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DOCTORAL THESIS

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Presented by

kamel KHECHIBA

With a view to obtaining the doctoral diploma in 3rd Cycle Doctoral (D-LMD)

Branch: Electrical Engineering

Specialty: Power Electronics and Power Quality

Topic

Study and realization of Shunt Active Filter controlled by advanced technics

Supported, on 06 /02/ 2021, before the jury composed of:

Last and first name	Grade	Institution of affiliation	Designation
Mr Lakhdar BESSISSA	MCA	Djelfa University	President
Mr Laid ZELLOUMA	Professor	El oued University	Supervisor
Mr Larbi BOUKEZZI	Professor	Djelfa University	Examiner
Mr Youcef BEKAKRA	MCA	El oued University	Examiner

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جامعة زيان عاشور بالجلفة

Université Ziane Achour de Djelfa

كلية العلوم والتكنولوجيا

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THESE DE DOCTORAT

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Présentée par

kamel KHECHIBA

En vue de l'obtention du diplôme de Docteur en 3ème Cycle D-LMD

Filière : Génie Electrique

Spécialité : Electronique de Puissance ET Qualité D'Energie Electrique

Thème

Etude et réalisation d'un filtre actif parallèle avec des techniques avancées

Soutenue publiquement, le 06/02/2021, devant le jury composé de :

Nom et Prénom	Grade	Etablissement de rattachement	Désignation
Mr Lakhdar BESSISSA	MCA	Université de Djelfa	Président
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Mr Youcef BEKAKRA	MCA	Université d'El oued	Examinateur

Université de Djelfa, FST, 2021

Dedication

To my dear father

In memory of my mother, I owe you everything after Allah. No words can express gratitude, the depth of my love, respect and gratitude.

Find peace and eternal rest.

- ✓ To my lovely wife
- ✓ To the little thinker Djaoued
- ✓ To my intelligent boy Anas
- ✓ To my beautiful Baraa Aicha
- ✓ To my cute Rahaf

Acknowledgement

First, I want to thank Allah the Almighty for the will, health and patience, which he gave me during all those long years.

At the end of this work, I would like to express my gratitude and my thanks to all the people who contributed, each in their own way, to the accomplishment of this thesis.

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I would like to warmly thank the jury members for having agreed to evaluate this work and this thesis:

Mr BESSISSA Lakhdar, Professor at the University of Djelfa, for having accepted to judge my work and to chair the defense jury for this thesis.

Gentlemen Larbi BOUKEZZI, Professor at the University of Djelfa, Youcef BEKAKRA, Professor at the University of El oued, for having done me the honor of accepting to be the examiners of this thesis.

I would like to thank with all my heart, my wife, my children for their infinite patience, their unconditional support, their encouragement throughout these years and their trust in this project.

Abstract

The change in the nature of energy production which mainly used fossil resources and which is becoming increasingly clean with various renewable sources such as wind turbines; photovoltaic panels is reflected in a paradigm shift where decentralized production takes precedence on centralized production. In addition, technological progress has considerably changed uses with the intensive diffusion of charges based on power electronics, which are certainly economical but very polluting, which directly affects the quality of energy.

The work carried out in this thesis focused on improving the quality of electrical energy via compensators connected to the electrical network. It is devoted to the PBT method (Power Balance Theory) generic solution that we offer. We present its principle on networks on the three-phase 3-wire network using in one hand SAPF as simple 3 phase inverter with simple capacitor as DC link source, in the other hand, we use SAPF as a Z source inverter with photovoltaic cells based MPPT P&O algorithm. For this command, we present the different simulation results for the different regimes (transient and permanent), with the different states of the electrical network (unbalanced and / or distorted).

Key words: Power Balance Theory; THD; SAPF; Anti-windup Regulation; Unbalanced grid.

Resumé

Le changement de nature de la production d'énergie qui utilise principalement des ressources fossiles et qui devient de plus en plus propre avec diverses sources renouvelables telles que les éoliennes, les panneaux photovoltaïques se traduit par un changement de paradigme où la production décentralisée prime sur la production centralisée. De plus, les progrès technologiques ont considérablement modifié les usages avec la diffusion intensive de charges basées sur l'électronique de puissance, certes économiques mais très polluantes, ce qui affecte directement la qualité de l'énergie.

Les travaux menés dans cette thèse ont porté sur l'amélioration de la qualité de l'énergie électrique via des compensateurs connectés au réseau électrique. Il est consacré à la solution générique de la méthode PBT (Power Balance Theory) que nous proposons. Nous présentons son principe sur les réseaux triphasés utilisant d'une part SAPF comme simple onduleur triphasé avec un simple condensateur comme source de liaison CC, d'autre part, nous utilisons SAPF comme onduleur source Z avec cellules photovoltaïques basé sur l'algorithme MPPT P&O. Pour cette commande, nous présentons les différents résultats de simulation pour les différents régimes (transitoire et permanent), avec les différents états du réseau électrique (déséquilibré et / ou déformé).

Mots clés : Théorie de l'équilibre de Puissance ; THD ; FAP ; Règlement anti-liquidation ; Grille déséquilibrée.

ملـــــــخص

ينعكس التغيير في طبيعة إنتاج الطاقة التي تستخدم بشكل أساسي الموارد الأحفورية والتي أصبحت أكثر نظافة مع العديد من المصادر المتجددة مثل توربينات الرياح والألواح الكهروضوئية في تحول نموذجي حيث يكون للإنتاج اللامركزي الأسبقية على الإنتاج المركزي. بالإضافة إلى ذلك، أدى التقدم التكنولوجي إلى تغيير الاستخدامات بشكل كبير مع الانتشار المكثف للشحنات القائمة على إلكترونيات الطاقة، والتي تعتبر بالتأكيد اقتصادية ولكنها ملوثة للغاية، مما يؤثر بشكل مباشر على جودة الطاقة.

ركز العمل المنفذ في هذه الرسالة على تحسين جودة الطاقة الكهربائية عبر المعوضات المتصلة بالشبكة الكهربائية. إنه مكرس لطريقة PBT (نظرية توازن الطاقة) التي نقدمها. نقدم مبدأها على الشبكات ثلاثية الطور باستخدام SAPF في يد واحدة كعاكس بسيط ثلاثي الطور مع مكثف بسيط كمصدر رابط DC، ومن ناحية أخرى، نستخدم SAPF كمصدر Z مع الخلايا الكهروضوئية خوارزمية MPPT P&O القائمة. بالنسبة لهذا الأمر، نقدم نتائج المحاكاة المختلفة للأنظمة المختلفة (عابرة ودائمة)، مع حالات مختلفة للشبكة الكهربائية (غير متوازنة و / أو مشوهة).

الكلمات المفتاحية: نظرية توازن القوى. مجموع التشويه التوافقي مرشح نشط متوازي لوائح مكافحة التصفية؛ شبكة غير متوازنة.

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List of Abbreviations

AC	Alternating Current
DC	Direct Current
THD	Total Harmonic Distortion
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electro-technical Commission
EMC	Electromechanical Commission
PCC	Point of common coupling
rms	Root mean square
CSI	Current Source Inverter
VSI	Voltage Source Inverter
UPQC	Unified Power Quality Conditioner
DPC	Direct power control
SAPF	Shunt active power filter
PLL	Phase locked loop
PWM	Pulse with modulation
VSF	Variable Switching Frequency
CSF	Constant Switching Frequency
PV	Photovoltaic
P-DPC	Predictive direct power control
MPPT	Maximum power point tracking
STC	Standard test condition
VOC	Voltage oriented control
LPF	Low pass filter
DTC	Direct torque control
STF	Self-tuning filter
P&O	Perturb and Observe
ZSI	Z source inverter
PBT	Power Balance Theory
SRF	Synchronous reference
SVPWM	Space Vector Modulation Control

Symbols

P	Active power
PF	Power factor
L	Inductor
C	Capacitor
S	Apparent power
v	The rms value of voltage
i	The rms value of current
D	Distortion power
Q	Reactive power
I_{SC}	Maximum short-circuit current
φ	Phase angle
C_{dc}	DC link capacitor
Hp and Hq	hysteresis bands
K_i	Integral controller
K_p	Proportional controller
G_s	Anti-windup gain
T_s	Sampling time
ζ	Frequency of damping
L_f	Filtering inductor
$S_a, S_b, S_c \ldots.$	Switching pulses
i_{sa}, i_{sb}, i_{sc}	Source current
i_{la}, i_{lb}, i_{lc}	Load current
i_{fa}, i_{fb}, i_{fc}	Filter current
T_{Sf}	The shoot through duty ratio
M_{Sr}	The switching cycle.
v_{sa}, v_{sb}, v_{sc}	Source Voltage

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General introduction

The change in the nature of energy production which mainly used fossil resources and which is becoming increasingly clean with various renewable sources such as wind turbines; photovoltaic panels is reflected in a paradigm shift where decentralized production takes precedence on centralized production [1]. In addition, technological progress has considerably changed uses with the intensive diffusion of charges based on power electronics, which are certainly economical but very polluting, which directly affects the quality of energy.

Mastery of energy management comes to the fore because managing production and ensuring continuity of service guarantees a good quality of energy on the grid. On the contrary, poor energy quality can cause malfunctions that can go as far as stopping services, which becomes very damaging from an economic point of view.

In an effort to improve energy efficiency and improve power quality, strong industrial demand is displayed for high-performance converters, with laws of adapted control ensuring filtering of harmonics [2].

In recent decades, significant technological developments have involved an increased use of modern power electronics in various applications, such as electric motor control, emergency power supplies, electric induction heating, compensation of harmonics, etc.

However, this increase in non-linear loads, especially rectifiers, which are widely used at the head of power conversion systems, leads to a significant deterioration in the quality of energy. The interconnection network is said to be polluted by generation of harmonic components and reactive power. In three-phase systems, they can cause imbalances by causing excessive currents at the neutral [3]. These excessive currents, the harmonics injected the presence of reactive power, imbalances and other problems generated by this type of load leads to a weakening of the overall efficiency of the system and of the power factor. They are also the cause consumer disruption and interference in local communication networks.

To reduce or eliminate these disturbances and thus improve the quality of the distributed energy, several solutions exist:

1. Reduced short circuit impedance.
2. Modification of the polluting static converter in terms of topology and / or control in order to intervene directly at the source of harmonic disturbances.
3. Filtering devices.

The use of filtering devices such as so-called resonant and / or damped passive filters can thus prevent harmonic currents from propagating in electrical networks. They can also be used to compensate for reactive power.

However, passive filtering poses certain problems [5]: lack of adaptability during variations in the network impedance, the load and possible resonance with the network impedance and in certain unfavourable cases where this resonance is excited, this can cause a high harmonic voltage and a large harmonic current in the capacity of the filter and in the network.

Thus, this solution has a major drawback, which can be intolerable in these particular circumstances.

Many active filter solutions for depolluting electrical networks have already been proposed in the literature [6]. Those that best meet today's industrial constraints are active parallel or series filters and active parallel-series combinations (also called Unified Power Quality Conditioner (UPQC)).

In this context and in order to meet the growing needs of the industry and the significant growth of harmonic pollution and to avoid the drawbacks of passive filters has led to the emergence of new structures called active filters.

In the case where the source currents are non-linear, the Shunt Active Power Filter (SAPF) is considered the best solution for the reduction of harmonic currents in low to medium power applications. Active filtering is more advantageous where a rapid response is necessary in the presence of dynamic loads. In addition, the APF represents a powerful tool for versatile conditioning because it can also compensate for reactive power and load imbalance.

Several topologies of active filters have been proposed in the literature, a first solution consists in connecting the active filter in parallel with the polluting system, and the principle of the active parallel filter consists in generating harmonic currents in phase opposition to those existing on the network. The current absorbed by the polluting charges is non-sinusoidal, while the current generated by the parallel active filter is such that the network current is sinusoidal. A second approach consists in connecting the active filter in series with the network: it then behaves like a voltage generator, which imposes a voltage harmonic, such that, added to that of the network, the voltage at the connection point is made sinusoidal.

On the other hand, it is important to note that the performance of an active filter is closely linked to the algorithm used to determine the reference harmonic currents as well as to the method used for tracking these references.

As part of this research issue, this doctoral thesis was initiated within the Electrical Engineering Laboratory of El oued in collaboration with LAADI in order to optimize the control performance of parallel active filters. The objective of the work presented here concerns both the study of harmonics (identification and filtering) and the control of the inverter. These two points will be approached by a theoretical study then by a simulation stage.

Based on this observation. The research work presented in this thesis is divided into four chapters:

The first chapter begins with the problem of harmonics (causes and consequences). Then, the harmonic filtering solutions are presented before choosing the filter parallel asset as a solution. We review the work carried out on the parallel active filter, which allowed us above all to position our study on the methods of extraction of the harmonics since they constitute the decisive criterion of the control strategy.

In the second chapter, we will present the state of the art of the control strategies proposed in the literature, namely the different types of current control, the different techniques for extracting harmonics, the main regulators and finally the different techniques control.

Chapter 3 is devoted to the PBT method (Power Balance Theory) generic solution that we offer. We present its principle on networks on the three-phase 3-wire network using in one hand SAPF as simple 3 phase inverter with simple capacitor as DC link source, in the other hand, we use SAPF as a Z source inverter with photovoltaic cells based MPPT P&O algorithm. For this command, we will present the different simulation results for the different regimes (transient and permanent), with the different states of the electrical network (unbalanced and / or distorted). In this chapter, the DC bus voltage regulation and current regulation blocks are presented and detailed as well as the methodology for generating the cyclic command reports.

Chapter 4 deals with the simulation of the system model (active filter inverter for the structure, three-phase without neutral and three different connected unbalanced loads for three different instant of time).

The last part of the document is devoted to the conclusion and the presentation of some perspectives.

CHAPTER I
Harmonic disturbances and pollution control solutions

I. Harmonic Disturbances and Pollution Control Solutions

I.1 Introduction

The increasing use of devices based on power electronics in industrial, tertiary or domestic appliances is causing more and more disturbance problems in the electrical networks. Although these devices provide flexibility of use and increase reliability with high efficiency, they behave like non-linear loads which absorb currents with waveforms different from supply voltages which affects the quality of electrical energy.

These periodic but non-sinusoidal currents flow through the impedances of the networks and give rise to non-sinusoidal voltages which are added to the initial voltage. Thus the single-phase loads connected to the three-phase network with distributed neutral absorb currents which are not necessarily equal and often cause an imbalance of the voltages. All the linear loads connected, at the common coupling point in parallel with the polluting loads, undergo in consequently disturbances and the imbalance of tensions. We are facing deterioration in the quality of power which has detrimental consequences on the proper functioning of electrical devices and which induces an additional cost for the installations [7].

In practice, we classify disturbances according to the duration of the phenomenon [8], [9]. We can then distinguish:

Alterations of the voltage wave (harmonic, imbalance, fIicker). These phenomena are permanent or last at least several minutes.

Voltage dips, overvoltage and brief outages lasting from one to a few seconds.

Transient overvoltage, lasting less than a period [10].

In what follows, we are interested in permanent disturbances affecting the waveform of the network voltage. These disturbances are superimposed on the fundamental wave. Consequently, they have the consequence of modifying the voltage or current wave which results in a degradation of the power factor and / or in the generation of alternating currents and voltages of frequency different from that of the fundamental [11].

It is therefore important for a given installation to know how to define, analyse and quantify the harmonics.

In this first chapter, the origins and consequences of harmonic pollution are exposed. Consequently, the standards and regulations in force will be presented before listing the possible solutions. Next, we present the parallel active filter APF as a curative solution for harmonic pollution as well as the evolution of its structures. Finally, the positioning of the thesis in this “harmonic” context closes the chapter.

I.2 Harmonic Disturbances

I.2.1 Sources of harmonics and their effects

The processes and devices based on power electronics become the most used loads because of their multiple advantages (flexibility of operation, excellent performance, high performance ...). We note the development and generalization of automation in production chains, variable speed drives (VV) in the industry, computer systems, lighting with compact fluorescent lamps (LFC) and LED in the tertiary and the domestic, all beside the sources renewable energies connected to the grid through power inverters. These devices have the particularity of being disturbing generators and at the same time sensitive to the disturbances of the tension. This requires good electrical quality of their power supply networks.

Figure 1.1 shows an example of a voltage waveform distorted containing, in addition to the fundamental term of frequency 50Hz, two harmonics of odd rank 5 and 7.

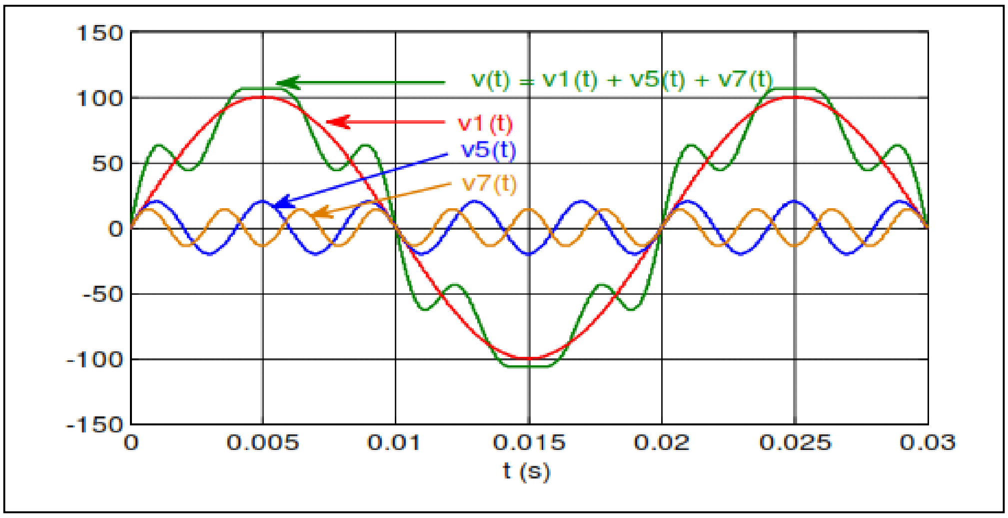


Figure I.1 Synthesis of a signal from harmonics

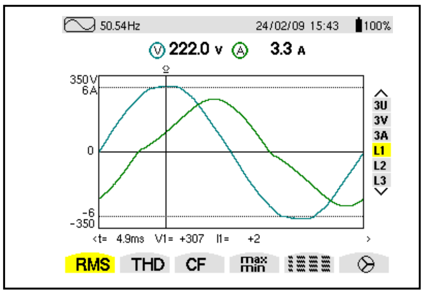
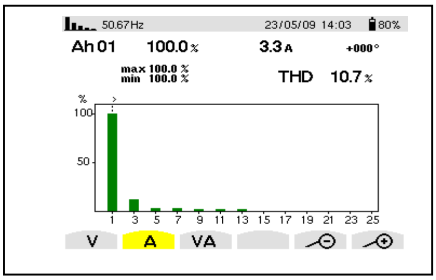
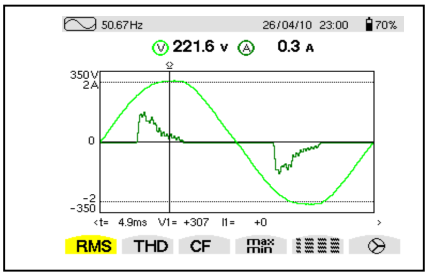
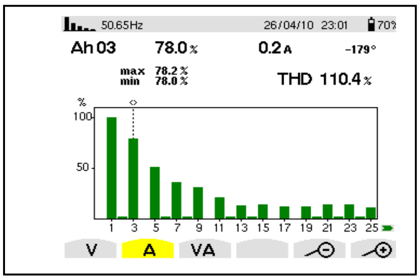
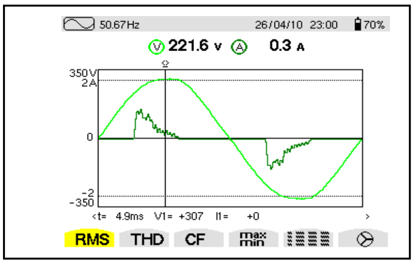
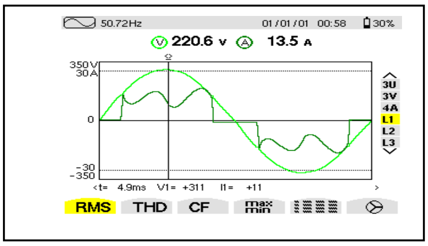
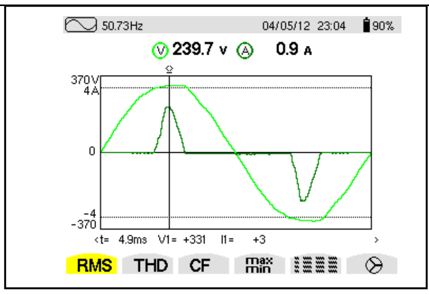
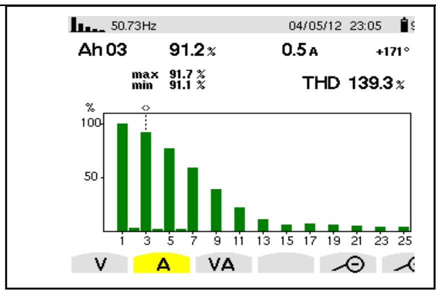
	
Current absorbed by 8 fluorescent tubes	Spectrum of the current of the 8 fluorescent tubes
	
Current absorbed by 1 CFL lamp	Current spectrum of a CFL
	
Current absorbed by 1 VV for elevator without AC side smoothing coil	Current absorbed by 1 VV for elevator with AC side smoothing coil
	
Current absorbed by 1 computer	Current spectrum of a computer

Figure I.2 Typical non-linear load currents (Surveys made with the Chauvin Arnoux CA 8332 device.)[12]

Figure I.2 shows the typical curves of lighting systems, computers and variable speed drives as well as their harmonic spectrum.

The presence of current or voltage harmonics leads to harmful effects on the distribution network, such as for example:

Heating of conductors, cables, capacitors and machines due to additional copper and iron losses.

The malfunction of certain electrical equipment such as command and control devices: Current and voltage can change sign several times in a half-period. Consequently, the equipment sensitive to the zero crossing of these electrical quantities is disturbed.

Resonance phenomena: The resonant frequencies of the circuits formed by the transformer inductances and the capacitances of the cables are normally quite high, but these can coincide with the frequency of a harmonic. In this case, there will be a significant amplification, which can destroy the equipment connected to the network degradation of the accuracy of measuring devices. [8][9].

I.2.2 Identifiable harmonic sources:

Equipment fitted with devices based on power electronics, in particular rectifiers and cycloconverters of large powers, installed on high and medium voltage networks are typically identifiable harmonic sources. With this type of non-linear load, the energy distributor is able to identify the point of injection of the harmonics and to quantify the disturbance caused. In this case, it is the user who must obtain the necessary means to reduce this disturbance below the threshold required by the energy distributor, under penalty of being penalized [13].

I.2.3 Unidentifiable harmonic sources:

This type of harmonic current generator is mainly represented by the devices used in the household or tertiary fields such as televisions and microcomputers. In view of their very wide distribution, these devices often comprising a single-phase diode rectifier with a smoothing capacitor, draw non-negligible harmonic currents. In this case, it is the responsibility of the electric power distributor to prevent the propagation of the harmonic disturbance on the network since each user individually generates a low harmonic rate [14].

I.3 Technical Consequences

In the absence of a good quality of the electrical energy, the receiver’s sensitive to the harmonic disturbances can have a malfunction or even stop. He is quoted in 1-2-3 that:

the temporary shutdown of an element of the chain can cause the stop of the production tool (manufacture of semiconductors, cement works, water treatment, handling, printing, iron and steel, petrochemical industry ...) or services (computer centers, banks, telecommunications ...).

Malfunctioning or stopping priority receivers such as computers, lighting and security systems can jeopardize the safety of people (hospitals, airport markings, public buildings, high-rise buildings, etc.) [15].

The reduction of the energy efficiency of the installation, which increases the energy bill.

The overload of the installation, hence its premature aging with the increased risk of failure which leads to over-dimensioning of the distribution equipment [16].

The thesis in [17] on the impact of harmonic pollution on network facilities and equipment details all the other effects of harmonics. Other studies show that the circulation of a current of = 25% (Total Harmonic Distortion) in an electric cable reduces its life time at 50% [18].

A transformer supplying harmonic loads sees these losses increase [19][20] and will be downgraded in power. The calculation of additional losses is subject to ANSI standard C57.110 [21], and the curve, in Figure 1.3 extracted from a draft 1996 IEEE 519 Application Guide [22] gives the typical derating to apply to a transformer supplying electronic loads, showing that if the transformer supplies 40% of electronic loads it will be downgraded by 40% of its nominal apparent power.

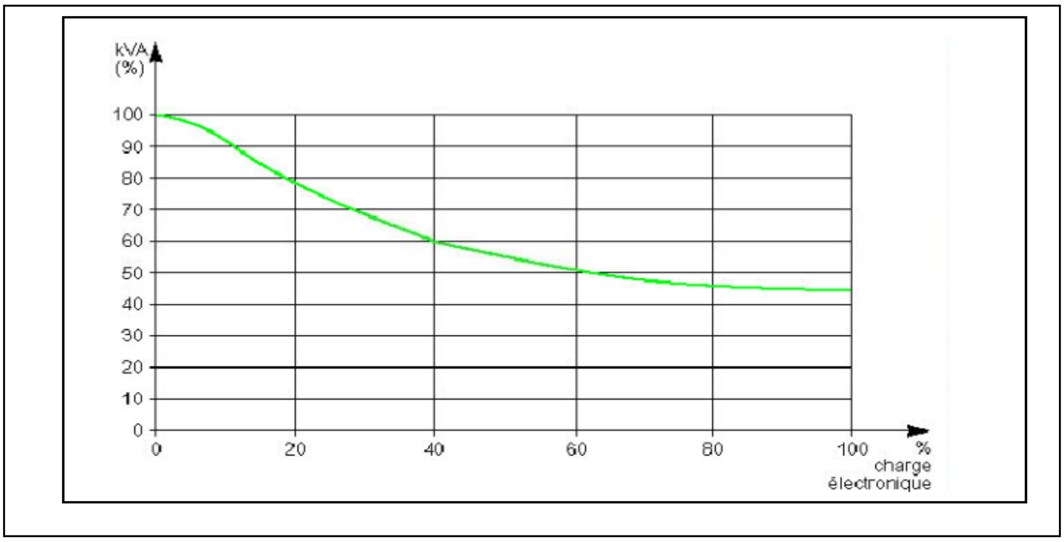


Figure I.3 Decommissioning rate to be applied to a transformer supplying electronic loads

However, what is not usually mentioned when we talk about harmonic disturbances, it is their effects on generators. It is true that in Europe and elsewhere, too, the use of generators is limited to temporary emergency power supplies for sensitive sites, which is not the case for Lebanon [23], which with the shortage 12 hours of rationing per day, diesel generators and uninterruptible power supplies are the alternative that provides about 65% energy available in the country. However, synchronous machines, such as alternators, do not withstand current disturbances (allowable distortion limit in the stator current of 1.3 to 1.4% [24]). What causes, in case of exceeding, an inadmissible heating in the machine and its thermal protection makes stop the group.

I.4 Long Term Effects

The following list gives an idea of the impact of harmonics on certain frequently used equipment that is an integral part of the electrical network, such as:

a) Alternators

Additional losses in the stator windings and in the shock absorbers linked to the increase in the effective value of the absorbed current. These losses cause additional heating and also reduce the efficiency of these machines.

b) The electric cables

Additional Joule losses, especially in the return cables of the neutral where homopolar harmonic currents circulate and corrosion of aluminium cables under the effect of the circulation of even harmonic currents associated with a DC component [25]. The presence of harmonics in the network also reduces the active power transmission capacity of lines.

c) Capacitors

They are also very affected by harmonic currents. The capacitors connected in parallel to networks for compensation of reactive power (power factor correction) have impedances that are lower the higher the frequency. Harmonic currents are superimposed on the fundamental current and cause additional losses which can exceed the thermal capacity of the capacitors and considerably reduce their lifetime. In addition, resonance phenomena can occur and subject the capacitors to overvoltage, which are liable to degrade them, or even to perforate their insulation [26].

d) Telecommunications networks

Generation of significant noise linked to the electromagnetic coupling between the power lines and the communication circuits. In special cases, especially during resonances, part of the telecommunication networks can be rendered unusable [27]

I.5 Economic Consequences

Electrical power quality has become a strategic topic for utilities, utility, maintenance or tertiary site management, and equipment manufacturers, primarily for the following reasons:

- ❖ The economic need to increase competitiveness for businesses.
- ❖ The generalization of equipment sensitive to voltage disturbances and / or disturbance generators themselves.
- ❖ The opening of the electricity market.
- ❖ Electricity is a product, which makes it necessary to define its essential characteristics.

Moreover, in the context of the liberalization of the energy market, the search for competitiveness by electricity companies means that power quality is a differentiating factor. Its guarantee can be, for an industrialist, a criterion of choice of an energy supplier.

The costs associated with the loss of continuity of service and the non-quality of the electrical energy supplied is high. Some examples to quantify these losses concern a glass works in France which loses 600,000 € with 3 days of production stoppage due to consecutive failures of 2 transformers following an excessive warm-up, a bank loses 1M € because of a fire resulting from overloading the neutral wire [28]. It is estimated, at the European level, that the bill linked to a low power quality is approximately 500 billion € / year, of which about 100 billion € / year are due to harmonics [29].

In [30], an energy quality monitoring study is carried out on 12 industrial sites of power up to 30 MVA, there are 858 disturbances during 10 months of which 42 had economic consequences as presented in Table I .1.

Industry	Typical financial losses per event
Semiconductor production	3 800 000 €
Financial Trade (Banks-Scholarships)	6 000 000 €/h
Computer Center	750 000 €
Telecommunications	30 000 €/mn
Steelworks	350 000 €
Glass	250 000 €

Table I.1 Economic impact of low PQ

Additional and detailed studies on the degradation of the PQ and its consequences for the energy efficiency of the systems and the additional costs incurred in the industrial, service and residential sectors are offered in [31] and [32].

I.6 Characteristic of Harmonic Pollution

Different quantities are defined to quantify these disturbances. Among these the most used are:

I.6.1 The harmonic rate of rank h:

$$S_h = \frac{C_h}{C_1} \qquad \text{(I.1)}$$

Where:

C_h Represents the harmonic component of rank h

C_1 Represents the fundamental component.

I.6.2 The overall rate of harmonic distortion:

$$THD = \sqrt{\sum_2^{\infty} \frac{{C_h}^2}{{C_1}^2}} \qquad \text{(I.2)}$$

I.7 International Standards

The scope of the standards is very wide; here we are limited to two sets of standards.

I.7.1 The series of electromagnetic compatibility standards (IEC 61000) and (IEEE 519-1995) that define certain limits for harmonics, including:

- ❖ IEC 61000-3-2 which defines harmonic current emission limits for devices consuming less than 16A per phase.

- IEC 61000-2-2 which defines harmonic voltage compatibility levels on low voltage public networks.
- IEC 61000-2-4 which defines compatibility levels in industrial plant networks.
- IEEE 519-1996 which defines the limits of voltage and current disturbances at the PCC.

I.7.2 The series of standards for the monitoring of energy quality (EN 50160, IEEE 1159-2009)

I.7.2.1 Electromagnetic compatibility

a) A Limitation of harmonic emissions. IEC 61000-3-2 standard.

In this standard [33], electrical appliances are classified in classes A, B, C, D.

- Class A: Three-phase apparatus and any other apparatus except those specified in one of the following classes.
- Class B: Portable tools, arc welding equipment off professional equipment.
- Class C: Lighting apparatus including dimming devices.
- Class D: Apparatus having input current "special waveform" and input active power ≤ 600.

b) Levels of compatibility. IEC 61000-2-2 standard.

This standard [34] sets the compatibility limits, for low-frequency conducted disturbances and signal transmission on public low-voltage power systems. Disruptive phenomena include harmonics, inter-harmonics, voltage fluctuations, voltage dips, voltage imbalances, transients, etc.

c) Levels of compatibility. Standard IEC 600001-2-4.

This standard [35] defines the compatibility limits for low voltage and medium voltage industrial and non-utility networks, excluding ship networks, aircraft, offshore platforms and railway installations.

d) IEEE Standard 519-1996.

This standard [25] determines the limits to be applied to harmonic emissions in current and voltage at the common coupling point PCC. In this standard, the limits for the currents are not calculated as a function of the fundamental current but as a function of the maximum current called by the load (actual current). The overall distortion is then quantified by the (Total

Demand Distortion) instead of the THD. The emission limits are also related to the short circuit current of the plant resulting from the short circuit power for each voltage level.

I.7.2.2 Energy quality supervision.

a) Network quality Standard EN 50160

EN 50160 [36] stipulates the admissible limits of disturbing phenomena affecting the sinusoidal signal at 50 Hz (harmonics, inter-harmonics, voltage fluctuations, voltage dips and brief interruptions, voltage imbalances three-phase, transmission of signals over the network, frequency variations of the power supply, DC components in AC networks, transient disturbances / shock voltages and currents, electrostatic discharges, electromagnetic fields and magnetic fields).

The electrical energy thus produced has a particularity: its characteristics depend not only on its production but also for a large part on its use. Certain phenomena can affect the transport or distribution systems (lightning, switching, remote transmission signals, etc.) but they generally only cause brief disturbances. We retain for this standard:

The limits of harmonic voltages: We find the same levels of compatibility recommended by the standards IEC 61000-2-2 (LV public network), IEC 61000-2-4 (Industrial installations).

The limit of reverse imbalance: The reverse component of the supply voltage must be between 0 and 2% of the direct component, the same for the zero sequence components. These are the same requirements as those of the IEEE 1159-2009 standard which follows.

b) IEEE 1159-2009 standard.

In terms of imbalance, this standard [37] retains the same requirements as those of standard EN 50160 for limit values ≤ 2%, but the calculation of the imbalance factor is treated differently.

I.8 Harmonic Delegation Solutions

Faced with these widespread problems of harmonics and their technical and economic consequences, effective solutions to limit harmonic emissions and / or to clean up the network are much sought after at all power levels for receivers and at all levels of the installation. Then there are sinusoidal absorption receivers that can mitigate the emissions of disturbances in the device itself (TV, electronic ballast for fluorescent lighting, etc ...), but these solutions concern low power devices (≤ 1kW) and generally single-phase [38]. This solution for AC / DC power supplies fulfils the requirements of IEC 61000-3-2.

Other proposed solutions [39] which consist in confining the harmonics, for specific loads, by the use of the particular couplings of the transformers. The transformer coupling effect allows the suppression of some harmonic ranks.

Passive filtering [19] is also a solution for the depollution and improvement of the power factor on the electrical networks. It consists in connecting in parallel to the power supply network an impedance of very low value around the frequency to be filtered and sufficiently large at the fundamental frequency of the network. Such a filter generally consists of passive components (R, L, C) thus providing static compensation for a fixed spectrum charge. However, when the harmonics of the load are very variable, causing frequencies that are not expected during sizing of the filter, there is a risk of resonance between the capacitor and the line inductance. This phenomenon has limited the use of these filters which are no longer suitable for current networks.

All the solutions reviewed are not a radical solution for harmonic disturbances, on the other hand, when the network comprises several polluting loads, a global compensation is necessary.

However, parallel active filtering is an effective and curative solution for harmonic pollution control of currents and is suitable for single-phase and three-phase circuits for all power levels.

It does not cause resonance with the network and provides compensation for even a variable spectrum. Serial active filtering allows the depollution of the network voltage, other hybrid structures are part of active filtering processes as well [40].

I.9 Active Parallel Filtering

Among all modern solutions, there are two types of structures conventionally used:

- ❖ The active filter (series, parallel or even combining the two).
- ❖ The active hybrid filter (series, parallel).
- ❖ In the following, different topologies of usual active filters are presented.

I.9.1 Series parallel filter

The role of a SAF is to locally modify the impedance of the network. It behaves as a source of harmonic voltage which cancels the disturbing voltages (dip, imbalance, harmonic) coming from the source and those generated by the circulation of disturbing currents through the impedance of the network. Thus, the voltage across the load can be made sinusoidal. However, the FAS does not compensate for the harmonic currents consumed by the load.

I.9.2 Parallel Active filter

The PAF connects in parallel with the network and injects in real time the harmonic components of the currents absorbed by the non-linear loads connected to the network. Thus, the current supplied by the energy source becomes sinusoidal.

I.9.3 UPS topologies implemented for active filters

The most common configuration is the active three-arm parallel power filters are:

I.9.3.1 Active three-phase filter consisting of a three-phase inverter with three arms

- ❖ Three-phase active filter consisting of a two-phase inverter with two arms and a mid-point capacitor.
- ❖ Three-phase active filter consisting of a three-phase three-arm inverter with mid-point capacitor.
- ❖ Active three-phase filter consisting of a three-phase inverter with four arms.

The three arms of the inverter are formed by six bidirectional current switches [41], which are semiconductor components controlled on closing and on opening (transistors bipolar, IGBT or IGCT) with an antiparallel diode. This inverter is connected to the electricity grid by a so-called decoupling filter.

I.9.4 Active filter control and implemented techniques

The performance of active or hybrid filters very strongly depends on several factors:

- ❖ The control algorithm used to identify the currents or voltages references [42].
- ❖ The control mode used (PWM, hysteresis, modulated hysteresis, etc.) for the generation of power switch control orders.
- ❖ The performance of the capacitive tank voltage regulation loop.

On the other hand, the performance of the active filter also depends on the technique chosen (analog or digital) during the practical implementation of the control. Active filtering indeed requires high real-time performance during the implementation of the control, taking into account the frequencies of the harmonics to be generated. The current trend is the development of digital controls (Digital Signal processor, Microcontroller, FPGA, DSPACE prototyping system) for the implementation of the selected control algorithm. [43].

First, we will study theoretically then by simulation (Matlab / Simulink) a new command, variant of the method of instantaneous real and imaginary powers. The APF studied will be intended to clean up a three-phase three-wire electrical network, unbalanced and distorted, connected to a three-phase non-linear load of the rectifier bridge type, discharging into three unbalanced RL loads.

I.10 Conclusion

In this chapter, we have presented different types of disturbances affecting the voltage wave of the electrical network. As we have seen, harmonics and current and voltage imbalances, reactive power and voltage dips have harmful effects on electrical equipment. These effects can range from overheating and degraded operation to the total destruction of this equipment.

Then, to reduce the effects of these harmonic disturbances, various traditional and modern solutions for pollution control have been presented. Conventional solutions are not very effective in dealing with this problem; the technologies used, such as passive filters, are often penalizing in terms of size and resonance. In addition, passive filters cannot adapt to changes in the network and polluting loads.

Recently, in addition to filtering harmonics, parallel and series active filters, and their combination, are being studied to compensate for all types of disturbance likely to appear in a low voltage electrical network.

The parallel active filter can be installed to compensate for all current disturbances such as harmonics, imbalances and reactive power.

Our research objective relating to the depollution of all kinds of disturbances, only active filtering solutions will be analysed in this thesis.

Thus, in order to improve the quality of electrical energy, which must comply with the new normative constraints, we will study, in the following chapters, classical and advanced regulation methods that we will apply in the case of the structures of active parallel filters.

CHAPTRE II

Control Strategies, Regulation and Dimensioning of the Shunt Active Filter

II. Control Strategies, Regulation and Dimensioning of the Shunt Active Filter

II.1 Introduction

The degradation of energy quality with harmonic pollution has been known for a long time. Non-linear charges form a strong source of harmonics which pollute the networks to which they are connected.

In this chapter, we will start by defining the polluting loads and the compensation of the harmonic currents, then we will present the general structure of the parallel active filter, in the third part, control and command, we will describe the different types of current command. The fourth part deals with the state of the art of the different techniques for extracting frequency and time harmonics, and we end this chapter with the main control techniques.

II.2 Characteristics Of Non-Linear Load

The supply network is modeled by three perfect sinusoidal voltage sources in series with an inductance L, and a resistance R. An additional inductor L_C is connected to the input of the rectifier bridge in order to limit the di/dt gradients when the thyristors / diodes are started.

The decomposition in Fourier series of the current of the first phase is given by the formula of Môltgen [44]:

$$I_{Ceff} = I_d\sqrt{\frac{2}{3}} \tag{II.1}$$

The effective value of the harmonic current to be compensated is written:

$$I_{ch} = \sqrt{I_{Ceff}^2 - I_{C1}^2} \tag{II.2}$$

With the fundamental current consumed by the non-linear load. It is written as a function of the direct current of the non-linear load as follows:

$$I_{ch} = I_d\sqrt{\frac{2}{3} - \frac{6}{\pi^2}} = 0.2423\, I_d \tag{II.3}$$

The peak value of the harmonic current is then written:

$$I_{ch\,max} = \frac{I_{C1}\sqrt{2}}{2} = I_d\,\frac{\sqrt{3}}{\pi} = 0.551\, I_d \tag{II.4}$$

$$V_d = \frac{3\sqrt{6}V_s}{\pi}\cos\alpha \qquad \text{(II.5)}$$

Where:

V_s Is the effective voltage of the three-phase bridge and $\alpha = 0$ for a diode rectifier.

II.3 General Structure Of The Parallel Active Filter

The active filter consists of a voltage inverter and an output inductive filter $L_{a,b,c}$ giving the nature of the current source for the filter. Typically, the power switches of the active filter inverter are insulated gate bipolar transistors (IGBTs).

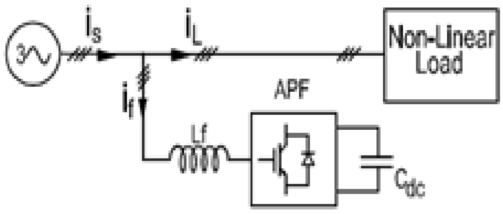


Figure II.1 Shunt Active Power Filter scheme

Figure II.2 shows a three-phase inverter with voltage structure. It consists of three arms with reversible current switches, controlled on closing and opening, made from a transistor (GTO or IGBT) and an antiparallel diode.

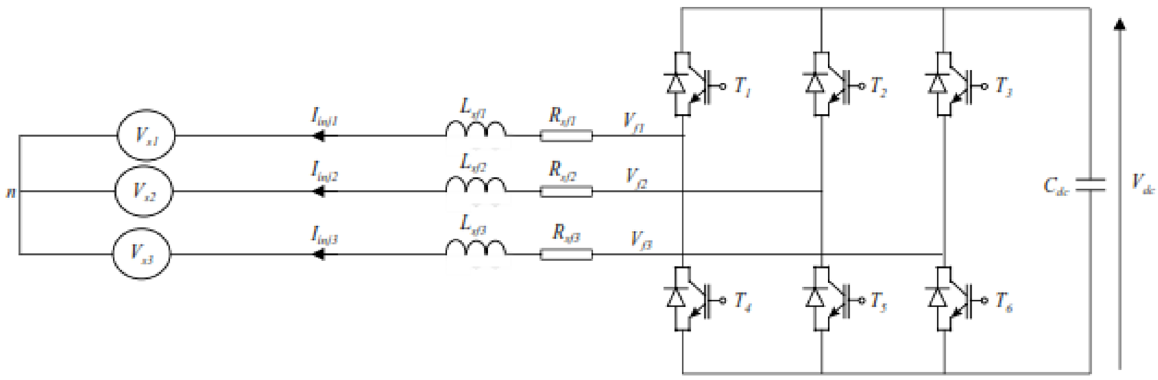


Figure II.2 Three phase voltage inverter

This structure of the parallel active filter does not allow the simultaneous closing of the semiconductors of the same arm; otherwise, the storage capacitor may be short-circuited. On the other hand, they can both be open (during a dead time). The continuity of the currents is then ensured by the conduction of one of the diodes of the same arm.

In practice, we control the two semiconductors of the same arm in a complementary manner: the conduction of one causes the blocking of the other. In reality, the mode, where the semiconductors of the same arm are both closed, only exists during switching.

II.3.1 Voltage supplied by the inverter

The opening and closing of the switches of the inverter of Figure II.2 depend on the state of the control signals as presented in Table II.1

switch	state	Opened	closed
S1	1	T4	T1
	0	T1	T4
S2	1	T5	T2
	0	T2	T5
S3	1	T6	T3
	0	T3	T6

Table II.1 State of the control signals

Thus, we can express eight possible cases of output voltage of the active filter.

Vectors	S_1	S_2	S_3	v_a	v_b	v_c
$\overrightarrow{V_0}$	0	0	0	0	0	0
$\overrightarrow{V_1}$	0	0	1	$2V_{dc}/3$	$-V_{dc}/3$	$-V_{dc}/3$
$\overrightarrow{V_2}$	0	1	0	$-V_{dc}/3$	$2V_{dc}/3$	$-V_{dc}/3$
$\overrightarrow{V_3}$	0	1	1	$V_{dc}/3$	$V_{dc}/3$	$-2V_{dc}/3$
$\overrightarrow{V_4}$	1	0	0	$-V_{dc}/3$	$-V_{dc}/3$	$2V_{dc}/3$
$\overrightarrow{V_5}$	1	0	1	$V_{dc}/3$	$-2V_{dc}/3$	$V_{dc}/3$
$\overrightarrow{V_6}$	1	1	0	$-2V_{dc}/3$	$V_{dc}/3$	$V_{dc}/3$
$\overrightarrow{V_7}$	1	1	1	0	0	0

Table II.2 Possible voltages at the output of the inverter

II.3.2 Vector representation

In the two-phase plane, considering V_f the vector corresponding to the voltages of the inverter, the eight possible cases of the vector are given in Figure II.3

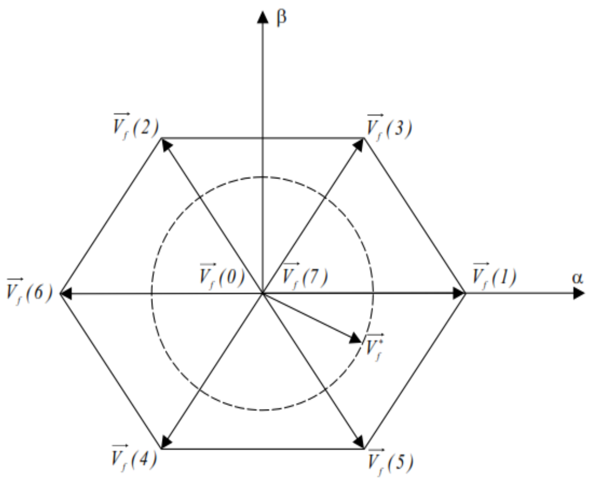


Figure II.3 Vector representation of the voltages generated by the inverter

Where, V_f represents the reference voltage that the inverter must produce in order to be able to create the identified disturbing currents.

II.3.2.1 Energy storage system

The choice of voltage V_{dc} and of capacitor capacity C affects the dynamics and compensation quality of the parallel active filter. Indeed, a high voltage V_{dc} improves the dynamics of the active filter. In addition, the ripples of the DC voltage V_{dc} caused by the currents generated by the active filter and limited by the choice of C [45], can degrade the compensation quality of the parallel active filter. These fluctuations are all the more important that the amplitude of the current of the filter is large and that its frequency is low. For this reason, we can estimate that only the first harmonics are taken into account in the choice of the parameters of the storage system.

An acceptable wavelength ΔV_{dc} is chosen, generally of the order of 2% of V_{dc} and on the basis of calculation of the energy supplied by the active filter during a half-period of the power pulsation linked to the first two harmonics (5 and 7 for a Graëtz rectifier bridge); we can calculate C_{dc} from the following relation.

$$C_{dc} = \frac{v_s\sqrt{I_5^2+I_7^2-2I_5I_7\cos(5\alpha-7\alpha)}}{2\Delta V_{dc}\omega V_{dc}^2} \quad \text{(II.6)}$$

Where:

v_s The simple network voltage.

I_5, I_7 The harmonic current of the row 5, 7 respectively.

α The ignition angle of the Graëtz bridge thyristors, zero in the case of a diode rectifier.

- The voltage V_{dc} is chosen as the largest voltage respecting the constraints of the switches. The minimum value of the voltage V_{dc} is twice as large as the maximum of the mains voltage to ensure the controllability of the output filter current at all times.
- A second, simpler method is based on the measurement of the harmonic current I_h of the lowest rank. [46] [47]. The capacity C_{dc} is calculated as follows:

$$C_{dc} = \frac{I_h}{V_{dc}\Delta V_{dc}\omega_h} \tag{II.7}$$

ω_h The weakest pulsation of the harmonics to compensate.

A third method based on the calculation of the energy supplied by the active filter and that of the pollutant load as follows [48]:

The effective value of the AC load current in the three phases is:

$$I_{eff} = \sqrt{\frac{2}{3}} I_d \tag{II.8}$$

Where I_d represents the continuous rated load current.

The fundamental of the load current is given by:

$$I_{foneff} = \frac{\sqrt{6}}{\pi} I_d \tag{II.9}$$

The harmonic current produced by the load represents the difference between the fundamental and the RMS value of the alternating current of the load. These currents are given by:

$$I_{Lhar} = \sqrt{I_{eff}^2 - I_{foneff}^2} = \sqrt{\frac{2}{3} - \frac{6}{\pi^2}} I_d = 0.2423\, I_d \tag{II.10}$$

The active filter must supply the power corresponding to the harmonics produced by the load. By choosing the period of the ripple of the voltage across the capacitor six times lower than that of the voltage of the electrical network, we can find:

$$C_{dc} \geq \frac{2.0{,}3036\, P_l}{6 f_s (V_{dc\,max}^2 - V_{dc\,min}^2)} \tag{II.11}$$

With $f_s$the fundamental frequency of the electrical network.

If we set the ripple of the DC voltage to $\Delta V_{dc} = 2\% \, V_{dc}$, we can write:

$$V_{dc(max,min)} = \frac{\Delta V_{dc}}{2} \mp V_{dc} \qquad \text{(II.12)}$$

II.3.3 Output filter

The output filter is a passive filter used to connect the voltage inverter to the power grid. The output filter is sized to meet the following two criteria:

1. Ensure the dynamics of the current:

$$\frac{d}{dt} I_{Li} = \frac{d}{dt} I_{fi} \qquad \text{(II.13)}$$

Where I_{Li} is the harmonic current of the load and I_{fi} is the injected current from the filter.

2. Prevent components due to switching from propagating on the electrical network.

II.3.3.1 First order filter

This type of filter is the most used. It is composed of an inductor L_f with internal resistance R_f, as shown in Figure II.2. A filter of this type does not make it possible to simultaneously satisfy the two sizing criteria of the output filter. Indeed, a relatively low value of L_f can achieve good dynamics of the active filter while satisfying equality (II.13), conversely, a relatively high value of L_f will prevent components from propagating on the electrical network but will affect the dynamics of the active filter and will then degrade the quality of compensation.

Thus, the correct sizing of the first order output filter will therefore depend on the trade-off between the dynamics and the efficiency of the parallel active filter.

II.4 Literature Review On Parallel Active Filters

The APF is the most used solution for the clean-up of harmonic currents [49]. The conventional structure of the two-level inverter is very common for LV applications. Several researches have been carried out around, from the control of the filter since its average model [50] or the direct and hybrid control [51] [52], the linear and nonlinear control [53] [54], or by slip mode [55].

Research continues to improve filter performance, especially for unbalanced and disturbed networks. It should be noted that the high quality of the waveforms of the current at the output of the converters is a function of the topology used, the intended application, the control algorithm, its dimensioning and its environment. Current research strives to improve converter performance by various means:

- Simplification of control and optimization of algorithms to improve the THD
- Balancing DC voltages
- Reduced current ripple
- Harmonic attenuation to meet a specific standard
- Development of new topologies

Our thesis aims to improve the performance of active filtering and it is not through the structures but by the control algorithm.

II.5 APF Control Strategy

The exact compensation on the part of the load current $i_{Li,rh}(t)$ requires good precision on the extraction of this current [56]. However, the control strategy of an APF, shown schematically in the figure II.4, is organized around 4 elementary blocks.

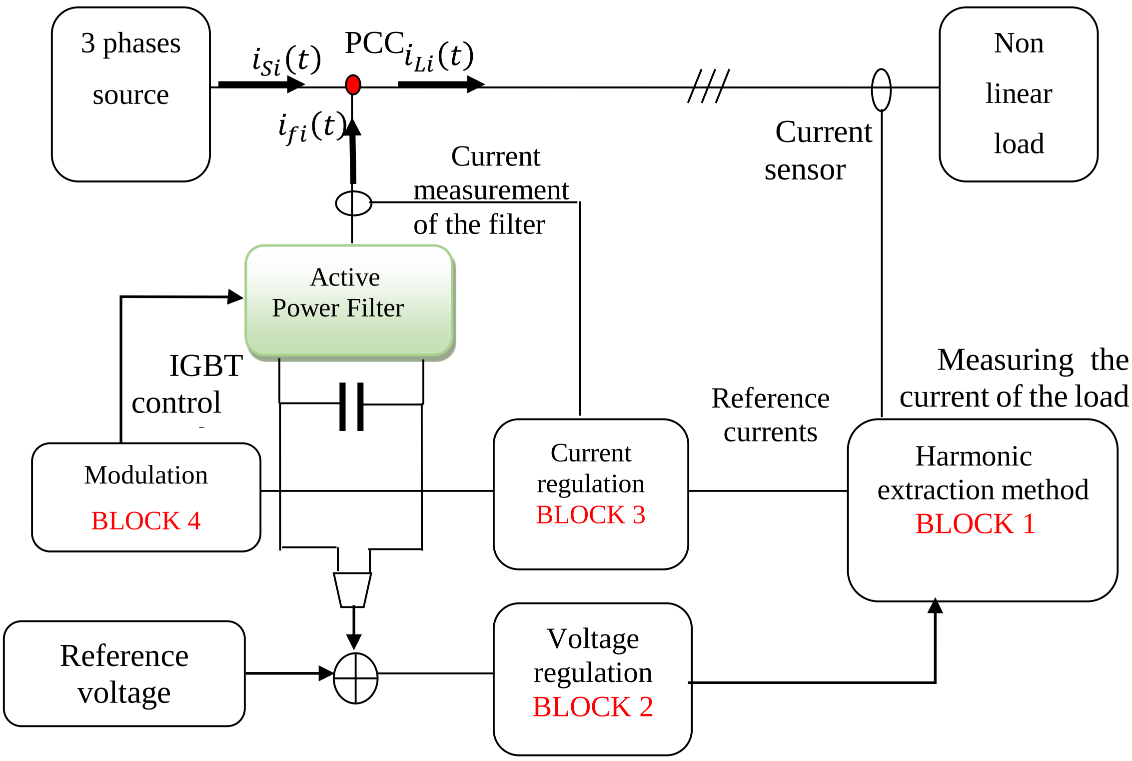


Figure II.4 Simplified diagram of the APF control strategy

- **BLOCK 1**, which is basic for any control strategy. It is at this stage that the reference currents are determined. This block can decide the control sequence and the performance of the control algorithms depend on it.
- **BLOCK 2** is used to regulate the DC bus voltages and subsequently to determine the losses in the filter that will be absorbed from the network [57].
- **BLOCK 3** regulates the filter currents at their reference currents. For example, a PI regulator reduces the filter current tracking error with respect to its reference. At the output of this block, the control reference signals are determined.
- **BLOCK 4** generates signals needed to control IGBTs from already established reference signals.

II.6 Principle Of Compensation Of Harmonic Currents

According to Figure II.2, the load absorbs the disturbed currents $i_{La,b,c}(t)$ in harmonics that the filter must compensate by injecting the current $i_{fa,b,c}(t)$ for the source to supply only the active currents $i_{Sa,b,c}(t)$, we write for the charge:

$$i_{Li}(t) = i_{Li,a}(t) + i_{Li,rh}(t) \tag{II.14}$$

With $i = a, b, c$

$i_{Li,a}(t)$ Is the active part of the charge current.

$i_{Li,rh}(t)$ Is the reactive and harmonic part of the charge current.

And for the source, considering that the desired currents $i_{Si,a}(t)$ are active and correspond mainly to the active part necessary for the load $i_{Li,a}(t)$ next to a weak current $i_{losses,i}(t)$ which will be absorbed by the filter to compensate for these losses.

We will have:

$$i_{Si}(t) = i_{Si,a}(t) + i_{losses,i}(t) \tag{II.15}$$

In the PCC we have:

$$i_{Li}(t) = i_{Si}(t) + i_{f,i}(t) \tag{II.16}$$

By replacing (II.15) & (II.16) in (II.17)

$$i_{Li,a}(t) + i_{Li,rh}(t) = i_{Si,a}(t) + i_{losses,i}(t) + i_{f,i}(t) \tag{II.17}$$

However, the active current supplied by the source $i_{Si,a}(t)$ corresponds to the active part $i_{Li,a}(t)$ demanded by the load, then equation (II.17) gives:

$$i_{fi}\,(t) = i_{Li,rh}(t) - i_{losses,i}(t) \tag{II.18}$$

Equation (II.18) summarizes the compensation principle expected by the active filter.

II.7 Positioning of The Thesis

After this review on harmonic disturbances and parallel active filters, our work is at the level of the active filter control strategy and the voltage regulation and more precisely, it concerns the extraction methods of reference currents of BLOCK 1 and BLOCK 2 respectively.

II.8 Conclusion

We present in chapter 2 a state of the art focused on the harmonic extraction methods based on the power concept by comparing the performances obtained in filtering on a disturbed network and imbalance.

Our goal is to evaluate the performance of existing methods in the case of a highly disturbed and unbalanced network. Then, develop an approach that can be applied to three-phase 3-wire system improving the quality of energy provided both at the balancing level and at the harmonic distortion rate of the source currents.

CHAPTRE III

State of the art on methods for extracting reference currents SAF

III. State of the art on methods for extracting reference currents SAF.

III.1 Introduction

Active filtering on the grid is becoming a necessity to overcome the problems generated by the use of non-linear loads of domestic, tertiary and industrial growth.

This need is all the more true when the voltages on the network are no longer sinusoidal and balanced [58]. This state generally results from the high level of harmonic current and / or the imbalance of the currents flowing in the lines due in particular to the disturbing single-phase loads connected on the three-phase network such as battery chargers for electric cars and renewable energy sources [59].

The work in [60] shows that the disturbances on the voltages could exceed the limits fixed by the norms in case of progression of use of the nonlinear loads.

The voltages on the electrical network can be qualified in this way:

- ❖ balanced in amplitude
- ❖ imbalanced amplitude
- ❖ balanced but disturbed by the presence of harmonics
- ❖ Unbalanced and disturbed by the presence of harmonics.

Still, the main objective of active compensation on the network (reactive energy and harmonics) is to have:

- ❖ A three-phase system balanced at the source.
- ❖ A unity power factor.
- ❖ A zero side neutral current of the source when connected.

The harmonic extraction method must meet the filter criteria already mentioned regardless of the state of the voltages. These criteria are strongly related to the requirements of power quality standards on networks. As a result, the filters should be able to correct a wide variety of power quality problems like:

- ❖ Harmonic distortion of currents (presence of nonlinear charges).
- ❖ The deterioration of the power factor (absorption of the reagent).
- ❖ The presence of an inverse component (current imbalance).
- ❖ The presence of a homopolar component (current in the neutral).
- ❖ Flicker effect (presence of a small ripple in the voltage).

In this chapter we will review the methods of extraction of harmonics and then examine more closely the methods based on the instantaneous power.

We begin the chapter by a state of the art on the principles of active compensation as well as on the evolution of the structures of the compensation systems to arrive at the current structure of the active filters.

III.2 Compensation Reactive and Harmonic: State of The Art

III.2.1 Brief history.

In 1902, invented by Peter Cooper Hewitt, the mercury vapour diodes used to rectify a voltage or alternating current (AC) in direct current (DC). They have been used for the control of electric motors of locomotives and trams, for radios and for the transmission of electricity to direct current. These converters lasted until the emergence of power semiconductors in the 1970s.

From the 1930s studies on the disturbing effects of these rectifiers on network currents and their possible effects on voltages were made by [61], other larger studies have been reported in the literature by the witness [62]. The effects of harmonic currents on communication networks are studied in [63]. A deepening on the harmful effects of the harmonics always related to these systems has generated a series of research works studied by [64], [65] and by [66] and are referenced by [67].

III.2.2 Compensation structures based on Thyristors.

During this era of high industrialization activity with a strong need to compensate Reactive power, generated by asynchronous machines, arc furnaces and converters based drives, to regulate and stabilize transmission lines and limit voltage drops.

Thyristor-based prototypes allowed moving from static compensation by capacitors and coils to controllable clearing systems known by thyristor reactive compensators or VAR compensators [68].

The goal was the correction of the power factor whose fundamental component of the current was involved.

Subsequently, significant progress has been made on power electronics components by switching larger and larger powers with higher and higher frequencies, and thus the first system based on

Thyristors for reagent compensation was installed in 1978 at Hydro Quebec's Rimouski substation in Canada. The system consisted of a fixed capacitor of 85 MVAR and a controlled inductance of 120 MVAR and this to regulate the voltage of 230 KV on a transmission line [69].

The first active filter harmonic principles by semiconductor converters have been proposed by [70], [71] followed by the work of [72] and [73]. These filters have been developed to eliminate harmonics generated by the converters used in high-voltage direct current transmission systems (HVDC). However, these active filters could not be realized in real systems because high-power, high-frequency devices were unavailable, but the evolution of the components of powers allied to progress on sensor voltages and currents made that in 1982, the first 800kVA APF, consisting of a PWM current inverter and GTO thyristors, has been installed for harmonic compensation [74].

The first devices only compensated for harmonic current disturbances. However, active filters have evolved and prototypes with more features appeared. Modern active filters, in addition to compensating and damping harmonic currents, compensate for current imbalances, control reactive power and flicker. Later, many PWM controlled power inverters were developed for active filtering applications [74].

As a result, parallel active filters began to be marketed and installed throughout the world and especially in Japan, where in 1996 there were more than five hundred parallel active filters installed with powers ranging from 50kVA to 2MVA [75].

Currently and with the availability, at reasonable prices, of digital signal processors, FPGAs as well as Hall Effect current and voltage sensors, modern filters perform better than first generations, they are lighter and less expensive and are very flexible and adapt to several functions and applications [76].

III.2.3 Control Algorithm in the Frequency Domain.

The first work on the active filters studied the compensation characteristics only in the case of steady states and a fixed harmonic spectrum. The algorithm for calculating harmonic currents was done in the frequency domain by the symmetrical components as proposed in [72].

However, in the case of transient conditions such as those caused by fluctuating loads, or the frequency / speed variation of asynchronous machines the design of the compensation circuits has become more difficult. The FFT or the DFT first require a static operating regime and a fixed period for the study. However, during transients, the periods are no longer identical, the regime is not stable, and the extraction of information by the Fourier method is no longer accurate [77].

The problems encountered during transients [72] give rise to the need to define the instantaneous reactive power which has was established in 1983 (in Japanese) and internationally known after its publication by [78] which is only the theory of Instant Reactive Power known by the Akagi theory or the p-q method. It took into account the compensation during the transient through instant reactive power. This induces that the power factor remains unitary, according to the study, even during the transient.

The IRP theory (P Q method) has been considered as the basis for time domain harmonic extraction methods for reactive power and harmonic compensation by means of active filtering on 3-wire balanced 3-phase networks. This method compensates the instantaneous reactive power without altering the instantaneous active power P (t). The active currents resulting from the compensation are then expressed as a function of the instantaneous magnitudes of the active power and the voltages as in (3.1).

$$i_{\alpha p}(t) = \frac{p(t)}{v_\alpha^2+v_\beta^2} v_\alpha(t) \; ; \; i_{\beta p}(t) = \frac{p(t)}{v_\alpha^2+v_\beta^2} v_\beta(t) \tag{III.1}$$

Two years later, another work [79] proposes the compensation of the undulations of the instantaneous active power expressed by $\tilde{p}$ in (III.2), $\bar{p}$ is the continuous share of the power $p(t)$.

$$p(t) = \tilde{p} + \bar{p} \tag{III.2}$$

The authors discuss in the same work the consequences of this consideration on the filtered current as a function of the frequency of the ripple of the power $\tilde{p}$. It is said, then, that if the frequency of the undulations is greater than twice the frequency of the fundamental, a harmonic 3 appears in the line current without being present in the current of the load. Inter-harmonics also appear for other frequencies of the corrugations.

During the compensation of $\tilde{p}$, the line currents provided after compensation are then expressed as a function of the average value (P) of the active power and the instantaneous magnitudes of the voltages. (III.3).

$$i_{\alpha p}(t) = \frac{P}{v_\alpha^2+v_\beta^2} v_\alpha(t)\ ;\ i_{\beta p}(t) = \frac{P}{v_\alpha^2+v_\beta^2} v_\beta(t) \quad \text{(III.3)}$$

In this formulation, the choice of the high pass filter to extract the undulations is essential in the control strategy and the compensation of $\tilde{p}$ imposes constraints on the DC bus capacitor. Details on this aspect are provided in [80].

Since the p-q theory, several studies and critiques have been undertaken on these two formulations, [81] considered that there is not a physical sense to the definition of the reactive power in IRP and proposed another concept for the reactive power.

Another work based on the definition of powers in the reference α, β defined two other quantities related to the inverse component beside the active and reactive powers for the control of thyristor compensators [82].

In the work [83], the authors show that the inverse and direct components are taken into account in the definition of powers according to the p q theory and this has been demonstrated by the analogy of the powers between the results obtained by the symmetrical components and the p q.

Other work focused directly on the definition of active and reactive currents without going through the transformation in the orthogonal coordinate system as the work of [84] which showed the analogy between the active current in (III.1) expressed in the reference α, β and that which it defines directly in the reference a, b, c (III.4) whose index (i) refers to the phases a, b, c.

$$i_{a,i}(t) = \frac{p(t)}{v_a^2+v_b^2+v_c^2}\ v_i(t) \quad \text{(III.4)}$$

Until then, the methods concerned 3-wire networks, but since the 1990s, studies on the effect of harmonics on the neutral current were multiplying [85], [86], [87], [88] accompanied growing interest in compensation on 4-wire networks. In addition, during this period, the research focused on unbalanced voltage networks and as the IRP theory was not made for, then several methods were developed afterwards for three-phase 4-wire systems to try to balance the currents in the presence of an imbalance of the tensions, that it is by means of the powers or directly from the decomposition of the currents. A compensation method called the UPF (Unit Power Factor) [89] allows having a current that has the same form of voltage to have a unit power factor mail it is obvious that if the voltage is disturbed, the current follows. In [90] a new definition of active and reactive currents, named i_p and i_q is established and shows the similarity between the powers defined by this new method and the p-q theory. The work of [91] leads to the theory of generalized instantaneous power also known by the "Cross Vectors" theory for 3-phase and 4-wire systems. The homopolar components in voltage and current are taken into account in this theory.

The authors show, for a case balanced in tension and unbalanced in current, that the homopolar component of the current is eliminated by this method and that the p-q method cannot treat the studied example since it is based for the systems of 3-wire.

As a replica of this study and in [92] the authors extend the p q method for a 4-wire system by introducing the known formulation by the pseudo mapping-matrix and show that the p q with the pseudo mapping-matrix makes it possible to eliminate the current in the neutral of the source if the voltages are even unbalanced. Then another work of [93] resumes the work on an unbalanced network and shows that the generalized theory does not allow the cancellation of the homopolar component if the tensions are unbalanced. Then a comparison work in [94] between the original p q theory, extended to a 4-wire application, and **Peng's theory**, which has been assigned for this work the modified name of p q, shows that the current required for the compensation of the zero-sequence component is not equal to the neutral of the load so that the neutral current of the load cannot be compensated when the voltages are unbalanced.

Then p-q-r theory in [95] and [96] was presented as a candidate for the compensation of neutral current in balanced and unbalanced diet. It offers two types of compensation, either through the powers either by currents. It has performed better than the p q, p q mapping-matrix and modified p q at the current balance and neutral current compensation but does not achieve the performance required by standards and its algorithm is complex because it is necessary to perform a double transformation of the reference a, b, c to the mark α, β, 0 and then to the mark p, q, r in order to determine the reference currents and redo the opposite way to establish the reference currents in the initial reference. The active current resulting from the compensation, in the reference p, q, r is formulated in (III.5).

$$i_{pdc}(t) = \bar{\imath}_p = \frac{P}{\sqrt{v_0^2+v_\alpha^2+v_\beta^2}} \tag{III.5}$$

All the methods (p q, modified p q, pseudo mapping-matrix and p q r) are based on the power compensation and they have the same performances for the case of voltage balanced systems but have different performances in the case of disturbed and / or unbalanced voltages

[97], [98], [99]. In addition, none of these methods can balance the currents when the voltages are unbalanced and disturbed and all cannot correctly cancel the current in the neutral [100].

Finally, and with regard to methods based on instantaneous quantities, the IRP method has remained an attractive and most used method for the first active filters, especially in Japan [76], and the discussions around this notion continue to generate research work [101], [97], [102] and [103] despite its inability to obtain a sinusoidal current system in the event of voltage unbalances.

III.2.4 Control algorithms based on the average value of the active power and the RMS values of the voltages.

The evolution of compensation methods was not isolated from the research that studied the formulation of active and reactive currents used to quantify the components of the current to be supplied by the source in the case of disturbed and unbalanced voltages.

The problem with electrical powers, before the compensation problem, lies in the definition and measurement of reactive energy whether static or transient.

Indeed, the reactive power was defined in static mode by **Budeanu (1927)** by:

$$Q = \sum_n U_n \,.\, I_n . \sin\varphi_n \tag{III.6}$$

Where

$$Q = \sqrt{S^2 - P^2} \tag{III.7}$$

In addition, in the case of non-sinusoidal regime it introduces the deforming power

$$D = \sqrt{S^2 - P^2 - Q^2} \tag{III.8}$$

Despite the objections, reported in [104], of **Fryze** (1932), which argued for breaking down Fourrier's voltage and current in series before defining power, and the objections of **Shepherd** and **Zakikhani** (1972) who considered that it there is no sense to this definition and suggested that another amount be chosen for reactive energy, **Budeanu's** concept remained the most used until the need to define instant reactive power became ubiquitous in research work for the compensation.

Based on the works of Fryze [in [105], the original being in Polish [106]] for the definition of the active current in single-phase by:

$$i_a(t) = \frac{P}{V^2} . v_a(t) \tag{III.9}$$

Where **V** is the effective value of voltage and **P** is the average active power, research work was aimed at extending this concept into three-phase.

Similarities in the definition of the three-phase active current are obtained in the work of [107], [108] and [105] which is finally formalized as a function of the average active power and the effective values of the voltages, but the definitions of apparent or reactive powers were not the same in the different works.

In [107] the reactive power is therefore formulated by:

$$Q = \sqrt{\sum_i V_i^2 . \sum_i i_{ir}^2} \tag{III.10}$$

Where i_{ir} is the reactive component of the current with (i) as an index for phases a, b, c.

And

$$S = \sqrt{\sum_i V_i^2 . \sum_i i_i^2} \tag{III.11}$$

Where i_i is the rms value of the current.

In [108], the authors introduce the concept of reactive currents with capacitive and reactive components and a residual part. The International Electro Technical Commission (IEC) has validated the latter model but the design of a measuring circuit is very complicated to achieve [105].

However, in the work of [105], the current of the load under disturbed and unbalanced voltages is decomposed into five currents whose active part is formulated as a function of the active power and the effective values of the voltages by (III.12). This decomposition is named by the author **CPC** theory (Current's Physical Components).

$$i_{a,i}(t) = \frac{P}{V_a^2 + V_b^2 + V_c^2} v_i(t) \tag{III.12}$$

The sum $(V_a^2 + V_b^2 + V_c^2)$ is supposed to represent the effective value (squared) of a three-phase system of voltages and this model was intended for unbalanced voltage systems.

The calculation of this sum is based on the mathematical formalism such that for a magnitude $y(t)$ (current or tension) its effective value is expressed by:

$$Y = \sqrt{\frac{1}{T}\int_0^T y(t).y^*(t)dt} \tag{III.12-a}$$

$y^*(t)$ Is the conjugate of $y(t)$.

However, the work of [109], which led a study based on the decomposition of the “Park vector” of voltages, and currents found the analogy between the effective value (squared) of the three-phase system $(V_a^2 + V_b^2 + V_c^2)$ according to the Park vector and the Czarneki formulation provided that the homopolar component of tension is zero. Moreover, in the opposite case, if the voltages are unbalanced, the magnitude $(V_a^2 + V_b^2 + V_c^2)$ no longer represents the effective value (squared) of the three-phase system and the formulation of the active current in (III.5) will be erroneous. In addition, this approach does not allow the elimination of neutral current in case of voltage imbalance.

Other approaches like FBD (**Fryze-Bucholz-Depenbrock**) in [110] which models an electrical circuit by "branches" each of which represents a source of voltage, a source of current and a conductance. The equivalent electrical diagram makes it possible to separate the currents (active, reactive, harmonic) or the voltages whose powers will thus be separated from each other. The equivalent active conductance, according to the method, is not instantaneous; it requires a period of operation to have average values. The active current resulting from this method is similar to that obtained in (III.12).

However, in the work of [111] the authors propose to separate the homopolar component of the voltage by writing:

$$u(t) = v(t) - v_0(t) \tag{III.13}$$

And the active currents become:

$$i_{a,i}(t) = \frac{P}{U_a^2+U_b^2+U_c^2} u_i(t) \tag{III.14}$$

With U, the effective value of the tensions without the homopolar component $v_0(t)$.

A comparison between the two approaches (formulation with and without homopolar component) in [112] leads to the conclusion that the neutral current will be eliminated according to the second approach.

This work is reinforced by [113] whose authors apply this concept to the active currents formulated as a function of the so-called Time-Average Compensation **(TAC)** values and also on the active currents formulated according to the instantaneous magnitudes of the voltages (Time- Instantaneous Compensation / **ICT**). The comparison between TIC and TAC shows that, only TAC compensation eliminates the neutral current and the concept of [112] in the case of an unbalanced network.

But for the networks disturbed by the harmonics, these methods, as they are formulated according to the effective values of the tensions do not allow to have a balanced system in currents and to remedy this problem, the authors of [108] propose a formulation based on the previous concept but using the direct system of fundamental voltages in the case of perturbed and unbalanced voltage system. The formulation of the active currents follows from it (III.15).

$$i_{a,i}(t) = \frac{P}{V_{fa}^2+V_{fb}^2+V_{fc}^2} v_{fi}^{+}(t) \qquad \text{(III.15)}$$

The authors justify the choice to consider only the direct component by the fact that the network voltages are, in general, slightly unbalanced and the small existing imbalance is rather of a direct nature. Nevertheless, this is only a special case and this amounts to saying that the system is not disturbed and the method requires a PLL. However, the use of a PLL for the extraction of the direct system from the voltages does not allow having the true values of the existing tensions, which induces system instability when the frequency of the system varies [96].

Research on definitions of active components and instantaneous reactants of the current continue to be a subject of scientific topicality or the latest publications are very recent [113] and during these last few years, a series of research works for the control of the active filters Parallels by an algorithm resulting from the i_p i_q method make emergence. Initiated by [90] and taken up by [114], the method i_p i_q derives from the p-q method and applies to single-phase and three-phase [115], [116], [117], [118] and [119]. In [120] a study is made on the compensation based on the ip method, which shows that the active power extracted by the method lacks information in case of imbalance and disturbance of the tensions. While the reference currents are affected and, consequently, the performance of active filtering.

It is useful at the end of this bibliographic review to cite the reference [121] which studies 223 publications and lists all the existing methods, until its date of appearance, for the control of the active filters as well as the control for the structures, single-phase, 3-phase 3-wire, 3-phase 4-wire next to other relevant references in the field.

III.3 Concepts of Harmonic Extraction Methods Based On Instantaneous Quantities

III.3.1 Archetype model of active harmonic reduction.

By the time, the harmonic disturbances became obvious on electrical networks; searches were oriented on solutions to these problems in order to reduce the said ***Harmonics***. Therefore, based on A. El Kandil thesis work in 1954, a first method for active reduction of harmonics in the network lines was developed by [67], which were to inject the harmonic 3 in the transformer windings supplying diode rectifiers, thus reducing harmonics in the current of the primary winding. This method applied only to a family of converters.

Then another concept for active compensation of harmonics was introduced in the early 70's by [66]

which was to compensate for the magnetic flux in the transformer that supplies a nonlinear load by injecting the existing harmonics into the secondary winding via a third winding disposed on the same magnetic core and this to cancel the harmonics in the magnetic circuit.

The Harmonic currents are deducted from the current disturbed after isolation of the fundamental component by a resonant filter, and these harmonic currents are amplified and injected in the third winding. The complexity of implementation has hindered the principle.

Next, another principle appeared [122] in the application on the converters, AC-DC powered by transformers, which takes into account all the harmonics in the secondary of the transformer and consists in injecting currents at given frequencies to have a signal sinusoidal at the primary of the transformer. This method was not based on the measurement and extraction of harmonics but rather on the prior knowledge of the harmonic content of the signal (usually a square signal at the input of converter whose development in series Fourrier is easy). The current sources are connected in parallel with each winding of the transformer and the authors propose as current sources, among others, the synchronous machines.

It should be noted that the injection of harmonic currents was not made previously by static converters and the method was part solution as defined in the frequency domain.

III.3.2 Introduction

Our work is based on compensation methods in the presence of a disturbed network and unbalanced voltage. We will therefore study three known methods in the literature, whose reference reactive currents are extracted from the calculated powers in the electrical circuit.

We will briefly present the concept of each method and then we will develop their harmonic extraction algorithms for the parallel active filter.

III.3.3 Concept of the original p-q method

III.3.3.1 Application on a balanced 3-wire network

The original p-q is defined according to a transformation of the electrical quantities of the reference a, b, c to the orthogonal reference α, β.

This method is based on a concept that defines in the electrical circuit beside the instantaneous active power $p(t)$ another instantaneous reactive power $q(t)$, which is the originality of the method.

However, to eliminate the reactive power simply compensate $q(t)$ without any action on the active power $p(t)$ as in equation (III.11) above. This is the compensation of the instantaneous reactive power.

In this case, the voltages $v_{\alpha}(t), v_{\beta}(t)$ are sinusoidal and in quadrature because the voltages are balanced, which induces that the sum of the quantities $v_{\alpha}^{2}(t) + v_{\beta}^{2}(t)$ is constant. On the other hand, the power $p(t)$ contains ripples $\tilde{p}$ related to the current harmonics and which appear in the active lines currents in (III.11) after the compensation. Existing frequencies in $\tilde{p}$ are different from the frequencies in the load which are the purpose of the compensation, so line currents are not purely sinusoidal [79]. In return, the compensation is done without the need for an energy storage component and no instantaneous active power flows in the filter. This gives$p_f(t) = 0$.

To attenuate the ripples of the power, it is then possible to compensate for them and make the power in the source constant [79] as in (III.13). In this case, the line currents are sinusoidal. On the other hand, the instantaneous active power in the filter $p_f(t) = \tilde{p}$ is no longer zero but its average value is zero [113]. As a result, compensation requires larger capacitor.

III.3.4 Concept of the modified p-q method

Designed for the 4-wire system, this second method is based on another concept of power in electrical circuits, so three reactive powers and one active power are defined. The active power is formulated as in the 4-wire p q and the reactive powers are linearly dependent so it is not possible to compensate the reactive of each phase separately from the others, on the contrary it would be necessary to compensate the reactive of the system and this requires that for a successful compensation it is necessary to have three identical loads on the phases.

III.4 Control Algorithms from Instantaneous Quantity Based Methods

III.4.1 Theory of instantaneous power. P-q Method Application on a balanced 3-wire network

A balanced three-phase system of voltages $v_a(t), v_b(t), v_c(t)$ and currents $i_a(t), i_b(t), i_c(t)$ is expressed by:

$$v_a(t) + v_b(t) + v_c(t) = 0 \quad \text{(III.16)}$$

$$i_a(t) + i_b(t) + i_c(t) = 0 \quad \text{(III.17)}$$

The transformations in the orthogonal coordinate system α, β of the currents and voltages of a balanced three-phase system without neutral are:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = C_{23} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad \text{(III.18)}$$

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = C_{23} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad \text{(III.19)}$$

With C_{23} the Concordia matrix:

$$C_{23} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \quad \text{(III.20)}$$

The instantaneous active power $p(t)$ is given by the scalar product of the electrical quantities in the same axis while the instantaneous reactive power $q(t)$ is defined by the vector product of the quantities in two different axes. It is considered to circulate between axes α, β.

Equality should exist between the powers in the two landmarks. We write:

$$p(t) = p_{\alpha\beta} = v_\alpha . i_\alpha + v_\beta . i_\beta = v_a . i_a + v_b . i_b + v_c . i_c \quad \text{(III.21)}$$

$$q(t) = q_{\alpha\beta} = v_\alpha . i_\beta - v_\beta . i_\alpha \quad \text{(III.22)}$$

These relationships can be written in matrix form by:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad \text{(III.23)}$$

Each power consists of a continuous image portion of the fundamental power of an alternating image portion of the power related to the undulations (III.24).

$$\begin{cases} p(t) = \bar{p} + \tilde{p} \\ q(t) = \bar{q} + \tilde{q} \end{cases} \tag{III.24}$$

However, the undulations of the powers represent in turn the power of the inverse component at the frequency 2ω $(p_{2\omega}, q_{2\omega})$ image of the imbalance of the currents of the charge and the harmonic power (p_h, q_h) image of the harmonics of the charging currents [123], [124], are expressed by (III.25).

$$\begin{cases} \tilde{p}(t) = p_{2\omega} + p_h \\ \tilde{q}(t) = q_{2\omega} + q_h \end{cases} \tag{III.25}$$

The diagram showing the exchange of energies in the reference α, β is in Figure (III.1). The source provides the average active power $\bar{p}_{\alpha\beta}$, the ripples of this power $\tilde{p}_{\alpha\beta}$ are exchanged between the source and the load and the reactive power $\bar{q}_{\alpha\beta} + \tilde{q}_{\alpha\beta}$ flows between the phases α, β.

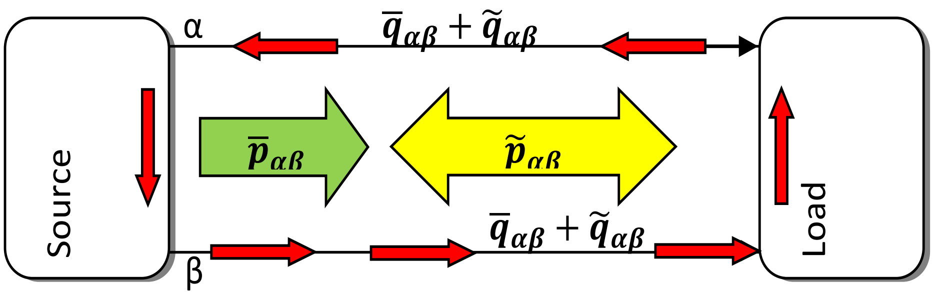


Figure III.1 Energy exchange for a 3-wire network

The ripples of the power are extracted by a high pass filter HPF given according to the criterion (HPF = 1-LPF). Where LPS is a low pass filter. Figure III.2 shows the means for extracting the DC and AC component for a quantity x (t) which can be the active $p(t)$ or reactive power $q(t)$.

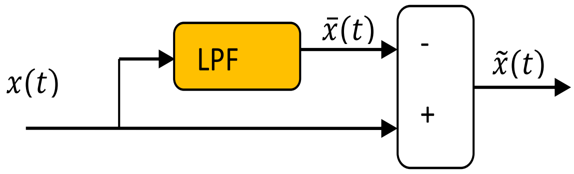


Figure III.2 High Pass Filter (HPF) obtained from Low Pass Filter (LPF)

Fourth or fifth order power filters have been proposed [125]. In our study, we chose a second-order low-pass filter to simplify the digital implementation approach of the latter. Indeed, a higher order would lead to longer computation times, which can be detrimental in our study. The following relationship gives the general expression of a second order low pass filter:

$$\frac{\omega_0^2}{S^2+2\delta\omega_0 S+\omega_0^2} \tag{III.26}$$

The cut-off frequency is chosen so that the power filter can block any disturbing component of the instantaneous powers. It must also allow the passage of the continuous components representing the active and reactive powers at the fundamental frequency. This frequency is therefore chosen according to the type of load that is:

- 60 Hz for balanced load current with a filter response time of 20 ms.
- 20 Hz for an unbalanced load current with a filter response time of 60 ms.

III.4.1.1 Calculation of interference currents

The reference currents are expressed starting from (III.23) according to the powers to compensate p_c, q_c as in (3.27):

$$\begin{bmatrix} i_{r\alpha} \\ i_{r\beta} \end{bmatrix} = \frac{1}{v_\alpha^2+v_\beta^2}\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} p_c \\ q_c \end{bmatrix} \tag{III.27}$$

The compensation powers are chosen according to the purpose of the compensation.

1. **Case 1**: If the objective is to compensate the instant reactive power then all the reactive power of the load is to compensate without altering the active power. This is explained by:

$$\begin{cases} p_c(t) = 0 \\ q_c(t) = \bar{q} + \tilde{q} \end{cases} \tag{III.28}$$

In this case, the ripples of the active power persist in the line currents, which will subsequently be unbalanced at frequency 2ω and contain the frequencies of p_h . The power absorbed by the source is then $p(t)$ and the filter does not provide any active component related to the compensation. This is called compensation without an energy storage element (for the moment losses in the filter are not taken into account).

The reference currents are in these conditions:

$$\begin{bmatrix} i_{r\alpha} \\ i_{r\beta} \end{bmatrix} = \frac{1}{v_\alpha^2+v_\beta^2}\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} 0 \\ \tilde{q}+\bar{q} \end{bmatrix} \tag{III.29}$$

Once the reference currents in the reference α, β are calculated, the inverse transformation of the Clark / Concordia matrix gives the reference currents in the reference a, b, c in (III.30):

$$\begin{bmatrix} i_{ra} \\ i_{rb} \\ i_{rc} \end{bmatrix} = C_{23}^{-1}\begin{bmatrix} i_{r\alpha} \\ i_{r\beta} \end{bmatrix} \tag{III.30}$$

With C_{23}^{-1} the inverse matrix of the matrix C_{23} given in (III.31):

$$C_{23}^{-1} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \tag{III.31}$$

As this compensation is done by the active filter composed of power switches which produce losses during operation, then it is necessary to take into account the power which will be absorbed by the filter p_f and which is necessary for the voltage regulation of the capacitor of the DC bus when it discharges to provide active power relative to the losses of the converter. For the compensation of the instantaneous power, the reference currents will be under these conditions:

$$\begin{bmatrix} i_{r\alpha} \\ i_{r\beta} \end{bmatrix} = \frac{1}{v_\alpha^2+v_\beta^2}\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} -p_f \\ \tilde{q}+\bar{q} \end{bmatrix} \tag{III.32}$$

The p_f are assigned a minus sign to say that they are absorbed at the moment when the filter injects the reactive power (the signs can be reversed according to the convention of the current chosen for the filter). In our writing for compensation quantities, the “generator” convention is chosen.

The reference currents extraction diagram for instantaneous reactive power compensation is shown schematically in Figure III.3.

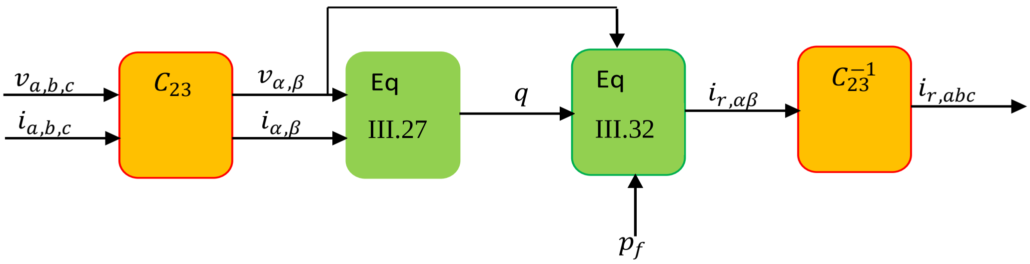


Figure III.3 Diagram for extracting reference currents for the p-q 3-wire method when compensation for instantaneous reactive power

❖ Case 2: If the objective is to compensate harmonics and reactive, then it would be necessary to compensate the undulations $\tilde{p}$ of the active power next to all the reactive power. Therefore:

$$\begin{cases} p_c(t) = \tilde{p} \\ q_c(t) = \bar{q} + \tilde{q} \end{cases} \tag{III.33}$$

The active power supplied by the source is then the average value $\bar{p}$ of the active power and the filter compensates this time the ripple of the active power. This is called compensation with energy storage element.

Taking into account the losses in the filter, the reference currents expressed by:

$$\begin{bmatrix} i_{r\alpha} \\ i_{r\beta} \end{bmatrix} = \frac{1}{v_\alpha^2+v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} - p_f \\ \tilde{q} + \bar{q} \end{bmatrix} \tag{III.34}$$

The reference current extraction diagram for the average compensation is shown schematically in Figure III.4

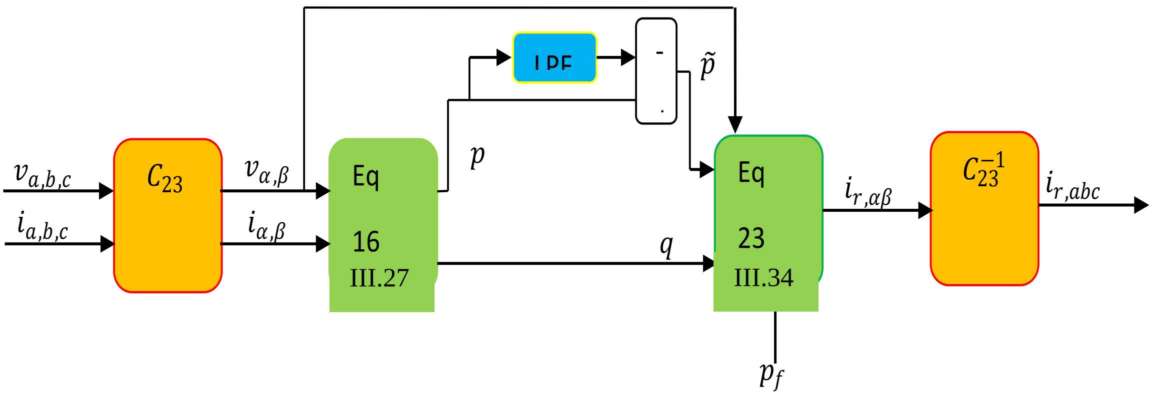


Figure III.4 Diagram for extracting reference currents for the 3-wire p-q method when compensation for reactive power and harmonics

III.4.1.2 Frequency analysis of instantaneous powers

We carry out this analysis using the example of a three-phase rectifier bridge (Graetz bridge). This analysis will then allow, on the one hand, to define the dynamics of the power filter responsible for isolating conventional active and reactive powers and, on the other hand, to know the limit of the applications of this identification method.

The current i_c consumed by this rectifier bridge can be broken down into Fourier series, as described in the following equation:

$$i_c\,(t) = \sqrt{2}I_1(\sin\omega t - \tfrac{1}{5}\sin 5\omega t - \tfrac{1}{7}\sin 7\omega t + \tfrac{1}{11}\sin 11\omega t + \dots\dots) \qquad \text{(III.35)}$$

With: I_1: the effective value of the fundamental current.

We note that the harmonic currents are of rank $(6K \pm 1)$ (K = 1, 2, 3,.... $etc.$) and that the effective value of each harmonic current $I_h = \frac{I_1}{h}$ is inversely proportional to the corresponding rank.

III.4.1.3 Balanced harmonic current with balanced sinusoidal voltage

The voltage of the electrical network, in this case, is a balanced sinusoidal voltage given by one of the following relationships:

$$V_{s1} = \sqrt{2}\,V\sin\omega t \qquad \text{(III.36)}$$

$$V_{s2} = \sqrt{2}\,V\sin(\omega t - 2\tfrac{\pi}{3}) \qquad \text{(III.37)}$$

$$V_{s3} = \sqrt{2}\, V \sin(\omega t + 2\frac{\pi}{3}) \qquad \text{(III.38)}$$

By doing the transformation α - β for the current of the polluting load, we obtain the following currents and voltages:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{3} I_1 \left(\begin{bmatrix} \sin \omega t \\ -\cos \omega t \end{bmatrix} - \frac{1}{5} \begin{bmatrix} \sin 5\omega t \\ -\cos 5\omega t \end{bmatrix} - \frac{1}{7} \begin{bmatrix} \sin 7\omega t \\ -\cos 7\omega t \end{bmatrix} + \cdots \right) \qquad \text{(III.39)}$$

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{3} V_s \begin{bmatrix} \sin \omega t \\ -\cos \omega t \end{bmatrix} \qquad \text{(III.40)}$$

So, the real power can be calculated as follows:

$$p_s(t) = v_\alpha i_\alpha + v_\beta i_\beta \qquad \text{(III.41)}$$

$$p_s(t) = 3VI_1 + \frac{3VI_1}{5} \cos 6\omega t - \frac{3VI_1}{7} \cos 6\omega t - \cdots \qquad \text{(III.42)}$$

The first (continuous) term in this relationship represents conventional active power, while the other terms represent the alternating power caused by disturbing currents (harmonic in this case).

Note that the network studied is composed of three wires which prevent the homo-polar components from flowing there.

III.4.2 PLL (Phase Locked Loop)

III.4.2.1 Classic PLL

Indeed, as we have shown previously, the network voltage must be healthy (sinusoidal and balanced), otherwise the instantaneous power method is not applicable. Since the network voltage is often disturbed and / or distorted, and in order to generalize the application of the identification method that we have adopted to any type of voltage, the PLL-based system is proposed to extract the direct fundamental component of the network voltage [126].

The principle of the PLL is based on the use of a simple PI regulator. Its functioning is based on the transformation of Park in the frame d-q.

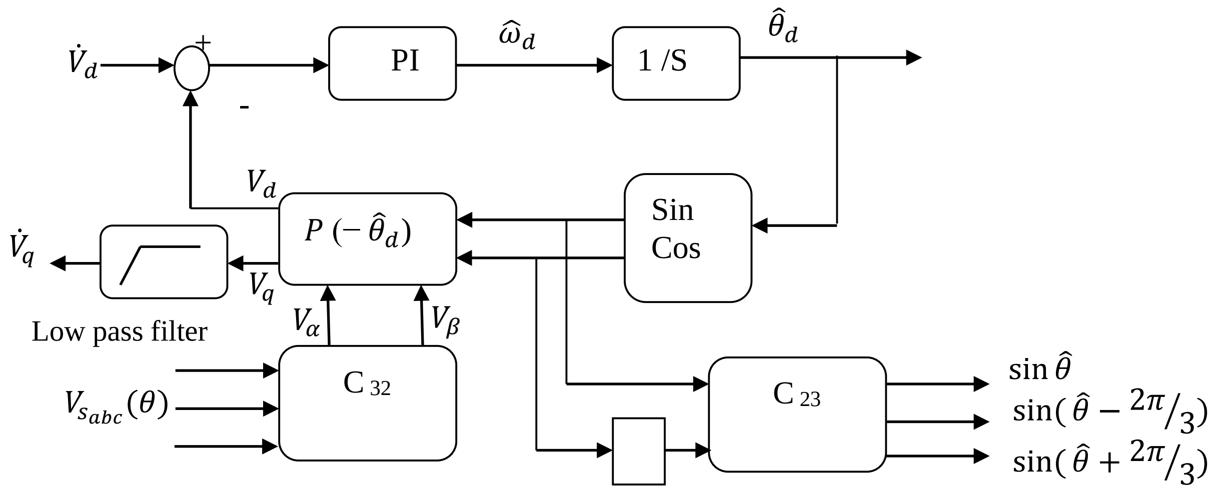


Figure III.5 Classic PLL scheme

From Figure III.5, the voltages $V_{s\_abc}(\theta)$, measured at the connection point of the parallel active filter, initially undergo the transformation of Concordia (α-β). The tensions thus obtained are expressed in the reference mark of Park by a rotation $P\,(-\,\hat{\theta}_d)$. The angle of this rotation, resulting from the integration of the pulsation estimate $\widehat{\omega}_d$ is determined by the PI regulator. The PLL will be locked when the estimated angle $\hat{\theta}_d$ is equal to $\hat{\theta}$

The PLL will be locked when the estimated angle $\hat{\theta}_d$will be equal to $\hat{\theta}$.

The simple voltages measured at the connection point in the α-β coordinate system are given by the following equation:

$$\begin{bmatrix} V_\alpha(\theta) \\ V_\beta(\theta) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \tag{III.43}$$

Then by applying the Park transform (d, q) with an angle of rotation $\hat{\theta}_d$ given by:

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \begin{bmatrix} \cos\hat{\theta} & \sin\hat{\theta} \\ -\sin\hat{\theta} & \cos\hat{\theta} \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{III.44}$$

We then obtain the following relation:

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \sqrt{3}V_m \begin{bmatrix} \sin(\theta - \hat{\theta}) \\ -\cos(\theta - \hat{\theta}) \end{bmatrix} \approx \sqrt{3}V_m \begin{bmatrix} \sin\Delta\theta \\ -\cos\Delta\theta \end{bmatrix} \tag{III.45}$$

Where V_m is the RMS value of the network voltage.

The PLL will be locked when the estimated angle $\hat{\theta}$ is equal to the angle θ of the network, which implies that $\Delta\theta$ = 0, we can thus write:

$$\begin{cases} V_{sd} = 0 \\ V_{sq} = -\sqrt{3}V_m \end{cases} \tag{III.46}$$

III.4.2.2 Modified PLL

To improve the performance of the classic PLL, a HSF (High Selective Filter) has been implemented. The role of the HSF is to extract the fundamental component of the voltage or current directly, without any phase shift or change in amplitude. The role of the HSF is to extract the fundamental component of the voltage or current directly, without any phase shift or change in amplitude.

The transfer function of the HSF filter can be expressed by the following equation (III.47) [127][128]:

$$\mathrm{H(s)} = \frac{\hat{x}_{\alpha\beta}(s)}{x_{\alpha\beta}} = k\frac{(s+k)+j\omega_c}{(s+k)^2+\omega_c^2} \tag{III.47}$$

From equation (III.47) we can write:

$$\mathrm{H(s)} = \frac{\hat{v}_{s\alpha\beta}(s)}{v_{s\alpha\beta}(s)} = \frac{\hat{v}_{s\alpha}(s)+j\hat{v}_{s\beta}(s)}{v_{s\alpha}(s)+jv_{s\beta}(s)} = k\frac{(s+k)+j\omega_c}{(s+k)^2+\omega_c^2} \tag{III.48}$$

Hence, the writing of the complex term of the filtered signals:

$$\hat{v}_{s\alpha}(s) + j\hat{v}_{s\beta}(s) = \frac{(v_{s\alpha}(s)+jv_{s\beta}(s))*k((s+k)+j\omega_c)}{(s+k)^2+\omega_c^2} \tag{III.49}$$

Real and imaginary parts are written after separation [129]

$$\hat{v}_{s\alpha}(s) = \frac{k(s+k)}{(s+k)^2+\omega_c^2} v_{s\alpha}(s) - \frac{\omega_c k}{(s+k)^2+\omega_c^2} v_{s\beta}(s) \tag{III.50}$$

$$\hat{v}_{s\beta}(s) = \frac{k(s+k)}{(s+k)^2+\omega_c^2} v_{s\beta}(s) - \frac{\omega_c k}{(s+k)^2+\omega_c^2} v_{s\alpha}(s) \tag{III.51}$$

Hence, the final writing of the structural form of the HSF filters is:

$$\hat{v}_{s\alpha}(s) = \frac{k}{s}[v_{s\alpha}(s) - \hat{v}_{s\alpha}(s)] - \frac{\omega_c}{s}\hat{v}_{s\beta}(s) \tag{III.52}$$

$$\hat{v}_{s\beta}(s) = \frac{k}{s}[v_{s\beta}(s) - \hat{v}_{s\beta}(s)] - \frac{\omega_c}{s}\hat{v}_{s\alpha}(s) \tag{III.53}$$

From the above equations, the block diagram of the HSF filter can be drawn as shown in figure III.6

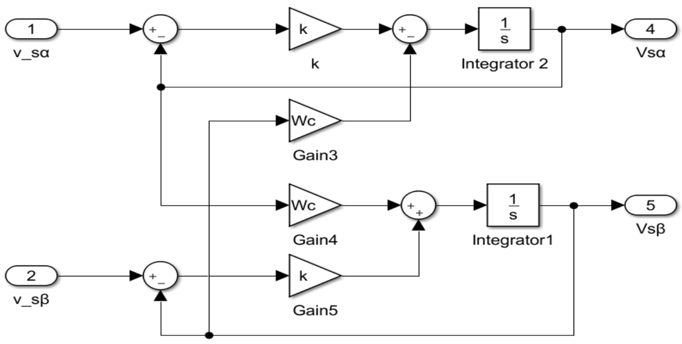


Figure III.6 Modified PLL after the addition of HSF to the classic PLL.

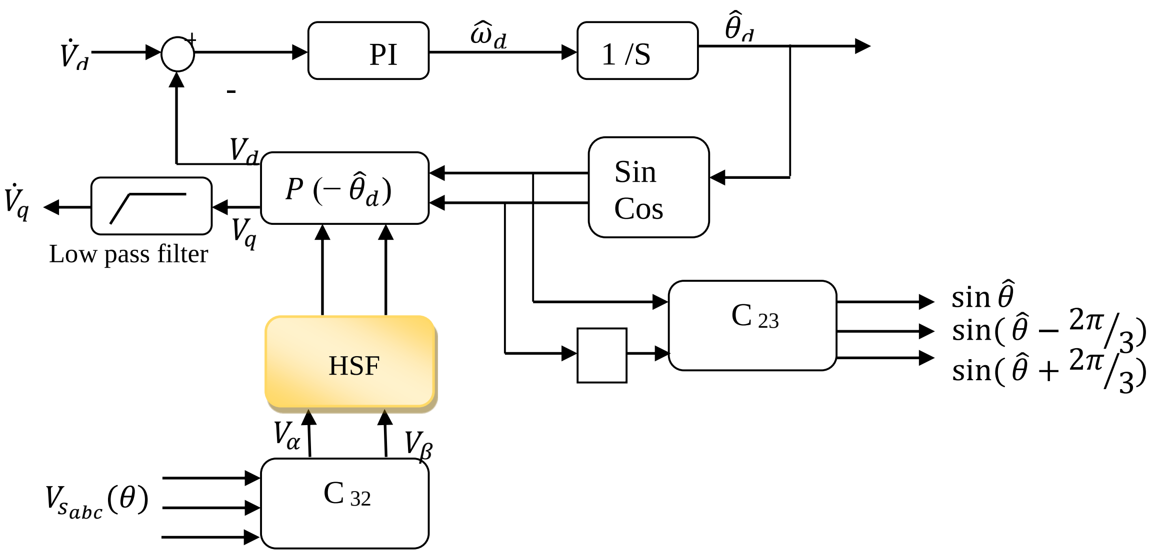


Figure III.7 Modified PLL scheme

III.5 State Of The Art Of The Main Regulators

III.5.1 Proportional-integral regulator (PI)

This type of controller is widely used for controlling linear systems. Its structure is given by the Figure below.

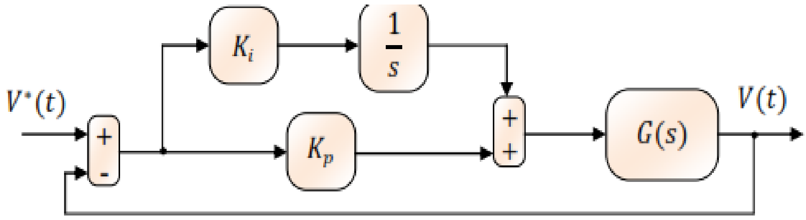


Figure III.8 System including a PI controller.

III.5.1.1 Proportional regulation

The role of the gain K_p is to reduce the adjustment error, which is inversely proportional to this gain. The greater the gain, the smaller the error and the more the response becomes more and more oscillatory.

III.5.1.2 Integral regulation

The main role of the integral action k_i/s is to eliminate the static error. However, the integral action is an element with phase delay; therefore, the increase in the integral action (i.e. decreased k_i) produces instability because it moves the place of Nyquist to the left. The optimal value is chosen to satisfy a stability-speed compromise [130].

III.5.1.3 Determination of the PI regulator parameters

The following relation gives the general expression of the PI regulator used in our study:

$$K(s) = K_p + \frac{K_i}{s} \tag{III.54}$$

With

K_p Proportional gain of the regulator.

K_i Integral gain of the regulator.

Block G (s) is defined by:

$$G(S) = \frac{1}{CS} \tag{III.55}$$

The closed loop transfer function is then given by:

$$F(s) = \frac{\left(1+\frac{K_p}{K_l}S\right)\frac{K_l}{C}}{S^2+\frac{K_p}{C}S+\frac{K_l}{C}} \quad \text{(III.56)}$$

The general expression for a second order transfer function is:

$$F(s) = \frac{\left(1+\frac{K_p}{K_l}S\right)\omega_c^2}{S^2+2\xi_c\omega_c S+\omega_c^2} \quad \text{(III.57)}$$

After identification with equation (III.56), we obtain:

$$K_l = \omega_c^2 C \;\; ; \; K_p = \; 2\xi_c\sqrt{K_l C} \quad \text{(III.58)}$$

III.5.2 Control by status feedback with integrator

The corrector by return of status does not allow the rejection of disturbance (cancellation of the error in steady state). This corrector is modified by adding an integral action to it so as to ensure rejection of disturbance. The control structure by status feedback is defined by the following equations:

$$x_1(k+1) = x_1(k) + \left(\dot{y}(k) - \; y(k)\right) \quad \text{(III.59)}$$

$$u(k) = -kx(k) - k_1 x_1 \quad \text{(III.60)}$$

Where k and k_1 are parameters to be determined. $u(k)$ Is the control law.

A new state variable x_1 is introduced. The variable x1 is determined by:

$$zx_1(k) = x_1(k) + \left(\dot{y}(k) - \; y(k)\right) \quad \text{(III.61)}$$

$$x_1(k) = \frac{\dot{y}(k) - \; y(k)}{z-1} \quad \text{(III.62)}$$

This corrector therefore contains an integrator represented by: $\frac{1}{z-1}$ .The closed loop system can be represented by the following Figure.

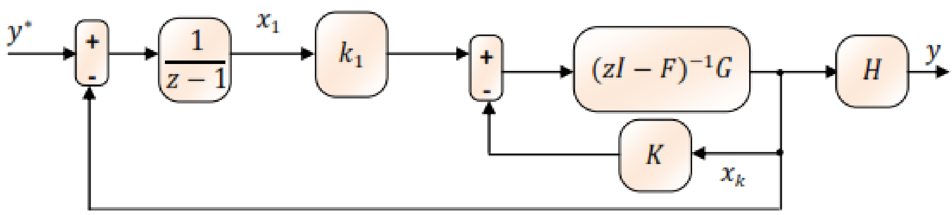


Figure III.9 System including a state feedback controller with integrator

With an appropriate choice by pole placement, the command by status feedback makes it possible to determine the gains k and $k_1$and ensure the rejection of disturbance [130].

III.5.3 Quasi-linear regulator

The general shape of the quasi-linear compensator is given by:

$$G_c(s) = \frac{\prod_{i=0}^{r-1}(s+z_i)}{\prod_{j=0}^{r-1}(s+ak^j)} \tag{III.63}$$

The reason for the introduction of this new concept is to eliminate the performance limitations imposed on the system. It is possible to follow the references under significant disturbances and for unknown system parameters. The answer is not oscillatory for significant gains. The concept of the quasi-linear regulator is explained by its automatic adaptation by the stability of the poles in closed loop [131].

III.5.4 Fuzzy regulator

Fuzzy logic was introduced by **Zadeh in 1987**. It intervenes in the manipulation of imperfect knowledge; it helps to formalize the representation and treatment of imprecise or approximate knowledge. The objective of using the fuzzy regulator is to achieve better results by comparing them to conventional regulators and to bring about a possible improvement in the response of the system (response time and overshoot) [130].

III.5.5 Mamdani fuzzy regulator

Mamdani's method uses an approach based on domain knowledge to develop the rules of inference and the choice of membership functions. Another method allowing these rules to be deduced is based on a priori knowledge of the results obtained with conventional linear regulators [132].

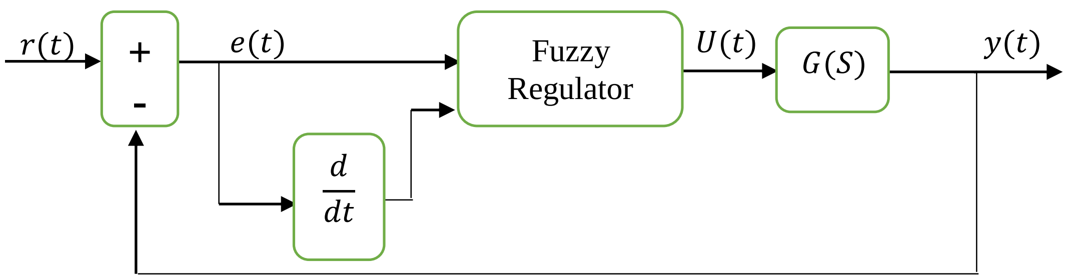


Figure III.10 Integrated fuzzy Mamdani regulator for system control

The fuzzification step consists of defining fuzzy sets for the input and output variables. For each of these variables, we must know a priori its definition interval [133]. The fuzzy regulator receives the error and the variation of the error as input and the control voltage as output. The inference stage is the stage where the fuzzy rules are established which allow the order to be reached according to the values of the error and the variation of the error [134]. These rules can be deduced by the expertise of the person, where can be deduced using results previously acquired with conventional regulators such as proportional-integral (PI), proportional-integral derived (PID).

The defuzzification step consists in obtaining a real value from the surface obtained in the inference step. Several defuzzification methods exist. We can cite **Centroid, Bisector, Mom, Som, lom** [130].

III.5.6 Sugeno-type fuzzy regulator

The Takagi-Sugeno-Khan method was introduced in 1985. It is similar to that of Mamdani in several aspects. The first two parts (inference engine and fuzzification) are exactly the same, the main difference lies in the output of the fuzzy regulator (u command). In Sugeno's method, the output is of linear type or of constant type [135].

III.6 State Of The Art Of The Main Control Techniques

The performance of active or hybrid filters depends very much on:

One hand on several factors:

- ❖ Of the control algorithm used to identify the references of currents or voltages.
- ❖ The control mode used (PWM, hysteresis, modulated hysteresis, ...) for the generation of power switch control orders.
- ❖ Of the performance of the capacitive tank voltage regulation loop.

On the other hand, the performance of the active filter also depends on the technique chosen (analog or digital) during the practical implementation of the control.

Active filtering indeed requires high real-time performance during the implementation of the control, taking into account the frequencies of the harmonics to be generated [136]. Today, research work in the field of control of electrical systems is oriented mainly towards two digital technologies during the implementation of orders: the **dSPACE** prototyping system or **FPGA** technology.

III.6.1 Synchronous reference (SRF) method

For the two control loops, the synchronous method (Synchronous Reference Frame) is used to identify the voltage references of the inverter. The principle of this method is based on the use of a PLL and the Concordia transformation in order to determine the components of the d-q axes of the currents and voltages in the Park frame.

Then the alternative components were extracted using two first order high pass filters for the feedback loop, and a band pass filter to extract the fifth harmonic component for the feed forward loop [137].

III.6.2 Non-linear control

Non-linear control is based on two main steps. The first step is to determine the control law by deriving the system output as many times until the system input u appears. The second step consists in applying linear controllers to the previously linearized system so as to impose very specific dynamics on the closed loop system. [138].

III.6.3 Sliding mode control

Sliding mode control is a non-linear control technique with variable structure, where the dynamics of a system are transformed by the application of a control law based on high frequency switching. This command is suitable perfectly for active filters whose configuration varies with the operating sequences. The fact that the dynamic model of an active filter varies over time makes the application of the drag mode command very appropriate. The concept of slip mode is also derived from **Lyapunov's** theory of stability to extract the control laws and verify the stability. It is a question of forcing the trajectories of states of a system dynamic towards a certain surface, called sliding surface or switching surface. [139].

III.6.4 Direct adaptive control

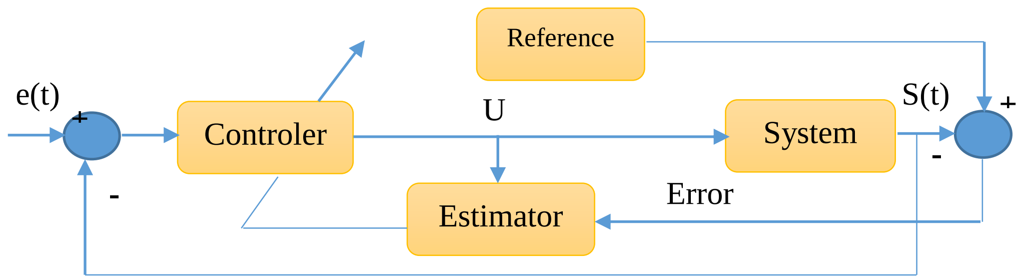


Figure III.11 Adaptive non-linear control with reference model

III.6.5 Indirect adaptive control

The indirect adaptive control is shown in Figure III.12, the controller parameters are estimated from the system parameters. This estimation uses a least square algorithm or other variants [140].

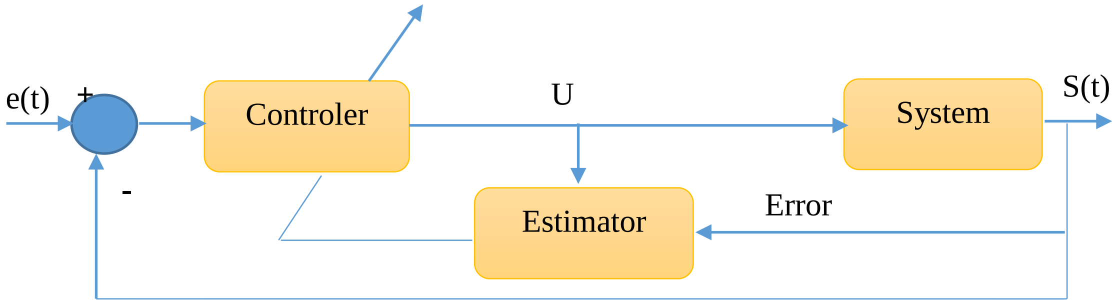


Figure III.12 Indirect adaptive nonlinear control.

III.6.6 Command based on Lyapunov stability

The philosophy of the method lies in the mathematical extension of a fundamental observation of physics. If the total energy of a system is dissipated continuously, then the system, (whether linear or non-linear) will eventually reach a point balance. We can therefore conclude that a system is stable by examining the total energy [141]. Lyapunov's direct method is based on the extension of these concepts.

The basic procedure is to generate an energy function for the dynamic system and to examine its time derivative. We can thus conclude that the system is stable without resorting to the explicit solution of non-linear differential equations [142].

III.7 Inverter Control

The purpose of inverter control is to control the currents at the filter output so that they follow their references. The principle is based on the comparison between the currents at the output of the active filter and their references calculated from the different methods of extracting and regulating harmonic currents and the voltage of the energy storage capacitor.

III.7.1 Hysteresis control

Conventional hysteresis control is very commonly used due to its ease of use and robustness. In fact, this strategy ensures satisfactory control of the current without requiring an in-depth knowledge of the model of the system to be controlled or of its parameters. This command consists in first establishing the error signal, which is the difference between the reference current i_{ref} and the current i_f produced by the inverter. This error is then compared to a template called a ***hysteresis band*** in order to set the switch control orders. Figure III.13

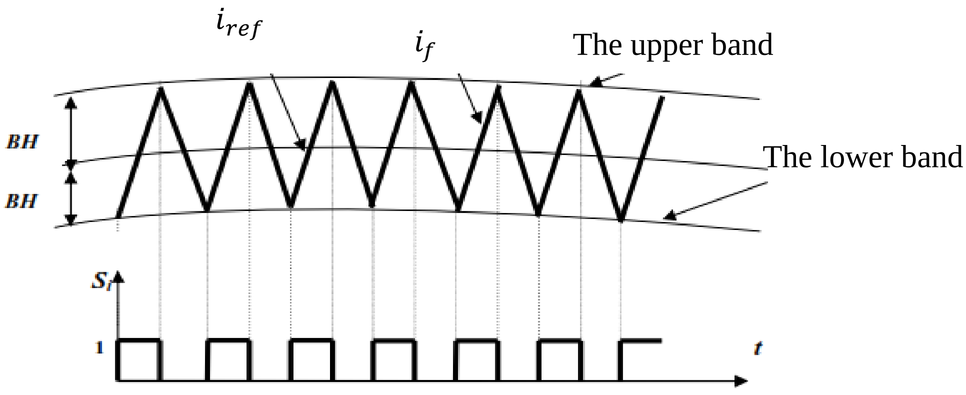


Figure III.13 Hysteresis control diagram

III.7.2 Sinusoidal PWM Control

The Pulse Width Modulation (PWM) control technique solves the problem of controlling the switching frequency by operating with a fixed frequency that is easy to filter. Perhaps the simplest and best known of the pulse width modulations is natural sampling PWM. This control technique first implements a regulator, which determines the reference voltage of the inverter from the difference between the measured current and its reference.

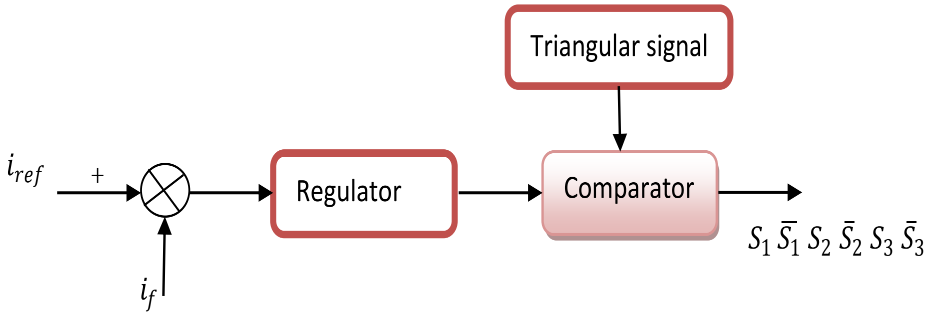


Figure III.14 Pulse Width Modulation (PWM) control scheme

This voltage is then compared with a saw tooth signal (high frequency carrier setting the switching frequency). The comparator output provides the control order of the switches [143].

III.7.3 Space Vector Modulation Control SVPWM

The SVPWM method is widely used in the control of inverters; it can increase the maximum value of the output voltage of the inverter with a reduced harmonic distortion rate compared to those obtained by the sinusoidal PWM method.

The aim of all modulation strategies is to reduce switching losses and harmonics, and to ensure precise control [144].

The principal of the SVPWM command is to place the command vector in the two-phase frame which will be obtained after using the **Clarck** transformation. The coding of the possible switching of the switches can be carried out on three states which gives eight possible vectors of which two are zero (V_0 et V_7) [12].

The commands in Clarck's two-phase repository are given by:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad \text{(III.64)}$$

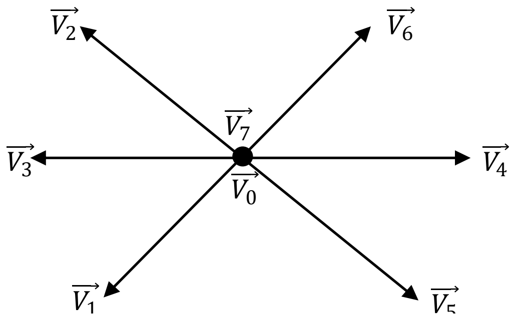


Figure III.15 Representation of the different voltage vectors

Table III.1 makes it possible to find for a given combination of switches, the vector obtained in the Clarck reference system.

Vectors	S_1	S_2	S_3	v_a	v_b	v_c	V_α	V_β
$\vec{V_0}$	0	0	0	0	0	0	0	0
$\vec{V_1}$	0	0	1	$2V_{dc}/3$	$-V_{dc}/3$	$-V_{dc}/3$	$2V_{dc}/3$	0
$\vec{V_2}$	0	1	0	$-V_{dc}/3$	$2V_{dc}/3$	$-V_{dc}/3$	$-V_{dc}/3$	$V_{dc}/\sqrt{3}$
$\vec{V_3}$	0	1	1	$V_{dc}/3$	$V_{dc}/3$	$-2V_{dc}/3$	$V_{dc}/3$	$V_{dc}/\sqrt{3}$
$\vec{V_4}$	1	0	0	$-V_{dc}/3$	$-V_{dc}/3$	$2V_{dc}/3$	$-V_{dc}/3$	$-V_{dc}/\sqrt{3}$
$\vec{V_5}$	1	0	1	$V_{dc}/3$	$-2V_{dc}/3$	$V_{dc}/3$	$V_{dc}/3$	$-V_{dc}/\sqrt{3}$
$\vec{V_6}$	1	1	0	$-2V_{dc}/3$	$V_{dc}/3$	$V_{dc}/3$	$-2V_{dc}/3$	0
$\vec{V_7}$	1	1	1	0	0	0	0	0

Table III.1 Possible voltages at the output of the inverter

III.8 Control Of The Parallel Active Filter

At present, researchers are continuing to improve the control methods of the parallel active filters in order to obtain better results, both from the point of view of better disturbance extraction, improvement of the dynamic regime, decrease in THD… etc, than developing new control strategies for better adaptation and robustness of the latter when faced with different types of non-linear loads.

There are mainly two control strategies to suppress the harmonic currents of the network depending on the measured current [145].

III.8.1 Direct method

This method is based on the measurement of the pollutant load current and then on the extraction of the harmonic components of this current [145]. In this way, the active filter injects the compensation currents without information on the network currents. All errors in the system such as parameter uncertainty, measurement or control errors will appear in the network as unfiltered harmonics.

III.8.2 Indirect method

This method consists of measuring the currents on the source side, and to impose the sinusoidal shape on these currents. The control algorithm is more or less complicated and requires fewer sensors than that in the direct method. In our work, we studied indirect control.

III.9 Conclusion

This chapter first identified the various problems for the compensation of disturbances generated by non-linear loads and their impact on the electrical distribution network. Then, the various problems which are related to the quality of the wave and which have a lot of impact on the cost and the performances of the compensators were raised.

This chapter also presents a review of the research literature on active, hybrid and passive compensators for disturbance compensation. These analyses will allow the reader to observe and evaluate the progress of research in this field. However, despite the multitude of these works, we notice that: the modelling of the three-phase shunt hybrid filter, the compensation of voltage disturbances using the series hybrid filter and the elimination of resonance phenomena using passive filters have not been addressed in a concrete way. This will allow us to locate the original contributions proposed in this thesis and which will be presented in the next chapter.

CHAPTRE IV

Power Balance Theory Control

IV. Power Balance Theory Control

IV.1 Introduction

The establishment of the definition of instantaneous reactive power has changed the methods for extracting harmonics relating to active filtering. Unwanted powers in an electrical circuit that need to be compensated are well identified. However, a difference exists on the nature of the homo polar component, which varies the concepts of compensation yielding to a variety in the compensation methods of harmonics and reactive energy.

We have reviewed the literature on methods based on instantaneous quantities and that based on effective values and we have noted for the most part their limits in the case of disturbed and unbalanced network.

In this chapter, the problem of harmonics and possible solutions has been discussed. We conclude that even if active hybrid filters are nowadays the most complete solution, APFs appear to be the most common solution for filtering harmonic currents. This is why; we have chosen the application to active parallel filtering. This application is considered very demanding because it involves very high bandwidths, which considerably influences the stability of the system. In this context, the internal current control loop becomes critical. In addition, the modelling of an APF is made more complex because the performance of each constituent block is interdependent, hence the proven need for a rigorous selection of the control techniques to be used. After a state of the art on classical and modern control methods are presented, the choice was made on techniques based on Power Balance Theory using tracking anti windup based PI regulator because of their learning capacity which makes it possible to design sufficiently adaptive structures and is the fast detection of distortion with high accuracy and quick response extraction of reference source currents. Thus, such a control strategy applied to APFs, should lead to robust filtering devices to variations in non-linear load, to situations of imbalances in network voltage, as well as to variations in its parameters (frequency, amplitude, phase), etc.

IV.2 Implication Of Power Balance Theory In Active Filtering

To better detail the existing research, work in the field of APFs, and involving our research the modified power balance theory techniques using tacking anti windup PI regulator for unbalanced nonlinear loads unbalanced gird voltage distribution networks, a separation is made according to the main blocks extracted from the control-command part. These blocks ensure:

- The extraction of the tension components.
- The identification of currents harmonics.
- Regulation and control of the inverter.

IV.2.1 Extraction of the voltage components

IV.2.1.1 Extraction of the phase and the direct voltage component

The Phase Locked Loop (PLL) is by far the most widely used technique for extracting the phase from the direct fundamental component of voltage in low voltage electrical networks [146]. This technique was born in 1932 in order to improve the reception of radio signals in amplitude modulation. At that time, the realization of the PLL was bulky, expensive and reserved for professional equipment until the appearance of integrated circuits. Today, the applications of PLL are numerous and varied (transmission in frequency modulation, Doppler Effect radars, automatic speed control of DC motors, etc.).

IV.2.1.2 Continued frequency

The PLL can follow the instantaneous phase of the fundamental network voltage and regain its frequency. Other methods have been developed, but most of them can only be used if the voltage signal is purely sinusoidal. A comparative study of classical methods is available in [147]. In the same year, P. K. Dash in his work uses an Adaline network in order to estimate only the fundamental frequency [148]. The authors identify the parameters of an electrical signal model written in the form of a difference equation including the first harmonics. Learning constrains the error between the desired output and the calculated output to satisfy the stability of a difference equation rather than minimizing an error function.

IV.2.2 Identification of current harmonics

A comparative analysis of the harmonics identification methods available in [149] according to their performance allows us to anticipate the possibilities of implementation. In the frequency domain, there are methods such as the Discrete Fourrier Transform (DFT), the Fast Fourier Transform (FFT) as well as the Recursive Discrete Fourrier Transform. In the time domain, the study concerns synchronous methods, instantaneous power methods and the generalized integrator method. This remarkable comparison proves that the choice of digital filtering is a key factor for obtaining exact results and good dynamics of an APF.

All the methods mentioned above prove to be insufficient when the voltages of the distribution networks vary in significant proportions. Although this aspect is taken into account with convincing results (**up to 30% of unbalance**) in the current work.

IV.2.3 Regulation and control methods of the inverter

The objective of the compensation method is to re-inject the reference currents into the electrical network. This operation is done by a control law through the power part (the voltage inverter, the energy storage element and the output filter).

Hysteresis commands and the PWM command are listed in the literature. Like the identification part of the APF currents, neural networks can also be used in the control part. The control of a single-phase inverter by a neural network is carried out in [150].

IV.3 The In Phase Component Of Reference Source Currents

The basic equations of power balance theory for generation of switching signals for VSC are given below.

$$V_t = \sqrt{2(V_{sa}^2 + V_{sb}^2 + V_{sc}^2)}/3 \tag{IV.1}$$

Where V_t Is the amplitude of the terminal voltage at PCC.

The unity sine waves of the phase main voltages are estimated as:

$$V_{au} = \frac{V_{sa}(t)}{V_t} \quad V_{bu} = \frac{V_{sb}\,(t)}{V_t} \quad V_{cu} = \frac{V_{sc}(t)}{V_t} \tag{IV.2}$$

The consumed load active power will be calculated as follows:

$$P_L = V_1(i_{la}V_{au} + i_{lb}V_{bu} + i_{lc}V_{cu}) \tag{IV.3}$$

The supply current has two components.

- The First is required for DC component of load-consumed power
- The magnitude of the fundamental active power component of load current can be estimated as:

$$i_{Ldc} = \frac{2}{3}\frac{P_{Ldc}}{V_t} \tag{IV.4}$$

Where P_{Ldc} is the DC component extracted from the total consumed active power after filter out by using a self-tuning filter (STF) which is the most important part of this control, which allows making insensible to the disturbances and filtering correctly the current.

The second component is required for the self-supporting DC bus voltage of the filter can be expressed as:

$$i_{Ld} = K_p V_{dce} + K_i \int V_{dce}\, dt \quad \text{(IV.5)}$$

Where $V_{dce} = V_{dc} - V_{dc}^{*}$ is the error in DC bus voltage between the sensed and the reference respectively. The proposed method is to use PI controller with anti-windup integral action.

After we obtain the two parts of the currents, we propose to filter out again to eliminate the ripple by using a second order low pass filter given in (IV.5a), where the cut-off frequency is 50 Hz and the damping factor Zeta ξ is 0.707.

$$F(s) = \frac{\left(1+\frac{K_p}{K_l}S\right)\omega_c^2}{S^2+2\xi_c\omega_c S+\omega_c^2} \quad \text{(IV.5a)}$$

IV.4 Extraction of The Three Reference Currents

The three-phase references of source current are calculated as:

$$i_{ref(a)} = (i_{Ldc} + i_{ld})V_{au} \quad \text{(IV.6)}$$

$$i_{ref(b)} = (i_{Ldc} + i_{ld})V_{bu} \quad \text{(IV.7)}$$

$$i_{ref(c)} = (i_{Ldc} + i_{ld})V_{cu} \quad \text{(IV.8)}$$

The compensating current could be obtained by subtracting the load current from the reference supply current. The generated currents pass through a Hysteresis Current Control HCC to obtain switching signals needed in semiconductors commutation of the VSC.

IV.5 Anti-Windup Regulator

In most of technical systems, the actuators are transducers [151], which transform a low power signal, generally electrical, into a high power "action". Examples are valves for flow control and high power electronics for electrical power control. For example, use the latter can in a second step for controlling the torque of an electric motor. In most cases, properly sized actuators saturate even during normal operation [152]. What happens if, or when, the actuators saturate depends critically on the ability of the control strategy (the controller) to handle a saturation event as well as the properties of the controlled system. Some systems are easier to control via constrained actuators than others. Some controllers are better suited to handle saturation events than others.

The control of linear systems with saturating actuators has been studied for many decades and research activity has increased considerably over the past decade. A chronological bibliography up to 1995 is presented in [153] and a more recent overview is provided in [154]. The least demand we put on a control system is that it is stable in normal operation. The stability of control systems with saturated actuators and the design of controllers where input saturations are taken into account a priori are discussed for example in [155] [156] [157].

Among the proposed control concepts, we can distinguish the one that is used more often than the others in practice, namely the **ANT WINDUP COMPOENSATOR**

Anti-winding compensators are widely used in practice for the control of saturated actuator systems. Anti-winding compensator design can be performed using linear design methods, which explains its usefulness and popularity with control engineers.

IV.5.1 Anti-windup compensation overview

An anti-windup compensator consists of a nominal controller (most often linear) associated with anti-windup compensation. An important property of anti-winding compensation is that it does not modify the loop until saturation occurs [158]. Consequently, the control action provided by the winding compensator is identical to that of the nominal controller, as long as the control signals operate within saturation limits. The design can be divided into two parts, the first part concerning the linear controller and the second part the anti-winding modification.

Anti-winding techniques have been discussed in academic literature for many decades and have probably been used in industrial applications for at least as long [159]. Important work on anti-winding techniques can be found for example in Fertik and Ross [160], Hanus [161], [162].

Whenever a linear controller has been designed assuming that its output will directly and without alteration affect the input of the installation, any input non-linearity, such as the saturation of the rate and / or the amplitude, causing a gap between the controller output and the installation input, almost always degrades performance and stability.

The closed loop system can be endangered. Anti-liquidation compensation is the simplest and most commonly used modification of a linear controller, designed to maintain the stability and most of the performance of such a system. In this thesis, we will show how reliable anti-winding compensators can be designed using linear methods.

IV.5.2 Anti-Windup Pi Control Schemes

IV.5.2.1 PI controller

Transfer function of a PI controller is expressed as

$$G_{PI}(s) = K_p + \frac{K_i}{s} \quad \text{(IV.9)}$$

Where K_p and K_i are the proportional and integrator constants respectively.

Thus, the output from the controller y can be expressed as:

$$y = K_p \times e + K_i \int edt \quad \text{(IV.10)}$$

Here e is the input error.

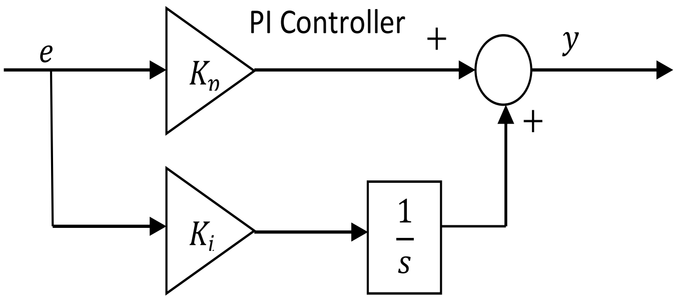


Figure IV.1 PI regulator scheme

In such cases, the error can be too large or it remains non-zero for long duration, in this condition, the integrator causes the roll over. To overcome this undesirable situation, a "saturation" block can be used at the output as shown in figure

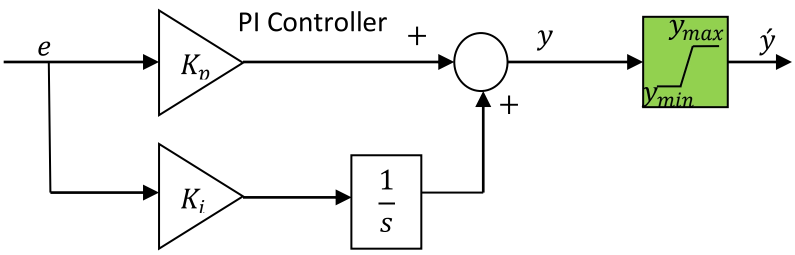


Figure IV.2 PI regulator with Saturation block scheme

The output $\acute{y}$ can be expressed as:

$$\acute{y} = \begin{cases} y_{max}, & for \quad y \geq y_{max} \\ y_{min}, & for \quad y \leq y_{min} \\ y, & for \; y_{min} < y < y_{max} \end{cases} \tag{IV.11}$$

But in this case, if the error e remains non zero for long duration and the output integrator keeps accumulating, the above approach would lead to problem and may introduce a delay response of the output if the rollover happening, to avoid this undesirable situation, it is necessary to check the integration process during each situation, known **Anti-windup**. There are many schemes of anti-windup technique, we introduce in this thesis two different schemes using conditional integration, and tracking anti-windup [163].

IV.5.2.2 Conditional Integration Scheme

The basic idea of this scheme is by stopping the integration process when the output y reaches the saturation limits as shown in figure

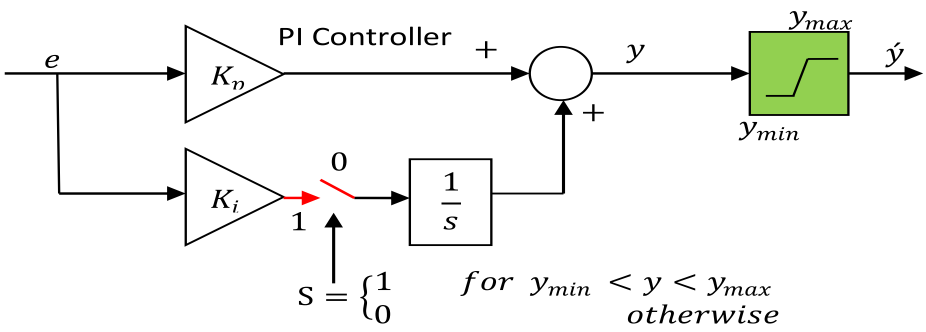


Figure IV.3 Conditional integration block diagram representation

This method ensures that there is no further increase in the value of the output while the controller is saturated. The integrator starts working again when the error reduced below certain level and the output comes out of saturation. This method is also called **conditional clamping.**

The conditional integration represents a drawback if the controller is saturated at the upper border; in this case the switch goes off and the controller changes between PI mode to P mode however the initial values of K_p and K_i has been chosen for the controller to work in PI mode; so with this scheme, it is difficult to choose gain to satisfy the anti-windup performance i.e. the selection of the integral gain is related to the zero of the transfer function.

IV.5.3 Tracking Anti-Windup Scheme

Figure 4.13 show another way for controlling a saturation in which we carried out our study

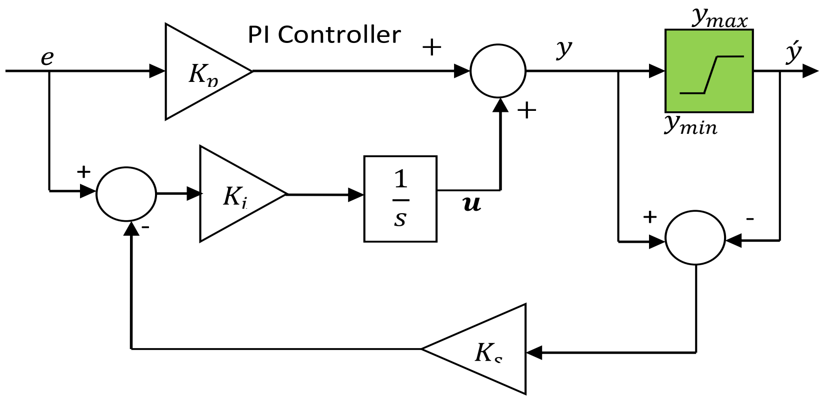


Figure IV.4 tracking Anti-windup scheme

In this scheme, and in order to reduce the input error going to the integrator, the difference between control signals y and $\acute{y}$ is fed back through a gain K_s.

From the circuit above, we can write

$$y = u + K_p e \tag{IV.12}$$

Where u is the output from the integrator

Therefore, the derivative of the output u will be:

$$K_i \frac{du}{dt} = (e - K_S(y - \acute{y})) \tag{IV.13}$$

Considering a situation where $y > y_{max}$ and in order to obtain dynamic behaviour of the PI controller under saturation, the equation (IV.5) will be:

$$K_i \frac{du}{dt} = (e - K_S(y - y_{max})) \tag{IV.14}$$

Hence, by replacing (IV.12) in (IV.13)

$$\frac{du}{dt} = K_i (e - K_S((u + K_p \times e) - y_{max})) \tag{IV.15}$$

$$\frac{du}{dt} = -K_i K_s u + K_i(1 - K_S K_p)e + K_i K_s y_{max} \tag{IV.16}$$

The solution of the above differential equation and by giving the error input the constant E

$$u(t) = \left(U_0 - \frac{E}{K_S} - y_{max} + K_p E\right) e^{-K_i K_S t} + (\frac{E}{K_S} + y_{max} - K_p e) \tag{IV.17}$$

By replacing (4.17) in (4.12) yields:

$$y(t) = (U_0 - \frac{E}{K_S} - y_{max} + K_p E)e^{-K_i K_S t} + (\frac{E}{K_S} + y_{max}) \qquad \text{(IV.18)}$$

Where

$\frac{E}{K_S} + y_{max}$ Is the dynamic part.

$(U_0 - \frac{E}{K_S} - y_{max} + K_p E)e^{-K_i K_S t}$ Is the steady state part.

Moreover, it can be seen that, both parts goes to zero if the gain K_S has to be high, therefore

$$y(t) \approx y_{max}$$

Hence, the controller will come out of saturation quickly.

IV.6 PHOTOVOLTAIC SYSTEMS:

PV systems are classified according to three types: stand-alone, hybrid and grid-connected [153].

IV.6.1 Autonomous systems

Autonomous systems are completely independent from other sources of energy [164]. They are usually used to power homes, cabins or camps in remote areas as well as applications such as remote monitoring and pumping water. In the majority of cases, a stand-alone system will require storage batteries to store energy [165]. Such systems are particularly useful and cost effective in summer applications, where access to a location is difficult or expensive or where maintenance needs should be kept to a minimum.

IV.6.2 Hybrid systems

Hybrid systems receive some of their energy from one or more additional sources. In practice, PV system modules are often combined with a wind turbine or a fuel generator. Such systems usually have energy storage accumulators [165]. They are best suited when energy demand is high (during winter or throughout the year).

IV.6.3 Systems connected to the network

Grid-connected systems reduce the consumption of electricity from the energy distributer and, in some cases, return excess energy to the distributer. In some cases, the utility may credit you for the energy returned to the grid. Since energy is normally stored in the grid itself, batteries are not needed unless you want a self-contained form of energy during blackouts [166].

These systems are used in buildings, homes or chalets already connected to the electricity network.

IV.6.4 The photovoltaic cell

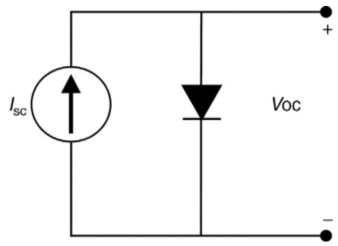


Figure IV.5 Model of a PV cell

The output open circuit voltage V_{OC}, can be expressed by [8]:

$$V_{OC} = (KT/q)In\big((I_{SC}/I_0) + 1\big) \quad \text{(IV.19)}$$

Is the Boltzmann constant $1.3854 \times 10^{-23} J°K^{-1}$.

q Is the charge of the electron in coulombs. 1.6×10^{-19}.

T Is the absolute temperature of the panel in degrees Kelvin.

I_0 Is reverse saturation current of the PN junction.

I_{SC} Is the short circuit current of the cell.

Both $I_0$and I_{SC} depends on the manufacturing parameters of the cell, while the short circuit current also depends on the incoming light irradiance.

IV.6.5 Photovoltaic cell characteristics

Technically, a PV sensor is approxematly the same as a PN diode due to its construction, the materials used, and the identical physical phenomena involved. The maximum cell voltage is about 0.72 V for zero current. This voltage is called the open circuit voltage Voc. The maximum current occurs when the cell terminals are short-circuited, it is called the current Icc circuit and is highly dependent on the level of illumination [166].

IV.6.5.1 Influence of temperature

The current depends on the temperature. It increases slightly as the temperature rises and that the temperature negatively influences the maximum power of the generator These characteristics show that the open circuit voltage undergoes a decrease as a result of the increase in temperature.

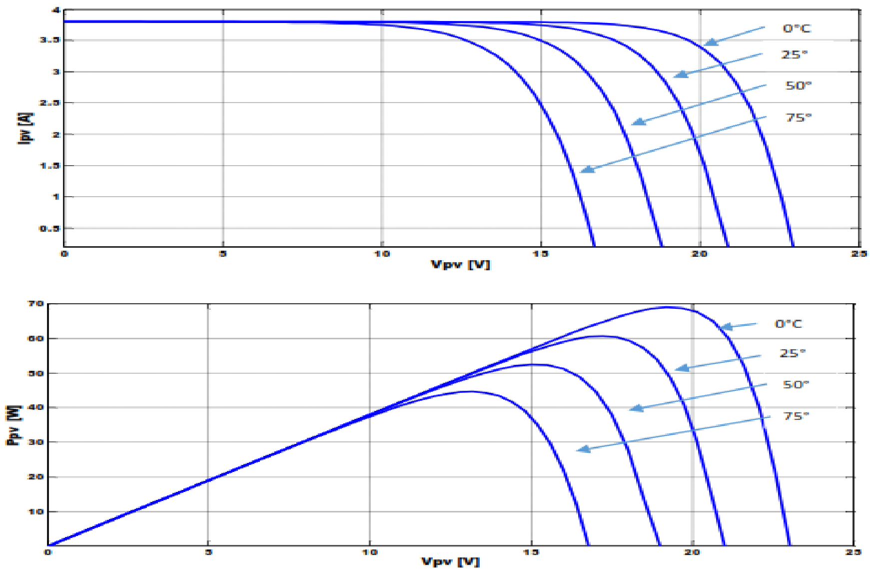


Figure IV.6 I-V and P-V characteristics of used PV cell with constant illumination and variable tempreture.

IV.6.5.2 Influence of illumination

In the case where we have fixed the temperature for different illuminations. We note that the current undergoes a significant variation On the other hand, the voltage varies slightly which results in an increase in power.

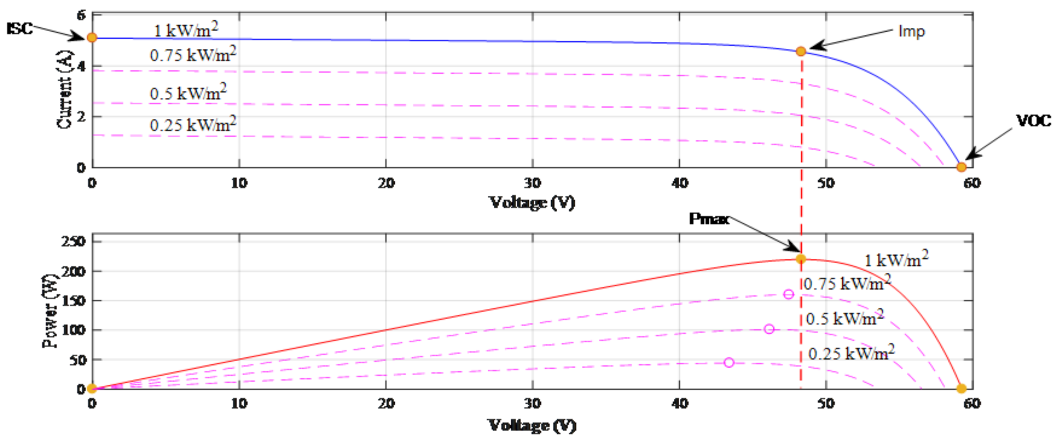


Figure IV.6.1 I-V and P-V characteristics of used PV cell with constant tempreture and variable illumination.

IV.7 Z-Source

IV.7.1 Introduction

DC / AC converters of impedant source inverter types appeared in scientific literature in the 2000s through the work of Professor Fang Zheng Peng published in 2002 [167].

The Z-source inverter has been recently introduced, its terminology (Source Impedance) being related to the replacement of the conventional inverter DC bus with a cross hybrid L C DC stage [168].

Its advantage is to be able to obtain a higher AC output voltage than with a conventional inverter, ie a "natural boost" effect. This modification is linked to the possibility of introducing short-circuit phases of the inverter arms.

In this part of chapter, we will study the operating principle of Z-source converter by passing the "Shoot-Through" state and develop the mathematical model of Z-source converter by extracting the equations governing the system.

In order to clarify the main role of the Z-source converter is to amplify the input voltage is based on the report of the state of "Shoot-Through" during the entire switching period.

IV.8 Z-Source Converters Overview

In recent years, distributed generation systems have attracted more attention due to their small size, modular structure, as well as great ecological benefits due to their low emissions. Due to their nature, decentralized sources dedicated to the production of electrical energy through renewable energy sources such as photovoltaic sources, fuel cells and wind turbines generate a variable direct voltage [169].

Indeed, the voltage of the photovoltaic generator varies with temperature and radiation, the voltage supplied by the battery drops sharply with the current, while the voltage of the wind generator varies with the wind speed.

However, the traditional voltage inverter coupled to the grid cannot operate correctly in the presence of low DC voltages and often requires the use of an additional dc-dc converter, generally of the boost type. In this situation, two separate commands are essential. One to increase the DC voltage and the other to control the inverter [170]. Recently, the step-up inverter (z-source converter) has been presented in the literature as a competitive alternative to overcome the voltage limitation of the traditional inverter.

The Z-Source network is symmetrical; it uses a combination of two inductors and two capacitors, connected in the shape of an X [171]. They are energy storage and filtering elements. Since the switching frequency is much higher than that of the source, the inductors and capacitors should be low [168].

A unique feature of "z-source" converters is the "Shoot Through" state whereby the two solid-state switches of the same phase branch can be activated simultaneously. Therefore, no dead time is required, the output distortion is greatly reduced, and therefore the reliability is considerably improved[171]. This feature is not available in traditional voltage and current sources

IV.8.1 Z-source inverter structure

IV.8.1.1 Topology of a three-phase z-source inverter

The topology of a three-phase voltage inverter with z-source structure is given in Figure (IV.7), this inverter consists of a main circuit which groups together the three (03) switching cells, connected to the DC voltage source via an impedance network and a protection diode. The latter prevents the discharge of two capacitors in the DC voltage source[172].

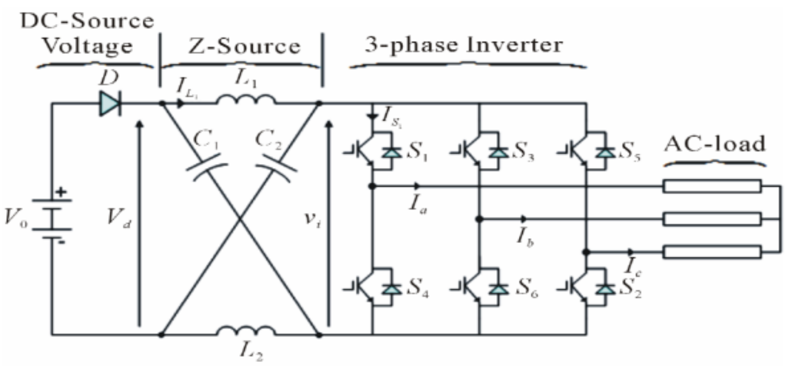


Figure IV.7 Topology of a three-phase inverter with z-source structure

Each arm (switching cell) is made up of two reversible current switches, the operation of which is complementary during the transfer of energy between the two sources.

The insertion of said network offers the possibility of simultaneously triggering the two (02) switches of the same cell (arm), which is strictly prohibited in conventional voltage inverters.

This possibility generates a new state which is recognized by its name **Shoot Through** Stat. This state can only be inserted in the short-circuit duration of the load (the converter zero state) [173].

The impedance network is both a power source and a filter for the converter, such that the inductor serves to limit current ripples during the short circuit state, while the capacitor is intended to absorb these ripples and keep the voltage constant, in order to provide a sinusoidal voltage at the output.

IV.8.1.2 Z-source inverter operating principle

We define vi the input voltage of the inverter $V_{M\,max}$ the peak value of the fundamental of the output phase-to-neutral voltage of the inverter, $V_{i\,max}$ the peak value of the input voltage of the inverter.

The modulation depth is defined by:

$$m = V_{M\,max}/V_{i\,max} \quad \text{(IV.20)}$$

Amplification of the continuous stage is defined by:

$$b = V_{i\,max}/V_{dc} \quad \text{(IV.21)}$$

The DC stage of the Z-source inverter is a symmetrical structure with two capacities named C1 and C2 of value C and two inductors L1 and L2 of value L.

We can deduce from this that the voltages at the capacitor terminals C1 and C2 are identical (denoted V_C) as well as the currents in the coils (denoted iL).

The Z-source inverter is an inverter capable of adjusting the output voltages thanks to its modulation depth m (as in a conventional inverter), but also by modifying the input voltage vi by adjusting the short-circuited durations of inverter arm [174]. These short-circuits are carried out during the freewheel phases on the three-phase load of the inverter. The states of the inverter seen by the load remain unchanged. Thus, the load is insensitive to short circuits made on the Z-source DC stage.

The operation of the device is linked to the behavior of the nonlinear elements surrounding the Z-source continuous stage:

- The state of the Ds diode: on or off
- The state of the inverter: freewheel
- The active state (exchange of power between the DC stage and the load), short circuit of the inverter arms.

The state of the Ds	The state of the inverter: freewheel	Z-source in short circuit
ON	YES	NO
OFF	NO	YES

Table IV.1 The states used with the Z-source command

1. If the inverter arms are short-circuited, the diode is necessarily blocked (linked to the lift mode of the assembly).
2. If the inverter is active (exchange of power between the DC stage and the load), then the Ds diode is conducting.
3. If the inverter is in freewheel state, Ds is normally on, this being linked to the choice of the switching frequency of the inverter and to the usual values of L and C.

IV.8.1.3 Working principle

We have two main states:

1. Shoot-through: the ZS circuit is shorted
2. Active state: the ZS impedance network sees the load through the inverter.

Mode 1 - Ds On and the inverter is active:

During this state the inverter can be represented as a current source seen from the Z-source DC stage

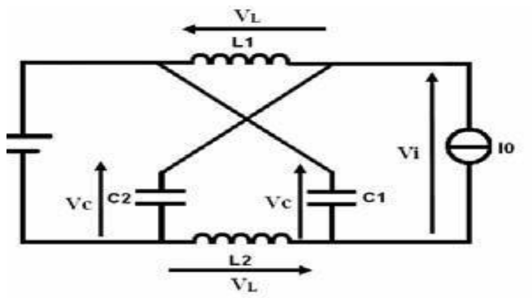


Figure IV.8 The equivalent circuit of Mode 1

The voltage values can be determined:

$$V_L = V_{dc} - V_C \quad \text{(IV.22)}$$

$$V_i = V_C - V_L = 2V_C - V_L \quad \text{(IV.23)}$$

Mode 2 – Ds Pass-through and inverter in freewheeling mode (without short circuit):

During this state, the inverter can be represented as an open circuit figure (IV.9) and the voltages V_L and V_i remain identical to equations (IV.22) and (IV.23).

This is a special case where I_s (the source curent) is zero.

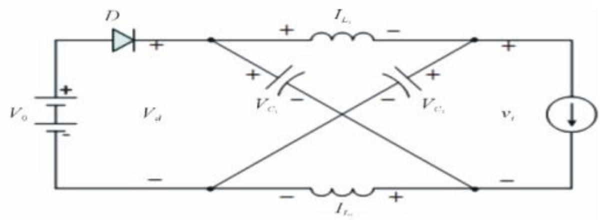


Figure IV.9 the equivalent circuit of Mode 2

Mode 3 - Ds blocked and Z-source short-circuited:

During this state, at least one arm of the inverter is short-circuited, which imposes a zero voltage at the output of the Z-source DC stage figure (IV.10).

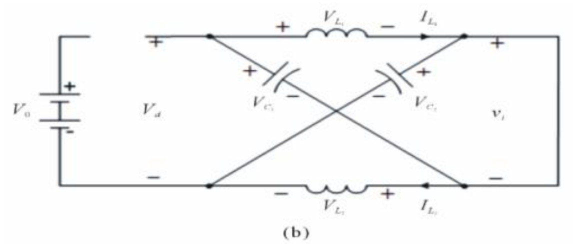


Figure IV.10 the equivalent circuit of Mode 3

So the load voltage is zero $V_i = 0$ and there is no energy transfer.

The duration of the Shoot-Through state is equal to T_0, and the switching period is equal to T.

From figure (IV.10) we can determine the equations the voltages:

$$v_i = 0\ ;\ V_d = 2V_C \tag{IV.24}$$

$$T_{Sf} = T_{Sr} + T_n \tag{IV.25}$$

$$M_{Sr} = T_{Sr}/T_{Sf} \tag{IV.26}$$

Where:

T_{Sf} is the shoot through duty ratio.

M_{Sr} is the switching cycle.

The voltage across Z-source capacitor can be obtained as:

$$V_{C1} = V_{C2} = V_C = ((1 - M_{Sr})/(1 - 2 \times M_{Sr}) \times V_o \quad \text{(IV.27)}$$

The peak dc voltage across the inverter can be expressed by:

$$\widehat{v_i} = 2V_C - V_o = (1/(1 - 2 \times M_{Sr}) \times V_o = kV_o \quad \text{(IV.28)}$$

Where:

k is the boost factor ≥ 1

And from (IV.28), the $0 < M_{Sr} < \frac{1}{2}$ therefore, $0 < T_{Sr} < \left(T_{Sf}/2\right)$

IV.9 Modelling Of Photovoltaic System And MPPT Control

IV.9.1 Introduction

The sun is an almost unlimited energy source; it could cover several thousand times our global energy consumption. This is why man has been seeking for a long time to take advantage of this important energy and diffused throughout the planet, he has managed to achieve this goal by means of the so-called photovoltaic cell [175].

This solar energy is available in abundance over the entire earth's surface, and despite significant attenuation as it passes through the atmosphere, the amount that remains is still quite large when it reaches the ground. We can thus count on 10,000 W/m² peak in temperate zones and up to 14,000 W/m² when the atmosphere is slightly polluted.

The photovoltaic effect is the direct conversion of energy from solar radiation into electrical energy by means of cells generally based on silicon [176]. To obtain sufficient power, the cells are interconnected and constitute the solar module.

IV.10The Mppt Control Technique:

IV.10.1 Definition

Photovoltaic generators have random electricity production directly dependent on weather conditions. Thus, the sizing and optimal use of the energy produced by these generators requires the use of appropriate management methods [176].

Likewise, improving the efficiency of the photovoltaic system requires maximizing the power of the PV generator which allows the proper control to be established in order to obtain the maximum power from these generators.

By definition, an MPPT control, allows a PV generator to operate in such a way as to continuously produce the maximum of its power [177]. Thus, whatever the weather conditions (temperature and irradiation), the converter control places the system at the maximum operating point.

IV.10.2 MPPT Principle Control

The MPPT control varies the duty cycle of the converter, using an appropriate electrical signal, to get the maximum power that the PV generator can deliver [177].

The MPPT algorithm can be more or less complicated to find the MPP. In general, it is based on the variation of the duty cycle of the according to the evolution of the input parameters of the (V and I and consequently of the power of the PVG) until it is placed on the MPP.

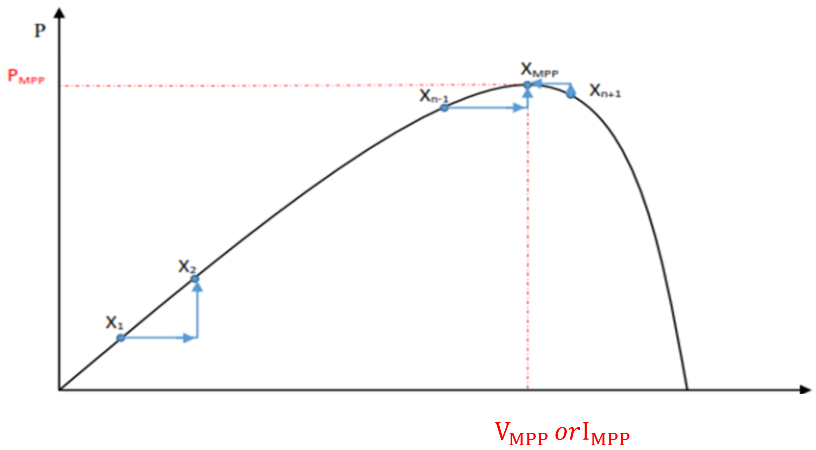


Figure IV.11 MPPT Principle Control

IV.10.3 Classification of MPPT commands

IV.10.3.1 Classification Of MPPT Commands According To Input Parameters.

We can generally classify MPPT commands according to:

1. MPPT commands operating from Converter input parameters
2. MPPT controls operating from converter output parameters.

However, it is more interesting to classify them according to the type of research.

IV.10.3.2 Classification Of MPPT Commands By Search Type

- Indirect MPPT

This type of MPPT command uses the link between the measured variables (Isc or Voc), which can be easily determined, and the approximate position of the MPP.

It also counts the commands based on an estimate of the operating point of the PVG made from a parametric model defined in advance [178]. There are also commands that establish an optimal voltage tracking by taking into account only the variations in the temperature of the cells given by a sensor. These commands have the advantage of being simple to perform. Rather, they are intended for inexpensive and imprecise systems to operate in geographic areas where there is little climate change.

- Direct MPPT

This type of MPPT control determines the optimum operating point (MPP) from the currents, voltages or powers measured in the system [179]. It can therefore react to unpredictable changes in the operation of the PVG. Usually, these procedures are based on a search algorithm, with which the maximum of the power curve is determined without interruption of operation.

For this, the operating point voltage is incremented at regular intervals [179]. If the output power is larger, then the seek direction is maintained for the next step, otherwise it will be reversed. The actual operating point then oscillates around the MPP. This basic principle can be preserved by other algorithms against misinterpretation [179]. These errors can occur, for example, due to poor search direction, resulting from an increase in power which is due to a rapid increase in the radiation level. The determination of the value of the power of the PV generator, essential for the search for MPP, requires the measurement of the voltage and the current of the generator, as well as the multiplication of these two variables.

IV.11MPPT Algorithms

There are several operating principles of more or less efficient MPPT controls based on the properties of the PVG [180].

IV.11.1 Constant Tension Approach

The constant voltage method also called the open circuit voltage method is based on the real-time measurement of the open circuit voltage V_{OC} and the approximate linear relationship (4.16) between this voltage and the point voltage maximum V_{MPP} of PVG.

$$V_{MPP} = K_1 * V_{OC} \tag{IV.29}$$

Where K_1 is a constant of proportionality; it is generally between 0.71 and 0.86. Once k1 is determined, the V_{MPP} can be calculated using the preceding expression (IV.29) with V_{OC} measured periodically by momentarily opening the power converter (open circuit). The voltage V_{MPP} is then taken as the reference voltage [180].

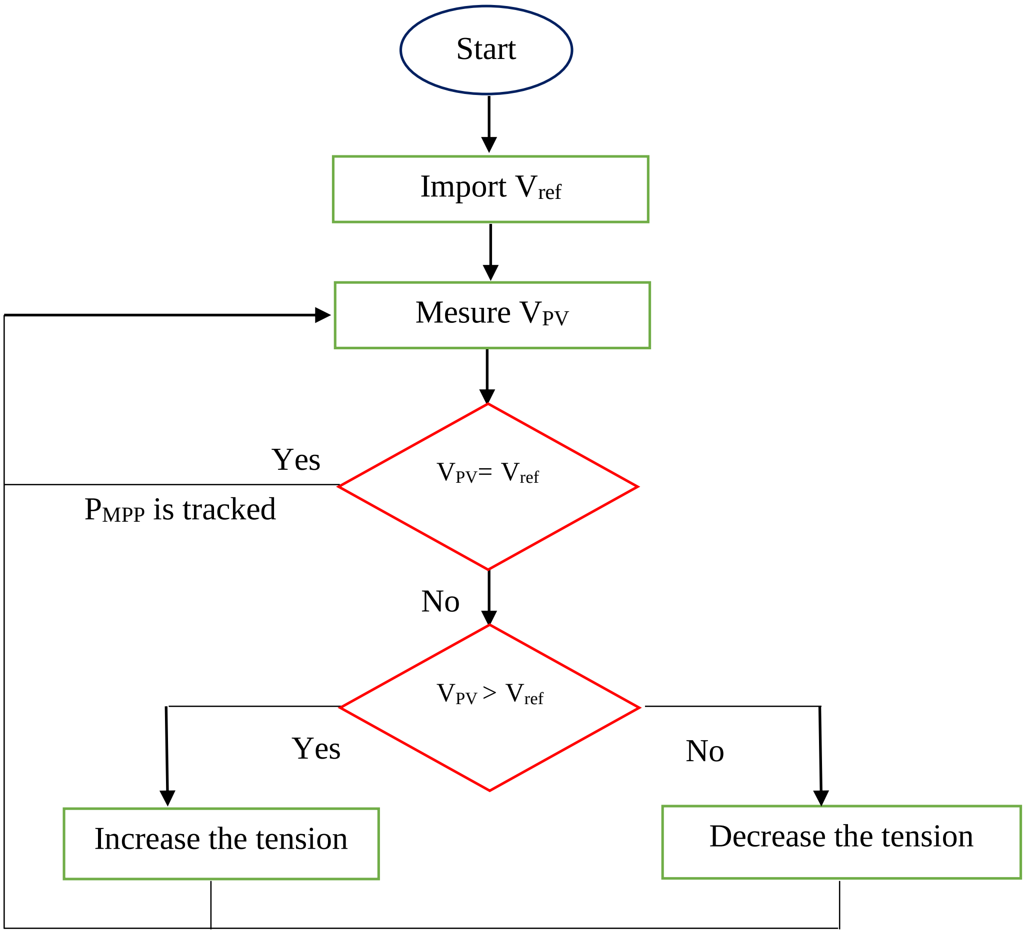


Figure IV.12 Constant Voltage Algorithm

The principle of this method is based on the comparison between the actual photovoltaic panel voltage V_{PV} and the reference voltage V_{ref} (V_{MPP}). The error signal is processed to make $V = V_{ref}$

This method has two advantages: the speed of the response to fluctuations and the absence of variations in a steady state. However, these strong points cannot hide their shortcomings, because of the dependence of the panel voltage on the insolation and temperature, the maximum power voltage is deviated, so the reference voltage must be corrected for different sunshine and temperature. throughout the periods of the year.

Also, the MPP is not always between 71% and 78% voltage Voc.remembering the loss of the power available when disconnecting the load from PVG.

IV.11.2 Constant Current Approach:

The constant current method also called the short-circuit method is based on the real-time measurement of the short-circuit current Isc and the approximate linear relationship (IV.30) linking this current with the current maximum point of the PVG [181].

$$I_{MPP} = K_2 * I_{SC} \quad \text{(IV.30)}$$

With k2 constant of proportionality is usually between 0.78 and 0.92.

For this constant value of the current, the power is calculated for different voltages. If the difference between the calculated power and the peak power is greater than the value of tolerance, then the voltage value is either incremented or decremented depending on the power obtained.

IV.11.3 Perturb And Observe (P&O)

The P&O method is generally the most used because of its simplicity and ease of implementation. As its name suggests, this method is based on the disturbance (an increase or decrease) of the voltage V_{ref} , or of the current I_{ref} , and the observation of the consequence of this disturbance on the measured power (P = VI).

The principle of P&O control consists in causing a disturbance of low value on the voltage V_{PV}, which generates a variation of the power [181].

Figure shows that we can deduce that if a positive increment of the voltage V_{pv} generates an increase in the P_{pv} power, this means the operating point is to the left of the MPP. If, on the contrary, the power decreases, this implies that the system has exceeded the MPP.

If, on the contrary, the power decreases, this implies that the system has exceeded the MPP [181].

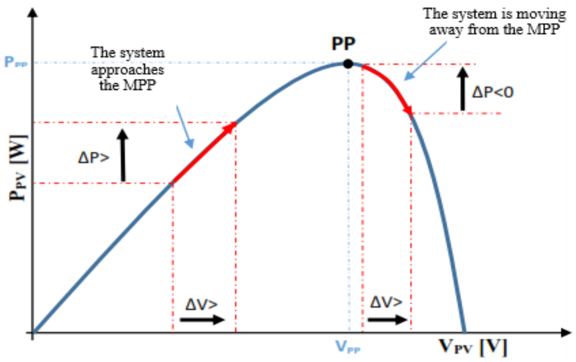


Figure IV.13 Search for MPP by the (P&O) method

From these various analyzes on the consequences of a voltage variation on the characteristic P(V), it is then easy to locate the operating point in relation to the MPP, and to make the latter converge towards the maximum power at through an appropriate order.

Figure (IV.14) shows the algorithm of a P&O type MPPT control, where the change in power is analyzed after each voltage disturbance.

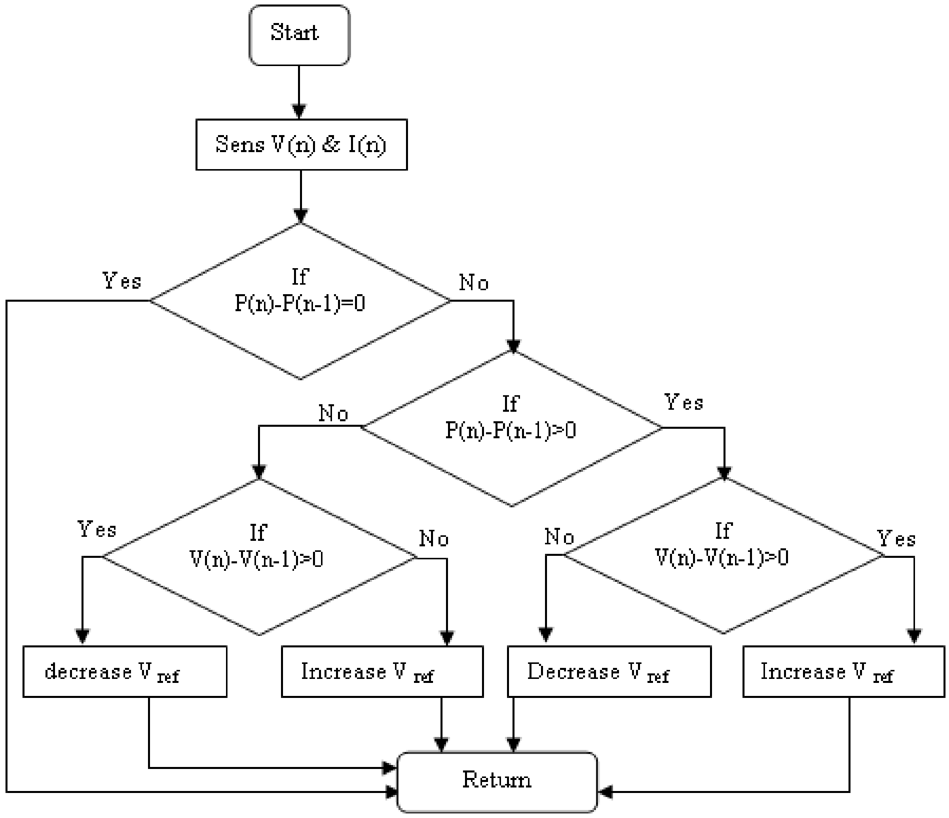


Figure IV.14 P&O algorithm flowchart

IV.12Validation of The Simulation Model

In this part, we will validate our simulation model in order to credit, the study already carried out to study the operation of the controlled filter with our method developed for the extraction of harmonics.

The validation will be done first qualitatively by extracting the waveforms of the currents and voltages and then extract quantitatively the effective values of the quantities and the THD of the currents and this for operation before and after filtering.

A MATLAB/Simulink model of the control system is developed to verify the performance of the proposed technique. Three variable RL type nonlinear load groups' gives in Table IV.2 and Table IV.3 and different operating unbalance supply voltage in Table IV.4.

Parameter	**value**
Source voltage	100V
System frequency	50Hz
DC link Capacitance	1100 µF
Source inductance	1.3 mH
Source resistance	0.42 Ω
Coupling inductance	2m H
Coupling resistance	0.1 Ω
Load 1	8Ω , 3mH
Load 2	12Ω , 5 mH
Load 3	30Ω , 4 mH
K_p	0.1074
K_i	0.2055

Table IV.2 Simulation parameters

Parameter	**value**
L1, L2	1 mH
C1, C2	1300 µF
Module Type	CS5P-220P
V_{OC}	59,2618 V
I_{SC}	5,09 A
V_{mp}	48,31V
I_{mp}	4,54 A

Table IV.3 Simulation parameters for ZSI

	0%	10%	20%	30%
Phase A	100 V	100V	100 V	100 V
Phase B	100 V	90 V	80 V	70 V
Phase C	100 V	110 V	120 V	130 V
THD%	1.115	1.286	1.711	2.411

Table IV.4 Simulation parameters

Figure IV.15 1 and 2 shows the different waves of tensions and currents, both before and after start-up of the APF. Before the APF was plugged in (before t = 0.02s), it was noted that the source current has the same shape as the charging current with a THD = 17.46%

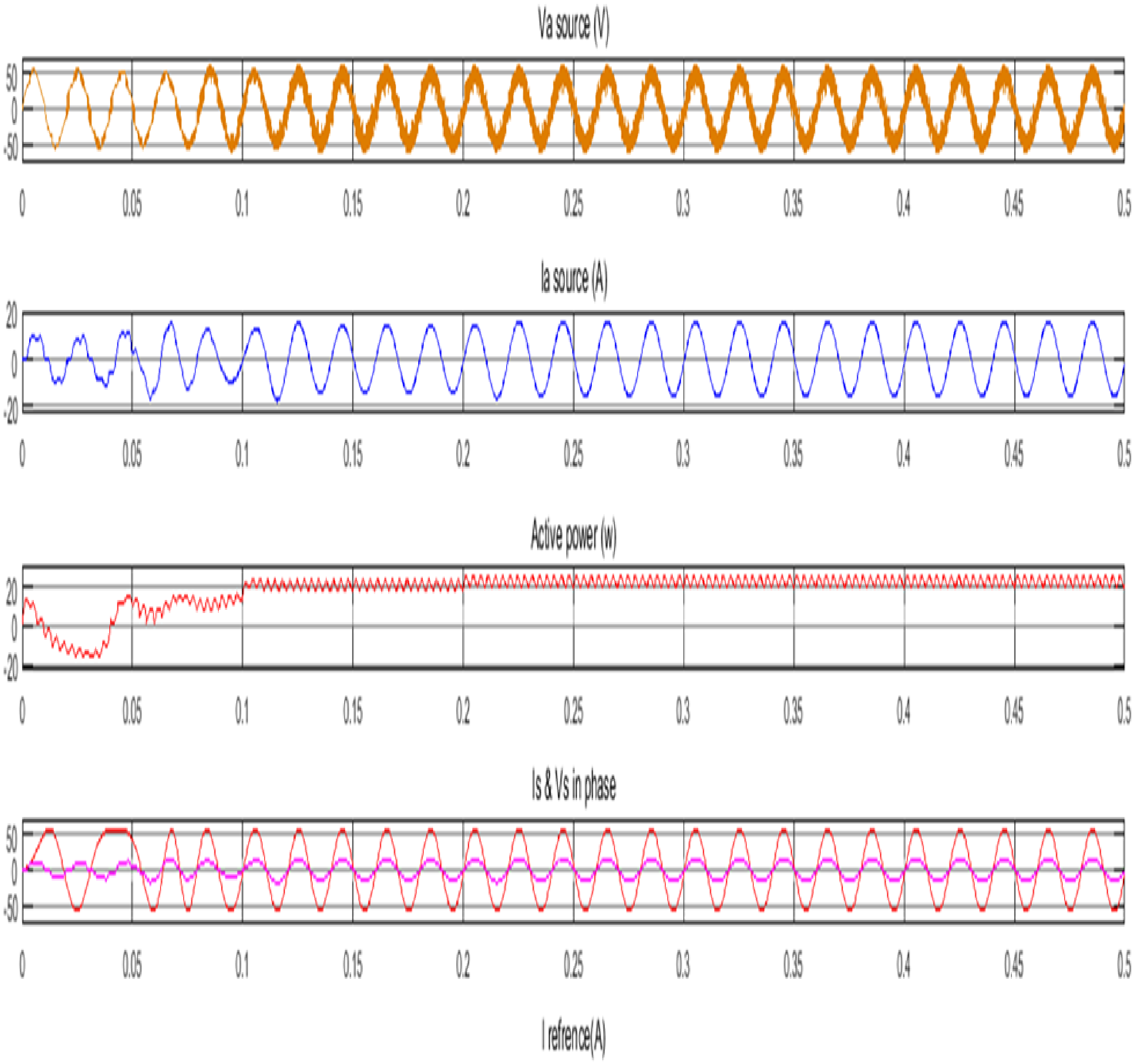


Figure IV.15-1 simulation results when connecting the APF

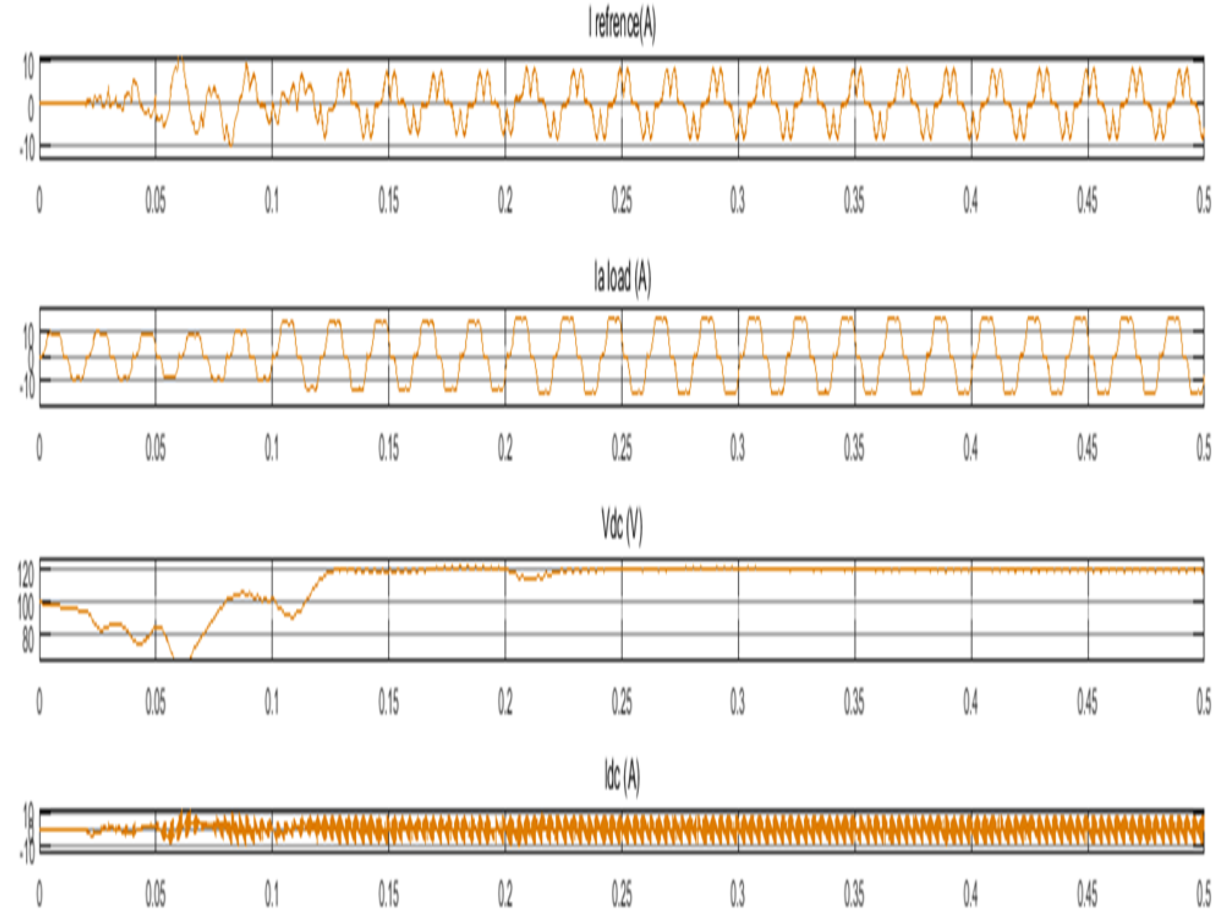


Figure IV.15-2 simulation results when connecting the APF

After connecting the APF (at t = 0.02s), it begins to compensate for the harmonic currents absorbed by the non-linear load, and after a transient the source current returns to its sinusoidal form with a THD = 1.115%.

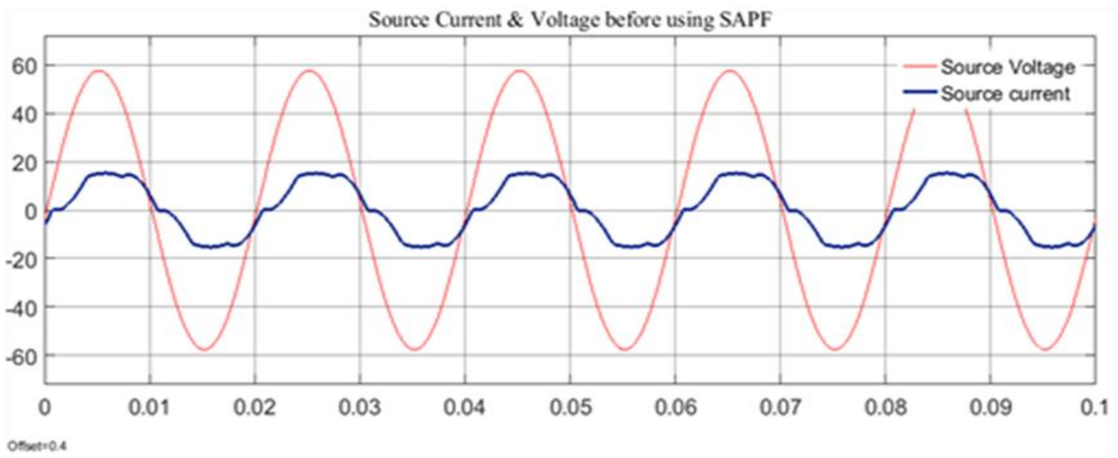


Figure IV.16 Source current before connecting the APF

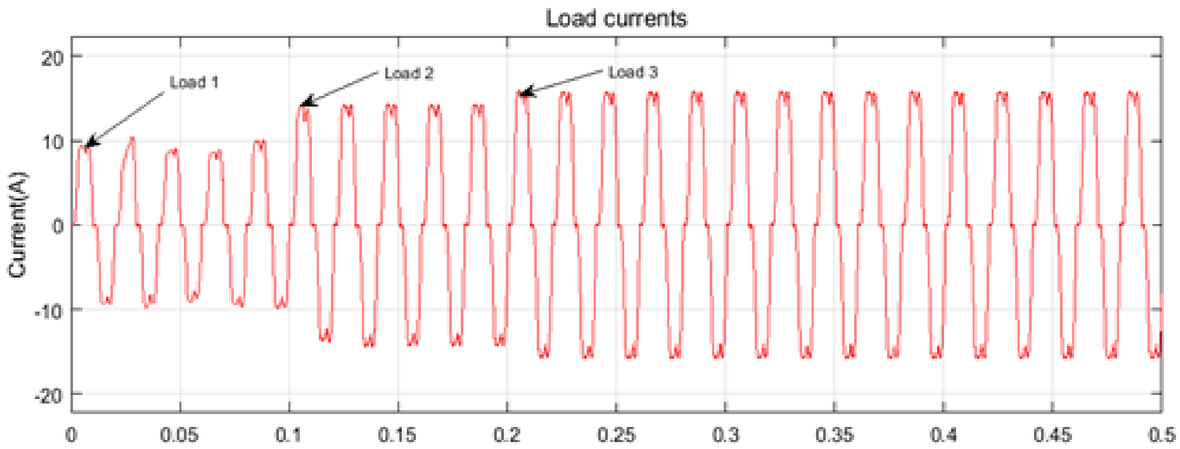


Figure IV.17 The Current of different loads (RL1, RL2, and RL3) integrated in the system

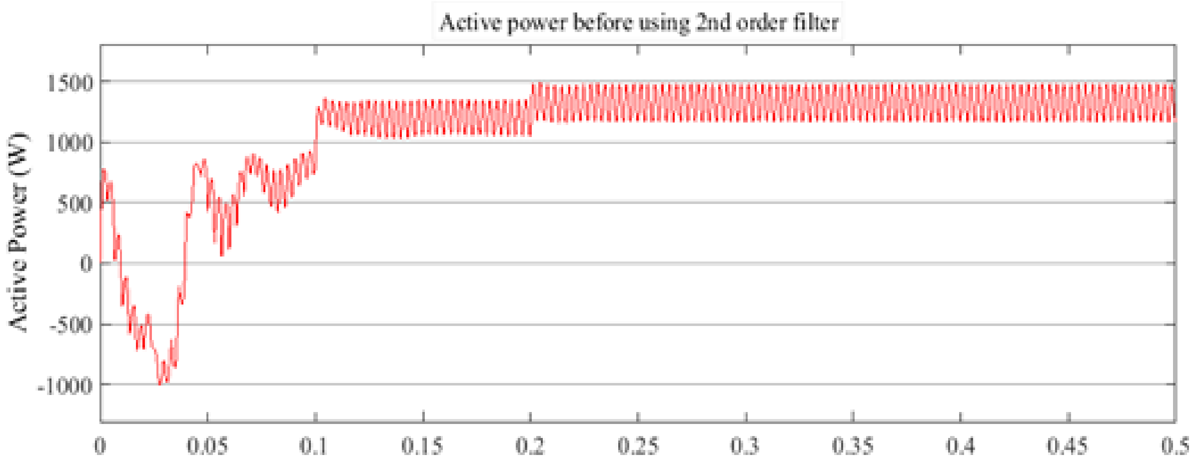


Figure IV.18 Active power consummation by the whole system

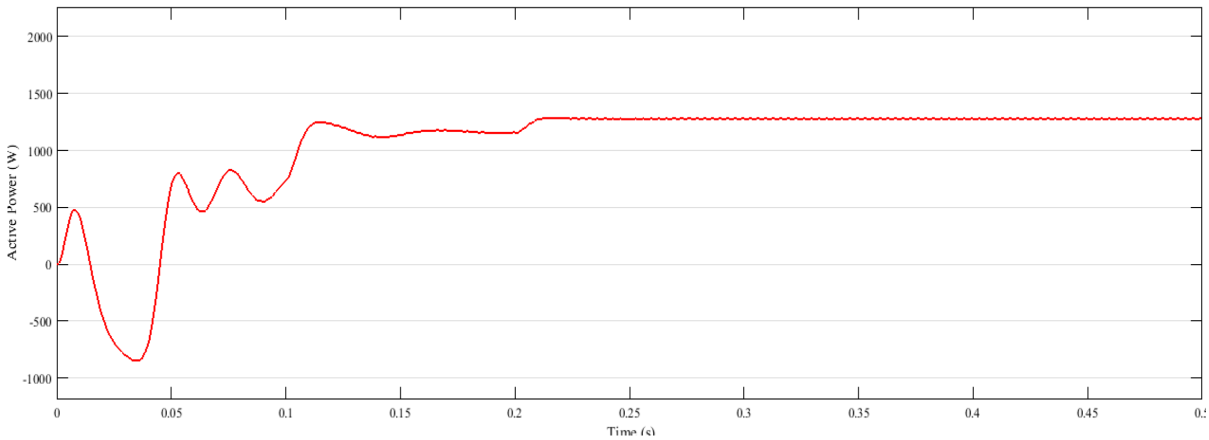


Figure IV.19 Active power consummation by the whole system after using a 2nd filter

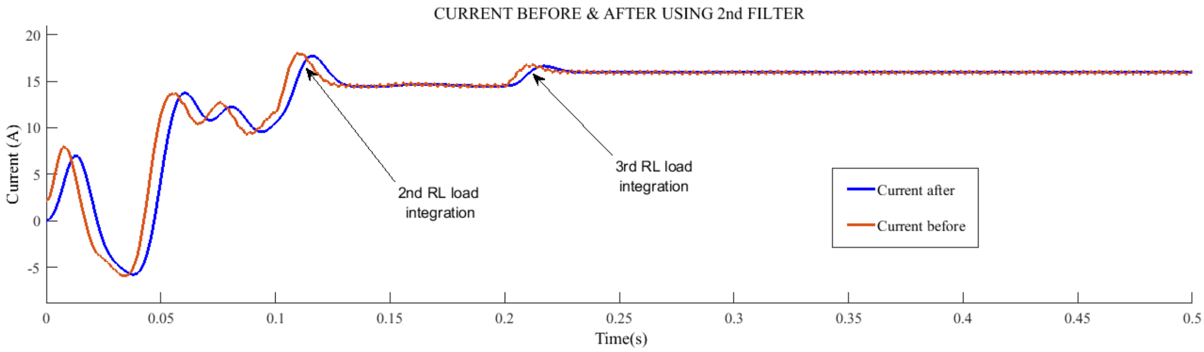


Figure IV.20 the fundamental current before and after applying the 2nd filter

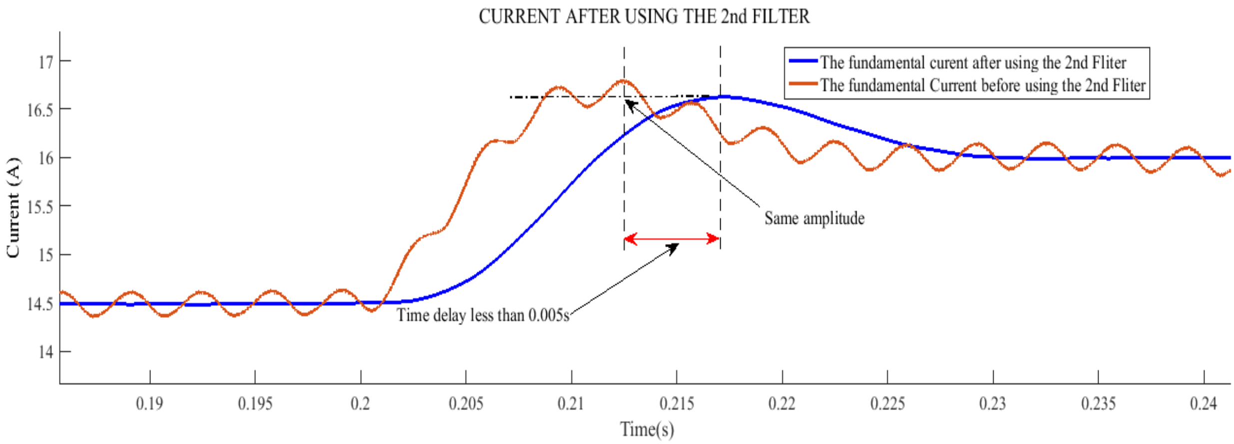


Figure IV.21 Elimination of the ripple presented in fundamental current waveform after using the 2nd filter

On the other hand, the DC bus voltage reaches its reference value fixed, in our case, at 120 V, and this, after only 100ms. The voltage Vdc presents oscillations due to those of the active power changed in different instant of time.

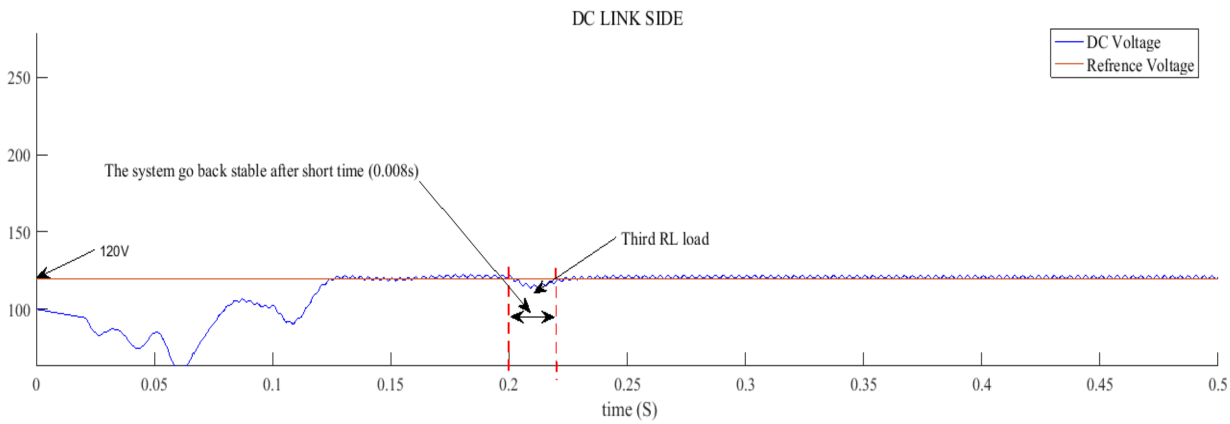


Figure IV.22 DC bus voltage

Source voltage and current returned to phase as soon as the APF is started

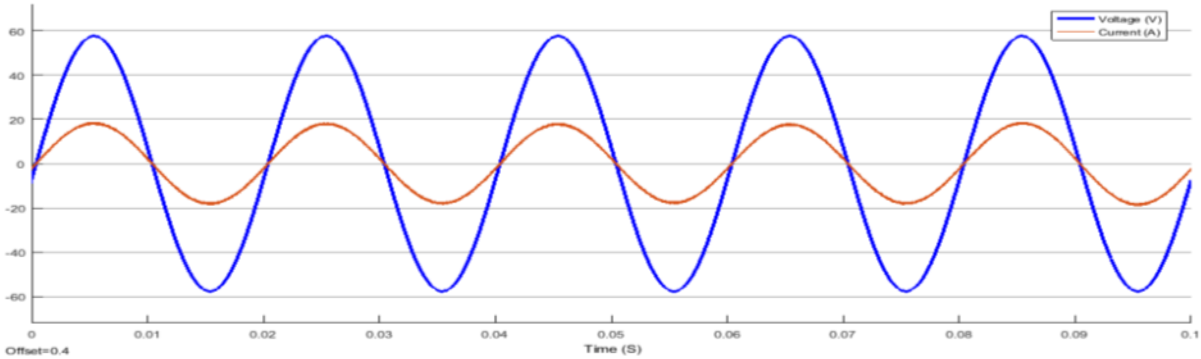


Figure IV.23 Voltage in phase with current after using APF

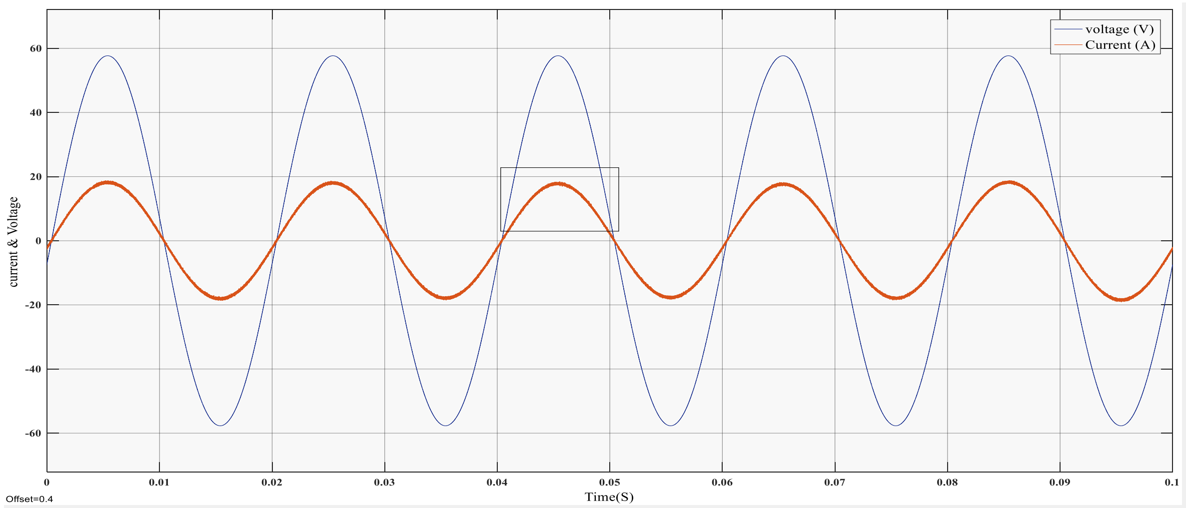


Figure IV.24 Voltage in phase with current after using APF using ZSI based on PV cells

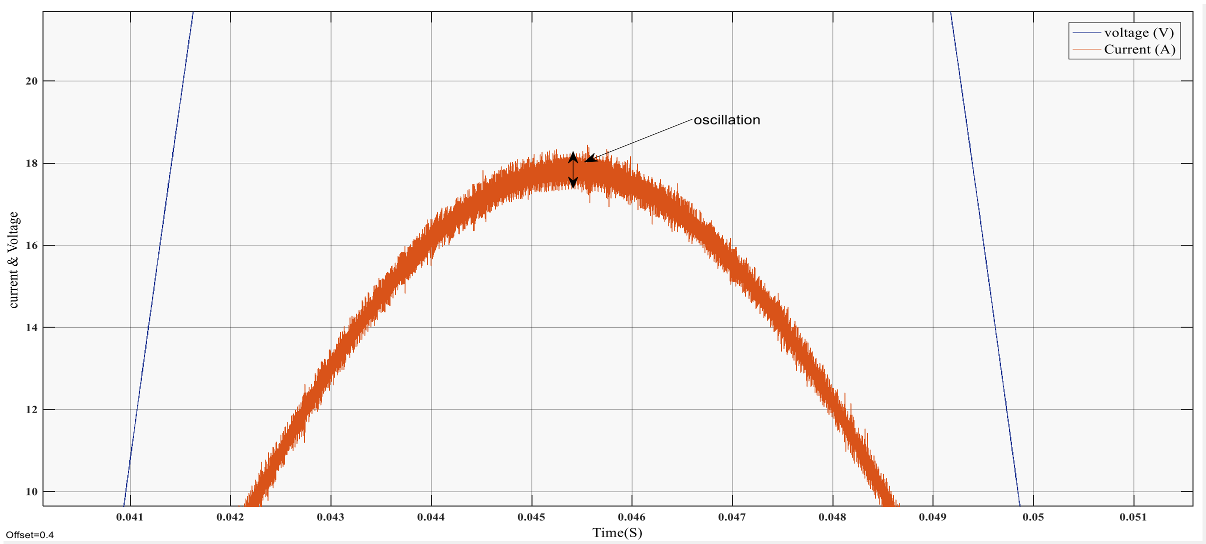


Figure IV.25 Current source after using APF using ZSI based on PV cells (Zoom)

Important oscillations appear on current source in case of using ZSI based on PV cells, this phenomenon illustrate when using MPPT based on P&O algorithm, however, this problems related to the oscillations around the MPP that it generates in steady state because the search procedure for the MPP must be repeated periodically, forcing the system to constantly oscillate around the MPP, once the latter is reached. These oscillations depend on the width of the step of the disturbance.

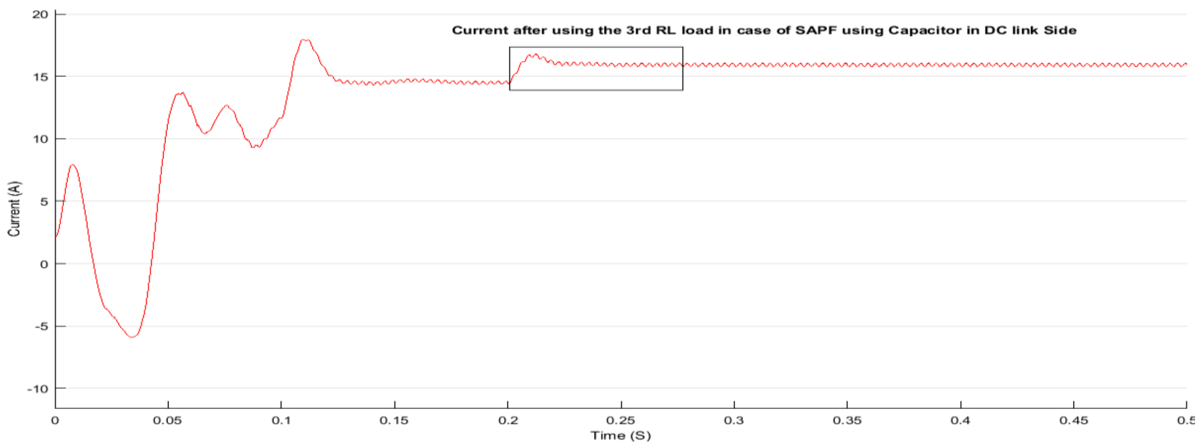


Figure IV.26 Current after using the 3rd RL load in case of APF based capacitor in the DC link Side

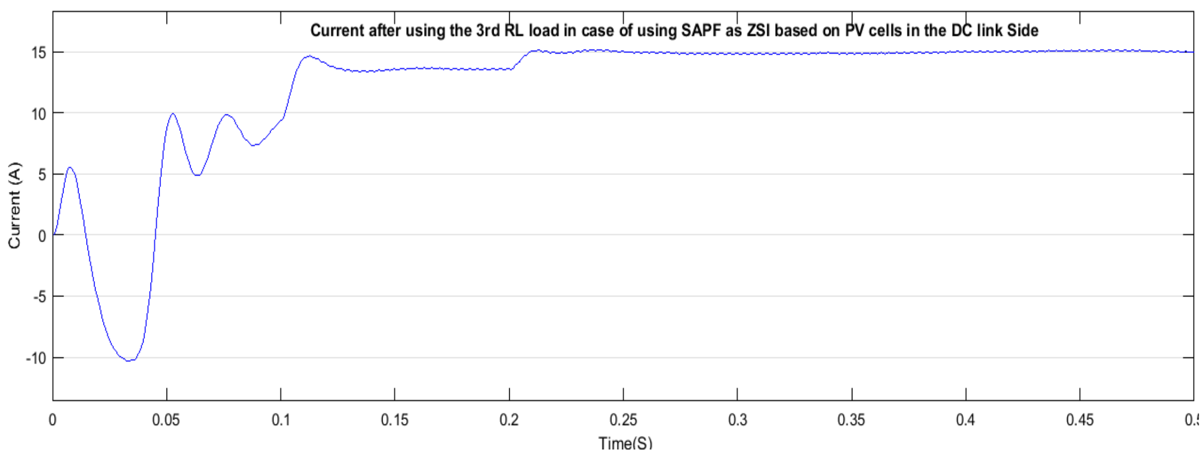


Figure IV.27 Current after using the 3rd RL load in case of ZSI based PV cells in the DC link Side

From figures (IV.26) and (IV.27), we can illustrate:

1. When the system introduce the 3rd RL load at 0.2s, there is an important overshoot approximately 10% as mention in the figure (IV.25); contrary in figure (IV.26) this phenomenon not appeared even at 0.1s when the system introduce the 2nd RL load and this because of the algorithm implemented P&O repeat periodically the searching point and measurement of the maximum power to deliver to the load. And

thus the MPPT algorithm will respond quickly to sudden changes in operating conditions

2. Nevertheless, losses increased under stable or slowly changing. In addition, we can see this in figure (IV.27) where the current is decreased to around 15A; while in figure; (IV.26) is about 16.5A.

IV.12.1 Behavior of APF with PBT control in dynamic mode

To verify the robustness of the PBT command and the behavior of the APF in transient regime, we worked with a double variation of the load RL1, RL2, and RL3 the first passage is made at time t = 0.1s, the second at 0.2s. We note in figure IV.26 that the load current has undergone a sudden increase (decrease), while that of the source preserves its dynamics and its sinusoidal form, without any disturbance at the level of the source voltage. On the other hand, the DC bus voltage temporarily decreases before it follows its reference value.

Finally, and from Table IV.5, IV.6 and IV.6, we can conclude that the APF with the proposed strategy, provides good compensation (THD <3%), whatever the network conditions (unbalanced grid voltage and unbalanced loads), with a short response time (t <100 ms) concerning the DC bus voltage to reach its reference.

The previous simulation results are summarized in the following table:

	Va		Vb		Vc	
% Of unbalance grid voltage	RMS(V)	THD%	RMS(V)	THD%	RMS(V)	THD%
0%	57.8	1.115	57.8	1.115	57.8	1.115
10%	57.8	1.315	52.02	1.320	63.58	1.288
20%	57.8	1.773	46.24	1.822	69.36	1.760
30%	57.8	2.294	40.46	2.38	75.14	2.263

Table IV.5 Simulation results in case of unbalanced grid voltage using conventional SAPF

	Va		Vb		Vc	
% Of unbalance grid voltage	RMS(V)	THD%	RMS(V)	THD%	RMS(V)	THD%
0%	57.8	1.945	57.8	1.945	57.8	1.945
10%	57.8	2.054	52.02	2.214	63.58	2.358
20%	57.8	2.27	46.24	2.413	69.36	2.398
30%	57.8	2.613	40.46	2.894	75.14	2.814

Table IV.6 Simulation results in case of unbalanced grid voltage using SAPF ZSI

Technical used	THD%
Modified PLL structure	2.7
Self-tuning filter	2.30
2nd order low pass filter wavelet-based multiresolution	2.08
Icosα	1.25
Presented work	1.115

Table IV.7 Simulation results of other technics with presented work

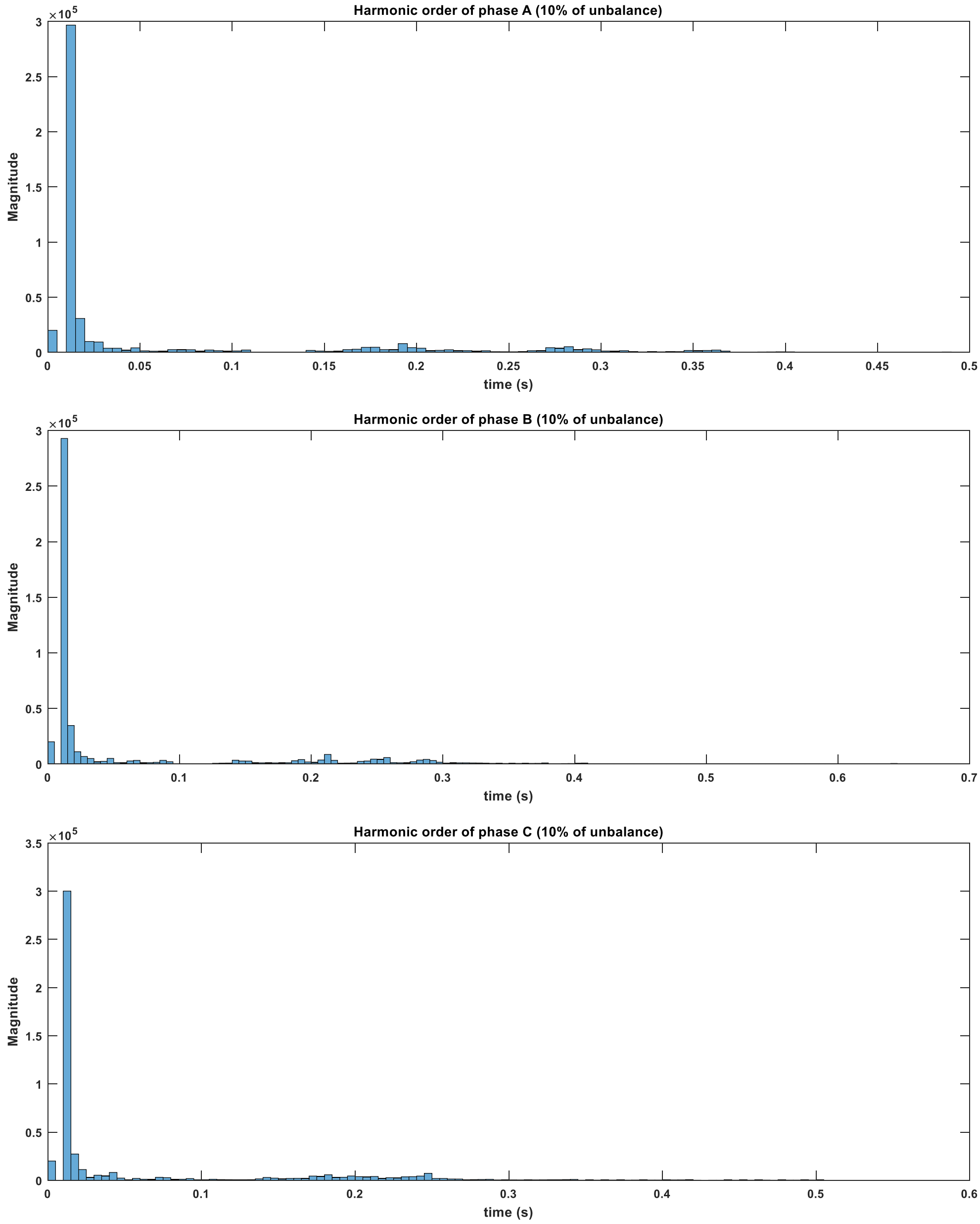


Figure IV.28 Harmonic Order of Phase A,B,C under 10% of unbalanced grid voltage

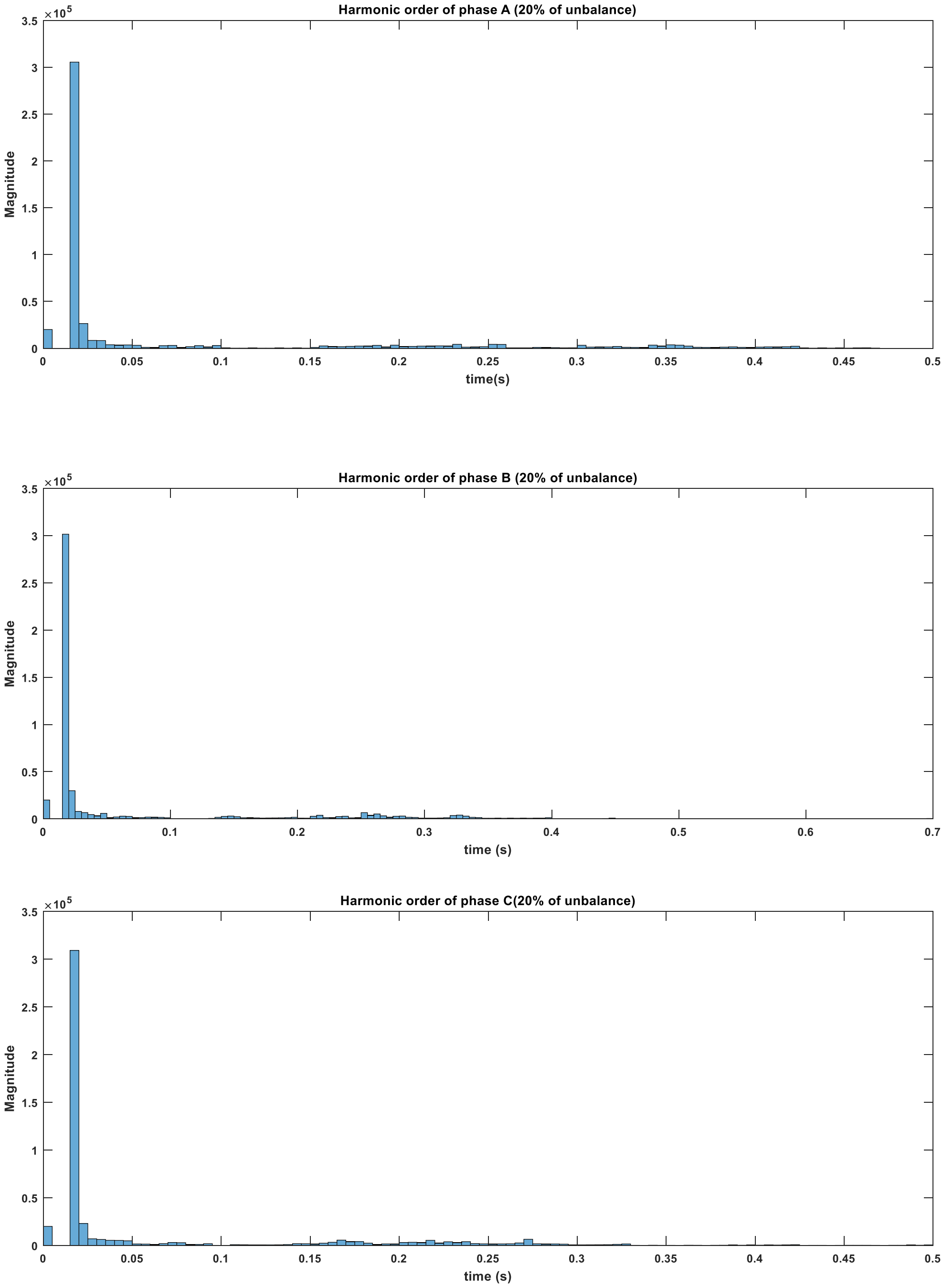


Figure IV.29 Harmonic Order of Phase A,B,C under 20% of unbalanced grid voltage

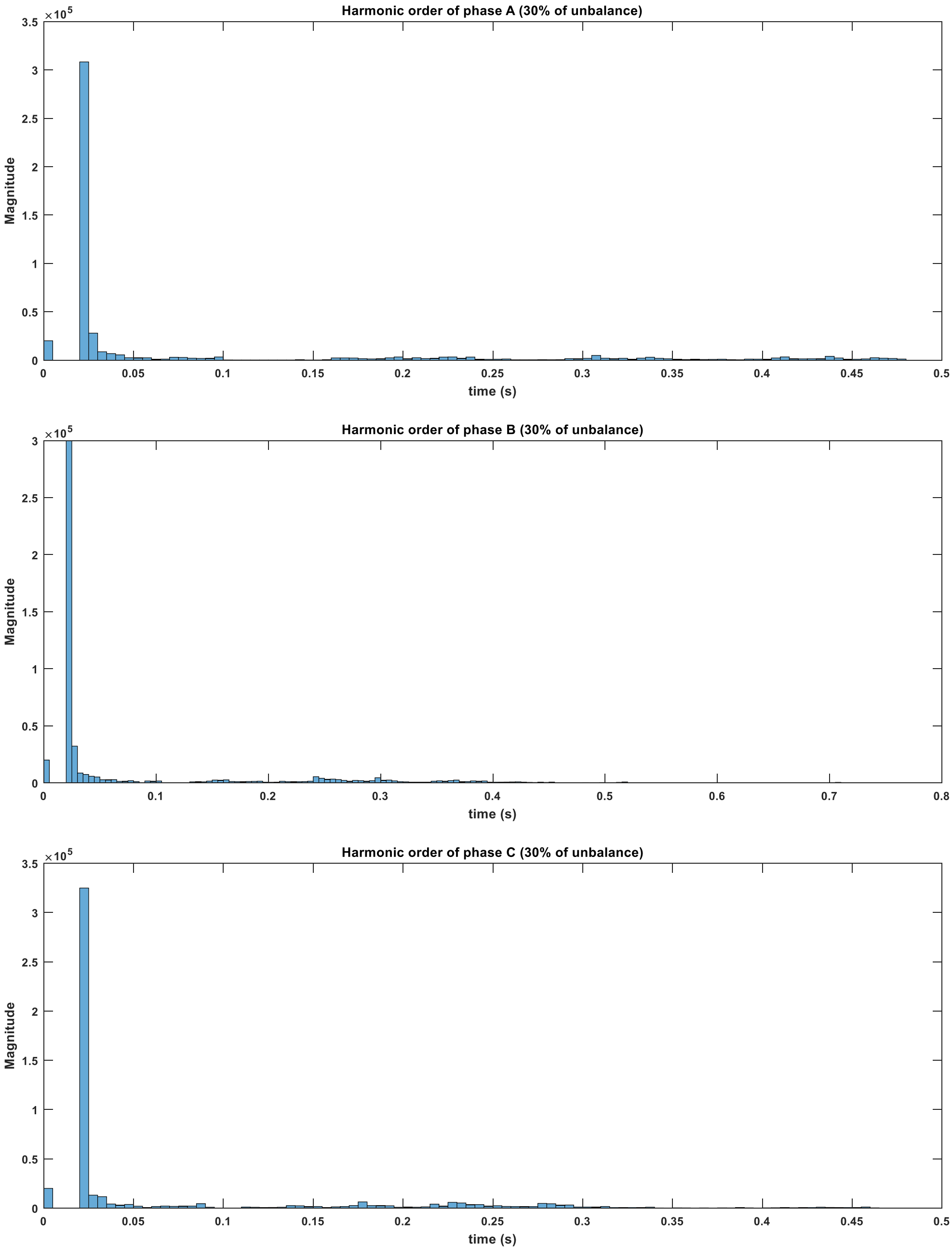


Figure IV.30 Harmonic Order of Phase A,B,C under 30% of unbalanced grid voltage

IV.13 Conclusion

This chapter has focused on the application of Power Balance Theory in the control of the parallel active filter using two filters in cascade to distinguish between the fundamental and the perturbed current. The generation of source reference currents based on DC voltage regulation has been used in direct control by introducing the tracking Anti windup to eliminate the saturation.

In the first part of the simulation, we used voltage source inverter VSI with a capacitor in the link DC side, and in the second part, we replace the capacitor by PV cells and we introduce ZSI where the possibility of simultaneously triggering the two (02) switches of the same cell (arm), which is strictly prohibited in conventional voltage inverters.

By using MPPT based perturbed and observer algorithm, we guarantee the maximum power generated by the PV cells and thus a constant DC voltage on the DC link side.

The PBT method has demonstrated its ability to adapt to structures for different loads in the presence of a strongly disturbed and unbalanced network in two topologies; where the THD% is about 1.115 for balanced and 2.294 for up to 30% of unbalance source voltage,while we registrar a slight difference in the second topology, where the THD% is about 1.945 for balanced and 2.613 which the other methods have failed to do.

IV.14 General Conclusion

This study is part of the work carried out within the LAADI laboratory on the subject of the control of static converters for active filtering for power quality purpose. The work carried out in this thesis focused on improving the quality of electrical energy via compensators connected to the electrical network.

An investigation was made to characterize the problem of power quality on the one hand and on the other hand to explore the possibilities offered by the control algorithms associated with the converters. The literature review carried out in the first chapter shows how important it is to reduce the degradation of energy quality in terms of both distortion rate and imbalances.

We have dealt with the problem of harmonic disturbances or distortions generated by non-linear loads connected to electrical networks; the origins and harmful effects of these disturbances were addressed and the standards in force were presented.

Thus, we presented, in a general way, the traditional and modern solutions used in filtering: passive filters, active filters or even the combination of the two.

We have presented the state of the art of control strategies proposed in the literature, namely the different types of current control.

The state of the art carried out perfectly positions the problematic linked to methods of extracting harmonics in an environment disturbed in tension.

The main regulators and finally the different control techniques.

The objectives of the APF structures and their controls are to compensate for harmonic currents and the reactive power absorbed by non-linear loads connected to the networks and to improve filtering performance.

We studied the parallel active filter with voltage structure. The strategy used is that of the active and reactive instantaneous powers, and this for three different structures, with conventional PLL, with modified PLL and with two very high selectivity filters (HSF), said PQ modified.

The simulations were carried out using **MATLAB/Simulink™ tools**. The simulation results allowed us to demonstrate the performance and efficiency of the parallel active filter for the proposed commands. We also studied the behaviour of the active filter in transient, permanent and unbalanced conditions with or without distortion.

The proposed method developed and applied to the control of the inverter mounted in active filtering, gave very satisfactory results in terms of filtering, and showed the role of control laws.

The PBT method has demonstrated its ability to adapt to structures for different loads in the presence of a strongly disturbed and unbalanced network in two topologies; where the THD% is about 1.115 for balanced and 2.294 for up to 30% of unbalance source voltage,while we registrar a slight difference in the second topology, where the THD% is about 1.945 for balanced and 2.613 which the other methods have failed to do.

Among the prospects, it becomes possible to apply this command for filtering with multi-level converters in order to combine the strengths of a structure with the recognized advantages of a command. Indeed, the recent progress made on multi-level converters, both in terms of structures and components, makes it possible to envisage medium voltage operations with very high bandwidths. These new converters are very interesting elements for cleaning up networks and we think that the proposed method could be used effectively.

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