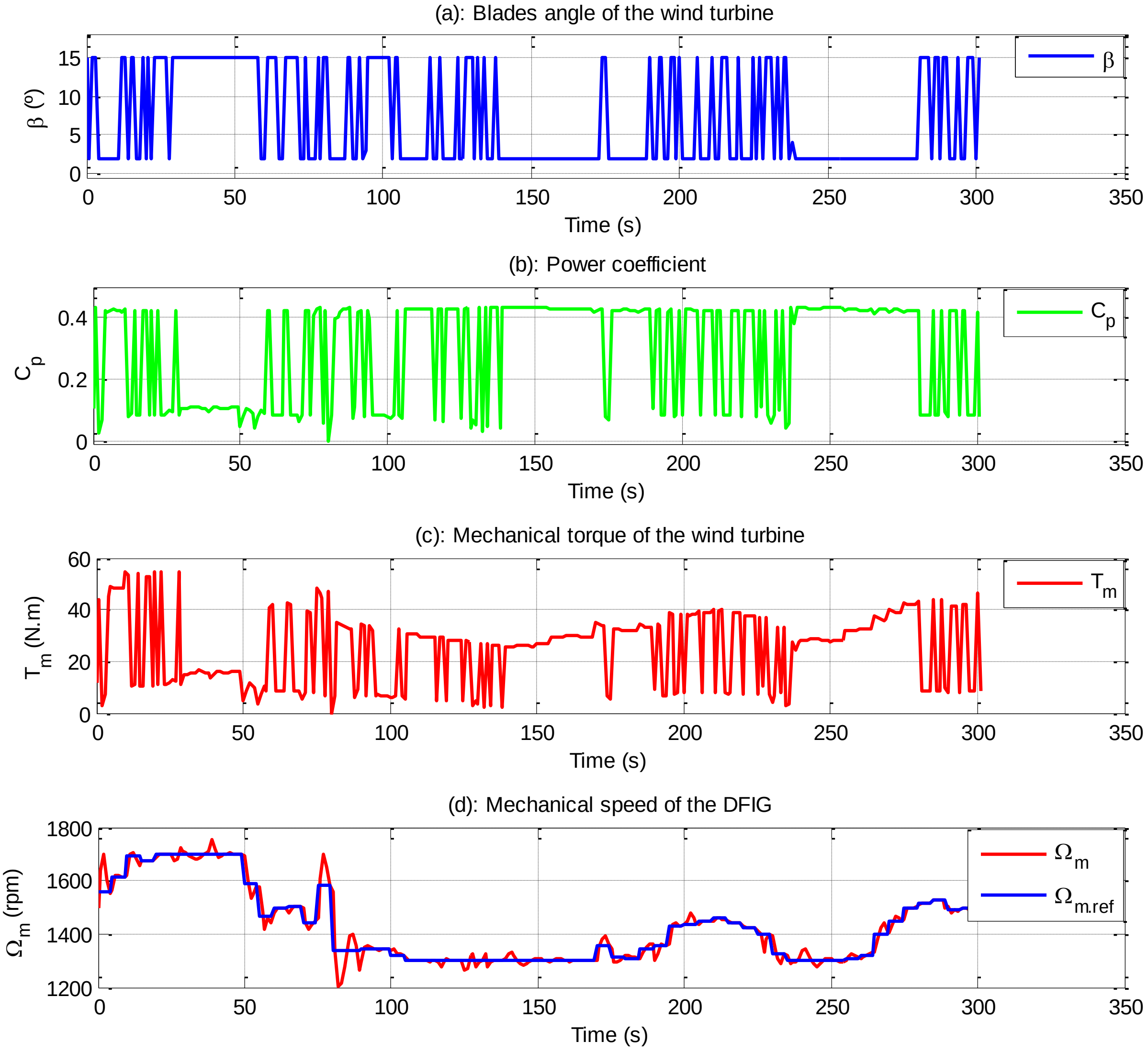


*Figure 6.80: Wind micro-plant mechanical variables*

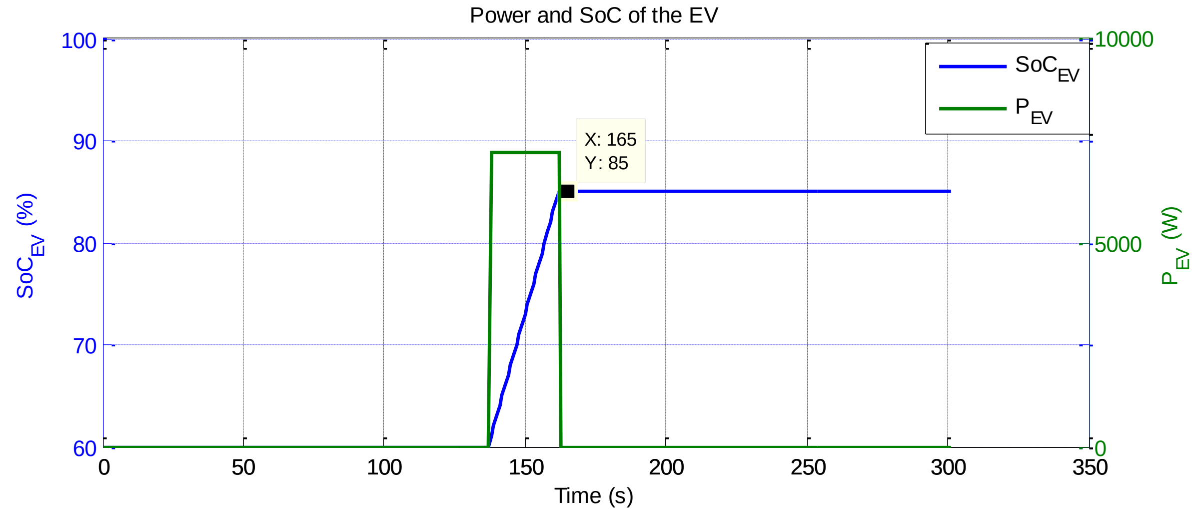


*Figure 6.81 Power and SoC of the EV*

### 6.6.5 Distributed control of the micro-grid in islanded mode

In islanded mode, the micro-grid does not have the possibility of exchanging the power with the main utility grid. Any power mismatch will affect the stability and reliability of the micro-grid. Thus, a diesel backup generator or an ESS is necessary for the proper operation of the micro-grid based renewable energy micro-plants. In the next scenarios, a 10 kVA BESS is interconnected to the micro-grid to support the renewable energy micro-plants. The characteristics of the BESS are presented in *Table 6.9*. The BESS stores the surplus power into the batteries and delivers it when needed. Three scenarios are presented in this subsection; the first is when the micro-grid manages only the supply-side resources including the 15 kVA wind micro-plant, the 20 kW PV micro-plant, and the 10 kVA BESS. A Battery Management System (BMS) is integrated to the SSM-LC to manage the charging and discharging processes and to protect the batteries from any overcharging or undercharging to extend the lifetime of the batteries. The BMS controls the State of Charge (SoC) of the batteries to keep it within its limits (100% > SoC > 20%).

#### *6.6.5.1 Scenario 1: Operation in islanded mode with SSM*

In this scenario, the micro-grid operates in islanded mode with managing only the power generation from the local renewable-energy micro-plants.

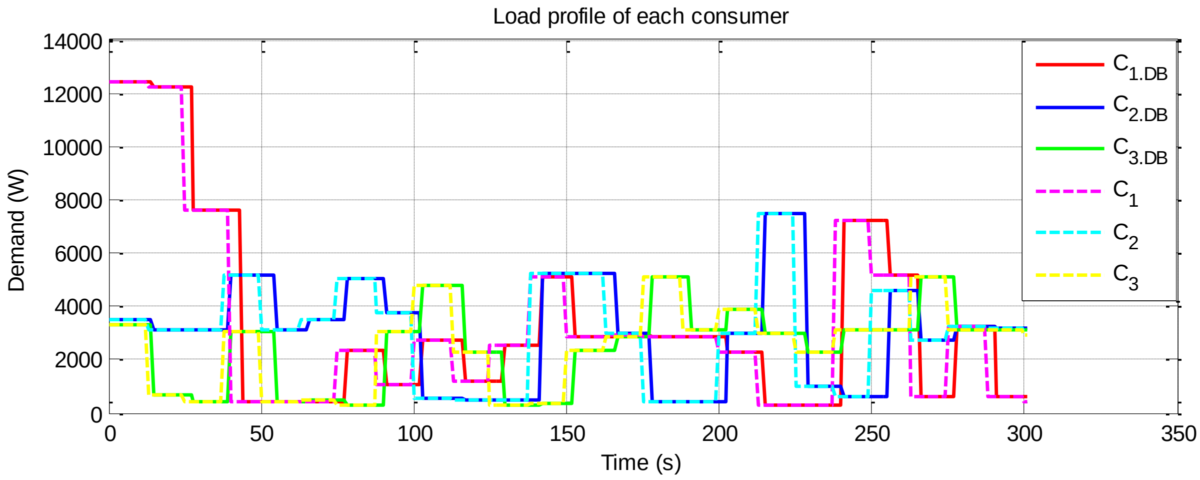


*Figure 6.82: Load profile of each consumer*

A BESS was interconnected to the micro-grid as a backup generator to store the surplus power and deliver it when needed to support the DREMPs. The objective is to adapt the supply to the load profile in islanded mode by using iterative real-time control instead of the traditional load forecasting methods. The same previous control strategies were used for controlling the power production from the wind and the PV micro-plants. The power consumption of the EV was supposed to be constant at its maximum level ($P_{EV}$ = 7200W) as shown in Figure 6.87. Figure 6.82 shows the load profile of each consumer and their associated data received from the DB by the SSM-LC to manage the DREMPs and adapts the total supply to the total demand. Figure 6.83 shows: (a) the power profile of each micro-plant, (b) the total demand and the total generation, and (c) the power mismatch between the total supply and the total demand. According to this figure, the power supply follows the real-time demand when the supply is greater than the demand, and the BMS starts charging the batteries. Thus, the SoC of the BESS increases as shown in Figure 6.84. When the power supply from the PV and wind micro-plants is not enough to feed the loads, the BMS starts discharging the batteries to compensate the lack of renewable power supply. In addition, the BESS compensates also the power mismatch due to communication delay.

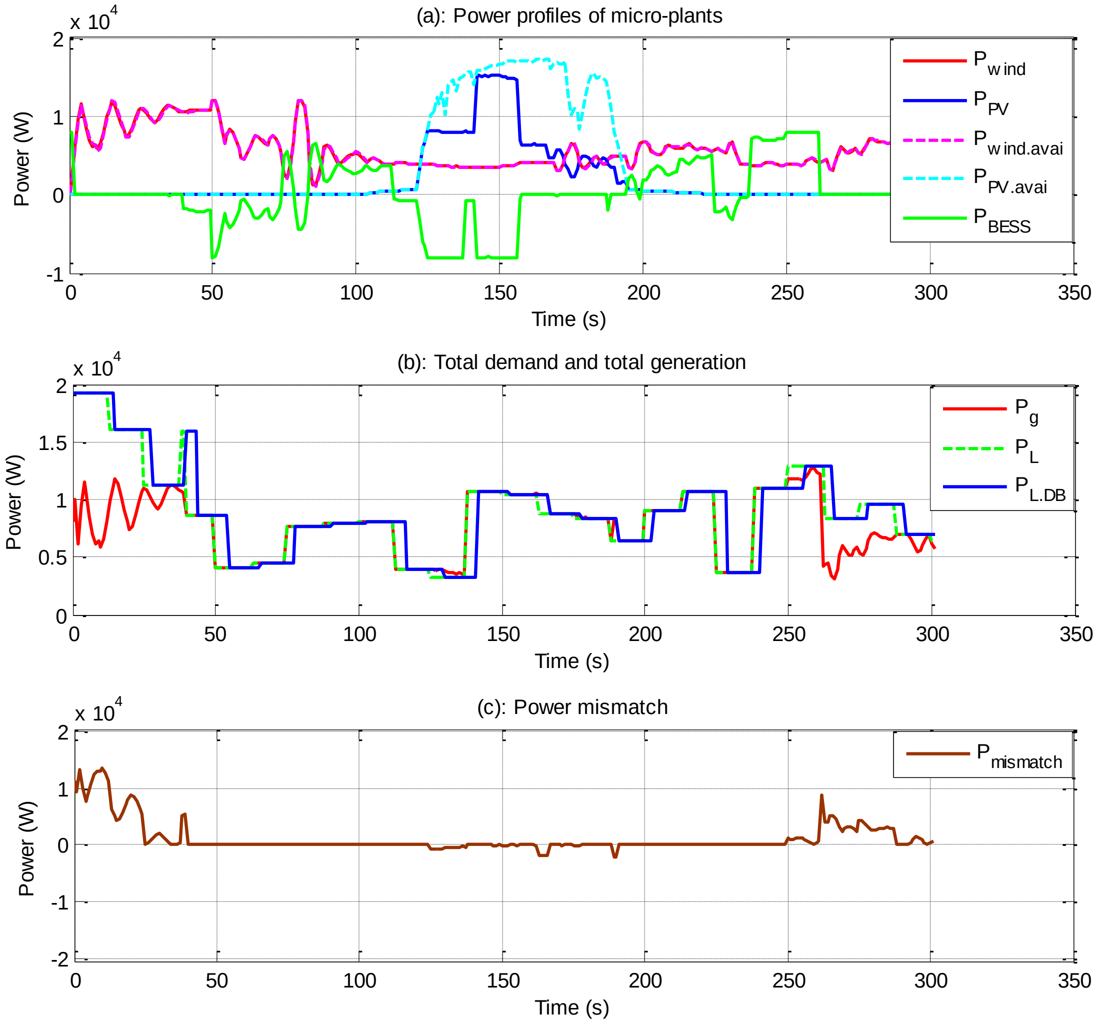


*Figure 6.83: (a) Power profile of each micro-plant, (b) total demand and total generation, (c) power mismatch between the total supply and the total demand.*

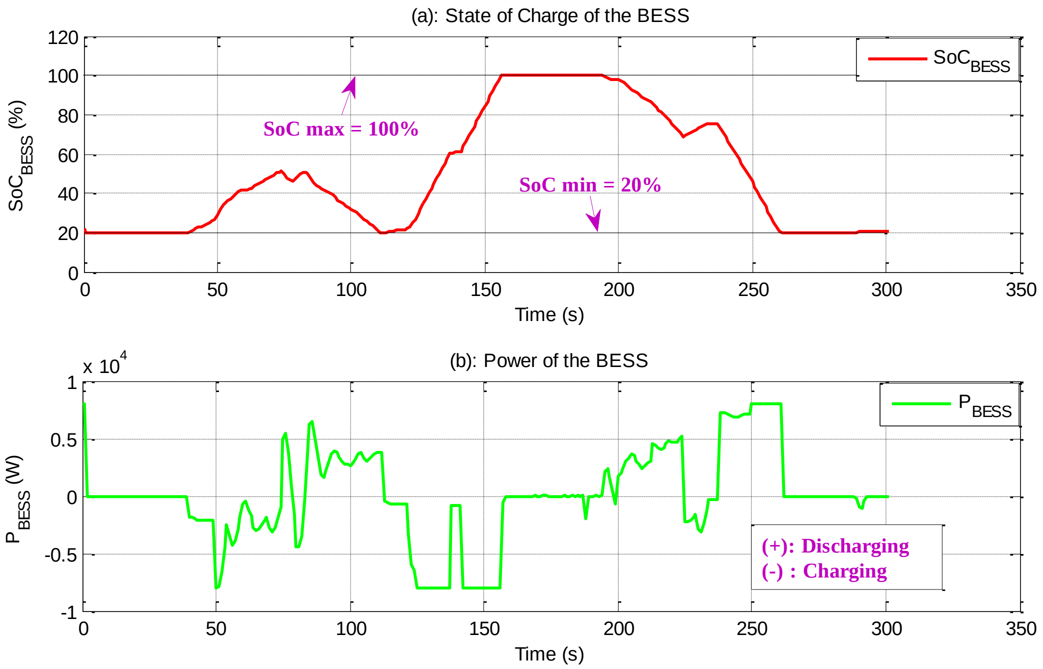


*Figure 6.84: Power and state of charge of the BESS*

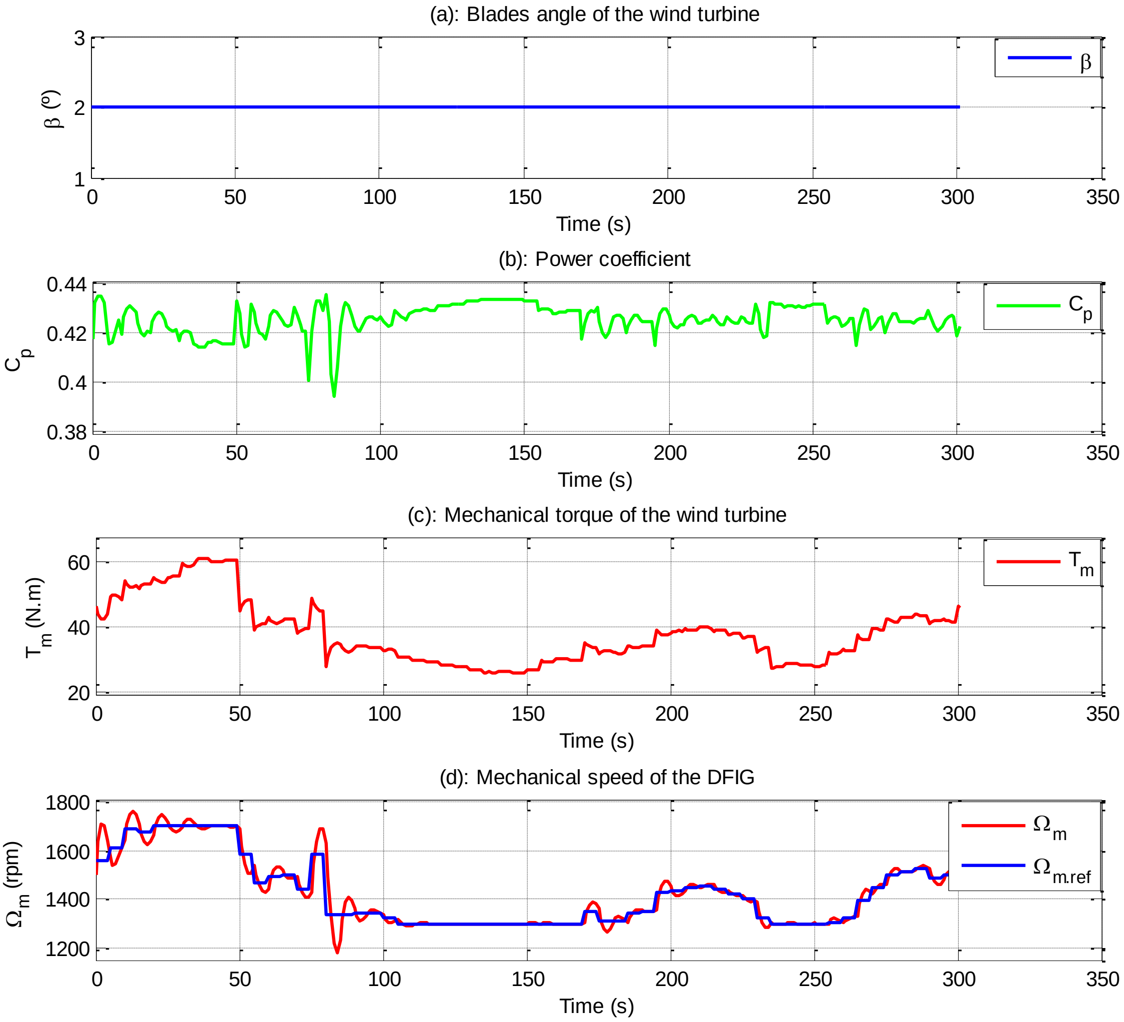


*Figure 6.85: Wind micro-plant mechanical variables*

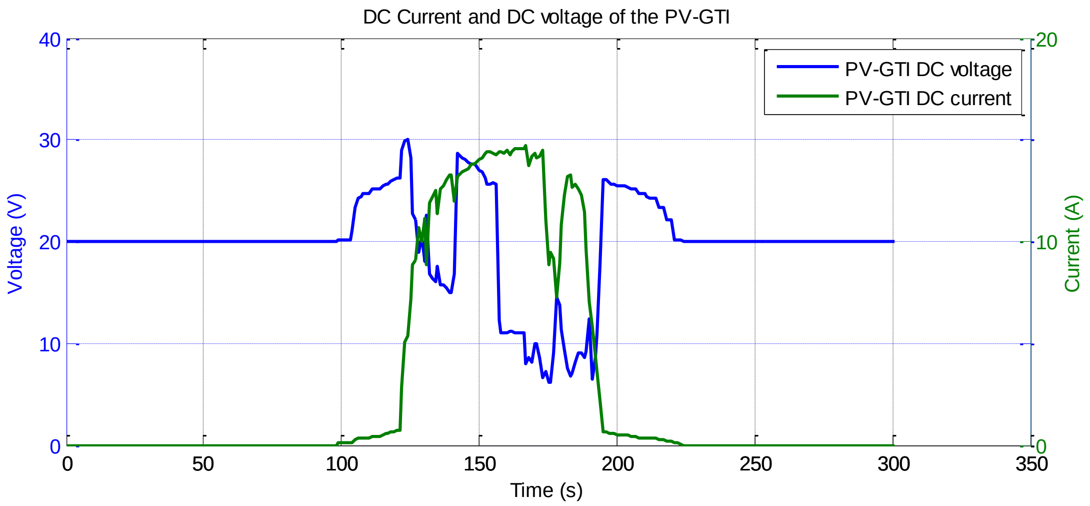


*Figure 6.86: PV micro-plant variables*

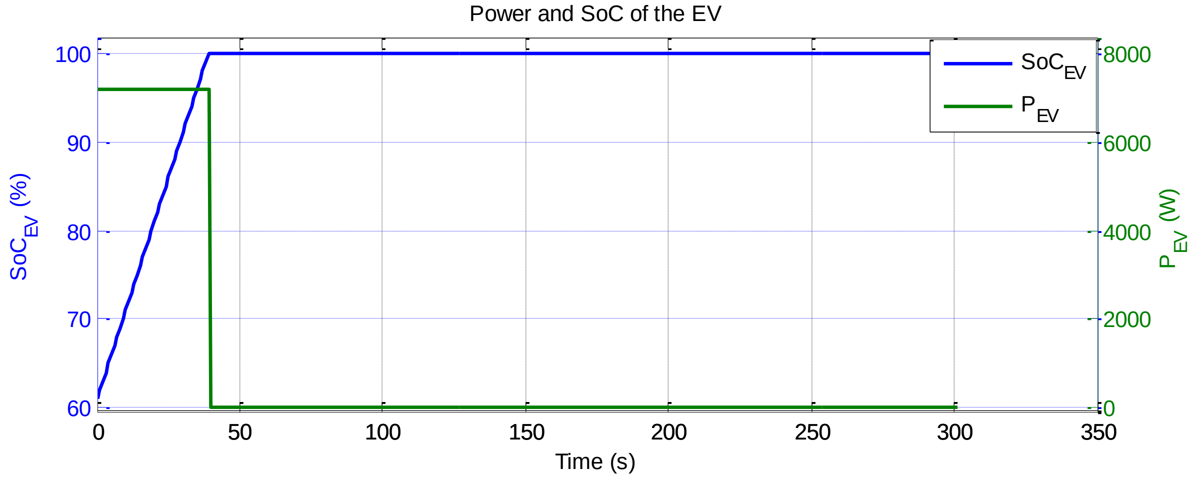


*Figure 6.87: Electric power and SoC of the EV*

Nevertheless, when the BESS is fully charged ($SoC_{BESS}$ = 100%), the BMS prevents any additional charging, thus the BESS could not consume the surplus power due to communication delay as shown in Figure 6.83. Moreover, when the BESS is fully discharged ($SoC_{BESS}$ = 20%) the BMS prevents any additional discharging to protect the batteries, thus the BESS could not support the renewable micro-plants to compensate the lack of power due to communication delay.

From this scenario, we conclude that even with a BESS, the micro-grid is not capable to feed the typical energy needs of its local consumers due to intermittent nature of RES. Thus, the micro-grid could not operate in islanded mode without any DSM strategies.

### 6.6.5.2 Scenario 2: Operation in islanded mode with both SSM and DSM based load shifting

In this scenario, the micro-grid operates in islanded mode with managing the power generation from the local renewable-energy micro-plants as well as the loads of consumers.

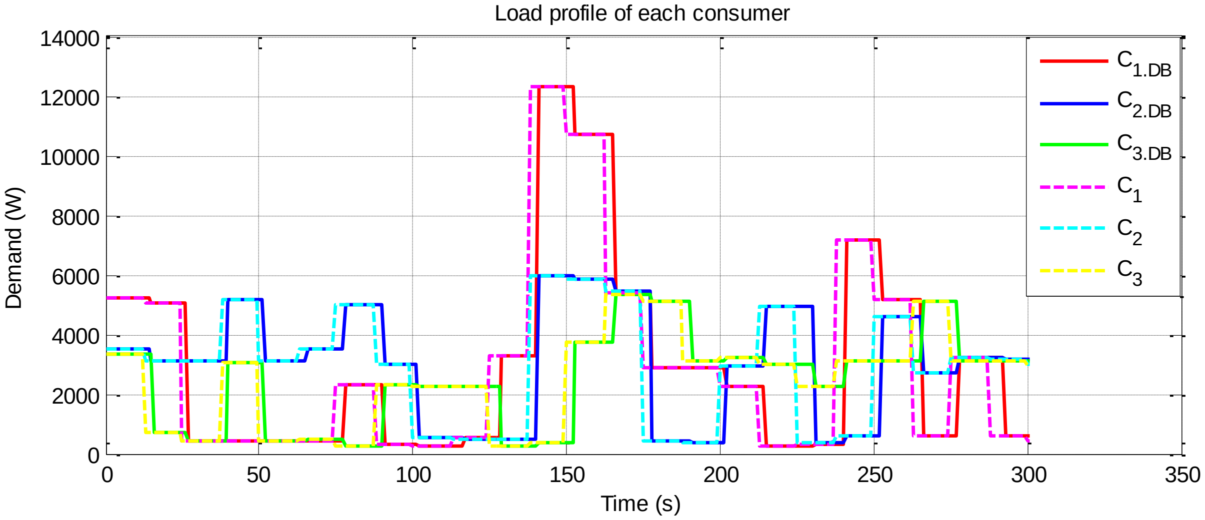


*Figure 6.88 Load profile of each consumer*

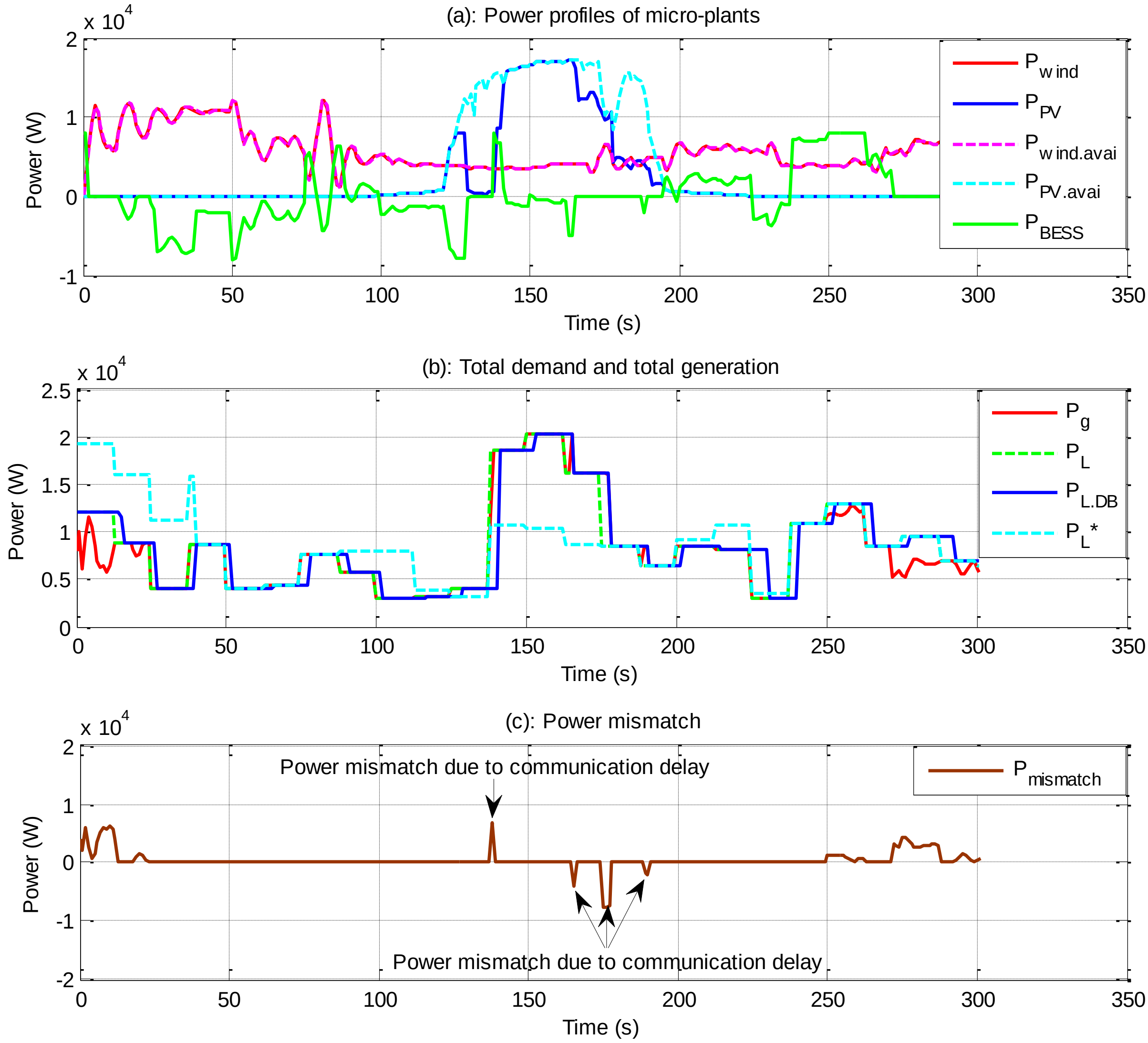


*Figure 6.89:* (a) Power profile of each micro-plant, (b) total demand and total generation, (c) *power mismatch between the total supply and the total demand*.

The DSM strategy that was applied in this scenario is the load shifting from low renewable power production times to high renewable power production times. The BESS is always interconnected to the micro-grid in islanded mode. Figure 6.88 shows the load profile of each consumer after performing the load shifting strategy by the DSM-LC. Figure 6.89 shows: (a) the power profile of each micro-plant, (b) the total demand and the total generation, and (c) the power mismatch between the total supply and the total demand. According to this figure, the power mismatch was reduced compared to the previous scenario thanks to the load shifting strategy. In addition, the BESS compensates the lack of the renewable power supply when its state of charge is above the minimum level ($SoC_{BESS} >$ 20%). Moreover, it compensates the surplus power when its state of charge is under the upper limit ($SoC_{BESS} >$ 100%). Thus, the power supply follows the real-time demand instead of the demand data received from the DB. Nevertheless, the micro-grid is not yet achieved the self-sufficiency even if there is an important available PV power that was not consumed nor stored in the BESS due to the limited storage capacity.

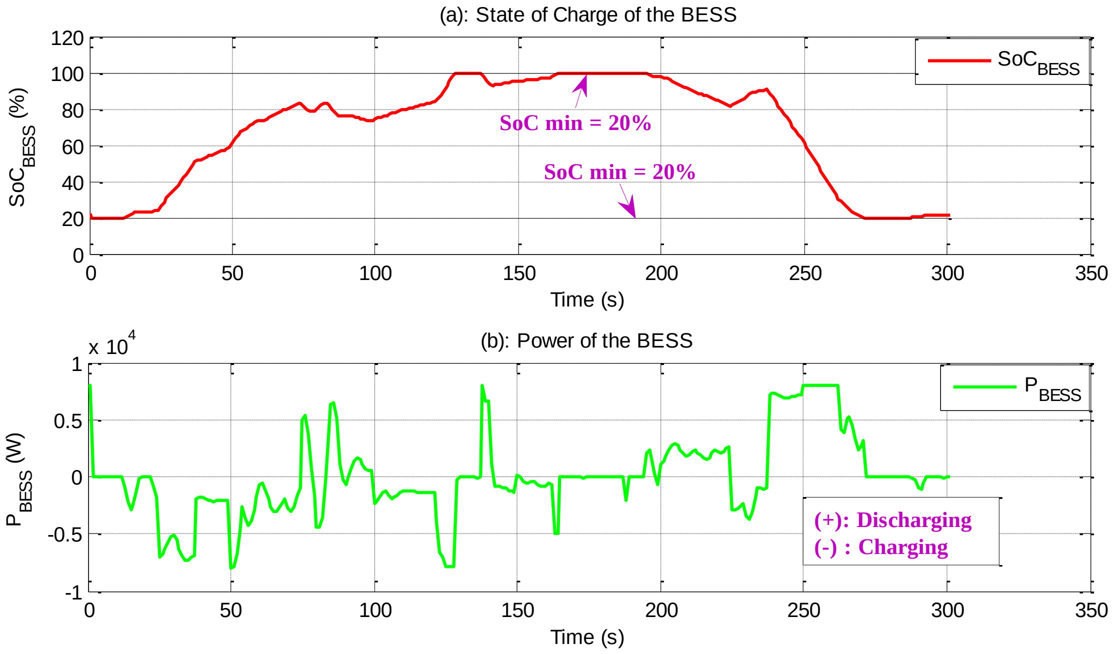


*Figure 6.90: Power and state of charge of the BESS*

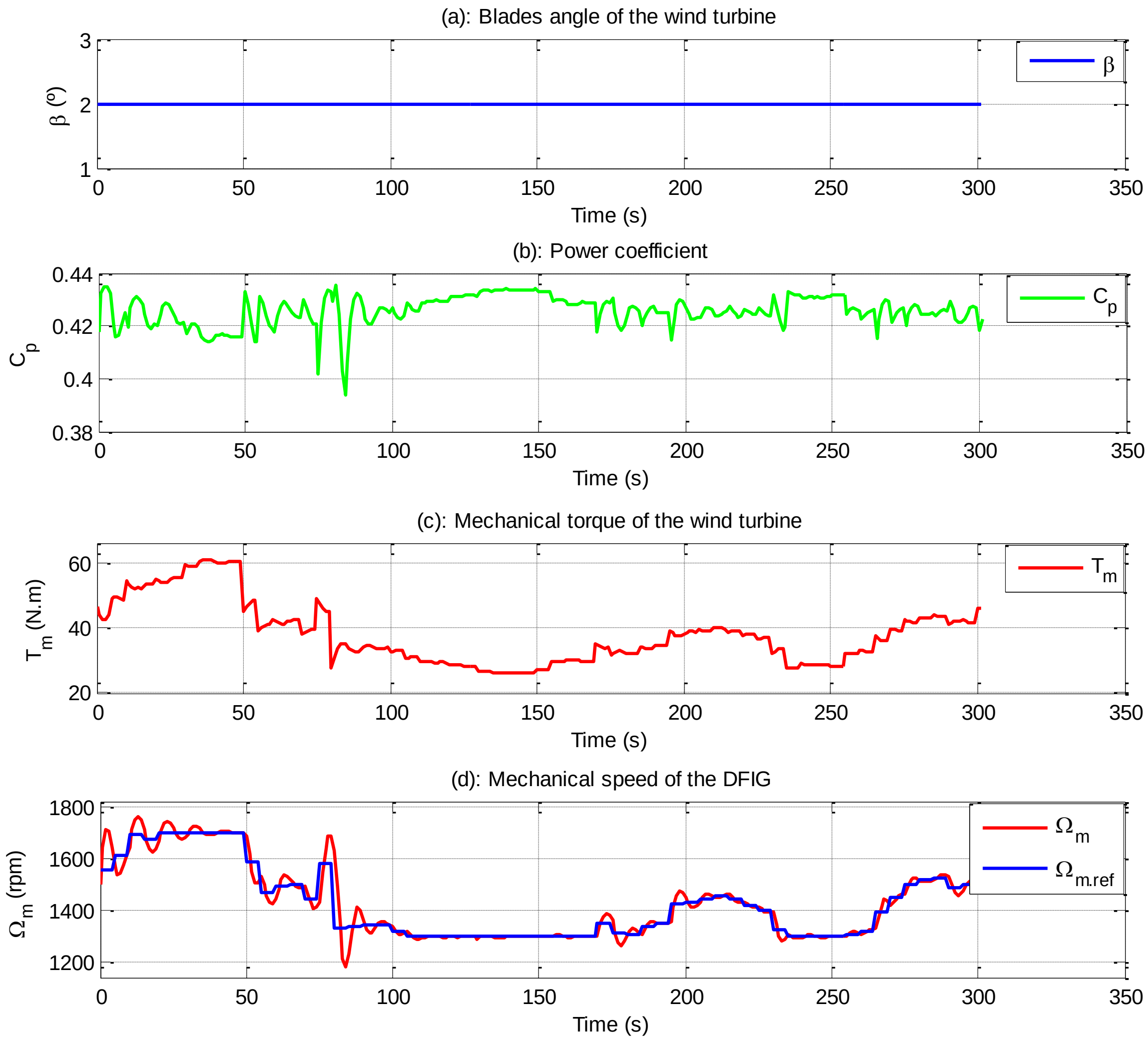


*Figure 6.91: Wind micro-plant mechanical variables*

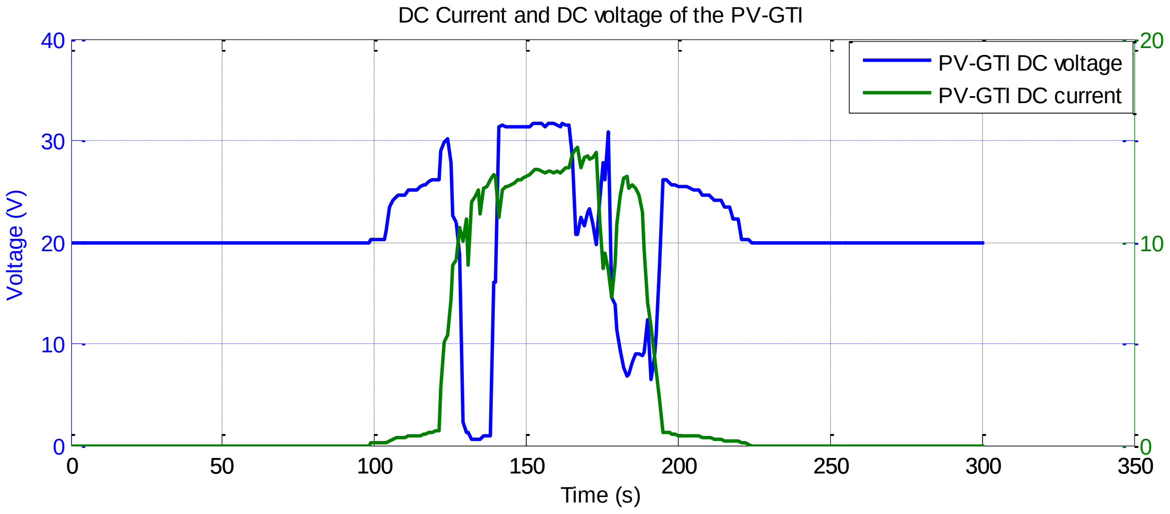


*Figure 6.92: PV micro-plant variables*

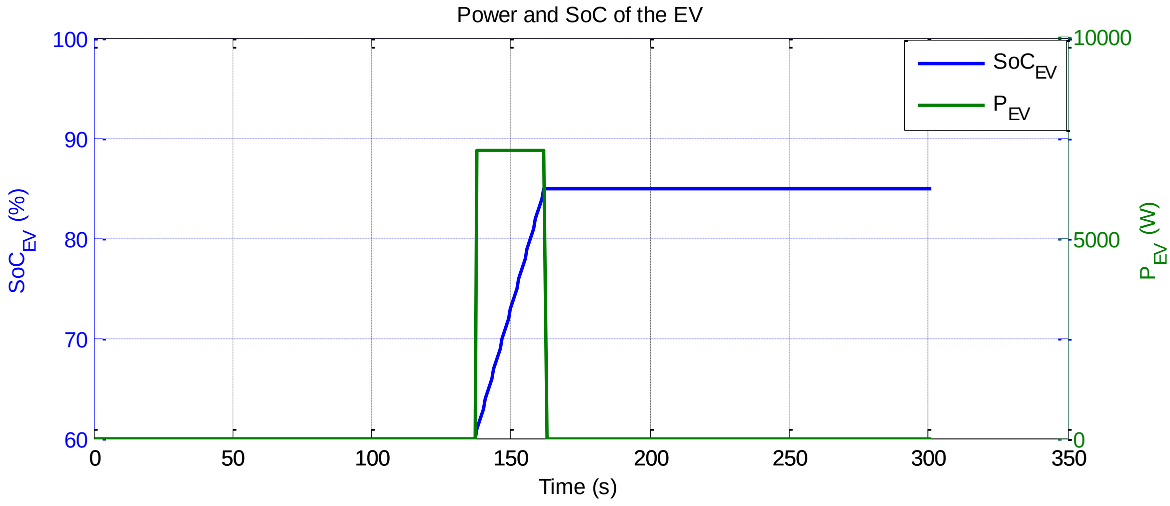


*Figure 6.93: Power and state of charge of the EV*

From this scenario, we conclude that even with a BESS and a load shifting strategy, the micro-grid is not capable to feed the typical energy needs of its local consumers due to intermittent nature of DREMPs. Thus, the load shifting strategy is not enough for the proper operation of the micro-grid in islanded mode. A load conservation strategy is very important in this case to reduce the flexible loads in critical times and skip the DREMPs' power supply limitations.

#### 6.6.5.3 Scenario 3: Operation in islanded mode with both SSM based BESS and DSM based load shifting and load conservation strategies

This scenario is the same as the previous one, but in addition to the SSM and DSM based load shifting, we have applied the load conservation strategy too.

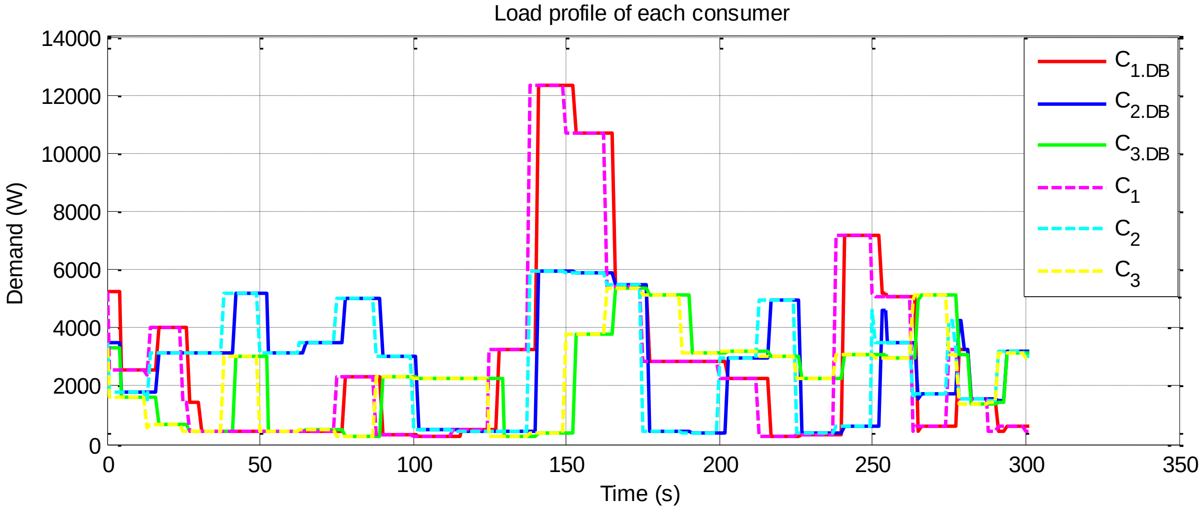


*Figure 6.94: Load profile of each consumer*

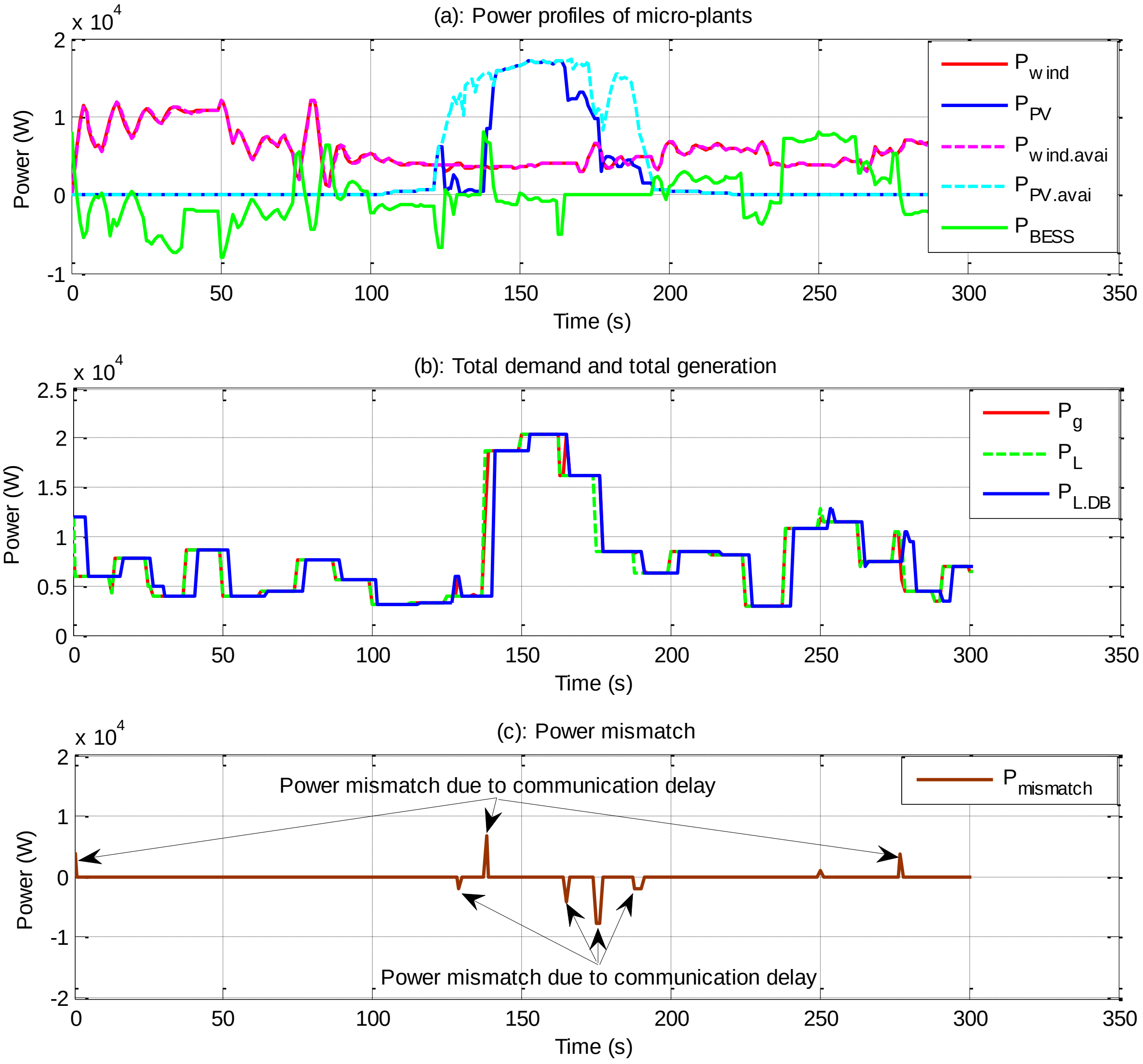


*Figure 6.95:* (a) Power profile of each micro-plant, (b) total demand and total generation, (c) *power mismatch between the total supply and the total demand.*

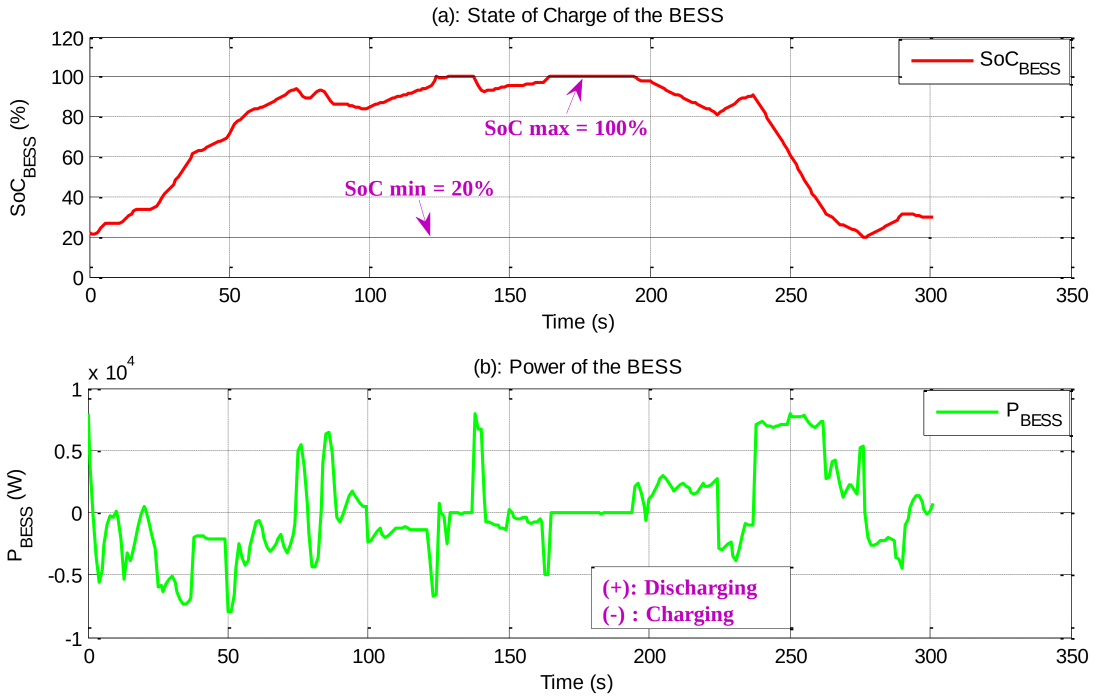


*Figure 6.96: Power and state of charge of the BESS*

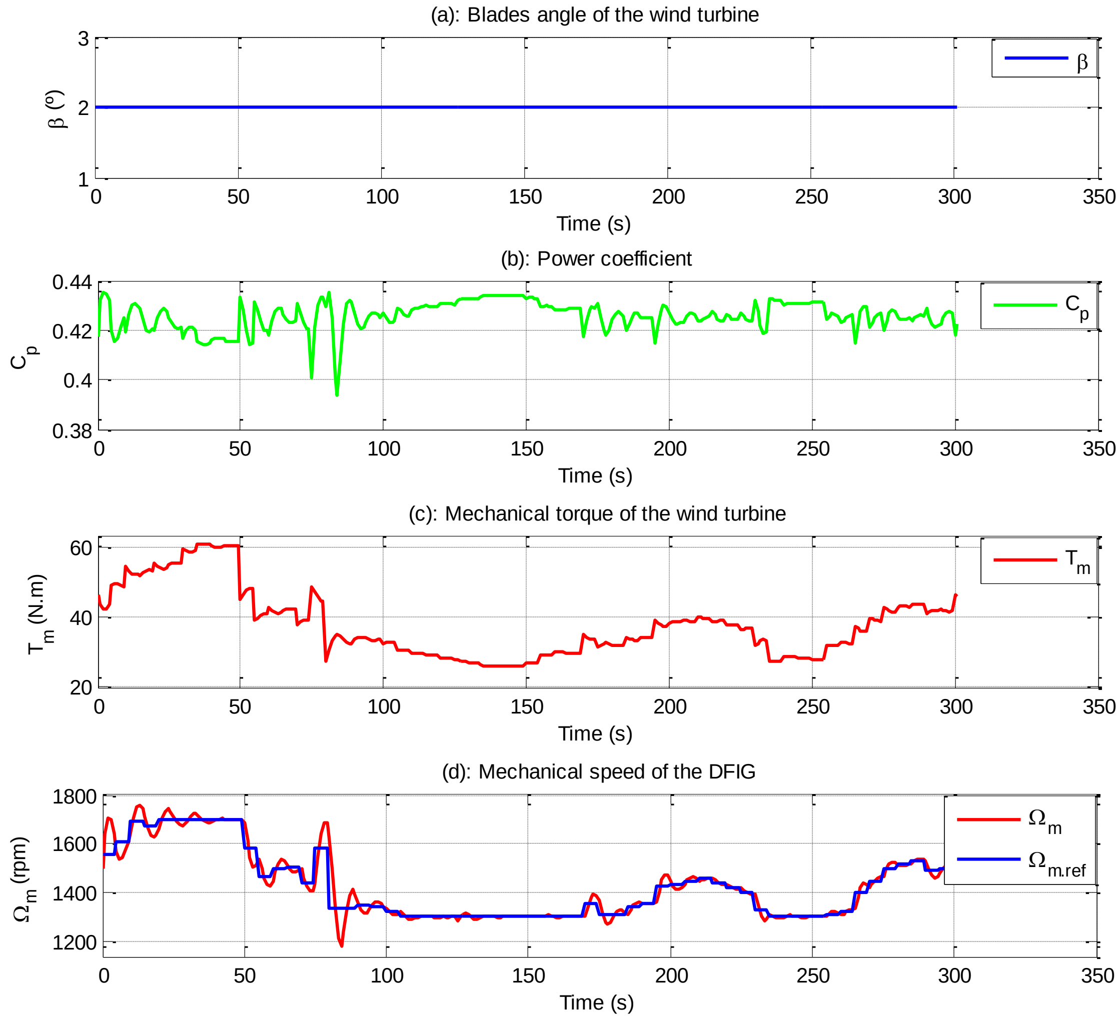


*Figure 6.97: Wind micro-plant mechanical variables*

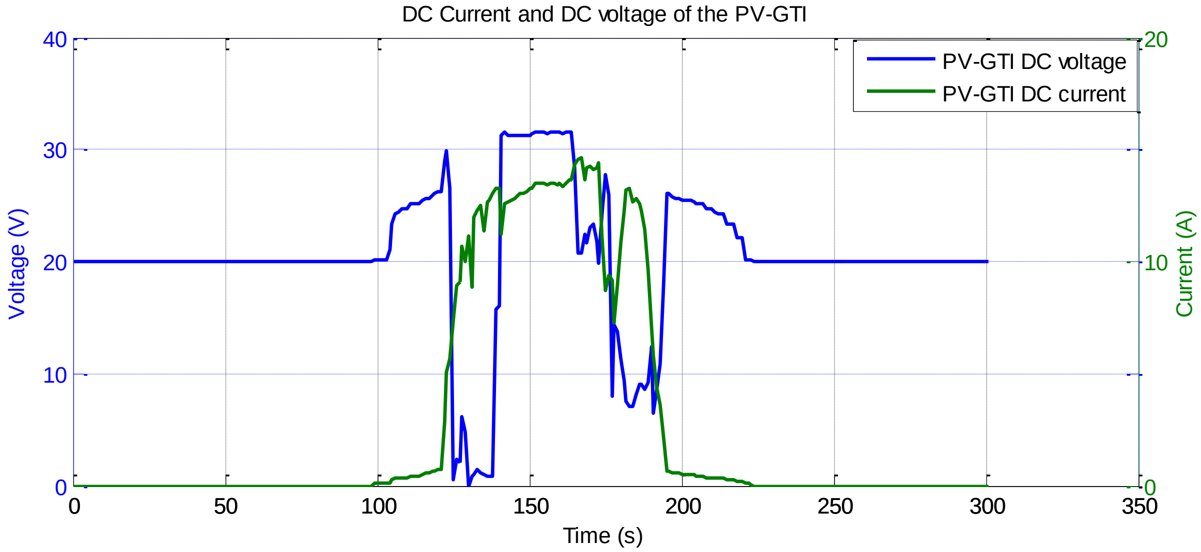


*Figure 6.98: PV micro-plant variables*

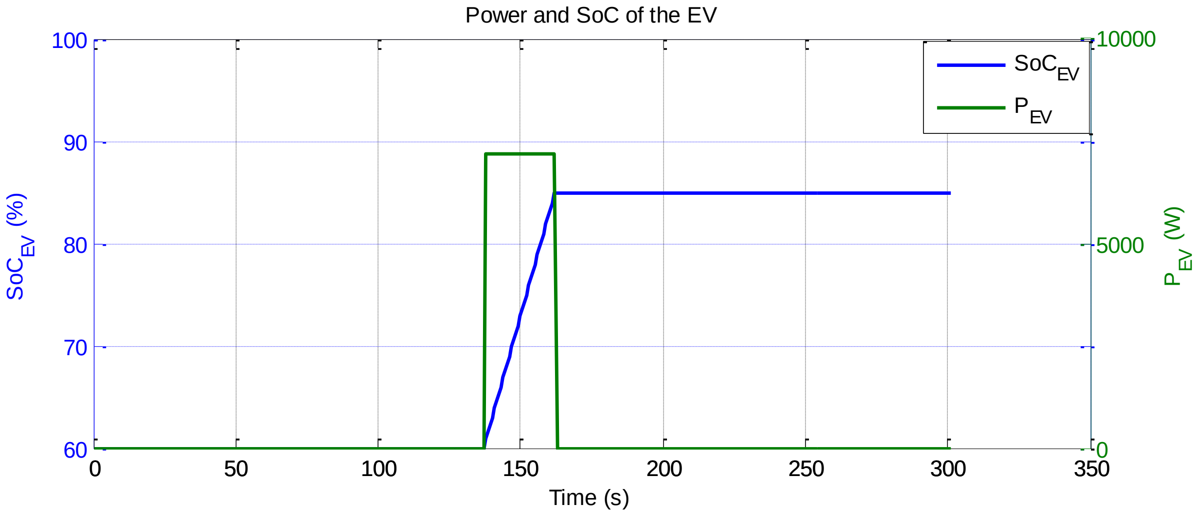


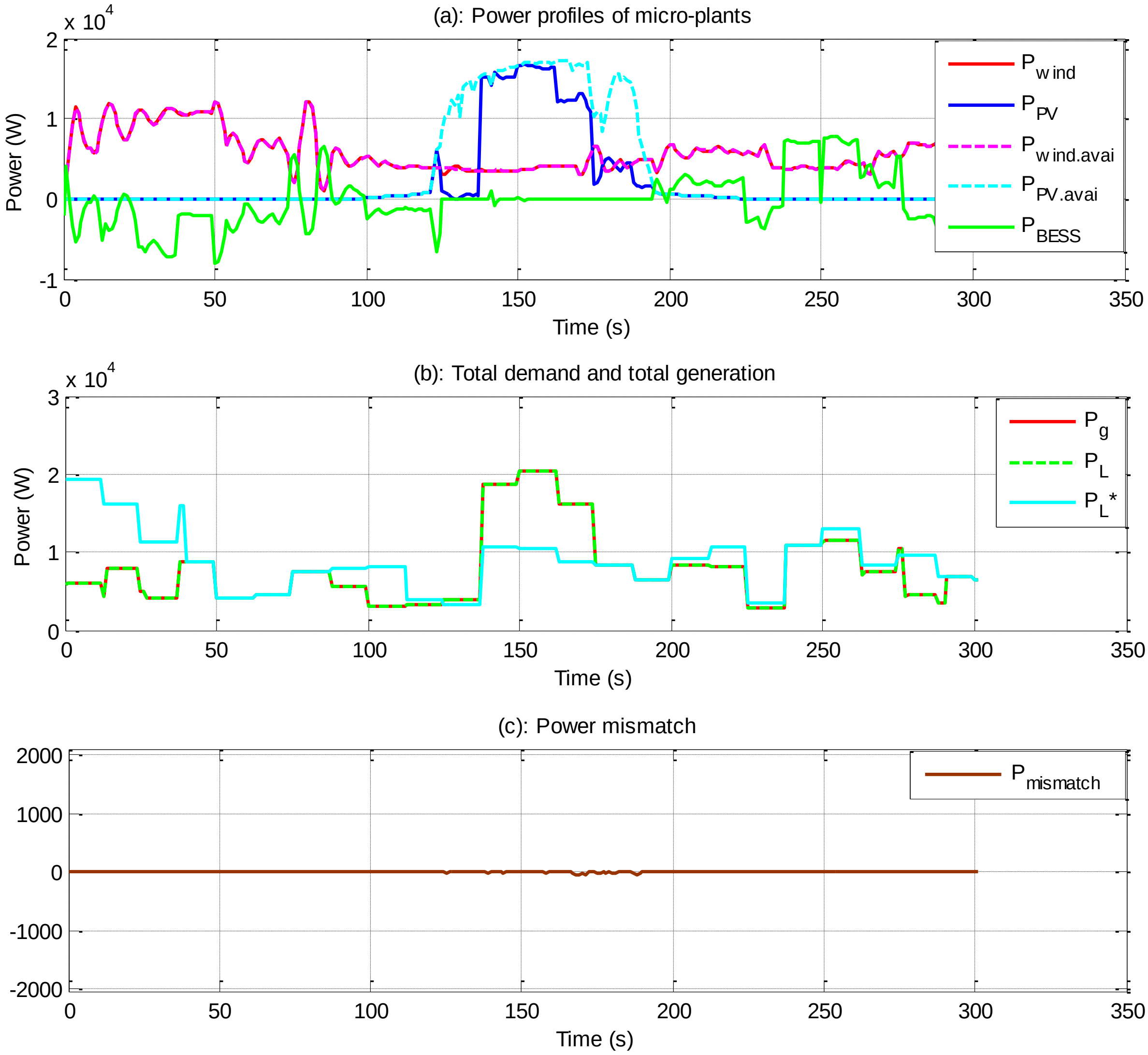
*Figure 6.99: Power and state of charge of the EV*

Figure 6.94 shows the load profile of each consumer after performing both load shifting and load conservation strategies by the DSM-LC. Figure 6.95 shows: (a) the power profile of each micro-plant, (b) the total demand and the total generation, and (c) the power mismatch between the total supply and the total demand. According to this figure, the power mismatch is totally eliminated except the one due to communication delay. The power supply follows perfectly the total demand thanks to the real-time control and the real-time communication between the SSM-LC and the DSM-LC. The BESS consumes the surplus power due to communication delay except when the batteries are fully charged. Moreover, it compensates the lack of power due to communication delay except when the batteries are at their minimum SoC. The BMS protects the BESS from being over-charged or undercharged for safety reasons and to extend the lifetime of the batteries.

Figure 6.100 shows the power mismatch between the total demand and the total supply when neglecting the communication delay of both SSM-LC and DSM-LC as well as the delay due to the

4G LTE network. It is clear that both supply and demand are perfectly matched in the presence of a BESS as well as DSM strategies.

From this scenario, we conclude that the BESS, the SSM of renewable micro-plants, and the DSM based load shifting and load conservation strategies are all important options for the appropriate operation of the micro-grid in islanded mode. Because in islanded mode there is no possibility to exchange power with the main grid and any power mismatch will lead to stability and power quality issues such as voltage flickers and harmonics.


(a): Power profiles of micro-plants

(b): Total demand and total generation

(c): Power mismatch

*Figure 6.100: Power profiles without communication delay*

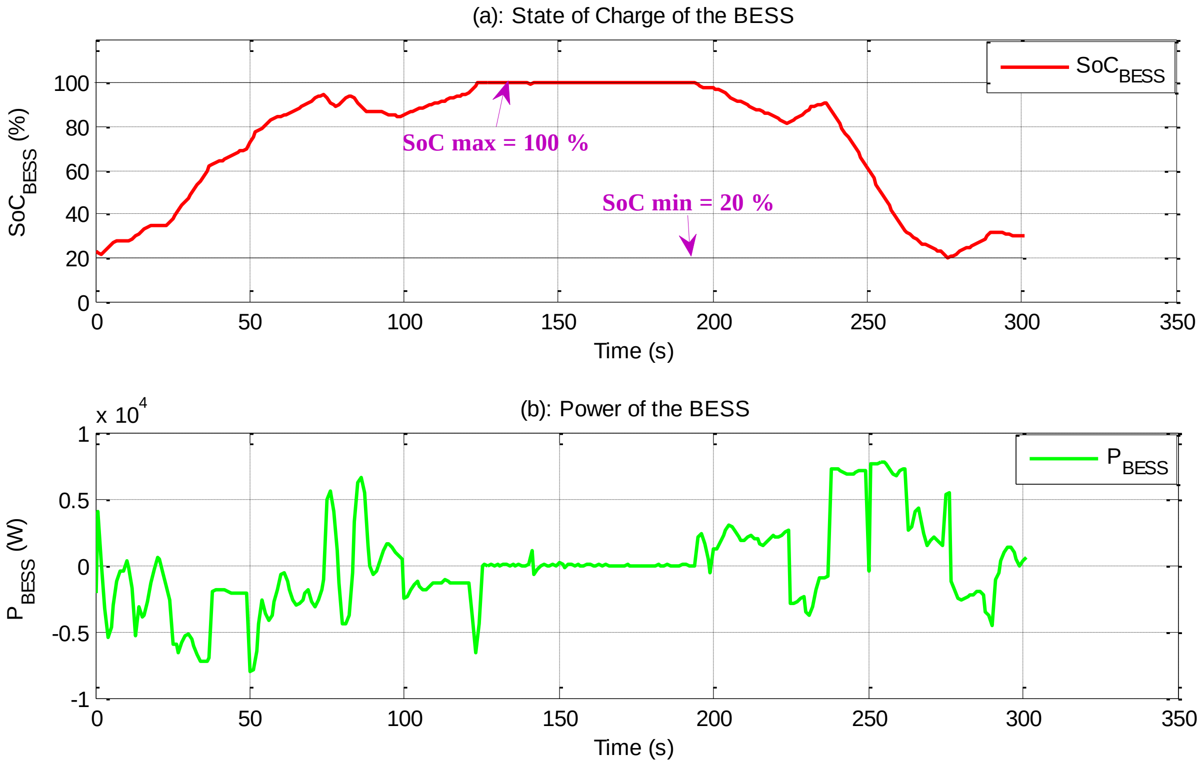


*Figure 6.101: Power and SoC of the BESS without communication delay*

## 6.7 Conclusion

In this chapter, we present the experimental works and the research studies conducted at our laboratory, LAT-Tlemcen, to achieve building prototypes of smart distributed renewable-energy micro-plants. Four types of renewable micro-plants are developed at the LAT-Tlemcen and are fully presented. In addition, we present the modeling and controlling of renewable-energy MPs. We saw that the micro-plants models have the same behavior as the experimental ones. In addition, our developed PV and wind micro-plants can operate in both MPPT and non-MPPT modes where they extract exactly the needed power from the maximum available power. Moreover, the impact of integrating renewable energy MPs on power grids is well presented. It was shown that the integration of distributed renewable-energy production thanks to MPs will enforce the weakness of power grids in Africa. It reduces the generated power from the conventional generators, hence, reducing the consumption of fuel, minimizing the Greenhouse Gas Emissions (GHE), and reducing many types of losses. The drawbacks are the negative impact on the quality of service and on the stability of the power grid such as voltage sag and voltage swell due to the intermittent availability of the sources. With an appropriate control of the e.m.f. and the mechanical power of the conventional generators, we can reduce the apparatus and the disturbances results from the renewable MPs. Due to the fact that apparatus and disturbances propagate rapidly in the connected network, the control and management of the generated power from renewable sources are very important to avoid fragilizing the power grid and to keep the system working at optimal efficiency.

We also tackled an important subject to explore the potential benefit of DREMPs in smart grids, which is the information and communication (ICT) technologies. We presented the communication interactions results between the supply-side and demand-side resources. In addition, we highlighted the communication issues such as communication delay and failures that may occur during the operation of the communication system. We saw that if the communication delay is high, then the information is lost and the much the data are wrong. This will lead to very wrong decisions during the energy management. Thus, a proper communication between the MPs and the demand-side resources will help in building a robust, self-sufficient, and stable micro-grid system.

Furthermore, some practical applications of smart micro-grids based renewable energy micro-plants for powering small-scale residential communities are developed and presented in this chapter. The idea concerns the development of renewable energy-based smart micro-grid solutions to support the development of small-scale communities in off-grid and on-grid areas and serve their typical energy needs such as cooling, heating, pumping, lightening, and other electricity usages. The main objective in this part consists in managing electricity production from renewable energy micro-plants as well as managing the loads of consumers to develop effective solutions for achieving the self-sufficiency of micro-grids in both grid-connected and islanded modes. We have replaced the traditional dispatch-based forecasting methods by iterative real-time control. A decentralized control strategy is developed to control the micro-grid in both grid-connected and islanded modes in a way that each micro-plant produces an exact quantity of energy in real time to follow the consumption variation. For the wind micro-plant, we used a pitch regulation strategy to control the blades angle of the wind turbine and produce an exact quantity of energy and maintain a constant power supply, less than the MPPT available power, even with a variable wind speed. Concerning the PV micro-plant, we implemented another algorithm besides the MPPT algorithm that searches for the appropriate PV-GTI DC voltage to produce a precise amount of power from the PV micro-plant and maintain a constant power supply, less than the MPPT available power, even with a variable solar irradiance. Concerning the demand-side resources, two strategies are proposed to manage consumers' appliances and skip the weather limitations: load shifting and load conservation strategies. Their effect on the power mismatch between the generation and the consumption in the micro-grid is well presented. We saw that, even if the total DREMPs' installed capacity is higher than the total demand in the micro-grid, the real-time generated power is, in many times, not enough to feed the typical energy needs of consumers without any demand-side management due to the intermittent nature of DREMPs and the weather limitations. Thus, the micro-grid imports a significant power from the main grid during low renewable power production times to feed the loads. The conventional solutions to develop a self-sufficient micro-grid is to make an extra-over-sizing of DREMPs to feed the load requirements which lead to an extra-expensive cost of installation. Our proposed solution is to manage the consumers' loads besides the SSM. We saw that the DSM strategies are very important to build a self-sufficient micro-grid. Moreover, the BESS is also important in case the micro-grid operates in islanded mode. We observed that the BESS compensates the decision-making errors due to communication delay. Nevertheless, when the BESS is fully charged, the BMS prevents any additional charging, thus the BESS could not consume the surplus power due to communication delay. Moreover, when the BESS is fully discharged, the BMS prevents any additional discharging to protect the batteries, thus the BESS could not support the renewable micro-plants to compensate the lack of power due to communication delay. We also noticed in this chapter that, even with a BESS, the micro-grid is not capable of operating in islanded mode without any DSM strategies due to the intermittent nature of DREMPs.

In general, the SSM eliminates the power mismatch due to the surplus power in islanded mode, and the power export to the main grid in grid-connected mode. Thus, the reverse power flow is eliminated and the power flows in one direction as the conventional radial grid, which reduces the stability issues presented in part 3 of this chapter, and reduces the voltage rises in load buses. In addition, the DSM eliminates the power mismatch due to the lack of renewable power. Thus, the micro-grid operation in both SSM and therefore the DSM is mandatory, especially in islanded mode, to achieve the self-sufficiency and conserve the system stability.

# General conclusion and perspectives

The work presented in this thesis was carried out within the Automatic Laboratory of Tlemcen LAT, at the Faculty of Technology of the University Aboubakr Belkaïd -Tlemcen. It is part of a large project, which consists of the design, modeling, control and real-time intelligent management of distributed renewable-energy microplants. It goes in the sense of the change undergone on the electrical power networks, since we are moving slowly but surely towards low-power distributed renewable-generation by compared to traditional centralized high-power fossil-fuel generation.

An exhaustive bibliographic research was carried out throughout this thesis about the latest researches and developments of distributed renewable MPs as promising technologies for the future smart grids and micro-grids. We saw that ESSs and power electronic converters are vital components of distributed renewable energy micro-plants due to their intermittent nature. We presented the numerous technical, economic, environmental and regulatory concerns arisen from the high penetration levels of renewable MPs including power quality issues, grid instability, increase in the fault level and more. According to the literature, these issues may have a great influence on supply security and reliability, equipment control and protection, islanding, and safety. In addition, the integration of a large number of renewable MPs in power network cause fundamental changes to the power network topology, which may eventually shift the power system architecture from vertical to a horizontal one. Moreover, we have noticed that the impact of DREMPs on power networks significantly depends on the type of DREMPs as well as the type of the network. In this context, more studies are needed to solve these challenges so that DREMPs can be successfully integrated. In addition, accessing various types of sources of significant operational flexibility become extremely crucial.

An approach that does not demand grid integration is off-grid HPS based renewable MPs. The literature demonstrated that in locations where the national utility grid is not accessible due to some financial and technical concerns, an HPS based renewable MPs and ESSs is a comparatively cost-effective alternative, making it suited for power applications in remote communities. However, controlling process and coordination is a difficult task. These systems necessitate a deep understanding due to the various types of renewable MPs and their different behaviors. Thus, an EMS with ML methods and AI are very important for the proper operation of future smart grids and micro-grids.

Concerning the results and discussions, we have presented the experimental works and the research studies conducted at our laboratory, LAT-Tlemcen, to achieve building prototypes of smart renewable-energy micro-plants. Four types of renewable micro-plants that are developed at the LAT-Tlemcen have been fully presented. We saw here all the advantage of the experiments, which allows us to better understand and identify the real difficulties and to allow a more appropriate modelling. In addition, we have presented the modeling and controlling of renewable-energy MPs. We saw that the micro-plants (MP) models have the same behavior as the experimental ones. In addition, our developed PV and wind micro-plants can operate in both MPPT and non-MPPT modes where they extract exactly the needed power from the maximum available power.

Moreover, the impact of integrating renewable energy MPs on power grids is well presented in different scenarios of the simulations. It was shown that the integration of distributed renewable-energy MPs would enforce the weakness of power grids. The drawbacks are the negative impact on the quality of service and on the stability of the power grid such as voltage sag and voltage swell due to the intermittent availability of the sources. With an appropriate control of the e.m.f.

and the mechanical power of the conventional generators, we can reduce the apparatus and the disturbances results from the renewable MPs.

In this thesis, we also tackled an important subject to explore the potential benefit of renewable MPs in smart grids, which is the information and communication technologies. We presented the communication interactions results between the supply-side and demand-side resources in a developed micro-grid. In addition, we highlighted the communication issues such as communication delay and failures that may occur during the operation of the communication system. We saw that the more the communication delay is high, the more the information is lost and the more the data are wrong. This will lead to erroneous decisions during the energy management. Thus, a proper communication between the MPs and the demand-side resources will help in building a robust, self-sufficient, and stable micro-grid system. We would have liked to better deal with the communication parts between the elements and the database in order to have a more experimental approach on this part, but the analysis would have been difficult due to the simultaneous operation of several experimental platforms, which was not possible given the small number of research personnel involved that would have had to be mobilized at the same time.

Some practical applications of renewable energy-based smart micro-grid solutions for powering small-scale residential communities in off-grid and on-grid areas and serve their typical energy needs are developed and presented in this thesis. The main objective consists in managing electricity production from renewable energy micro-plants as well as managing the loads of consumers to develop effective solutions for achieving the self-sufficiency of micro-grids in both grid-connected and islanded modes. We replaced the traditional dispatch-based forecasting method by iterative real-time control.

We sought, not, as always in renewable energy theses, the maximum power (by MPPT) but rather to control the power produced in order to minimize the impact on the stability of the network to which the microgrid is connected. Indeed, we showed during the preliminary study, that the behavior of the global power network could be very negatively impacted during sudden variations in the production of electrical energy via intermittent and variable sources.

A decentralized control strategy is developed to control the micro-grid in both grid-connected and islanded modes in a way that each micro-plant produces an exact quantity of energy in real time to follow the consumption variation. We have tested the control strategies without prior knowledge or estimation of the consumption and availability of renewable energy resources.

We saw that, even if the total DREMPs' installed capacity is more important than the total demand in the micro-grid, the real-time generated power is, in many times, not enough to feed the typical energy needs of consumers without any demand-side management due to the intermittent nature of DREMPs and the weather limitations. The conventional solutions to develop a self-sufficient micro-grid is to make an extra-over-sizing of DREMPs to feed the load requirements which lead to an extra-expensive cost of installation. Our proposed solutions is to manage the consumers' loads besides the SSM. We saw that the DSM strategies are very important to build a self-sufficient micro-grid. Moreover, the BESS is also important in case the micro-grid operates in islanded mode.

We saw that the BESS compensates the decision-making errors due to communication delay. Nevertheless, when the BESS is fully charged / discharged, the BMS prevents any additional charging / discharging, thus the BESS could not compensate the power mismatch due to communication delay.

In general, the SSM eliminates the power mismatch due to the surplus power in islanded mode, and the power export to the main grid in grid-connected mode. Thus, the reverse power flow is eliminated and the power flows in one direction as the conventional radial grid, which reduces the stability issues, and reduces the voltage rises in load buses. In addition, the DSM eliminates the power mismatch due to the lack of renewable power. Thus, the micro-grid operation in both SSM and DSM is mandatory, especially in islanded mode, to achieve the self-sufficiency and conserve the system stability.

The perspectives to this work can be:

- Participating in finishing the works on the four experimental prototypes, especially WTE based on a SG, developed by the LAT team and validating them to be used for other PhD and master students.
- Interfacing the experimental benches of the developed prototypes of renewable MPs and performing real-time communications between them and distributing the production power demand over the microplants.
- Developing experimental benches of grid-connected / islanded micro-grid based on the developed prototypes of renewable MPs, internet of things and smart meters to study the micro-grid stability in term of voltage and frequency with unpredictable loads. We will try to make full use of ICT to instantly relay information and match supply with demand, support well-informed decisions, and keep systems operating at optimal efficiency.
- We will try also to detect grid problems from the micro-plants (such as transmission line failure) and help make appropriate changes; thereby, we will enhance the supply security.
- Using a cluster of 6 RPi3 available at the LAT-Tlemcen, we would like to develop a blockchain technology-based system composed of many neighborhood microgrids and to code the real-time energy packet transactions between them. A variable real-time pricing will be used, and the objective is to maximise the benefits of each micro-grid while minimizing the technical and financial constraints using the AI and ML methods.

# Appendix A.

Figure A. 1 shows the printed circuit boards that used for the PWM control and for the measurement of currents and voltages.

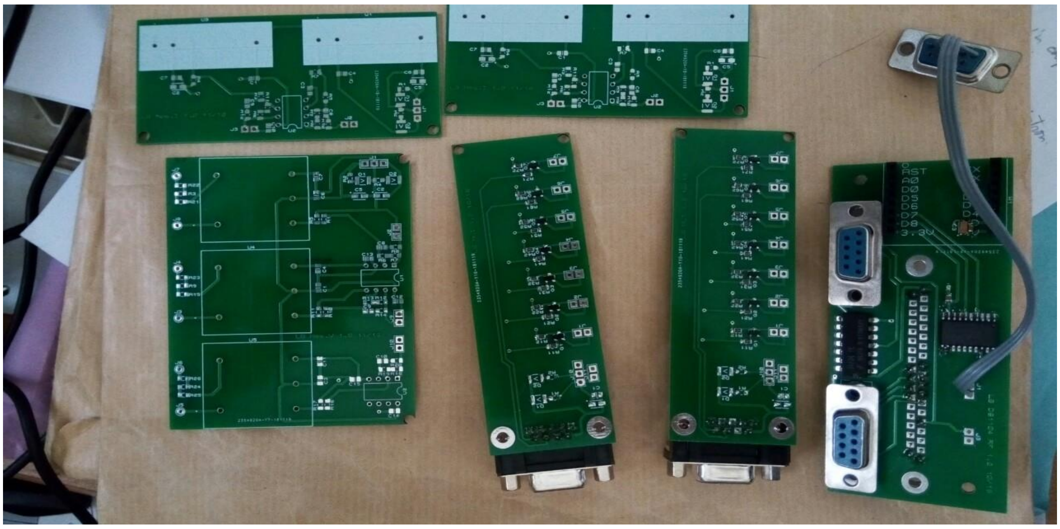


*Figure A. 1 Printed Circuits Board for PWM control and voltage/current measurement*

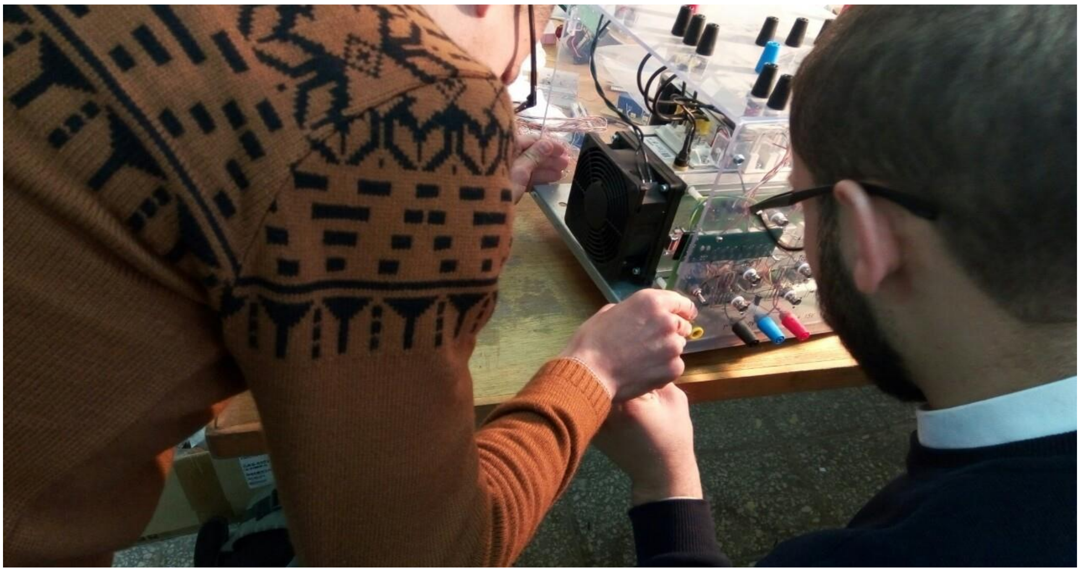


*Figure A. 2 Welding the PWM cards and place them in the inverters*

*Table A. 1 Equipment bought by UNU*

| **Description** | **Vendor** | **Price € (ex VAT)** |
|---|---|---|
| **Machines** | Langlois | 12147.60 |
| **Control board** | dSAPCE GmbH | 4400.00 |
| **Sun power converter** | GWL Power | 859.22 |

| | | |
|---|---|---|
| **Power converter** | Semikron | 1865.30 |
| **Measurement and electronic parts** | Farnell | 9581.77 |
| | **Total** | 28853.89 |

*Table A. 2 Equipment bought by UoT/LAT*

| **Description** | **Vendor** | **Price DZD** |
|---|---|---|
| **6 PV panels** | ALPV | 139230 |
| **Power converter** | Semikron/ENTEC | 300000 |
| **Fluke43b** | Fluke/ESLI | 550000 |
| | **Total** | 989 230 |

## References

ABB, 2021. How poor power quality is damaging system performance | ABB [WWW Document]. News. URL https://new.abb.com/news/detail/79505/how-poor-power-quality-is-damaging-system-performance (accessed 5.30.22).

Abdi, H., Mohammadi-ivatloo, B., Javadi, S., Khodaei, A.R., Dehnavi, E., 2017. Energy Storage Systems, in: Distributed Generation Systems. Elsevier, pp. 333–368. https://doi.org/10.1016/B978-0-12-804208-3.00007-8

Abdullah Asuhaimi, F. binti, 2019. Delay and energy efficiency optimizations in smart grid neighbourhood area networks (PhD). University of Glasgow.

Abdulwahid, A., 2018. A Novel Method of Protection to Prevent Reverse Power Flow Based on Neuro-Fuzzy Networks for Smart Grid. Sustain. Switz. 10. https://doi.org/10.3390/su10041059

Abu-Mouti, F.S., El-Hawary, M.E., 2011. Optimal Distributed Generation Allocation and Sizing in Distribution Systems via Artificial Bee Colony Algorithm. IEEE Trans. Power Deliv. 26, 2090–2101. https://doi.org/10.1109/TPWRD.2011.2158246

Acharya, N., Mahat, P., Mithulananthan, N., 2006. An analytical approach for DG allocation in primary distribution network. Int. J. Electr. Power Energy Syst. 28, 669–678. https://doi.org/10.1016/j.ijepes.2006.02.013

Ackermann, T., Andersson, G., Söder, L., 2001a. Distributed generation: a definition1In addition to this paper, a working paper entitled ‘Distributed power generation in a deregulated market environment’ is available. The aim of this working paper is to start a discussion regarding different aspects of distributed generation. This working paper can be obtained from one of the authors, Thomas Ackermann.1. Electr. Power Syst. Res. 57, 195–204. https://doi.org/10.1016/S0378-7796(01)00101-8

Ackermann, T., Andersson, G., Söder, L., 2001b. Distributed generation: a definition1In addition to this paper, a working paper entitled ‘Distributed power generation in a deregulated market environment’ is available. The aim of this working paper is to start a discussion regarding different aspects of distributed generation. This working paper can be obtained from one of the authors, Thomas Ackermann.1. Electr. Power Syst. Res. 57, 195–204. https://doi.org/10.1016/S0378-7796(01)00101-8

Ackermann, T., Knyazkin, V., 2002. Interaction between distributed generation and the distribution network: operation aspects, in: IEEE/PES Transmission and Distribution Conference and Exhibition. Presented at the IEEE/PES Transmission and Distribution Conference and Exhibition, pp. 1357–1362 vol.2. https://doi.org/10.1109/TDC.2002.1177677

Adamiak, M., Baigent, D., Mackiewicz, R., 2009. IEC 61850 communication networks and systems in substations: An overview for users. Prot. Control J. 61–68.

Adaramola, 2014. Wind Turbine Technology: Principles and Design [WWW Document]. Routledge CRC Press. URL https://www.routledge.com/Wind-Turbine-Technology-Principles-and-Design/Adaramola/p/book/9781774633366 (accessed 6.16.22).

Adefarati, T., Bansal, R. c., 2016. Integration of renewable distributed generators into the distribution system: a review. IET Renew. Power Gener. 10, 873–884. https://doi.org/10.1049/iet-rpg.2015.0378

Adil, A.M., Ko, Y., 2016. Socio-technical evolution of Decentralized Energy Systems: A critical review and implications for urban planning and policy. Renew. Sustain. Energy Rev. 57, 1025–1037. https://doi.org/10.1016/j.rser.2015.12.079

Adzic, E., Ivanovic, Z., Adzic, M., 2009. Maximum power search in wind turbine based on fuzzy logic control. Aeta Polytech. Hung. 131–148.

Afework, B., Elbaz, J., Hanania, J., Stenhouse, K., Donev, J., 2021. Non-dispatchable source of electricity [WWW Document]. Energy Educ. URL https://energyeducation.ca/encyclopedia/Non-dispatchable_source_of_electricity (accessed 6.17.22).

Agah, S.M., Abyaneh, H.A., 2011. Distribution Transformer Loss-of-Life Reduction by Increasing Penetration of Distributed Generation. IEEE Trans. Power Deliv. 26, 1128–1136. https://doi.org/10.1109/TPWRD.2010.2094210

Ahmad, J., Imran, M., Khalid, A., Iqbal, W., Ashraf, S.R., Adnan, M., Ali, S.F., Khokhar, K.S., 2018. Techno economic analysis of a wind-photovoltaic-biomass hybrid renewable energy system for rural electrification: A case study of Kallar Kahar. Energy 148, 208–234. https://doi.org/10.1016/j.energy.2018.01.133

Ahmed, F., Naeem, M., Iqbal, M., 2017. ICT and renewable energy: a way forward to the next generation telecom base stations. Telecommun. Syst. 64, 43–56. https://doi.org/10.1007/s11235-016-0156-4

Ahn, S., Lee, K.-T., Bhandari, B., Lee, G.-Y., Lee, C.S., Song, C., 2012. Formation Strategy of Renewable Energy Sources for High Mountain Off-grid System Considering Sustainability. https://doi.org/10.7736/KSPE.2012.29.9.958

Ajjarapu, V., Lee, B., 1998. Bibliography on voltage stability. IEEE Trans. Power Syst. 13, 115–125. https://doi.org/10.1109/59.651622

Akikur, R.K., Saidur, R., Ping, H.W., Ullah, K.R., 2013. Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid rural electrification: A review. Renew. Sustain. Energy Rev. 27, 738–752. https://doi.org/10.1016/j.rser.2013.06.043

Akorede, M.F., Hizam, H., Aris, I., Kadir, M.Z.A.A., 2011. Effective method for optimal allocation of distributed generation units in meshed electric power systems. IET Gener. Transm. Amp Distrib. 5, 276–287. https://doi.org/10.1049/iet-gtd.2010.0199

Akorede, M.F., Hizam, H., Pouresmaeil, E., 2010a. Distributed energy resources and benefits to the environment. Renew. Sustain. Energy Rev. 14, 724–734. https://doi.org/10.1016/j.rser.2009.10.025

Akorede, M.F., Hizam, H., Pouresmaeil, E., 2010b. Distributed energy resources and benefits to the environment. Renew. Sustain. Energy Rev. 14, 724–734. https://doi.org/10.1016/j.rser.2009.10.025

Al Abri, R.S., El-Saadany, E.F., Atwa, Y.M., 2013. Optimal Placement and Sizing Method to Improve the Voltage Stability Margin in a Distribution System Using Distributed Generation. IEEE Trans. Power Syst. 28, 326–334. https://doi.org/10.1109/TPWRS.2012.2200049

Al Talaq, M., Belhaj, C.A., 2020. Optimal PV Penetration for Power Losses Subject to Transient Stability and Harmonics. Procedia Comput. Sci., The 17th International Conference on Mobile Systems and Pervasive Computing (MobiSPC),The 15th International Conference on Future

Networks and Communications (FNC),The 10th International Conference on Sustainable Energy Information Technology 175, 508–516. https://doi.org/10.1016/j.procs.2020.07.072

Ali, M., Zia, M.F., Sundhu, M.W., 2016. Demand side management proposed algorithm for cost and peak load optimization, in: 2016 4th International Istanbul Smart Grid Congress and Fair (ICSG). Presented at the 2016 4th International Istanbul Smart Grid Congress and Fair (ICSG), pp. 1–5. https://doi.org/10.1109/SGCF.2016.7492421

AlRashidi, M.R., AlHajri, M.F., 2011. Optimal planning of multiple distributed generation sources in distribution networks: A new approach. Energy Convers. Manag. 52, 3301–3308. https://doi.org/10.1016/j.enconman.2011.06.001

Alsokhiry, F., Lo, K.L., 2013. Distributed generation based on renewable energy providing frequency response ancillary services, in: 4th International Conference on Power Engineering, Energy and Electrical Drives. Presented at the 4th International Conference on Power Engineering, Energy and Electrical Drives, pp. 1200–1205. https://doi.org/10.1109/PowerEng.2013.6635783

Alumona, T.L., Nwosu Moses, O., Ezechukwu, A.O., Jonah, C., 2014. Overview Of Losses And Solutions In Power Transmission Lines. Network and Complex Systems 4.

Alves, M., Segurado, R., Costa, M., 2019. Increasing the penetration of renewable energy sources in isolated islands through the interconnection of their power systems. The case of Pico and Faial islands, Azores. Energy 182, 502–510. https://doi.org/10.1016/j.energy.2019.06.081

Aman, M.M., Jasmon, G.B., Bakar, A.H.A., Mokhlis, H., 2013. A new approach for optimum DG placement and sizing based on voltage stability maximization and minimization of power losses. Energy Convers. Manag. 70, 202–210. https://doi.org/10.1016/j.enconman.2013.02.015

Aman, S., Simmhan, Y., Prasanna, V.K., 2013. Energy management systems: state of the art and emerging trends. IEEE Commun. Mag. 51, 114–119. https://doi.org/10.1109/MCOM.2013.6400447

Arabali, A., Ghofrani, M., Etezadi-Amoli, M., Fadali, M.S., 2014. Stochastic Performance Assessment and Sizing for a Hybrid Power System of Solar/Wind/Energy Storage. IEEE Trans. Sustain. Energy 5, 363–371. https://doi.org/10.1109/TSTE.2013.2288083

Archana, R., subramaniya, S.A., 2018. Top PDF A Perspective Analysis for the Impact of PV and Wind Hybrid Distributed Generation Using ETAP - 1Library [WWW Document]. URL https://1library.net/title/perspective-analysis-impact-wind-hybrid-distributed-generation-using (accessed 6.27.22).

Ardizzon, G., Cavazzini, G., Pavesi, G., 2014. A new generation of small hydro and pumped-hydro power plants: Advances and future challenges. Renew. Sustain. Energy Rev. 31, 746–761. https://doi.org/10.1016/j.rser.2013.12.043

Arikiez, M.K.M., 2016. Algorithms for Energy Management in Micro-grids. School of Electrical Engineering, Electronics and Computer Science. University of Liverpool.

Arriaga, M., Nasr, E., Rutherford, H., 2017. Renewable Energy Microgrids in Northern Remote Communities. IEEE Potentials 36, 22–29. https://doi.org/10.1109/MPOT.2017.2702798

Arrillaga, J., 1998. High Voltage Direct Current Transmission, 2nd edition. ed. The Institution of Engineering and Technology, London, UK.

Ashglaf, M.O., 2019. Development of Hybridization concept for horizontal axis wind / tidal systems using functional similarities and advanced real-time emulation methods (Theses). Normandie Université.

Asmus, P., 2010. Microgrids, Virtual Power Plants and Our Distributed Energy Future. Electr. J. 23, 72–82. https://doi.org/10.1016/j.tej.2010.11.001

Atwa, Y.M., El-Saadany, E.F., 2011. Probabilistic approach for optimal allocation of wind-based distributed generation in distribution systems. IET Renew. Power Gener. 5, 79–88. https://doi.org/10.1049/iet-rpg.2009.0011

Atwa, Y.M., El-Saadany, E.F., Salama, M.M.A., Seethapathy, R., 2010. Optimal Renewable Resources Mix for Distribution System Energy Loss Minimization. IEEE Trans. Power Syst. 1, 360–370. https://doi.org/10.1109/TPWRS.2009.2030276

Baghli, L., 2022. Applied Computation In Energy Engineering.

Baghli, L., 1994. Réalisation d’un Environnement Graphique avec Base de Données pour l’Analyse et la Simulation de Réseaux Electriques (PFE). Ecole Nationale Polytechnique d’Algier, Algiers, Algeria.

Baghli, L., Didier, G., BENDALI, S., Lévêque, J., 2010. An Open Source Real-Time Power System Simulator with HIL, in: International Conference on Electrical Networks ICEN 2010.

Bailey, O., Creighton, C., Firestone, R., Marnay, C., Stadler, M., 2003. Distributed energy resources in practice: A case study analysis and validation of LBNL’s customer adoption model [WWW Document]. Inf. PBD 1 Feb 2003. https://doi.org/10.2172/821040

Bakos, G.C., 2002. Feasibility study of a hybrid wind/hydro power-system for low-cost electricity production. Appl. Energy 72, 599–608. https://doi.org/10.1016/S0306-2619(02)00045-4

Balkanski, M., Wallis, R., 2012. Electronic energy bands: semiconductors. 44–72.

Bank, J., Mather, B., Keller, J., Coddington, M., 2013. High Penetration Photovoltaic Case Study Report [WWW Document]. UNT Digit. Libr. https://doi.org/10.2172/1062441

Bansal, R.C., 2007. Small Signal Analysis of Isolated Hybrid Power Systems: Reactive Power and Frequency Control Analysis. Alpha Science International.

Bansal, R.C., 2002. AUTOMATIC REACTIVE POWER CONTROL OF AUTONOMOUS HYBRID POWER SYSTEMS. Indian Institute of Technology, Delhi India 13.

Barghi Latran, M., Teke, A., Yoldaş, Y., 2015. Mitigation of power quality problems using distribution static synchronous compensator: a comprehensive review. IET Power Electron. 8, 1312–1328. https://doi.org/10.1049/iet-pel.2014.0531

Barnett, B.M., Teagan, W.P., 1992. The role of fuel cells in our energy future. J. Power Sources, Proceedings of the Second Grove Fuel Cell Symposium. Progress in Fuel Cell Commercialisation 37, 15–31. https://doi.org/10.1016/0378-7753(92)80060-O

Basak, P., Chowdhury, S., Halder nee Dey, S., Chowdhury, S.P., 2012. A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid. Renew. Sustain. Energy Rev. 16, 5545–5556. https://doi.org/10.1016/j.rser.2012.05.043

Bayer, B., Marian, A., 2020. Innovative measures for integrating renewable energy in the German medium-voltage grids. Energy Rep. 6, 336–342. https://doi.org/10.1016/j.egyr.2019.12.028

Bayer, B., Matschoss, P., Thomas, H., Marian, A., 2018. The German experience with integrating photovoltaic systems into the low-voltage grids. Renew. Energy 119, 129–141. https://doi.org/10.1016/j.renene.2017.11.045

Bekele, G., Tadesse, G., 2012. Feasibility study of small Hydro/PV/Wind hybrid system for off-grid rural electrification in Ethiopia. Appl. Energy, Energy Solutions for a Sustainable World - Proceedings of the Third International Conference on Applied Energy, May 16-18, 2011 - Perugia, Italy 97, 5–15. https://doi.org/10.1016/j.apenergy.2011.11.059

Belcher, B., Petry, B.J., Davis, T., Hatipoglu, K., 2017. The effects of major solar integration on a 21-Bus system: Technology review and PSAT simulations, in: SoutheastCon 2017. Presented at the SoutheastCon 2017, pp. 1–8. https://doi.org/10.1109/SECON.2017.7925361

Berrada, A., Ameur, A., El Maakoul, A., El Mrabet, R., 2021. Chapter 2 - Optimization modeling of hybrid DG systems, in: Berrada, A., El Mrabet, R. (Eds.), Hybrid Energy System Models. Academic Press, pp. 45–73. https://doi.org/10.1016/B978-0-12-821403-9.00005-6

Bhandari, B., Lee, K.-T., Lee, C.S., Song, C.-K., Maskey, R.K., Ahn, S.-H., 2014. A novel off-grid hybrid power system comprised of solar photovoltaic, wind, and hydro energy sources. Appl. Energy 133, 236–242. https://doi.org/10.1016/j.apenergy.2014.07.033

Bhandari, B., Lee, K.-T., Lee, G.-Y., Cho, Y.-M., Ahn, S.-H., 2015. Optimization of hybrid renewable energy power systems: A review. Int. J. Precis. Eng. Manuf.-Green Technol. 2, 99–112. https://doi.org/10.1007/s40684-015-0013-z

Billinton, R., Chen, H., Ghajar, R., 1996. A sequential simulation technique for adequacy evaluation of generating systems including wind energy. IEEE Trans. Energy Convers. 11, 728–734. https://doi.org/10.1109/60.556371

Bills, G.W., 1964. Voltage and Current Control for Spacecraft Fuel-Cell Systems. IEEE Trans. Aerosp. 2, 478–482. https://doi.org/10.1109/TA.1964.4319627

Bizon, N., 2018. Effective mitigation of the load pulses by controlling the battery/SMES hybrid energy storage system. Appl. Energy 229, 459–473. https://doi.org/10.1016/j.apenergy.2018.08.013

Blazev, A.S., 2012. Photovoltaics for commercial and utilities power generation. Fairmont Press ; CRC Press, Lilburn, GA; Boca Raton, FL.

Borbely, A.-M., Kreider, J.F., CRC Press, 2001. Distributed generation: the power paradigm for the new millennium. CRC Press, Boca Raton.

Bouznit, M., Pablo-Romero, M. del P., Sánchez-Braza, A., 2020. Measures to Promote Renewable Energy for Electricity Generation in Algeria. Sustainability 12, 1468. https://doi.org/10.3390/su12041468

Boyle, G., 2004. Renewable energy. 2nd edition. Oxford University Press & The Open University, Oxford, UK.

Brahma, S.M., Girgis, A.A., 2004. Development of adaptive protection scheme for distribution systems with high penetration of distributed generation. IEEE Trans. Power Deliv. 19, 56–63. https://doi.org/10.1109/TPWRD.2003.820204

Brearley, B.J., Prabu, R.R., 2017. A review on issues and approaches for microgrid protection. Renew. Sustain. Energy Rev. 67, 988–997. https://doi.org/10.1016/j.rser.2016.09.047

BSI, 2008. BS EN 61400-21:2008 - Wind turbines. Measurement and assessment of power quality characteristics of grid connected wind turbines (British Standard) [WWW Document]. URL https://webstore.ansi.org/Standards/BSI/bsen61400212008 (accessed 7.14.22).

Buizza, R., Du, J., Toth, Z., Hou, D., 2019. Major Operational Ensemble Prediction Systems (EPS) and the Future of EPS, in: Duan, Q., Pappenberger, F., Wood, A., Cloke, H.L., Schaake, J.C. (Eds.), Handbook of Hydrometeorological Ensemble Forecasting. Springer, Berlin, Heidelberg, pp. 151–193. https://doi.org/10.1007/978-3-642-39925-1_14

Burger, E.M., Moura, S.J., 2015. Gated ensemble learning method for demand-side electricity load forecasting. Energy Build. 109, 23–34. https://doi.org/10.1016/j.enbuild.2015.10.019

Caldognetto, T., Tenti, P., 2014. Microgrids Operation Based on Master–Slave Cooperative Control. IEEE J. Emerg. Sel. Top. Power Electron. 2, 1081–1088. https://doi.org/10.1109/JESTPE.2014.2345052

Camille, D., 2010. L’éolien offshore en Europe : état des lieux, politiques, impacts. 107.

Candusso, D., Valero, L., Walter, A., Bacha, S., Rulliere, E., Raison, B., 2002. Modelling, control and simulation of a fuel cell based power supply system with energy management, in: IEEE 2002 28th Annual Conference of the Industrial Electronics Society. IECON 02. Presented at the IEEE 2002 28th Annual Conference of the Industrial Electronics Society. IECON 02, pp. 1294–1299 vol.2. https://doi.org/10.1109/IECON.2002.1185462

Carrette, L., Friedrich, K.A., Stimming, U., 2001. Fuel Cells – Fundamentals and Applications. Fuel Cells 1, 5–39. https://doi.org/10.1002/1615-6854(200105)1:1<5::AID-FUCE5>3.0.CO;2-G

Carvallo, J., Schnitzer, D., Lounsbury, D., Deshmukh, R., Apt, J., Kammen, D., 2014. Microgrids for Rural Electrification: A critical review of best practices based on seven case studies. https://doi.org/10.13140/RG.2.1.1399.9600

Casini, M., 2015. Small Vertical Axis Wind Turbines for Energy Efficiency of Buildings. J. Clean Energy Technol. 4, 56–65. https://doi.org/10.7763/JOCET.2016.V4.254

Catherine, L., 2021. What are the different types of solar batteries? [WWW Document]. Sol. Rev. URL https://www.solarreviews.com/content/blog/types-of-solar-batteries (accessed 1.3.23).

Çelik, D., Meral, M.E., 2019. A novel control strategy for grid connected distributed generation system to maximize power delivery capability. Energy 186, 115850. https://doi.org/10.1016/j.energy.2019.115850

Celli, G., Ghiani, E., Mocci, S., Pilo, F., 2005. A multiobjective evolutionary algorithm for the sizing and siting of distributed generation. IEEE Trans. Power Syst. 20, 750–757. https://doi.org/10.1109/TPWRS.2005.846219

Cena, G., Seno, L., Valenzano, A., Zunino, C., 2010. On the Performance of IEEE 802.11e Wireless Infrastructures for Soft-Real-Time Industrial Applications. IEEE Trans. Ind. Inform. 6, 425–437. https://doi.org/10.1109/TII.2010.2052058

Chaibi, Y., Allouhi, A., Malvoni, M., Salhi, M., Saadani, R., 2019. Solar irradiance and temperature influence on the photovoltaic cell equivalent-circuit models. Sol. Energy 188, 1102–1110. https://doi.org/10.1016/j.solener.2019.07.005

Chakravorty, M., Das, D., 2001. Voltage stability analysis of radial distribution networks. Int. J. Electr. Power Energy Syst. 23, 129–135. https://doi.org/10.1016/S0142-0615(00)00040-5

Chambers, A., 2001. Distributed Generation : A Non-Technical Guide. Fire Engineering Books & Videos, Tulsa, Oklahoma, U.s.a.

Chen, C., Duan, S., Cai, T., Liu, B., Hu, G., 2011. Smart energy management system for optimal microgrid economic operation. Renew. Power Gener. IET 5, 258–267. https://doi.org/10.1049/iet-rpg.2010.0052

Cobben, J.F.G., 2007. Power Quality Implications at the Point of Connection.

Cole, M.A., Elliott, R.J.R., Occhiali, G., Strobl, E., 2018. Power outages and firm performance in Sub-Saharan Africa. J. Dev. Econ. 134, 150–159. https://doi.org/10.1016/j.jdeveco.2018.05.003

Colmenar-Santos, A., Reino-Rio, C., Borge-Diez, D., Collado-Fernández, E., 2016. Distributed generation: A review of factors that can contribute most to achieve a scenario of DG units embedded in the new distribution networks. Renew. Sustain. Energy Rev. 59, 1130–1148. https://doi.org/10.1016/j.rser.2016.01.023

Conti, S., Raiti, S., Tina, G., 2003. Small-scale embedded generation effect on voltage profile: an analytical method. IEE Proc. - Gener. Transm. Distrib. 150, 78–86. https://doi.org/10.1049/ip-gtd:20020739

Ćosić, B., Krajačić, G., Duić, N., 2012. A 100% renewable energy system in the year 2050: The case of Macedonia. Energy, 6th Dubrovnik Conference on Sustainable Development of Energy Water and Environmental Systems, SDEWES 2011 48, 80–87. https://doi.org/10.1016/j.energy.2012.06.078

Costa, D.C.L., Nunes, M.V.A., Vieira, J.P.A., Bezerra, U.H., 2016. Decision tree-based security dispatch application in integrated electric power and natural-gas networks. Electr. Power Syst. Res. 141, 442–449. https://doi.org/10.1016/j.epsr.2016.08.027

Coster, E.J., Myrzik, J.M.A., Kruimer, B., Kling, W.L., 2011. Integration Issues of Distributed Generation in Distribution Grids. Proc. IEEE 99, 28–39. https://doi.org/10.1109/JPROC.2010.2052776

Dalwadi, P., Shrinet, V., Mehta, C.R., Shah, P., 2011. Optimization of solar-wind hybrid system for distributed generation, in: 2011 Nirma University International Conference on Engineering. Presented at the 2011 Nirma University International Conference on Engineering (NUiCONE), IEEE, Ahmedabad, Gujarat, India, pp. 1–4. https://doi.org/10.1109/NUiConE.2011.6153300

Daud, A.-K., Ismail, M.S., 2012. Design of isolated hybrid systems minimizing costs and pollutant emissions. Renew. Energy 44, 215–224. https://doi.org/10.1016/j.renene.2012.01.011

Dekali, Z., 2021. Contribution à la commande d'un simulateur HIL d'éolienne et d'une génératrice asynchrone à double alimentation. https://doi.org/10.13140/RG.2.2.16447.84642

Dekali, Z., Baghli, L., Boumediene, A., 2019. Indirect power control for a Grid Connected Double Fed Induction Generator Based Wind Turbine Emulator, in: 2019 International Conference on Advanced Electrical Engineering (ICAEE). Presented at the 2019 International Conference on Advanced Electrical Engineering (ICAEE), pp. 1–6. https://doi.org/10.1109/ICAEE47123.2019.9014778

DEKALI, Z., Lotfi, B., Abdelmadjid, B., 2021a. Improved hardware implementation of a TSR based MPPT algorithm for a low cost connected wind turbine emulator under unbalanced wind speeds. Energy 232, 121039. https://doi.org/10.1016/j.energy.2021.121039

DEKALI, Z., Lotfi, B., Thierry, L., Abdelmadjid, B., 2021b. Grid Side Inverter Control for a Grid Connected Synchronous Generator Based Wind Turbine Experimental Emulator. Eur. J. Electr. Eng. 23, 1–7. https://doi.org/10.18280/ejee.230101

Delfanti, M., Falabretti, D., Merlo, M., 2013. Dispersed generation impact on distribution network losses. Electr. Power Syst. Res. 97, 10–18. https://doi.org/10.1016/j.epsr.2012.11.018

Dendouga, A., 2020. A Comparative Study Between the PI and SM Controllers Used by Nonlinear Control of Induction Motor Fed by SVM Matrix Converter. IETE J. Res. 0, 1–11. https://doi.org/10.1080/03772063.2020.1743781

Dhand, A., Pullen, K., 2015. Review of battery electric vehicle propulsion systems incorporating flywheel energy storage. Int. J. Automot. Technol. 16, 487–500. https://doi.org/10.1007/s12239-015-0051-0

Díaz-González, F., Sumper, A., Gomis-Bellmunt, O., Villafáfila-Robles, R., 2012. A review of energy storage technologies for wind power applications. Renew. Sustain. Energy Rev. 16, 2154–2171. https://doi.org/10.1016/j.rser.2012.01.029

Dondi, P., Bayoumi, D., Haederli, C., Julian, D., Suter, M., 2002. Network integration of distributed power generation. J. Power Sources, Proceedings of the Seventh Grove Fuel Cell Symposium 106, 1–9. https://doi.org/10.1016/S0378-7753(01)01031-X

Dutta, S., 2014. A review on production, storage of hydrogen and its utilization as an energy resource. J. Ind. Eng. Chem. 20, 1148–1156. https://doi.org/10.1016/j.jiec.2013.07.037

Ebrahimi, R., Ehsan, M., Nouri, H., 2013. A profit-centric strategy for distributed generation planning considering time varying voltage dependent load demand. Int. J. Electr. Power Energy Syst. 44, 168–178. https://doi.org/10.1016/j.ijepes.2012.07.039

Eco-Business, 2012. Global market outlook for photovoltaics until 2016 - EPIA [WWW Document]. Eco-Bus. URL https://www.eco-business.com/news/global-market-outlook-for-photovoltaics-until-2016-epia/ (accessed 7.18.22).

EERE, n.d. Hydrogen Storage [WWW Document]. Energy.gov. URL https://www.energy.gov/eere/fuelcells/hydrogen-storage (accessed 6.25.22).

Eftekharnejad, S., Vittal, V., Heydt, G.T., Keel, B., Loehr, J., 2013. Impact of increased penetration of photovoltaic generation on power systems. IEEE Trans. Power Syst. 28, 893–901. https://doi.org/10.1109/TPWRS.2012.2216294

EIA, 2018. Major utilities continue to increase spending on U.S. electric distribution systems [WWW Document]. URL https://www.eia.gov/todayinenergy/detail.php?id=36675 (accessed 6.29.22).

El Aimani, S., 2015. Comparison of control structures for variable speed wind turbine, in: 2015 27th International Conference on Microelectronics (ICM). Presented at the 2015 27th International Conference on Microelectronics (ICM), pp. 261–264. https://doi.org/10.1109/ICM.2015.7438038

El Batawy, S.A., Morsi, W.G., 2017. On the Impact of High Penetration of Rooftop Solar Photovoltaics on the Aging of Distribution Transformers. Can. J. Electr. Comput. Eng. 40, 93–100. https://doi.org/10.1109/CJECE.2017.2694698

El-Khattam, W., Bhattacharya, K., Hegazy, Y., Salama, M.M.A., 2004. Optimal investment planning for distributed generation in a competitive electricity market. IEEE Trans. Power Syst. 19, 1674–1684. https://doi.org/10.1109/TPWRS.2004.831699

El-Khattam, W., Hegazy, Y.G., Salama, M.M.A., 2005. An integrated distributed generation optimization model for distribution system planning. IEEE Trans. Power Syst. 20, 1158–1165. https://doi.org/10.1109/TPWRS.2005.846114

Ellabban, O., Abu-Rub, H., Blaabjerg, F., 2014. Renewable energy resources: Current status, future prospects and their enabling technology. Renew. Sustain. Energy Rev. 39, 748–764. https://doi.org/10.1016/j.rser.2014.07.113

Eluri, H.B., Naik, M.G., 2021. Challenges of RES with Integration of Power Grids, Control Strategies, Optimization Techniques of Microgrids: A Review. Int. J. Renew. Energy Res. IJRER 11, 1–19.

El-Zonkoly, A.M., 2011. Optimal placement of multi-distributed generation units including different load models using particle swarm optimization. Swarm Evol. Comput. 1, 50–59. https://doi.org/10.1016/j.swevo.2011.02.003

Enslin, J.H.R., Hulshorst, W.T.J., Atmadji, A.M.S., Heskes, P.J.M., Kotsopoulos, A., Cobben, J.F.G., Van der Sluijs, P., 2003. Harmonic interaction between large numbers of photovoltaic inverters and the distribution network, in: 2003 IEEE Bologna Power Tech Conference Proceedings,. Presented at the 2003 IEEE Bologna Power Tech Conference Proceedings, p. 6 pp. Vol.3-. https://doi.org/10.1109/PTC.2003.1304365

Esmaili, M., 2013. Placement of minimum distributed generation units observing power losses and voltage stability with network constraints. IET Gener. Transm. Distrib. 7, 813–821. https://doi.org/10.1049/iet-gtd.2013.0140

Ettehadi, M., Ghasemi, H., Vaez-Zadeh, S., 2013. Voltage Stability-Based DG Placement in Distribution Networks. IEEE Trans. Power Deliv. 28, 171–178. https://doi.org/10.1109/TPWRD.2012.2214241

Fadaeenejad, M., Radzi, M.A.M., AbKadir, M.Z.A., Hizam, H., 2014. Assessment of hybrid renewable power sources for rural electrification in Malaysia. Renew. Sustain. Energy Rev. 30, 299–305. https://doi.org/10.1016/j.rser.2013.10.003

Faizollahzadeh Ardabili, S., Mahmoudi, A., Mesri Gundoshmian, T., 2016. Modeling and simulation controlling system of HVAC using fuzzy and predictive (radial basis function, RBF) controllers. J. Build. Eng. 6, 301–308. https://doi.org/10.1016/j.jobe.2016.04.010

Farmad, H.S., Biglar, S., 2012. Integration of demand side management, distributed generation, renewable energy sources and energy storages, in: CIRED 2012 Workshop: Integration of Renewables into the Distribution Grid. Presented at the CIRED 2012 Workshop: Integration of Renewables into the Distribution Grid, IET, Lisbon, Portugal, pp. 166–166. https://doi.org/10.1049/cp.2012.0784

Farrokhabadi, M., Canizares, C.A., Simpson-Porco, J.W., Nasr, E., Fan, L., Mendoza-Araya, P.A., Tonkoski, R., Tamrakar, U., Hatziargyriou, N., Lagos, D., Wies, R.W., Paolone, M., Liserre, M., Meegahapola, L., Kabalan, M., Hajimiragha, A.H., Peralta, D., Elizondo, M.A., Schneider, K.P., Tuffner, F.K., Reilly, J., 2020. Microgrid Stability Definitions, Analysis, and Examples. IEEE Trans. Power Syst. 35, 13–29. https://doi.org/10.1109/TPWRS.2019.2925703

Fathabad, A.M., Cheng, J., Pan, K., 2021. Chapter 5 - Integrated power transmission and distribution systems, in: Ren, J. (Ed.), Renewable-Energy-Driven Future. Academic Press, pp. 169–199. https://doi.org/10.1016/B978-0-12-820539-6.00005-4

Favuzza, S., Graditi, G., Ippolito, M.G., Sanseverino, E.R., 2007. Optimal Electrical Distribution Systems Reinforcement Planning Using Gas Micro Turbines by Dynamic Ant Colony Search Algorithm. IEEE Trans. Power Syst. 22, 580–587. https://doi.org/10.1109/TPWRS.2007.894861

FCHEA, 2019. Unlocking the Potential of Hydrogen Energy Storage [WWW Document]. Fuel Cell Hydrog. Energy Assoc. URL https://www.fchea.org/in-transition/2019/7/22/unlocking-the-potential-of-hydrogen-energy-storage (accessed 6.25.22).

Fortenbacher, P., Demiray, T., 2019. Linear/quadratic programming-based optimal power flow using linear power flow and absolute loss approximations. Int. J. Electr. Power Energy Syst. 107, 680–689. https://doi.org/10.1016/j.ijepes.2018.12.008

Franco, J.F., Macedo, L.H., Arias, N.B., Tabares, A., Romero, R., Soares, J., 2021. Chapter 15 - Mathematical models and optimization techniques to support local electricity markets, in: Pinto, T., Vale, Z., Widergren, S. (Eds.), Local Electricity Markets. Academic Press, pp. 259–276. https://doi.org/10.1016/B978-0-12-820074-2.00019-8

Fridleifsson, I.B., 2001. Geothermal energy for the benefit of the people. Renew. Sustain. Energy Rev. 5, 299–312. https://doi.org/10.1016/S1364-0321(01)00002-8

Fuchs, E., Fuchs, H.A., 2007. Distributed generation and frequency/load control of power systems. Proc. - Front. Power Conf. II1–II9.

Fuchs, E., Masoum, M.A.S., 2008. Torques in induction machines due to low-frequency voltage/current harmonics. Int. J. Power Energy Syst. 28. https://doi.org/10.2316/Journal.203.2008.2.203-4055

Fuchs, E., Roesler, D., Masoum, M., 2004. Are Harmonic Recommendations According to IEEE and IEC Too Restrictive? Power Deliv. IEEE Trans. On 19, 1775–1786. https://doi.org/10.1109/TPWRD.2003.822538

Fuchs, E.F., Masoum, M.A.S., 2011. Power Conversion of Renewable Energy Systems. Springer Science & Business Media.

Funabashi, T., 2016. Chapter 1 - Introduction, in: Funabashi, T. (Ed.), Integration of Distributed Energy Resources in Power Systems. Academic Press, pp. 1–14. https://doi.org/10.1016/B978-0-12-803212-1.00001-5

Gabash, A., Li, P., 2012. Active-Reactive Optimal Power Flow in Distribution Networks With Embedded Generation and Battery Storage. IEEE Trans. Power Syst. 27, 2026–2035. https://doi.org/10.1109/TPWRS.2012.2187315

Gaillard, A., 2010. Système éolien basé sur une MADA : contribution à l'étude de la qualité de l'énergie électrique et de la continuité de service (These de doctorat). Nancy 1.

Gelazanskas, L., Gamage, K.A.A., 2014. Demand side management in smart grid: A review and proposals for future direction. Sustain. Cities Soc. 11, 22–30. https://doi.org/10.1016/j.scs.2013.11.001

Georgilakis, P.S., Hatziargyriou, N.D., 2013. Optimal Distributed Generation Placement in Power Distribution Networks: Models, Methods, and Future Research. IEEE Trans. Power Syst. 28, 3420–3428. https://doi.org/10.1109/TPWRS.2012.2237043

Gezer, C., Buratti, C., 2011. A ZigBee Smart Energy Implementation for Energy Efficient Buildings, in: 2011 IEEE 73rd Vehicular Technology Conference (VTC Spring). Presented at the 2011 IEEE 73rd Vehicular Technology Conference (VTC Spring), pp. 1–5. https://doi.org/10.1109/VETECS.2011.5956726

Gil, H.A., Joos, G., 2006. On the Quantification of the Network Capacity Deferral Value of Distributed Generation. IEEE Trans. Power Syst. 21, 1592–1599. https://doi.org/10.1109/TPWRS.2006.881158

Gözel, T., Hocaoglu, M.H., 2009. An analytical method for the sizing and siting of distributed generators in radial systems. Electr. Power Syst. Res. 79, 912–918. https://doi.org/10.1016/j.epsr.2008.12.007

Grove, W.R., 1838. LVI. On a new voltaic combination. Lond. Edinb. Dublin Philos. Mag. J. Sci. 13, 430–431. https://doi.org/10.1080/14786443808649618

Gungor, V.C., Sahin, D., Kocak, T., Ergut, S., Buccella, C., Cecati, C., Hancke, G.P., 2013. A Survey on Smart Grid Potential Applications and Communication Requirements. IEEE Trans. Ind. Inform. 9, 28–42. https://doi.org/10.1109/TII.2012.2218253

Gupta, A., Saini, R.P., Sharma, M.P., 2008. Hybrid Energy System for Remote Area - An Action Plan for Cost Effective Power Generation, in: 2008 IEEE Region 10 and the Third International Conference on Industrial and Information Systems. Presented at the 2008 IEEE Region 10 and the Third international Conference on Industrial and Information Systems, pp. 1–6. https://doi.org/10.1109/ICIINFS.2008.4798396

Gupta, H., Roy, S., 2007. Worldwide status of geothermal resource utilization. pp. 199–229. https://doi.org/10.1016/B978-044452875-9/50008-3

Hafez, O., Bhattacharya, K., 2012. Optimal planning and design of a renewable energy based supply system for microgrids. Renew. Energy 45, 7–15. https://doi.org/10.1016/j.renene.2012.01.087

Hamlyn, A., Cheung, H., Wang, L., Yang, C., Cheung, R., 2008. Adaptive protection and control strategy for interfacing wind-power electricity generators to distribution grids, in: 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century. Presented at the 2008 IEEE Power and Energy Society General Meeting -

Conversion and Delivery of Electrical Energy in the 21st Century, pp. 1–8. https://doi.org/10.1109/PES.2008.4596673

Hamzeh, M., Karimi, H., Mokhtari, H., 2012. A New Control Strategy for a Multi-Bus MV Microgrid Under Unbalanced Conditions. IEEE Trans. Power Syst. 27, 2225–2232. https://doi.org/10.1109/TPWRS.2012.2193906

Hansen, M., 2016. Smart grid development and households in experimental projects. Technical University of Denmark, Kgs. Lyngby.

Harmonics White Paper [WWW Document], 2022. URL https://www.eaton.com/us/en-us/forms/automation-and-control/harmonics-white-paper.html (accessed 6.29.22).

Harrison, G.P., Piccolo, A., Siano, P., Wallace, A.R., 2008. Hybrid GA and OPF evaluation of network capacity for distributed generation connections. Electr. Power Syst. Res. 78, 392–398. https://doi.org/10.1016/j.epsr.2007.03.008

Hatziargyriou, N., 2004. MICROGRIDS-large scale integration of micro-generation to low voltage grids.

Hatziargyriou, N., Asano, H., Iravani, R., Marnay, C., 2007. Microgrids. IEEE Power Energy Mag. 5, 78–94. https://doi.org/10.1109/MPAE.2007.376583

Hedayati, H., Nabaviniaki, S.A., Akbarimajd, A., 2008. A Method for Placement of DG Units in Distribution Networks. IEEE Trans. Power Deliv. 23, 1620–1628. https://doi.org/10.1109/TPWRD.2007.916106

Helman, U., 2019. Chapter 19 - Distributed Energy Resources in the US Wholesale Markets: Recent Trends, New Models, and Forecasts, in: Sioshansi, F. (Ed.), Consumer, Prosumer, Prosumager. Academic Press, pp. 431–469. https://doi.org/10.1016/B978-0-12-816835-6.00019-X

Hemdan, N.G.A., Kurrat, M., 2009. Allocation of decentralized generators in distribution networks for enhancing normal operation loadability, in: 2009 IEEE Bucharest PowerTech. Presented at the 2009 IEEE Bucharest PowerTech, pp. 1–7. https://doi.org/10.1109/PTC.2009.5281890

Heskes, P.J.M., Cobben, J.F.G., Moor, de, H.H.C., 2005. Harmonic distortion in residential areas due to large scale PV implementation is predictable. Int. J. Distrib. Energy Resour. 1, 17–32. https://doi.org/10.1080/15501320490886314

Hien, N.C., Mithulananthan, N., Bansal, R.C., 2013. Location and Sizing of Distributed Generation Units for Loadabilty Enhancement in Primary Feeder. IEEE Syst. J. 7, 797–806. https://doi.org/10.1109/JSYST.2012.2234396

Horch, M., 2018. Contribution à l'observation et la commande non linéaire d'actionneur électrique asynchrone sans capteur mécanique (Thesis). Université de Tlemcen.

Horch, M., Boumédiène, A., Baghli, L., 2019. Sensorless high-order sliding modes vector control for induction motor drive with a new adaptive speed observer using super-twisting strategy. Int. J. Comput. Appl. Technol. 60, 144–153. https://doi.org/10.1504/IJCAT.2019.100131

Howlader, A.M., Urasaki, N., Yona, A., Senjyu, T., Saber, A.Y., 2013. Design and Implement a Digital H∞ Robust Controller for a MW-Class PMSG-Based Grid-Interactive Wind Energy Conversion System. Energies 6, 2084–2109. https://doi.org/10.3390/en6042084

Hu, P., Karki, R., Billinton, R., 2009. Development of an interactive reliability model for wind and hydro power systems, in: 2009 IEEE Electrical Power & Energy Conference (EPEC). Presented at the Energy Conference (EPEC), IEEE, Montreal, QC, Canada, pp. 1–6. https://doi.org/10.1109/EPEC.2009.5420767

Huang, A.Q., Crow, M.L., Heydt, G.T., Zheng, J.P., Dale, S.J., 2011. The Future Renewable Electric Energy Delivery and Management (FREEDM) System: The Energy Internet. Proc. IEEE 99, 133–148. https://doi.org/10.1109/JPROC.2010.2081330

Huang, X., Zhang, Z., Jiang, J., 2006. Fuel Cell Technology for Distributed Generation: An Overview, in: 2006 IEEE International Symposium on Industrial Electronics. pp. 1613–1618. https://doi.org/10.1109/ISIE.2006.295713

Humayd, A.S.B., Bhattacharya, K., 2013. Comprehensive multi-year distribution system planning using back-propagation approach. IET Gener. Transm. Amp Distrib. 7, 1415–1425. https://doi.org/10.1049/iet-gtd.2012.0706

Hung, D.Q., 2014. Smart integration of distributed renewable generation and battery energy storage. https://doi.org/10.14264/uql.2014.384

Hung, D.Q., Mithulananthan, N., 2013. Multiple Distributed Generator Placement in Primary Distribution Networks for Loss Reduction. IEEE Trans. Ind. Electron. 60, 1700–1708. https://doi.org/10.1109/TIE.2011.2112316

Hung, D.Q., Mithulananthan, N., 2011. DG Allocation in Primary Distribution Systems Considering Loss Reduction, in: Handbook of Renewable Energy Technology. WORLD SCIENTIFIC, pp. 587–635. https://doi.org/10.1142/9789814289078_0023

Hung, D.Q., Mithulananthan, N., Bansal, R.C., 2010. Analytical Expressions for DG Allocation in Primary Distribution Networks. IEEE Trans. Energy Convers. 25, 814–820. https://doi.org/10.1109/TEC.2010.2044414

Huskinson, B., Marshak, M.P., Suh, C., Er, S., Gerhardt, M.R., Galvin, C.J., Chen, X., Aspuru-Guzik, A., Gordon, R.G., Aziz, M.J., 2014. A metal-free organic–inorganic aqueous flow battery. Nature 505, 195–198. https://doi.org/10.1038/nature12909

IEA, 2022a. Renewable Energy Market Update - May 2022 – Analysis [WWW Document]. IEA. URL https://www.iea.org/reports/renewable-energy-market-update-may-2022 (accessed 1.4.23).

IEA, 2022b. Renewable Electricity – Analysis [WWW Document]. IEA. URL https://www.iea.org/reports/renewable-electricity (accessed 1.4.23).

IEA, 2021. Renewables – Global Energy Review 2021 – Analysis [WWW Document]. IEA. URL https://www.iea.org/reports/global-energy-review-2021/renewables (accessed 6.12.22).

IEC 61850, 2004. IEC 61850 Stack Overview [WWW Document]. URL https://www.trianglemicroworks.com/products/source-code-libraries/iec-61850-scl-pages?gclid=Cj0KCQjwmdGYBhDRARIsABmSEePZNsUuPtS1uG6fqHEK6gs-e2YaDNp5cWq9nbQ9SjPn2lrTc62uI-UaAtN3EALw_wcB (accessed 9.4.22).

IEC 61970-1, 2005. IEC 61970-1:2005 - Energy management system application program interface (EMS-API) - Part 1: Guidelines and general requirements | Joinup [WWW Document]. URL https://joinup.ec.europa.eu/collection/ict-standards-procurement/solution/iec-61970-12005-

energy-management-system-application-program-interface-ems-api-part-1-guidelines-and (accessed 9.4.22).

IEEE SA Working Groups, 2021. How To Manage Distributed Energy Resources More Effectively. IEEE Stand. Assoc. URL https://standards.ieee.org/beyond-standards/how-to-manage-distributed-energy-resources-more-effectively/ (accessed 12.28.22).

Illindala, M., Siddiqui, A., Venkataramanan, G., Marnay, C., 2007. Localized Aggregation of Diverse Energy Sources for Rural Electrification Using Microgrids. J. Energy Eng. 133, 121–131. https://doi.org/10.1061/(ASCE)0733-9402(2007)133:3(121)

Injeti, S.K., Prema Kumar, N., 2013. A novel approach to identify optimal access point and capacity of multiple DGs in a small, medium and large scale radial distribution systems. Int. J. Electr. Power Energy Syst. 45, 142–151. https://doi.org/10.1016/j.ijepes.2012.08.043

Ipakchi, A., Albuyeh, F., 2009. Grid of the future. IEEE Power Energy Mag. 7, 52–62. https://doi.org/10.1109/MPE.2008.931384

IRENA, 2017. IRENA – International Renewable Energy Agency [WWW Document]. /. URL https://www.irena.org/ (accessed 6.17.22).

i-SCOOP, 2018. Smart grids: electricity networks and the grid in evolution [WWW Document]. URL https://www.i-scoop.eu/industry-4-0/smart-grids-electrical-grid/ (accessed 8.23.22).

Ishchenko, D., Oudalov, A., Stoupis, J., 2012. Protection coordination in active distribution grids with IEC 61850, in: PES T&D 2012. Presented at the PES T&D 2012, pp. 1–6. https://doi.org/10.1109/TDC.2012.6281478

Ismail, M., Bayram, I.S., Qaraqe, K., Serpedin, E., 2019. 5G-Enhanced Smart Grid Services. pp. 28–102. https://doi.org/10.1002/9781119515579.ch4

Ismail, M.S., Moghavvemi, M., Mahlia, T.M.I., 2013. Design of an optimized photovoltaic and microturbine hybrid power system for a remote small community: Case study of Palestine. Energy Convers. Manag. 75, 271–281. https://doi.org/10.1016/j.enconman.2013.06.019

Iweh, C.D., Gyamfi, S., Tanyi, E., Effah-Donyina, E., 2021. Distributed Generation and Renewable Energy Integration into the Grid: Prerequisites, Push Factors, Practical Options, Issues and Merits. Energies 14, 5375. https://doi.org/10.3390/en14175375

Iyer, H., Ray, S., Ramakumar, R., 2005. Voltage profile improvement with distributed generation. IEEE Power Eng. Soc. Gen. Meet. 2005. https://doi.org/10.1109/PES.2005.1489406

Jabr, R.A., Pal, B.C., 2009. Ordinal optimisation approach for locating and sizing of distributed generation. IET Gener. Transm. Amp Distrib. 3, 713–723. https://doi.org/10.1049/iet-gtd.2009.0019

Jain, S., Kalambe, S., Agnihotri, G., Mishra, A., 2017. Distributed generation deployment: State-of-the-art of distribution system planning in sustainable era. Renew. Sustain. Energy Rev. 77, 363–385.

Jamdade, P.G., Patil, S.V., Jamdade, S.G., 2013. Assessment of Power Coefficient of an Offline Wind Turbine Generator System. Electron. J. Energy Environ. 1. https://doi.org/10.7770/ejee-V1N3-art683

Jane, N.-K., 2020. DESIGN AND OPTIMIZATION OF A RENEWABLE ENERGY BASED SMART MICROGRID FOR RURAL ELECTRIFICATION. Department of Electrical and Electronic Engineering - School of Engineering.

Jaramillo, O.A., Borja, M.A., Huacuz, J.M., 2004. Using hydropower to complement wind energy: a hybrid system to provide firm power. Renew. Energy 29, 1887–1909. https://doi.org/10.1016/j.renene.2004.02.010

Jin, T., Tian, Y., Zhang, C.W., Coit, D.W., 2013. Multicriteria Planning for Distributed Wind Generation Under Strategic Maintenance. IEEE Trans. Power Deliv. 28, 357–367. https://doi.org/10.1109/TPWRD.2012.2222936

Kalalas, C., Thrybom, L., Alonso-Zarate, J., 2016. Cellular Communications for Smart Grid Neighborhood Area Networks: A Survey. IEEE Access 4, 1469–1493. https://doi.org/10.1109/ACCESS.2016.2551978

Kalogirou, S.A., 2013. Solar Energy Engineering: Processes and Systems, 2nd edition. ed. Academic Press.

Kansal, S., Kumar, V., Tyagi, B., 2013. Optimal placement of different type of DG sources in distribution networks. Int. J. Electr. Power Energy Syst. 53, 752–760. https://doi.org/10.1016/j.ijepes.2013.05.040

Kantamneni, A., Winkler, R., Gauchia, L., Pearce, J.M., 2016. Emerging economic viability of grid defection in a northern climate using solar hybrid systems. Energy Policy 95, 378–389. https://doi.org/10.1016/j.enpol.2016.05.013

Karki, R., Hu, P., Billinton, R., 2010. Reliability assessment of a wind integrated hydro-thermal power system, in: 2010 IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems. Presented at the 2010 IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems, pp. 265–270. https://doi.org/10.1109/PMAPS.2010.5528651

Katiraei, F., Agüero, J.R., 2011. Solar PV Integration Challenges. IEEE Power Energy Mag. 9, 62–71. https://doi.org/10.1109/MPE.2011.940579

Kayal, P., Chanda, C.K., 2013. Placement of wind and solar based DGs in distribution system for power loss minimization and voltage stability improvement. Int. J. Electr. Power Energy Syst. 53, 795–809. https://doi.org/10.1016/j.ijepes.2013.05.047

Kayastha, N., Niyato, D., Hossain, E., Han, Z., 2014. Smart grid sensor data collection, communication, and networking: A tutorial. Wirel. Commun. Mob. Comput. 14. https://doi.org/10.1002/wcm.2258

Khalesi, N., Rezaei, N., Haghifam, M.-R., 2011. DG allocation with application of dynamic programming for loss reduction and reliability improvement. Int. J. Electr. Power Energy Syst. 33, 288–295. https://doi.org/10.1016/j.ijepes.2010.08.024

Khaligh, A., Onar, O., 2011. Energy Sources. Power Electron. Handb. 1289–1330. https://doi.org/10.1016/B978-0-12-382036-5.00045-8

Khan, I.U., 2022. Optimal demand-supply energy management in smart grids (phd). Lancaster University.

Khatod, D.K., Pant, V., Sharma, J., 2013. Evolutionary programming based optimal placement of renewable distributed generators. IEEE Trans. Power Syst. 28, 683–695. https://doi.org/10.1109/TPWRS.2012.2211044

Khetrapal, P., 2020. Distributed Generation: A Critical Review of Technologies, Grid Integration Issues, Growth Drivers and Potential Benefits. Int. J. Renew. Energy Dev. 9, 189–205. https://doi.org/10.14710/ijred.9.2.189-205

Kollu, R., Rayapudi, S.R., Sadhu, V.L.N., 2014. A novel method for optimal placement of distributed generation in distribution systems using HSDO. Int. Trans. Electr. Energy Syst. 24, 547–561. https://doi.org/10.1002/etep.1710

Kömürcü, M.İ., Akpınar, A., 2009. Importance of geothermal energy and its environmental effects in Turkey. Renew. Energy 34, 1611–1615. https://doi.org/10.1016/j.renene.2008.11.012

Kose, R., 2007. Geothermal energy potential for power generation in Turkey: A case study in Simav, Kutahya. Renew. Sustain. Energy Rev. 11, 497–511.

Kousksou, T., Bruel, P., Jamil, A., El Rhafiki, T., Zeraouli, Y., 2014. Energy storage: Applications and challenges. Sol. Energy Mater. Sol. Cells 120, 59–80. https://doi.org/10.1016/j.solmat.2013.08.015

Krishna, M., Daniel, S.A., 2009. Design methodology for autonomous operation of a Micro-grid. p. I–40.

Krizhevsky, A., Sutskever, I., Hinton, G.E., 2017. ImageNet classification with deep convolutional neural networks. Commun. ACM 60, 84–90. https://doi.org/10.1145/3065386

Kroposki, B., Basso, T., DeBlasio, R., 2008. Microgrid standards and technologies, in: 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century. Presented at the 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, pp. 1–4. https://doi.org/10.1109/PES.2008.4596703

Kucuksari, S., Khaleghi, A.M., Hamidi, M., Zhang, Y., Szidarovszky, F., Bayraksan, G., Son, Y.-J., 2014. An Integrated GIS, optimization and simulation framework for optimal PV size and location in campus area environments. Appl. Energy 113, 1601–1613. https://doi.org/10.1016/j.apenergy.2013.09.002

Kumar, A., Gao, W., 2010. Optimal distributed generation location using mixed integer non-linear programming in hybrid electricity markets. Gener. Transm. Distrib. IET 4, 281–298. https://doi.org/10.1049/iet-gtd.2009.0026

Kumar, A., Selvan, M., 2017. Grid Stability Analysis for High Penetration Solar Photovoltaics [WWW Document]. URL https://www.semanticscholar.org/paper/Grid-Stability-Analysis-for-High-Penetration-Solar-Kumar-Selvan/add09457912ab7537bc16db905f4f6b163cbd252 (accessed 6.27.22).

Kusko, A., DeDad, J., 2005. Short-term, long-term, energy storage methods for standby electric power systems. Fourtieth IAS Annu. Meet. Conf. Rec. 2005 Ind. Appl. Conf. 2005. https://doi.org/10.1109/IAS.2005.1518837

Laaksonen, H., Kauhaniemi, K., 2008. Voltage and current THD in microgrid with different DG unit and load configurations, in: CIRED Seminar 2008: SmartGrids for Distribution. Presented at the CIRED Seminar 2008: SmartGrids for Distribution, pp. 1–4. https://doi.org/10.1049/ic:20080476

Labouret, A., Villoz, M., 2010. Solar photovoltaic energy. Institution of Engineering and Technology, Stevenage.

Lasseter, R.H., Kevin, T., 2000. Scenarios for Distributed Technology Applications with Steady State and Dynamic Models of Loads and Micro-Sources | Grid Integration Group [WWW Document]. URL https://gridintegration.lbl.gov/publications/scenarios-distributed-technology (accessed 5.10.22).

LeCun, Y., Bengio, Y., Hinton, G., 2015. Deep learning. Nature 521, 436–444. https://doi.org/10.1038/nature14539

Leisch, J., Cochran, J., 2015. Greening the Grid [WWW Document]. greeningthegrid.org. URL https://greeningthegrid.org/ (accessed 5.13.22).

Li, J., Liu, P., Li, Z., 2020. Optimal design and techno-economic analysis of a solar-wind-biomass off-grid hybrid power system for remote rural electrification: A case study of west China. Energy 208, 118387. https://doi.org/10.1016/j.energy.2020.118387

Liu, Y., Yao, X., 1999. Ensemble learning via negative correlation. Neural Netw. 12, 1399–1404. https://doi.org/10.1016/S0893-6080(99)00073-8

Lo, C.-H., Ansari, N., 2012. The Progressive Smart Grid System from Both Power and Communications Aspects. IEEE Commun. Surv. Tutor. 14, 799–821. https://doi.org/10.1109/SURV.2011.072811.00089

Logenthiran, T., Srinivasan, D., Shun, T.Z., 2012. Demand Side Management in Smart Grid Using Heuristic Optimization. IEEE Trans. Smart Grid 3, 1244–1252. https://doi.org/10.1109/TSG.2012.2195686

Lopes, J.A.P., Hatziargyriou, N., Mutale, J., Djapic, P., Jenkins, N., 2007a. Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities. Electr. Power Syst. Res., Distributed Generation 77, 1189–1203. https://doi.org/10.1016/j.epsr.2006.08.016

Lopes, J.A.P., Hatziargyriou, N., Mutale, J., Djapic, P., Jenkins, N., 2007b. Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities. Electr. Power Syst. Res., Distributed Generation 77, 1189–1203. https://doi.org/10.1016/j.epsr.2006.08.016

Lopes, V.S., Borges, C., 2015. Impact of the Combined Integration of Wind Generation and Small Hydropower Plants on the System Reliability. IEEE Trans. Sustain. Energy. https://doi.org/10.1109/TSTE.2014.2335895

Loucif, M., 2016. Synthèse de Lois de Commande Non Linéaires Pour Le Contrôle d’une Machine Asynchrone à Double Alimentation Dédiée à Un Système Aérogénérateur. Université de Tlemcen, Tlemcen, Algeria.

Luhmann, T., Wieben, E., Treydel, R., Stadler, M., Kumm, T., 2015. An Approach for Cost-Efficient Grid Integration of Distributed Renewable Energy Sources. Engineering 1, 447–452. https://doi.org/10.15302/J-ENG-2015099

Lund, H., Andersen, A.N., Østergaard, P.A., Mathiesen, B.V., Connolly, D., 2012. From electricity smart grids to smart energy systems – A market operation based approach and understanding. Energy, 8th World Energy System Conference, WESC 2010 42, 96–102. https://doi.org/10.1016/j.energy.2012.04.003

Macken, K.J.P., Bollen, M.H.J., Belmans, R.J.M., 2004. Mitigation of voltage dips through distributed generation systems. IEEE Trans. Ind. Appl. 40, 1686–1693. https://doi.org/10.1109/TIA.2004.836302

Mahmud, M.A., Hossain, M.J., Pota, H.R., 2014. Voltage Variation on Distribution Networks With Distributed Generation: Worst Case Scenario. IEEE Syst. J. 8, 1096–1103. https://doi.org/10.1109/JSYST.2013.2265176

Mahmud, N., Zahedi, A., 2016. Review of control strategies for voltage regulation of the smart distribution network with high penetration of renewable distributed generation. Renew. Sustain. Energy Rev. 64, 582–595. https://doi.org/10.1016/j.rser.2016.06.030

Manditereza, P.T., Bansal, R., 2016a. Renewable distributed generation: The hidden challenges – A review from the protection perspective. Renew. Sustain. Energy Rev. 58, 1457–1465. https://doi.org/10.1016/j.rser.2015.12.276

Manditereza, P.T., Bansal, R., 2016b. Renewable distributed generation: The hidden challenges – A review from the protection perspective. Renew. Sustain. Energy Rev. 58, 1457–1465. https://doi.org/10.1016/j.rser.2015.12.276

Margeta, J., Glasnovic, Z., 2010. Feasibility of the green energy production by hybrid solar+hydro power system in Europe and similar climate areas. Renew. Sustain. Energy Rev. 14, 1580–1590. https://doi.org/10.1016/j.rser.2010.01.019

Márk, C., Tamus, Z.Á., Varga, Á., 2017. Impact of Distributed Generation on the Thermal Ageing of Low Voltage Distribution Cables. pp. 251–258. https://doi.org/10.1007/978-3-319-56077-9_24

Markiewicz, H., Klajn, A., 2008. Voltage Disturbances Standard EN 50160 - Voltage Characteristics in Public Distribution Systems. undefined.

MARNAY, C., AKHIL, A.A., KIPMAN, T., Sandia National Laboratories, United States, Department of Energy, United States, Department of Energy, Office of Scientific and Technical Information, 2003. Review of Test Facilities for Distributed Energy Resources. United States. Dept. of Energy ; Distributed by the Office of Scientific and Technical Information, U.S. Dept. of Energy, Washington, D.C; Oak Ridge, Tenn.

Marnay, C., Blanco, R., Hamachi, K.S., Kawaan, C.P., Osborn, J.G., Rubio, F.J., 2000. Integrated assessment of dispersed energy resources deployment [WWW Document]. Inf. PBD 1 Jun 2000. https://doi.org/10.2172/776601

Marnay, C., Robio, F.J., Siddiqui, A.S., 2001. Shape of the microgrid. pp. 150–153 vol.1. https://doi.org/10.1109/PESW.2001.917022

Martín García, J.A., Gil Mena, A.J., 2013. Optimal distributed generation location and size using a modified teaching–learning based optimization algorithm. Int. J. Electr. Power Energy Syst. 50, 65–75. https://doi.org/10.1016/j.ijepes.2013.02.023

Martin, J., 2009. An introduction to distributed generation.

Mashhour, E., Moghaddas-Tafreshi, S.M., 2011. Bidding Strategy of Virtual Power Plant for Participating in Energy and Spinning Reserve Markets—Part I: Problem Formulation. IEEE Trans. Power Syst. 26, 949–956. https://doi.org/10.1109/TPWRS.2010.2070884

Masoum, M., Ladjevardi, M., Jafarian, A., Fuchs, E., 2004. Optimal placement, replacement and sizing of capacitor Banks in distorted distribution networks by genetic algorithms. IEEE Trans. Power Deliv. https://doi.org/10.1109/TPWRD.2004.835438

Masoum, M.A.S., Dehbonei, H., Fuchs, E.F., 2002. Theoretical and experimental analyses of photovoltaic systems with voltageand current-based maximum power-point tracking. IEEE Trans. Energy Convers. 17, 514–522. https://doi.org/10.1109/TEC.2002.805205

Masoum, M.A.S., Fuchs, E.F., 2015. Power Quality Solutions for Renewable Energy Systems, in: Power Quality in Power Systems and Electrical Machines. Elsevier, pp. 961–1084. https://doi.org/10.1016/B978-0-12-800782-2.00011-7

Masoum, M.A.S., Jafarian, J., Ladjevardi, M., Fuchs, E.F., Grady, W.M., 2005. Closure on “Fuzzy approach for optimal placement and sizing of capacitor banks in the presence of harmonics.” IEEE Trans. Power Deliv. 20, 1214–1216. https://doi.org/10.1109/TPWRD.2004.839747

Masoum, M.A.S., Ladjevardi, M., Fuchs, E.F., Grady, W.M., 2004. Application of local variations and maximum sensitivities selection for optimal placement of shunt capacitor banks under nonsinusoidal operating conditions. Int. J. Electr. Power Energy Syst. 26, 761–769. https://doi.org/10.1016/j.ijepes.2004.05.008

Mechter, A., Kemih, K., Ghanes, M., 2015. Sliding Mode Control of a Wind Turbine with Exponential Reaching Law. Acta Polytech. Hung. 12. https://doi.org/10.12700/APH.12.3.2015.3.10

Mehrtash, A., Wang, P., Goel, L., 2012. Reliability Evaluation of Power Systems Considering Restructuring and Renewable Generators. IEEE Trans. Power Syst. 27, 243–250. https://doi.org/10.1109/TPWRS.2011.2161350

Meliani, M., Barkany, A.E., Abbassi, I.E., Darcherif, A.M., Mahmoudi, M., 2021. Energy management in the smart grid: State-of-the-art and future trends. Int. J. Eng. Bus. Manag. 13, 18479790211032920. https://doi.org/10.1177/18479790211032920

Méndez, V.H., Rivier, J., Fuente, J.I. de la, Gómez, T., Arceluz, J., Marín, J., Madurga, A., 2006. Impact of distributed generation on distribution investment deferral. Int. J. Electr. Power Energy Syst. 28, 244–252. https://doi.org/10.1016/j.ijepes.2005.11.016

Meng, W., Ma, R., Chen, H.-H., 2014. Smart grid neighborhood area networks: a survey. IEEE Netw. 28, 24–32. https://doi.org/10.1109/MNET.2014.6724103

Menshsari, A., Ghiamy, M., Mohammad, M., Mousavi, M.M., Bagal, H., 2013. Optimal design of hybrid water-wind-solar system based on hydrogen storage and evaluation of reliability index of system using ant colony algorithm. Int. Res. J. Appl. Basic Sci. 4, 3582–3600.

Merah, M., Baghli, L., Boumediene, A., 2019. Prototyping of photovoltaic grid-tie inverter with active and reactive power injection, in: 2019 International Conference on Advanced Electrical Engineering (ICAEE). Presented at the 2019 International Conference on Advanced Electrical Engineering (ICAEE), pp. 1–6. https://doi.org/10.1109/ICAEE47123.2019.9014764

Meshram, S., Agnihotri, G., Gupta, S., 2013. Performance Analysis of Grid Integrated Hydro and Solar Based Hybrid Systems. Adv. Power Electron. 2013. https://doi.org/10.1155/2013/697049

Meyer, B., Bamberger, Y., Bel, I., 2006. Electricite de France and integration of distributed energy resources, in: 2006 IEEE Power Engineering Society General Meeting. Presented at the 2006 IEEE Power Engineering Society General Meeting, p. 6 pp.-. https://doi.org/10.1109/PES.2006.1709136

Millar, B., Jiang, D., Haque, M.E., 2013. A novel partitioning strategy for distribution networks featuring many small scale generators, in: 2013 IEEE PES Innovative Smart Grid Technologies Conference (ISGT). Presented at the 2013 IEEE PES Innovative Smart Grid Technologies Conference (ISGT), pp. 1–6. https://doi.org/10.1109/ISGT.2013.6497813

Mishra, S., Singal, S.K., Khatod, D.K., 2012. A review on electromechanical equipment applicable to small hydropower plants. Int. J. Energy Res. 36, 553–571. https://doi.org/10.1002/er.1955

Misra, R., Singh, D., 2007. Effect of Load Models in Distributed Generation Planning. IEEE Trans. Power Syst. https://doi.org/10.1109/TPWRS.2007.907582

Mistry, K.D., Roy, R., 2014. Enhancement of loading capacity of distribution system through distributed generator placement considering techno-economic benefits with load growth. Int. J. Electr. Power Energy Syst. 54, 505–515. https://doi.org/10.1016/j.ijepes.2013.07.032

Montoya, M., Sherick, R., Haralson, P., Neal, R., Yinger, R., 2013. Islands in the Storm: Integrating Microgrids into the Larger Grid. IEEE Power Energy Mag. 11, 33–39. https://doi.org/10.1109/MPE.2013.2258279

Montuori, L., Alcázar-Ortega, M., Álvarez-Bel, C., Domijan, A., 2014. Integration of renewable energy in microgrids coordinated with demand response resources: Economic evaluation of a biomass gasification plant by Homer Simulator. Appl. Energy 132, 15–22. https://doi.org/10.1016/j.apenergy.2014.06.075

Moodley, P., 2021. 1 - Sustainable biofuels: opportunities and challenges, in: Ray, R.C. (Ed.), Sustainable Biofuels, Applied Biotechnology Reviews. Academic Press, pp. 1–20. https://doi.org/10.1016/B978-0-12-820297-5.00003-7

Morren, J., Haan, S.W.H.D., 2008. Impact of distributed generation units with power electronic converters on distribution network protection, in: 2008 IET 9th International Conference on Developments in Power System Protection (DPSP 2008). Presented at the 2008 IET 9th International Conference on Developments in Power System Protection (DPSP 2008), pp. 664–669. https://doi.org/10.1049/cp:20080118

Mosavi, A., Salimi, M., Faizollahzadeh Ardabili, S., Rabczuk, T., Shamshirband, S., Varkonyi-Koczy, A.R., 2019. State of the Art of Machine Learning Models in Energy Systems, a Systematic Review. Energies 12, 1301. https://doi.org/10.3390/en12071301

Mousavi Agah, S.M., Askarian Abyaneh, H., 2011. Quantification of the Distribution Transformer Life Extension Value of Distributed Generation. IEEE Trans. Power Deliv. 26, 1820–1828. https://doi.org/10.1109/TPWRD.2011.2115257

Mozina, C.J., 2010. Impact of Green Power Distributed Generation. IEEE Ind. Appl. Mag. 16, 55–62. https://doi.org/10.1109/MIAS.2010.936970

Mundada, A.S., Shah, K.K., Pearce, J.M., 2016. Levelized cost of electricity for solar photovoltaic, battery and cogen hybrid systems. Renew. Sustain. Energy Rev. 57, 692–703. https://doi.org/10.1016/j.rser.2015.12.084

Murugan, R., Ramasamy, R., 2015. Failure analysis of power transformer for effective maintenance planning in electric utilities. Eng. Fail. Anal. 55, 182–192. https://doi.org/10.1016/j.engfailanal.2015.06.002

Nabavi, S.M.H., Hajforoosh, S., Masoum, M.A.S., 2011. Placement and sizing of distributed generation units for congestion management and improvement of voltage profile using particle swarm optimization, in: 2011 IEEE PES Innovative Smart Grid Technologies. Presented at the 2011 IEEE PES Innovative Smart Grid Technologies, pp. 1–6. https://doi.org/10.1109/ISGT-Asia.2011.6167086

Naderi, E., Seifi, H., Sepasian, M.S., 2012. A Dynamic Approach for Distribution System Planning Considering Distributed Generation. IEEE Trans. Power Deliv. 27, 1313–1322. https://doi.org/10.1109/TPWRD.2012.2194744

Nagy, K., Körmendi, K., 2012. Use of renewable energy sources in light of the "New Energy Strategy for Europe 2011–2020." Appl. Energy, Smart Grids 96, 393–399. https://doi.org/10.1016/j.apenergy.2012.02.066

Narbel, P.A., Hansen, J.P., Lien, J.R., 2014. Energy Technologies and Economics, 2014th edition. ed. Springer, New York.

Nassar, M., 2017. Microgrid Enabling Towards the Implementation of Smart Grids. Waterloo, Ontario, Canada.

Nema, P., Nema, R.K., Rangnekar, S., 2009. A current and future state of art development of hybrid energy system using wind and PV-solar: A review. Renew. Sustain. Energy Rev. 13, 2096–2103. https://doi.org/10.1016/j.rser.2008.10.006

Neufeld, J.S., Buscher, U., Lasch, R., Möst, D., Schönberger, J., 2020. Operations Research Proceedings 2019: selected papers of the Annual International Conference of the German Operations Research Society (GOR), Dresden, Germany, September 4-6, 2019. Springer, Cham, Switzerland.

Newman, D.E., Carreras, B.A., Kirchner, M., Dobson, I., 2011. The Impact of Distributed Generation on Power Transmission Grid Dynamics, in: 2011 44th Hawaii International Conference on System Sciences. Presented at the 2011 44th Hawaii International Conference on System Sciences, pp. 1–8. https://doi.org/10.1109/HICSS.2011.414

NFCRC, 2022. National Fuel Cell Research Center (NFCRC), UC Irvine [WWW Document]. URL https://www.nfcrc.uci.edu/Fuel_Cells.html (accessed 6.8.22).

Ni, M., Leung, D.Y.C., Leung, M.K.H., Sumathy, K., 2006. An overview of hydrogen production from biomass. Fuel Process. Technol. 87, 461–472. https://doi.org/10.1016/j.fuproc.2005.11.003

NiagaraFallsInfo, 2017. Niagara Falls History of Power Development - The Schoellkopf Power Plant [WWW Document]. Niagara F. Info. URL https://www.niagarafallsinfo.com/niagara-falls-history/niagara-falls-power-development/the-history-of-power-development-in-niagara/schoellkopf-power-plant/ (accessed 7.1.22).

Nick, M., Cherkaoui, R., Paolone, M., 2014. Optimal Allocation of Dispersed Energy Storage Systems in Active Distribution Networks for Energy Balance and Grid Support. Power Syst. IEEE Trans. On 29, 2300–2310. https://doi.org/10.1109/TPWRS.2014.2302020

Nielsen, K.E., Molinas, M., 2010. Superconducting Magnetic Energy Storage (SMES) in power systems with renewable energy sources, in: 2010 IEEE International Symposium on Industrial Electronics. Presented at the 2010 IEEE International Symposium on Industrial Electronics, pp. 2487–2492. https://doi.org/10.1109/ISIE.2010.5637892

Niknam, T., Taheri, S.I., Aghaei, J., Tabatabaei, S., Nayeripour, M., 2011. A modified honey bee mating optimization algorithm for multiobjective placement of renewable energy resources. Appl. Energy 88, 4817–4830. https://doi.org/10.1016/j.apenergy.2011.06.023

Nourai, A., Kogan, V.I., Schafer, C.M., 2008. Load Leveling Reduces T&D Line Losses. IEEE Trans. Power Deliv. 23, 2168–2173. https://doi.org/10.1109/TPWRD.2008.921128

Ochoa, L.F., Harrison, G.P., 2011. Minimizing Energy Losses: Optimal Accommodation and Smart Operation of Renewable Distributed Generation. IEEE Trans. Power Syst. 26, 198–205. https://doi.org/10.1109/TPWRS.2010.2049036

Ochoa, L.F., Padilha-Feltrin, A., Harrison, G.P., 2008. Evaluating Distributed Time-Varying Generation Through a Multiobjective Index. IEEE Trans. Power Deliv. 23, 1132–1138. https://doi.org/10.1109/TPWRD.2008.915791

Ochoa, L.F., Padilha-Feltrin, A., Harrison, G.P., 2006. Evaluating distributed generation impacts with a multiobjective index. IEEE Trans. Power Deliv. 21, 1452–1458. https://doi.org/10.1109/TPWRD.2005.860262

Olivieri, M.M. de A., Rocha, M.S., Castro, M.R.V. de, Souza, S.M. de, Klaus, W., Medeiros, J.C., Visconti, I.F., Galdino, M.A.E., Borges, E.L. de P., Silva, I.W.F. da, Lima, A.A.N., de Carvalho, C.M., Soares, Y.M.S., Vieira, J.J., 2014. Distributed Generation in the Smart Grid – Case Study of Parintins. Energy Procedia 57, 197–206. https://doi.org/10.1016/j.egypro.2014.10.024

Ouedraogo, N.S., 2017. Modeling sustainable long-term electricity supply-demand in Africa. Appl. Energy 190, 1047–1067. https://doi.org/10.1016/j.apenergy.2016.12.162

Ouedraogo, N.S., 2013a. Energy consumption and economic growth: Evidence from the economic community of West African States (ECOWAS). Energy Econ. 36, 637–647. https://doi.org/10.1016/j.eneco.2012.11.011

Ouedraogo, N.S., 2013b. Energy consumption and human development: Evidence from a panel cointegration and error correction model. Energy 63, 28–41. https://doi.org/10.1016/j.energy.2013.09.067

Ozdemir, S., Demirtas, M., Aydin, S., 2016. Harmonic Estimation Based Support Vector Machine for Typical Power Systems. Neural Netw. World 26, 233–252. https://doi.org/10.14311/NNW.2016.26.013

Paliwal, P., Patidar, N.P., Nema, R.K., 2014. Planning of grid integrated distributed generators: A review of technology, objectives and techniques. Renew. Sustain. Energy Rev. 40, 557–570. https://doi.org/10.1016/j.rser.2014.07.200

Papadimitriou, C.N., Vovos, N.A., 2010. Transient Response Improvement of Microgrids Exploiting the Inertia of a Doubly-Fed Induction Generator (DFIG). Energies 3, 1049–1066. https://doi.org/10.3390/en30601049

Parikh, P.P., Kanabar, Mitalkumar.G., Sidhu, T.S., 2010. Opportunities and challenges of wireless communication technologies for smart grid applications, in: IEEE PES General Meeting. Presented at the IEEE PES General Meeting, pp. 1–7. https://doi.org/10.1109/PES.2010.5589988

Parikh, P.P., Sidhu, T.S., Shami, A., 2013. A Comprehensive Investigation of Wireless LAN for IEC 61850–Based Smart Distribution Substation Applications. IEEE Trans. Ind. Inform. 9, 1466–1476. https://doi.org/10.1109/TII.2012.2223225

Park, B., Hur, J., 2018. Spatial prediction of renewable energy resources for reinforcing and expanding power grids. Energy 164, 757–772. https://doi.org/10.1016/j.energy.2018.09.032

Pastuszak, J., Węgierek, P., 2022. Photovoltaic Cell Generations and Current Research Directions for Their Development. Materials 15, 5542. https://doi.org/10.3390/ma15165542

PAUWES, 2017. WESA. Pan Afr. Univ. - PAUWES. URL https://www.pauwes.dz/?page_id=1411 (accessed 5.29.22).

Pedrasa, M., 2006. A Survey of Techniques Used to Control Microgrid Generation and Storage during Island Operation. undefined.

Peng, F.Z., Li, Y.W., Tolbert, L.M., 2009. Control and protection of power electronics interfaced distributed generation systems in a customer-driven microgrid, in: 2009 IEEE Power Energy Society General Meeting. Presented at the 2009 IEEE Power Energy Society General Meeting, pp. 1–8. https://doi.org/10.1109/PES.2009.5275191

Pepermans, G., Driesen, J., Haeseldonckx, D., Belmans, R., D'haeseleer, W., 2005. Distributed generation: definition, benefits and issues. Energy Policy 33, 787–798. https://doi.org/10.1016/j.enpol.2003.10.004

Piccolo, A., Siano, P., 2009. Evaluating the Impact of Network Investment Deferral on Distributed Generation Expansion. IEEE Trans. Power Syst. 24, 1559–1567. https://doi.org/10.1109/TPWRS.2009.2022973

Pinheiro, J.M.S., Dornellas, C.R.R., Schilling, M.Th., Melo, A.C.G., Mello, J.C.O., 1998. Probing the new IEEE Reliability Test System (RTS-96): HL-II assessment. IEEE Trans. Power Syst. 13, 171–176. https://doi.org/10.1109/59.651632

Plug-In Electric Vehicles: What Role for Washington?, 2009. . Brookings Institution Press.

Pogaku, N., Prodanović, M., Green, T., 2007. Modeling, Analysis and Testing of Autonomous Operation of an Inverter-Based Microgrid. IEEE Trans. Power Electron. https://doi.org/10.1109/TPEL.2006.890003

Population of Africa (2020) - Worldometer [WWW Document], 2020. URL https://www.worldometers.info/world-population/africa-population/ (accessed 2.26.20).

Population of Africa (2022) - Worldometer [WWW Document], 2022. URL https://www.worldometers.info/world-population/africa-population/ (accessed 11.22.22).

Porkar, S., Poure, P., Abbaspour-Tehrani-fard, A., Saadate, S., 2010. A novel optimal distribution system planning framework implementing distributed generation in a deregulated electricity market. Electr. Power Syst. Res. 80, 828–837. https://doi.org/10.1016/j.epsr.2009.12.008

Prabhakar, J.R., Ragavan, K., 2013. Power Management Based Current Control Technique for Photovoltaic-Battery Assisted Wind-Hydro Hybrid System. Int. J. Emerg. Electr. Power Syst. 14, 351–362. https://doi.org/10.1515/ijeeps-2013-0056

Prada, R.B., Souza, L.J., 1998. Voltage stability and thermal limit: Constraints on the maximum loading of electrical energy distribution feeders. IEE Proc. - Gener. Transm. Distrib. 145, 573–577.

Puttgen, H.B., MacGregor, P.R., Lambert, F.C., 2003. Distributed generation: Semantic hype or the dawn of a new era? IEEE Power Energy Mag. 1, 22–29. https://doi.org/10.1109/MPAE.2003.1180357

Qdr, Q., 2006. Benefits of Demand Response in Electricity Markets and Recommendations for Achieving Them. A report to the United States Congress Pursuant to Section 1252 of the Energy Policy Act of 2005 (February 2006) [WWW Document]. Energy.gov. URL https://www.energy.gov/oe/downloads/benefits-demand-response-electricity-markets-and-recommendations-achieving-them-report (accessed 9.3.22).

Qian, K., Zhou, C., Allan, M., Yuan, Y., 2011. Effect of load models on assessment of energy losses in distributed generation planning. Int. J. Electr. Power Energy Syst. 33, 1243–1250. https://doi.org/10.1016/j.ijepes.2011.04.003

Rabiee, A., Khorramdel, H., Aghaei, J., 2013. A review of energy storage systems in microgrids with wind turbines. Renew. Sustain. Energy Rev. 18, 316–326.

Rahman, S., 2003. Green power: What is it and where can we find it? IEEE Power Energy Mag. 1, 30–37. https://doi.org/10.1109/MPAE.2003.1180358

Rajkumar, R.K., Ramachandaramurthy, V.K., Yong, B.L., Chia, D.B., 2011. Techno-economical optimization of hybrid pv/wind/battery system using Neuro-Fuzzy. Fuel Energy Abstr. 36, 5148–5153. https://doi.org/10.1016/j.energy.2011.06.017

Rao, R.S., Ravindra, K., Satish, K., Narasimham, S.V.L., 2013. Power Loss Minimization in Distribution System Using Network Reconfiguration in the Presence of Distributed Generation. IEEE Trans. Power Syst. 28, 317–325. https://doi.org/10.1109/TPWRS.2012.2197227

Reka, S., Dragicevic, T., Siano, P., Prabaharan, S., 2019. Future Generation 5G Wireless Networks for Smart Grid: A Comprehensive Review. Energies 12, 2140. https://doi.org/10.3390/en12112140

REN21, 2020a. REN21 - Building the sustainable energy future with renewable energy [WWW Document]. REN21. URL https://www.ren21.net/ (accessed 6.18.22).

REN21, 2020b. Renewables Global Status Report. REN21. URL https://www.ren21.net/reports/global-status-report/ (accessed 5.9.22).

REN21, 2017. Renewables Global Status Report. REN21. URL https://www.ren21.net/reports/global-status-report/ (accessed 5.9.22).

REN21, 2015. Renewables Global Status Report. REN21. URL https://www.ren21.net/reports/global-status-report/ (accessed 5.9.22).

Rengaraju, P., Lung, C.-H., Srinivasan, A., 2012. Communication requirements and analysis of distribution networks using WiMAX technology for smart grids, in: 2012 8th International Wireless Communications and Mobile Computing Conference (IWCMC). Presented at the 2012 8th International Wireless Communications and Mobile Computing Conference (IWCMC), pp. 666–670. https://doi.org/10.1109/IWCMC.2012.6314284

Roadmap to the New Deal on Energy for Africa: An analysis of optimal expansion and investment requirements, 2018.

Rocabert, J., Luna, A., Blaabjerg, F., Rodríguez, P., 2012. Control of Power Converters in AC Microgrids. IEEE Trans. Power Electron. 27, 4734–4749. https://doi.org/10.1109/TPEL.2012.2199334

Rohouma, W., Balog, R.S., Peerzada, A.A., Begovic, M.M., 2020. D-STATCOM for harmonic mitigation in low voltage distribution network with high penetration of nonlinear loads. Renew. Energy 145, 1449–1464. https://doi.org/10.1016/j.renene.2019.05.134

Roy, N.K., Pota, H.R., 2015a. Current Status and Issues of Concern for the Integration of Distributed Generation Into Electricity Networks. IEEE Syst. J. 9, 933–944. https://doi.org/10.1109/JSYST.2014.2305282

Roy, N.K., Pota, H.R., 2015b. Current Status and Issues of Concern for the Integration of Distributed Generation Into Electricity Networks. IEEE Syst. J. 9, 933–944. https://doi.org/10.1109/JSYST.2014.2305282

Rueda-Medina, A.C., Padilha-Feltrin, A., 2013. Distributed Generators as Providers of Reactive Power Support—A Market Approach. IEEE Trans. Power Syst. 28, 490–502. https://doi.org/10.1109/TPWRS.2012.2202926

Safdarian, A., Fotuhi-Firuzabad, M., Aminifar, F., 2012. Compromising Wind and Solar Energies From the Power System Adequacy Viewpoint. IEEE Trans. Power Syst. 27, 2368–2376. https://doi.org/10.1109/TPWRS.2012.2204409

Saha, N.C., Acharjee, S., Mollah, Md.A.S., Rahman, K.T., Rafi, F.H.M., Rabin, Md.J.A., Samad, M.A., 2013. Modeling and performance analysis of a hybrid power system, in: 2013 International Conference on Informatics, Electronics and Vision (ICIEV). Presented at the 2013 International Conference on Informatics, Electronics and Vision (ICIEV), pp. 1–5. https://doi.org/10.1109/ICIEV.2013.6572669

Salameh, Z.M., Borowy, B.S., Amin, A.R.A., 1995. Photovoltaic module-site matching based on the capacity factors. IEEE Trans. Energy Convers. 10, 326–332. https://doi.org/10.1109/60.391899

Salih, T., Wang, Y., Adam, M.A.A., 2014. Renewable Micro Hybrid System of Solar Panel and Wind Turbine for Telecommunication Equipment in Remote Areas in Sudan. Energy Procedia, International Conference on Applied Energy, ICAE2014 61, 80–83. https://doi.org/10.1016/j.egypro.2014.11.911

Sayed, K., Gabbar, H.A., 2017. Chapter 18 - SCADA and smart energy grid control automation, in: Gabbar, Hossam A. (Ed.), Smart Energy Grid Engineering. Academic Press, pp. 481–514. https://doi.org/10.1016/B978-0-12-805343-0.00018-8

Schneuwly, A., Maher, B., Auer, J., 2006. Ultracapacitors, the new thinking in the automotive world 186.

Schœnbein, C.F., 1839. X. On the voltaic polarization of certain solid and fluid substances. Lond. Edinb. Dublin Philos. Mag. J. Sci. 14, 43–45. https://doi.org/10.1080/14786443908649658

Services of the Algerian Prime Minister, 2022. Transition énergétique en Algérie : Défis et perspectives [WWW Document]. URL https://premier-ministre.gov.dz/fr/post/transition-energetique-en-algerie-defis-et-perspectives (accessed 5.4.23).

SGCG, 2014. SGCG/M490/G_Smart Grid Set of Standards Version 3.1.

Shaaban, M.F., Atwa, Y.M., El-Saadany, E.F., 2013. DG allocation for benefit maximization in distribution networks. IEEE Trans. Power Syst. 28, 639–649. https://doi.org/10.1109/TPWRS.2012.2213309

Shamseldein, M.Z., Abdelaziz, A.Y., 2019. 2 - Energy Management for Medium-Voltage Direct Current Networks, in: Eissa, M.M. (Ed.), Medium Voltage Direct Current Grid. Academic Press, pp. 43–57. https://doi.org/10.1016/B978-0-12-814560-9.00002-1

Siano, P., 2014. Demand response and smart grids—A survey. Renew. Sustain. Energy Rev. 30, 461–478. https://doi.org/10.1016/j.rser.2013.10.022

Siano, P., Ochoa, L.F., Harrison, G.P., Piccolo, A., 2009. Assessing the strategic benefits of distributed generation ownership for DNOs. IET Gener. Transm. Amp Distrib. 3, 225–236. https://doi.org/10.1049/iet-gtd:20080235

Simoes, M.G., Roche, R., Kyriakides, E., Suryanarayanan, S., Blunier, B., McBee, K.D., Nguyen, P.H., Ribeiro, P.F., Miraoui, A., 2012. A Comparison of Smart Grid Technologies and Progresses in Europe and the U.S. IEEE Trans. Ind. Appl. 48, 1154–1162. https://doi.org/10.1109/TIA.2012.2199730

Singh, Deependra, Singh, Devender, Verma, K.S., 2009. Multiobjective Optimization for DG Planning With Load Models. IEEE Trans. Power Syst. 24, 427–436. https://doi.org/10.1109/TPWRS.2008.2009483

Sissine, F., 2007. Energy Independence and Security Act of 2007: A Summary of Major Provisions 28.

Soetedjo, A., Lomi, A., Mulayanto, W.P., 2011. Modeling of wind energy system with MPPT control, in: Proceedings of the 2011 International Conference on Electrical Engineering and Informatics. Presented at the Proceedings of the 2011 International Conference on Electrical Engineering and Informatics, pp. 1–6. https://doi.org/10.1109/ICEEI.2011.6021836

Soroudi, A., Ehsan, M., 2011. Efficient immune-GA method for DNOs in sizing and placement of distributed generation units. Eur. Trans. Electr. Power 21, 1361–1375. https://doi.org/10.1002/etep.501

Soroudi, A., Ehsan, M., Caire, R., Hadjsaid, N., 2011a. Possibilistic Evaluation of Distributed Generations Impacts on Distribution Networks. IEEE Trans. Power Syst. 26, 2293–2301. https://doi.org/10.1109/TPWRS.2011.2116810

Soroudi, A., Ehsan, M., Zareipour, H., 2011b. A practical eco-environmental distribution network planning model including fuel cells and non-renewable distributed energy resources. Renew. Energy 36, 179–188. https://doi.org/10.1016/j.renene.2010.06.019

Strachan, N., Farrell, A., 2006. Emissions from distributed vs. centralized generation: The importance of system performance. Energy Policy 34, 2677–2689. https://doi.org/10.1016/j.enpol.2005.03.015

Strunz, K., 2006. Developing benchmark models for studying the integration of distributed energy resources, in: 2006 IEEE Power Engineering Society General Meeting. Presented at the 2006 IEEE Power Engineering Society General Meeting, p. 2 pp.-. https://doi.org/10.1109/PES.2006.1709568

Szabó, S., Bódis, K., Huld, T., Moner-Girona, M., 2011. Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension. Environ. Res. Lett. 6, 034002. https://doi.org/10.1088/1748-9326/6/3/034002

Tan, W.S., Hassan, M.Y., Abdul Rahman, H., Abdullah, M.P., Hussin, F., 2013. Multi-distributed generation planning using hybrid particle swarm optimisation- gravitational search algorithm including voltage rise issue. Gener. Transm. Distrib. IET 7, 929–942. https://doi.org/10.1049/iet-gtd.2013.0050

Tazvinga, H., Thopil, M., Numbi, P.B., Adefarati, T., 2017. Distributed Renewable Energy Technologies, in: Bansal, R. (Ed.), Handbook of Distributed Generation. Springer International Publishing, Cham, pp. 3–67. https://doi.org/10.1007/978-3-319-51343-0_1

Terfa, H., Baghli, L., Bhandari, R., 2022. Impact of renewable energy micro-power plants on power grids over Africa. Energy 238, 121702. https://doi.org/10.1016/j.energy.2021.121702

Terfa, H., Baghli, L., Bhandari, R., 2020. Distributed Renewable Energy Micro-Power Plants: a Solution for New and Existing Power Grids over Africa. Presented at the 4th SEE SDEWES international conference, Sarajevo, Bosnia and Herzegovina.

Terfa, H., Baghli, L., Bhandari, R., 2019. Real Time Simulations of Power Systems in Transient Stability with Power System Stabilizers. Presented at the 1st International Conference on Electrical Engineering - CEE2019, Algiers, Algeria.

Terfa, H., Baghli, L., Bhandari, R., 2018. Study of Distributed Smart Renewable Energy Micro-Plants. Presented at the Research-2-Practice Forum, Tlemcen, Algeria.

The Algerian Ministry of Energy and Mines, 2019. Ministère de l'Énergie | Algérie [WWW Document]. URL https://www.energy.gov.dz/?rubrique=energies-nouvelles-renouvelables-et-maitrise-de-lrenergie (accessed 4.25.23).

ThinkGeoEnergy, 2022. Geothermal Energy Production & Utilisation | ThinkGeoEnergy - Geothermal Energy News. URL https://www.thinkgeoenergy.com/geothermal/geothermal-energy-production-utilisation/ (accessed 1.3.23).

Thong, V.V., Driesen, J., Belmans, R., 2005. Power quality and voltage stability of distribution system with distributed energy resources. Int. J. Distrib. Energy Resour. 1, 227–240.

Tomal, M.U., Gabbar, H.A., 2015. Key performance assessment of fuel cell based distributed energy generation system in resilient micro energy grid, in: 2015 IEEE International Conference on Smart Energy Grid Engineering (SEGE). Presented at the 2015 IEEE International Conference on Smart Energy Grid Engineering (SEGE), pp. 1–6. https://doi.org/10.1109/SEGE.2015.7324618

Trichakis, P., Taylor, P.C., Lyons, P.F., Hair, R., 2008. Predicting the technical impacts of high levels of small-scale embedded generators on low-voltage networks. IET Renew. Power Gener. 2, 249–262. https://doi.org/10.1049/iet-rpg:20080012

Tsado, Y., Gamage, K., Adebisi, B., Lund, D., Rabie, K., Ikpehai, A., 2017. Improving the Reliability of Optimised Link State Routing in a Smart Grid Neighbour Area Network based Wireless Mesh Network Using Multiple Metrics. Energies 10, 287. https://doi.org/10.3390/en10030287

Tsikalakis, A.G., Hatziargyriou, N.D., 2007. Environmental benefits of distributed generation with and without emissions trading. Energy Policy 35, 3395–3409. https://doi.org/10.1016/j.enpol.2006.11.022

Ugranlı, F., Karatepe, E., 2013. Optimal wind turbine sizing to minimize energy loss. Int. J. Electr. Power Energy Syst. 53, 656–663. https://doi.org/10.1016/j.ijepes.2013.05.035

UNU-EHS, 2017. "Water and Energy Security for Africa (WESA)" project launched at 'Kickoff' Workshop - Institute for Environment and Human Security [WWW Document]. URL https://ehs.unu.edu/news/announcement/water-and-energy-security-for-africa-wesa-project-launched-at-kickoff-workshop.html (accessed 6.26.22).

Urasaki, N., Howlader, A.M., Senjyu, T., Funabashi, T., Saber, A.Y., 2011. High Efficiency Drive for Micro-Turbine Generator Based on Current Phase and Revolving Speed Optimizations. Int. J. Emerg. Electr. Power Syst. 12. https://doi.org/10.2202/1553-779X.2760

US Department of Energy, 2019. Smart Grid: The Smart Grid | SmartGrid.gov [WWW Document]. URL https://www.smartgrid.gov/the_smart_grid/smart_grid.html (accessed 7.1.22).

US EPA, O., 2015a. Centralized Generation of Electricity and its Impacts on the Environment [WWW Document]. URL https://www.epa.gov/energy/centralized-generation-electricity-and-its-impacts-environment (accessed 1.4.22).

US EPA, O., 2015b. Distributed Generation of Electricity and its Environmental Impacts [WWW Document]. URL https://www.epa.gov/energy/distributed-generation-electricity-and-its-environmental-impacts (accessed 1.6.22).

UWEC, 2004. Geothermal Energy [WWW Document]. URL https://people.uwec.edu/piercech/210webs/renewable/geothermal.htm (accessed 6.17.22).

Vahidinasab, V., 2014. Optimal distributed energy resources planning in a competitive electricity market: Multiobjective optimization and probabilistic design. Renew. Energy 66, 354–363. https://doi.org/10.1016/j.renene.2013.12.042

Vallem, Mitra, Patra, 2006. Distributed Generation Placement for Optimal Microgrid Architecture, in: 2005/2006 IEEE/PES Transmission and Distribution Conference and Exhibition. Presented at the 2005/2006 IEEE/PES Transmission and Distribution Conference and Exhibition, pp. 1191–1195. https://doi.org/10.1109/TDC.2006.1668674

Van Dijk, M., van Vuuren, S., Loots, I., Barta, B., Scharfetter, B., 2014. Conduit Hydropower Development Guide.

Varaiya, P.P., Wu, F.F., Bialek, J.W., 2011. Smart Operation of Smart Grid: Risk-Limiting Dispatch. Proc. IEEE 99, 40–57. https://doi.org/10.1109/JPROC.2010.2080250

VDE, 2016. Voltage Regulating Distribution Transformer (VRDT) – Use in Grid Planning and Operation.

Veerapen, N., Ochoa, G., Harman, M., Burke, E.K., 2015. An Integer Linear Programming approach to the single and bi-objective Next Release Problem. Inf. Softw. Technol. 65, 1–13. https://doi.org/10.1016/j.infsof.2015.03.008

Vergara, P.P., Rey, J.M., da Silva, L.C.P., Ordóñez, G., 2017. Comparative analysis of design criteria for hybrid photovoltaic/wind/battery systems. IET Renew. Power Gener. 11, 253–261. https://doi.org/10.1049/iet-rpg.2016.0250

Vergara, P.P., Rey, J.M., López, J.C., Rider, M.J., da Silva, L.C.P., Shaker, H.R., Jørgensen, B.N., 2019. A Generalized Model for the Optimal Operation of Microgrids in Grid-Connected and Islanded Droop-Based Mode. IEEE Trans. Smart Grid 10, 5032–5045. https://doi.org/10.1109/TSG.2018.2873411

Viral, R., Khatod, D.K., 2012. Optimal planning of distributed generation systems in distribution system: A review. Renew. Sustain. Energy Rev. 16, 5146–5165. https://doi.org/10.1016/j.rser.2012.05.020

Virginia Tech, 2018. Introduction to Distributed Generation [WWW Document]. URL https://web.archive.org/web/20181210181948/https://www.dg.history.vt.edu/ch1/introduction.html (accessed 1.6.22).

Wang, C., Nehrir, M.H., 2004. Analytical approaches for optimal placement of distributed generation sources in power systems. IEEE Trans. Power Syst. 19, 2068–2076. https://doi.org/10.1109/TPWRS.2004.836189

Wang, Y., Chen, Q., Kang, C., Zhang, M., Wang, K., Zhao, Y., 2015. Load Profiling and Its Application to Demand Response: A Review. Tsinghua Sci. Technol. 20, 117–129. https://doi.org/10.1109/TST.2015.7085625

Wang, Z., Tian, H., Lu, Z., Zhou, W., 2014. High-speed axial impact of aluminum honeycomb – Experiments and simulations. Compos. Part B Eng. 56, 1–8. https://doi.org/10.1016/j.compositesb.2013.07.013

Wasiak, I., Hanzelka, Z., 2009. Integration of distributed energy sources with electrical power grid. Bull. Pol. Acad. Sci. Tech. Sci. 57. https://doi.org/10.2478/v10175-010-0132-1

Williams, N.J., Jaramillo, P., Taneja, J., Ustun, T.S., 2015. Enabling private sector investment in microgrid-based rural electrification in developing countries: A review. Renew. Sustain. Energy Rev. 52, 1268–1281. https://doi.org/10.1016/j.rser.2015.07.153

Xyngi, I., Popov, M., 2013. An Intelligent Algorithm for the Protection of Smart Power Systems. IEEE Trans. Smart Grid 4, 1541–1548. https://doi.org/10.1109/TSG.2013.2244621

Yan, Y., Qian, Y., Sharif, H., Tipper, D., 2013. A Survey on Smart Grid Communication Infrastructures: Motivations, Requirements and Challenges. IEEE Commun. Surv. Tutor. 15, 5–20. https://doi.org/10.1109/SURV.2012.021312.00034

Yang, H., Li, P., He, Z., Guo, X., Fong, S., Chen, H., 2016. A decision support system using combined-classifier for high-speed data stream in smart grid. Enterp. Inf. Syst. 10, 947–958. https://doi.org/10.1080/17517575.2015.1086495

Yang, Q., 2012. Satellite based "Power Utility Intranet" for smart management of electric distribution networks: The AuRA-NMS case study, in: 2012 IEEE International Conference on Communications (ICC). Presented at the 2012 IEEE International Conference on Communications (ICC), pp. 2822–2826. https://doi.org/10.1109/ICC.2012.6364365

Yang, Q., Barria, J.A., Green, T.C., 2011. Communication Infrastructures for Distributed Control of Power Distribution Networks. IEEE Trans. Ind. Inform. 7, 316–327. https://doi.org/10.1109/TII.2011.2123903

Yang, Q., Ehsan, A., Jiang, L., Fang, X., 2019. Optimal energy dispatch in residential community with renewable DGs and storage in the presence of real-time pricing, in: Smart Power Distribution Systems. Elsevier, pp. 447–465. https://doi.org/10.1016/B978-0-12-812154-2.00019-5

Yerasimou, Y., Kynigos, M., Efthymiou, V., Georghiou, G.E., 2021. Design of a Smart Nanogrid for Increasing Energy Efficiency of Buildings. Energies 14, 3683. https://doi.org/10.3390/en14123683

Yilmaz, O.N.C., Li, Z., Valkealahti, K., Uusitalo, M.A., Moisio, M., Lundén, P., Wijting, C., 2014. Smart mobility management for D2D communications in 5G networks, in: 2014 IEEE Wireless Communications and Networking Conference Workshops (WCNCW). Presented at the 2014 IEEE Wireless Communications and Networking Conference Workshops (WCNCW), pp. 219–223. https://doi.org/10.1109/WCNCW.2014.6934889

Yoldaş, Y., Önen, A., Muyeen, S.M., Vasilakos, A.V., Alan, İ., 2017. Enhancing smart grid with microgrids: Challenges and opportunities. Renew. Sustain. Energy Rev. 72, 205–214. https://doi.org/10.1016/j.rser.2017.01.064

Yuen, C., Oudalov, A., Timbus, A., 2011. The Provision of Frequency Control Reserves From Multiple Microgrids. IEEE Trans. Ind. Electron. 58, 173–183. https://doi.org/10.1109/TIE.2010.2041139

Zahedi, A., 2011. A review of drivers, benefits, and challenges in integrating renewable energy sources into electricity grid. Renew. Sustain. Energy Rev. 15, 4775–4779. https://doi.org/10.1016/j.rser.2011.07.074

Zaheeruddin, Manas, M., 2015. Renewable energy management through microgrid central controller design: An approach to integrate solar, wind and biomass with battery. Energy Rep. 1, 156–163. https://doi.org/10.1016/j.egyr.2015.06.003

ZEF, 2017. WESA: Water and Energy Security for Africa. Cent. Dev. Res. ZEF. URL https://www.zef.de/projects/project-details.html?contact=1332&project=92&cHash=262db9b7d30e57973a9860a7ed05c295 (accessed 6.26.22).

Zhang, S., Huang, M., 2011. Microgrid: A strategy to develop distributed renewable energy resource, in: 2011 International Conference on Electrical and Control Engineering. Presented at the 2011 International Conference on Electrical and Control Engineering, pp. 3520–3523. https://doi.org/10.1109/ICECENG.2011.6058404

Zhang, Y., Chowdhury, A.A., Koval, D.O., 2010. Probabilistic wind energy modeling in electric generation system reliability assessment, in: 2010 IEEE Industrial and Commercial Power Systems Technical Conference - Conference Record. Presented at the 2010 IEEE Industrial and Commercial Power Systems Technical Conference - Conference Record, pp. 1–8. https://doi.org/10.1109/ICPS.2010.5489894

Zhu, Z., Tang, J., Lambotharan, S., Chin, W.H., Fan, Z., 2012. An integer linear programming based optimization for home demand-side management in smart grid, in: 2012 IEEE PES Innovative Smart Grid Technologies (ISGT). Presented at the 2012 IEEE PES Innovative Smart Grid Technologies (ISGT), pp. 1–5. https://doi.org/10.1109/ISGT.2012.6175785

Zia, M.F., 2020. On energy management optimization for microgrids enriched with renewable energy sources (phdthesis). Université de Bretagne occidentale - Brest.

Zia, M.F., Elbouchikhi, E., Benbouzid, M., 2019. Optimal operational planning of scalable DC microgrid with demand response, islanding, and battery degradation cost considerations. Appl. Energy 237, 695–707. https://doi.org/10.1016/j.apenergy.2019.01.040

Zia, M.F., Elbouchikhi, E., Benbouzid, M., 2018. Microgrids energy management systems: A critical review on methods, solutions, and prospects. Appl. Energy 222, 1033–1055. https://doi.org/10.1016/j.apenergy.2018.04.103