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Sujet

Study and simulation of a modular active power filter

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Dedication to

I dedicate this fruit of my long years of study first of all:

To my dearest parents, who are the light of my life, who have suffered and sacrificed so much to make me happy for their advice, affection and encousragement.

I thank you for all your efforts for me, may God keep you, protect, and bless you

And I dedicate also

All the members of my family

To all my friends and colleagues with whom I have shared great moments throughout these years

Assets the teachers and colleagues of the second year Master's class

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Symbols	
T	the state the switch (opend or closed)
L_f	coupling filter inductance
R_f	coupling resistance
L_s	source side network inductance
R_s	source side network resistance
L_c	network inductance on the load side
R_c	network resistance on the load side
C_{dc}	DC bus capacitor
V_{dc}	voltage across the capacitor
I_{ref}	reference current
I_{inj}	the currents injected by the inverter
I_s	source current
I_c	load current
V_s	RMS voltage of the source
K_i	integral controller gain
K_p	proportional controller gain
p	instantaneous value of real power
q	instantaneous value of the imaginary power
V_m	RMS voltage source
α-β	axes of the concordia den
V_α	instantaneous voltage (de l’axe α)
V_β	instantaneous voltage (de l’axe β)
I_α	instantaneous current (de l’axe α)
I_β	instantaneous current (de l’axe β)
θ	estimated angle
F_c	cut-of frequency
ξ	depreciation coefficient
Abbreviations	
APF	actif power filter
HPF	high pass filter
LPS	low pass filter
IGBT	Insolated Gate Bipolar Transistor
PLL	Phase Locked Loop
MVF	multi-variable filter
SRF	Synchronous reference frame
THD	total harmonics distortion

General Introduction

Introduction générale

The change in the nature of energy production, which was mainly based on fossil fuels has become increasingly clean through various renewable sources such as wind turbines and photovoltaic panels, leads to a paradigm shift from centralized to decentralized production. Moreover, technological progress has considerably modified the uses with the intensive use of power electronics-based loads, which are certainly economical but very polluting, which has directly affected the quality of the energy. The control of energy management comes first because production management and service continuity are the guarantees of good energy quality on the power grid. On the other hand, poor energy quality can cause dysfunction that can even lead to the shutdown of services, which can be very damaging economically. Electrical energy must be supplied in the form of a set of voltages forming a balanced three-phase alternating system with four major characteristics: amplitude, frequency, waveform and symmetry.

Currently, the situation of the power systems is quite worrying because the quality of power in the electrical installations is inexorably deteriorating. As a result, it becomes a major source of problems for energy distributors and their customers. This deterioration is directly caused by the proliferation of nonlinear load. This type of load is used to convert, control and regulate electrical current in commercial, industrial and residential systems [01], [02] and [03].

In order to improve energy efficiency and power quality, there is a strong need to use high performance converters with appropriate control laws, which ensure harmonic filtering.

The problem of harmonics in the electrical system, also known as harmonic pollution, is not new. Nonlinear loads connected to the power system that absorb non-sinusoidal currents cause harmonic distortion. These current harmonics, in turn, will propagate to the various nodes of the network. Injected current harmonics, reactive power, imbalances and other problems caused by this type of loads result in reducing overall system performance and power factor.

The traditional and long-standing method to solve this problem is to use passive filters. This is the most complete option, as well as the simplest and cheapest, but it has some disadvantages, such as, lack of adaptability to changes in network impedance and possible resonance with the network impedance

Thus, our objective in this Master thesis is to study and simulate a parallel active power filter to eliminate the pollution caused by non-linear loads.

Therefore, the first chapter will be dedicated to the problematic of electrical networks, as well as to the disturbace that can appear and the standards imposed on these disturbances.

The work presented in the second chapter will focus on the study of harmonic disturbances and how to deal with them using a parallel active power filter, a recent approach chosen to compensate for current harmonic disturbances. Moreover, we will show in this chapter the different methods of identification of harmonic currents.

In the last chapter, we will present, study and simulate a parallel active filter topology called modular active power filter in order to compensate the current harmonics produced by nonlinear loads consuming high current.

Chapter I

Power system disturbances

I. Introduction

Electrical energy must be supplied as a set of voltages constituting a balanced three-phase alternating system, which has four main characteristics amplitude frequency waveform and symmetry. However, in reality, the voltage wave is never perfectly sinusoidal, the amplitude of this wave varies constantly, and this is partly due to the presence of non-linear loads.

In this chapter, we will classify the different disturbances that can appear in an electrical system and expose their causes and consequences. We also present some traditional and modern solutions used to maintain the current waveform clean in the power system. [1].

I.1 Classification of electrical disturbances

Power quality monitoring is an essential service that many electricity producers provide to their large industrial and commercial customers [04] and [11].

The voltages in an electrical network form a three-phase alternating system with a base frequency of 50 or 60 Hz. The characteristics of such a system are as follows:

- The frequency.
- The amplitude of the voltages.
- The waveform should be as close as possible to a sinusoid.
- The symmetry of the three-phase system (equality of the amplitudes and phase shifts between the phases).

The classification of these electrical disturbances is a difficult problem that requires advanced engineering knowledge, but it is also one that can be solved with the help of an expert, among the existing disturbances we have:

- Amplitude variations (voltage dips, short interruptions and overvoltages or spikes, flicker).
- Frequency fluctuations around the fundamental frequency.
- Waveform changes (harmonics, inter harmonics, noise).
- Asymmetry of the three-phase system: unbalance.

We can also classify these electrical disturbances on the basis of their time frame and we note that there are [12]:

- Temporary disturbances.
- Short-term disturbances.
- Permanent disturbances.

a. Voltage dips and short interruptions

A voltage dip is defined as a voltage drop of 10% to 90% of the nominal value for a period of "10ms" milliseconds to one minute "1m".

A short break is defined as a voltage drop greater than 90% of the nominal value and lasting between "10 ms" milliseconds and one minute "1m".

Voltage dips are caused by natural phenomena such as lightning strikes, or by faults in the installation or in the public networks as well as those used by users. Moreover, the voltage dips are caused by short circuits that affect the electrical network or connected installations, as well as by the starting of high-capacity and high-power motors [05].

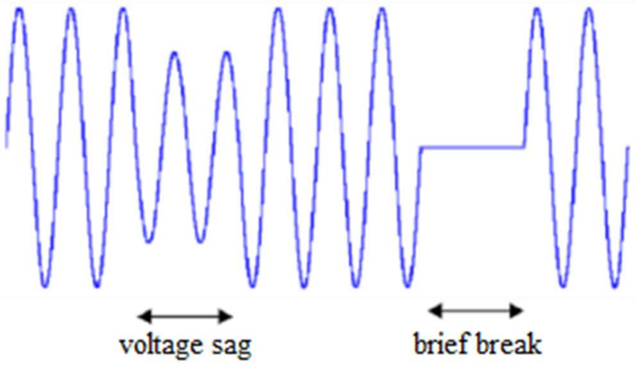

Figure 1: Voltage dips and short interruptions

b. Voltage fluctuations

The term "voltage fluctuations" refers to changes in the voltage envelope that occur in a regular or irregular manner. It is a series of changes in voltage amplitude that occur within a 10% band during a time interval of a few hundredths of a second. The main source of these currents arc arc furnaces and arc welders.

These fluctuations are represented by intensity variations, which are visible in the lighting and cause detectable discomfort for a 1% variation in voltage [05].

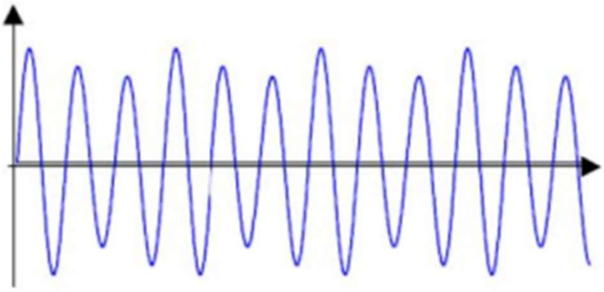

Figure 2: Voltage fluctuation

c. Unbalanced system

When the three voltages are not of equal amplitude and are not separated by an angle of 120°, the system is said to be unbalanced. On the other hand, when three quantities of the same nature and of the same pulsation have the same amplitude and are shifted in phase by 120° degrees, they produce a balanced three-phase system.

Most of the time, unbalances systems are caused by single-phase loads, because the currents drawn in this case are of varying magnitude and phase in each of the three phases.

When the three-phase loads are not balanced, the voltages can be unbalanced, so it can be said that unbalance is also linked with three-phase loads [05].

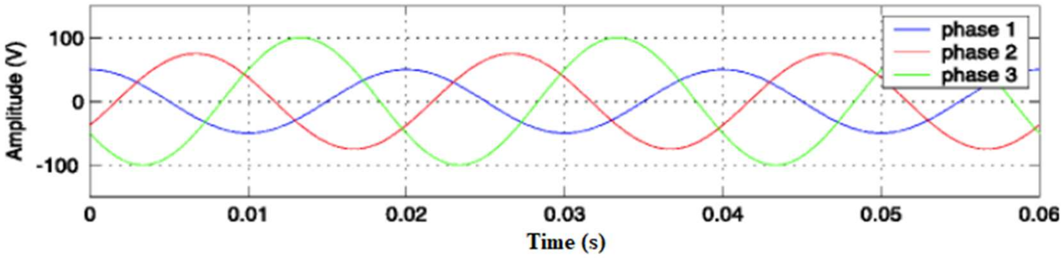

Figure 3:Unbalance of three-phase voltage systems

d. Overvoltages and overcurrents (Surges and overcurrents)

Overvoltage is a phenomenon that occurs when the input voltage at the terminals of a device or network exceeds the acceptable limit: it is an increase in voltage over a short period of time. The causes of a power surge are [03]:

- Electrical appliances.
- Lightning.
- Fluctuations and failures in the electricity network.

And for overcurrent there are two groups which are:

Overloads: The latter produces an overcurrent occurring in an electrical circuit, which is not due to an electrical fault. Overloads are small and often caused by too many connected devices or by devices that are too powerful.

Short circuits: The overcurrent produced by a fault with negligible impedance between active conductors with a potential difference in normal operation. Short circuits can have very large values.

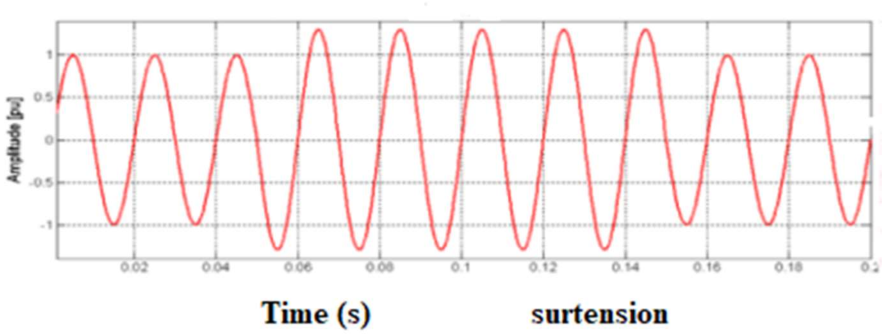

Figure 4: Example of overvoltage

e. Frequency variation

For the users that are not interconnected to the networks or supplied by an independent electrical source, a significant change in network frequency may occur.

This frequency fluctuation is extremely rare in distribution or transmission networks, and only occurs in exceptional circumstances, for example when the network has serious faults. Under typical operating conditions, the average value of the fundamental frequency should be within ±1% of 50 Hz [05].

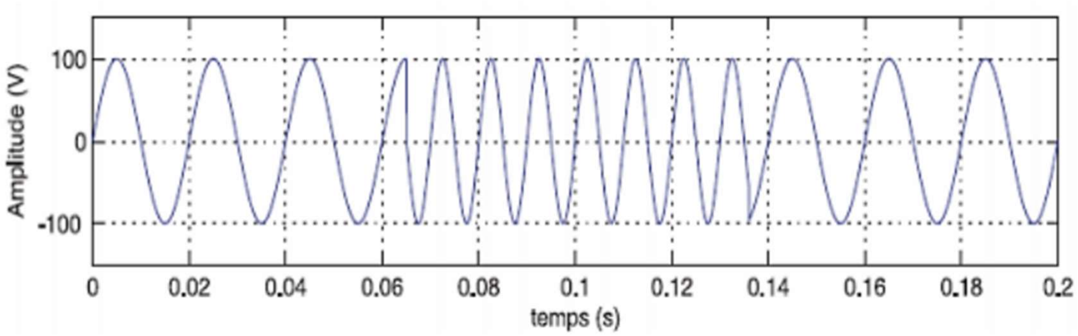

Figure 5: Frequency variation

I.2 Harmonics and inters harmonics

The line frequency is often 50 Hz or 60 Hz, depending on the country. In practice, voltage and current waveforms are not sinusoidal, especially when non-linear loads are present and cause harmonics in the power system. These harmonics are part of a periodic wave that oscillates at a frequency that is a multiple of the line frequency. Interharmonics, on the other hand, are components whose frequency is not a multiple of the fundamental frequency.

The most common sources of harmonics today are rectifiers: a diode or a thyristor, which convert AC voltages or currents into DC voltages or currents. Other sources of harmonics include variable speed drives, arc furnace and power electronic devices.

Current harmonics have the potential to cause energy dissipation in the form of heat. Moreover, in the presence of a resonance, these harmonics have the potential to destroy electrical equipment or block circuit breakers [06].

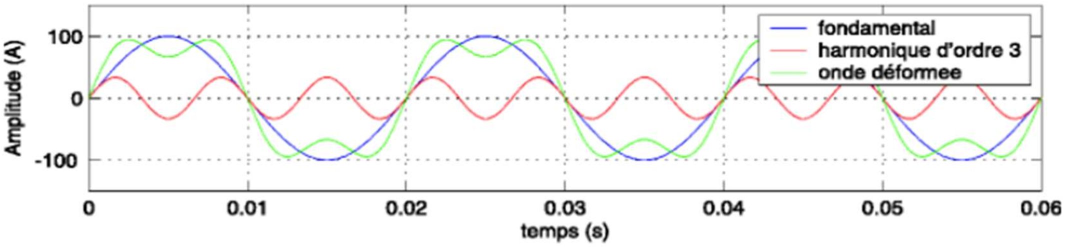

Figure 6: Example of the presence of harmonics

a. Harmonics origin

The proliferation of electrical equipment using static converters has led to a significant increase in the level of harmonised pollution of electrical networks in recent years. These electrical devices are considered to be non-linear loads that produce harmonic currents whose frequencies are multiples of the fundamental frequency. The passage of these harmonic currents through the impedances of the electrical network could cause harmonic voltages at the connection points, polluting the consumers served by the same electrical network [07].

b. Harmonics sourcess

The main reason for the appearance of voltage harmonics is the injection of non-sinusoidal currents by non-linear loads. Here are a few examples:

Single-phase dimmers (phase angle control):

- Power control of resistance ovens.
- Power modulation of halogen lights.

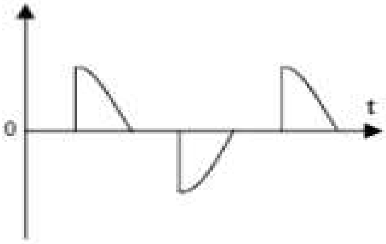

Figure 7: Absorbed current

Three-phase thyristor rectifier:

- Variable speed drive for DC motors and synchronous motors.

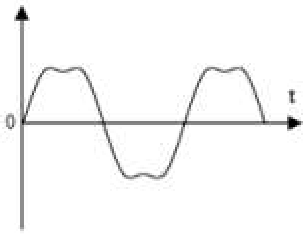

Figure 8: Absorbed current

Asynchronous motor :

- Machine tools.
- Household appliances.
- Lifts (elevator).

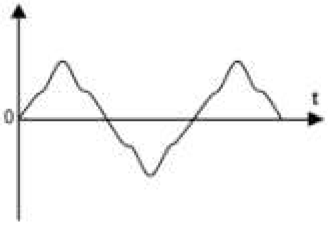

Figure 9: Absorbed current

And we have also:

- Transformers.
- Interruptible power supplie (UPS).
- The lights.
- Electric arc appliances.

c. <u>Characterisation of harmonic disturbances</u>

When an energy receiver absorbs non-sinusoidal or unbalanced currents or consumes reactive energy, it behaves like a polluting load. Harmonic disturbance is often defined as the rate of harmonic distortion for the voltage or current relative to a sine wave, and the term "power factor" is commonly used to describe the level of reactive energy consumption [04]. Thus, with regard to:

I.2.c.1 Rank of the harmonic :

The harmonic range is defined as the ratio of its frequency Fn (fundamental frequency) to the fundamental frequency (often 50 or 60 Hz) [04].

$$\boldsymbol{n} = \boldsymbol{f}_n / \boldsymbol{f}_1 \qquad \text{(I.1)}$$

I.2.c.2 The harmonic distortion ratio :

Harmonic disturbance is defined by the rate of harmonic distortion (THD) in voltage or current [04].

$$\text{THD}\ \% = 100 \times \frac{\sqrt{\sum_{n-2}^{\infty} I_n^2(t)}}{I_1} \qquad \text{(I.2)}$$

I.2.c.3 The power factor:

In the presence of harmonics, the apparent power S is composed of three parts: active P, reactive Q, and deforming D. The following equation gives the expression [12]:

$$S = \sqrt{p^2 + Q^2 + D^2} \qquad \text{(I.3)}$$

With:

$$P = V.\ I\ s \cos \phi \qquad \text{(I.4)}$$

$$Q = V.\ I\ s \sin \phi \qquad \text{(I.5)}$$

$$D = 3V_1 \sqrt{\sum_{h_1}^{\infty} I_h^2} \qquad \text{(I.6)}$$

the RMS value:

$$I_{eff} = \sqrt{\sum_{n-0}^{\infty} I_n^2} \qquad \text{(I.7)}$$

And the power factor:

$$F = \frac{P}{\sqrt{p^2 + Q^2 + D^2}} \qquad \text{(I.8)}$$

d. **Impact of harmonics**

Harmonic currents propagate through the power system, reducing the availability of power from the source and polluting the consumers served by the power system. They can cause problems with customer equipment, leading to a significant increase in power generation costs. The effects produced by harmonics can be divided into two types: instantaneous effects and long-term effects, as follow:

I.2.d.1 Instantaneous effects :

Instant effects appear immediately on specific devices [04]. Such as:

- **Malfunctions of certain electrical equipment:** In the presence of harmonics, the voltage and the current can change sign several times in half a period. Devices whose operation is based on the zeroing of electrical magnitudes may be affected.
- **Functional disorders of microcomputers:** The effects on this equipment can be seen in reduced picture quality and pulse pairs in disc drive motors.
- **Errors in measuring equipment:** Some energy meters show measurement degradation due to additional reading errors in the presence of harmonics.
- **Vibrations and noises:** Harmonic currents generate vibrations and acoustic noise, especially in electromagnetic devices (transformers, inductors and rotating machines).

I.2.d.2 Long-term effects :

They appear after a more or less prolonged exposure to a harmonic disturbance. The most important effect is of a thermal type, it results in heating, which leads to a premature exhaustion of the material, of the lines, and to a downgrading of the material [04][06]. For example, we have:

- **Heating of cables and equipment:** These effects can be short term (seconds to hours) or long term (hours to years) and affect cables, which can be the seat of neutral overheating, and windings such as those of transformers or motors.
- **Capacitor heating:** Heating is caused by losses due to hysteresis in the dielectric. Capacitors are therefore sensitive to overloads, whether due to a too high fundamental voltage or to the presence of harmonics. This overheating can lead to breakdown.
- **Heating due to additional losses in electrical machines and transformers:** Heating is caused by losses in the stator of electrical machines and mainly in their rotor circuits due to the large speed differences between the harmonic inductor rotating fields and the rotor. Harmonics also caused additional losses in transformers, Joule effect in windings, accentuated by the skin effect and hysteresis and Foucault current losses in magnetic circuits.

I.3 Solutions for cleaning up the electricity network

To compensate for all the disturbances, we have two methods of pollution control solution, traditional and modern, which are presented by filters.

Filtering is a method of harmonic reduction in which the harmonic distortion gradually decreases or as an overall solution to absorb the current harmonics, the filter is therefore a harmonic current absorber [04][09]. The following filtering techniques can be identified:

- Passive filters.
- Active filters.
- Hybrid filters.

a. Traditional solutions

Several strategies have been proposed in order to limit the propagation and effect of harmonics in power systems [10].

- The short-circuit power of the grid is increased, as well as the use of low-emission converters, thus reducing harmonic distortion.
- **Passive filters:** This solution consists of placing a very low impedance in parallel on the power supply network around the frequency to be filtered and a sufficiently high impedance at the fundamental frequency of the network. Among the most popular filtering devices, two types of filters are used to limit harmonic voltages, which are:

I.3.a.1 Resonant passive filter :

It consists of the series connection of an inductor, a resistor and a capacitor. This figure clearly shows the assembly of the device and their impedances as a function of frequency.

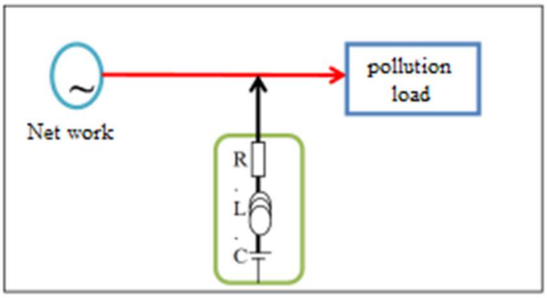

Figure 10: Passive resonant filter scheme

I.3.a.2 Passive damped or high-pass filter:

The high-pass filter compensates for harmonics greater than or equal to its fundamental frequency. It can be connected in parallel with other resonant filters.

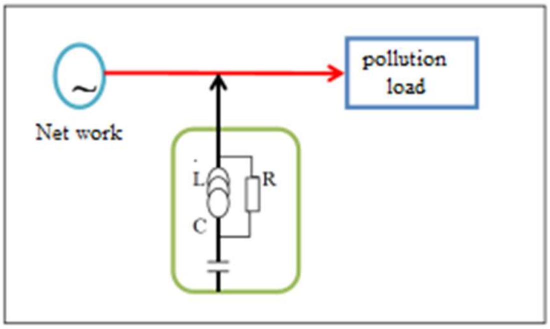

Figure 11: Damped passive filter scheme

These devices are used to prevent harmonic currents from propagating through the power system. They can also be used to compensate reactive power.

Despite their widespread use in industry, these devices can have a number of drawbacks:

- Lack of flexibility to adapt to network and load variations.
- Large-scale equipment.
- Resonance problem with network impedance.

b. Modern solutions

There are two main reasons for the development of a new and efficient filter structure known as active power filter. The first reason is due to the inherent inefficiencies of traditional filtration systems, which no longer meet the changing loads and power grids.

The second reason is the introduction and development of semiconductors components. The objective of these filters is to generate current or voltage harmonics but in phase opposition to compensate the harmonics current or voltage and reactive power generated by non-linear loads [09]. There are several types of this solution, namely:

I.3.b.1 Parallel active power filter (PAF):

Also called shunt compensator, it is connected in parallel to the distribution network. It is usually controlled as a current generator. It restores the harmonic currents I_{inj} equal to those absorbed by the non-linear load into the electrical network but in phase opposition, so that the current supplied by the network is sinusoidal and in phase with the corresponding simple voltage. Its independence from the source and the load ensures self-adaptability, reliability and performance.

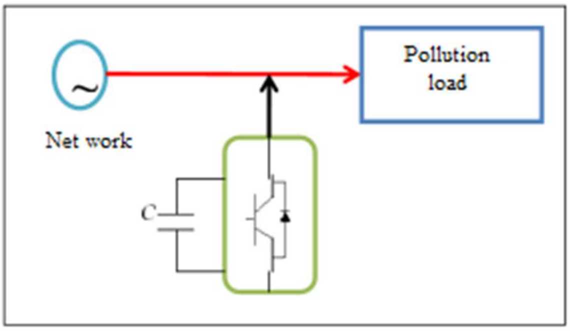

Figure 12: Parallel active power filter scheme

I.3.b.2 Series active power filter (AFS):

Series active power filter (FAS) generates harmonic voltages V_h whose sum with the mains voltage V_s is a sinusoidal wave. It is intended to protect installations sensitive to disturbances from the network such as voltage harmonics and overvoltages. On the other hand, series filtering does not compensate harmonic currents produced by the loads.

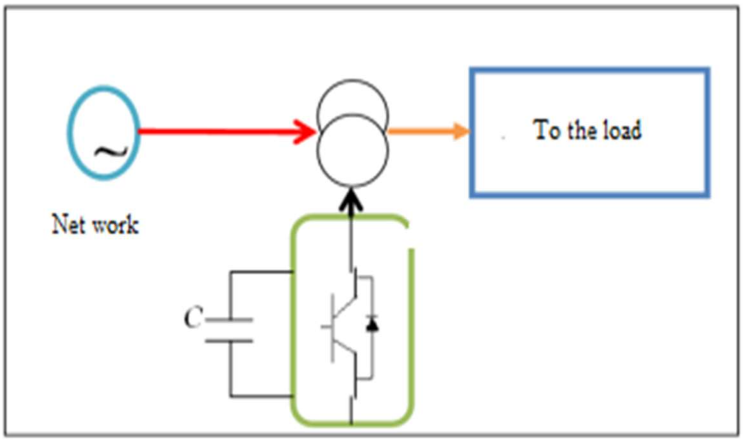

Figure 13: Serial active filter scheme

I.3.b.3 Unified Power Quality Conditioner (UPQC):

This Unified Power Quality Conditioner (UPQC), results from the combination of the two active power filters, parallel and series filters. Taking advantage of the benefits of the two active filters, the UPQC ensures a sinusoidal current and voltage of the electrical network from a disturbed current and voltage of the latter.

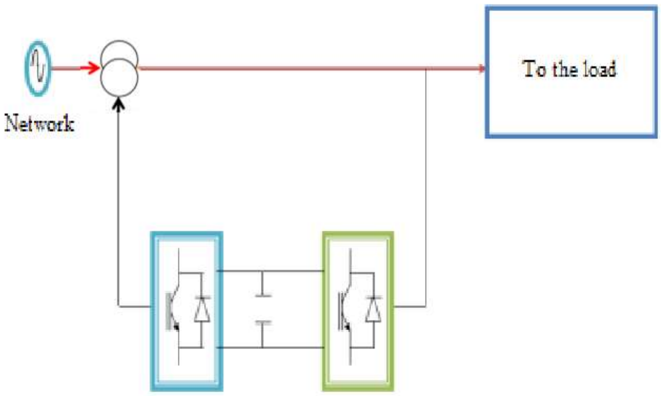

Figure 14: Active parallel-serial filter scheme (UPQC)

There are several other mixed groups of active power filters, this time with passive filters, such as:

- The series active power filter connected in series with parallel passive filters.
- The series active power filter with parallel passive filters.
- The parallel active power filter with a parallel passive filter.

Conclusion

Non-linear loads are increasingly used as consumption outlets in electrical networks. They generate harmonic pollution, which requires the use of a device to eliminate these disturbances and compensate for the reactive energy they use. The rapid development of harmonic generators will lead to a significant increase in the number of disturbances caused by customers.

In this chapter, we have discussed the many causes of disturbances in electrical networks, and the main disturbance, which are harmonic currents; we will talk about their origins, sources, characteristics and consequences. We will then look at depollution techniques and methods for limiting harmonic effects.

Chapter II

Parallel Active Power Filter, Principle and Command Strategy

II. Introduction

In recent years, several research projects have been carried out to compensate harmonic currents generated by polluting loads connected to the electrical networks, and among these researches, a very effective solution has been found like the use of an active power filter. In single or three phase, the parallel active power filter APF is a modern and efficient technique to compensate harmonic currents and reactive energy [02], [03] and [07].

In this chapter, we will study the general structure of an APF, and we will see the control methods applied to this filter and the different parts constituting a parallel active power filter.

II.1 Active power filter

a. Definition

The ideal role of the active power filter is to remove all current harmonics generated by the non-linear, by injecting curant harmonics of equal amplitude to those generated by the load but in phase opposition. This ensures that the source current is sinusoidal and equal to the fundamental current of the load [14].

The needs for harmonic pollution control are diverse, as we always want to make sure:

- Non-pollution of a clean network supplying a sensitive load.
- The proper functioning of a sensitive load in a polluted environment.

b. Operation principle

The active power filter, connected in parallel to the network, is most often used as a current generator. It injects into the network harmonics currents similar to those absorbed by the polluting load, but in phase opposition. Therefore, the purpose of a parallel active power filter is to prevent disturbing currents (harmonic, reactive and unbalanced), produced by polluting loads, from flowing through the network impedance, located upstream of the active power filter connection point [12] and [15].

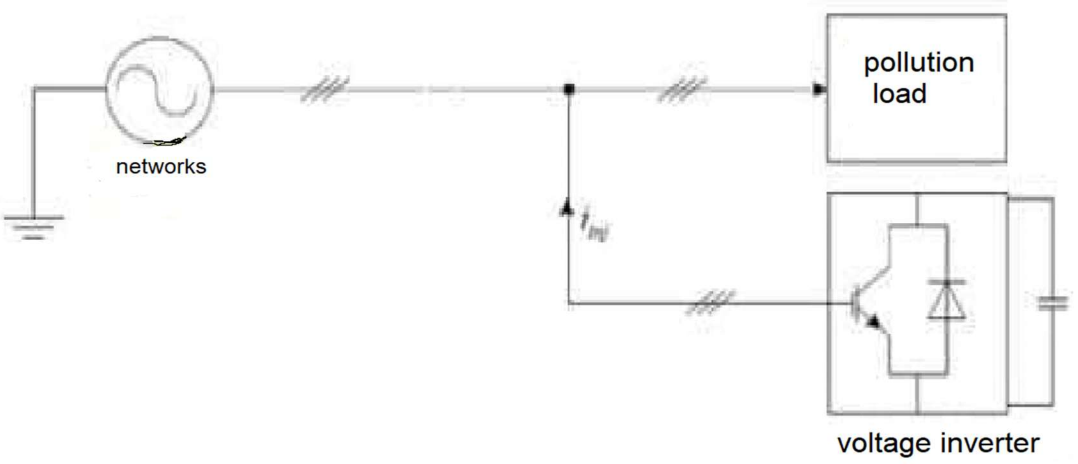

Figure 15: Illustrative diagram of a parallel active power filter

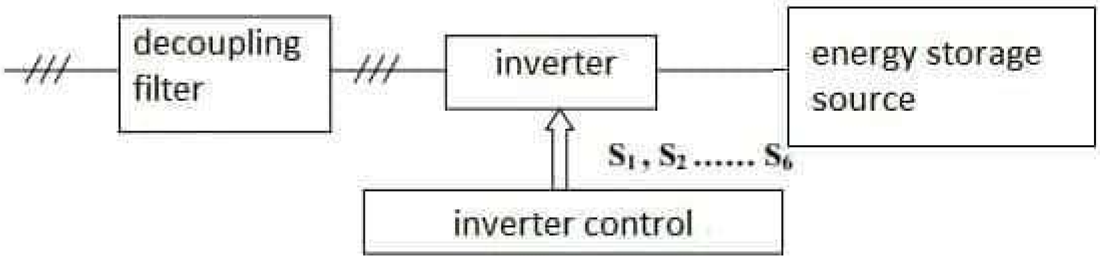

Figure 16: Parallel active power filter components

II.2 Classification of parallel active power filters

There are several types of parallel active power filters according to the number of phases, the inverter technology and the topology. We have thus:

- Single or three-phase active power filters.
- Active power filters with or without connected neutral.
- Active power filters based on voltage or current inverter.

Regardless of the fact that single-phase active filters have received a lot of attention in the literature, a single-phase are normally limited to low power applications, three-phase are more widely used in industrial applications.

The second categorisation is based on the topology used, with or without a corresponding neutral. An active power filters with a corresponding neutral have been developed to inject and compensate for zero sequence components. The majority of the filters are connected without a neutral to the field.

In terms of inverter technology, active power filters are based either on a voltage inverter with a DC capacitor and an inductance filter on the grid side, or on a DC with an inductance and a capacitance filter on the grid side.

Although there are articles based on the current inverter, the voltage inverter is often preferred because of its higher efficiency, lower cost and has smaller volume (when comparing the capacitor and inductor on the DC side) [13].

II.3 General structure of a parallel active power filter

An active power filter consist of two independent parts. The first part consists of an inverter, a main coupling filter and a power supply. The latter two factors determine the type of active power filter. It can be a voltage or current structure depending on whether it is realised with a voltage or current inverter [12] and [15].

The power part consists of:

- A voltage inverter.
- An energy storage circuit, often capacitive.
- And an output filter.

The control part consists of:

- A circuit for identifying the disturbed currents.
- DC voltage regulation applied to energy storage elements.
- Regulation of the current fed into the grid from the voltage inverter.

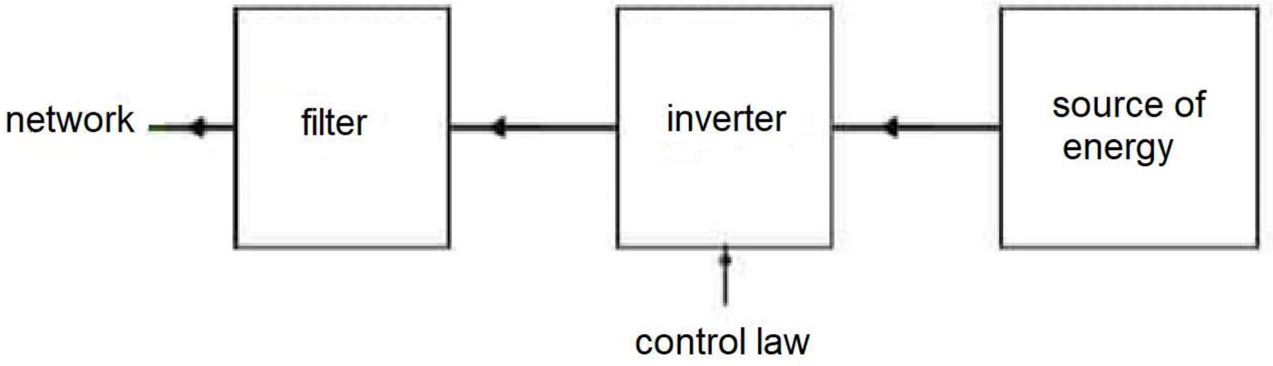

Figure 17: General structure of a parallel active power filter

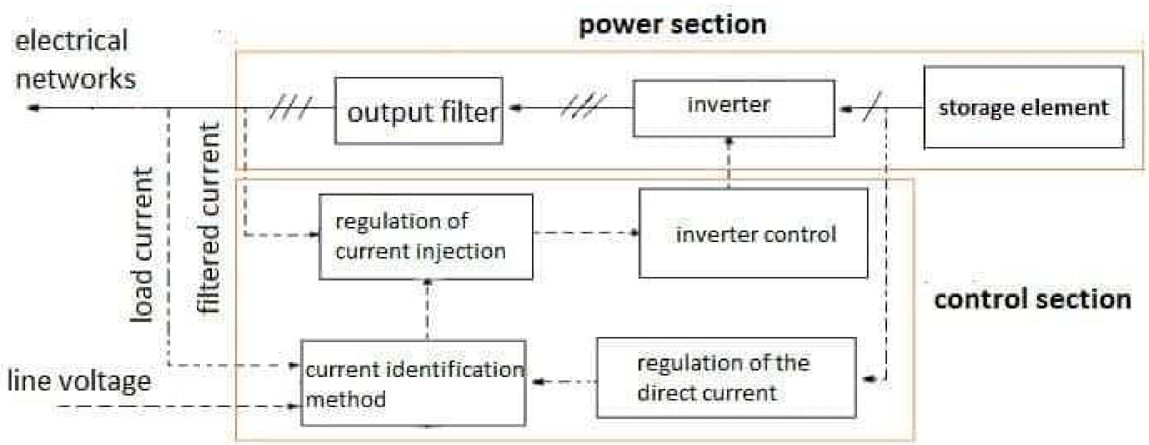

Figure 18: Structure of a parallel active power filter

II.4 Study of the active power filter power part

The use of non-linear loads that produce current harmonics in the distribution system plays an important role in power quality deterioration. The most effective option is to use parallel active power filters to eliminate current harmonics and compensate for reactive power in order to achieve a very high-power quality.

It should be noted that parallel active power filters are inverters, consisting of converters based on power switches and connected to an adaptable control and command system.

The most common general construction of a parallel active power filter connected to a three-wire three-phase power system is a three-leg inverter.

So, our inverter is connected with the DC side via a C_{dc} capacitor storage system to provide a nearly constant voltage V_{dc}, and for the AC side, it is connected to the grid via a first order passive filter (L, R), as shown in the figure below [14].

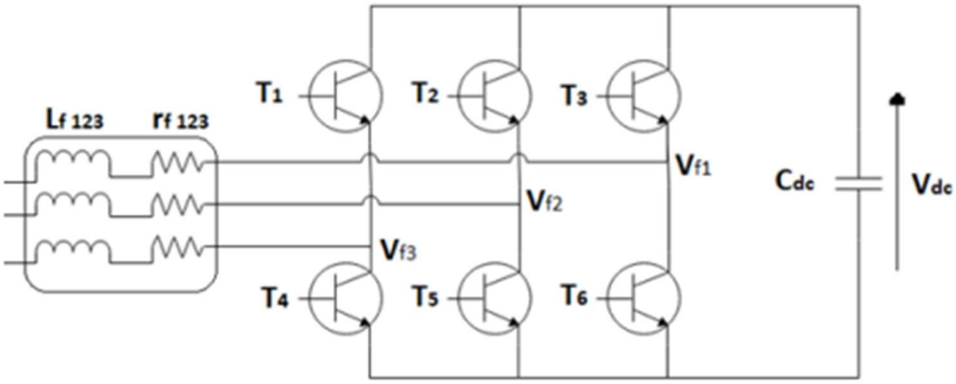

Figure 19: Inverter connected with capacitor and grid

The inverter is the essential part of the active power filter, the figure below represents the general structure of a three-phase inverter, it is composed of three leg based on controllable power switches.

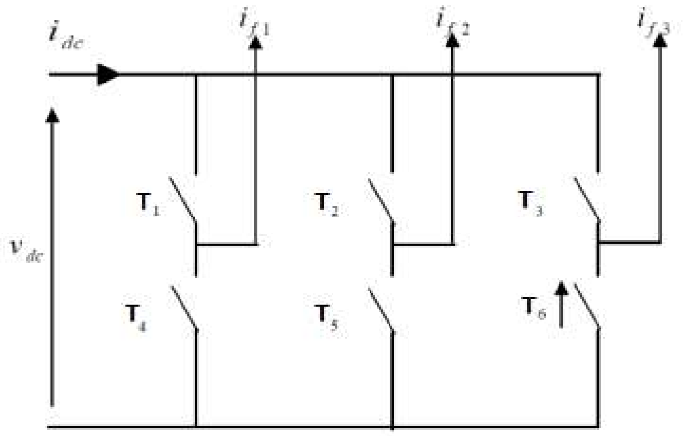

Figure 20: The APF inventer

The capacitor C_{dc} serves as a constant voltage source. The voltage V_{dc} in its terminals must be positive and almost constant. Its variations must be small in order to not exceed the voltage limit of the semiconductors, which compose the switches, and in order to not degrade the performances of the active power filter.

The selection of the voltage V_{dc} and the capacitor capacity C_{dc} influences the dynamic range and the compensation performance of the parallel active power filter. In fact, a high V_{dc} voltage improves the dynamic range of the active filter. In addition, the ripples of the DC voltage contribute significantly to the currents generated by the active power filter and are limited by the choice of the option that could degrade the compensation quality of the parallel active power filter. These variations become more significant as the filter current amplitude increases and its frequency decreases. Therefore, we can assume that only the first harmonics are taken into account when determining the parameters of the storage system.

The inverter uses programmed on/off switches in conjunction with diodes [16]. The voltage regulator uses bi-directional current switches:

- MOSFET for low power.
- IGBT for medium currents.
- The GTO thyristor for high currents.

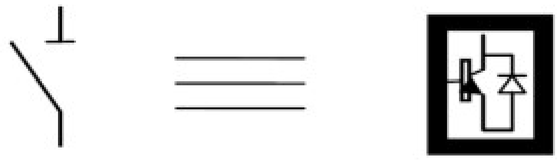

Figure 21: type of switches

Concerning the output filter, the primary function is to integrate the voltage converter with the electrical network. This filter has a double purpose: it reduces the dynamics of the current and reduces the proliferation of components on the electrical network due to switching.

In the case of the APF, this filter consists of an inductance L_f and an internal resistance R_f.

The image below shows that a three-leg active power filter is composed of six switches. This inverter is connected to an electrical network by a first-order input filter. However, the DC voltage source consists of a capacitor C_{dc}, with V_{dc} indicating the voltage at their steps, which is maintained at a nearly constant positive value, as shown in the following figure.

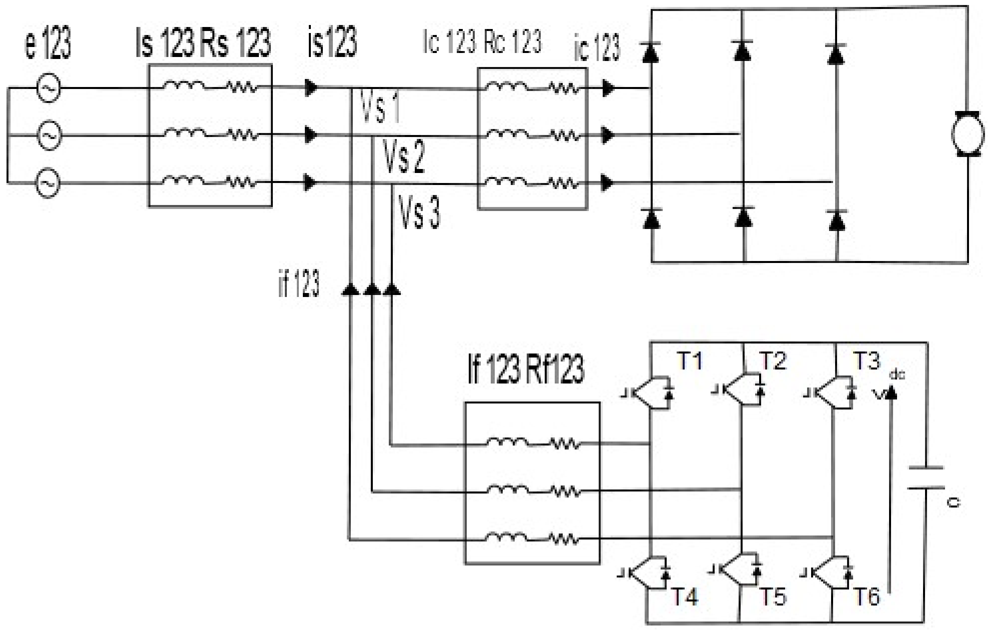

Figure 22: Active power filter with voltage structure with three legs inverter connected in parallel to the electrical network

The state of the control signals defined at the opening and closing of the active power filter switches is defined as follows:

$$\mathrm{S_1} = \begin{cases} 1, & \mathrm{T_1 \text{ is closed and } T_4 \text{ is open}} \\ 0 & \mathrm{T_1 \text{ is open and } T_4 \text{ is closed}} \end{cases}$$

$$\mathrm{S_2} = \begin{cases} 1, & \mathrm{T_2 \text{ is closed and } T_5 \text{ is open}} \\ 0 & \mathrm{T_2 \text{ is open and } T_5 \text{ is closed}} \end{cases} \qquad \text{(II.1)}$$

$$\mathrm{S_3} = \begin{cases} 1, & \mathrm{T_3 \text{ is closed and } T_6 \text{ is open}} \\ 0 & \mathrm{T_3 \text{ is open and } T_6 \text{ is closed}} \end{cases}$$

The voltages between phases imposed by the inverter are then equal to:

$$\begin{bmatrix} \mathrm{V_{f1}} & - & \mathrm{V_{f2}} \\ \mathrm{V_{f2}} & - & \mathrm{V_{f3}} \\ \mathrm{V_{f3}} & - & \mathrm{V_{f1}} \end{bmatrix} = \begin{bmatrix} \mathrm{S_1} & - & \mathrm{S_2} \\ \mathrm{S_2} & - & \mathrm{S_3} \\ \mathrm{S_3} & - & \mathrm{S_1} \end{bmatrix} \mathrm{V_{dc}} \qquad \text{(II.2)}$$

The simple voltages (V_{f1}, V_{f2}, V_{f3}) are referred to the neutral point of the source and verified using the equation:

$$\begin{bmatrix} V_{f1} \\ V_{f2} \\ V_{f3} \end{bmatrix} = \begin{bmatrix} V_{s1} \\ V_{s2} \\ V_{s3} \end{bmatrix} + L_f \frac{d}{dt} \begin{bmatrix} i_{f1} \\ i_{f2} \\ i_{f3} \end{bmatrix} \qquad \text{(II.3)}$$

Assuming that the power system constraints are balanced and that the total number of currents flowing through the active power filter is zero. We now have the following equations:

$$\begin{cases} V_{s1} + V_{s2} + V_{s3} = 0 \\ i_{f1} + i_{f2} + i_{f3} = 0 \end{cases} \qquad \text{(II.4)}$$

So we get $V_{f1} + V_{f2} + V_{f3} = 0$ and we get $\begin{bmatrix} V_{f1} \\ V_{f2} \\ V_{f3} \end{bmatrix} = \begin{bmatrix} 2S_1 & -S_2 & -S_3 \\ -S_1 & 2S_2 & -S_3 \\ -S_1 & -S_2 & 2S_3 \end{bmatrix} \frac{V_{dc}}{3}$ (II.5)

From this equation, we can get a table that resumes all the cases of voltages generated by the three legs voltage inverter:

Table 1: Voltages generated by the three-arm voltage inverter

Nº of cases	**S1**	**S2**	**S3**	**Vf1**	**Vf2**	**Vf3**
0	0	0	0	0	0	0
1	0	0	1	$-V_{dc}/3$	$-V_{dc}/3$	$2V_{dc}/3$
2	0	1	0	$-V_{dc}/3$	$2V_{dc}/3$	$-V_{dc}/3$
3	0	1	1	$-2V_{dc}/3$	$-V_{dc}/3$	$-V_{dc}/3$
4	1	0	0	$2V_{dc}/3$	$-V_{dc}/3$	$-V_{dc}/3$
5	1	0	1	$-V_{dc}/3$	$-2V_{dc}/3$	$-V_{dc}/3$
6	1	1	0	$-V_{dc}/3$	$-V_{dc}/3$	$-2V_{dc}/3$
7	1	1	1	0	0	0

For a second inverter topology, we have chosen a two-arm inverter with a midpoint capacitor. For this topology, our voltage inverter consists of two switch arms, for the third arm it is replaced by two capacitors connected to the third phase of the electrical network. The two capacitors act as a constant voltage source. The voltage in their ends is also kept at a constant level $\frac{V_{dc}}{2}$ [14] and [17].

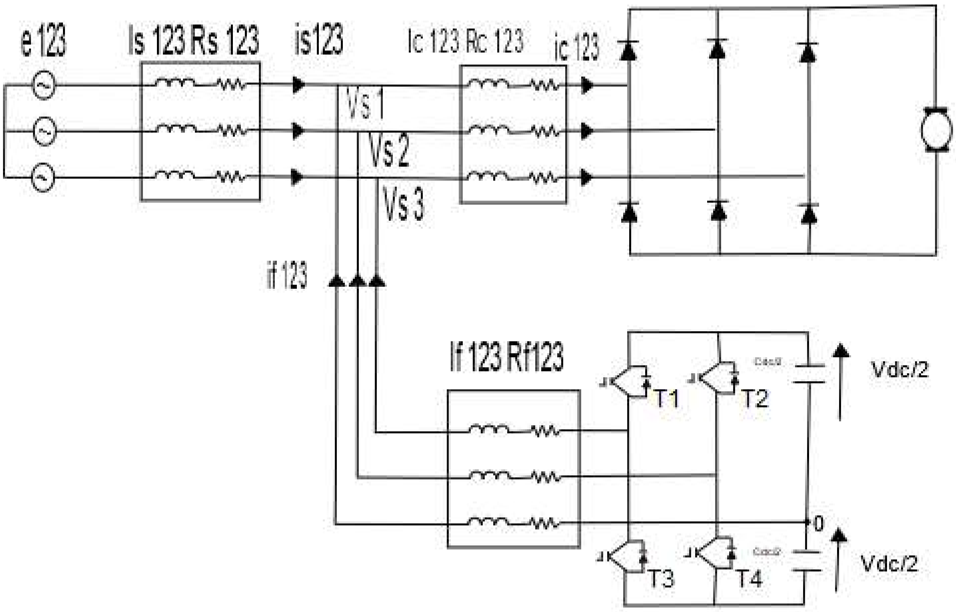

Figure 23: Two-arm inverter with a midpoint capacitor structure

The status of the switching signals determines whether the switches are closed or open as follows:

$$S_1 = \begin{cases} 1, & T_1 \text{ closed and } T_3 \text{ open} \\ 0 & T_1 \text{ open et } T_3 \text{ closed} \end{cases}$$

(II.6)

$$S_2 = \begin{cases} 1, & T_2 \text{ closed and } T_4 \text{ open} \\ 0 & T_2 \text{ open and } T_4 \text{ closed} \end{cases}$$

The voltages between phases generated by the inverter are then equal to:

$$\begin{cases} V_{fan} = V_{fa0} + V_{0n} \\ V_{fbn} = V_{fb0} + V_{0n} \\ \quad V_{fcn} = V_{0n} \end{cases} \tag{II.7}$$

The addition of the 3 voltages gives:

$$V_0 n = -\frac{v_{fa_0} + v_{fb_0}}{3} \tag{II.8}$$

After replacing the previous equations, we obtain simple voltages in matrix form:

$$\begin{bmatrix} V_{fan} \\ V_{fbn} \\ V_{fcn} \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & \frac{-1}{3} \\ \frac{-1}{3} & \frac{2}{3} \\ \frac{-1}{3} & \frac{-1}{3} \end{bmatrix} \cdot \begin{bmatrix} v_{fa_0} \\ v_{fb_0} \end{bmatrix} \tag{II.9}$$

$$\begin{bmatrix} v_{fa_0} \\ v_{fb_0} \end{bmatrix} = \frac{v_{dc}}{2} \cdot \begin{bmatrix} 2S1 - 1 \\ 2S2 - 1 \end{bmatrix} \tag{II.10}$$

The following table gives a total illustration for the voltages generated by the dual inverter with midpoint capacitor:

Table 2: Voltages generated by the two-arme voltage inverter with midpoint capacitor

N° of cases	S_1	S_2	S_3	Vf1	Vf2	Vf3
0	0	0	0	$—V_{dc}/6$	$—V_{dc}/6$	$—V_{dc}/3$
1	0	0	1	$V_{dc}/2$	$—V_{dc}/2$	0
2	0	1	0	$—V_{dc}/2$	$V_{dc}/2$	0
3	0	1	1	$V_{dc}/6$	$V_{dc}/6$	$—V_{dc}/3$

Finally, a theoretical study shows that:

$(V_{dc})_{\text{two arms middle point}} = 2*(V_{dc})_{\text{three arms}}$. [14].

II.5 Control study of the active power filter

In this section, we will talk about the control part and its strategies. So, we will describe:

- The method for identifying harmonic currents.
- The regulation of the DC bus of the voltage inverter (in this work we will use the PI).
- Controlling the voltage inverter to generate semiconductor-switching signals using hysteresis or conventional PWM.

Concerning the parallel active power filter there are two control strategies for identifying harmonic currents of a non-linear loads, which are:

- The direct method, which is based on measuring the current of the polluting load and then extracting the harmonic components of this current.
- The indirect method, which consists of measuring the source currents, and imposing the sinusoidal form on these currents.

Several methods are reported in the literature that describe various identification algorithms, among of this method of identification we have the synchronous reference frame (SFR) detection method, based on the Concordia transformation function. This technique is mainly based on the calculation of the fundamental signal obtained by a PLL. This requires absolute accuracy in the calculation of this sinusoidal signal in order to avoid erroneously identified currents.

a. Direct method

The direct control, its operating principle is based on the comparison of the reference current $I_{ref}(t)$, which is obtained by extracting the harmonic currents on load, with the currents injected by the active power filter $I_{inj}(t)$, as illustrated in Figure below.

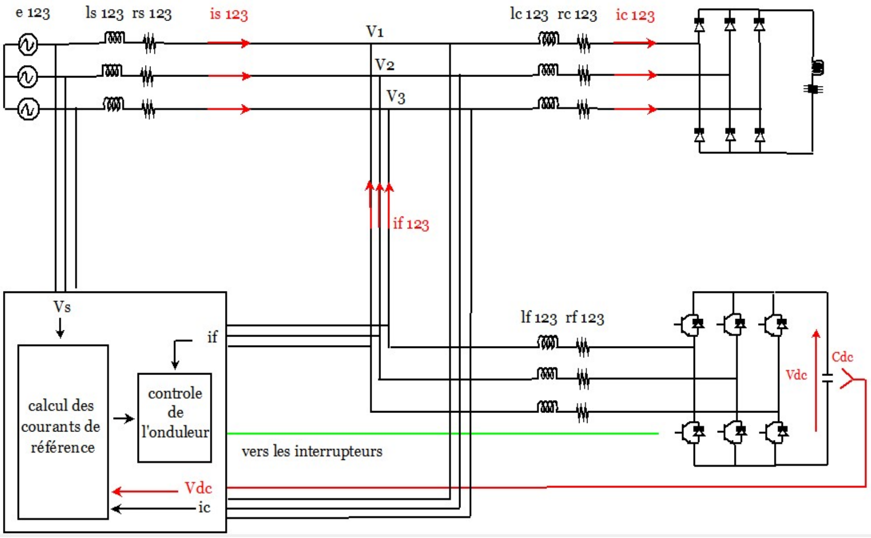

Figure 24: Stratégie de commande directe d'un filtre actif de puissance à trois fils

b. Indirect method

The indirect control is based on the comparison of the reference current I_{ref} with the source current I_s as shown in Figure below.

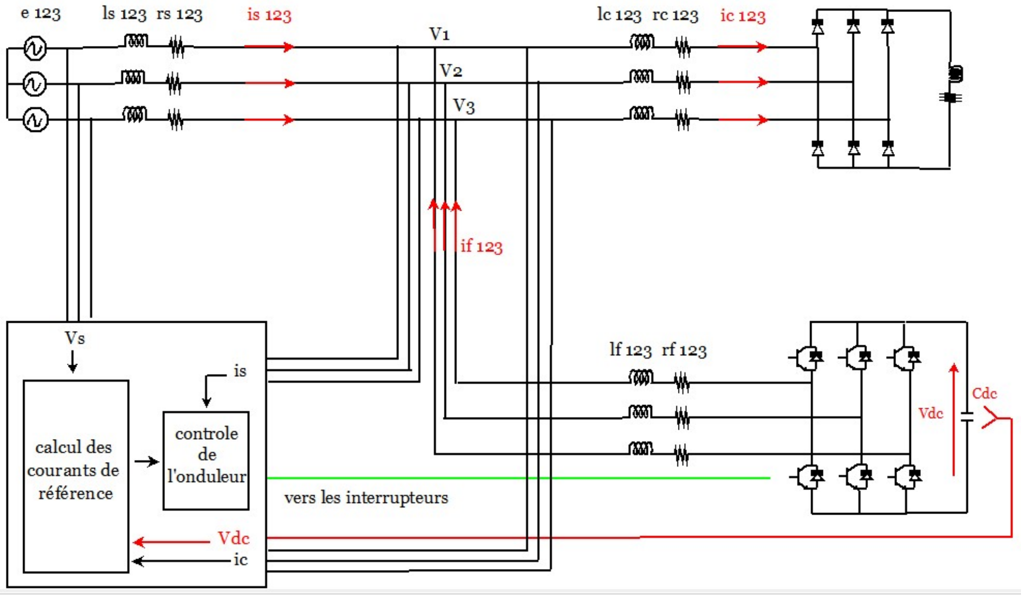

Figure 25: Indirect control strategy for a three-wire active power filter

c. Real and imagin/ary instantaneous power method (p-q)

The most commonly used identification method for generating reference currents is the real and imaginary instantaneous power method (direct method). This has the advantage that the disturbance to be compensated can be selected accurately, quickly and easily. This approach is widely used to compensate harmonic currents and reactive power.

H. Akagi was the first to introduce this method [22]. By transforming the simple voltages $v_{s1}(t), v_{s2}(t), v_{s3}(t)$from the source and the line currents $i_{c1}(t), i_{c2}(t), i_{c3}(t)$ in the (α, β) frame. So, this called Concordia transformation.

This transformation transforms a balanced three-phase system into a two-phase system, which simplifies the mathematical equations and reduces installation costs. In the (α, β) diagram, the general vector x_{abc} can be represented by the expressions below:

The apparent power in the presence of harmonics consists of three parts [14]:

Active (P), reactive (Q) and distorting power (D).

$$S = \sqrt{p^2 + Q^2 + D^2} \tag{II.11}$$

This method makes use of the α-β transformation (Clarke transformation), to obtain real and imaginary powers through (V_α, V_β) and (I_α, I_β), the orthogonal components of the α-β representative associated with the connection voltages of the parallel active power filter (V_s) and the currents absorbed by the polluting loads (I_c).

$$\begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_{s1} \\ v_{s2} \\ v_{s3} \end{bmatrix} \tag{II.12}$$

$$\begin{bmatrix} I_{c\alpha} \\ I_{c\beta} \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{c1} \\ i_{c2} \\ i_{c3} \end{bmatrix} \tag{II.13}$$

The instantaneous active power in the absence of harmonics, denoted P(t), is characterised by the following formula:

$$p(t) = v_\alpha\, i_\alpha + v_\beta\, i_\beta \tag{II.14}$$

In the absence of harmonics, the instantaneous imaginary power can be expressed in terms of:

$$q(t) = -v_\beta\, i_\alpha - v_\alpha\, i_\beta \tag{II.15}$$

q-power has a deeper significance than typical reactive power. In fact, unlike reactive power, which considers frequency as secondary, imaginary power must take into account all harmonic components of the current and voltage. Therefore, we can construct the following correlation matrix:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{II.16}$$

This term can be used to divide the real and imaginary instantaneous powers into two parts:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} \bar{p} + \tilde{p} \\ \bar{q} + \tilde{q} \end{bmatrix} \tag{II.17}$$

$\bar{p}$ and $\bar{q}$ The continuous components of p and q.

$\tilde{p}$ and $\tilde{q}$ The alternative components of p and q.

For more or less satisfactory removal of the DC component, we use a low-pass filter with subtraction between the input and output of the filter to create a filter equivalent to a high-pass filter when we use the direct control strategy [19].

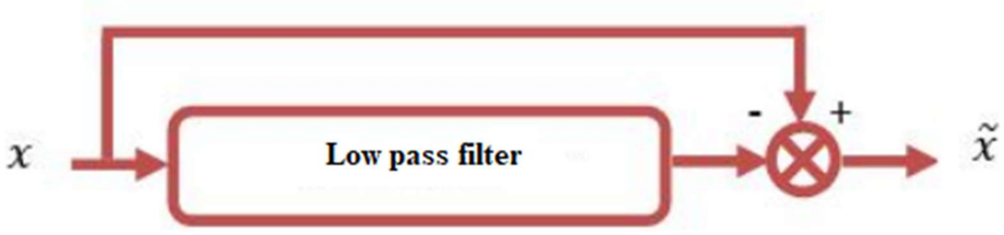

Figure 26: Schematic diagram of the power separation method

The low-pass filter used is a second-order Butterworth filter, and its transfer function is given by the formula below:

$$H_{HPF}=\frac{\omega_c^2}{2+2\xi w0s+W\ \ c} \qquad (II.18)$$

Another key control element is the management of the average voltage at the terminals of the capacitor, which is kept at a nearly constant value through the use of a proportional integral (PI) controller. The measured voltage V_{dc} is compared to its reference V_{dc}^{reF}, and the resulting error signal is applied to the input of the PI [19].

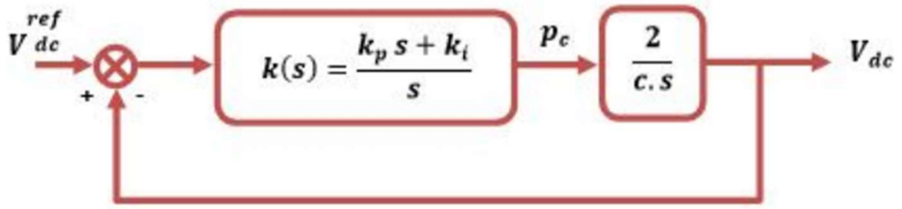

Figure 27: Regulation loop of the supply voltage of the parallel active filter

After calculating the transfer function in a closed loop and identifying it with the transfer function in the second order, we obtain:

$$K_p=\frac{c\omega_c^2}{2} \qquad (II.19)$$

$$K_i=\frac{\xi C\omega_C}{2} \qquad (II.20)$$

with ξ: the depreciation factor $\frac{\sqrt{2}}{2}$

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \frac{1}{v_\alpha^2+v_\beta^2} \cdot \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \cdot \begin{bmatrix} p \\ q \end{bmatrix} \tag{II.21}$$

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \frac{1}{v_\alpha^2+v_\beta^2} \cdot \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \cdot \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} + \frac{1}{v_\alpha^2+v_\beta^2} \cdot \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \cdot \begin{bmatrix} \tilde{P} \\ \tilde{q} \end{bmatrix} \tag{II.22}$$

Depending on the function we assign to the active power filter, we can compensate for either current harmonics or reactive energy, or a combination of both. The following table summarises the different compensation methods available.

Table 3: Compensation modes for instantaneous power control

	Harmonic current compensation	Reactive power compensation	Compensation of harmonic currents and reactive power
Control settings	$p_f = \tilde{p}$ et $q_f = \tilde{q}$	$p_f = 0$ et $q_f = \bar{q}$	$p_f = \tilde{p}$ et $q_f = \bar{q}$

Our main objective is to compensate for harmonic currents and reactive power.

From the inverse Concordia transformation, we can determine the reference currents:

$$\begin{bmatrix} I_{ref\,\alpha} \\ I_{ref\,\beta} \end{bmatrix} = \frac{1}{v_\alpha^2+v_\beta^2} \cdot \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \cdot \begin{bmatrix} p \\ q \end{bmatrix} \tag{II.23}$$

$$\begin{bmatrix} I_{ref\,1} \\ I_{ref2} \\ I_{ref3} \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} I_{ref\,\alpha} \\ I_{ref\,\beta} \end{bmatrix} \tag{II.24}$$

The following figure gave the complet control of the direct strategy:

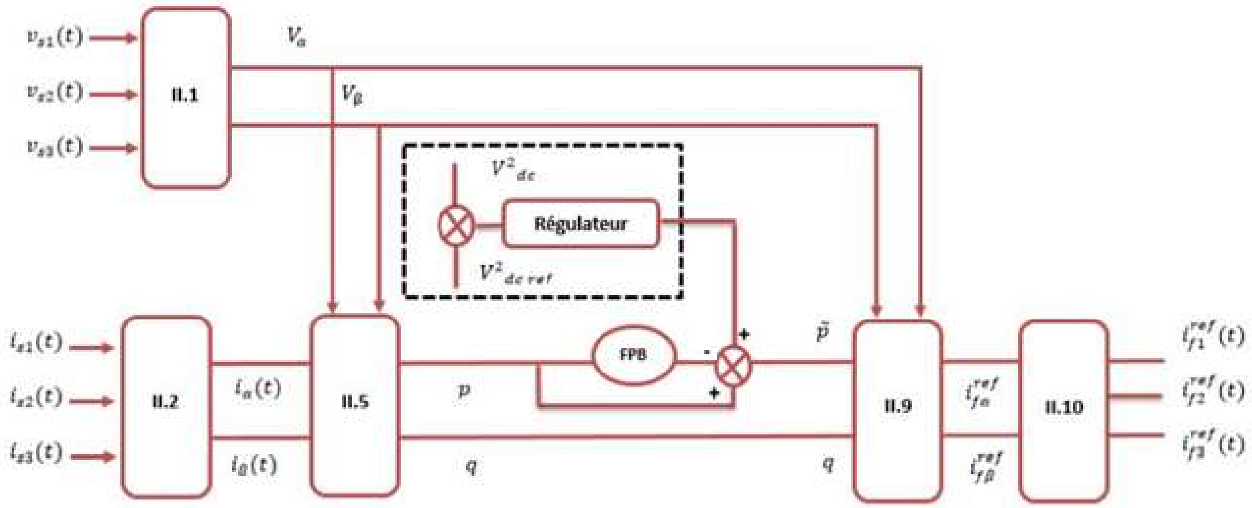

Figure 28: p-q algorithm for identifying reference currents

d. **Synchronous frame of reference method (SRF)**

This approach was developed by BHATTACHRAYA. It also uses the Concordia transformation, but only on the line currents, I_{c1}, I_{c2} and I_{c3}.

Then a second transformation is performed to convert the line currents to d-q, which converts the fundamental component of the current to a DC component and the harmonic components of the current to alternating components. This allows us to eliminate the component that continues to pass the current with the use of a simple low-pass filter. The main advantage of this approach over the previous one is that the harmonic voltages have no effect on the identified currents, allowing for better filtering. Its principle is based on the Concordia transformation applied to the line currents, i_{c1}, i_{c2} and i_{c3}, to a diphase system (α-β).

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{3}{2}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} i_{c1} \\ i_{c2} \\ i_{c3} \end{bmatrix} \qquad \text{(II.25)}$$

Then, using a PLL, two signals cos $(\hat{\theta})$ and sin $(\hat{\theta})$ are build from the fundamental network voltage, giving us:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin(\hat{\theta}) & -\cos(\hat{\theta}) \\ \cos(\hat{\theta}) & \sin(\hat{\theta}) \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad \text{(II.26)}$$

Then the fundamental currents in the d-q axes contain two parts:

$$\begin{bmatrix} \mathrm{i_d} \\ \mathrm{i_q} \end{bmatrix} = \begin{bmatrix} \overline{\iota_\mathrm{d}} + \tilde{\mathrm{i}}_\mathrm{d} \\ \bar{\mathrm{i}}_\mathrm{q} + \tilde{\mathrm{i}}_\mathrm{q} \end{bmatrix} \qquad \text{(II.27)}$$

Where $\overline{I_d}$ *and* $\bar{I}_q$ The continuous components of d and q.

$\tilde{I}_d$*and* $\tilde{I}_q$ The alternative components of d and q.

$$\begin{bmatrix} \mathrm{i}_\alpha \\ \mathrm{i}_\beta \end{bmatrix} = \begin{bmatrix} \sin(\hat{\theta}) & -\cos(\hat{\theta}) \\ \cos(\hat{\theta}) & \sin(\hat{\theta}) \end{bmatrix} . \begin{bmatrix} \bar{\mathrm{i}}_\mathrm{d} \\ \bar{\mathrm{i}}_\mathrm{q} \end{bmatrix} + \begin{bmatrix} \sin(\hat{\theta}) & -\cos(\hat{\theta}) \\ \cos(\hat{\theta}) & \sin(\hat{\theta}) \end{bmatrix} . \begin{bmatrix} \iota_\mathrm{d} \\ \tilde{\iota}_\mathrm{q} \end{bmatrix} \qquad \text{(II.28)}$$

Depending on the function we assign to the active power filter, we can compensate for current harmonics and/or reactive power.

Table 4: Compensation modes for instantaneous power control

	Current harmonics compensation	Reactive power compensation	Compensation of current harmonics and reactive power
Control settings	$i_{dc} = \tilde{\iota}_d$ And $i_{q_c} = i_q$	$i_{dc} = 0$ And $iq_c = \bar{\iota}_q$	$i_{dc} = \tilde{\iota}_d$ And $i_{q_c} = i_q$

To compensate the harmonic current and the reactive energy we have:

$$\begin{bmatrix} \mathrm{i_{ref\,\alpha}} \\ \mathrm{i_{ref\,\beta}} \end{bmatrix} = \begin{bmatrix} \sin(\hat{\theta}) & -\cos(\hat{\theta}) \\ \cos(\hat{\theta}) & \sin(\hat{\theta}) \end{bmatrix} . \begin{bmatrix} \tilde{\iota}_d \\ \bar{\iota}_q + \tilde{\iota}_q \end{bmatrix} \qquad \text{(II.29)}$$

The reference currents will be calculated using the inverse Concordia transformation, which is:

$$\begin{bmatrix} \mathrm{i_{ref\,1}} \\ i_\mathrm{ref2} \\ i_\mathrm{ref3} \end{bmatrix} = \sqrt{\frac{3}{2}} . \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} . \begin{bmatrix} \mathrm{i_{ref\,\alpha}} \\ \mathrm{i_{ref\,\beta}} \end{bmatrix} \qquad \text{(II.30)}$$

Then the control algorithm is illustrated in the figure above:

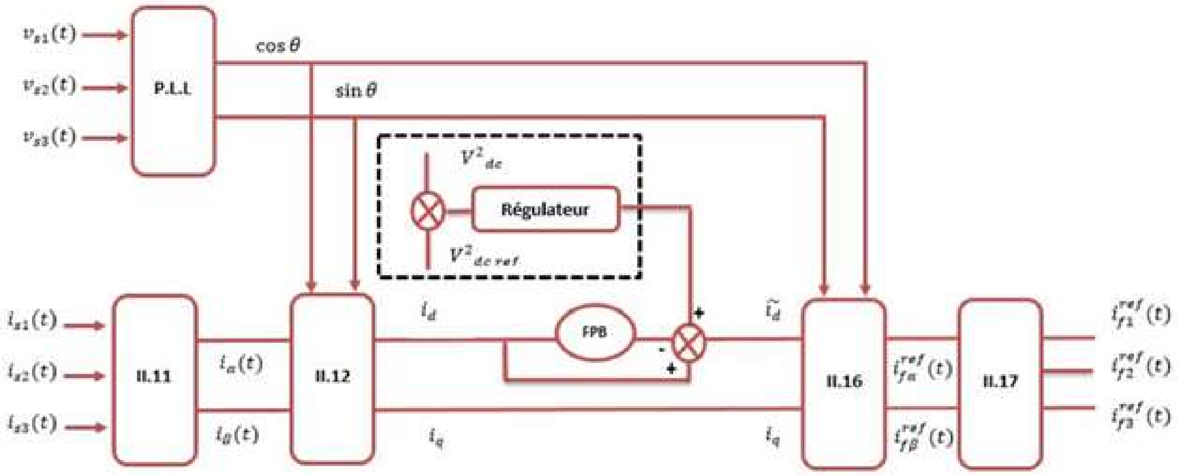

Figure 29: Control of the active filter by the SRF instantaneous current method

The calculation of the power extraction filter and the regulation of the voltage across the regulator are performed in the same way as the previous instruction. The only difference between the two control systems is the addition of a PLL, which is used to extract the phase of the fundamental forward voltage component (V_{dc}).

This PLL is used to extract the phase of the fundamental component of the forward voltage. Its operation on the Park transformation in the dq axis [19].

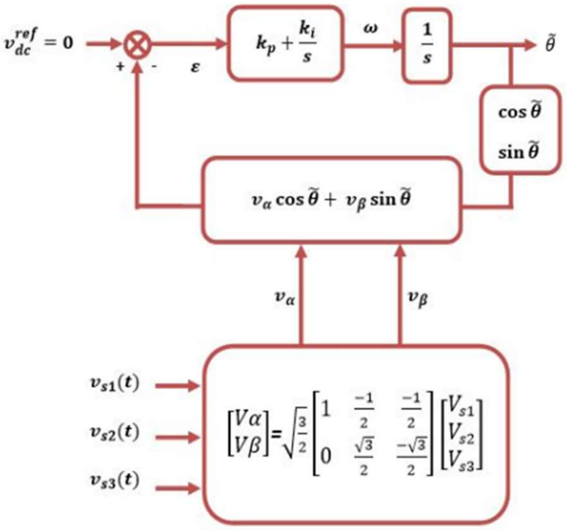

Figure 30: Schematic diagram of a classic P. L.L

e. **<u>Control by multi-variable extraction filter (MVF)</u>**

This control is based on the use of a multi-variable filter which is proposed by Mr. ben habib in his PhD thesis [14], and also based on the work of Song Hong Scok [18], This filter is intended to extract the fundamental component of electrical signals (voltage or current) directly along the axes (α-β). This multi-variable filter gives better results than traditional filters.

the expressions of this filter give by:

$$\hat{x}_\alpha = \frac{K}{s}\left(x_\alpha(s) - \hat{x}_\alpha(s)\right) - \frac{w_c}{s}\hat{x}_\beta(s) \tag{II.31}$$

$$\hat{x}_\beta = \frac{K}{s}\left(x_\beta(s) - \hat{x}_\beta(s)\right) - \frac{w_c}{s}\hat{x}_\alpha(s) \tag{II.32}$$

$\boldsymbol{x_{\alpha\beta}}$: The input signal is determined by the α-β axis and is either voltage or current nature.

$\hat{x}_{\alpha\beta}$: The fundamental components, de $\boldsymbol{x_{\alpha\beta}}$.

K: constant is fixed to K=80, and $\omega_c = 2\pi f$, with Fundamental pulse of the network f=50HZ.

The following figure gave the scheme of the multivariable filter:

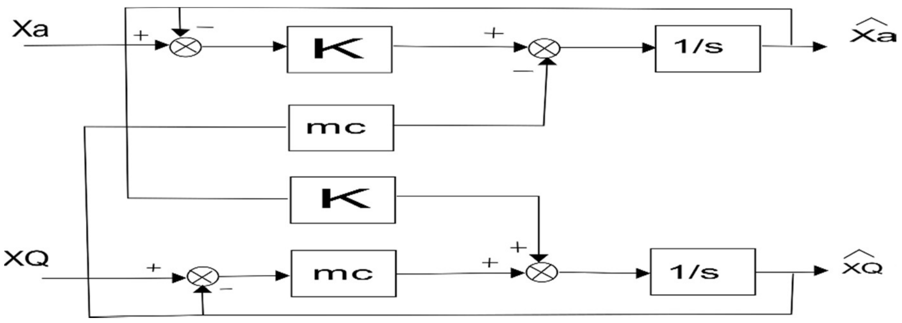

Figure 31: Multi variable filter

We will also use this multi-variable filter with a PLL, as presented in the figure below, to better protect it from harmonic disturbances caused by the power grid. As a result, the PLL scheme becomes as follows.

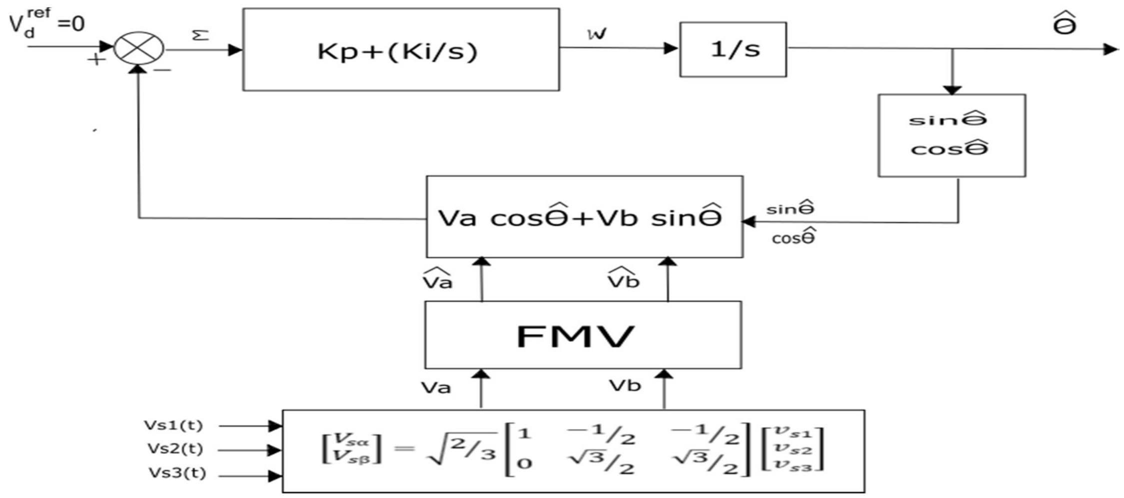

Figure 32 : PLLwith MVF

The following figures describe the direct and indirect control method with multi-variable filter:

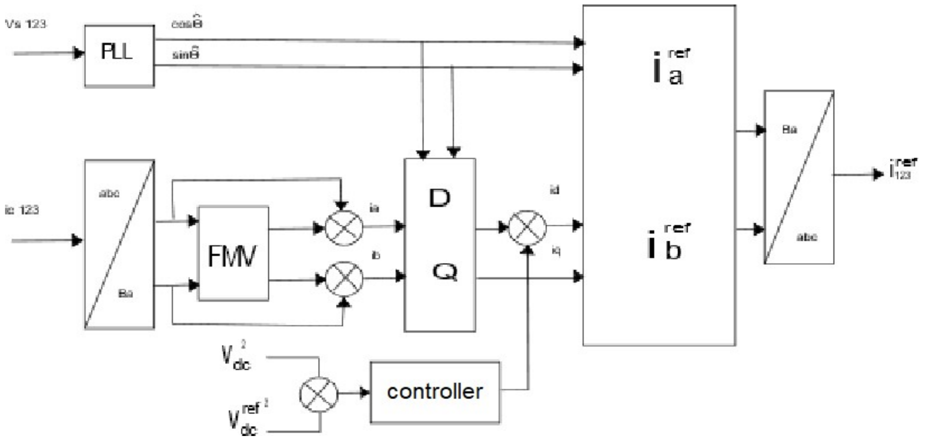

Figure 33: Control of an active power filter by the direct synchronous reference frame (SRF) method with MVF.

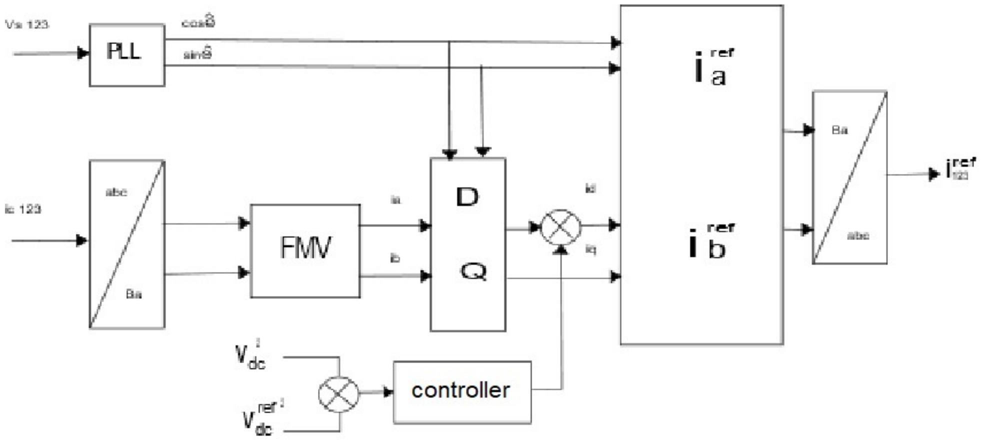

Figure 34: Control of an active power filter by the indirect synchronous reference frame (SRF) method with MVF.

Conclusion

In this chapter, we have discussed the performance of a parallel active power filter, his general structure, and the various methods of identifying reference currents, the theory of real and imaginary instantaneous power, Synchronous reference frame method, as well as the basic principle and control strategies of a voltage inverter.

The instantaneous power identification method and the SRF method with PLL has been chosen to allow the identification of one, several or all power system harmonics disturbances.

Chapter III

Modular active power filter

III. Introduction

We have already seen the in the first chapters, the most suitable topologies of the active power filter that are used to compensate harmonic currents generated by the non-linear loads, which are connected to a three-phase three-wire electrical network. Among these topologies, we have the parallel structure of the active power filter.

This topology is one of the modern solutions used for harmonic current compensation. Among these structures, we have a topology called modular active power filter. This topology is based on the concept of running several active power filter simultaneously in parallel. It has been developed to compensate harmonic currents in high power applications.

At the level of three-phase three-wire electrical networks, two major topologies can be identified for the parallel active modular power filters in which the DC bus is common. We have:

- The modular active filter consisting of two inverters with three-arm.
- And the modular active filter consisting of two inverters of two-arm with midpoint capacitor.

Those topologies are the most important structures in this mater thesis. For this reason, we will make a detailed simulation of these two commonly used topologies in three-wire networks.

III.1 Simulation of a parallel active power filter

First of all, we will present the electrical network who is represented by the following pictures:

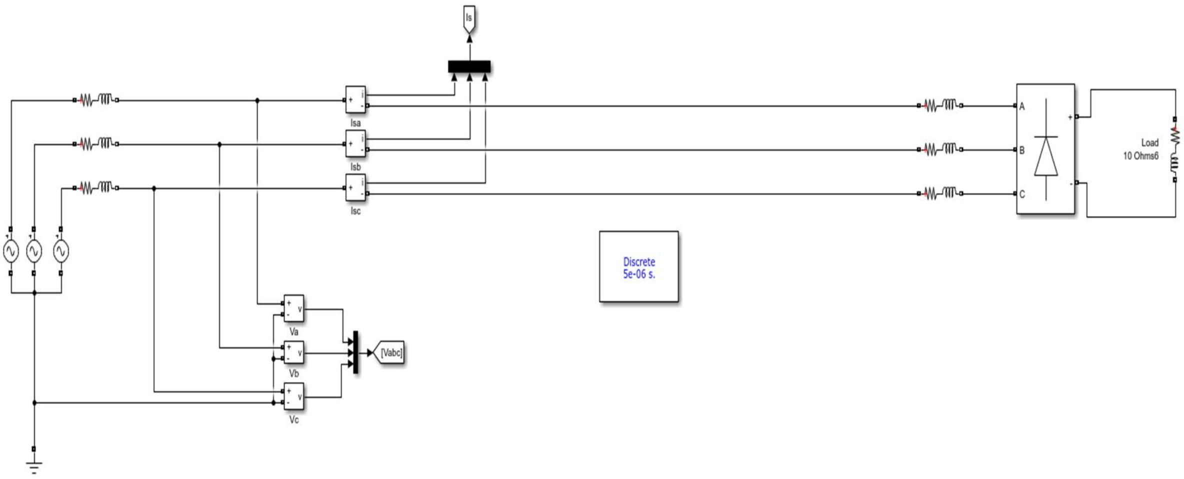

Figure 35: Source and charge connected with three-phase three-wire network

The following table gives the parameters of this electrical network:

Table 5: Parameters of the electrical network

Vs (v)	Rs (Ω)	Ls (H)	Rc (Ω)	Lc (H)	Rch (Ω)	Lch (H)
400	1e-3	1e-6	2.73e-3	23.19e-6	0.79	2.6e-6

We simulate this electrical network, using MATLAB Simulink/simpower system. We get the following results:

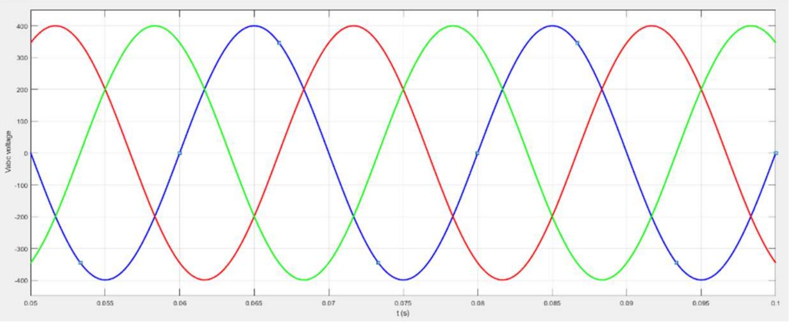

Figure 36: Three-phase source voltage

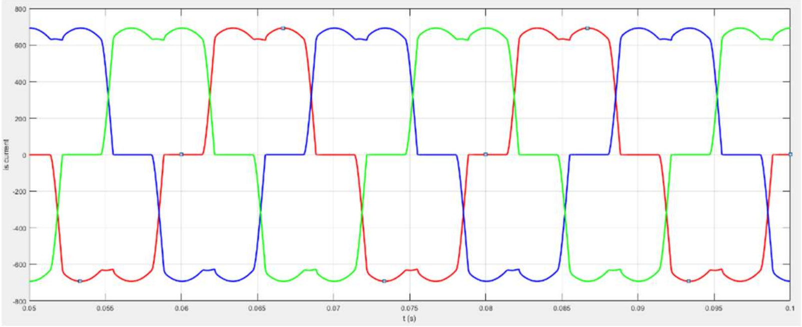

Figure 37: Three-phase source current.

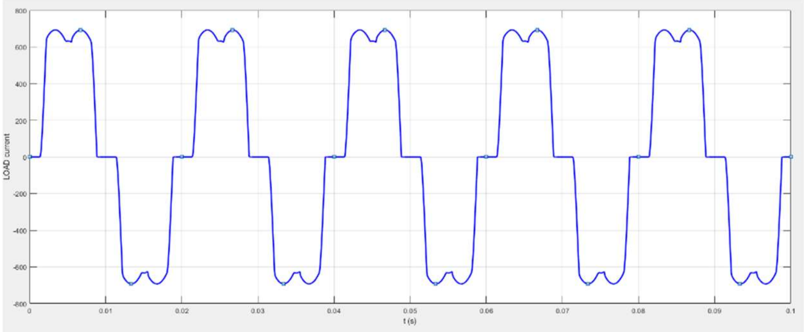

Figure 38: One-phase source current.

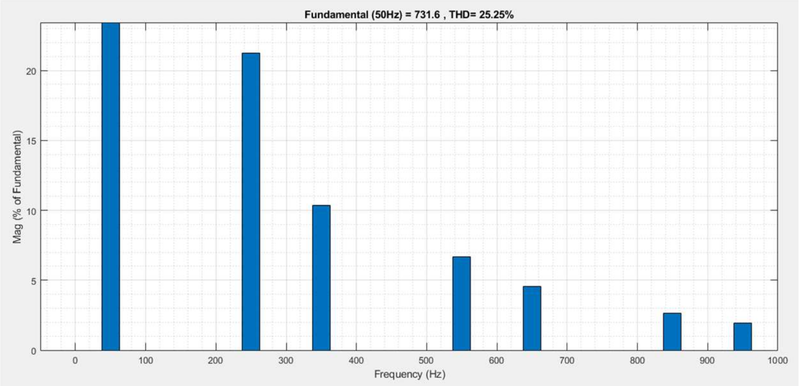

Figure 39: First phase current source harmonic spectrum.

We note that before the insertion of the active filter, figure (37) shows the distortion of the source current wave I_{s123}. This distortion is confirmed by the harmonic spectrum of the figure (39) which the THD is equal to 25.25%.

The main purpose of active filtering is to reduce this THD to a value below 5%, as required by the IEC standard. Thus, the complete system of our system, which will include the active power filter, is shown in the following figure:

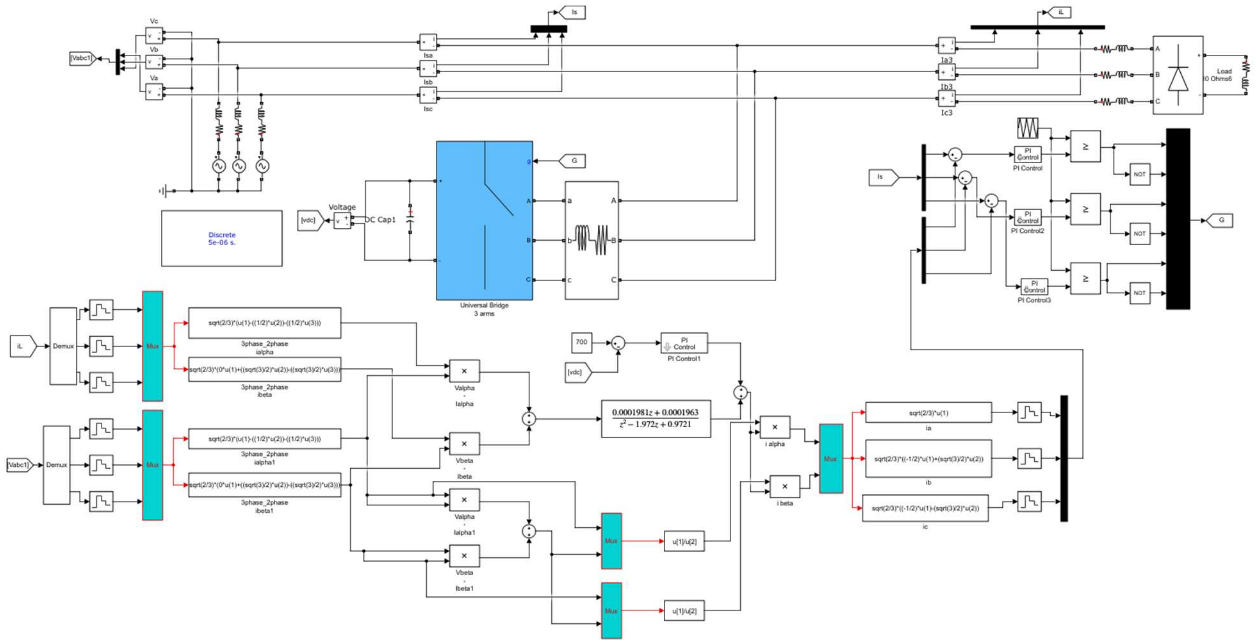

Figure 40: Active power parallel filter scheme.

The parameters of this electrical network connected to the parallel active power filter are given in the following table:

Table 6: Parameters of the electrical network containing the active parallel power filter.

Vs (v)	Rs (Ω)	Ls (H)	Rc (Ω)	Lc (H)	Rch (Ω)	Lch(H)	Rf (Ω)	Lf (H)	Cdc (F)
400	1e-3	1e-6	2.73e-3	23.19e-6	0.79	2.6e-6	10e-6	0.1e-3	8e-3

The power part of the active power filter contains a 3-arm inverter; each arm contains two reversible switches with a V_{dc} capacitor that acts as a DC voltage source with an output filter.

For the command part we have controlled our active power filter by using the indirect p-q method which is based on the comparison of the reference current I_{ref} with the source current $I_s(t)$. The following figure shows the indirect p-q control used by the active power filter.

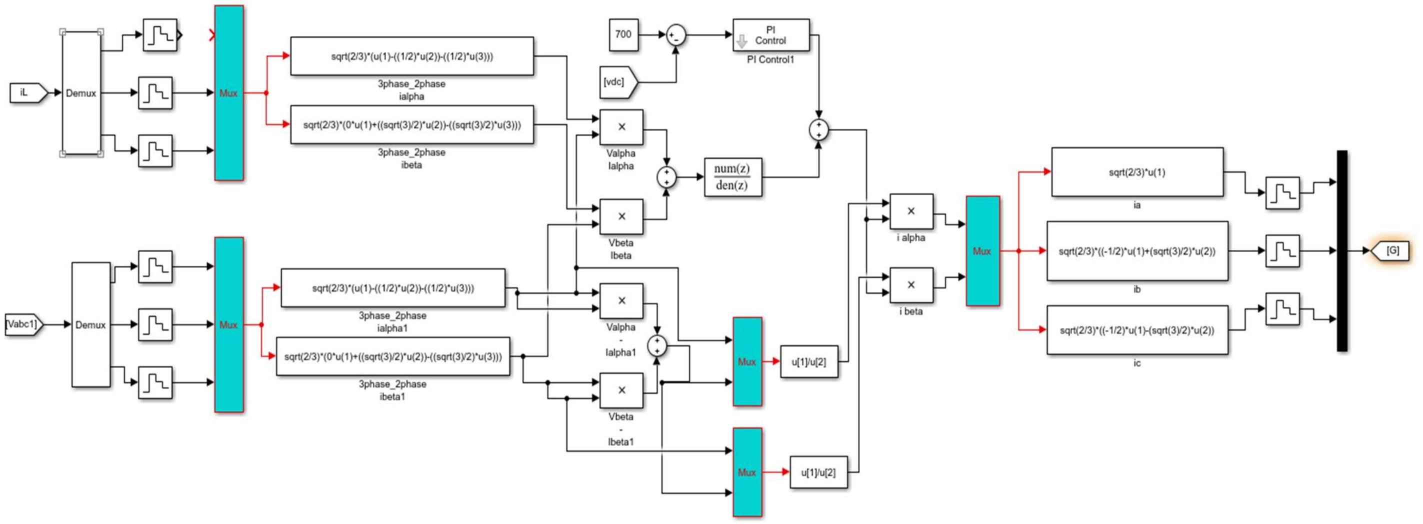

Figure 41: Indirect p-q control of the APF

The following figure shows the inverter control which is based on the PWM method. In this case we should use, the difference between the references current I_{ref} and the current source I_s, which gives an error that is applied to the input of the PWM regulator.

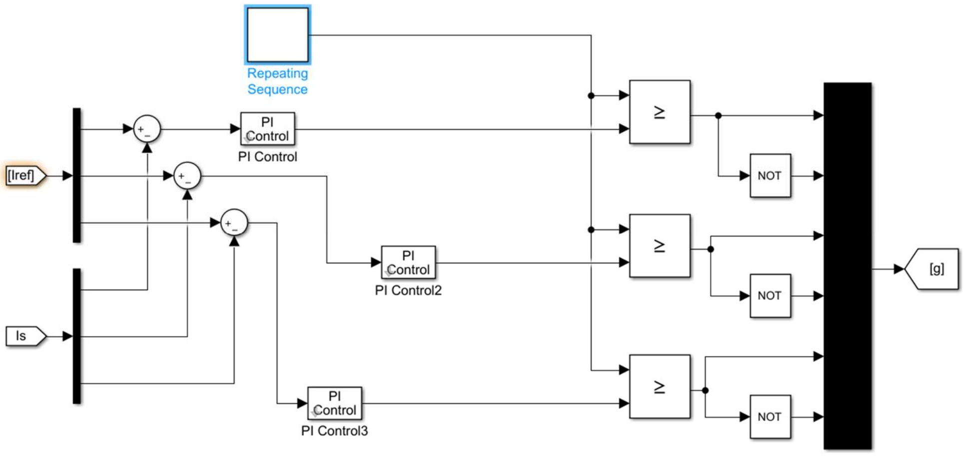

Figure 42: PWM control of the APF

The two following figures shows the low pass filter used in the control of the active filter to extract the continuous component of the active pwer and the PI regulator to stabilize the voltage across the capacitor.

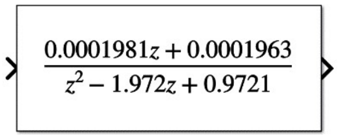

Figure 43: Low-pass filter (LPF)

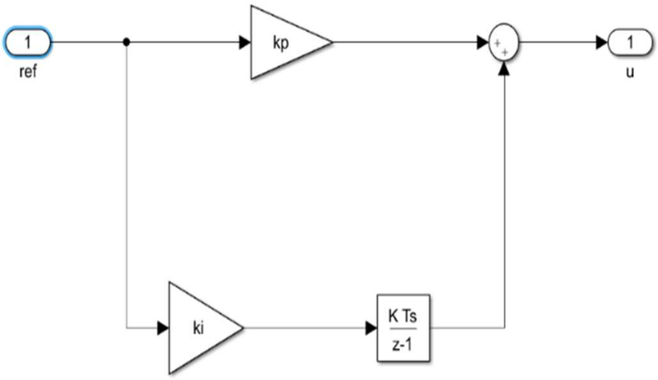

Figure 44: PI (proportional integrator) regulator of APF

The simulation results we obtained are shown in the following Figures:

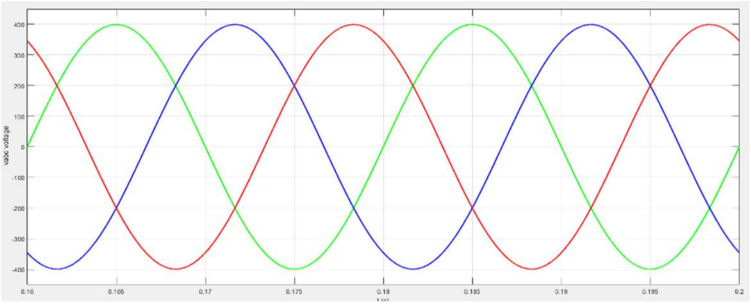

Figure 45: Three-phase source voltage

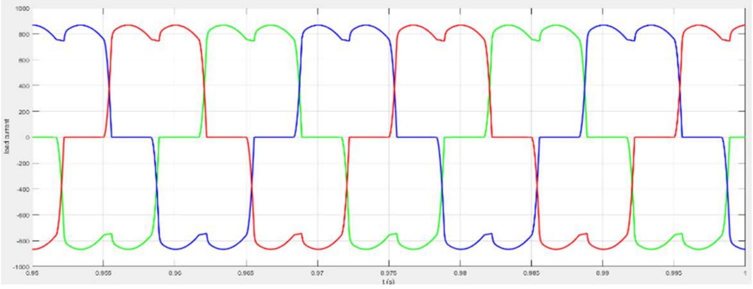

Figure 46: Three-phase load current (before fitering)

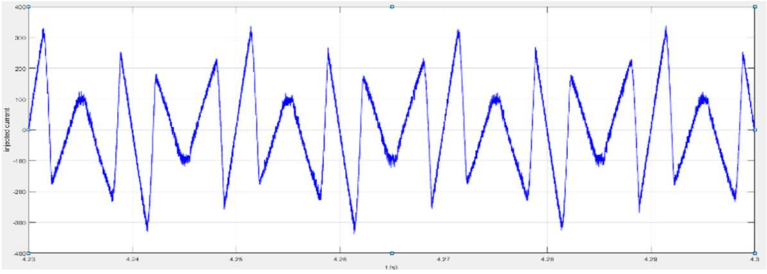

Figure 47: First phase injected current by the APF

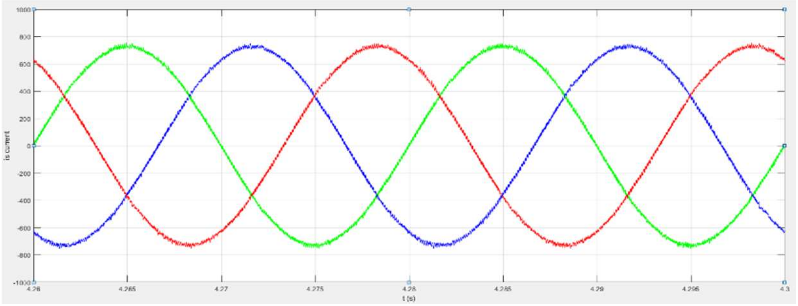

Figure 48: Three-phase source current (after fitering)

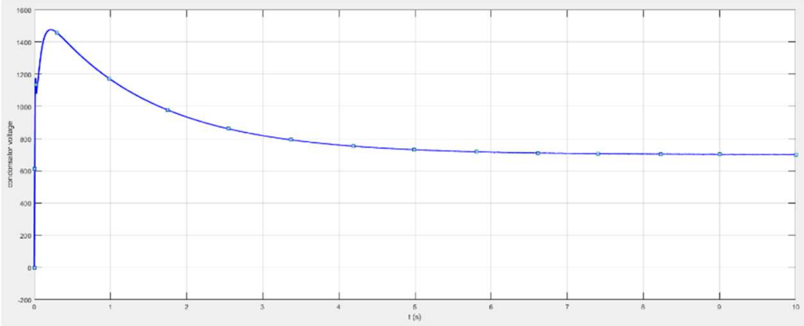

Figure 49: Voltage at the capacitor terminals (Vdc voltage source)

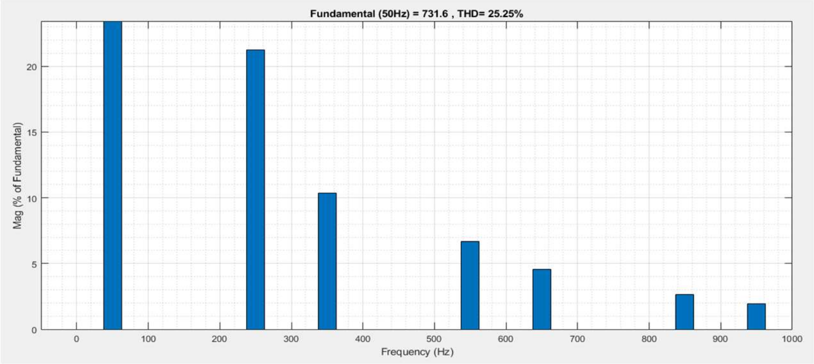

Figure 50: Harmonic spectrum of the current load (before filtering)

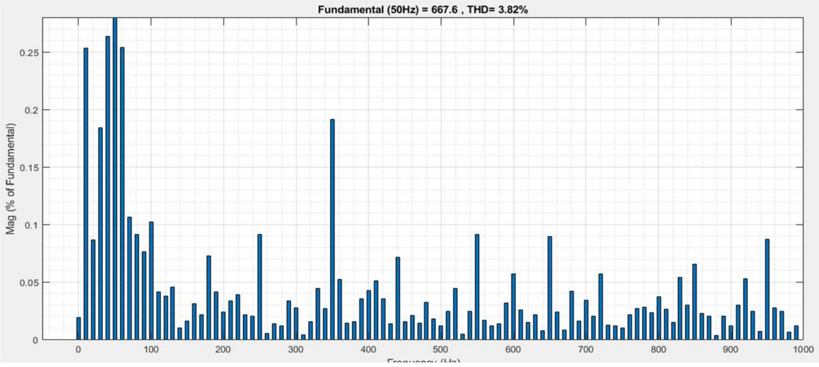

Figure 51: Harmonic spectrum of the current source (after filtering)

From the picture 48 we can see that the active power filter eliminates the harmonics currents from each phase. Therefore, the source current after filtering is sinusoidal and the THD is less than 5%. In our case the THD is equal to 3,82%.

Furthermore, we notice that the DC voltage of the inverter V_{dc}, in figure 49, is constant in permanent regime.

III.2 APF simulation contains a two-arms inverter with a mid-point capacitor

Now we will present the simulation results of a three-phase three-wire electrical network with an active power filter that contains two-arms inverter with a midpoint capacitor is connected as shown in the following figure. The indirect p-q control methode it is also used and this time we change to the hysteresis control methode for the inverter is used instead of the PWM.

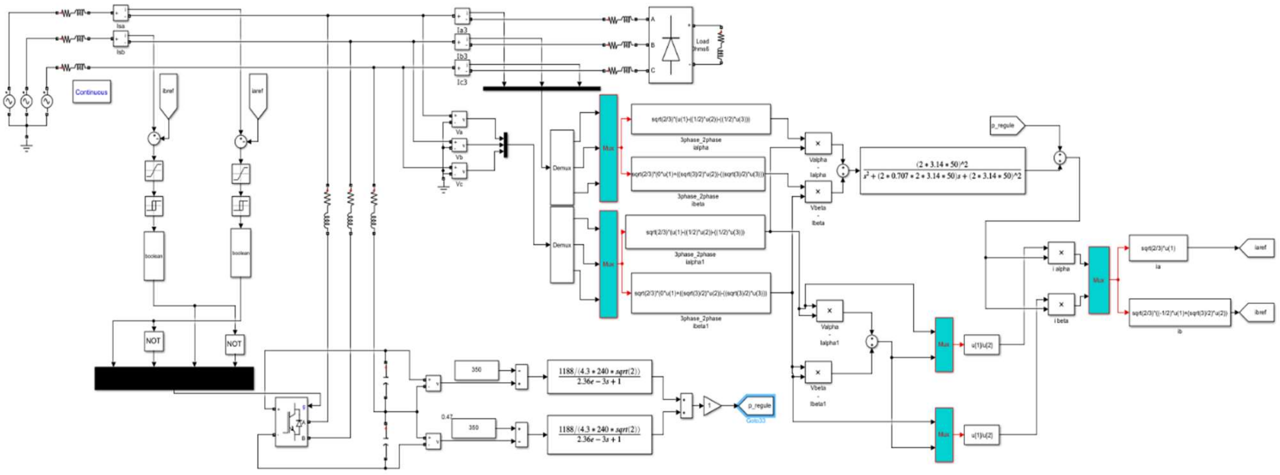

Figure 52: APF with midpoint capacitor inverter connect to the power system

The parameters of this system is given in the following table:

Table 7: Parameters of the electrical network containing a midpoint active power filter.

Vs (v)	Rs (Ω)	Ls (H)	Rc (Ω)	Lc (H)	Rch (Ω)	Lch(H)	Rf (Ω)	Lf (H)	Cdc1 (F)	Cdc2 (F)
400	**1e-3**	**1e-8**	**2.73e-3**	**23.19e-6**	**0.79**	**2.6e-6**	**5e-3**	**1e-4**	**60e-3**	**60e-3**

The simulation results we obtained are shown in the following Figures:

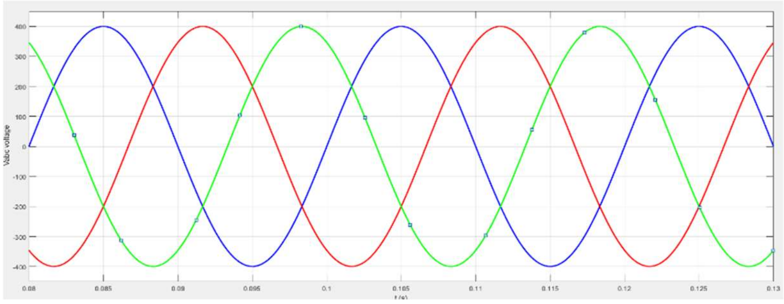

Figure 53: Three-phase source voltage

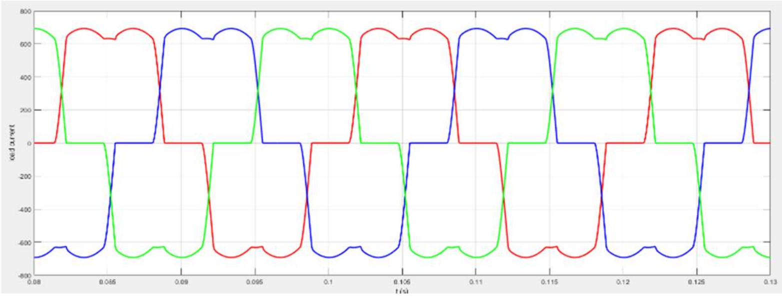

Figure 54: Three-phase load current (before fitering)

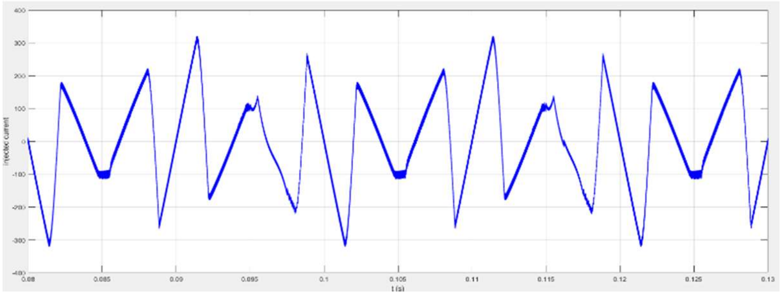

Figure 55: First phase injected current by the APF

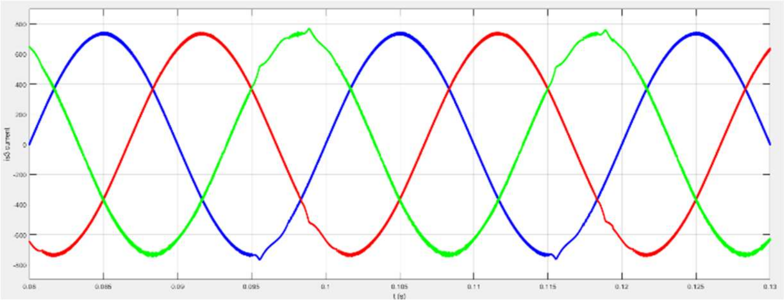

Figure 56: Three-phase source current (after fitering)

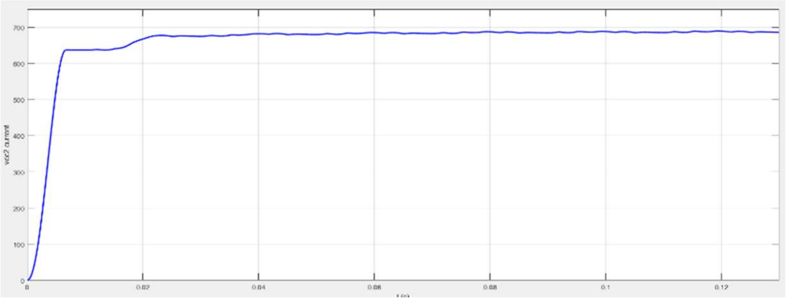

Figure 57: Voltage of the first capacitor terminals

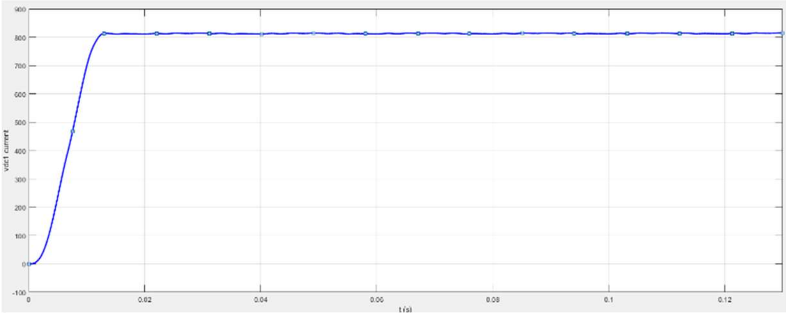

Figure 58: Voltage of the second capacitor terminals

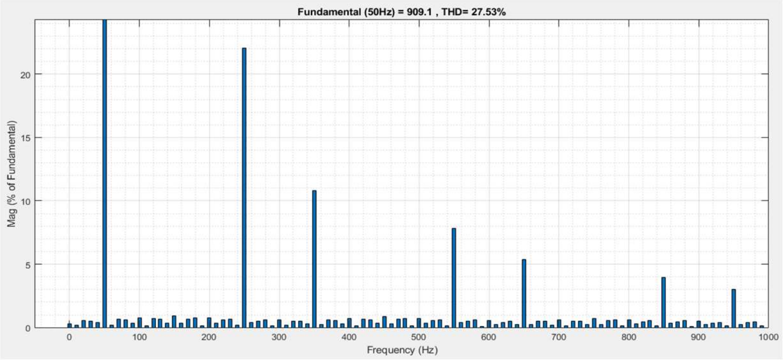

Figure 59: Harmonic spectrum of the current load (before filtering)

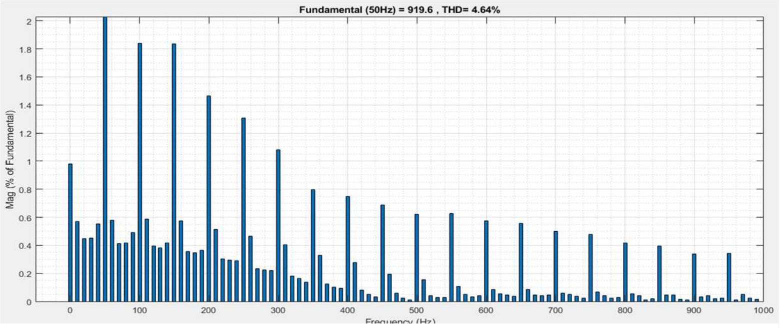

Figure 60: Harmonic spectrum of the current source (after filtering)

The figures shows that this type of active filter topologies has also a capacity to remove all harmonics currents created by the non-linear load. We also see that the two voltages V$_{dc}$ values is constant in the permanent regime.

III.3 Modular APF simulation

This structure mentioned in the beginning of this chapter, is a topology that use two actives power filter as shown in the following figure. Each inverter of the APF is composed of 3 arms each containing two reversible switches. These two inverters are connected in the DC side to the same capacitor C$_{dc}$. In the Ac side of the APF a 1st order passive filter, constituted by a resistance R_f and an inductance L_f is connected to the network. For the control part, we used the indirect p-q control with the use of the PWM control.

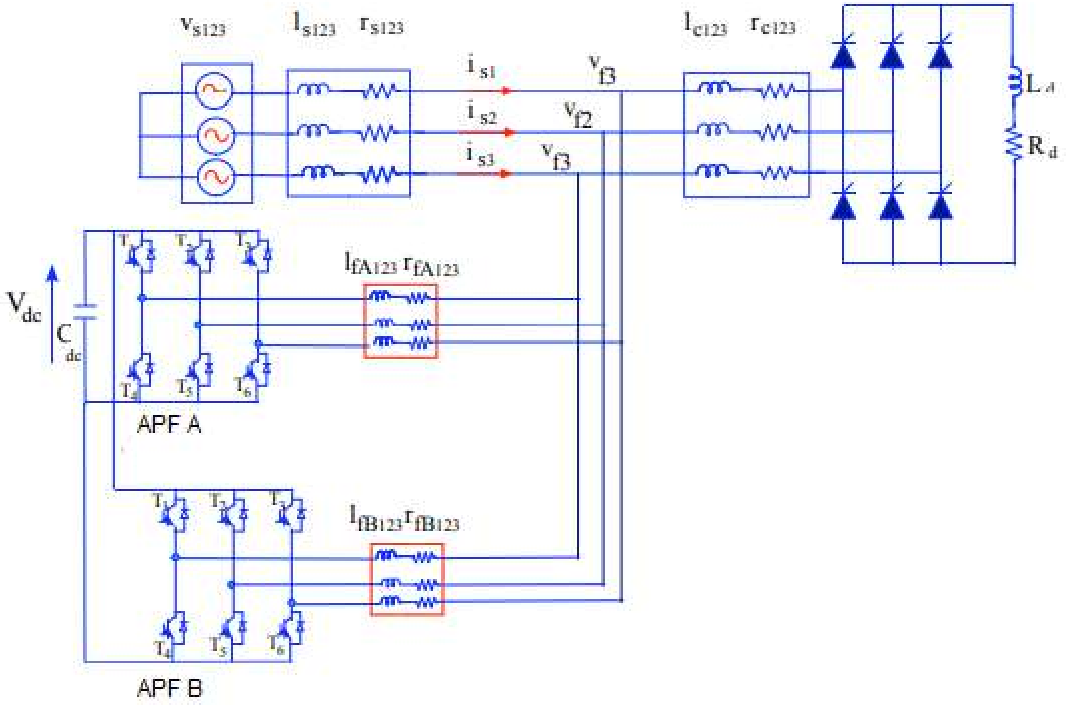

Figure 61: General structure of the modular active power filter connected to the power system

The following figure show the full system simulated using Matlab / Sympoer system.

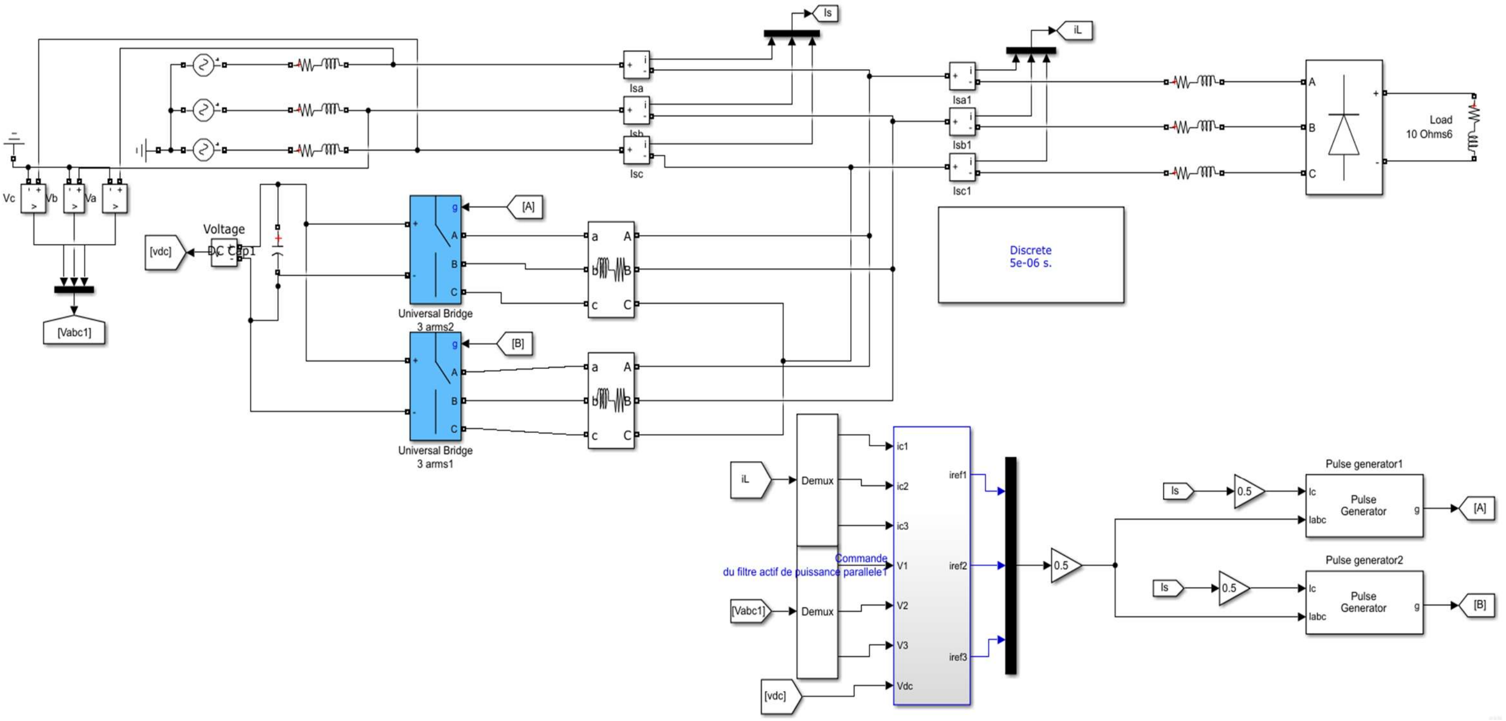

Figure 62: General structure of the modular active power filter connected to the power system made on Matlab

The parameters of this system is given in the following table:

Table 8: Parameters of the electrical network containing a modular active power filter

Vs (v)	Rs (Ω)	Ls (H)	Rc (Ω)	Lc (H)	Rch (Ω)	Lch(H)	Rf1(Ω)	Lf1 (H)	Rf2 (Ω)	Lf2 (H)	Cdc
400	0.0377	1e-8	2.73e-3	23.19e-6	0.79	2.6e-6	10e-6	0.1e-3	10e-6	0.1e-3	60e-3

The command used for this simulation is identical to the one used previously, namely the indirect p-q command. The results of this simulation are in the following figures:

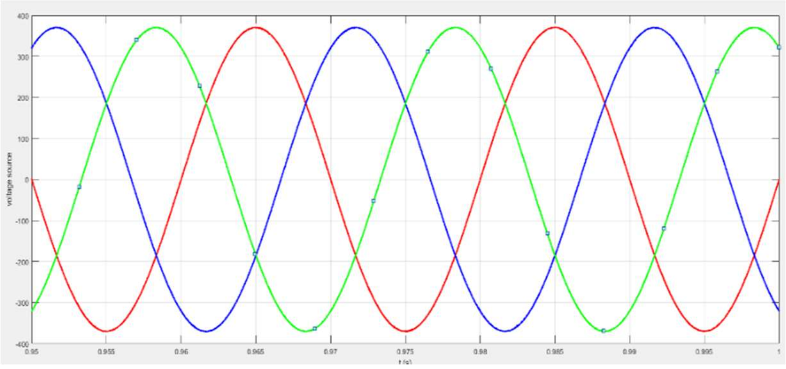

Figure 63: Three-phase voltage source

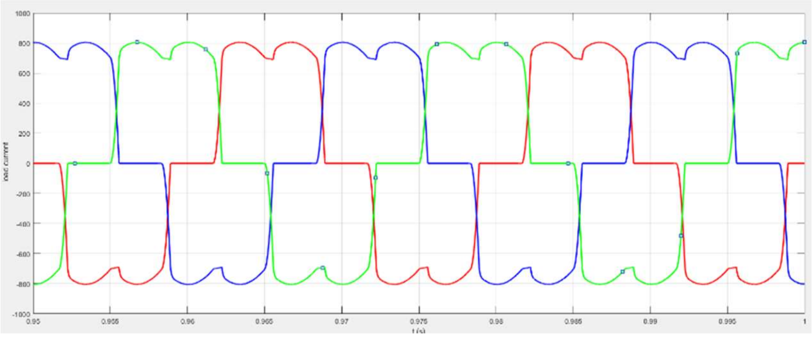

Figure 64: Three-phase load current (before filtering)

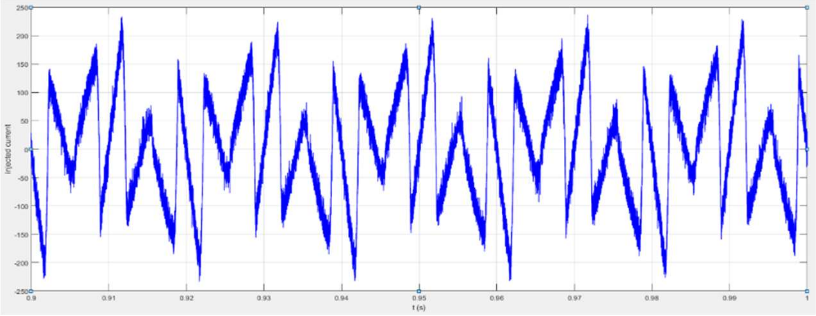

Figure 65: Reference current injected by the 1st APF inerter

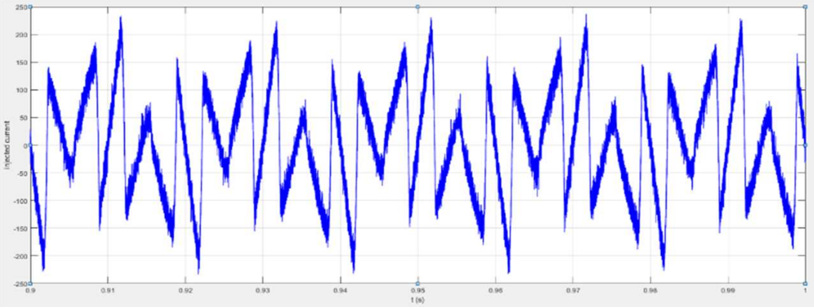

Figure 66: Reference current injected by the 2nd APF inverter

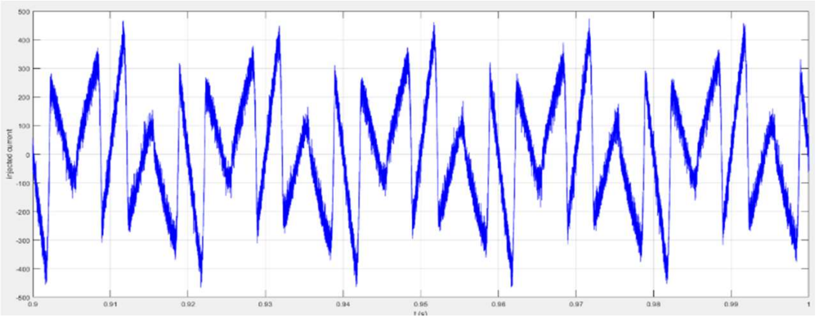

Figure 67: Reference current injected by the two APF inverters

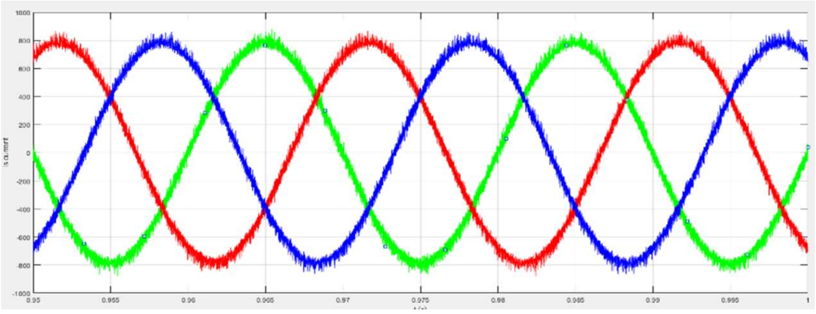

Figure 68: Three-phase current source (after filtering)

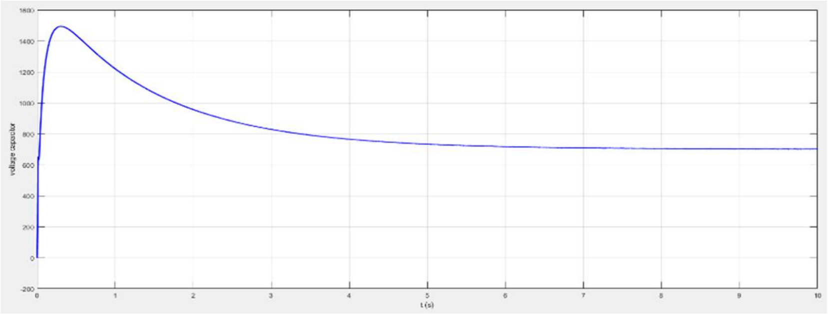

Figure 69: Capacitor voltage Vdc

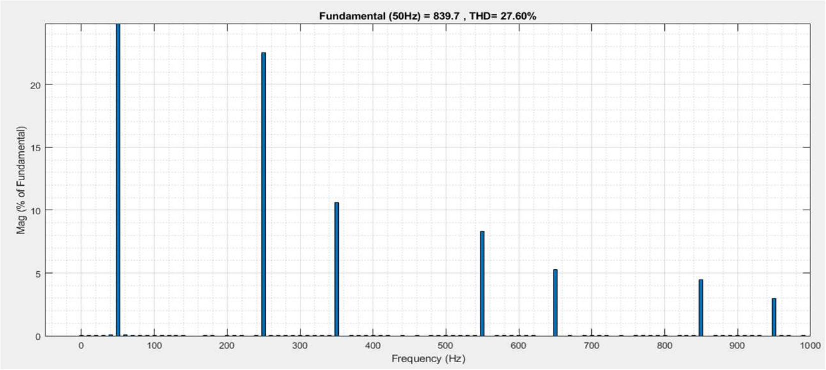

Figure 70: Harmonic spectrum of the current load (before filtering)

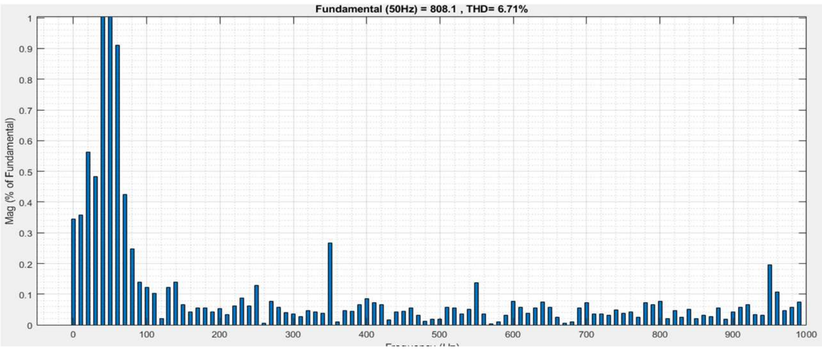

Figure 71: Harmonic spectrum f the current source (after filtering)

From the pictures, we can notice the good functioning of our modular active power filter and his high capacity to eliminate the harmonics effects in high current. We can also see the reduction of the THD spectrum value from 27.60% to 6.71%.

III.4 Modular APF simulation contains a two-arms inverter with a mid-point capacitor

This active power filter topology consists of two active power filter connected in parallel. Each inverter is reversible in current and contains four switches forming the two arms. The third arm is replaced by two capacitors connected to the 3rd phase of the electrical network. Each of the two capacitors acts as a DC voltage source. The voltage across them is equal to $\frac{V_{dc}}{2}$ and is maintained at a constant value [14].

A first-order passive filter, consisting of a resistor Rf and an inductance Lf, ensures the connection between the grid and the inverters.

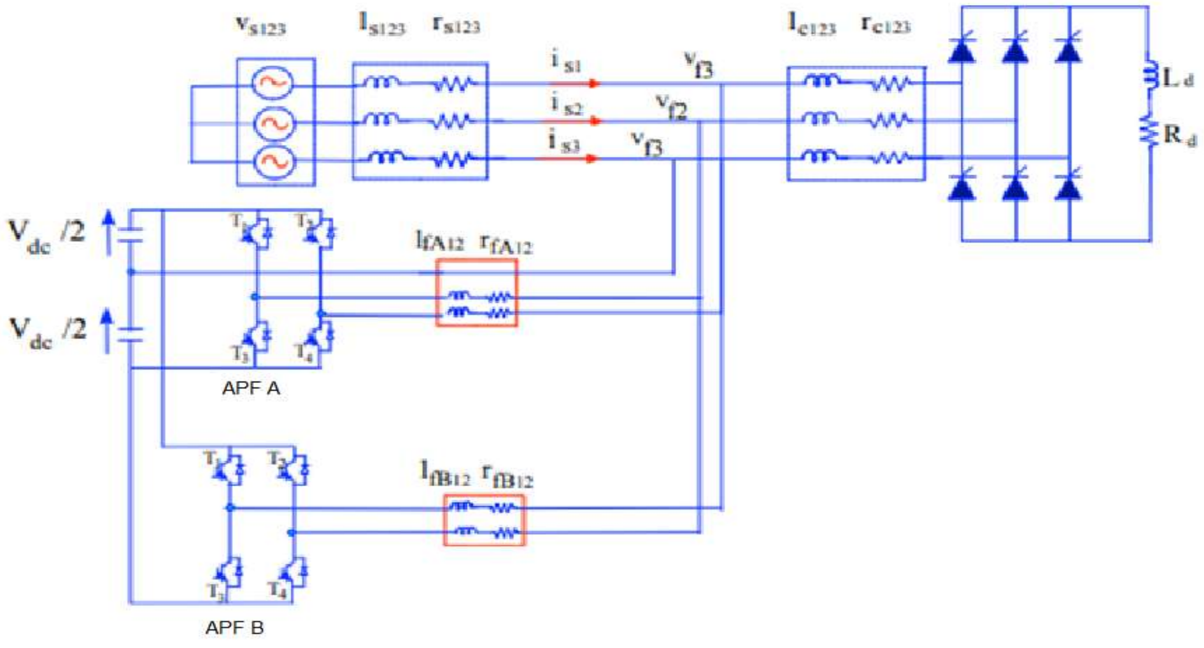

Figure 72: Modular two-arm active power filter with midpoint capacitor.

The fowwing figure show the full system simulated using Matlab / Sympoer system.

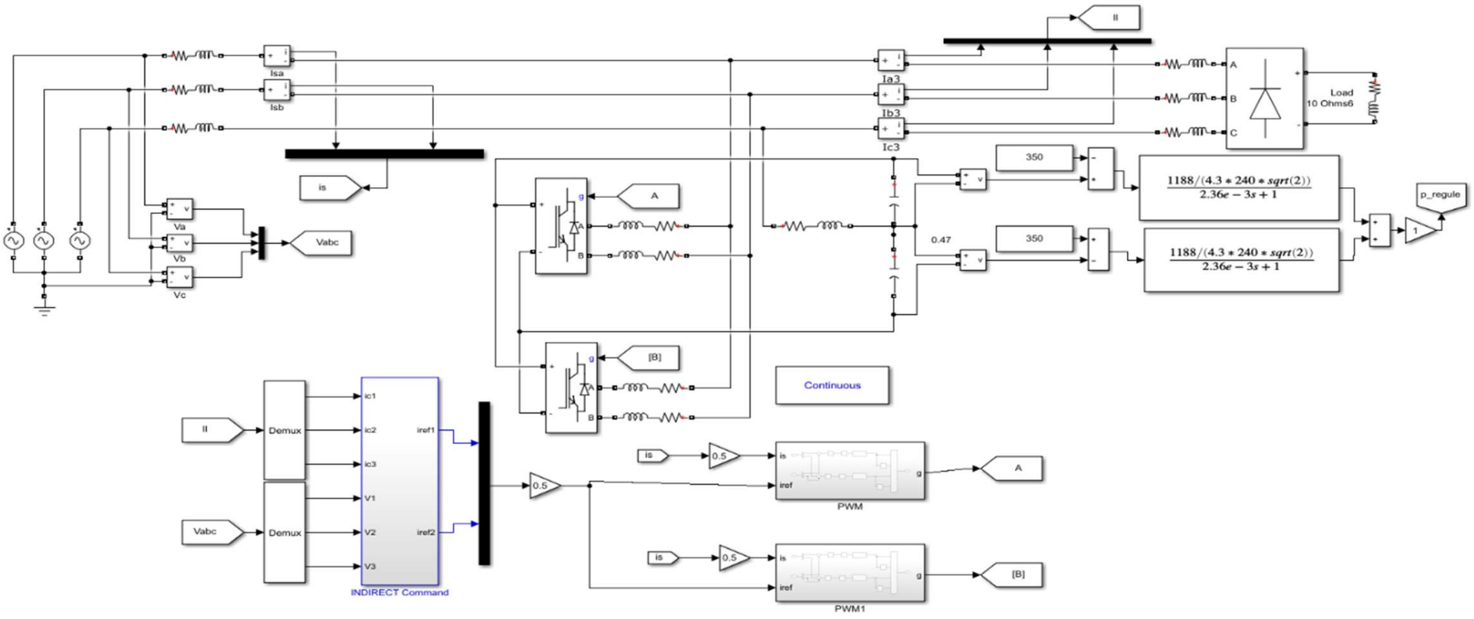

Figure 73: Modular two-arm active power filter with midpoint capacitor in MATLAB

The parameters of this system is given in the following table:

Table 9: Parameters of the electrical network containing a modular two-arm active power filter with midpoint capacitor

Vs (v)	Rs (Ω)	Ls (H)	Rc (Ω)	Lc (H)	Rch (Ω)	Lch(H)	Rf1(Ω)	Lf1 (H)	Rf2 (Ω)	Lf2 (H)	Cdc
400	0.001	1e-8	2.73e-3	23.19e-6	0.79	2.6e-6	5e-3	100e-6	5e-3	100e-6	60e-3

The results of this simulation are in the following figures:

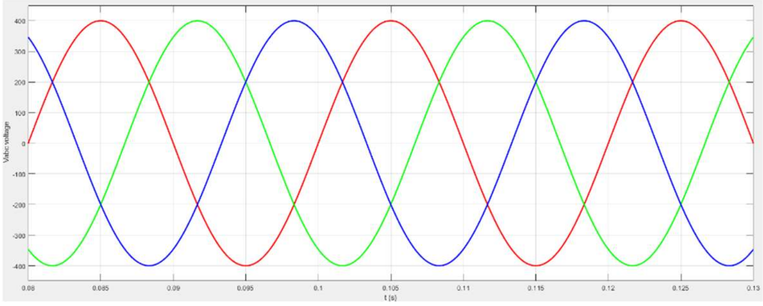

Figure 74: Three-phase voltage source

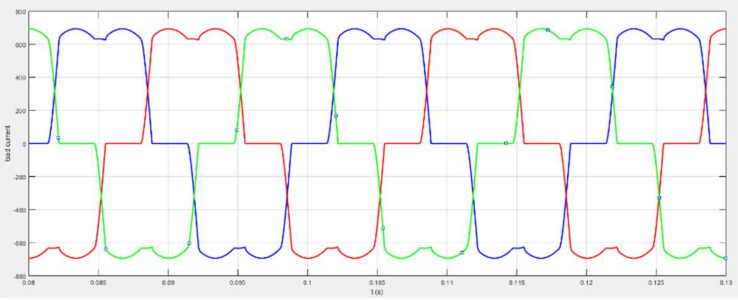

Figure 75: Three-phase load current (before filtering)

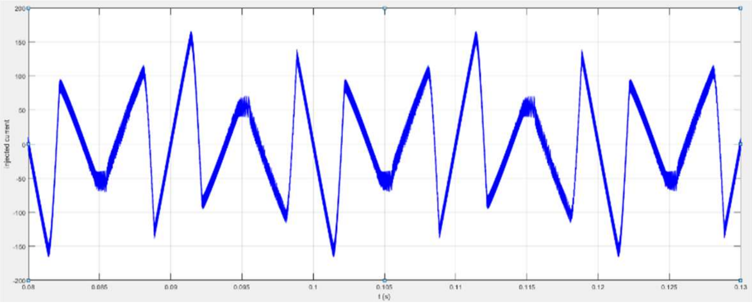

Figure 76: Reference current injected by the first APF inverter

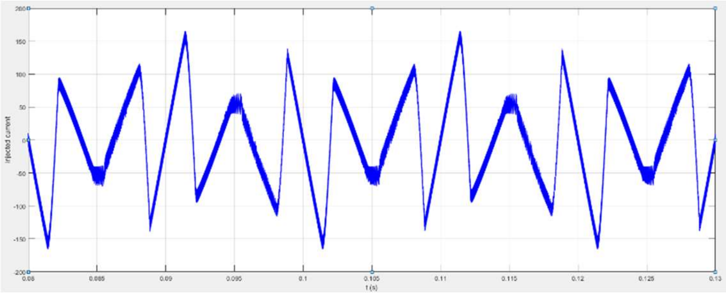

Figure 77: Reference current injected by the second APF inverter

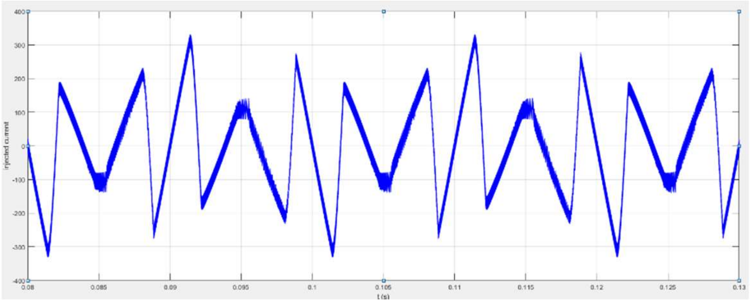

Figure 78: Reference current injected by the two APF inverters

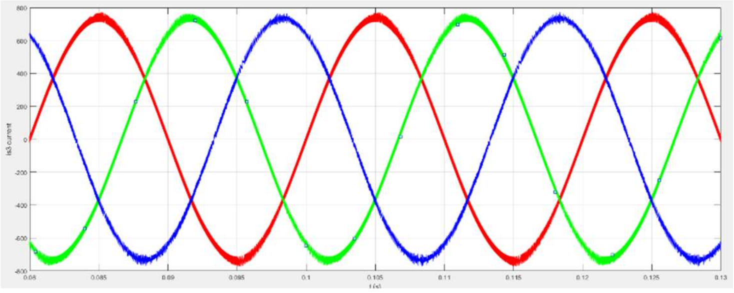

Figure 79: Three-phase current source (after filtering)

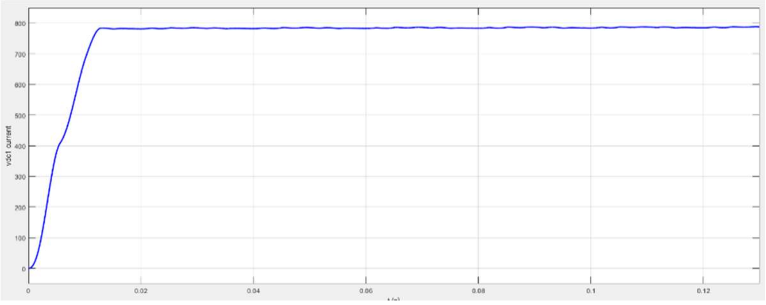

Figure 80: First capacitor voltage Vdc1

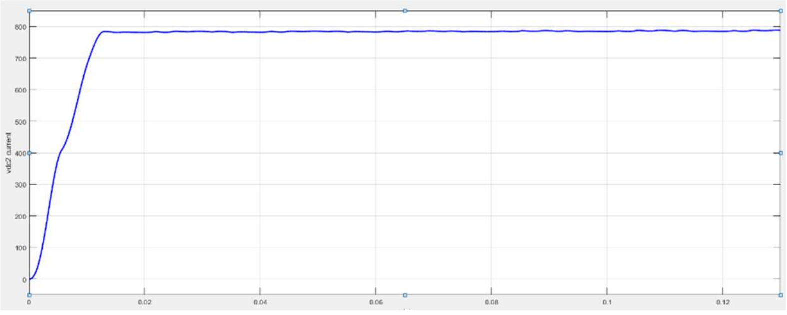

Figure 81: Second capacitor voltage Vdc2

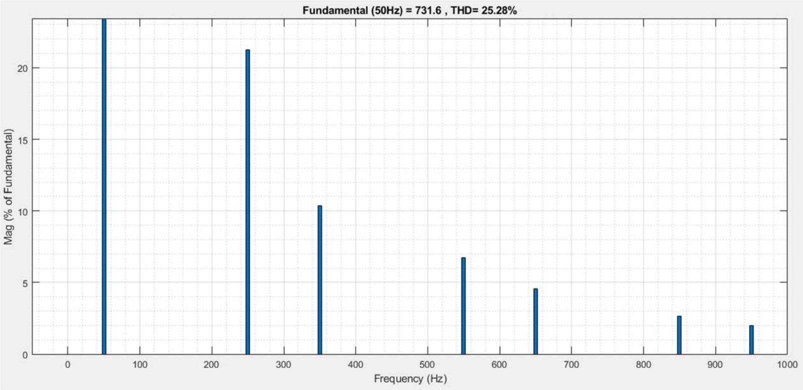

Figure 82: Harmonic spectrum of the current load (before filtering)

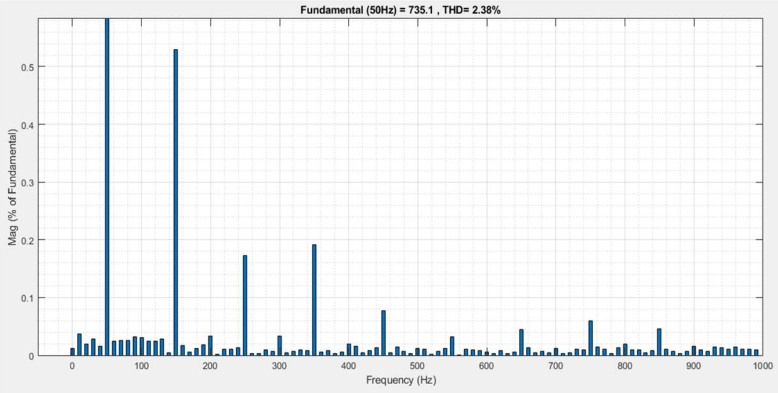

Figure 83: Harmonic spectrum of the current source (after filtering)

These last figures give the simulation's results of our modular two-arm APF with a midpoint capacitor. In terme of functionalite, we note that our filter work's really well. We eliminate the entire current harmonic generated by the non-linear loads very well. The Thd before filtering was equal to 25.28% and after filtering, we get 2.38%. We notice that this modular two arm active power filter with midpoint gives better results than the classic modular active power filter.

Conclusion

In this chapter, we have created the overall schematics of our different structure of active power filters (one APF or modular APF) with different inverter topologies (3-arms or 2-arms with midpoint capacitor), using the MATLAB Simulink/simpowersysteme tool. We notice that all these topologies allowed to eliminate harmonic currents generated by the nonlinear loads.

General conclusion

The problem of harmonic pollution in the distribution networks becomes more and more worrying with the increasing use of non-linear loads. That is why it is important to treat them and to eliminate them in order to minimize their influence on the electrical network. To better understand these harmonics, we first try to see their origins and know what their effects on the electrical network are.

Then we tried to see the principle of operation of the active power filters and we simulated different topologies such as the active power filter with three arms and the active power filter with two arms with a middle point. We have used different commands (direct and indirect) for these two structures and we have tried to see which one gives the best results.

After that, we tried to understand the modular structures of active power filters to compensate the current harmonics consumed by the non-linear loads consuming high current. We have noticed that the modular two arms active power filters with midpoint give better results than conventional modular active power filters.

These simulation results have also shown the feasibility of these topologies and their efficiency to compensate the current harmonics produced by high power nonlinear loads.

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Resumé

Avec l'utilisation accrue de charges non linéaires et le problème de la pollution harmonique dans les réseaux de distribution, la situation devient de plus en plus problématique. L'une des solutions les plus efficaces à ce problème est le filtrage actif de puissance. Elle semble être la plus utilisée en pratique. Dans ce mémoire de master nous avons présenté et simulé les filtres actifs de puissance modulaires pour compenser les harmoniques de courant générer par ces charges non linéaires consommant de fort courant. Notre travail c'est concentré sur la détection des harmoniques de courant en utilisant les startégies de commandes basées sur la méthode indirecte (p-q), la méthode indirecte (d-q) SRF et la méthode indirecte utilisant un filtre multi variable. Les résultats obtenus par simulation effectuée à l'aide du logiciel Matlab Simulink et de la bibliothèque Sim Power System on montré leurs efficacité pour compenser les harmoniques de courant généré par ces charges nonlinéaire consommant de fort courant.

Abstract

With the increased use of non-linear loads and the problem of harmonic pollution in distribution networks, the situation is becoming more and more problematic. One of the most effective solutions to this problem is active power filtering. It seems to be the most used in practice. In this master thesis, we have presented and simulated modular active power filters to compensate for the current harmonics generated by these high current consuming non-linear loads. Our work focused on the detection of current harmonics using control strategies based on the indirect (p-q) method, the indirect (d-q) SRF method and the indirect method using a multivariate filter. The results obtained by simulation using Matlab Simulink software and Sim Power System library showed their effectiveness in compensating for the current harmonics generated by these high current consuming nonlinear loads.

ملخص

مع زيادة استخدام الأحمال غير الخطية ومشكلة التلوث التوافقي في شبكات التوزيع ، أصبح الوضع أكثر وأكثر إشكالية. أحد الحلول الأكثر فعالية لهذه المشكلة هو ترشيح الطاقة النشط. يبدو أنه الأكثر استخدامًا في الممارسة. في هذه الرسالة الرئيسية قدمنا وحاكينا فلاتر طاقة نشطة معيارية للتعويض عن التوافقيات الحالية الناتجة عن هذه الأحمال غير الخطية التي تستهلك تيارًا عاليًا. ركز عملنا على اكتشاف التوافقيات الحالية باستخدام استراتيجيات التحكم القائمة على الطريقة غير المباشرة (p-q) وطريقة SRF غير المباشرة (d-q) والطريقة غير المباشرة باستخدام مرشح متعدد المتغيرات. أظهرت النتائج التي تم الحصول عليها عن طريق المحاكاة باستخدام برنامج Matlab Simulink ومكتبة Sim Power System فعاليتها في التعويض عن التوافقيات الحالية الناتجة عن هذه الأحمال غير الخطية عالية الاستهلاك الحالية.