COMPARATIVE STUDY OF PASSIVE, SERIES AND SHUNT ACTIVE POWER FILTERS WITH HYBRID FILTERS ON NONLINEAR LOADS

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We certify that this thesis is satisfactory for the award of the degree of

Master of Science in Electrical and Electronic Engineering

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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Signature:

Date:

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ÖZET

Günümüzde lineer olmayan yükler elektrik kullanımında artış göstermiştir. Lineer olmayan yükler şebekeye harmonik pompalamaktadır. Bu sebeple şebeke akım ve gerilimleri sinuzoit olmayan şekiller almaktadır. Bu tez harmonik problemlerini ve farklı çözüm yöntemlerini sunmaktadır. Farklı çözüm yöntemleri karşılaştırılmakta bu yöntemlerin güçlü ve zayıf yönleri irdelenmektedir. Harmoniklerin filtrelenmesinde paralel aktif filtreler temel fitreleme yöntemi olarak tanımlanmaktadır. Hibrid filtreler Aktif ve Pasif filtrelerin bileşiminden oluşmaktadır. Bu tezde hibrid bir aktif güç filtresi simule edilerek farklı başka filtreler MATLAB/ Simulink programı ile modellenerek simule edilmiş ve sonuçlar karşılaştırılarak irdelenmiştir.

Anahtar Kelimeler: Aktif Güç Filtresi, Hibrid Filtre, Seri Aktif Filtre, Paralel Aktif Güç Filtresi, Harmonikler, Lineer olmayan Yükler, Pasif Filtreler.

ABSTRACT

Recently, the use of non-linear loads has expanded and covered different fields of electricity. Bridge rectifiers, line converters, and switching mode power supplies are the most important used non-linear loads. Non-linear loads inject harmonic currents into the electrical grid. The grid currents and voltages become non-sinusoidal having different types of disturbances. The flow of these harmonic currents and voltages into the supply affect the power systems and cause noises in the user side. As a result, the quality of the electrical power currents and voltages has become an important aspect in the last decades. Active power filters have been introduced as efficient devices for power quality improvement as like as reactive power compensation. In this work, harmonic problem are introduced and discussed. The different harmonic solutions are presented and discussed. A comparison between the results presented in the literary is held and the points of strength and weakness are discussed. Recently, artificial intelligence including fuzzy logic and neural networks has been introduced into the active filtering topologies. The use of these intelligent non-linear topologies has improved the performance and efficiency of the active filtering. In this work, the study are limited to the linear methods to show the usefulness and capability of active and hybrid filters to compensate harmonics.

Parallel active power filter is introduced as the main filter for harmonic currents. The use of Series Active Power Filter for filtering the harmonics of the voltage is also discussed. The passive filters are used also for elimination of harmonic currents and voltages. The use of hybrid filters composed of parallel active power filter with passive filters, or series active power filter with passive filters is applied and studied. Different studied filters and topologies are implemented in MATLAB\Similink. Simulation results are tabulated and discussed. A comparison between the results obtained in this work and other works in literature is carried out and discussed.

***Keywords**:* Active Power Filters, Hybrid Filters, Series Active Filters, Parallel Active Power Filters, Harmonics, Non Linear Loads, Passive Filters.

Dedicated to my memory of my parents, with love to my wife and all my family who have been always with me . . .

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LIST OF USED SYMBOLS

PQ: Active and reactive instantaneous power.

L_f : Active power filter's inductance.

R_f : Active power filter's resistance.

S : Apparent power.

C : Capacitance of direct current capacitor.

V_{dc} : Capacitor's voltage.

k_i, k_p : Gains of PI controller.

f_c : Cut off frequency of a filter.

d-q: Synchronous plan axis.

i_{fabc} : Filter currents.

$i_{f\alpha\beta}$: Filter currents in stationary reference frame.

i_{fdq} : Filter currents in synchronous reference frame.

f : Fundamental frequency of grid.

i_{sabc} : Grid currents.

$i_{s\alpha\beta}$: Grid currents in the stationary reference.

i_{sdq} : Grid currents in the synchronous reference.

L_s : Grid inductance.

R_s : Grid resistance.

v_{sabc} : Grid voltage system.

p : Instantaneous active power.

q : Instantaneous reactive power.

i_{labc} : Load currents.

I_d : Rectified current.

U_d : Rectified voltage.

i_{fabc}^{ref} : Reference filter's currents.

T_s : Switching period.

LIST OF USED ABBREVIATIONS

P:	Active power.
AC:	Alternative current.
APF:	Active power filter.
S:	Apparent power.
DC:	Direct current.
F_d :	Distortion factor.
F:	Farad.
f:	Frequency.
GTO:	Gate turn OFF thyristor.
H:	Henry.
HAPF:	Hybrid active power filter.
Hz:	Hertz.
IGBT:	Insulated gate bipolar transistor.
IP :	Integral proportional controller.
LPF :	Low pass filter.
MOSFET:	Metal Oxide Silicon Field Effect Transistor.
PF:	Power factor.
PI :	Proportional integral controller.
PLL:	Phase locked loop.
PWM:	Pulse width modulation.
PAPF	Parallel active power filter
Q:	Reactive power.
RLC:	Resistor, inductor, and capacitor.
RMS:	Root mean square value.
SAPF:	Series active power filter.
SVPWM:	Space vector pulse width modulation.
THD:	Total harmonic distortion.
UPQC:	Unified power quality conditioner.
VAr:	Reactive Volt Ampere.
VSC:	Voltage source converter.
VSI:	Voltage source inverter.

CHAPTER ONE

INTRODUCTION

1.1 Overview

In this chapter, the different problems of nonlinear loads and the spread of harmonics into power grids are discussed and presented. The voltages and current harmonic problems have been discussed with a nice literature review on the nonlinear problems are discussed.

1.2 Introduction

The increasing use of nonlinear loads which use switching elements has caused many power quality problems. The harmonic emission is increasing noticeably with the development of power electronics devices. The spread of harmonics into power grid causes many problems for the users of these power grids. It affects the normal function of the devices connected to the grid. Harmonic currents can cause the creation of harmonic voltages whose spread can be dangerous for the different users of the electrical power. Control systems, protection circuits, communication systems, and biomedical devices are the most affected devices by harmonic pollution. Different standards and regulations have been adopted by the international electrical committees like IEC and IEEE limiting the harmonic emission of the loads.

Problems of system voltage unbalances and sudden changes in the grid voltages are an important issue in electrical engineering. Many devices are designed to work under limited ranges of voltage and frequency. The sudden changes in the voltage can either affect the function of the devices or even stop their function permanently. For that reason, the use of different types of voltage regulators and protection devices is an important precaution. These regulators can protect the connected devices from voltage variations by keeping the load side of the grid at a fixed voltage level. The main cause of voltage variations in power systems is the turning on and off of the electrical motors. These motors are absorbing high currents in the starting phase of function for a duration of many seconds. The simultaneous starting of many motors in the same time can cause huge variations in the grid voltage.

In order to face the harmonic problems, different solutions have been proposed. These solutions differ from applying modifications on the grid or the load, so it emits fewer harmonic to connecting special designed devices to suppress the harmonics and filter them.

The simplest method of harmonic filtering was to use RLC elements under the form of filter banks adjusted to offer a short circuit or low impedance for the frequencies of harmonics to be cancelled. These filters will present high impedance for the main frequency and called passive filters. Passive filters were the first proposed solutions due to their simplicity and ease of installation. They can be considered as good approach in the case of stable static systems where many variations are not expected. In the case of dynamic non predictable systems, the passive filters can be less suitable for the reason of their static behavior and that they can't react to the changes in the load. Also they can cause resonance with some frequencies which can cause some stability troubles.

Active filters were the introduced in the 80^{th} of the last century into the electrical power systems. They are dynamic systems designed carefully to compensate harmonic currents and voltages dynamically. They can react instantly for the load and system changes without the need for any interrupt. Researchers are paying more and more attention for active filters since the day they were introduced. The main advantage of the active filters is their flexibility for the system parameters. They can change effectively their behavior based on the system parameters.

Active power filters are divided into different categories; some are used for voltage regulation and voltage harmonics mitigation. Other active filters can be used for filtering the currents and eliminating their harmonics. The third type can be used for simultaneous voltage regulation and harmonic currents cancelling. Series active power filters are used for voltage regulation. Shunt APF was proposed for current harmonics and reactive power compensation. The Unified Power Quality Filter or Conditioner combines the two types Shunt and Series APF in one device responsible for the simultaneous compensation of voltage, current harmonics and reactive power. Different combinations of APFs with passive filters have been also used and proposed in the literary in the so-called Hybrid APFs (HAPFs). The combination between the simple and the modern in one HAPF has the aim of amelioration of different types of APF compensation performance, also the minimization of cost and complexity of compensation systems. It is considered to combine the advantages of old passive filter and the new APFs and reject the drawbacks related to each of them when used individually.

Although there are different types of APF, the Shunt APF is still the most famous and used type APF. The main function of Shunt Active Power Filter is to cancel harmonic currents occurring in power grids. The principle of SAPF is to generate harmonic currents equal in magnitude and opposite in phase to those harmonics that circulate in the grid. The non-linear loads absorb non-sinusoidal currents from the grid. The simulation of different structures was carried out windows 7 PC with a sampling time of $1e^{-6}$ S.

1.3 Literature Review

Active power filters and power quality issues have been widely discussed in literary. Many aspects of active and passive filtering have been covered with a lot of researches. Some of the researchers have covered the analytical study of the power quality problems. Others have concentrated on the quantitative description of harmonics and their effects on the power losses and consumers. Other researches were pointed toward the study of different possibilities offered to treat the power quality problems. In other researches, the different control methods of active power filters were discussed and improved. While others discussed the structure of active filters itself and proposed new topologies for the different types of active filters. Concerning the topologies of active filters, the two level and three level power inverters were the main topologies used for active filtering. Multilevel filters were also discussed in literary but with less concentration due to their complex structure and difficulties of their control. Control methods of active filters based on PQ theory and DQ theory were the most discussed methods. The use of PI controllers or fuzzy logic controllers were discussed widely also.

Fuzzy logic control and sliding mode current control with sine multiplication theory was presented by (Sharmeela et al., 2007). Instantaneous active and reactive power method with hysteresis control was discussed in (Pei Ling, 2004). The function of APF with DC power generation was proposed in (Cichowlas, 2004). In (Prusty, 2011), fuzzy logic and hysteresis control based on synchronous reference mode function was presented and discussed.

In (Cheng, 2007), the use of PQ, synchronous reference method and sine multiplication theory was discussed. PI and hysteresis controllers were also used in this research. Sine multiplication theory with IP current controller was presented in (Chaoui et al., 2006). Fuzzy logic controller with sine multiplication method in single phase Active Power Filter has been presented in (Colak et al., 2010). In (Fei, Jingrong, and Yu, 2010), an adaptive fuzzy low pass filter for harmonic extraction has been proposed with shunt active power filter. Three phase active power filter based on DQ method and space vector pulse width modulation control was studied in (Li-ping, 2010). PQ theory, active and reactive currents theory performance was studied in (Xi et al., 2010). Study of PQ, DQ, constant active and reactive power theory, and unity power factor algorithm have been proposed in (El-Habrouk, 1998). Sliding mode based DC voltage controller for grid current's peak detection was proposed by (Singh et al., 1997).

(Akagi, 1997) discussed the shunt active power filter and its best connection point. Different connections configuration were discussed and analyzed. In (Al-zamil et al., 2001) a passive series filter with shunt active power filter configuration was proposed and discussed. In (Tey et al., 2005) an adaptive topology of shunt active power filter was discussed. Neural network based control approach was proposed and discussed. Three single phase shunt active power filters were designed for the compensation of a three phase four wire system harmonics was proposed by (Hou et al., 2010). Stationary reference frame based active power filter topology was proposed for the compensation of unbalanced system has been discussed in (Asadi et al., 2010).

Fuzzy logic control of shunt active power filter using PQ theory and sine multiplication method was studied in (Georgios, 2010). A shunt active power filter connected to a photovoltaic array for harmonic and reactive power compensation has been presented in (Jian et al., 2011). (Jian et al., 2011). (Zheng et al., 1991) and (Bhattacharya et al., 1993) presented a hybrid topology composed of shunt passive and series active power filters. Hybrid series active filter was also discussed in (Bhattacharya et al., 1995). Hybrid series active power filter controlled using synchronous reference frame was discussed in (Bor-Ren & Yang, 2001). The series active power filter for harmonic currents cancelling was proposed in (Bor-Ren et al., 2002). In (A Bakar, 2007), a hybrid active series parallel passive power filter was implemented for voltage and current harmonic elimination. Series active filter for the neutral was proposed for cancelling the third harmonic of a three phase four wire systems was proposed.

Many other papers and researches have been written and discussed in the field of active and passive filtering. The subject of power quality and power filtering is a wide and developing subject that can expand continuously with the development of processing systems and power electronics.

1.4 Thesis Overview

This thesis contains four chapters arranged as follow:
First chapter presents a general introduction on power quality and active power filters. It includes also a literature review and thesis overview.

The second chapter discusses different power quality problems and focuses on the study of harmonics, harmonic sources, and their effects on grids and equipments. It discusses also the different solutions of harmonic problems.

In the third chapter, the study is pointed toward the parallel and series active power filters and their uses. Also the study of passive filters and the combination of hybrid filters is proposed. Many harmonic extraction methods are introduced in this chapter including the active and reactive instantaneous power theory and the synchronous reference theory. The results of all studied topologies of active filters were tabulated and discussed in the fourth chapter. All the results were discussed and printed carefully. A comparison between the different methods and their efficiency in harmonic elimination in addition to their stability has been discussed.

1.5 Summary

This chapter has been summarized the introduction to the topologies of active power filters, the problems caused by current and voltages harmonics in the power grids are discussed. The literature review overall the thesis is discussed.

CHAPTER TWO

PROBLEMS IN THE POWER GRIDS

2.1 Overview

In this chapter, the different problems of power grids are discussed and presented. The distortion of current and voltage and current signals are presented. The effect of voltage and current distortion on the power grids and users' devices are discussed and different solutions of the power grids problems are presented. Passive, active and hybrid filters and their uses as power quality conditioners were discussed and their advantages and disadvantages were presented. The aim of this chapter is to present the different power problems in combination with their different old and modern solutions.

2.2 Problems in the Power Grids

The power grid systems face usually different unexpected changes in their voltages and currents. These changes vary between voltage sags and swells, voltage interruption, frequency changes, harmonics and many other instant troubles. The different troubles which occur in the power grids are due to the existence of different loads which are connected to these grids. The conditions of starting and braking of electrical motors and power electronics devices are the main causes of voltage and current troubles. The increasing spread of the use of power electronic switching devices has increased the pollution levels in electrical grids and cause more problems related to the stability of these grids. As consequence, researchers have proposed different methods for the solution of the problems related to the power quality and pollution. The proposed solutions vary between simple low efficiency solutions and more complex high efficiency solutions, in addition to the compound solutions where both the complex and simple solutions are used together to increase the stability and efficiency of systems. In this chapter of our thesis, different power grids' problems in addition to their solutions will be presented and discussed.

2.2.1 Voltage variation for short period

A problem in one of the systems connected to the grid, starting of high power electric motors, in addition to the currents rush into power electronic devices cause instantaneous variation in the voltage for short period. The change can be in the form of increase or decrease in the grid voltage. The increase in voltage varies between 10-90% of the nominal value and can last from 10 milliseconds to the period of one minute. The increase or decrease of voltage can affect the function of the connected devices to the grid and higher increase of voltage can cause the permanent failure of these devices (Kmail, 2012).

2.2.2 Frequency variation

Under normal conditions, the frequency of the electrical power systems is either 50 Hz in some countries or 60 Hz in the other countries. A change of frequency of 0.5 Hz less or more than the nominal frequency are normally accepted due to the continuous changes of the load levels on the main power stations. This continuous changes cause instant changes in the speed of main generators which mostly last for very short period before the speed automatic regulators adjust the speed to its nominal frequency. These changes in the frequency of the mains affect mainly the auxiliary power sources like solar and wind energy connected to the grid (Kmail, 2012).

2.2.3 Voltage interruption

It happened when the voltage of the grid goes less than 10% of its nominal value for a short period of time. It can be caused by troubles in the electric systems, control systems or the different devices connected to the grid. The main property of the voltage interrupt is the period in which it happens (Kmail, 2012).

2.2.4 Voltage sags

They appear as an effect of the use of switching devices like MOSFETs, IGBTs, TRIACs and other power electronic components. The start of big induction machines also can cause voltage sags and swells. Short circuit and overload can also cause the voltage sags to happen. The protection equipment are the main affected devices by the voltage sags and swells.

2.2.5 Harmonics

Power systems work under nominal frequency of 50 or 60 Hz. Small changes in the frequency can happen because of increase or decrease of grids loads. Some loads produce currents and voltages with higher frequencies and inject them into the electrical grids. The frequencies of these currents and voltages are integer multiple of the fundamental frequencies. These high frequency currents and voltages are known by the name of harmonics. The loads which cause harmonics are called non-linear loads because the relation between the voltage applied on the load and the current drawn by the load is not linear and based of switching function. The rapid revolution in the industry of power electronic devices has increased the number of non-linear loads in the electric systems. Most of nowadays devices includes non-linear function device like power supplies which are based on switching mode function, motor drivers and many other devices. The concept of harmonics has been introduced first by the mathematician Joseph Fourier. Fourier proved that all non-sinusoidal signals can be decomposed into an infinite sum of sinusoidal signals with discrete frequencies and has given a formula to find these sinusoidal signals:

$$i(t) = I_0 + \sum_{h=1}^{\infty} I_h \cos(h\omega t + \varphi_h) \tag{2.1}$$

The first component given in the formula is the direct component with zero frequency. While the second shows the sum of the sinusoids of fundamental and the different harmonics. The next figure shows a non sinusoidal signal and its Fourier decomposition.

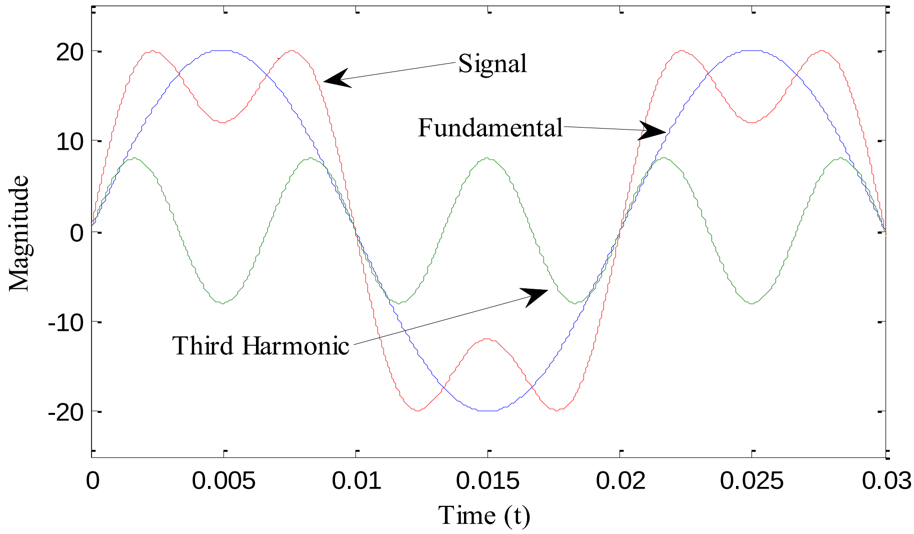


Figure 2.1: Harmonic components of a non sinusoidal signal

It is to be noticed that in three phase electrical systems, the ranges of harmonic existent are $6h \pm 1$ (A Bakar, 2007).

The harmonic currents can be produced by the excitation currents of transformers where the hysteresis cycle of a magnetic material and the saturation phenomena produce harmonics. The third harmonic is very important for the production of sinusoidal voltages at the secondary side of transformers. In three phase transformers with primary connected in Y connection, this third harmonic circulates between phases and neutral while in the D connection it keep circulating inside the transformer windings (Fitzgerald, Kingsley, and Umans, 2003). Arc furnaces, rectifiers, and many other loads will produce harmonics and inject them in the grid lines. Most utilities limit the allowable harmonic current levels to the values shown in IEEE 519.

2.2.6 Different measures of harmonics

There are many methods for the evaluation and quantification of the harmonic pollution existing in the power systems. These methods or quantities include: total harmonic distortion THD, the distortion factor and the crest factor.

2.2.6.1 Total harmonic distortion

The total harmonic distortion of a signal is a method of quantifying the harmonic distortion level that present in currents or voltages. It is known as the ratio of the total sum of the squares of all harmonic components to the squares of the fundamental frequency component. Harmonic distortion is caused by the introduction of waveforms at frequencies in multiples of the fundamental to the signal by different non-linear loads.

$$THD(\%) = \frac{\sqrt{\sum_{i=2}^{\infty} x_i^2}}{|x_1|} \tag{2.2}$$

The THD quantity is the most used quantity for harmonic description although it is suffering the problem of being not able to describe the stresses in capacitors because it is related to the peak values of signals (Prusty, 2011).

2.2.6.2 Distortion factor

It is known to be the ratio between the fundamental and the root mean squared value of a signal. It is well known that this ratio must be equal to 1 in an ideal sinusoidal signal. The level of harmonics increases with the decrease of the ratio.

$$F_d = \frac{I_{L1}}{I_{rms}} \tag{2.3}$$

2.2.6.3 Crest factor

From its name it is clear that is equal to the ratio between the peak value to the RMS value of a signal. In a pure sinusoidal signal this factor is equal to 1.41 and can increase till 5 in the highly distorted systems.

$$CF = \frac{crest\,value}{effective\,value} \tag{2.4}$$

2.2.7 Power factor and harmonics

Power factor is known as the ratio of active power to apparent power and is the cosine of the phase angle between the voltage and its current in an AC circuit. These quantities are defined for sinusoidal signals. Power factor can be improved by the use of capacitors to the power grid to draw a leading current and supply lagging VArs to the system. Power factor correction capacitors can be switched in and out automatically or manually as necessary to maintain the reactive power at minimum levels and for voltage control (Sueker, 2005).

For an ideal sinusoidal signal, the power factor is found by the ratio between the active and the apparent power. A low power factor means bad use of the electrical equipments. The apparent power is defined by:

$$S = V_{rms}.I_{rms} = V_{rms}.\sqrt{\frac{1}{T}\int_0^T i_L^2 dt} \tag{2.5}$$

And the active power P and reactive power Q are defined as:

$$\begin{aligned} P &= V_{rms}.I_{L1}.\cos(\alpha 1) \\ Q &= V_{rms}.I_{L1}.\sin(\alpha 1) \end{aligned} \tag{2.6}$$

As a result, the power factor will be given as:

$$\mathrm{P.F} = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} \tag{2.7}$$

If the system is producing harmonics to the power grid, an additional power by distorted power will appear and cause more losses. This power is defined by:

$$D = V_{rms}.\sqrt{\sum_{n=2}^{\infty} I_{Ln}^2} \tag{2.8}$$

In this case, the apparent power and the power factor will be defined by :

$$\begin{aligned} S &= \sqrt{P^2 + Q^2 + D^2} \\ PF &= \frac{P}{\sqrt{P^2 + Q^2 + D^2}} \end{aligned} \tag{2.9}$$

From the new formula of the power factor it is clear that the power factor in the case of existence of harmonics is less than the power factor in a harmonic free system. It can be concluded that the existence of harmonics increase power losses and applies extra stresses on the power transformers and transmission lines.

2.2.8 Effects of harmonics

Harmonic currents rush in the grids and can cause a number of problems. They can be trapped by power factor correction capacitors and overload them or cause resonant with them causing their failure. They can also cause problems in computers, telephone lines, motors, and power supplies, and may even cause transformer failures due to eddy current losses. The harmonic currents can be cancelled by using series capacitive inductive filters designed for the harmonic frequency. Such filters provide low impedance to the harmonic frequencies compared to the grid impedance. Good experience says that multiple resonant filters must be installed first at the lowest harmonic frequency of interest and then at the higher-frequencies (Sueker, 2005).

The effect of harmonic currents or voltages is a function of different loads sensitivity; some loads are more sensitive for harmonics where as other loads are slightly sensitive. The least sensitive loads are heating equipments of all types. The most sensitive kinds of equipments are the electronic devices which have been designed expecting an ideal sinusoidal voltage or current waveforms. Electric motors are the most popular loads which are situated between these two categories.

2.2.9 Harmonic currents sources

Nonlinear loads injecting non sinusoidal currents into the electrical supplies are the main source of harmonics. The bridge rectifiers of diodes are the most non-linear loads present in the power applications because they don’t need a control and they have long life duration with low cost (A Bakar, 2007). There are also many other harmonic producing loads with different harmonic emission levels (Prusty, 2011) and (Schneider E. I., 2008).

The feeding of non-linear loads generates harmonic currents which spread into the electrical grid. The flow of harmonics into the feeder impedances (transformers and grid) causes harmonic voltages in these feeders. Remembering that the conductor impedance increases with the frequencies of the currents passing through it; different impedance will appear for each range of current harmonics. The harmonic current of a given frequency will create through the impedance harmonic voltage. All the loads connected to the same feeder will be fed with the same harmonic voltage (Schneider E. I., 2008). The equivalent circuit per phase of a non-linear load connected to the grid is given by Figure 2.2.

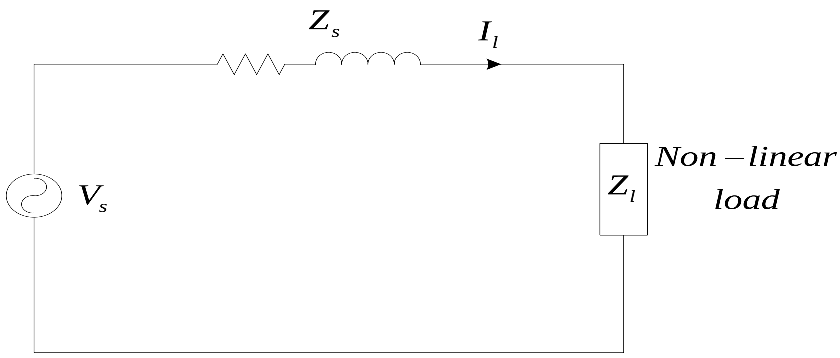


Figure 2.2: Equivalent circuit of a non-linear load connected to the grid

2.3 Treatment of Harmonic Problems

The purification of the currents and voltage in the electric systems is a very important issue for the users and the distributers of electrical power. The increasing use of harmonic emitting non-linear loads has implied the existence of more interest of finding solutions of harmonic problems. The harmonics are causing annual losses in all countries because of their effects on the grids in addition to the noise applied on the communication systems. International committees limit the acceptable harmonic emission that can be produced by different loads. Producers of electrical equipments try to produce equipments that meet the limitations and standards of these international committees. Users of electric grids are also encouraged continuously to use different means of filtering currents and voltages and improving power factor of their systems. Batteries of harmonic elimination and reactive power compensation are used to reduce the pollution levels and increase the efficiency of electric systems.

Since the mid of the 20th century, many classic and new solutions for harmonics elimination and power quality improvement were proposed in literary. These methods varies between the investigation in the load to reduce the harmonic emission amounts while the others impose the use of external special constructed filtering equipments that stop the expansion of harmonics toward the electric grids (Kmail, 2012). The main methods of harmonic limiting are the use of special connections of three phase power transformers that prevent the harmonic of defined orders from circulation through the neutral to the grid. The use of line reactors which prevent higher frequency harmonic from being spread into the grid is also another classic solution for the reduction of harmonics. More efficient solutions include the use of combination of passive elements connected to the distorted systems and calculated in concordance with defined levels of harmonics. These elements trap the harmonics before being spread to the grids. Many types of these filters have been proposed in the literary. These types include resonant, high pass, and resonant high pass filters in addition to other combinations of passive filters.

The use of especially constructed active filters has been introduced into literary by the beginning of the 80th of the last century. These active filters include shunt, series, and shunt series combination filter. The use of hybrid active and reactive filters has been considered as a useful solution for power quality problems.

2.3.1 Resonant filter

The resonant passive filter is constructed by an inductance connected in series with a capacitor calculated in accordance with the harmonic range that to be eliminated. This filter has low impedance to the concerned harmonics and enough high for the fundamental frequency. As a result there must be one filter for each harmonic range to be eliminated (Kmail, 2008). The equivalent circuit of the resonant filter with the harmonic source and grid impedance is shown in Figure 2.4.

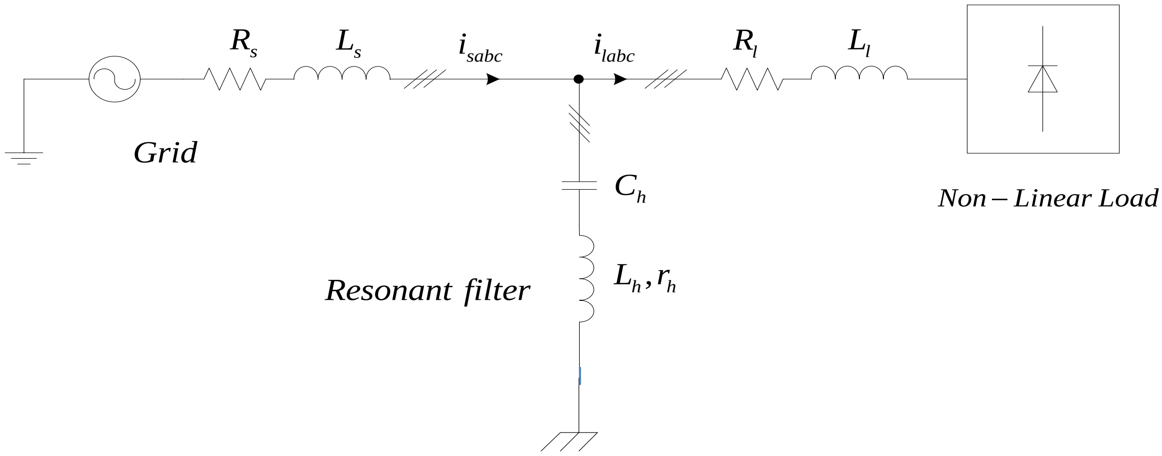


Figure 2.3: Resonant filter in parallel with non-linear load (Biricik et al., 2012)

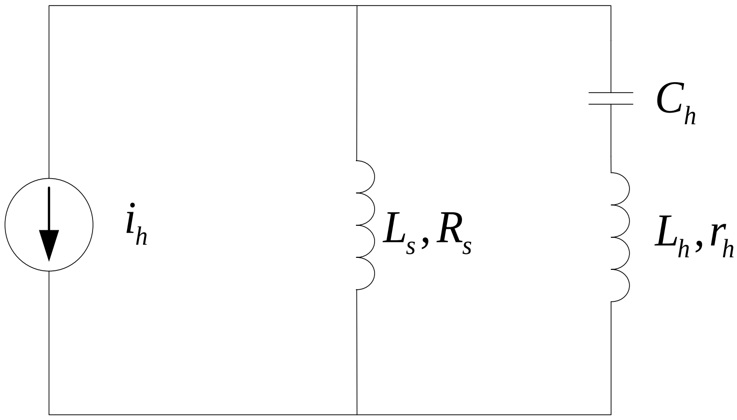
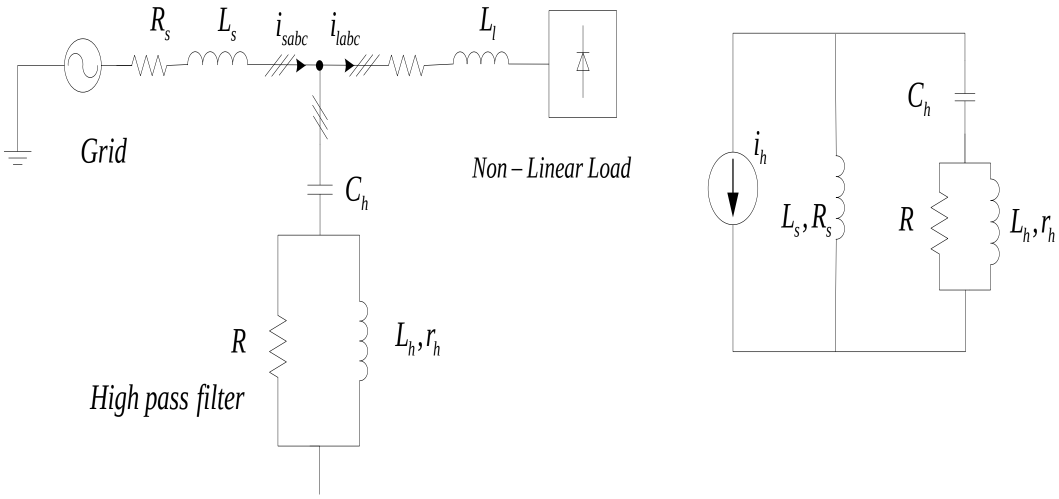


Figure 2.4: Equivalent circuit of resonant passive filter with the grid impedance

2.3.2 High pass filter

The high pass filter includes passive elements RLC as shown in Figure 2.5. The use of this filter is to eliminate the harmonics in a large band of frequencies. It is usually used in the suppression of high frequency harmonics that are enough away from the fundamental of the system. This insures that the filter will not affect the fundamental frequency of the system.



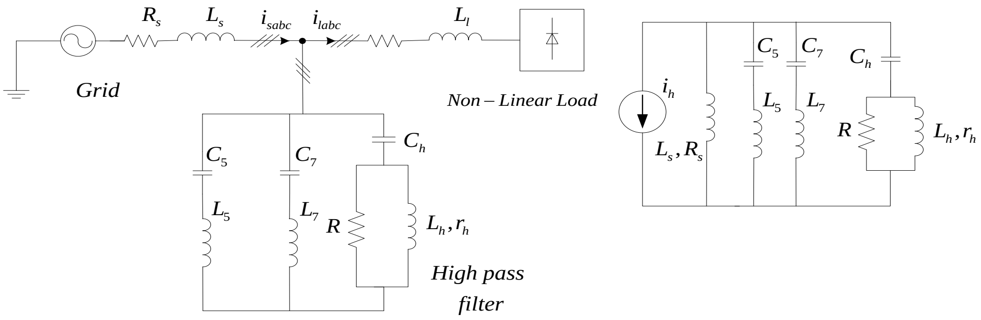
(a) Diagram of high pass

(b) Equivalent circuit of HPF

Figure 2.5: Diagram of the high pass filter with Equivalent circuit of the HPF (Kmail, 2012)

2.3.3 Resonant high pass filter

These filters are composed of resonant filters for certain harmonic ranges, connected in parallel with high pass filter to eliminate the higher harmonics. Figure 2.6 shows the connection of resonant filter for 5th and 7th harmonics with high pass filter.



(a) Diagram of the connection of amortized resonant filters (b) Equivalent circuit diagram

Figure 2.6: Circuit diagram of the resonant high pass filter (Cheng, 2007)

In general, the classic solutions used for harmonics reduction and power factor correction are composed of passive filters connected in parallel to trap the harmonic currents. These solutions enormously simple and widely used have at the same time important problems. These problems comprise mainly the possibility of resonance with some frequencies in addition to the lack of flexibility with the changes of load:

- The assembly of filter needs a brief awareness of the design of the electric grid.
- The sizing of the filter is dependent on the harmonic specter and the grid impedance.
- Due to the existence of voltage harmonics, some current harmonics can be generated by the passive filters and injected into the grid.
- The deviation of the source frequency affects the passive filter’s compensation characteristics. In power systems we consider a high variation of frequency with about 0.5 Hz.
- Any modifications in the grid (restructuring, new clients,… etc) can affect the adaptation of the passive filter. That is, any modifications in the grid must be accompanied with modifications in the passive filter.

- There is a risk of resonance between the grid and the passive filters at specified frequencies. To solve this problem the quality factor of the filter is reduced which provoke the consumption of active power.
- These circuits are capacitive for the fundamental frequency and they are considered as reactive power sources.

These problems make the use of passive filters difficult and useless in many cases. The grid parameters are dynamically changing and the harmonic specter is unpredictable. The use of passive filters in accordance with defined harmonics is not enough to alleviate grids harmonics.

New solutions were projected as competent solutions for the removal of electric grid harmonics in order to overcome the disadvantages of the conventional methods like passive filters (Anooja & Leena, 2013). Between these solutions we find two categories which are the most used:

- Active filters (series, parallel, or a combination of both of them in Unified Power Quality Conditioner (UPQC)).
- Hybrid filters composed of active and passive filters at once.

2.4 Active Power Filters

The purpose of the active power filters (APF) is to produce harmonic currents or voltages in an approach such that the grid current or voltage waves preserve the sinusoidal structure. The APFs can be connected to the grid in series (Series APF), parallel (PAPF) to compensate voltage harmonics or current harmonics correspondingly. Or can be connected with passive filters to build the hybrid filters (HAPF).

Active filters are fairly new types of devices for eliminating harmonics. This kind of filter is based on power electronic devices and is much more costly than passive filters. They have the individual advantage that they do not resonate with the power system and they work autonomously with respect to the system impedance. They are used in difficult circumstances where passive filters can’t work effectively because of resonance problems and they don’t have any intervention with other elements installed anywhere in the power system (Javadi, 2009).

The active filters have many other advantages over the old methods for harmonic compensation such as:

- Adjustment with the variation of the loads.
- Opportunity of selective harmonics compensation.
- Limitations in the compensation power.
- Possibility of reactive power compensation.

Many combinations of active and reactive power filters can be used to achieve high efficiency in terms of harmonic and reactive power compensation and in terms of stability.

2.4.1 Series active power filter (SAPF)

The intend of the series APF is to locally modify the grid impedance. It is considered as a source of harmonic voltages that withdraw the voltage harmonics coming from the grid or those twisted by the circulation of the harmonic currents into the grid. However, series APFs can't balance the harmonic currents produced by the loads.

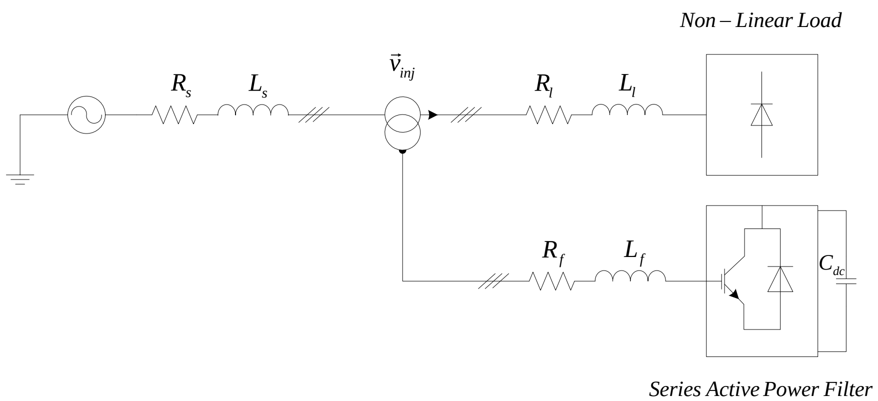


Figure 2.7: Series active power filter connected to the grid (Kmail, 2012)

Series active power filters are connected to the power grids by means of coupling transformers in series with the grid. Voltages are then injected to the grid such that it compensates for the voltages harmonics and perturbations.

Series active power filters were introduced in the 80s of the last century; they operate mainly as voltage regulators and separate the loads from power source. The series filter protects the consumer from unexpected supply voltage faults such as high voltages or low voltage sequences. This type of filtering is recommended for compensation of voltage unbalances and sags from the supply. Series compensators inject voltages in series with the supply voltage; that is, they can be considered as controlled voltage regulators (Kantaria, 2012).

2.4.2 Parallel active power filter (PAPF)

The PAPFs are associated in parallel with the harmonic emitting loads. They are anticipated to introduce in real time the harmonic currents absorbed by the pollutant loads. Thus, the mains currents will happen to being sinusoidal.

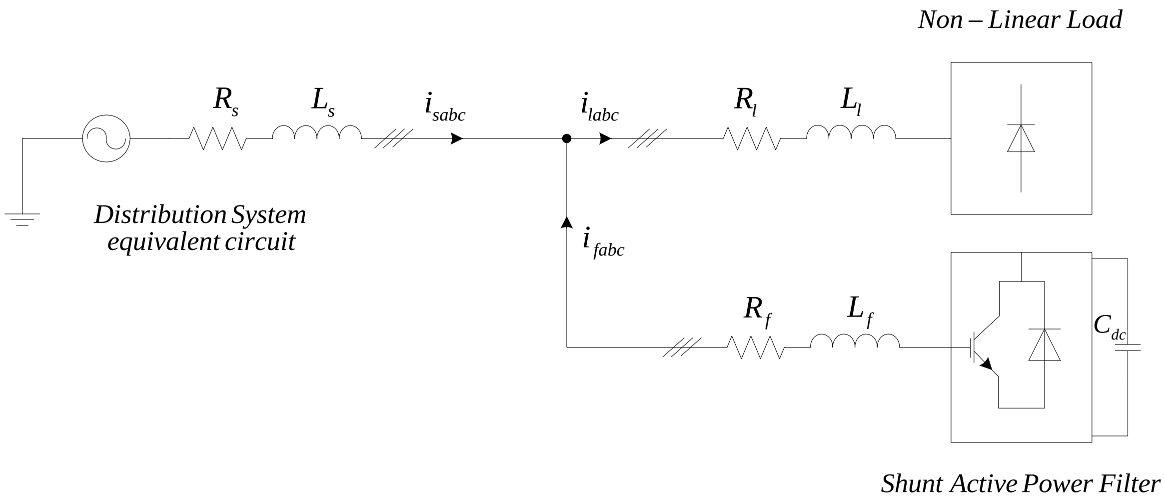


Figure 2.8: Shunt APF connected in parallel with non-linear load

2.4.3 Combination of parallel and series APF (UPQC)

Figure 2.9 shows the combination of parallel and series active power filters, called also (Unified Power Quality Conditioner) and abbreviated UPQC. This configuration combines the advantages of the two APF type's series and parallel. So it allows concurrently achieving sinusoidal source current and voltage (A. nooja & Leena, 2013).

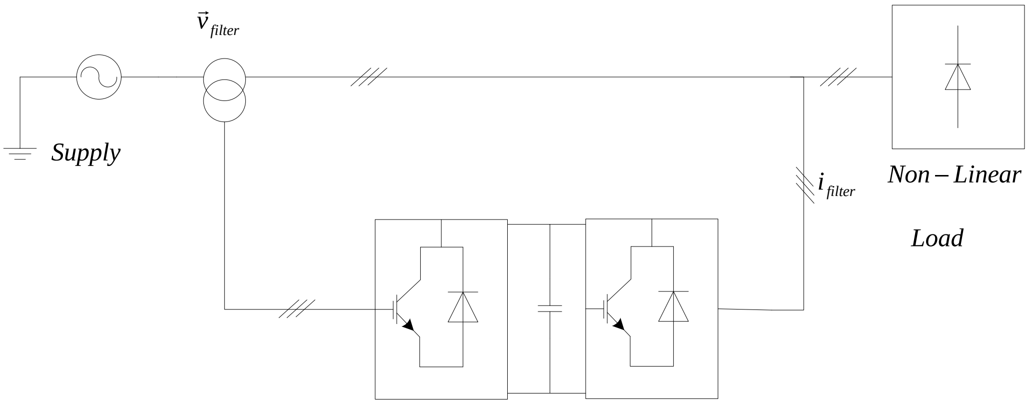


Figure 2.9: Unified Power Quality Conditioner's Diagram

2.4.4 Hybrid filters

Hybrid filter is a filter topology that combines the rewards of the passive and active filters. For this reason, it is considered as the finest solution to take away the harmonic currents from the grids. The prime motivation for the use of hybrid filters is the progress of the power semiconductors like MOSFETs and IGBTs. Over more, from an economical point of view, the hybrid power filters permit dropping the cost of APF (Chen et al., 2004).

2.4.4.1 Series connection of active filter with passive filter

In this configuration the active and passive filters are connected together directly in series. Then the system is connected in parallel with the grid as shown in Figure 2.10.

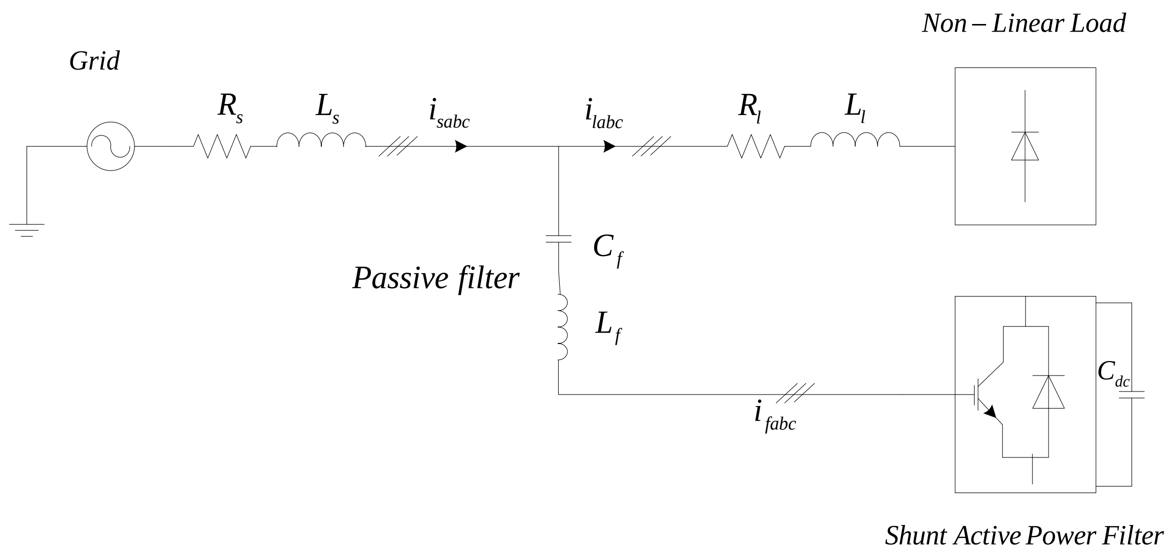


Figure 2.10: Series association of SAPF and passive filter

2.4.4.2 Parallel connection of PAPF with passive filters

In this topology, the active filter is connected in parallel with the passive filter. Both of them are shunted with the load as shown in Figure 2.11. The passive filters compensate certain harmonic ranges, while the active filter compensates the rest of the grid harmonics.

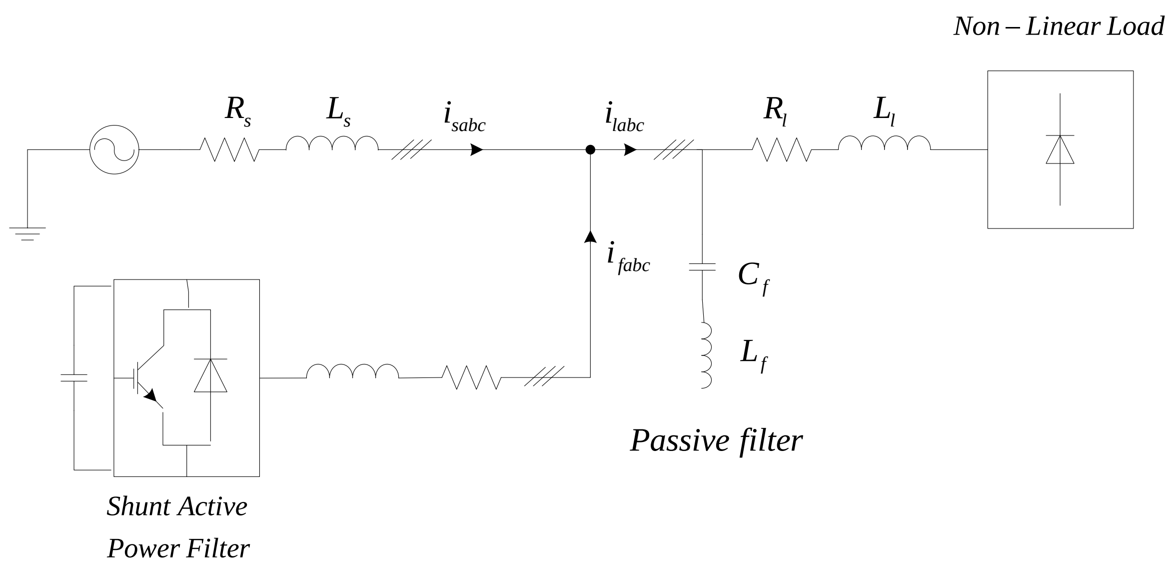


Figure 2.11: Parallel association of SAPF and passive filters

2.4.4.3 Series active filter with passive filter

This structure shown in Figure 2.12 allows the reduction of the risk of anti-resonance between the elements of passive filter and the grid impedance. In this case, the series active filter plays the role of a resistance against the harmonic currents and forces them to pass toward the passive filter without affecting the fundamental .

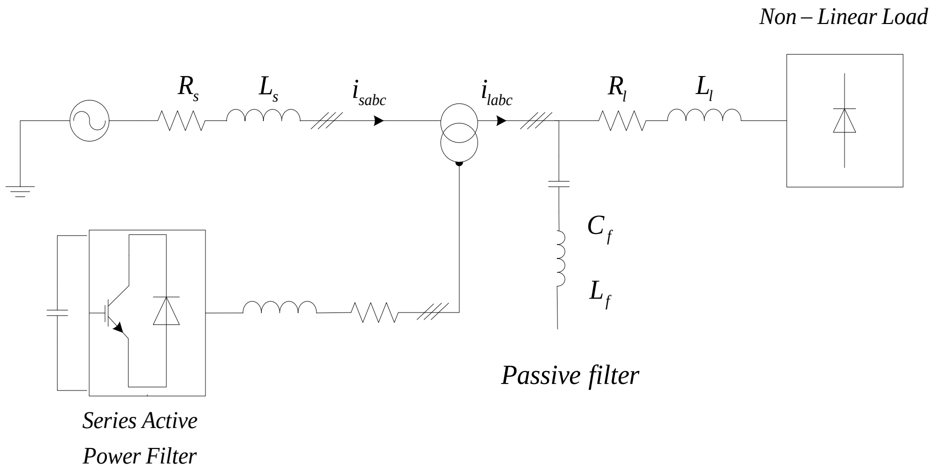


Figure 2.12: Series active power filter with passive filter

2.5 Summary

In this chapter we have presented the different types of pollutions and power grids problems. These problems include the voltage and current harmonics and frequency variations in addition to the long duration voltage sags and swells. The harmonic problem as one of the most important problems in power grids was presented and discussed in this chapter. The different methods of voltage and current harmonics treatment were presented and discussed. The discussed methods were the old passive filters based on RLC circuits coupled to present low impedance for the harmonics to be eliminated. The advantages of these passive filters and their disadvantages were also presented. The main disadvantage of these filters was their incapability of dynamically being adjusted with the variation of the load and grid. The recent active and hybrid filters were also discussed and presented in this chapter. Different series and parallel combinations of active and passive filters were presented and their characteristics were also discussed.

CHAPTER THREE

ACTIVE POWER FILTERS

3.1 Overview

In this chapter, the structures of active power filters is presented and discussed. Parallel, series, and hybrid active power filters structures and control topologies are presented. It discusses the construction of the active filter and the power inverter in addition to the function principles. A discussion about the different control methods such as hysteresis, PWM, and SVPWM of the power inverter used in active filters is presented and a comparison between the three methods is presented. The control of the active filters using different methods such as active and reactive power method is also discussed in this chapter. Active and reactive power theory has proved its high performance since it has been implemented in 80s of the 20th century for three phase balanced systems. But under the condition of unbalanced systems with neutral, this theory has encountered some problems in term of extraction efficiency. As a result, the park transform has been introduced as a more efficient extraction method for the harmonics. This method is also discussed and applied in this chapter. The PID controller was also included and discussed with practical examples in this chapter. Finally, a brief summary of this chapter is included.

3.2 Overview of Active Filters

Active filters are used for compensation of harmonic currents and voltages. The parallel filters inject currents in opposite phase with those harmonics circulating in the grid. Or in other words, it is absorbing the currents generated by the nonlinear loads such that they don't spread into the electric grid. They also can be used to compensate reactive power consumed by inductive or capacitive loads. This function reduces the stresses on the transformers and transmission lines because of higher currents consumed by these non-pure resistive loads. The loads with the filter are then seen as linear load (Hussain and Satyanarayana, 2011). Separately, series active filters are meant mainly by the compensation of voltages harmonic spreading from the grids. They can reduce the non-balance in the grid voltages and purify it from any perturbations. The Figures 3.1 and Figure 3.2 show the general topology of the shunt and series active power filters.

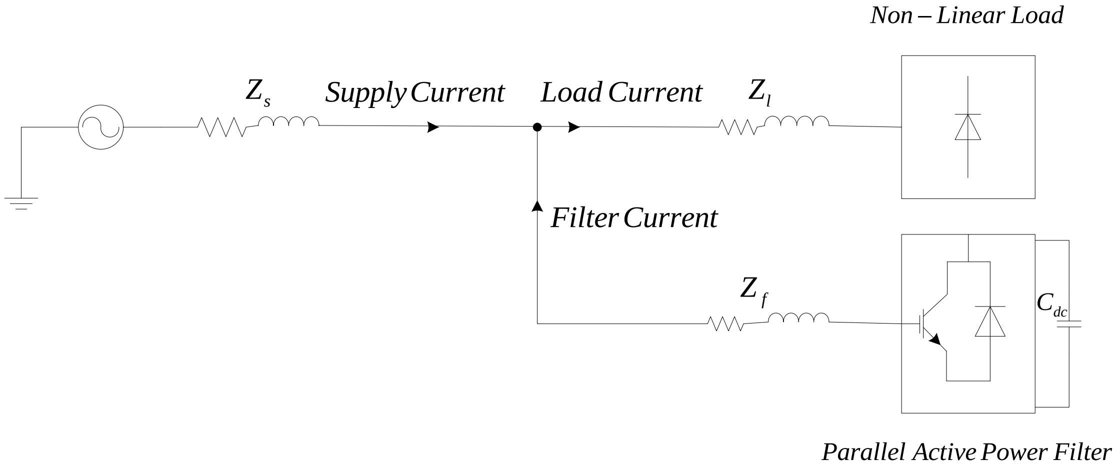


Figure 3.1: General topology of parallel active power filter (Kmail, 2012)

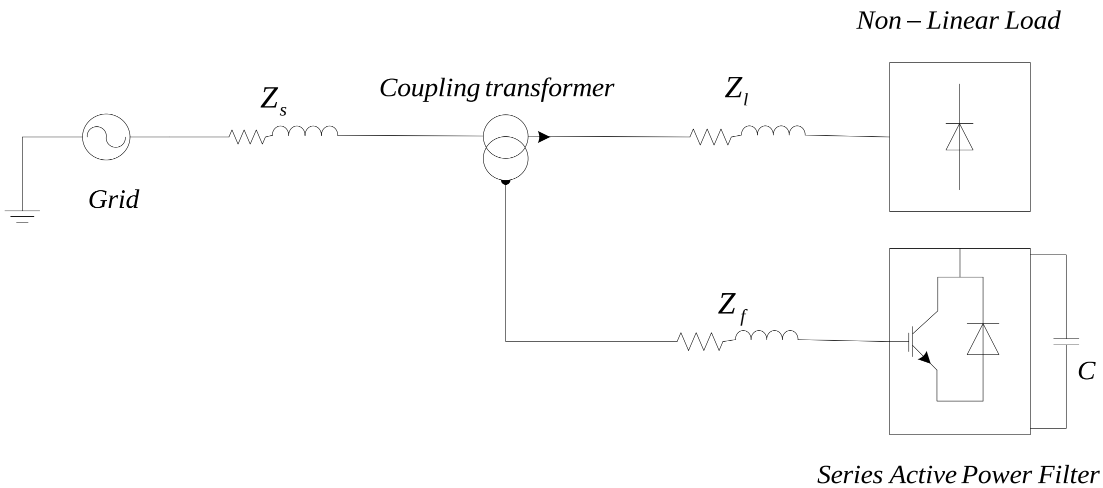


Figure 3.2: General topology of series active power filter

3.3 Construction of Active Power Filter

The active power filter is constructed mainly of four parts, these are the dc power source, the power circuit, the AC filter, and the control circuit. The power circuit is composed of power MOSFETS or IGBTs whose switching function create the current and voltage of filter. The switching of these elements needs to be controlled through a control circuit taking in consideration the currents and voltages of the different parts of system. The DC power source is used to feed the filter with the power need for compensation. Usually this source is either a bridge rectifier with DC capacitor connected itself to the grid and feeding the filter, or the DC capacitor of the filter itself used as a battery storing instantly the energy to be fed to the filter. Using an appropriate control scheme, the power transmission between the filter and the capacitor is controlled such that its voltage keeps constant. The stability of the capacitor voltage is very important for the stability of the function of the filter. The main purpose of the filter is to provide controllable three or single phase current or voltage that will be injected to the grid. The development of these filters is due to the development of digital electronics offering PWM control method; in addition to the fast development of semiconductors industry. Multi levels voltage source inverters are also used in high power applications for providing higher stability and better response and filtering efficiency (Kmail, 2012).

The main structure of a three phase voltage source inverter is shown in Figure 3.3. It is constructed of three – or more in multilevel inverters – legs having two semiconductor switches with antiparallel diode each. The function of antiparallel diodes is to provide path for the currents circulating in the circuit after the switching off of the switch.

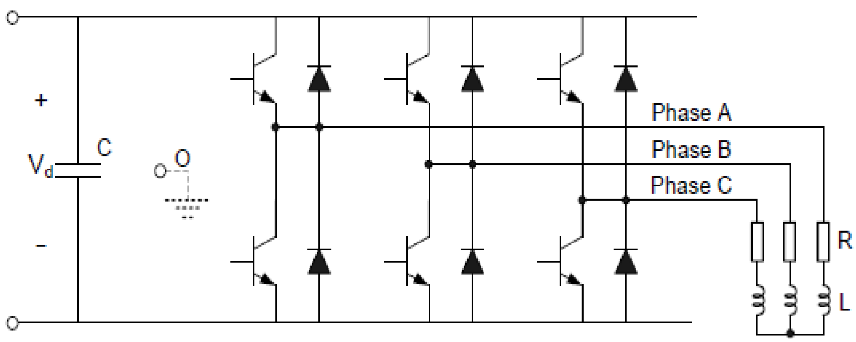


Figure 3.3: Three phase voltage source inverter (Hou et al., 2010)

As seen from the figure, it is having three legs, which offers 2^3 different states. The output of the inverter is defined in function of the different states of switches. The voltage changes between 2/3 and -2/3 of the capacitor's voltage.

3.4 Control of the Filter

The control of the filter can be derived from the 8 different states given in the previous paragraph. Many methods of control of filters are used, some of them are based on directly controlling the current through using a hysteresis band. The others uses regulators after finding the error in the current. The regulator generates the voltage reference of the filter which will be used to generate the switching function using the appropriate methods. our study will consider using hysterisis and PWM methods. other methods like SVPWM will not be included in our thesis.

3.4.1 Hysteresis control

Hysteresis current control method is very famous for its fast response and stability. It is the most used until not long time before where the PWM control has become easy and feasible. The main structure of the hysteresis control is shown in figure 3.4. the reference current is enveloped by two limits. Whenever the current generated by the inverter goes out the limits of the envelope, the control changes its output so the the current change its direction or stop. Likewise, the current keep oscillating between the two limits of the envelop around the reference. The frequency of oscillation of current, and by consequence the switching speed of the switches is a function of the width of the band of the limits envelopping the reference. Also, the AC filter play an important rule in controlling the switching function in the case of the hysteresis control. The filter controls the slope of the current such that it can arrive more quickly or faster to the hysteresis limit; the thing which increase or decrease the switching frequency (Kasmieh & Omran, 2010). We can reduce the switching frequency by increasing the band of hysteresis; that will limit the compensation ability and increase the current error but help in keeping the switching frequency within the limits of the IGBT's switching frequency. In our study, the work will concentrate on the PWM control as it is the most used method nowadays. Also its offering a fix switch frequency and good current tracking if using good regulators.

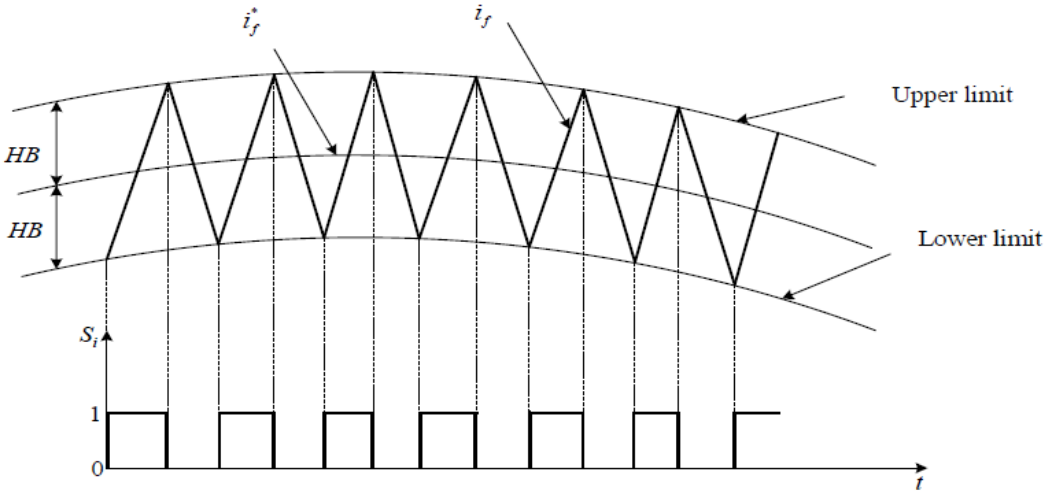


Figure 3.4: Hysteresis control principle

3.4.2 Pulse width modulation (PWM) control

The main purpose of the pulse width or duration based modulation was to control the flow of power from higher power supply to a load which is need for less power or voltage. It is widely used in many modern devices because it offers high efficiency than the linear methods. Switching mode power supplies change the output voltage of the device using pulse with modulation with efficiency of about 98% compared to linear power supplies which have efficiency of 80-85% (Srikanthand Ganesh, 2013). The PMW offers a fix switching frequency which offers an advantage over the hysteresis control method.

Figure 3.5 shows the principle function of the PWM control, the first part shows the reference sinusoidal voltage in addition to a triangular modulator signal. The comparison between the reference and the modulator produces the control signal shown in the second part of the figure. Controlling the width of the pulse controls the ON and OFF states of the switches and as aresults the flow of power from the source to the load. The power disippated in the OFF case is practically zero as the current is null and thus the efficiency is higher in this mode of function. The frequency of the modulator controls the switching frequency of the power switchs as seen in the figure.

It is important that the modulation frequency be higher enough than the reference frequency if we seek a pure sinusoidal output.

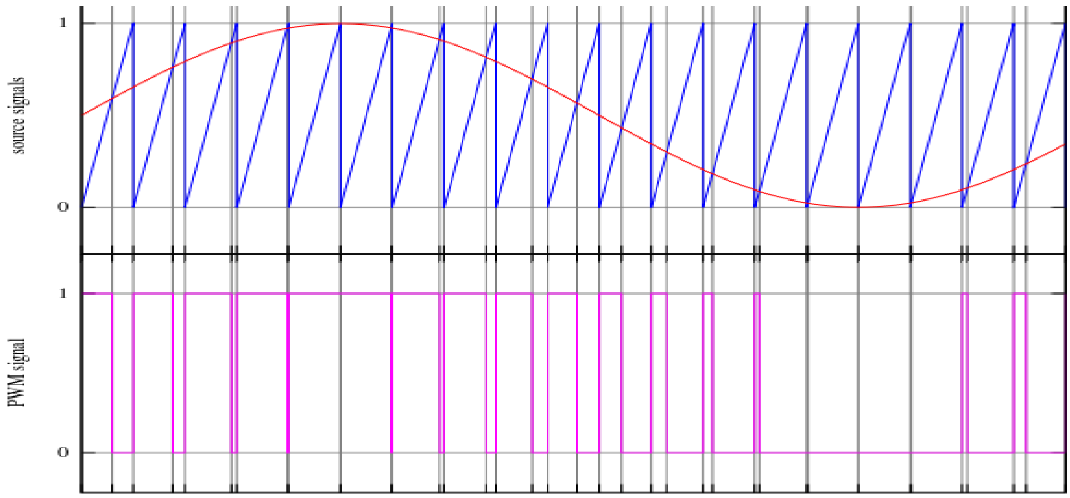


Figure 3.5: PWM control, modulator, reference, and pulse signals

A look into Figure 3.6 shows the duration control and duty cycle of PWM signal, considering a pulse waveform f(t) having a period T. and duty cycle D as shown in the figure. The upper and lower limits of the output are y_{max} and y_{min} as presented. The average value of the output signal can be then given by:

$$\bar{y} = \int_0^T f(t)dt \tag{3.1}$$

$$\Rightarrow \bar{y} = \int_0^{DT} y_{\max} dt + \int_{DT}^{T} y_{\min} dt \tag{3.2}$$

$$= \frac{1}{T}(y_{\max} DT + y_{\min}(T - DT)) = y_{\max} D + y_{\min}(1 - D) \tag{3.3}$$

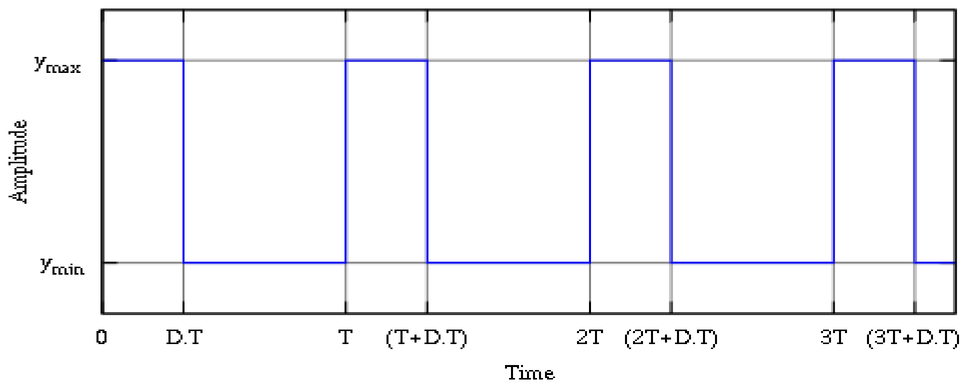


Figure 3.6: Function of PWM control

In controlling active filters using PWM signal, the current of the filter is compared to its reference current. The error is then passed to a regulator which is responsible to generate a reference voltage for the filter as it is using voltage source inverter. The reference voltage generated by the regulator is then fed to another comparator circuit which will compare it with a triangular high frequency signal. This signal is the so called modulator. The intersection points between the modulator and its reference determine the switching points of the power switches. It is important to mention here that the switching frequency must be kept away from the fundamental of the desired signal. That is, switching function produce harmonics at its modulator frequency and higher. These harmonics are highly recommended to be kept far enough from the fundamentals such that we can filter them using AC filter without affecting the fundamentals of our system. Figure 3.7 presents the main principle of PWM control using a triangular modulator. It is also important to mention that the method described here is appropriate for analogue applications. In the new digital processors a time proportioning method is used to generate PWM signals. This method uses a precise timer to provide clock function to a counter incrementing or decrementing. Whenever the précised time for the duty cycle is passed, the output changes its status. The counter reset happen at the end of each period to avoid the overflow and errors of timing. Most of processors and microcontrollers nowadays are provided with many PWM channels which are easy to use and very code and time efficient.

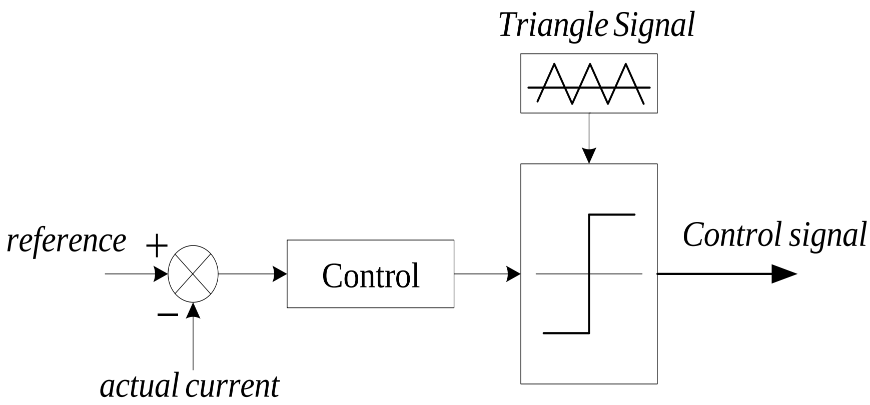


Figure 3.7: Comparator, controller and modulator of PWM

3.5 Control of the Active Filter

The control of active power filters needs the instantaneous knowledge of the parameters of the grid, load and filter. The control system must be able to react to all instant in the system's currents and voltages. For that reason, sensors of load currents, filter currents and DC voltage, and supply currents are used. All these reading are to be sent to the control system which will reply directly with the control signal for the filter. This part of the chapter discusses the construction of the control system and its functional diagrams. The control system will contain different part as follow:

1- The calculation part, which will be responsible for receiving the different readings of the sensors and finding the reference currents of the active filter. We will call this part the reference generation part, many theories and methods exist for the generation of reference of series and shunt active filters. We will discuss some of them in this part.
2- The regulation part, where all references will be compared with their real values generated by the filter. The error will be fed to controllers whose function is to determine the best reference which react to reduce the errors.
3- PWM control which has been discussed earlier in this chapter.

3.5.1 Reference generation in shunt active power filter

The generation of reference current is very important in the control of the APF as it is the first step of filtering. Any error in this stage will lead to serious problems during the next steps and cause the malfunction of the filter. Many methods are used for this purpose such as Fourier transform which is costly in terms of processing. Other methods use the instantaneous active and reactive power theory. Some others proposes the use of Park transform based method (Srikanthand Ganesh, 2013).

3.5.1.1 Instantaneous active and reactive theory

This method presents high precision and simple for implementation. Its problem resides in its lack of flexibility in case of non-balanced or distorted three phase voltage (Manmek, 2006). Most of APFs are working on the basis of the active and reactive power theory. It has been introduced by Akagi and others in the 80s of the last century. The theory is based on the transformation of three phase system into a two phase. Using this new system we can calculate the active and reactive power instantaneously, filter it from all the harmonics and then recalculate the original pure or harmonic contents of the current or voltage. The transformation of three phase system into two phase system is given by:

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{3.4}$$

This transform is applied also on the currents which contain harmonics. The powers can be found then in function of the currents and voltages by:

$$\begin{aligned} p(t) &= v_\alpha i_{l\alpha} + v_\beta i_{l\beta} \\ q(t) &= u_\alpha i_{l\beta} - u_\beta i_{l\alpha} \end{aligned} \tag{3.5}$$

Where p is the active instantaneous power, q is the reactive instantaneous power consumed by the nonlinear load. Each one of these powers contains one part related to the fundamental parts of voltages and currents, and another part related to the harmonics of the current and voltage. Using appropriate methods to separate these components we can have pure fundamentals or harmonics which we can use as reference of our system.

In order to extract the harmonics from the active power components we can either use a high pass filter or use a low pass filter with feed forward. The Figure 3.8 shows the use of low pass filter with feed forward for the harmonic extraction. The low pass filter allows the low frequency (fundamental) to pass through it while rejecting the high frequency signals representing the harmonics. This fundamental is then subtracted from the whole original signal to produce harmonic power.

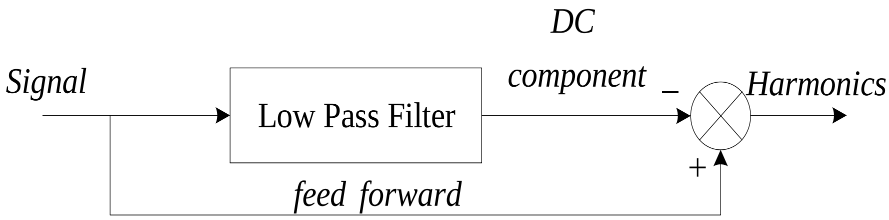


Figure 3.8: Low pass filter used for harmonic extraction

The harmonic power can be then used to find the reference currents as follow:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p_{harmonic} \\ q \end{bmatrix} \tag{3.6}$$

The reference current in three phase system can be found by using the inverse transform from two phase into three phase:

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3.7}$$

The Figure 3.9 shows in brief the principle of the application of this theory for reference generation.

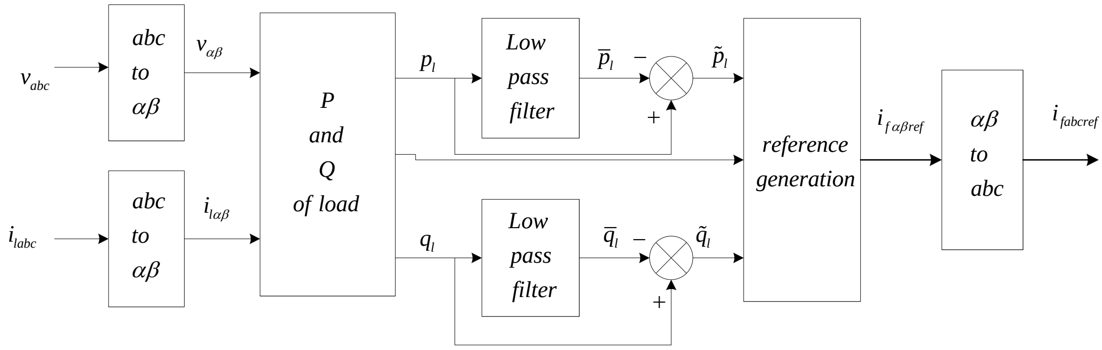


Figure 3.9: PQ theory principle and its implementation

3.5.1.2 Sine multiplication method

This method is the most used in single phase systems and can be used also in three phase systems due to its simple principle and ease of use. Its main idea is to use the direct measured grid voltages for the calculation of reference currents phase. The rest is to find the peak value of the reference current. This task is accomplished by using a DC voltage regulator. The voltage regulator will work to keep the voltage of the capacitor at the set voltage. As a result the filter will keep the source current fix and sinusoidal.

3.5.1.3 Park theory method

In this method, two direct components of the three phase currents using the Park transform. The two found direct components can be easily filtered and the harmonics can be extracted. The park transform is defined by:

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.8}$$

The load currents are fed to the Park transform to find the Park components. After finding the Park components, these components are fed to a low pass filter similar to the one used in the instantaneous power theory method. The angle used is the phase of the system, it can be found using a PLL circuit. After finding the harmonic contents of each current, the three phase system can be composed by using the inverse Park transform defined by:

$$\begin{bmatrix} i_{fa} \\ i_{fb} \\ i_{fc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & -\sin\theta \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{3.9}$$

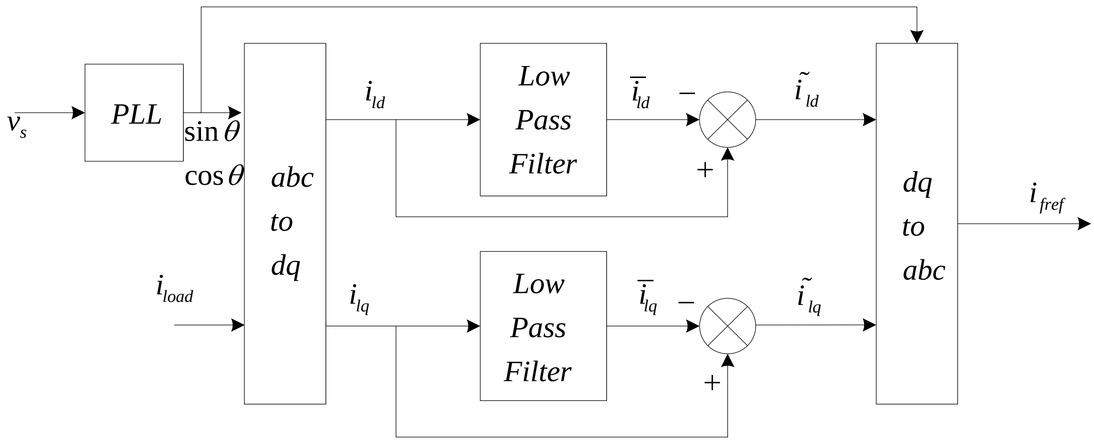


Figure 3.10: Park method block diagram (Kmail, 2012)

3.6 Control of Shunt Active Power Filter

Figure 3.11 shows the general control of shunt active power filter. The DC voltage of filter is measured and compared to a given reference. The error is provided to a PI controller which plays an important role in keeping track of the reference voltage. The output of the PI controller is then fed to the reference generation block; where output is added to the DC signal produced by the filtering block. The result then is the power or the current of the filter that can keep the voltage of capacitor constant and compensate the harmonics at once (Escobar et al., 2002). The figure shows the control blocks in addition to the nonlinear load and the active filter. The PWM control was applied in this work.

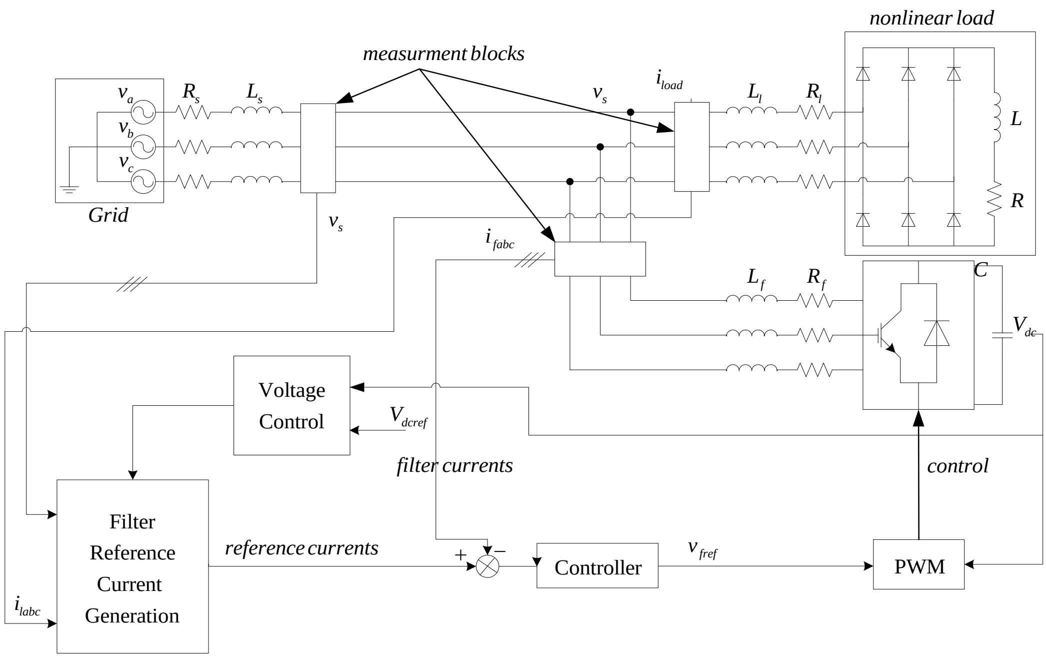


Figure 3.11: General control of parallel (Shunt) active power filter

3.7 Series Active Power Filter Control

Series active power filter behaves like a voltage source which opposes the unbalance or the perturbation in the voltages. As a result the voltage of the load to be protected is purely sinusoidal. There are many structures of series active power filters, the proposed one is a PWM inverter with a control strategy. The control method imposes the identification of harmonic voltages and the regulation of these voltages. The voltage source inverter is similar to that used in shunt active filter, the only difference is in the level of the AC filter; an LC circuit is used for the filtering of the injected voltages of the system.

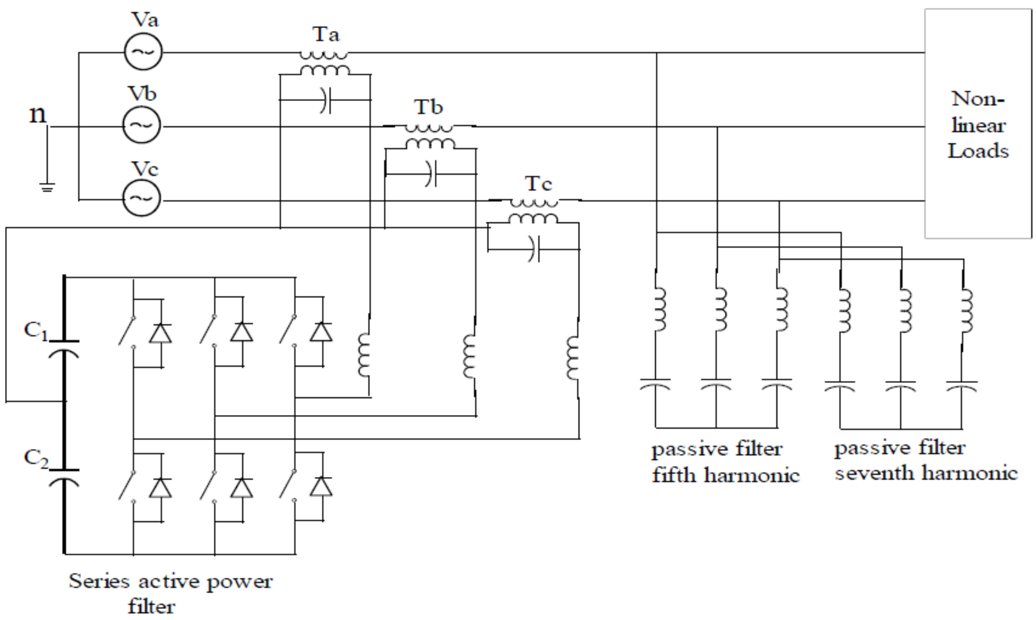


Figure 3.12: General structure of series active power filter

3.7.1 Coupling transformer

Coupling transformer allows the injection of harmonic voltages inverse to the grid and compensation of these harmonics. This transformer can be considered as current transformer and share in the protection of the filter against the faults in the load side. It is mentioned in some literature that the use of the transformer can be avoided by using three separated single phase voltage source inverters with separated DC sources.

3.7.2 Generation of the reference voltages

The objective in this part is to separate the harmonic contents from the fundamentals of the supply voltage. There are many methods proposed for doing so, some of them are going to be presented in this work. The most important method that will be used is the Park transform method; another method is also the instantaneous active and reactive power theory.

3.7.3 Park transform reference

In this method, the three phase voltages are decomposed into direct and quadrature components using the Park transform. The result is then filtered and the fundamentals and harmonics of the voltage are separated. The Park transform is given by:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{3.10}$$

After separating the components of the voltage, the reference is produced by applying the inverse Park transform on the system. The reference voltages are then fed to the filter to be injected into the grid. The phase of the voltages is found using a three phase PLL system. Just by adjusting the direct component to a desired value and adjusting the indirect component to be zero; we can obtain the desired reference voltage of our system. Extracting that voltage from the real voltage measured from the connection point we can find the reference voltage of the series filter as shown in the Figure 3.13. The inverse Park transform is applied and the three phase voltages can be found. This method seems very exact and gives very good results but it needs a highly optimized PLL circuit. The PLL is very important for the determination of the exact angular position of the voltage vector. Any error in the PLL leads to errors in the reference generation.

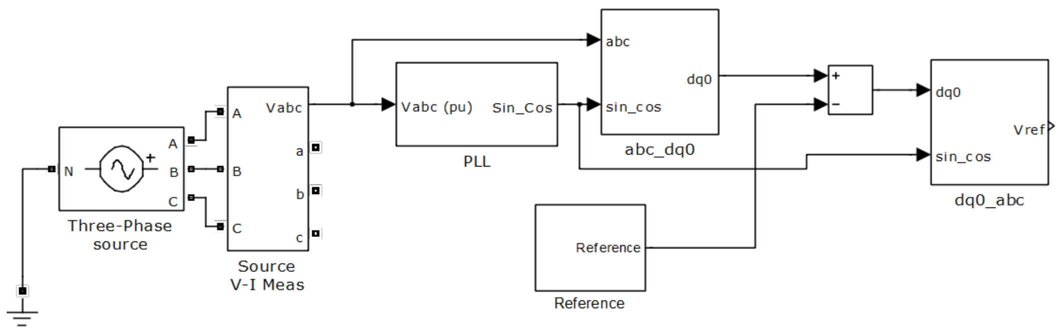


Figure 3.13: DQ based method algorithm for voltage reference generation

3.7.4 PQ Theory based reference generation

In this section, the control method of series active power filter is introduced and discussed. This method is also based on the so called instantaneous active and reactive power theory. The three phase voltages and currents are transformed into two phase system. The instantaneous active and reactive powers are calculated and passed through a filter to separate the harmonic components from the fundamentals. The equations used in this theory are (Arnob et al., 2012):

$$\begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \tag{3.11}$$

Such that u represents the quantity to be used, it can be either the line current or the load voltage. The instantaneous power can be then found by:

$$\begin{aligned} p(t) &= u_\alpha i_{l\alpha} + u_\beta i_{l\beta} \\ q(t) &= u_\alpha i_{l\beta} - u_\beta i_{l\alpha} \end{aligned} \tag{3.12}$$

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix} \begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix} \tag{3.13}$$

After separating the harmonic components in the instantaneous power from the fundamentals; the separated values can be then used to find the reference voltages as follow:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{1}{i_\alpha^2 + i_\beta^2} \begin{bmatrix} i_\alpha & -i_\beta \\ i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p}_l \\ \tilde{q}_l \end{bmatrix} \tag{3.14}$$

It is important to mention that the power equations given here are valid just in the case of zero sequence system; where the voltages are balanced.

3.7.5 PI Regulator use for currents and voltages control

The PID controllers are very famous since their beginning in 1922 (Balestrino, 2012).. In particular, Minorski was the first to introduce three-term controllers with Proportional-Integral-Derivative (PID) actions. The PID controller has succeeded fast and strongly to attract the attention of researchers and scientists due to many reasons. They have been proposed in the industrial processes and proved their ability to control different systems. Their main characteristics which led to their success were:

1- Reduced number of parameters: the parameters to be tuned are very little and that reduces the time of tuning and design of controller.
2- Tuning rules are easy and well established: the method of finding the parameters are clear and easy to use, there are practical and theoretical tuning rules.
3- Good performance: the PID shows good performance in the most of cases where the process to be controlled is linear. Especially if the variable is stable or its frequency is low. It is showing good response in the case of DC parameters.

The equation of a conventional PID can be given by:

$$u_{PID} = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{de(t)}{dt} \tag{3.15}$$

Where the error e(t) is defined as the difference between the real output of a plant and its desired output. The PID controller is one of the most important feedback controllers. The error is fed to the PID such that the PID generates the suitable input of the process or plant that reduces the error. The simple representation of the PID is shown in Figure 3.14.

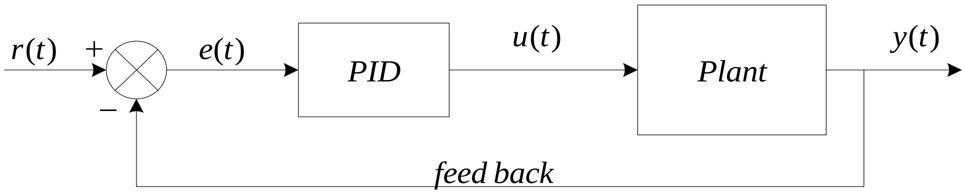


Figure 3.14: PID controller general structure (Balestrino, 2012)

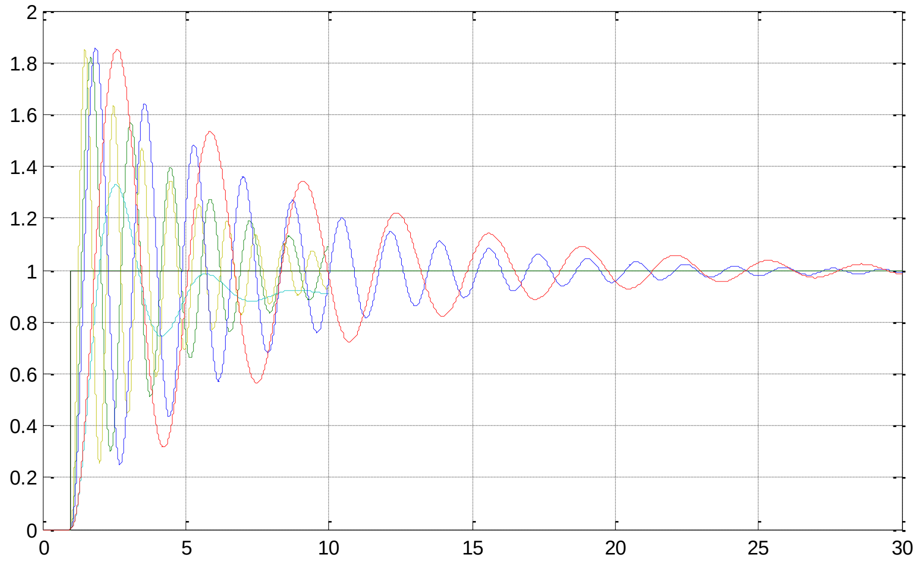


Figure 3.15: The time response of a PID controller with different parameters

Figure 3.15 shows the different responses of a PID controller controlling a process defined by the transfer function (1/3s^2 + 5s +1). We can notice the shape of the response and the convergence of the output to its desired reference.

In the active power filter we need to two types of regulators, one for keeping the voltage of the capacitor at the desired value; and the second to keep tracking of the reference current of the filter. Different types of controllers can be used such as fuzzy controller, PI, IP, PID, Neural Network controller, RST controller or any other type of controllers. In this work, a PI controller has been chosen to be used for the regulation of the current and voltage. The simplicity and ease of implementation of the PI controller has made it a best choice.

3.8 PI Controller for DC Voltage

The voltage of the DC side of the inverter or active power filter must be kept constant as much as possible. The fluctuations in this voltage can cause ripples in the injected current to the grid and affect the quality of the filtering process. In order to keep the DC voltage constant with the different changes of the grid and filter parameters, either a DC power source can be used or a capacitor. The capacitor which must be relatively high enough can support the filter and keep its DC side near to a defined value for short period of time. The energy stored in a capacitor can be given by:

$$E = \frac{1}{2} C_{dc} . V_{dc}^2 \tag{3.16}$$

Deriving it with respect to time can give us the power delivered from or to the capacitor. Such that:

$$p = \frac{d}{dt}(\frac{1}{2} C.V^2) = CV \frac{dV}{dt} = CV(\frac{V_f - V_i}{\Delta t}) \tag{3.17}$$

In order to keep the difference between the initial and final value of a capacitor, we need to increase its capacitance. Also the time must be small that is; the power gained or lost during a small period of time must be readjusted as fast as possible to keep the energy of the capacitor constant. A PI controller can be used as shown in Figure 3.16. The figure shows the transfer function of a capacitor link with the PI regulator:

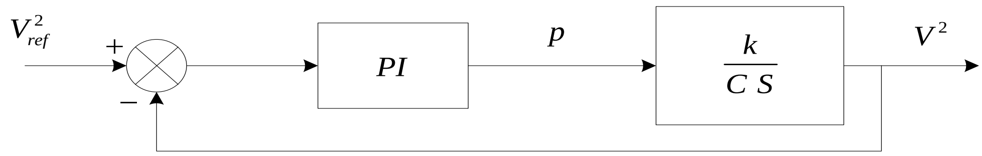


Figure 3.16: PI control of a capacitor voltage

Using the appropriate PI controller can keep the voltage of the capacitor fix to its reference.

3.9 PI Controller for Filter Currents

A PI controller is used for each one of the filter currents. The input of the controller is the error between the measured filter current and the reference current generated using appropriate method. The output is then the voltage necessary to control the filter and keep tracking of the reference current. Considering the transfer function of the inverter and the AC filter to be 1/ (LS+R), the PI with the transfer function represent a second order system. The system of the inverter, filter, and PI controller is shown in Figure 3.17.

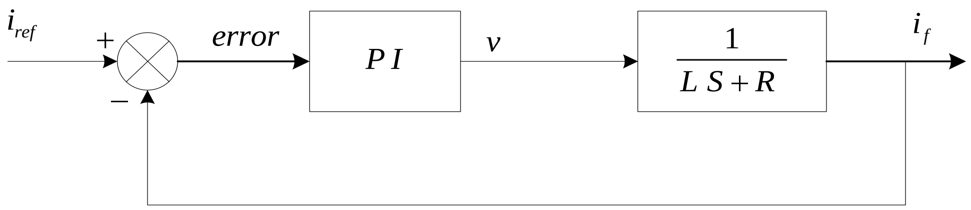


Figure 3.17: PI controller for current control

3.10 Summary

Active parallel and series filters were discussed in this chapter. The parallel filter general structure and its control using PI controller were presented and discussed. The use of PQ, DQ, and sine multiplication methods for harmonic extraction were discussed in this chapter. The disadvantages and advantages of each one of these methods were discussed also. DQ theory has proved its high performance with different systems under balanced and unbalanced system conditions. The use of PI controller for the current tracking was explained and presented. Series active filters were also discussed in this chapter. The control and extraction methods for series topologies were introduced and discussed. The discussion in this chapter was exclusively concentrated on the well-known topologies and their main advantages and disadvantages. However, new modern control methods and topologies were mentioned briefly in this chapter. Finally, a brief conclusion was included to summarize the work carried out in this chapter.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Overview

This chapter was dedicated for the results and discussion of different topologies and structures discussed in this work. All the results are tabulated and presented in this chapter. Comparison between the results of each one of the presented topologies is applied. The different results are printed in tables and figures showing the performance and efficiency of each method. The simulation schemes are also presented in this chapter and general comparison is carried out.

4.2 Passive Filter, Band Pass and High Pass

As mentioned in the second chapter of this work, band pass passive filters are constructed by the use of series RLC circuits. These RLC circuits represent low impedance at the harmonics to be cancelled. Looking to the nonlinear loads as current sources that inject harmonic currents into the power grid; the passive filters will appear in parallel to the grid. Presenting low impedance for harmonic frequencies compared to the grid impedance will force these harmonics to flow through the passive filters instead of spreading into the higher impedance grid. As a result the power grid will remain clean with the close possible to the sinusoidal waveform. The calculation of the values of RLC elements must ensure that the impedance will be close to zero at the intended frequency. Table 4.1 present the values of the resistance, capacitance, and inductance for the 5^{th}, 7^{th}, 11^{th}, and 13^{th} harmonic cancelling in addition to the high pass filter.

Table 4.1: Values of elements of passive filters

Band pass Filter			
	C (µF)	L(H)	R(Ω)
5th harmonic	11.09	0.0365	0.54
7th harmonic	11.09	0.0186	0.38
11th harmonic	11.09	0.0075	0.24
13th harmonic	11.09	0.0054	0.21
High pass filter			
Higher harmonics	11.09	0.01	50

Figure 4.1 shows the connection of the passive filters; we can notice that the resonant filters are composed of series RLC circuit. While the high pass filter is built by using a parallel RL branch connected in series with a capacitor bank. Figure 4.2 shows the block diagram of the nonlinear load connected to the grid; in addition to the passive filters. The results of simulation of the system treated using passive filters are presented in Figure 4.3 and Figure 4.4; it is well seen that the load current is non sinusoidal and contains a lot of harmonic components as presented by Figure 4.5 after treatment with passive filters, the grid current became closer to sinusoidal form with Less harmonic contents. The THD before the use of passive filter was 24.6% with fundamental current of 40.6 A. the fifth harmonic had current amplitude of 8.74 A. the fifth harmonic has been reduced to an amplitude of 1.17A after using the passive filters as shown from the spectrum analysis presented in Figure 4.6.

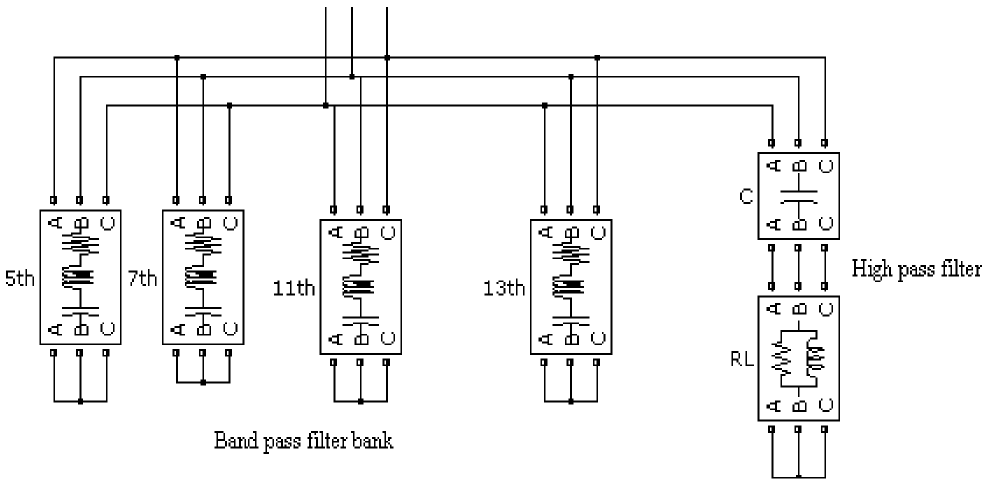


Figure 4.1: Connection of passive high and band pass filters

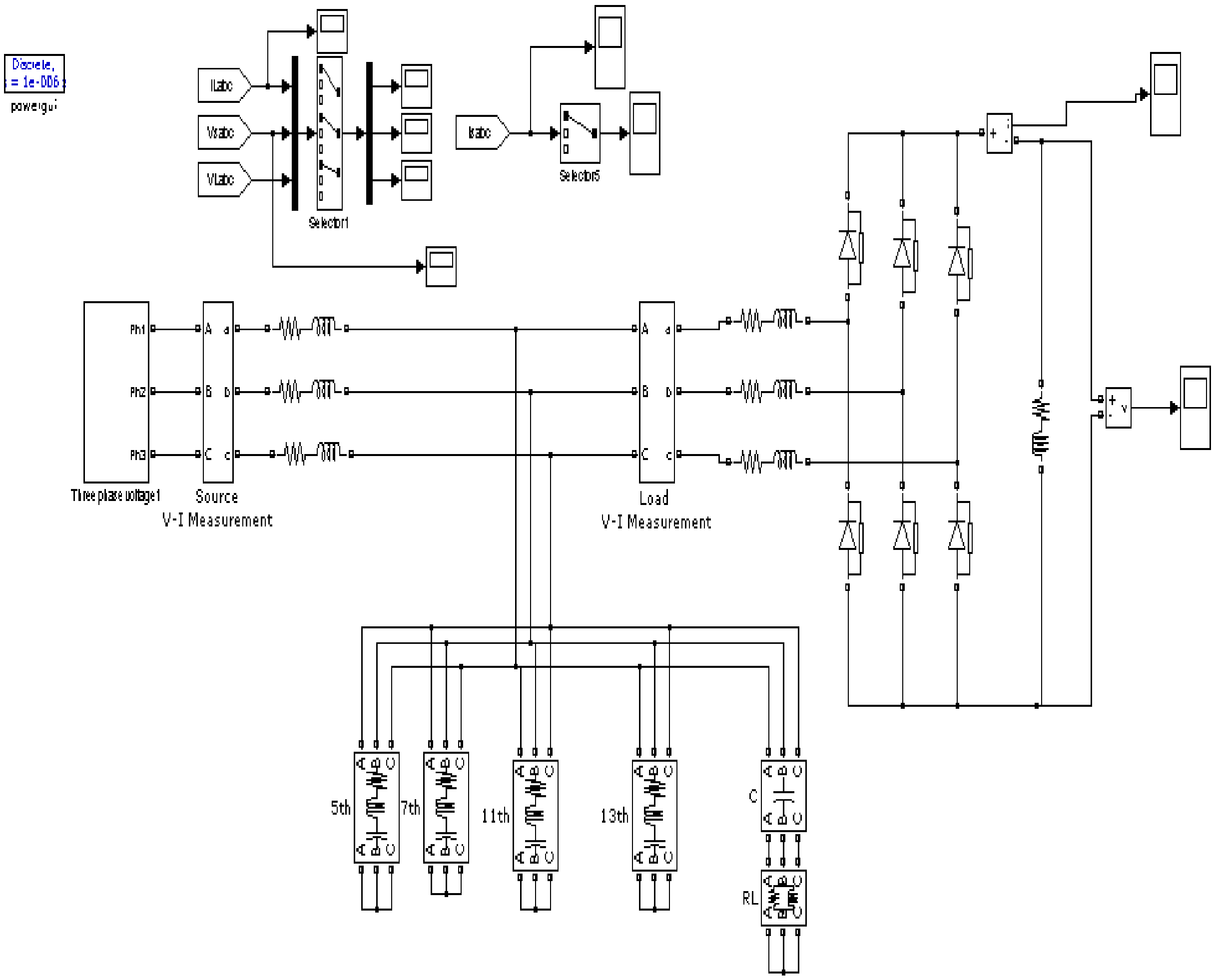


Figure 4.2: Circuit of the nonlinear load with passive high and band pass filters connected to grid

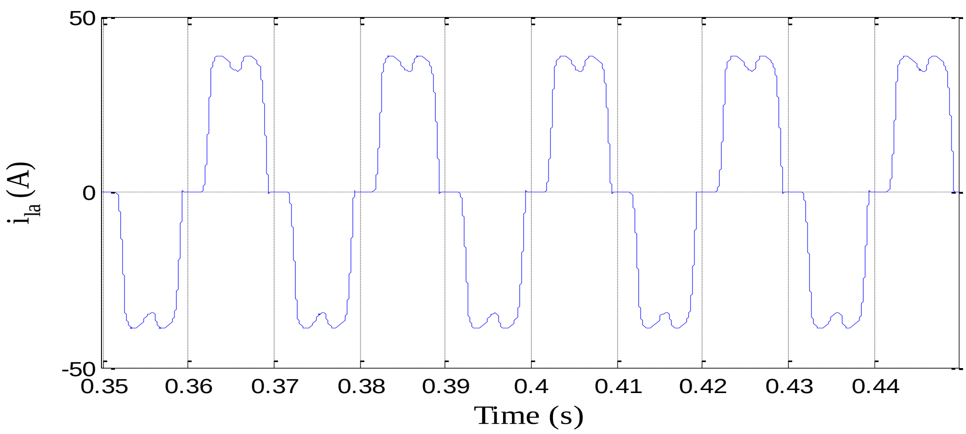


Figure 4.3: Load current and its waveform without filtering

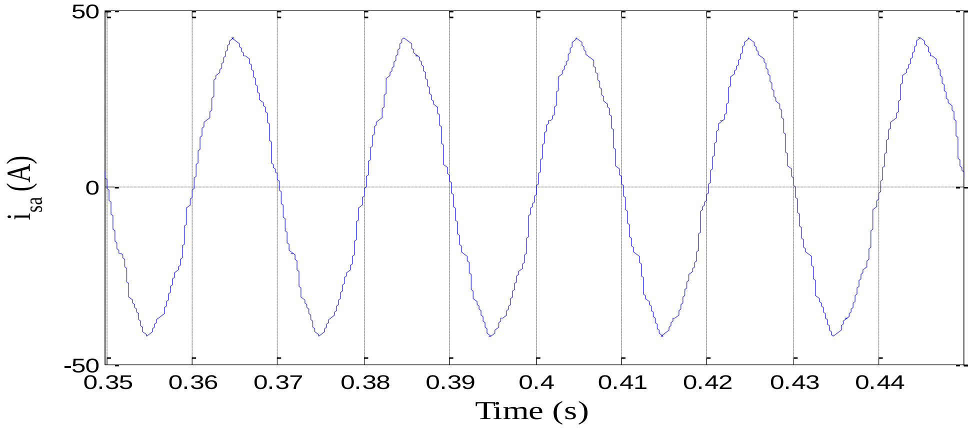


Figure 4.4: Grid Current and its waveform after filtering

Table 4.2: Fourier analysis of Grid (Load) current before filtering

FFT analysis

Total Harmonic Distortion (THD) = 24.60%

Maximum harmonic frequency
used for THD calculation = 499950.00 Hz (9999th harmonic)

0 Hz	(DC):	0.00	270.0°
50 Hz	(Fnd):	40.61	0.0°
100 Hz	(h2):	0.00	15.7°
150 Hz	(h3):	0.00	157.5°
200 Hz	(h4):	0.00	0.0°
250 Hz	(h5):	8.74	124.4°
300 Hz	(h6):	0.00	29.1°
350 Hz	(h7):	3.73	95.7°
400 Hz	(h8):	0.00	53.4°
450 Hz	(h9):	0.00	246.3°
500 Hz	(h10):	0.00	134.3°
550 Hz	(h11):	2.47	227.5°
600 Hz	(h12):	0.00	140.8°

Table 4.3: Fourier analysis of Grid current after filtering

Total Harmonic Distortion (THD) = 5.14%

Maximum harmonic frequency
used for THD calculation = 499950.00 Hz (9999th harmonic)

0 Hz	(DC):	0.00	270.0°
50 Hz	(Fnd):	40.47	0.0°
100 Hz	(h2):	0.00	31.2°
150 Hz	(h3):	0.00	97.7°
200 Hz	(h4):	0.00	0.0°
250 Hz	(h5):	1.17	30.6°
300 Hz	(h6):	0.00	185.5°
350 Hz	(h7):	0.09	0.0°
400 Hz	(h8):	0.00	176.6°
450 Hz	(h9):	0.00	224.4°
500 Hz	(h10):	0.00	181.8°
550 Hz	(h11):	1.38	209.8°
600 Hz	(h12):	0.00	169.7°

.

A careful look into the harmonic analysis shown in Table 4.3 can show that the third harmonic and its multiples are not existent in a three phase system. Also we can notice that the other filtered individual harmonics (7, and 11) has been reduced to low values.

In the next part of our study, the nonlinear load will be changed to be controlled rectifier based on thyristors. The nature of controlled rectifiers is totally different from diode based rectifiers. Also harmonics injected by thyristor controlled rectifier are totally different from those created because of diode bridge rectifier. Discussion about the Thyristor Bridge will be presented in the appendix. The aim of this part is to check the ability of passive filter to come over the harmonics injected by different nonlinear loads. The use of Thyristor Bridge has changed totally the harmonics of the system as shown in Table 4.4 where we notice that the system THD has been increased significantly to 78%. It is clear from the figure that high level of second and fourth harmonics has been injected due to the existence of passive filters.

Table 4.4: Harmonic spectrum of load current using thyristor bridge

Total Harmonic Distortion (THD) = 78.11%

Maximum harmonic frequency
used for THD calculation = 49900.00 Hz (998th harmonic)

0 Hz	(DC):	0.42	90.0°
50 Hz	(Fnd):	32.01	0.0°
100 Hz	(h2):	24.10	107.1°
150 Hz	(h3):	1.05	0.0°
200 Hz	(h4):	5.78	184.7°
250 Hz	(h5):	2.28	260.8°
300 Hz	(h6):	0.20	0.0°
350 Hz	(h7):	1.59	0.0°
400 Hz	(h8):	0.87	15.6°
450 Hz	(h9):	0.08	0.0°
500 Hz	(h10):	0.71	31.2°
550 Hz	(h11):	0.45	111.1°

A new design considering the second and fourth harmonics becomes a must in this case. Two other damped band pass filters tuned at the frequencies of the second and fourth harmonics will be then added. The elements of the new two filters are given in Table 4.5.

Table 4.5: Values of elements of passive filters for 2nd and 4th harmonics

Band pass Filter			
	C (μF)	L(H)	R(Ω)
2nd harmonic	110.9	0.0228	0.33
4th harmonic	110.9	0.0057	0.066

The results of simulation of the new approach for the passive filter are shown in Table 4.6.

Table 4.6: Spectrum analysis of harmonic contents of the grid current after filtering

```
Total Harmonic Distortion (THD) = 19.32%

Maximum harmonic frequency
 used for THD calculation  = 49900.00 Hz (998th harmonic)

    0 Hz   (DC):           0.69     90.0°
   50 Hz  (Fnd):          32.74     31.4°
  100 Hz   (h2):           5.24     45.5°
  150 Hz   (h3):           2.68    115.3°
  200 Hz   (h4):           1.89      0.0°
  250 Hz   (h5):           0.30      0.0°
  300 Hz   (h6):           0.28      5.5°
  350 Hz   (h7):           0.59      0.0°
  400 Hz   (h8):           0.62      0.0°
  450 Hz   (h9):           0.34      0.0°
  500 Hz  (h10):           0.52      0.2°
  550 Hz  (h11):           0.22     29.8°
  600 Hz  (h12):           0.22      0.0°
  650 Hz  (h13):           0.14     47.4°
```

Figure 4.5 shows the grid current after being filtered using damped filters. It is easy to notice that the use of damped filters for the second and fourth harmonics in addition to some higher order ones was totally useful. The THD has been decreased to 19.32% with low amounts of the 2nd and 4th harmonics. The results obtained during these experiments shows that the passive filters can reduce readily the amount of harmonic distortion in the case of stable loads with good knowledge of the behavior of the system. In the case of dynamic loads with non-predictable behaviors, the passive filters are afraid of being non stable, inefficient, or even increase the harmonic distortion by injecting harmonics with frequencies under their own cut off frequency.

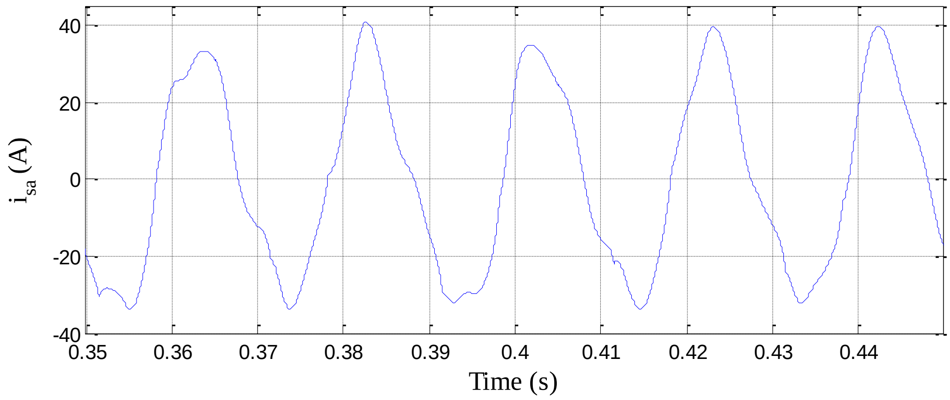


Figure 4.5: Grid current waveforms after filtering. (THD=19.32%)

4.3 Active Power Filter for Harmonic Compensation

Active filters are dynamic filters that can adjust automatically with the load changing and have more ability to compensate harmonics and reactive power at once. Shunt, series, and combined shunt and series active power filters are used for current and voltage harmonics compensation. Shunt (parallel) active filter will be used with the nonlinear load composed of Thyristor Bridge. The results of simulation will be tabulated and discussed. Figure 4.6 shows the simulation model of the PAPF. Figure 4.7 presents the waveform of the grid current after filtering.

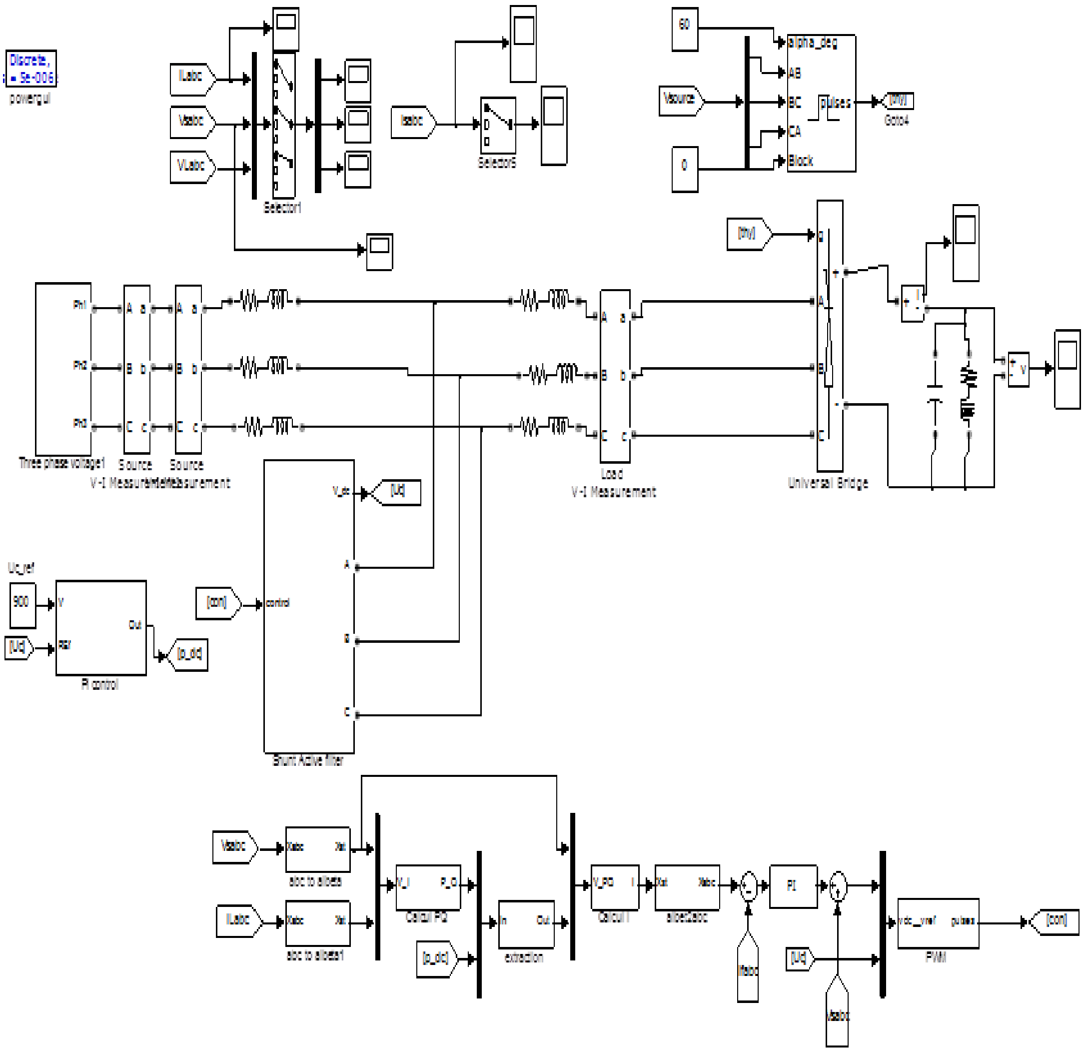


Figure 4.6: Simulation model of Parallel active power filter (PAPF)

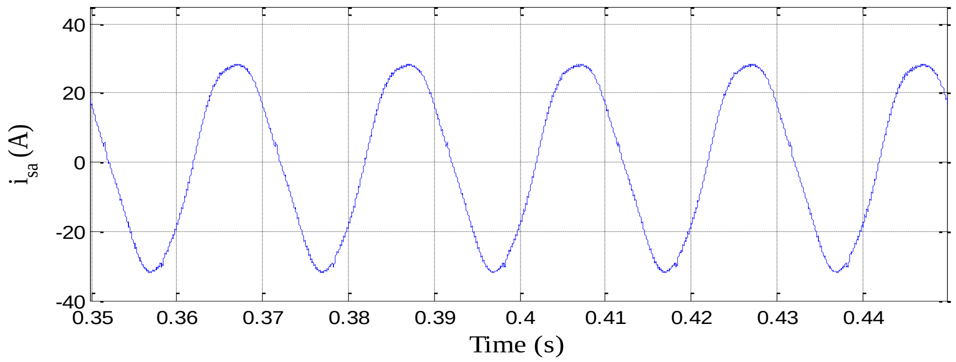


Figure 4.7: Waveform of grid current after filtering using PAPF

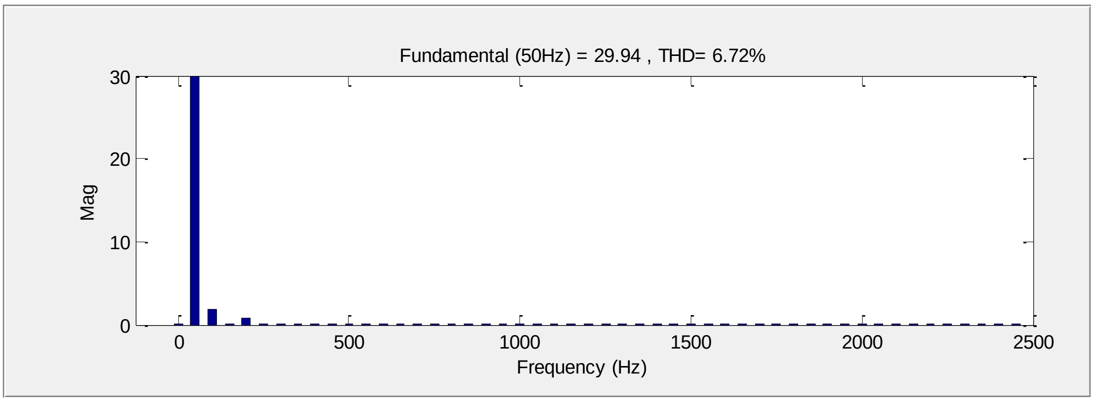


Figure 4.8: Spectrum analysis of the grid current (THD=6.72%)

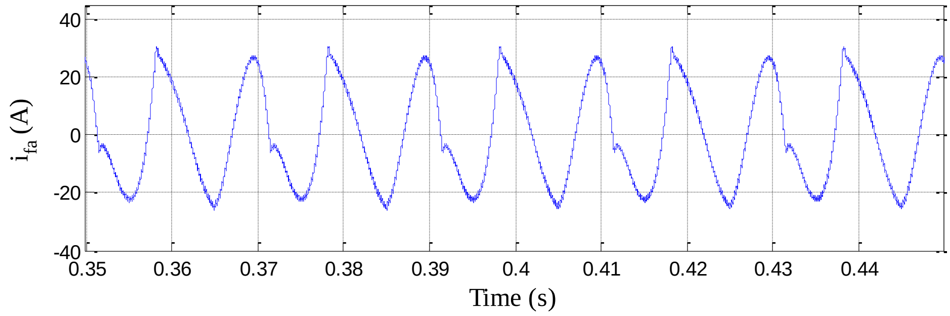


Figure 4.9: Active power filter's Current

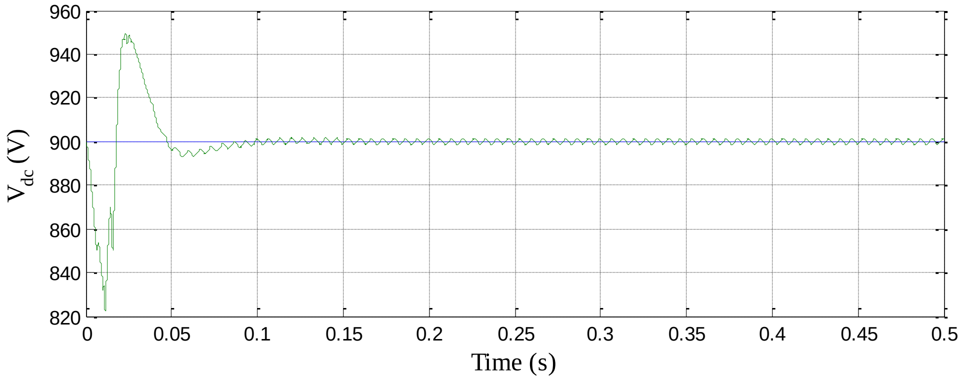


Figure 4.10: DC side voltage of active filter

4.4 Active Power Filter with Passive Filters (Hybrid Combination)

This combination is used to minimize the currents drawn by the active filter and reduce its power. The passive filters are used here to compensate for the harmonics of low order -2nd, 4th, 5th, 7th, 11th, and 13th – which are the most significant harmonics in the grid. The active filter is then responsible for the compensation of the other harmonics which are not compensated by the passive filters. This structure is very useful and efficient in the case of higher power compensation and/or reactive power compensation. The filter in this case will not be charged by the compensation of the reactive power or low order components of the harmonic spectrum. The simulation of the system has been carried out under the same conditions with the parameters of the system as given in Figure 4.1.The results of simulation are shown in the next paragraph. The simulation model of the system is presented in Figure 4.11.

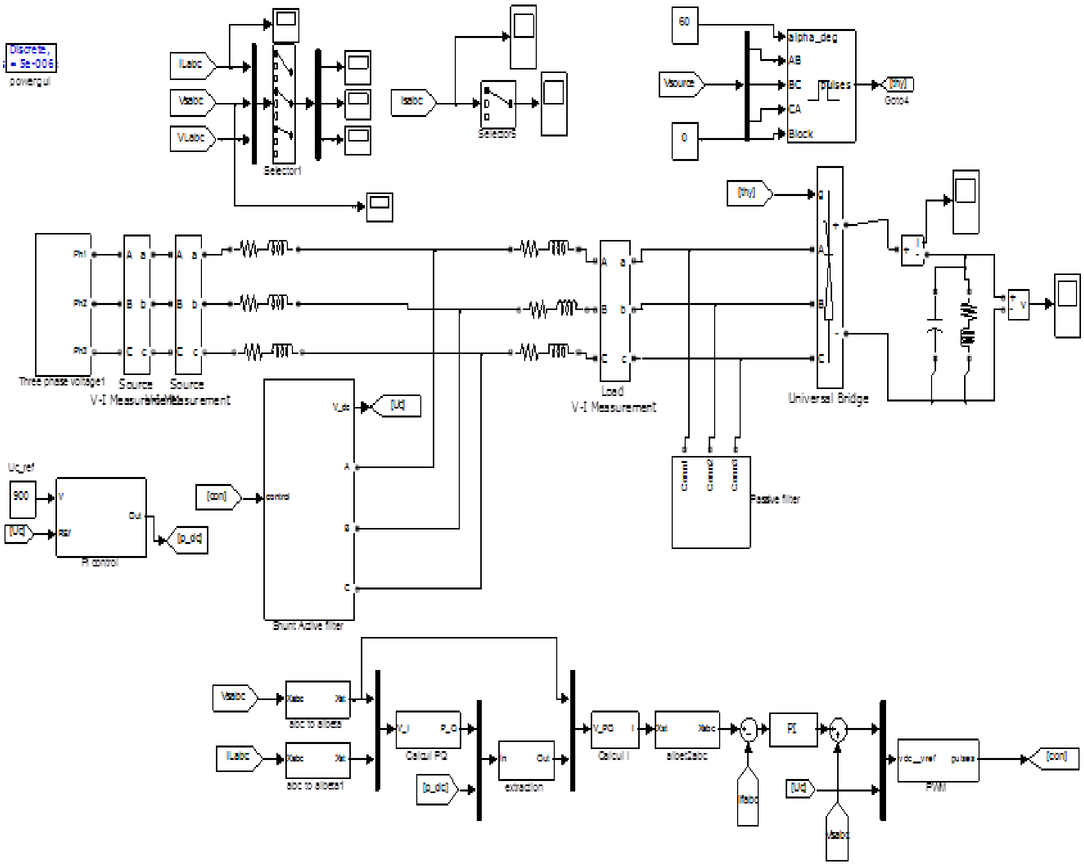


Figure 4.11: Model of PAPF with passive filter (Hybrid filter)

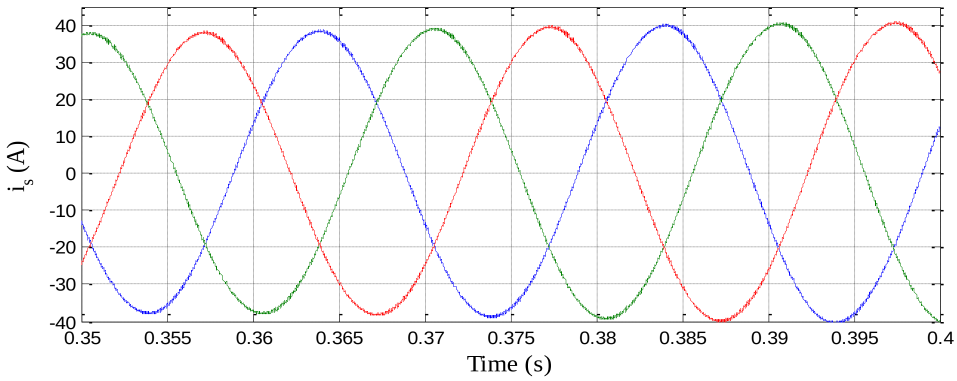


Figure 4.12: Supply current after compensation with hybrid Filter

(PAPF + Passive filters)

Table 4. 7: Harmonic spectrum of the supply current (PAPF + Passive Filters)

Total Harmonic Distortion (THD) = 1.43%

Maximum harmonic frequency
used for THD calculation = 499950.00 Hz (9999th harmonic)

0 Hz	(DC):	0.69%	90.0°
50 Hz	(Fnd):	100.00%	17.0°
100 Hz	(h2):	1.01%	186.7°
150 Hz	(h3):	0.17%	217.2°
200 Hz	(h4):	0.68%	2.1°
250 Hz	(h5):	0.11%	0.0°
300 Hz	(h6):	0.06%	0.0°
350 Hz	(h7):	0.04%	0.0°
400 Hz	(h8):	0.03%	0.0°
450 Hz	(h9):	0.03%	0.0°

Figures 4.12 and Table 4. 7 show the supply current and its harmonic contents after being filtered using hybrid filter composed of parallel active filter and damped resonant passive filters. It is neatly clear that the current is perfect sinusoidal and balanced. The THD of the supply current has been brought to 1.43% with very low content of the second harmonic. We can notice that a very small amount of the second harmonic is present in the current. The presence of this harmonic is due mainly to the smooth response of the second order filter used for filtering the signal. A look into the filter currents as shown in Figure 4.13 clarifies that a very small power was drawn by the active filter. Most of the compensation current was then drawn by the passive filters. The active filter in this case has played the rule of ameliorating the filtering process and stabilizing the system in addition to its ability

for adjustment with different loads. Also Table 4.8 supports our notes about the filter currents. It is showing the harmonic analysis of filter currents, we can see that the second harmonic is 875% of the fundamental (at 50 Hz). Other harmonics vary between 200% and 0% of the fundamental. It is clear also that the filter current is very small compared to that shown in Figure 4.9 previously.

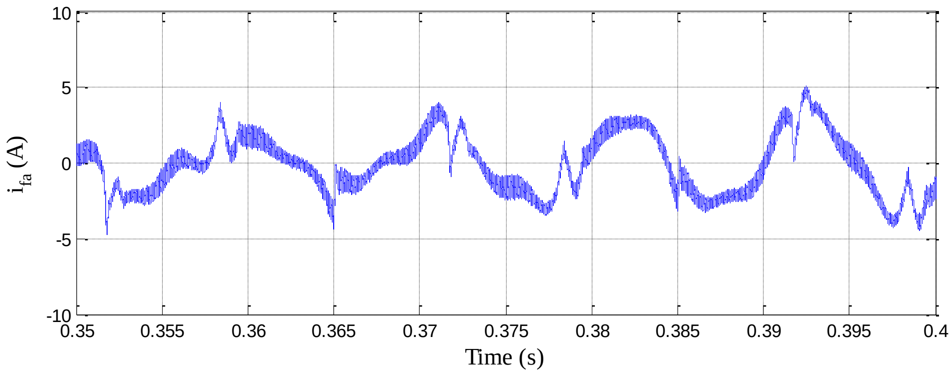


Figure 4.13 : PAPF current during compensation

Table 4.8: Harmonic analysis of PAPF current

Total Harmonic Distortion (THD) = 965.75%

Maximum harmonic frequency
used for THD calculation = 499950.00 Hz (9999th harmonic)

0 Hz	(DC):	11.43%	90.0°
50 Hz	(Fnd):	100.00%	197.5°
100 Hz	(h2):	875.84%	0.0°
150 Hz	(h3):	73.50%	8.4°
200 Hz	(h4):	73.80%	0.0°
250 Hz	(h5):	56.04%	157.6°
300 Hz	(h6):	25.27%	0.3°
350 Hz	(h7):	72.92%	0.0°
400 Hz	(h8):	205.39%	0.0°
450 Hz	(h9):	17.10%	0.0°

4.5 Series Active Filter

Series active power filters were designed mainly for compensation of harmonic voltages appearing in the grid waveforms. They are not able to compensate harmonic currents injected by nonlinear loads. They can also provide balanced three phase voltage from a three phase non balanced voltages. By consequence, they can be used for voltage regulation of the grid systems. They are also used in combination with passive filters and/or parallel active filters for the total compensation of current and voltage harmonics. The last combination is called unified power quality conditioning and it will be out of the topics of our study. The compensation using series active filter and passive filters will be discussed and presented in this part of the chapter. The DQ based extraction method will be used for mains voltages extraction and reference generation. The results of the simulation will be presented and discussed.

Figure 4.14 presents the simulation model of a series active power filter used in this work. Figure 4.15 shows the grid voltage having some harmonics begins in the moment 0.05s until 0.2s. An increase of voltage of about 0.2pu happens at the moment 0.1s until 0.12s. Figure 4.16 shows the three phase voltage at the load side after compensation using series active power filter. It is clear that the voltages are balanced and have less harmonic contents. The shape of the voltage is perfectly sinusoidal and balanced. Figure 4.17 shows the waveform of the voltage of one phase of the grid voltage before using SAPF. Figure 4.18 presents the harmonic spectrum analysis of this voltage. It is seen that the voltage is not stable and its harmonic content is 12.9%. Figures 4.19 and Figure 4.20 show the load voltage and harmonic analysis after using SAPF. It is clear that the voltage is sinusoidal and the THD is 1.35%.

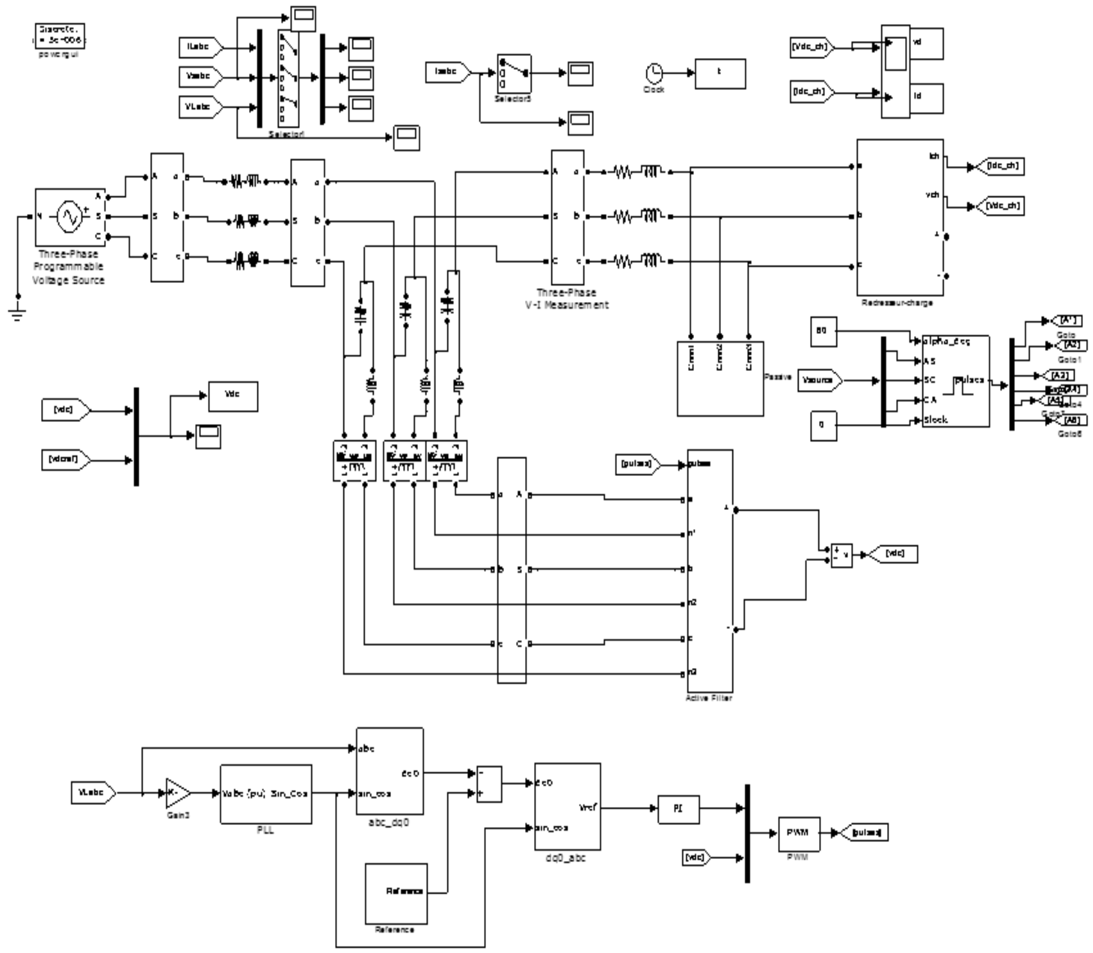


Figure 4.14: Simulation model of series active power filter (SAPF)

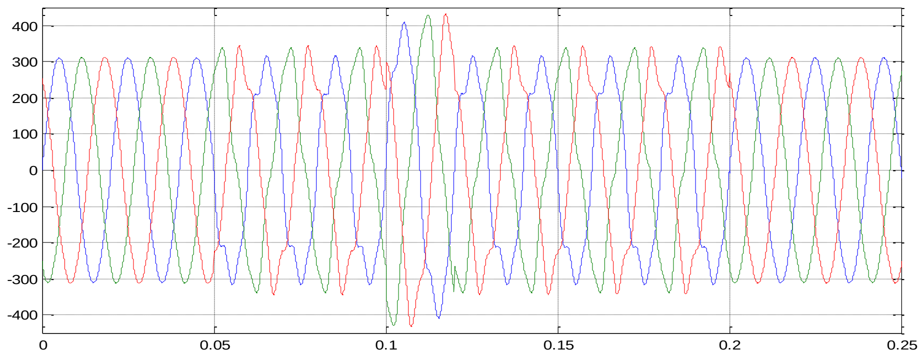


Figure 4.15: Grid voltages with harmonics and over voltage

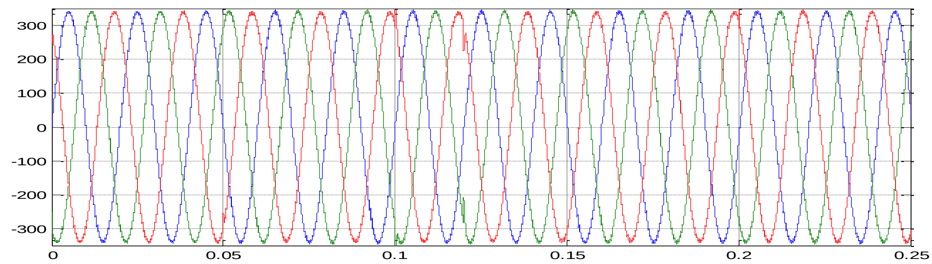


Figure 4.16: Load voltage after compensation using SAPF

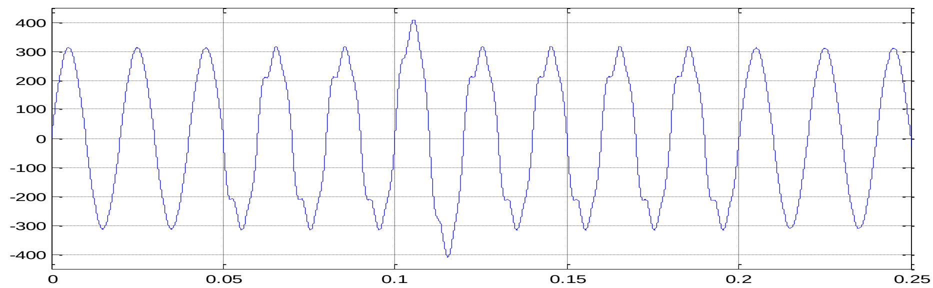


Figure 4.17: Grid Voltage before compensation (one phase)

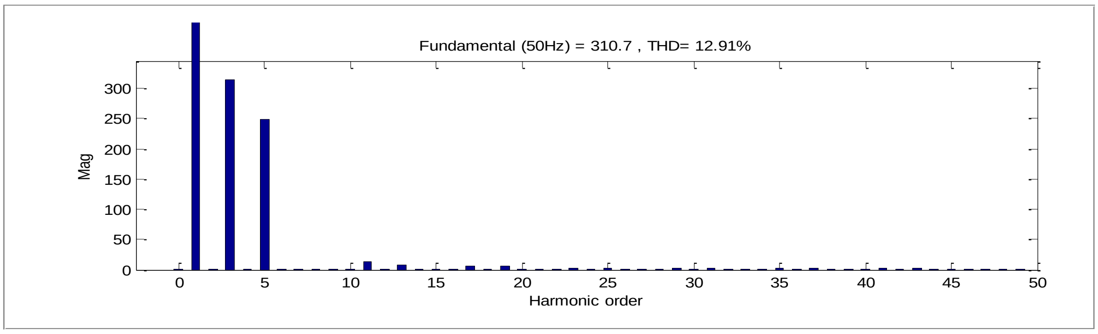


Figure 4.18: Harmonic spectrum of the voltage wave before compensation

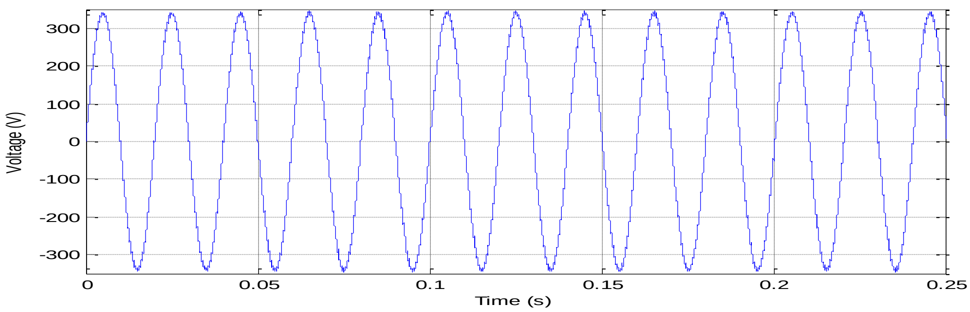


Figure 4.19: Load voltage after compensation

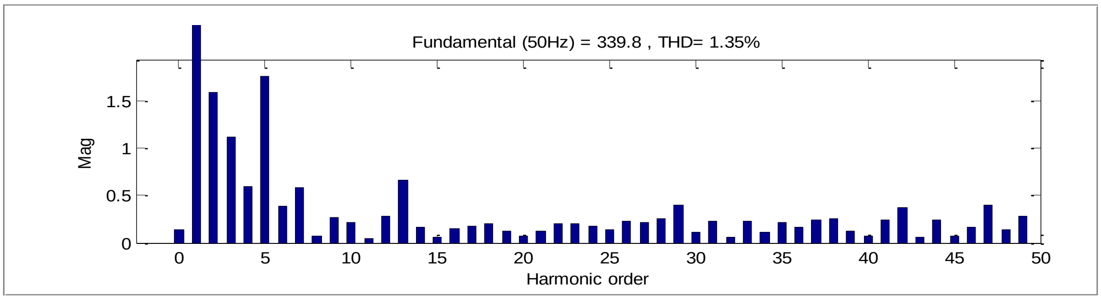


Figure 4.20: Harmonic spectrum of the load voltage (after compensation)

The Figure 4.21 presents the load current without using compensation. It is not sinusoidal and contains higher amount of harmonics. In order to eliminate these harmonics, passive filters tuned for the 5^{th}, 7^{th}, 11^{th}, 13^{th}, and 2^{nd} harmonic were connected to the grid. The passive filters are charged by filtering the grid currents and reducing their harmonic contents. The result of using passive filters can be seen in Figure 4.22. This figure shows the grid currents after using passive filters. We can notice that these currents are more pure and well shaped after compensation. In order to make sure about our results, a look on the harmonic contents presented in Figure 4.23 shows that its THD is about 4.94% which is less than the maximum accepted value.

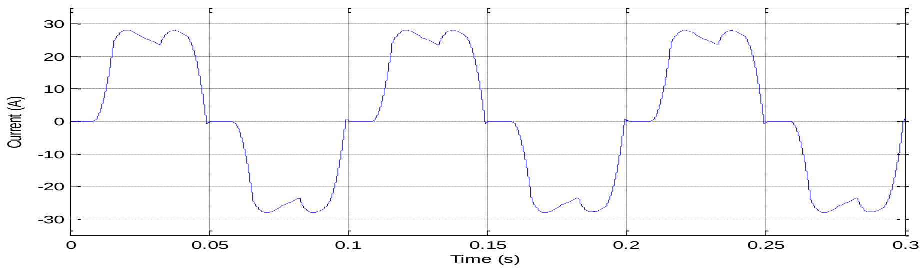


Figure 4.21: Distorted grid current before compensation

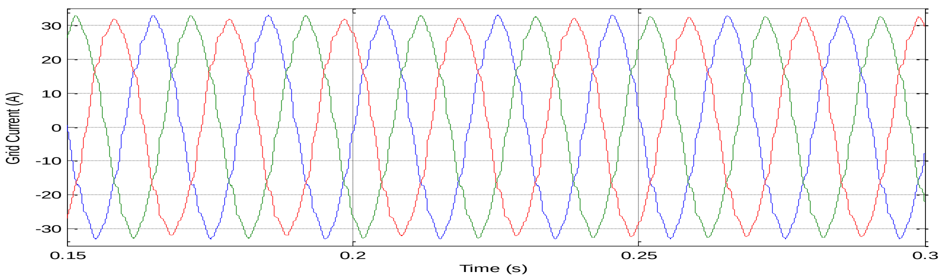


Figure 4.22: Grid current after compensation using passive filter with SAPF

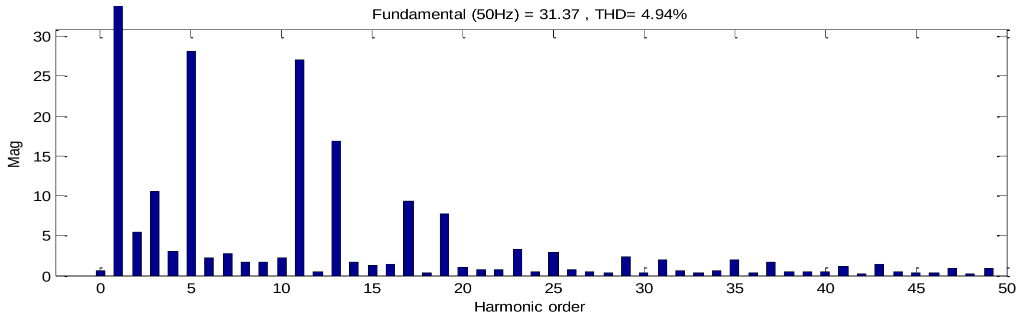


Figure 4.23: Harmonic analysis of the grid current

The case of the voltage decrease is discussed in the next paragraph. A voltage sudden decrease of about 0.5Pu in addition to some harmonics is applied on the system. The series active power filter response will be discussed and studied. Figure 4.24 presents the voltage injected by the active filter under the case of harmonics and voltage decrease. Figure 4.25 presents the grid voltage before using the series filter, while Figure 4.26 is the load voltage after the compensation. It is clear from these two figures that the compensator was able to compensate the harmonics and increase or decrease of grid voltage. As a result, the load will receive a constant pure voltage whatever the conditions on the grid side.

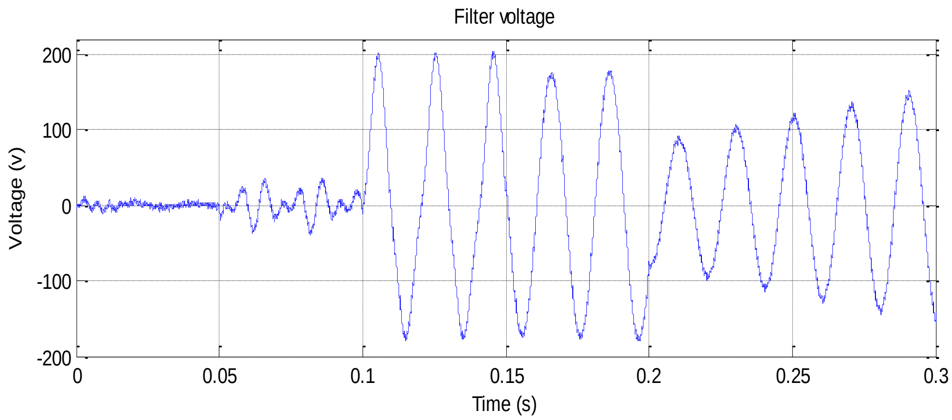


Figure 4.24: Series filter voltage injected to the grid

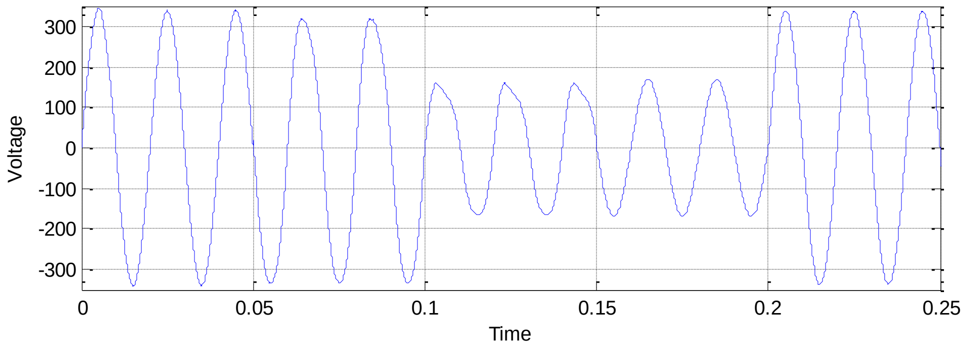


Figure 4.25: Load voltage before compensation

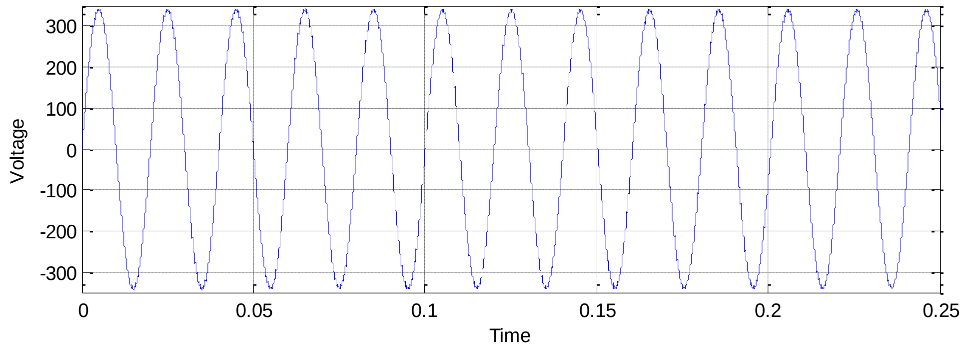


Figure 4.26: Load voltage after filtering using SAPF

It is clear from the different experiments applied using series active power filter that this type of filter is able to compensate different types of voltage problems. Separately, series active filter are rarely used for current filtering due to the need of the transformers which can be avoided by the use of parallel active filters. The use of series active filter in a hybrid structure with shunt passive filters has presented the advantage of filtering voltages and currents at once. The voltages of the grid after compensation were purely sinusoidal with fixed RMS value. The currents were also sinusoidal with acceptable THD values. It is important to mention here that a battery bank was used in the case of series active filter. This bank is being charged continuously using a bridge rectifier.

4.6 Summary

The results presented in this chapter have shown the performance of passive filters for power quality treatment under ideal stable conditions. In the case of dynamic systems, the passive filters were incapable of giving good performance and Total Harmonic Distortion reduction. The parallel active filters have shown extremely better performance in the case of dynamic systems with small drawbacks including the high power rating of the filters. This chapter has discussed the use of hybrid filters combining active parallel and passive filters in one topology. This combination has shown higher performance with low power rating and flexibility with dynamic loads. The THD has been reduced from 78% to 1.4% by using the hybrid topology whereas the passive filter has reduced it to 19%.

The use of series active filter has also reduced the unbalance factor and harmonic content of the grid voltage to obtain sinusoidal balanced three phase voltage. The harmonic analysis of all currents and voltages was applied the harmonic contents were presented and discussed. The results has proved that the use of hybrid filters ameliorates the performance of the harmonic filtering process with less power rated filters.

CHAPTER FIVE

CONCLUSION

5.1 Conclusion

This work has discussed the active and hybrid power filtering for power quality issues treatment. Active filtering has become an important topic in power engineering due to the sensitivity of the power grids. Active filtering has gained an increasing interest of the researchers in the last decades. This interest is due mainly to the importance of the power quality and the costly side effects of the existence of power quality problems. The harmonics can be considered in addition to the reactive power as the main quality problems in power grid. The spread of these harmonics is due mainly to the existence of non-linear loads connected to the supply.

In the past, the use of especially designed LC filters was considered to suffice the need of harmonic filtering in addition to the reactive power compensation. The quantities of harmonics in power grids were less and their capturing using LC simple filters was fairly easy. With the development of power electronics, rectifiers, and motor drivers these passive filters became low efficient and can’t cover the wide range of harmonics. Over more, with the existence of high frequency harmonics theses filters offer more possibility of resonance with the grid systems. As a result, the research have been pointed toward finding more efficient and less dangerous solutions presented by the active power filters.

Active filters were proposed recently for current and voltage harmonics cancelling. They are composed of instantly controlled elements that can offer variable impedance for different types of harmonics. These harmonics will then flow to the filter instead of spreading into grid. Two types of active filters were discussed in this work, these are the parallel active and series active power filter. The parallel active filters are the mostly used types of filters and deals with current harmonics. The series active power filters are interested more in voltage problems. Both passive and series active power filters were used also in hybrid combinations with passive filters to offer better efficiency and to reduce the stresses on the active filter. Hybrid filters are said to be more efficient than the separated active or passive filters.

In this work, the study of passive filter, parallel active power filter, series active power filter, hybrid series active power filter, and parallel hybrid active power filter have been performed. A comparative study of the performance and efficiency of these different types of active filters has been applied. The main aim of the work was to compare between the results obtained in each case. The performance and results of passive filter for harmonic compensation was firstly evaluated. The use of PAPF has then been performed and evaluated. A hybrid parallel APF with parallel passive filter performance was then applied and the results were discussed and tabulated. At the last stage, comparison between series active filter and hybrid series active with parallel passive filter was performed. The results of the different experiments were presented and discussed.

From the results obtained, it was clear that parallel active filters were very efficient in terms of harmonic currents treatment. The currents consumed from the supply were perfectly sinusoidal with low THD although the load was producing high amount of harmonics. The use of hybrid parallel active filter with parallel passive filter has increased noticeably the performance of filtering process and reduced the stresses of the parallel active filter. The currents of the active filter have been reduced noticeably and the passive filter compensated for the most present harmonics. The active filter was then charged to compensate the higher harmonics which are less existent in the systems.

The series active filter has shown good performance for the compensation of the harmonic voltages and voltage variations. It has been used for stabilization of the grid voltage and the balancing of three phase system voltages. The obtained results have shown the capability of series active filter for voltage variations balancing and voltage harmonics cancelling. Hybrid series active filter with parallel passive filter was used to compensate for voltage and current harmonics and to compensate the sudden variations in the voltage of the system. The obtained results have shown the ability of the hybrid filter to compensate for the harmonic currents while keeping the voltage of the system at a constant pure sinusoidal shape. A comparison between the work done and other literary works shows that the results obtained in this work were very good. In (Anooja and Leena, 2013), hybrid filtering has offered a THD reduction from 55% to 25%, and in the case of using a special construction harmonics emitter (Pulse Diode Rectifier) the THD has been reduced from 5.52% to 2.43%. A thyristor rectifier was also used to produce harmonics, hybrid active filter was able to reduce the THD from 28.20% to 5.1% and from 16.13% to 4.86%. In (Al-zamil et al., 2001) the proposed shunt active filter has reduced the THD from 28.16% to 3.9% while in (Tey et al., 2005) the neural network based shunt active power filter has given an overall THD reduction from 27.39% to 2.14%. The single phase dead time based controller in (Hou et al., 2010) has reduced the THD from 64% to 4%. In (Asadi et al., 2010) the use of PI controller has given good results in term of wave form shape, no numerical results were provided. The fuzzy logic controller used in (Georgios, 2011) has reduced the THD from the levels of 19% and 15% to the levels of 4.05% and 3.8%.

The use of Series APF with Shunt Passive filter has eliminated the voltage harmonics and reduced the THD of currents to less than 2.5% in in (Zheng et al., 1990). (Bhattacharya et al., 1993) the author claims that the use of passive filter has reduced voltage harmonics from 46.6% to 3.39%, while the use of hybrid combination of series active and passive filters the THD reached the value of 6.3%. In (Bhattacharya et al., 1995) the use of series active shunt passive filter has reduced voltage THD to 3.1% and the current THD from 35.4% to 1.1%. In (Bor-Ren & Yang, 2001) the series active power filter has been implemented to compensate the current harmonics. The THD after the use of SAPF was 2.4%. (Javadi, 2009) has presented simulation and real time implementation of active filtering for current and voltage harmonic compensation. Good results were obtained while no numeric results were provided. (Chen et al., 2004) the use of active filters has reduced THD values from 21.8% to 0.4%, in another studied case, the THD was reduced from 22.05% to 2.3%, and from 15% to 1.1%.

In this work the THD was reduced from 24.6% to 5.14% by using a suitable designed passive filter. The use of the same passive filter with a highly distorted system with 78.11% THD has given a THD reduction until the value of 19.32%. This result shows the incapability of passive filters for dynamically compensating harmonics currents. A shunt active power filter was connected to this system. The THD was decreased to 6.72% with sinusoidal wave forms. The active filter has shown better performance than the passive filter in the case of higher harmonic distortion or dynamic system. The addition of a passive filter to the active filter caused the THD to drop down till the value of 1.43% which is difficult to be reached practically. The use of series active power filter has shown two benefits: the first is voltage harmonic reduction, the second was voltage regulation and three phase balancing. The THD of the voltage was reduced from 12% to 1.35% in the case of series active power filter. The parallel connection of passive filter with the series active filter has reduced the current harmonics to 4.94%.

After doing this work it can be concluded that the active power filters are efficient for the compensation of harmonics of the voltage and current. It has been shown that the use of hybrid filters ameliorates clearly the performance of the used active filter. It also reduces the stresses applied on the active filter by reducing the harmonics to be compensated by the filter. The hybrid filter has reduced the harmonic contents to less than 5% in all the studied cases and created sinusoidal system voltage and current.

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APPENDIX A

Thyristor Bridge Rectifier

The thyristor rectifier is a controlled rectifier which can be controlled for the changing of the DC voltage side. In a three phase rectifier, the diodes are replaced by thyristors which are controlled for the turn ON and turn OFF automatically when their currents are null and their voltage are inverse biased. The normal control of the thyristors starts from the point where the forward voltage of the thyristor is positive. This point is the cross point of two phase to neutral voltages in a three phase system as shown in Figure A.1.

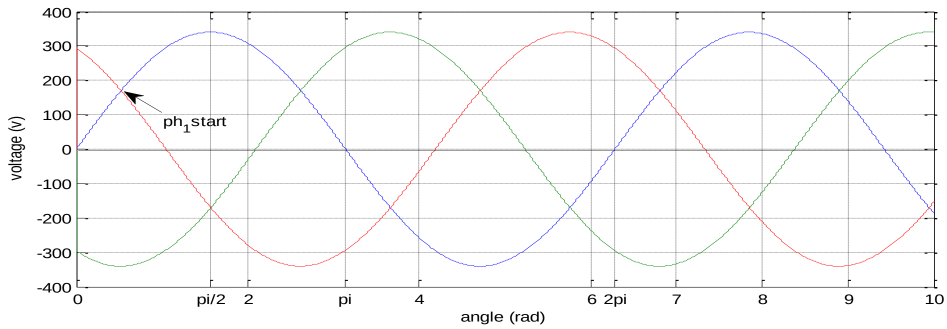

Figure A.1: Three phase voltage and start of firing angle of the thyristor

The function of any thyristor of the upper side of rectifier starts between the angle of 30° until 150° with respect to its phase. With a 120° control range, increasing the angle of switching ON the thyristor will decrease the conduction time and reduce the delivered power as a result. The figures below shows the different output power with different firing angles of the thyristor.

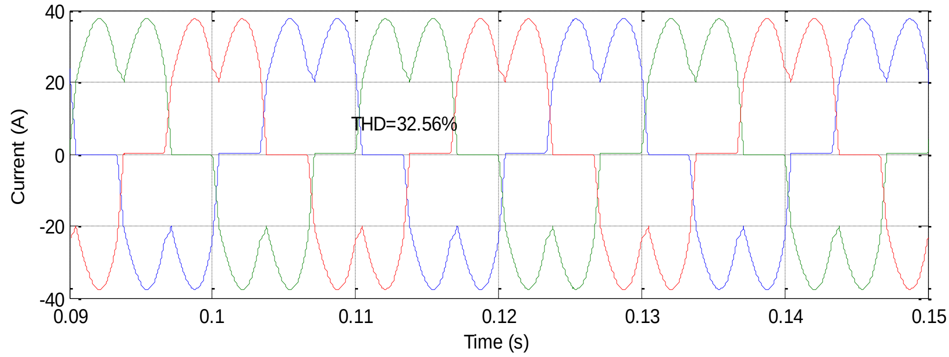

Figure A.2: Line current under firing angle of 30 degrees

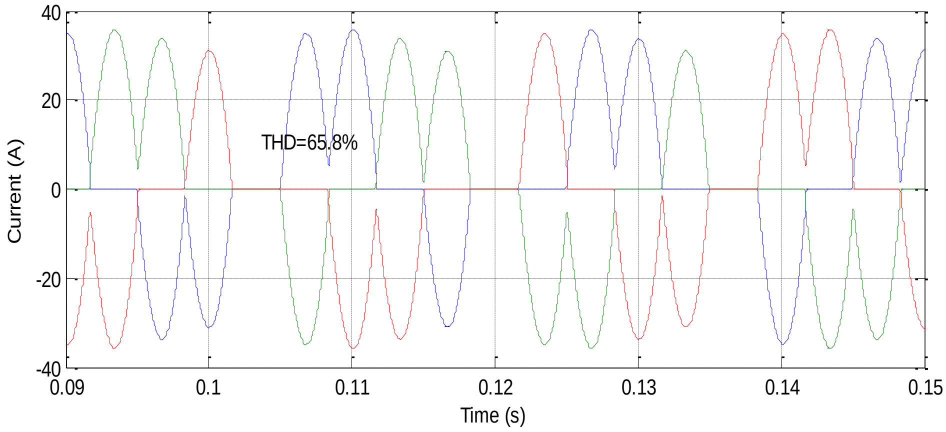

Figure A.3: Line current with firing angle of 60 degrees

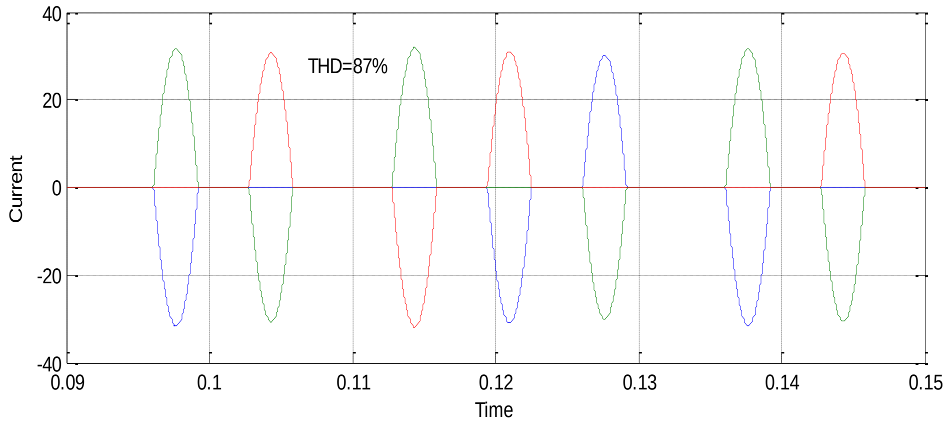

Figure A.4: Line current with firing angle of 80 degrees

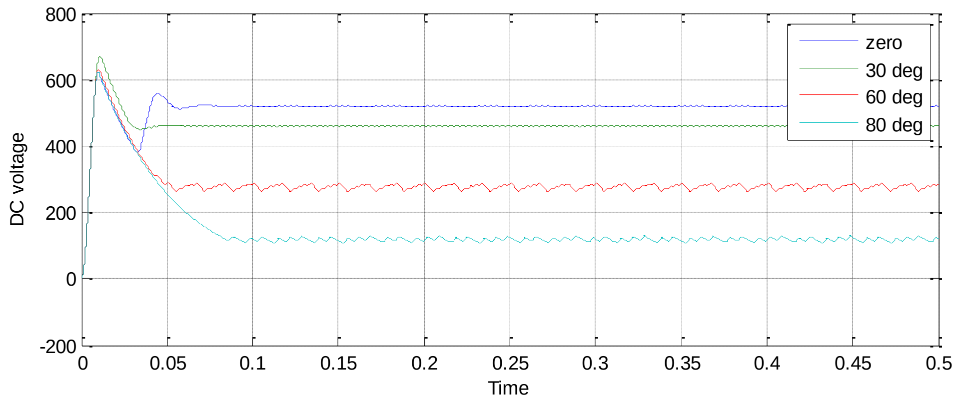

Figure A.5: DC side voltage of controlled rectifier