POWER QUALITY IMPROVEMENT USING SHUNT ACTIVE POWER FILTER IN POWER SYSTEM

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by

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LUCKNOW

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DECLARATION

I hereby declare that the work, which is being presented in the dissertation entitled **"Power quality improvement using shunt active power filter in power system** " in partial fulfillment for the award of degree of **Master of Technology** in Department of Electrical Engineering with Specialization in **Power System & Control** and submitted to the **Department of Electrical Engineering, Babu Banarasi Das University** is a record of my own investigations under the guidance of **Prof. Padmesh Singh, Associate Professor, Department of Electrical Engineering, Babu Banarasi Das University, Lucknow.** I have not submitted the matter presented in this thesis anywhere for the award of any other degree.

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ABSTRACT

Modern active filters are superior in filtering performance, smaller in physical size, and more flexible in application, compared to conventional passive filters using capacitors, inductors and a registers. However, the active filters are slightly inferior in cost and efficiency to the passive filters. Problems caused by power quality have great adverse economical impact on the utilities and customers. Current harmonics are one of the most common power quality problems and are usually resolved by the use of shunt passive or active filters. Hans filters is designed to using PI controller to improve power quality. Over the past few years, the growth in the use of nonlinear loads has caused many power quality problems like high current harmonics, low power factor and excessive neutral current. Nonlinear loads appeared to be current sources injecting harmonic current into the supplier network through the utility's point of common coupling (PCC). Other customers at the same PCC will receive distorted supply voltage, which may cause overheating of power factor correction capacitors, motors, transformers and cables, and mal-operation of some protection devices. Therefore, it is important to install compensating devices to eliminate the harmonic currents produced by the nonlinear loads.

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LIST OF ABBREVIATIONS

ABBREVIATIONS	**DESCRIPTION**
DC	Direct current
AC	Alternating current
SAPF	Shunt Active Power Filter
MATLAB	MATrix-LABoratry
PI	Proportional, Integral
MPP	Maximum power point
PID	Proportional Integral Derivative
RMS	Root mean square
PF	Power Factor
THD	Total Harmonic Distortion
PF	Power factor
V_g	Supply Voltage
F	Grid frequency
M	Mutual inductance between phases
SAPF	Shunt active power filter
APF	Active power filter

LIST OF SYMBOLS

SYMBOL	DESCRIPTION
K_p	Proportional gain
K_i	Integral gain
Vg	Supply Voltage
LL	Line inductance
Kp	Proportional gain
Ki	Integral gain
Lsh	Coupling Inductance
Cdc	APF DC Capacitor
Vdc	DC link capacitor voltage
Ea	Back- EMF
Vt	Terminal voltage

CHAPTER 1

1.1 Introduction

Power Quality is a combination of Voltage profile, Frequency profile, Harmonics contain and reliability of power supply**.** The Power Quality is defined as the degree to which the power supply approaches the ideal case of stable, uninterrupted, zero distortion and disturbance free supply.

The increasing use in the industry of nonlinear, unbalanced loads based on the power electronic elements introduced serious perturbation problems in the electric power distribution grids. Also, regular increase in the harmonic emissions and current unbalance in addition to high consumption of reactive power can be noticed. The flow of harmonic currents in the electric grids can cause also voltage harmonics and disturbance. These harmonic currents will interact adversely with a wide range of power system equipments, control systems, protection circuits, and other harmonic sensible loads. The energy distributers as like as consumers was then concerned by imposing some regulations protecting against the expansion of harmonic problem. Many regulations concerning the harmonic emissions has been proposed by the international electrical committee’s like IEC-61000 and by the recommendations IEEE Std. 519-92 [1, 2].

The consumption of reactive power in industrial and domestic loads presents also an important issue in the discussion of power quality problems. The reactive power consumed by non-resistive loads causes higher RMS current values in addition to extra heating of power transmission and distribution systems. The use of batteries of capacitors or synchronous machines for local reactive power production has been proposed for a long time. The accelerated development of power electronics and semiconductor production had encouraged the use of STATIC VAR compensators for the reactive power compensation. However, these solutions looks inefficient and can cause extra problems in power systems in the case of high current and voltage harmonic emissions. The fact that these systems are especially designed to compensate the fundamental based reactive power, in addition to high possibilities of interaction between these compensation elements and system harmonics make it unstable solutions in modern technologies.

In order to face the problem of harmonics, many solutions has been proposed. These solutions included modifications on the load itself for less harmonic emissions like the case of special structure single phase and three phase rectifier, and PWM rectifiers. Or the connection on the polluted power grids of other traditional or modern compensation systems.

Most of traditional harmonic reduction solutions includes the use of harmonic trapping passive filters based on RLC elements calculated in accordance with the harmonic ranges has been trapped. In addition, these passive filters could be designed to compensate the reactive power simultaneously with the desired harmonics. Nevertheless, these solutions are of poor efficiency due to different factors [3].

- Insufficient fitness for large bands of harmonic frequencies, which implies the use of many filters.

- Possibility of series and parallel resonance produces with the grid, which lead to dangerous amplification of neighboring frequency harmonics.

.

- Highly dependent on the grid and load parameters and also main frequency.

- Bulky equipments size are large. [4, 5].

- Very low flexibility for load variations which implies new filter design for each load variation.

During the last three decades, the researchers were encouraged by the development of power electronics industry, the revolution in digital signal processing production and the increasing demand for efficient solutions of power quality problems including harmonics problem. They are encouraged to develop modern, flexible, and more efficient solutions for power quality problems. These modern solutions have been given the name of active compensators or active power filters. The objective of these active power filter abbreviated mostly APF is to compensate harmonic currents and voltages in addition to selective reactive power compensation. The use of APFs for harmonic and reactive power compensation and DC power generation was proposed in [4]. The main advantages of the APFs are their flexibility to fit load parameters' variations and harmonic frequencies in addition to high compensation performance.

Many types of APF has been proposed and used in harmonic compensation. Series APF are used for voltage harmonics compensation. Shunt APF were 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 traditional and the modern in one HAPF has the aim of amelioration of different types of shunt and series 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 removes the drawbacks related to each of them when used individually.

Although there are different types of APF, the Shunt APF are 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. Whereas, the SAPF current is generated in a manner that grid current keeps the sinusoidal form. SAPF is controlled to be seen with the non-linear load by the grid either as linear resistive load; in case of reactive power compensation, capacitive or inductive load in the case when the APF is not responsible for reactive power compensation.

There are two main structures for the control of Shunt Active Power Filter; that is the direct control and the indirect control of APF. In the direct control the main idea is to generate filter current references using the appropriate methods. The generated reference currents are then to be compared with the measured APF currents. The error is then used to produce control signals of the filter. The indirect control interests in controlling the grid currents instead of filter currents. It compares the measured grid currents with their generated references. The error is then sent to the control circuit which determines the control signal of the APF.

1.2 Literature Review

The literary of APF are very rich and covers many aspects including power topologies, control theories, and harmonic extraction and reference generation methods of APF. The instantaneous active and reactive power PQ theory and the synchronous reference frame SRF or d-q theory based on Park transform had attracted the attention of researchers due to their simple principle and high efficiency. The direct control strategy of APF has been the mostly used in literary. In [6] the author presented the use of PQ theory for harmonic extraction. The direct control based on PI current and voltage controllers, also a fix and auto adaptive band hysteresis in addition to fuzzy logic DC voltage controller was studied. [4] have presented in his PHD thesis a study of SAPF and series APF. He discussed the use of PQ theory and SRF theory for current and voltage harmonics extraction. The control of APF using PI controllers in addition to the use of RST controllers was covered. A new modified RST controller was proposed in this work. PQ theory modified PQ theory, SRF theory were presented by [7]. Current and voltage control based on linear PI controllers, sliding mode controllers, linearization, and back stepping control methods were also presented in his work. Fuzzy logic DC voltage control with sliding mode current control based on sine multiplication extraction theory was presented by [8]. Instantaneous active and reactive power theory with hysteresis

SVPWM control were studied in [9]. The function of APF with DC power generation was proposed in [10]. In [11], fuzzy logic and hysteresis control based on SRF theory were presented and discussed.

In [12], the use of PQ, SRF and sine multiplication theories was discussed in addition to the PI and hysteresis controllers. Sine multiplication theory based SAPF with IP current controller was proposed by [13]. The use of fuzzy logic controller with sine multiplication theorem in single phase APF has been presented in [14]. In [15], an adaptive fuzzy low pass filter for harmonic extraction has been proposed to ameliorate the performance of APF. three phase APF based on SRF theory with SVPWM control was proposed in [16]. PQ theory, active and reactive currents theory performance were studied under unbalanced voltage system in [17]. Study of PQ, SRF, constant active and reactive power theory, constant (unity) power factor algorithm, sine multiplication theory have been proposed in [18]. Sliding mode based DC voltage controller for grid current's peak detection was proposed by [19]. The use of self tuning filter in unbalanced distorted grid voltage conditions (STF) has been proposed by [20, 21, 22, and 23]. PQ, SRF, and modified PQ theory were studied in [23]. The use of two legs with midpoint capacitor, three legs and four legs VSI with PQ theory in balanced and unbalanced voltage system has been studied in [20].

Artificial intelligence have been recently introduced in the harmonic extraction and the control of active power filter. In [24] a comparison between the performances of UPQC based on PI controller and ANN based controller were presented. The use of ANN for harmonic content extraction was proposed and discussed by [25]. The use of adaptive neural network in the control of series APF was proposed in [26].

Separately, the indirect control of APF has been discussed and proposed in different works. In [27, 28, and 29] indirect control based on PI controller has been proposed. sliding mode control of DC voltage with indirect PI current controllers were used in [30]. Finally, Indirect fuzzy logic control has been proposed in [8].

Thesis Overview

This dissertation report contains six 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 the 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 traditional and modern solutions of harmonic problems.

In the third chapter, the study is pointed toward the designing shunt active power filter and its uses.

Chapter four covers the design and control scheme of Shunt Active Power Filter.
In chapter five of this dissertation work there is elaborative explanation of modeling of SAPF , simulation results and detail discussion.

In last chapter we discuss about conclusions & future scope.

CHAPTER 2

Power Quality

Electric systems and grids are complex dynamic systems. These systems suffer usually from unexpected or sudden changes of the currents and voltages. These changes are due to mainly the different types of linear and non-linear loads which they are connected. In addition, to different types of accidents which can intervener into the grid [31]. With the increasing use of power semiconductor devices in the most of industrial and domestic procedures, the electric grids is polluted with different harmonic currents and voltages. These harmonics affect the normal function of the most of the grid connected devices; in addition to considerable economic losses. Many classic and modern solutions have been proposed in the literary for the harmonic problems. In this chapter ,we discuss the harmonic problem as one of the most common power quality problems will be presented. The different modern and traditional solutions will then be discussed.

2.1 Power Systems Distortion and Problems

In power systems, different voltage and current problems can be faced. The main voltage problems can be summarized in short duration variations, voltage interruption, frequency variation, voltage dips, and harmonics. Harmonics represent the main problem of currents of power systems.

2.1.1 Voltage Variation for Short Duration

The short duration voltage variation are the results of the problems in the function of some systems or the start of many electric loads at the same time. The defaults can increase or decrease the amplitude of the voltage or even cancel it during a short period of time [31]. The increase of voltage is a variation between 10-90% of the nominal voltage. It can hold from half of a period to 1 minute according to the IEEE 1159-1995. According to the same reference, the increase in voltage is defined when the amplitude of the voltage is about 110-180% of its nominal value.

2.1.2 Voltage Interruption

The cutoff of the voltage happens when the load voltage decreases until less than 10% of its nominal value for a short period of time less than 1 minute. The voltage interruption can be the effect of defaults in the electrical system, defaults in the connected equipments, or bad control systems. The main characteristic of the voltage interruption are the period over which it happens.

2.1.3 Frequency Variations

In the normal conditions the frequency of the distribution grid must be within the interval 50±1 Hz. The variations of the frequency of the grid can appears to the clients who is using auxiliary electric source (solar system, thermal station…etc). These variations are rare and happen in the case of exceptional conditions like the defaults in the turbines.

2.1.4 Unbalance in Three Phase Systems

The three phase system is unbalanced when the currents and voltages are not identical in amplitude; or when the phase angle between each two phases are not 120°. In the ideal conditions, the three phase system is balanced with identical loads. In reality, the loads are not identical, in addition to the problems of the distribution grids which can interfere.

2.1.5 Voltage Dips (Sags)

The voltage dips is periodic perturbations. They appear as a natural effect of the switching of the transistors. They are due also to the start of big loads like motors. Lifts, lights, heaters…etc. this phenomena causes bad functioning of the protection equipment.

2.1.6 Harmonics

Power systems are designed to operate at frequencies of 50 or 60 Hz. However, certain types of loads produces currents and voltages with frequencies that are integer multiples of the 50 or 60 Hz fundamental frequency. These frequencies components are a form of electrical pollution known as harmonic distortion. There are two types of harmonics that can be encountered in a power system [32].

- Synchronous harmonics.
- Asynchronous harmonics.

Synchronous harmonics is sinusoids with frequencies which are multiples of the fundamental frequency. The multiplication factor is often referred to as the harmonic number. The synchronous harmonics can be subdivided into two categories.

- Sub-harmonics: when the harmonic frequency is less than the fundamental frequency.
- Super harmonics: when the harmonic frequency is more than the fundamental frequency.

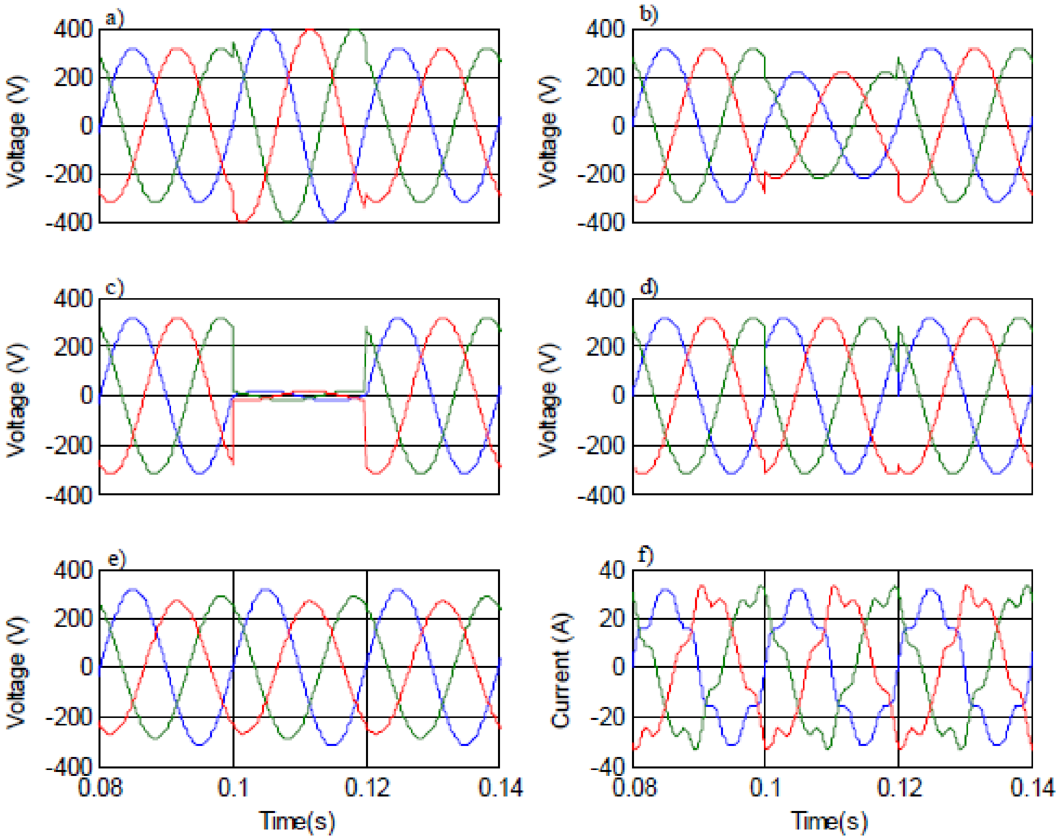


Figure 2.1: Most encountered power system problems. a) Voltage swells. b) Voltage sags. c) Voltage interruption. d) Frequency variation. e) Voltage unbalance. f) Harmonics.

Harmonics is familiar to the musicians as the overtones from an instrument. They are the integer multiples of the instrument's fundamental or natural frequency that is produced by a series of standing waves of higher and higher order.

Exactly the same thing happens in power circuits when non-linear loads create harmonic currents that is integer multiples of the supply fundamental frequency. The rapid growth of solid-state power electronics has greatly increased the number and size of these loads.

The concepts of harmonic were introduced in the beginning of the 19th century by Joseph Fourier. Fourier has demonstrated that all periodic non-sinusoidal signals can be represented by infinitive sum or series of sinusoids with discontinuous frequencies as given by Eqn. 2.1.

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

The component I_o in the Fourier series is the direct component. The first term of the sum with the index h=1 is the fundamental of the signal. The rest of the series components is called the harmonics of the range h. Figure 2.2 Shows the form of a wave containing the third harmonic (h=3). In the three phase electric grid, the principle harmonic components are the harmonics of ranges (h±1) [33].

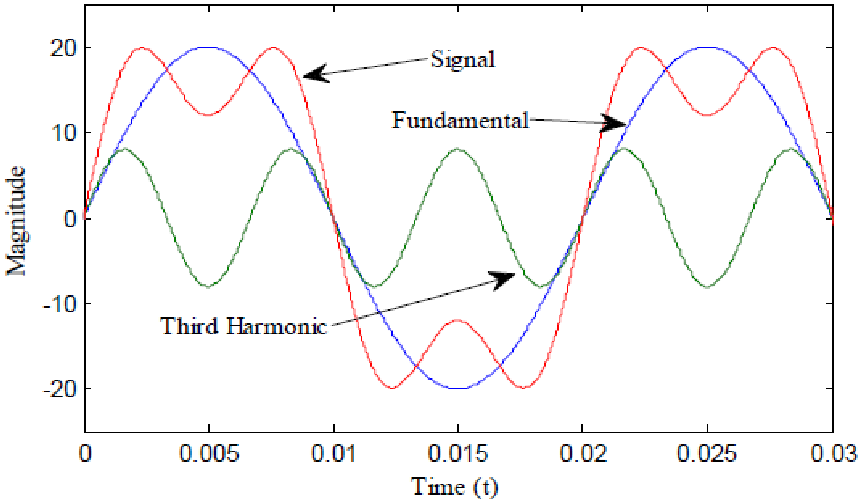


Figure 2.2: Harmonic content of a signal and its fundamental.

Transformer exciting current, arc furnaces, rectifiers, and many other loads will produce harmonics in the utility lines. Most utilities limit the allowable harmonic current levels to the values shown in IEEE 519.

2.1.6.1 Total Harmonic Distortion (THD)

The total harmonic distortionof a signal are a measurement of the harmonic distortion present in current or voltage. It is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency. Harmonic distortion is caused by the introduction of waveforms at frequencies in multiplies of the fundamental.

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

The THD is a very useful quantity for many applications. It is the most commonly used harmonic index. However, it havethe limitations that, it is not a good indicator of voltage stress within a capacitor because that is related to the peak value of voltage waveform [11].

2.1.6.2 Distortion Factor

The distortion factor F_d is defined as the ratio between the fundamental and the signal in RMS values. It is given by:

$$F_d = \frac{I_{L1}}{I_{rms}} \qquad (2.3)$$

It is then equal to unity when the current is purely sinusoidal and decreases when the distortion appears.

2.1.6.3 Crest Factor

The crest factor of a signal Fc is defined by Eqn. (2.4):

$$F_c = \frac{crest\ value}{effective\ value} \qquad (2.4)$$

For sinusoidal waves, the crest factor is 1.41. It can achieve the value of 5 in the case of highly distorted waves.

2.1.6.4 Effects of Harmonics

Harmonic currents will flow into the utility feeder and may create a number of problems in so doing. They may be trapped by power factor correction capacitors and overload them or cause resonant over-voltages. They can distort the feeder voltage enough to cause problems in computers, telephone lines, motors, and power supplies, and may even cause transformer failures from eddy current losses. The harmonic currents may be trapped by installing series LC filters resonant at the offending frequencies. These filters should be designed to offer low impedance at the resonant frequency compared to the source impedance at that frequency. But, again, there is a hidden “gotcha.” If a filter is installed that have a series resonance at the 7th harmonic, it will also have a parallel resonance with the utility at a lower frequency when the source inductance is added to the filter inductance. If this parallel resonance should lie on or near the 5th harmonic, there is the possibility of the resonant over-currents described earlier. The installation of series resonant traps will always introduce parallel resonances at frequencies below the trap frequencies. Good practice dictates that multiple resonant traps be installed first at the lowest harmonic frequency of concern and then in the sequence at the higher-frequency harmonics. If switched, they should be switched on in sequence starting with the lowest frequency trap and switched out in sequence starting from the highest frequency trap [34].

The voltage or current distortion limit are determined by the sensitivity of loads (also of power sources), which are influenced by the distorted quantities. The least sensitive is heating equipment of any kind. The most sensitive kind of equipments are those electronic devices which have been designed assuming an ideal (almost) sinusoidal fundamental frequency voltage or current waveforms. Electric motors are the most popular loads which are situated between these two categories.

2.1.6.5 Power Factor

Power factor is defined as the ratio of real power to volt-amperes and is the cosine of the phase angle between the voltage and the current in an AC circuit. These are neatly defined quantities with sinusoidal voltages and currents. Power factor can be improved by adding capacitors on the power line to draw a leading current and supply lagging VArs to the system. Power factor correction capacitors can be switched in and out as necessary to maintain VAr and voltage control [34].

For a sinusoidal signal, the power factor is given by the ratio between the active and the apparent power. Electrical equipments' parameters are normally given under nominal voltage and current. A low power factor can indicate bad use of these equipments. The apparent power can be defined by:

$$S=V_{\mathrm{rms}}I_{\mathrm{rms}}=V_{\mathrm{rms}}\sqrt{\frac{1}{T}\int_0^T i_L^2\,dt} \qquad (2.5)$$

The active power P can be given by the relation:

$P=V_{rms}I_{L1}\cos(\alpha 1)$ (2.6)

The reactive power Q is defined by:

$Q=V_{rms}I_{L1}\sin(\alpha 1)$ (2.7)

The power factor in this case can be given by Eqn. 2.8

$P.F.=\frac{P}{S}=\frac{P}{\sqrt{P^2+Q^2}}$(2.8)

In the case where there is harmonics, a supplementary power called the distorted power D appears. This power can be given by the relation 2.9.

$D=V_{rms}\sum_{n=2}^{\alpha} I_{Ln}^2$ (2.9)

The apparent power can then be expressed as:

$S=\sqrt{P^2+Q^2+D^2}$ (2.10)

The power factor is then given by:

$PF=\frac{P}{\sqrt{P^2+Q^2+D^2}}$ (2.11)

From eqn. 2.11, we can notice that the power factor decreases because of the existence of harmonics in addition to the reactive power consumption [35]. The Fresnel diagram of the power is given in Figure 2.3.

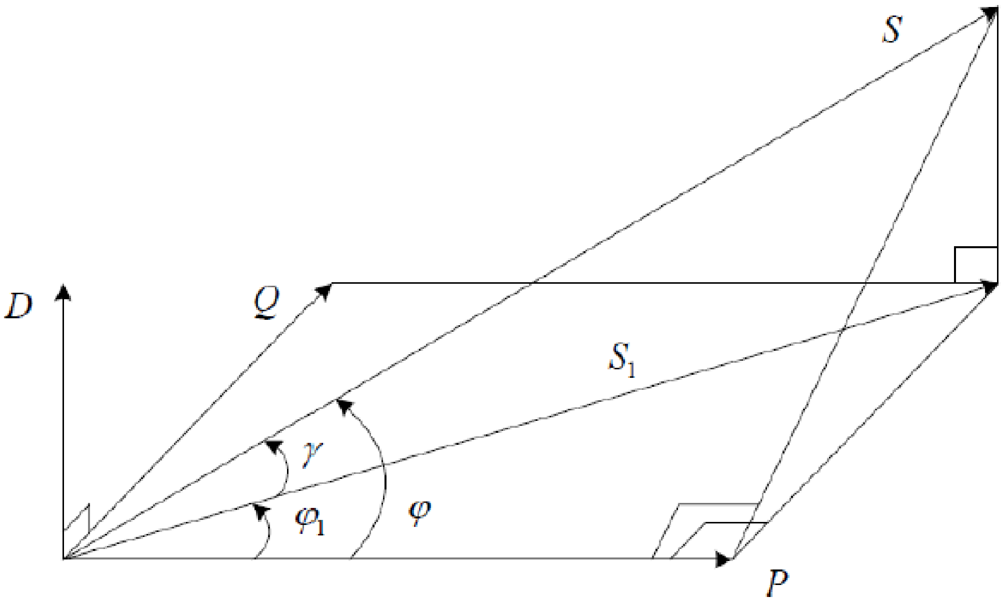


Figure 2.3: Fresnel representation of the power [36].

φ: The phase between active power P and apparent power S.

φ1: The phase between active power P and apparent power S1.

γ: The phase between apparent power in a linear system and that in a non-linear system.

2.2 Harmonic Currents Sources

The main cause of harmonics is the injection of harmonic currents by the non-linear loads. The bridges 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 [33]. There are also many other harmonic producing loads such as [11, 37]:

- Industrial equipments (welding machines, arc furnaces, induction furnaces, rectifiers).
- Offices equipments (computers, photocopier, etc).
- Domestic devices (TVs, micro-wave furnaces, neon lightening, etc).
- Power inverters.
- Power transformers when working in the saturation zone also are considered as non-linear loads that produce harmonics.

The feeding of non-linear loads generates the harmonic currents which spread into the electrical grid. The spread of current the harmonics into the feeding impedances (transformers and grid) creates harmonic voltages in these feeders. Remember that the conductor impedance increases with the frequencies of the currents which pass through it, different impedance will appear for each range of current harmonics. The harmonic current of range h would create through the impedance harmonic voltage. All the loads connected to the same point will be fed with the same perturbed voltage [37]. The equivalent circuit per phase of a non-linear load connected to the grid is given by Figure 2.4.

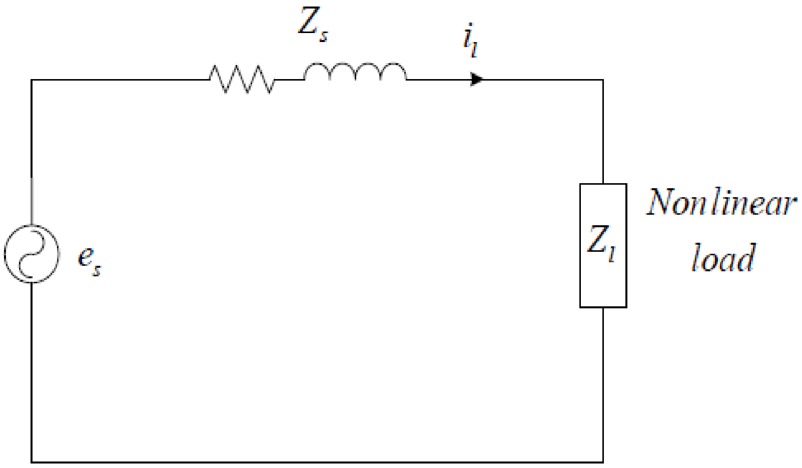


Figure 2.4: Equivalent circuit per phase of a non-linear load connected to the grid

The spread of harmonic currents from different loads can be represented as in Figure 2.5.

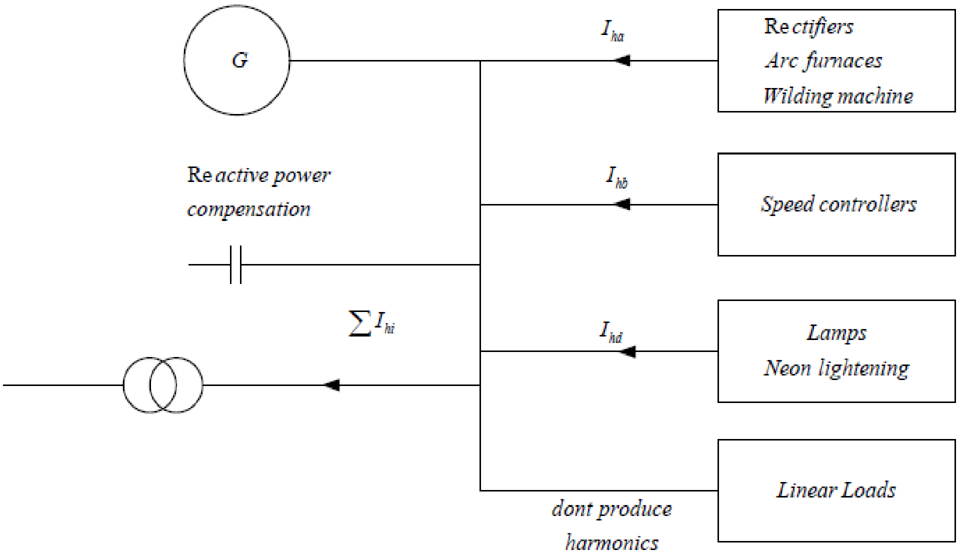


Figure 2.5: Spread of harmonic currents into the grid.

2.3 Economic effects of harmonics

- Premature aging of materials which forces its replacement, in addition to an initial over sizing of these materials.
- The overloading of the grid which implies to increase the nominal power and to oversize the installations and causing more and more losses.
- The current distortions can cause sudden triggers and the stop of production equipments.

These material costs, energetic and production losses that affect the competitiveness and the productivity of factories and companies.

2.4 Solutions for the Harmonics

The filtering of the grid currents and voltage are a priory problem for the distributer as like as the client. Because the limits on harmonic emission are not equally applied in the low of the different countries, the producers of the different electrical devices try to construct devices that satisfy for the conditions and limits of the international standards. The electric companies, from its side, use different filtering equipments and encourage the researches toward finding new efficient solutions for the power quality problems. The clients install also sometimes reactive power and harmonic compensation batteries to ameliorate the power factor and reduce the energy consumption bill.

Many traditional and modern solutions for harmonics mitigation and power quality improvement was proposed in literary. Some of these solutions investigate in the load to minimize the harmonic emission while the others propose the use of external filtering equipments that prevent the spread of harmonics into the grid [7].

2.4.1 In-Line Reactor

In-line reactor or choke is a simple solution to control harmonic distortion generated by adjustable speed drives. The solution is come up with inserting a relatively small reactor, or choke, at the input of the drive. The inductance prevents the capacitor to be charged in a short time and forces the drive to draw current over a longer time and reduces the magnitude of the current with much less harmonic content while still delivering the same energy [38].

2.4.2 Transformers with Passive Coupling

Some types of triangle zigzag coupling of transformers allow the elimination of the harmonics of order 3 and its multiples. The cost of these coupling types is the augmentation of the source impedance, and then the augmentation of voltage harmonic distortion [33, 38].

2.4.3 Passive Filters

Passive filter, which are relatively inexpensive in comparison with the other harmonic reduction methods, is the most used method. Inductance, capacitor and the load as a resistance are tuned in a way to control the harmonics. However, they suffer from interfering with the power systems. Actually, passive filter is designed to shunt harmonics from the lines or block their flow through some parts of the systems by tuning the elements to create a resonance at the selected frequency. These filters are tuned and fixed according to the impedance of the point at which they will be connected and hence cannot be adjusted instantaneously in accordance to the load. As a result their cutoff frequency changes unexpectedly after any change in the load impedance resulting in producing a resonance with other elements installed in the system.

2.4.3.1 Resonant Filter

The resonant passive filter shown in Figure 2.6 is constructed by an inductor 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 [35]. The equivalent circuit of the resonant filter with the harmonic source and grid impedance is shown in Figure 2.7.

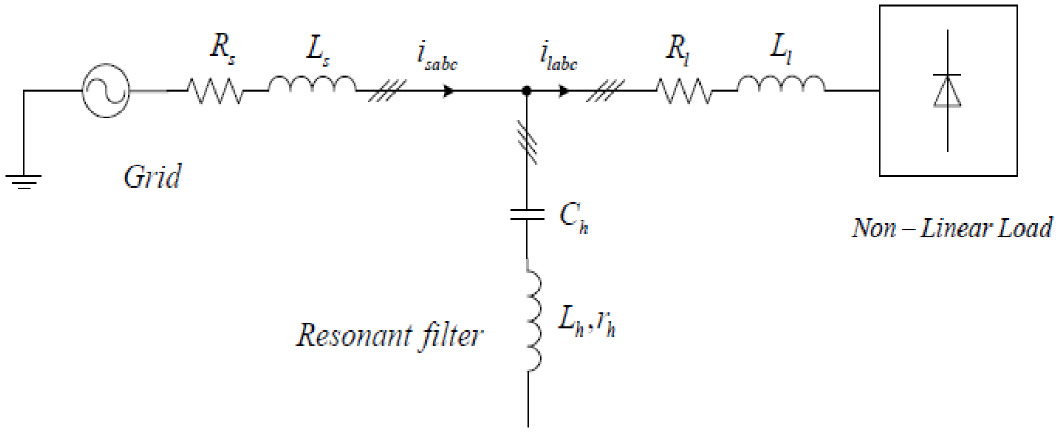


Figure 2.6: Resonant filter in parallel with non-linear load

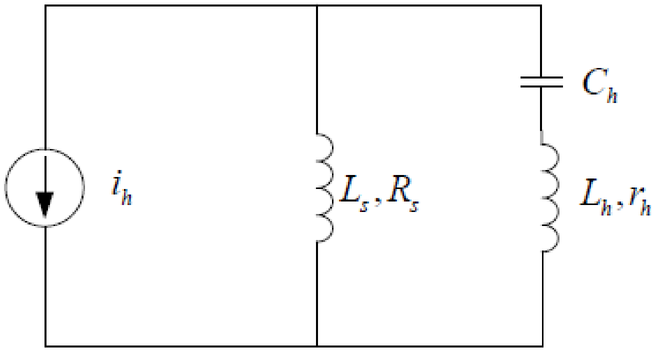


Figure 2.7: Harmonic equivalent circuit of passive filter with the grid impedance

2.4.3.2 Amortized Filter or High Pass Filter of Second Order

The second order high pass filters are constructed of passive elements RLC as shown in figure 2.8. The aim of this filter is to eliminate the harmonics in a large band. It is usually used in the elimination of high order harmonics which are enough away from the fundamental of the system.

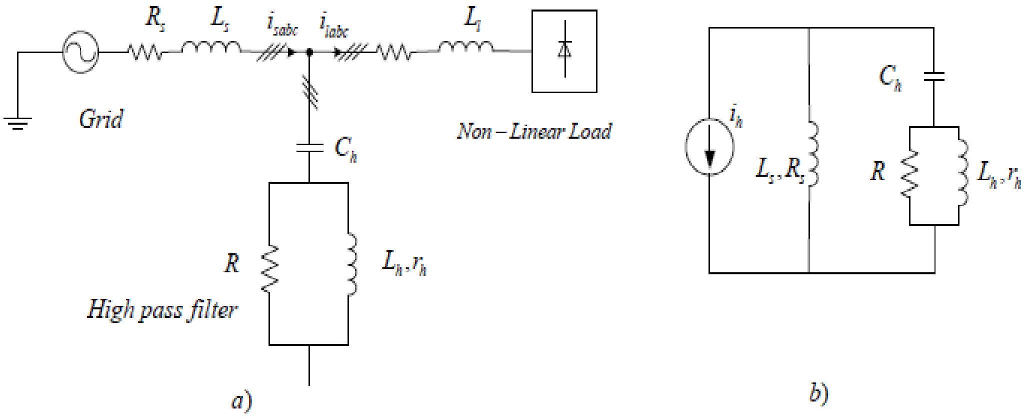


Figure 2.8: a) Diagram of the high pass filter. b) Equivalent circuit of the HPF.

2.4.3.3 Resonant Amortized 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 2.9 shows the connection of resonant filter for 5th and 7th harmonics with high pass filter.

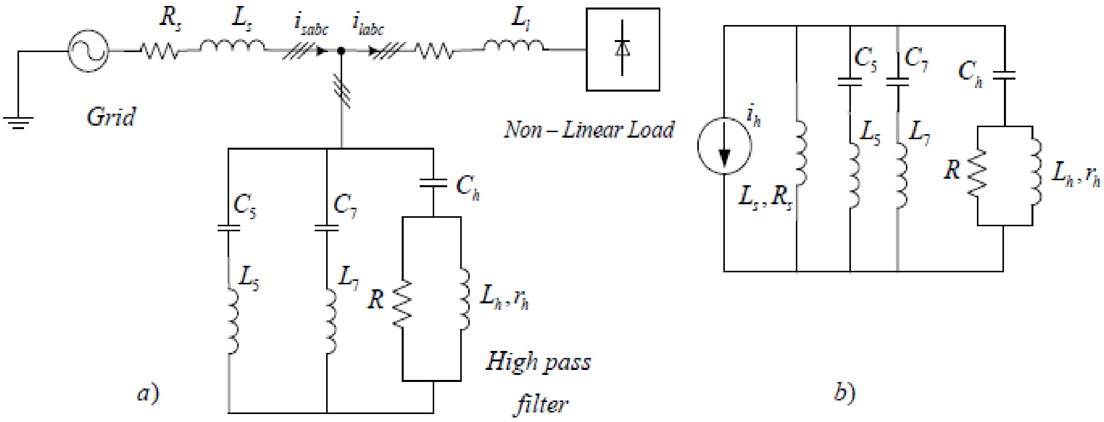


Figure 2.9: a) Diagram of the connection of amortized resonant filters. b) Equivalent circuit diagram.

The traditional solutions generally used for harmonics reduction and power factor correction is composed of passive filters connected in parallel to trap the harmonic currents. These are composed of resonant filters or high pass filters of the second degree or amortized. These solutions extremely simple and widely used have at the same time important problems [35]:

- The construction of filter needs a brief knowledge of the configuration 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 variation 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 factors of the filter are reduced which provoke the consumption of active power.
- These circuit is 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 parameter is dynamically changing and the harmonic specters are variable. The construction of passive filters in accordance with specified harmonics is not sufficient to eliminate grid harmonics.

2.5 Modern Solutions for Harmonics’ Problems

Modern solution was proposed as efficient solutions for the elimination of electric grid harmonics in order to defeat the disadvantages of the traditional methods like passive filters [20]. 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.

2.5.1 Active Power Filters

The function of the active power filters (APF) is to generate either harmonic currents or voltages in a manner such that the grid current or voltage waves conserve the sinusoidal form. The APFs can be connected to the grid in series (Series APF), shunt (SAPF) to compensate voltage harmonics or current harmonics respectively. Or can be associated with passive filters to construct the hybrid filters (HAPF).

Active filters are relatively new types of devices for eliminating harmonics. This kind of filters are based on power electronic devices and are much more expensive than passive filters. They have the distinct advantage that they do not resonate with the power system and they work independently with respect to the system impedance characteristics. They are used in difficult circumstances where passive filters don’t operate successfully because of resonance problems and they don’t have any interference with other elements installed anywhere in the power system [38].

The active filters present many other advantages over the traditional methods for harmonic compensation such as [33]:

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

2.5.1.1 Series Active Power Filter (series APF)

The aim of the series APF is to locally modify the impedance of the grid. It is considered as harmonic voltage source which cancel the voltage perturbations which come from the grid or these created by the circulation of the harmonic currents into the grid impedance. However, series APFs can not compensate the harmonic currents produced by the loads.

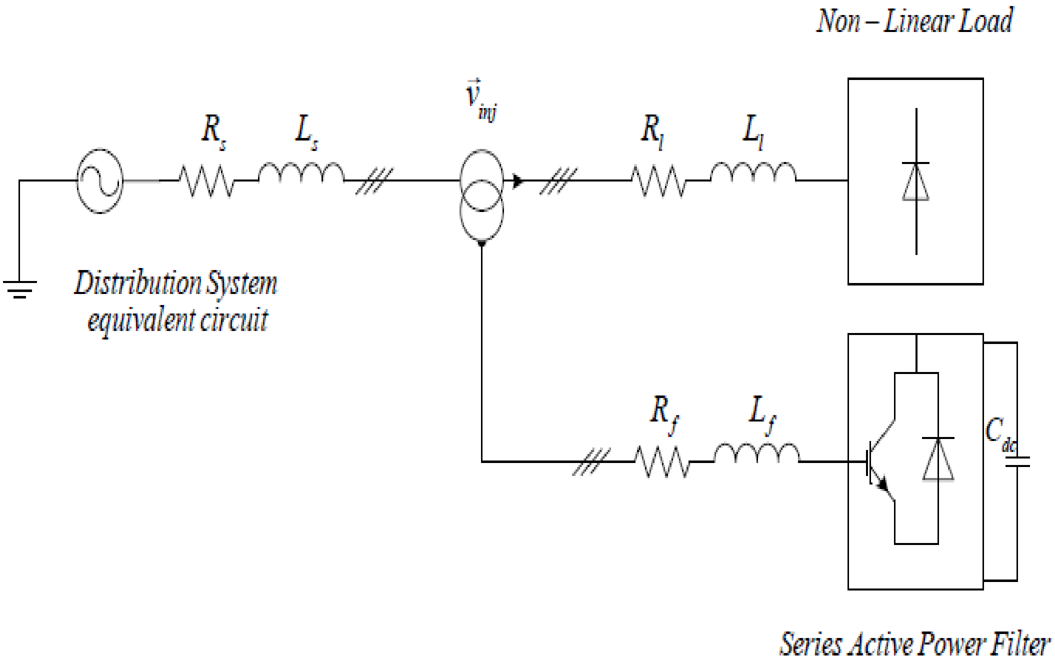


Figure 2.10: Series active power filter connected to the grid

2.5.1.2 Shunt Active Power Filter (SAPF)

The SAPFs are connected in parallel with the harmonic producing loads. They are expected to inject in real time the harmonic currents absorbed by the pollutant loads. Thus, the grid current will become sinusoidal.

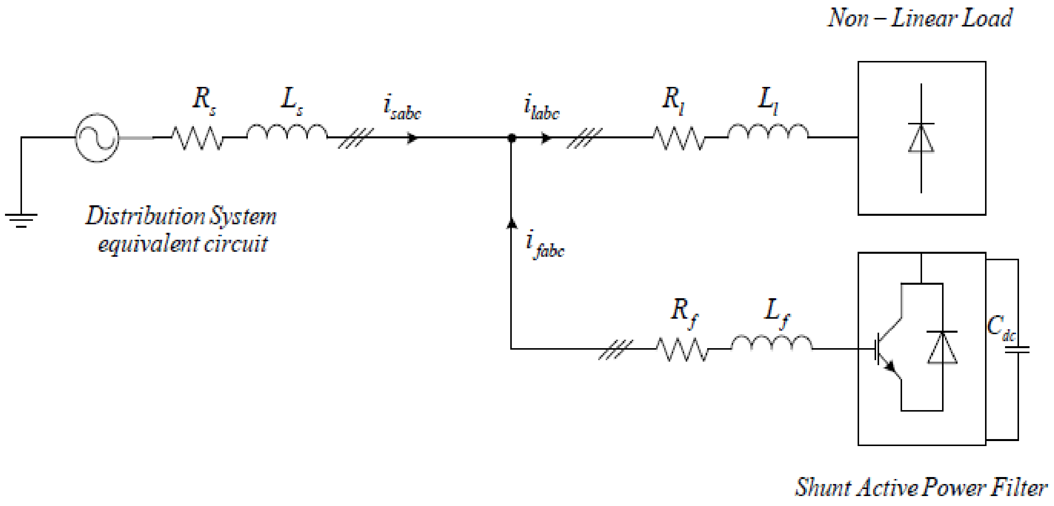


Figure 2.11: Shunt APF connected in parallel with non-linear load

2.5.1.3 Combination of Parallel and Series APF (UPQC)

Figure 2.12 explains the combination of two APFs parallel and series, called also (Unified Power Quality Conditioner). This structure combines the advantages of the two APF type’s series and parallel. So it allows simultaneously achieving sinusoidal source current and voltage [20].

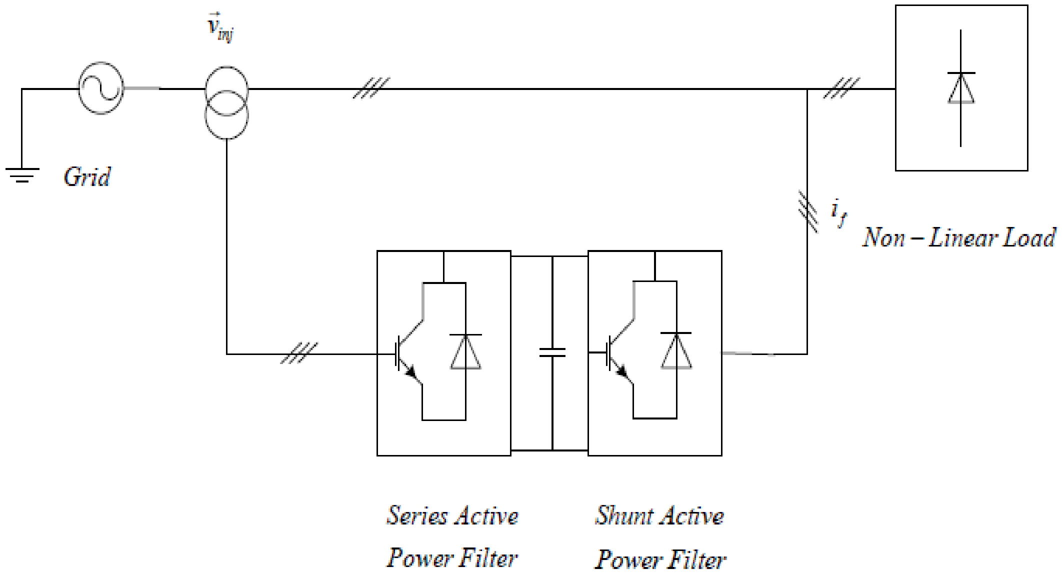


Figure 2.12: Unified Power Quality Conditioner’s Diagram

2.5.2 Hybrid Filters

Hybrid filter are a filter topology which combines the advantages of the passive and active filters. For this reason, it is considered as the best solution to eliminate the harmonic currents from the grid. The principal reason for the use of hybrid filters is the development of the power semiconductors like MOSFETs and IGBTs. Over more, from an economical point of view, the hybrid power filters allow reducing the cost of APF [39].

Hybrid power filters can be classified according to the number of elements used in the topology, the treated system (single phase, three phase three legs or four legs) and the used inverter type (current source inverter or voltage source inverter) [20].

2.5.2.1 Series Association of Active Filter with Passive Filter

In this configuration the active and passive filters are connected together directly in series. Then the systems are connected in parallel with the grid as shown in figure 2.13.

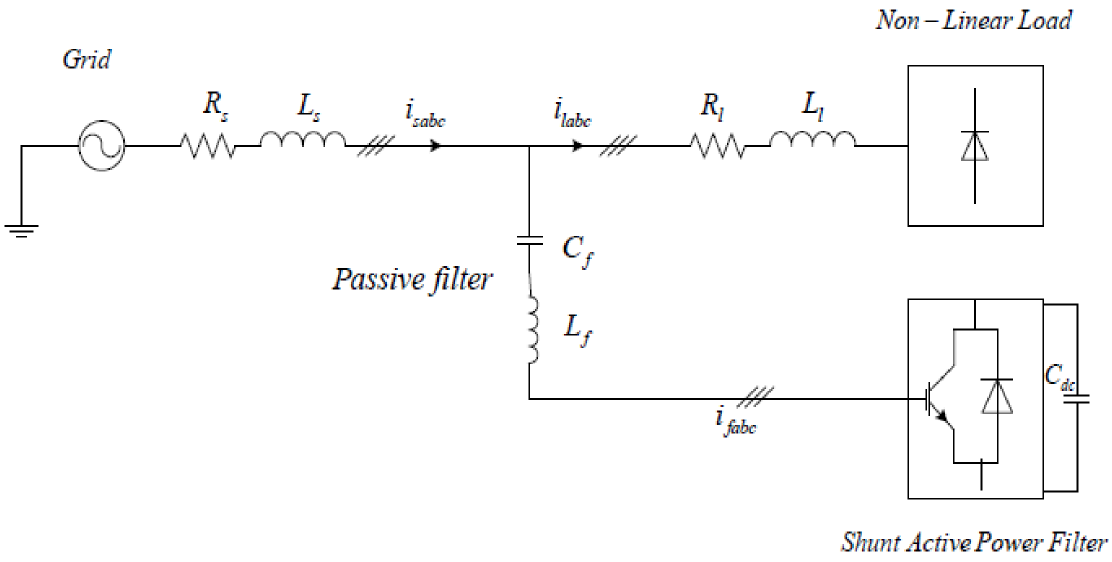


Figure 2.13: Series association of SAPF and passive filter

2.5.2.2 Parallel Association of SAPF 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 2.14. The passive filters compensate certain harmonic ranges, while the active filter compensates the rest of the grid harmonics.

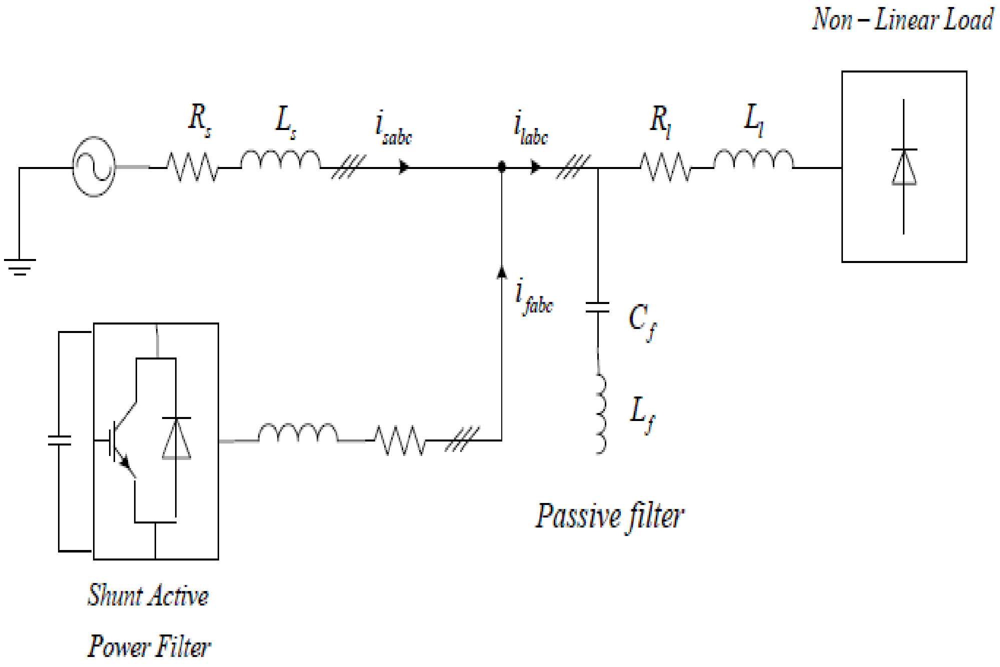


Figure 2.14: Parallel association of SAPF and passive filters

2.5.2.3 Series Active Filter with Passive Filter

This structure shown in figure 2.15 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 [20].

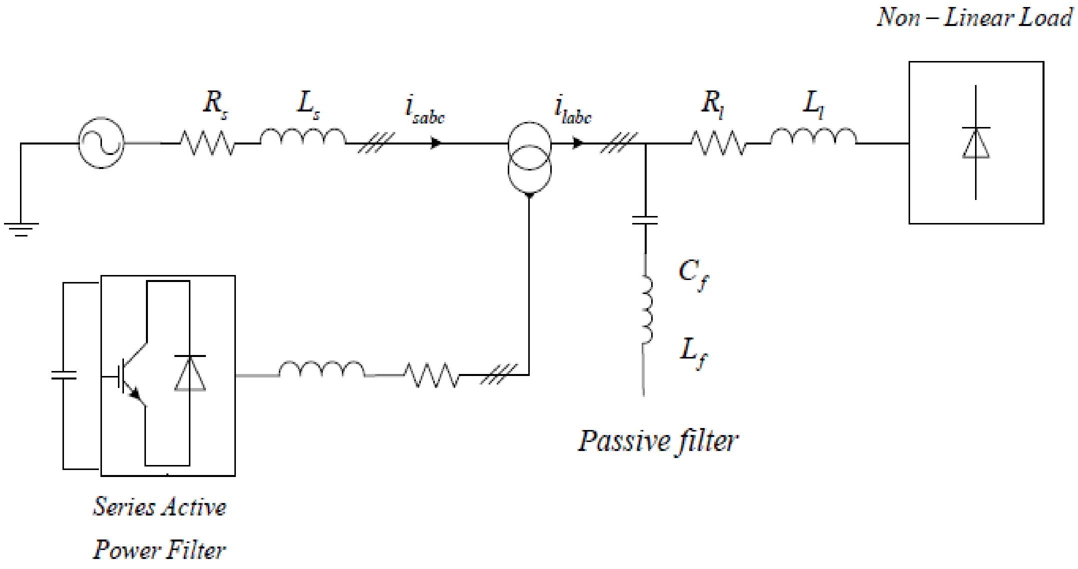


Figure 2.15: Series active power filter with passive filter

2.6 Non-Linear Loads

When the input current into the electrical equipment does not follow the impressed voltage across the equipment, then the equipment is said to have a nonlinear relationship between the input voltage and input current [35 , 37, 40]. All equipments that employ some sort of rectification are examples of nonlinear loads. Nonlinear loads generate voltage and current harmonics that can have adverse effects on equipment designed for operation as linear loads. Transformers that bring power into an industrial environment are subject to higher heating losses due to harmonic generating sources (nonlinear loads) to which they are connected [40].

2.6.1 Modeling of the Non-Linear Load (Diode Bridge with Inductive Load)

The non-linear load is a three phase bridge rectifier connected to the grid by the means of line inductor (*Ll*, *Rl*) feeding an inductive load (*Rdc*, *Ldc*) as shown in figure 2.16.

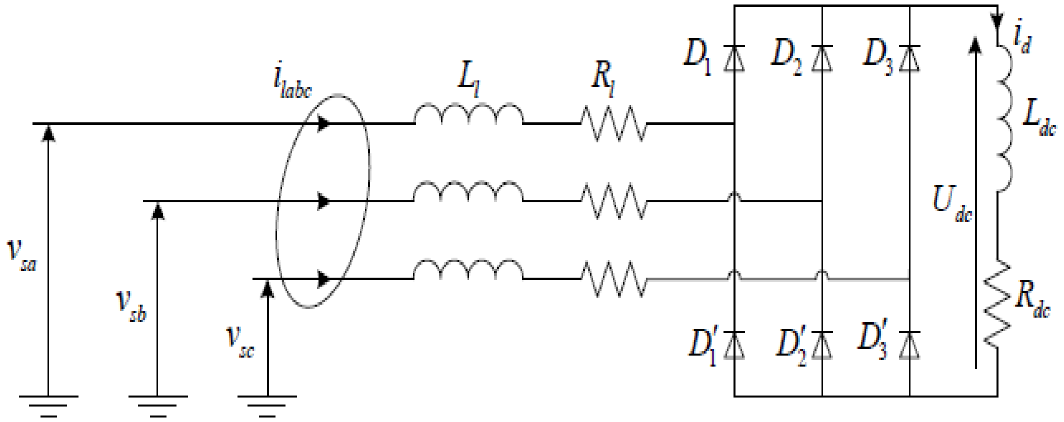


Figure 2.16: Diode bridge rectifier with RL load

For the reason of simplification we suppose that the rectifier is ideal. Two diodes on the same leg of the rectifier can't have the same state at the same time. If D1 is closed, one of the two diodes D5 or D6 is closed also. It is well known that D1 is passing when the voltage vsa is more than vsb and vsc or:

V_{sa}=Max(Vsj); j=1,2,3.. (2.12)

The same condition is applied on the other diodes and we find:

D_i passes if V_{si}= Max(V_{sj}) i,j = 1,2,3

D_{i+3}passes if V_{si}=Min(V_{sj}) i,j=1,2,3 (2.13)

The output voltage is given then by:

U_{dc}=Max(V_{sj})–Min(V_{sj}) j=1,2,3 (2.14)

From where we can calculate the average of the output voltage, it is given by:

$$U_{dc}=\frac{\sqrt[3]{3}}{\pi}v_{peak}=\frac{\sqrt[3]{3}}{\pi}\sqrt{2}v = 1.654\sqrt{2}\mathrm{v} \qquad (2.15)$$

Figure 2.17 shows the output voltage of the three phase diode rectifier and the line voltage on the PCC.

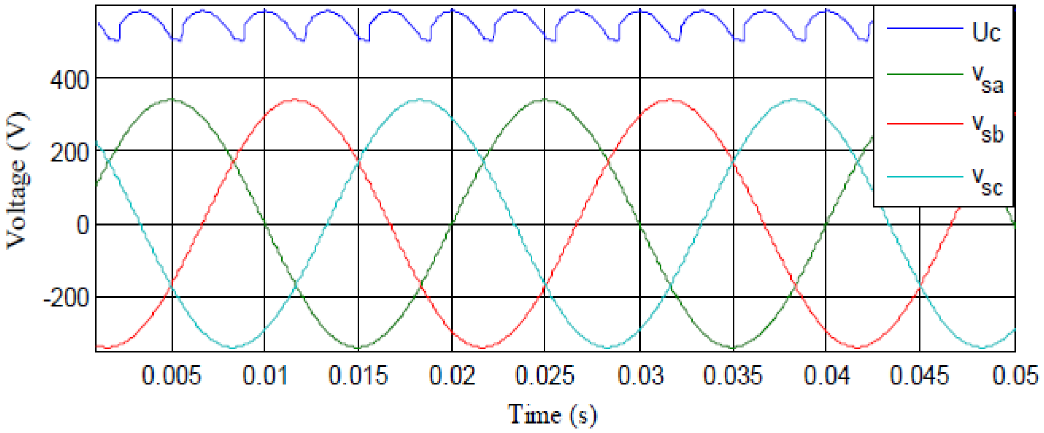


Figure 2.17: Input and output voltage of three phase bridge rectifier.

When any circuit containsinductive or capacitive type elements or combination of both then it becomes non-linear circuit.

CHAPTER 3

Shunt Active Power Filter

Modern active filters are superior in filtering performance, smaller in physical size, and more flexible in application, compared to conventional passive filters using capacitors, inductors and/ arresistors. However, the active filters are slightly inferior in costand efficiency to the passive filters.

The concept of using active power filters to mitigate harmonic problems and to compensate reactive power was proposed more than two decades ago [41]. It has proven its ability to control the grid current and to ameliorate the power quality. The theories and applications of active power filters have become more popular and have attracted great attention. Without the drawbacks of passive harmonic filters, such as component aging and resonant problems, the active power filter appears to be a viable solution for reactive power compensation as well as for eliminating harmonic currents. As we mentioned earlier, the SAPF is connected in parallel with the non-linear load to behave as another controlled non-linear load. The system of the non-linear load and the SAPF will be seen by the grid as a linear load connected to the PCC. In the case of compensation of reactive power this load will be resistive. Otherwise it will be either inductive or capacitive linear load.

3.1 Shunt Active Power Filter

The SAPF, also called pure active filter, meets overall specifications and constitutes the optimal harmonic filtering solution as it is viable and cost-effective for low to medium kVA industrial loads where system engineering effort is a large part of overall cost. This system does not create displacement power factor problems and utility loading. Moreover supply side inductance Ls does not affect the harmonic compensation capability of parallel active filter system, controlled as a

harmonic current source. The SAPF can damp harmonic propagation in a distribution feeder or between two distribution feeders, controlled as a harmonic current source its performance is not affected by supply voltage harmonics.

Shunt active power filter compensates current harmonics by injecting equal-but-opposite harmonic compensating currents into the grid. In this case the shunt active power filter operates as a current source introducing the harmonic components generated by the load but phase difference by 180° [42]. This principle is applicable to any type of load considered as harmonic source. Moreover, with an appropriate control scheme, the active power filter can also compensate the load power factor. In this way, the power distribution system sees the non-linear load and the active power filter as an ideal resistor. The current compensation characteristics of the shunt active power filter is shown in Figure 3.1 [43].

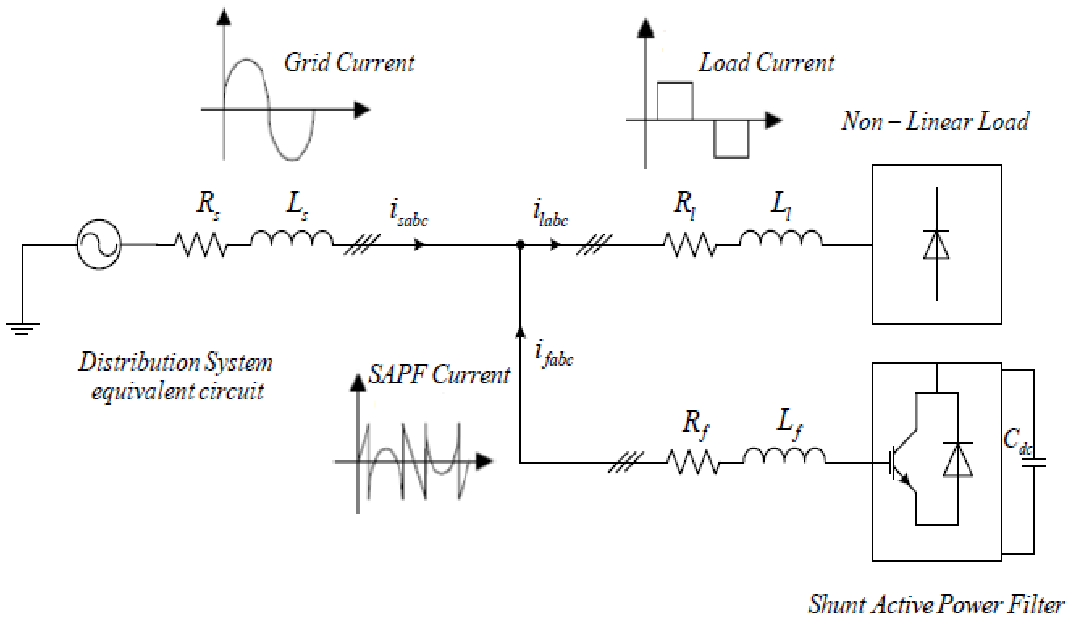


Figure 3.1 : Compensation characteristic of shunt active power filter

The SAPF, also called pure active filter, meets overall specifications and constitutes the optimal harmonic filtering solution [4] as it is viable and cost-effective for low to medium kVA industrial loads where system engineering effort is a large part of overall cost. This system does not create displacement power factor problems and utility loading. Moreover supply side inductance *Ls* does not affect the harmonic compensation capability of parallel active filter system, controlled as a harmonic current source. The SAPF can damp harmonic propagation in a distribution feeder or between two distribution feeders [5], controlled as a harmonic current source its performance is not affected by supply voltage harmonics. Figure shows the basic circuit diagram of a pure shunt active filter. It should be connected in parallel as close as possible to a harmonic-producing load. The power circuit of the SAPF consists of a three phase Voltage-Source PWM Inverter (*VSI*), using the IGBTs, coupled at the Point of Common Coupling (PCC) via an output ac filter (*L*, *LC*, *LCL*) and a dc capacitor, generally considered as an energy storage element. The control circuit is usually based on a modern digital controller using DSPs, FPGAs, etc

3.2 Modeling of Active Power Filter

The connection of the shunt active power filter to the point of common coupling of the grid is done mostly by the mean of a RL low pass filter as shown in figure.

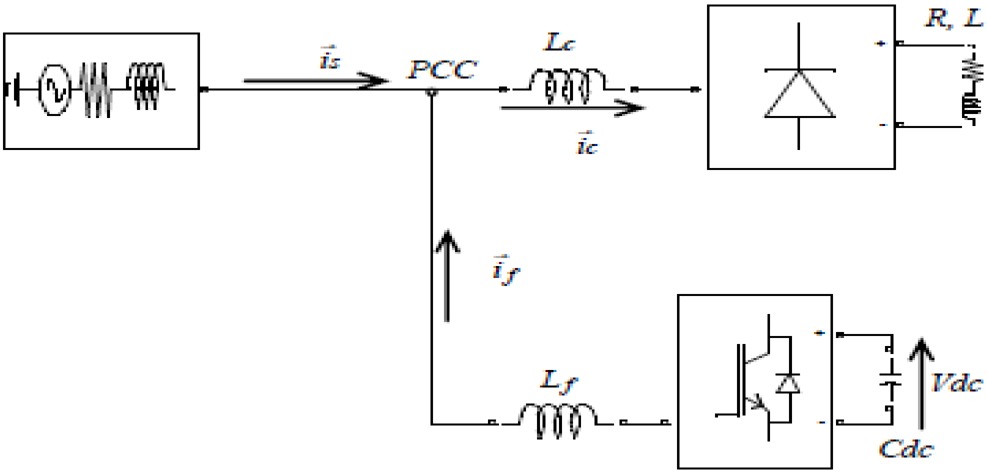


Figure 3.2 : SAPF connection to the PCC

The SAPF are connected in parallel with the harmonic producing loads. They are expected to inject in real time the harmonic currents absorbed by the pollutant loads. Thus, the grid current will become sinusoidal.

3.3 Calculation of Capacitor Reference Voltage V_{dc}

The dc bus nominal voltage V_{dc} must be greater than or equal to line-line peak voltage in order to actively control *if* .Considering a space phased modulation, it is calculated by the

$$Vdc \ = \sqrt[2]{2}Vs \ (3.1)$$

And a value of *1.1·Vdc* is used, based on the assumption that the dc voltage is regulated to be 10% above the peak input voltage. However, the required *Vdc* can be reduced if the sine reference for PWM is modulated with third and ninth harmonics. The minimum required voltage can then be expressed in terms of the source voltage as:

$$V_{dc} = \frac{\sqrt[2]{2}}{1.155} V_s \qquad (3.2)$$

3.4 Calculation of Output filter inductor Lf

Three requirements can be imposed on the estimation of output filter inductor value.

- The transfer unattenuated harmonics necessary, requested by the control.
- Provide compensation for reactive power to obtain a unity power factor.
- .Ensure filtering, to a certain quality level, of inverter output current and voltage source ripples.

By limiting the inductor value with *L fmax* and *L fmin*, in [22], to calculate the minimum value of the inductor from the point of view of minimizing the ripple current, the authors assume that the inverter reproduces exactly the mains voltage (i.e. zero current reference) , of when the minimum value of the inductor is:

$$L_{fmin} = \frac{V_{dc}}{8f_{s\Delta I_{(p-p)max}}} \qquad (3.3)$$

Once calculated the minimum value, it is necessary to analyze the system's ability to generate the desired harmonics. As well as from the knowledge of harmonic current type, one can calculate the maximum limit inductor that enables their generation from.

3.5 Calculation of the DC side Capacitor C_{dc}

The determination of the value of energy-storage capacitors are made either on the instantaneous released stored capacitor energy to support the step increase/reduction in the power consumed by the load , using the energy-balance concept, or on the mitigation oscillations possibility of continuous bus voltage imposed by the lower order harmonics or unbalanced of linear/non-linear loads.

The capacitor may have to supply the real power demand of the load for one cycle of the utility voltage in the worst case of transient. Hence, the capacitor value equation based on this principle is:

$$C_{dc} = \frac{2.E_{max}}{V_{dc}^2 - V_{dcmin}^2} \qquad (3.4)$$

The dc-link capacitor deals with ripple power at 2ω due to the negative-sequence load current. The minimum capacitor value can be determined by:

$$C_{dc} = \frac{S}{2.\omega.V_{dc}\Delta V_{dc}} \qquad (3.5)$$

CHAPTER 4

Design and Control Scheme of Shunt Active Power Filter

In this dissertation an overview of design parameters of a SAPF ispresented and analyzed. Since the increase in the value of theDC voltage improves the controllability of the active filter andknowing that the choice of this voltage is reflected in large parton the choice of switches, the Vdc value continues to be chosen as the greatest voltage respecting the switches. The inductor value is an optimal one taking the HF filtering and harmonics injection in consideration. A reduction in the value of the capacity will cause a significant increase ripple voltage.

However, the modification of Cdc can have a serious impact on the variation of ΔVdc during load transients creating voltage drop that can negatively affect the controllability of current compensation

The design of these components is based on the following assumptions:

a. The source voltage is sinusoidal

b. To design the Lf ac side line current distortion is assumedto be 5%

c. There is fixed capability of reactive power compensation of the active filter

d. The PWM converter is assumed to operate in the linear modulation mode ($0 \leq ma \leq 1$).

e. The switching frequency is selected in function of the highest order of harmonic to be compensated. Theoretically it is possible to control the harmonics up to half the switching frequency to be compensated.

The controlling of shunt Active Power Filter is done by Active Current Component, Hysteresis Control Method.

4.1 Active Current Component Theory

The power management operation, the inverter is actively controlled in such a way that it always supplies fundamental active power to the grid. If the load connected to the PCC is non-linear or unbalanced or the combination of both, the given control approach compensates the harmonics, unbalance, and neutral current. The duty ratio of inverter switches are varied in a power cycle such that the combination of load and inverter injected power appears as balanced resistive load to the grid. The regulation ofdc-link voltage carries the information regarding the exchange of active power in between renewable source and grid. Thus the output of dc-link voltage regulator results in an active current. The multiplication of active current component with unity grid voltage vector templates generates the reference grid currents . The reference grid neutral current is set to zero, being the instantaneous sum of balanced grid currents. The grid synchronizing angle obtained from phase locked loop (PLL) is used to generate unity vector template as [9]–[11]

$$
\begin{aligned}
U_a &= \mathrm{Sin}(\theta) \\
U_b &= \mathrm{Sin}(\theta - \frac{2\pi}{3}) \\
U_c &= \mathrm{Sin}(\theta + \frac{2\pi}{3}).
\end{aligned}
\tag{4.1}
$$

Error current can be calculated as

$I_{err} = I^{*}-I$ (4.2)

The actual dc-link voltage is sensed and passed througha first-order *low pass filter* (LPF) to eliminate the presence of switching ripples on the dc-link voltage and in the generated reference current signals. The difference of this filtered dc-link voltage and reference dc-link voltage is given to a discrete- PI regulator to maintain a constant dc-link voltage under varying generation and load conditions. The dc-link voltage error at seventh sampling instant is given as:

$$V_{\mathrm{dcerr}(n)} = V^{*}_{\mathrm{dc}(n)} - V_{\mathrm{dc}(n)}. \tag{4.3}$$

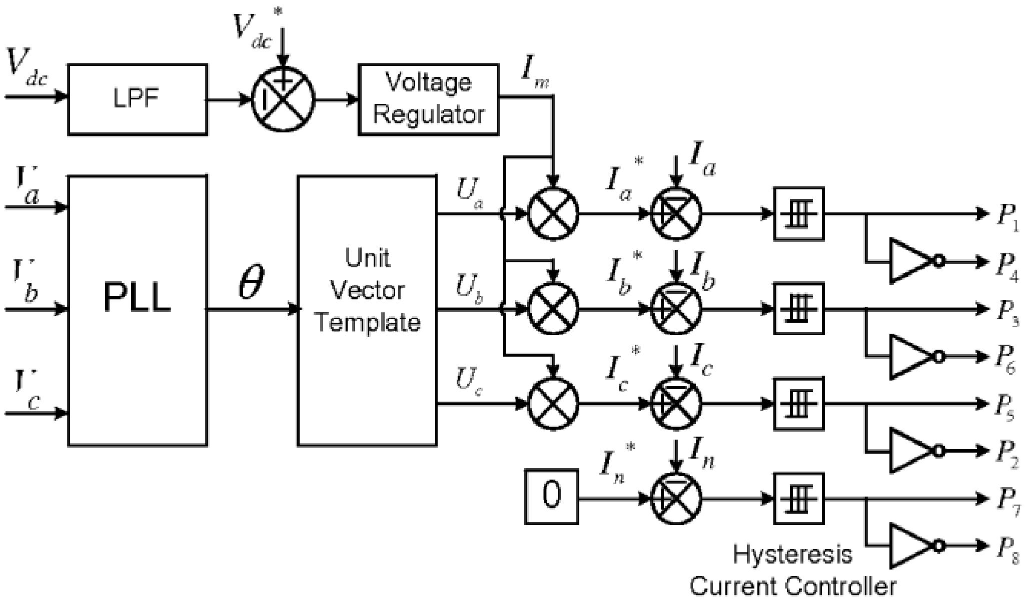


Figure 4.1: Block diagram representation of grid-interfacing inverter control.

The duty ratio of inverter switches are varied in a power cycle such that the combination of load and inverter injected power appears as balanced resistive load to the grid. The regulation of dc-link voltage carries the information regarding the exchange of active power in between renewable source and grid. Thus the output of dc-link voltage regulator results in an active current The multiplication of active current component with unity grid voltage vector templates generates the reference grid currents. The reference grid neutral current is set to zero, being the instantaneous sum of balanced grid currents. The grid synchronizing angle obtained from phase locked loop (PLL) is used to generate unity vector template.

CHAPTER 5

Modeling, Simulation Results and Discussions

In the last two chapters, different topologies and control methods of Shunt Active Power Filter (SAPF) were presented and discussed. These methods include the harmonic contents extraction from one part, and the control of SAPF from the other part. Different direct and indirect methods were presented and discussed. The control schemes of these methods were also presented.

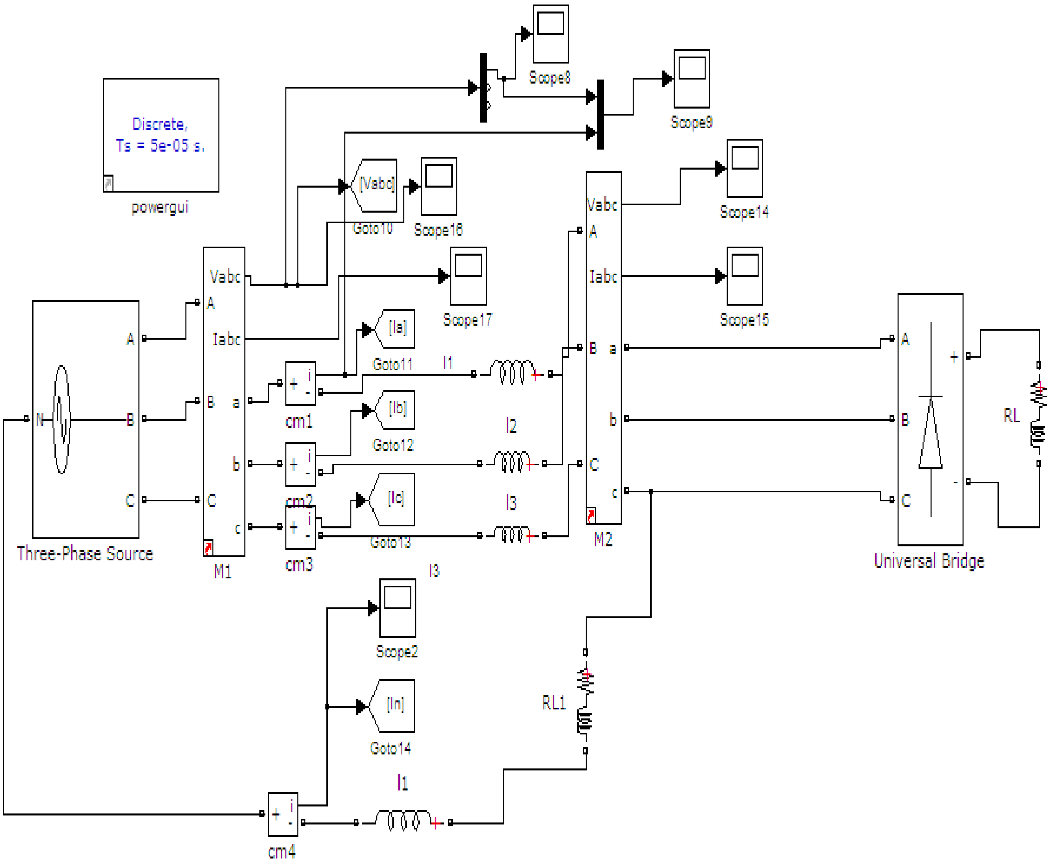
This chapter presents the simulation results of models discussed in this work in addition to different parameters of grid and filter. The simulation results are shown and discussed. Different grid conditions will be discussed and results will be compared. The comparison includes the extraction methods, VSI control theories, DC voltage control, in addition to the function under non ideal system conditions and the use of Self Tuning Filter (STF) for non ideal system.

5.1 System Description

The simulated system is a three phase balanced and non-balanced voltage system, the non-linear load used in this work is a three phase non controlled universal bridge rectifier discussed in the previous chapters. The parameters of the grid and rectifier in addition to the APF are given in table.

The basic model of power system with three phase ac source , distribution system, non-linear , unbalanced loads and measurement devices is shown below.

5.2 Model Without SAPF



Figure; 5.1 Simulation Model without SAPF

When we run this model in Simulink and see the results of the measurement devices in graphical form and measure the THD of the three phase currents separately. All the graphs are shown below and THD of each phase is tabulated.

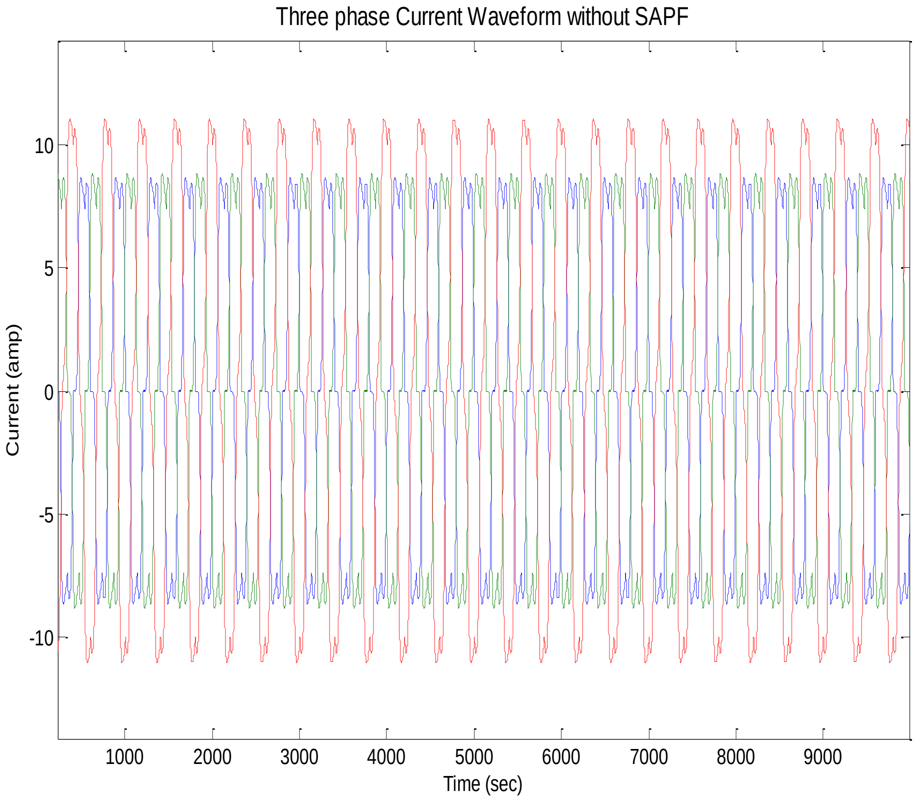
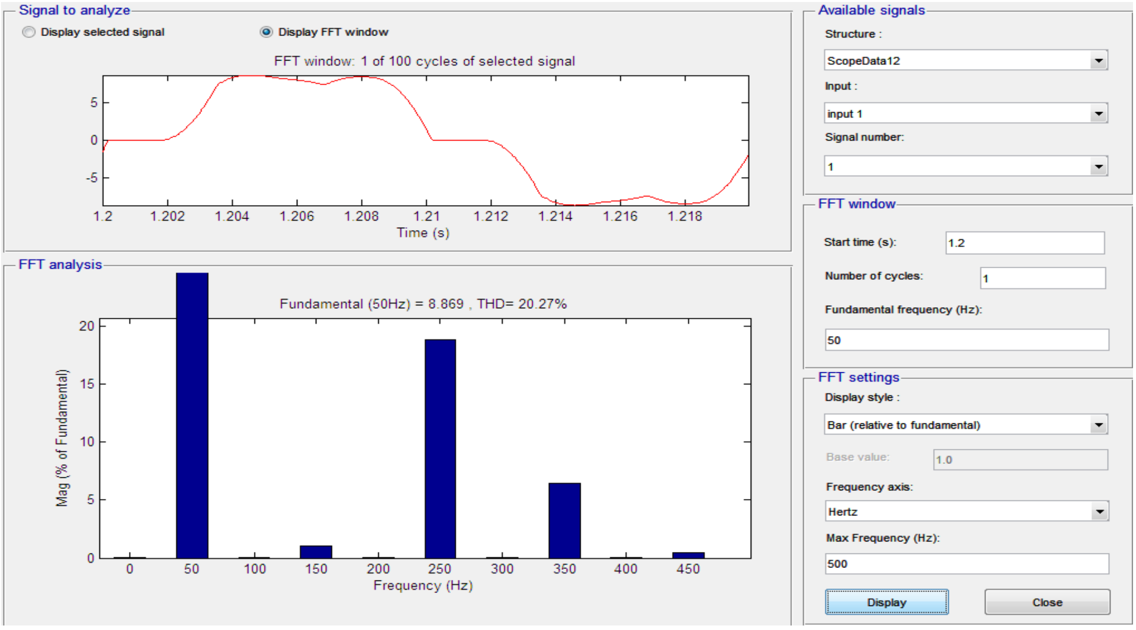


Figure: 5.2 Current waves without SAPF

Figure shows the waveform of three phase line current when SAPF is not connected in the system. The THD of each phase is shown below in FFT measurement window of power GUI. All values of THD of each phase is tabulated in result section.



FFT window: 1 of 100 cycles of selected signal

Fundamental (50Hz) = 8.869 , THD= 20.27%

Structure : ScopeData12

Input : input 1

Signal number: 1

Start time (s): 1.2

Number of cycles: 1

Fundamental frequency (Hz): 50

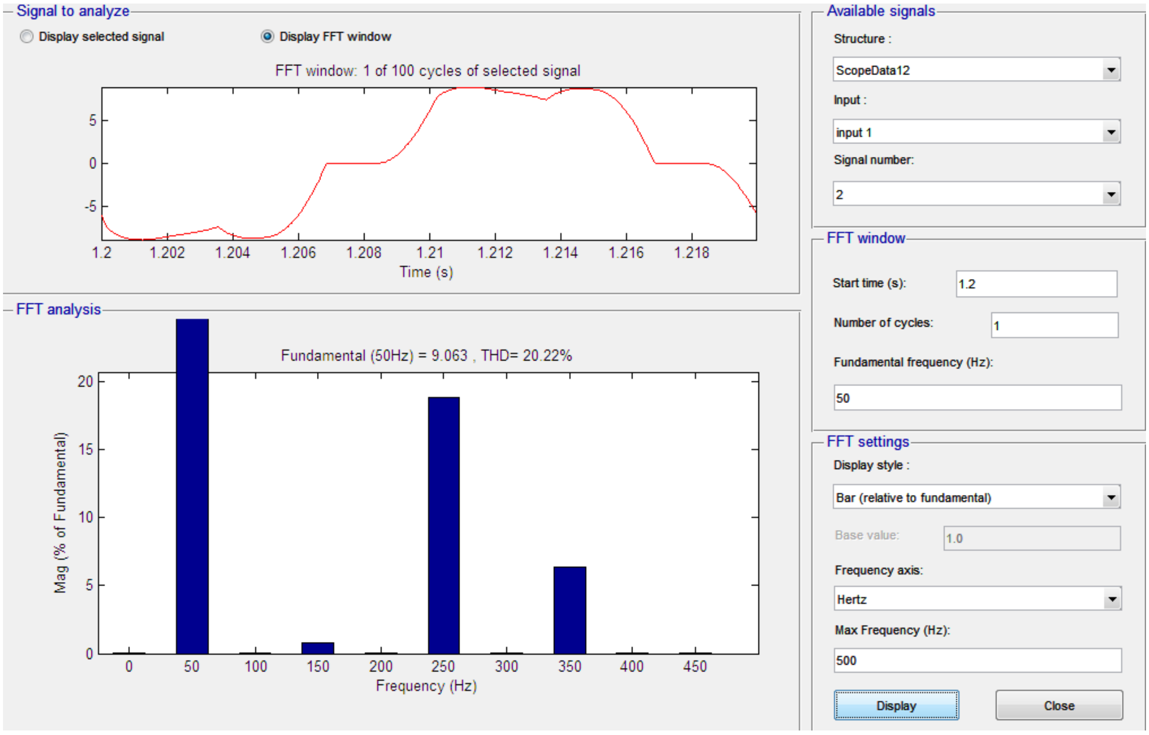
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 500

Figure: 5.3 THD of phase a without SAPF



FFT window: 1 of 100 cycles of selected signal

Fundamental (50Hz) = 9.063 , THD= 20.22%

Structure : ScopeData12

Input : input 1

Signal number: 2

Start time (s): 1.2

Number of cycles: 1

Fundamental frequency (Hz): 50

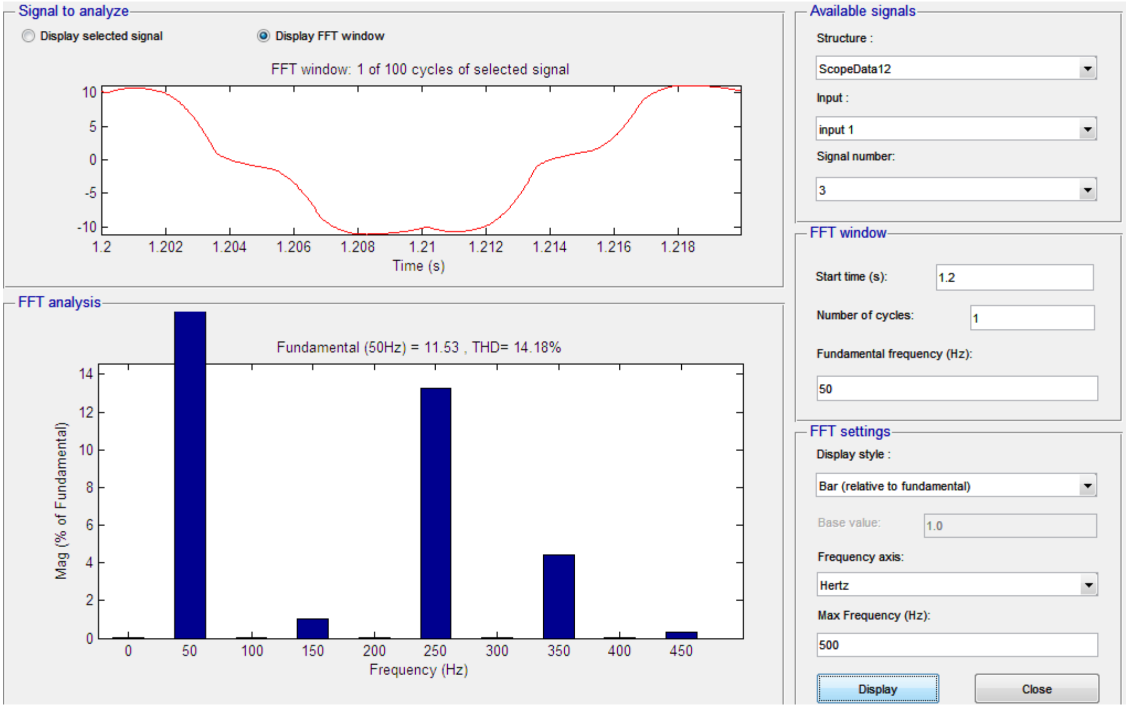
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 500

Figure: 5.4 THD of phase b without SAPF



Structure : ScopeData12

Input : input 1

Signal number: 3

Start time (s): 1.2

Number of cycles: 1

Fundamental frequency (Hz): 50

Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 500

Figure: 5.5 THD of phase c without SAPF

5.3 Simulation Model with SAPF

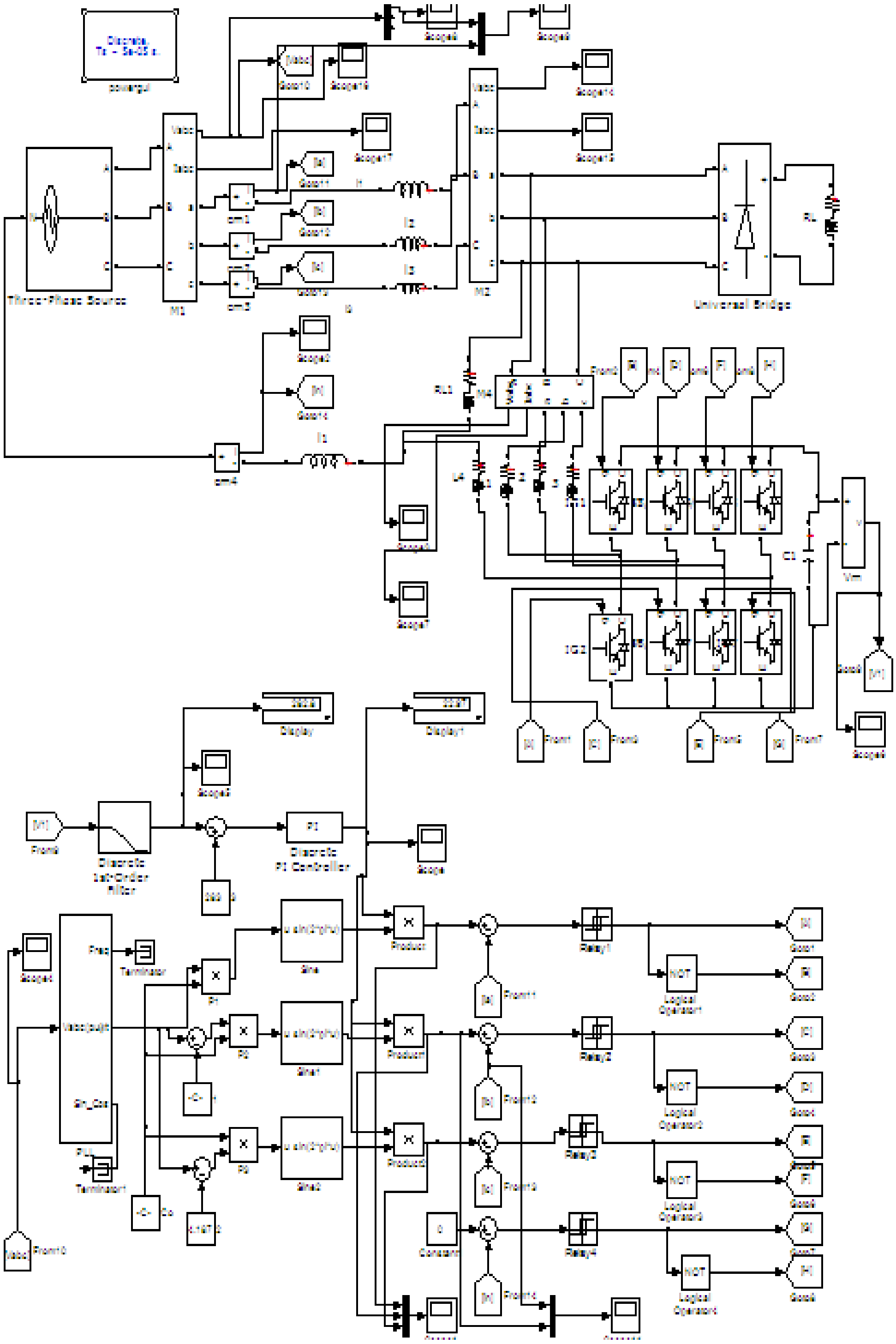


Figure: 5.8 Simulation model with SAPF

Above figure shows the simulation model of analyzed system with Shunt Active Power Filter. All control schemes used in SAPF is shown in model. Their parameters values are tabulated as below.

TABLE 5.I

PARAMETERS OF THE ANALYZED SYSTEM

Symbol	**Quantity**	**Value**
V_g	Supply voltage	100V(r.m.s.)
F	Grid frequency	50 Hz
L_L	Line Inductance	4.66mH
K_P	Proportional Gain	1.9
K_I	Integral Gain	7.5
L_{sh}	Coupling Inductance	1.5mH
C_{dc}	APF DC Capacitor	1100e-6F
V_{dc}	DC link Capacitor Voltage	283V

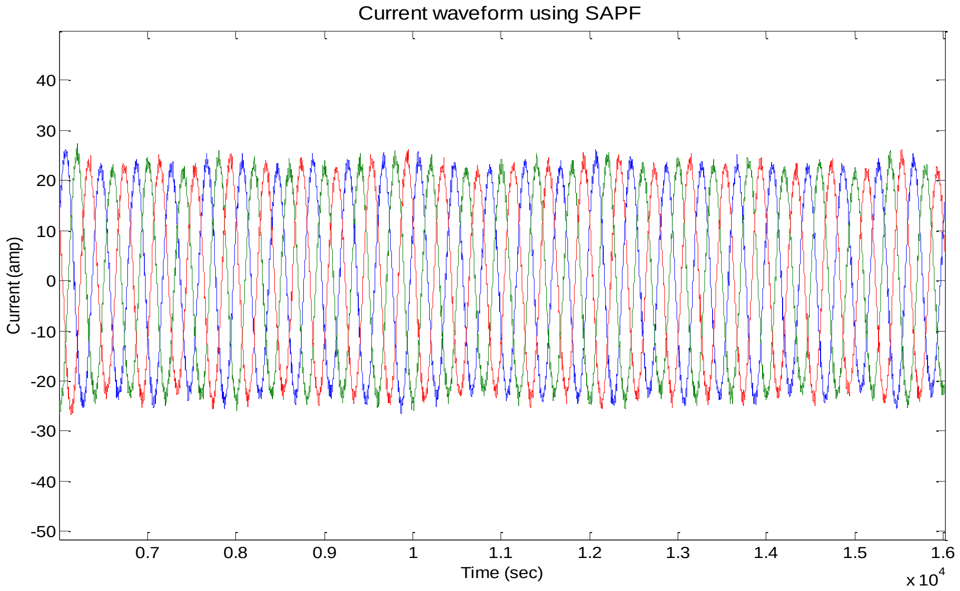
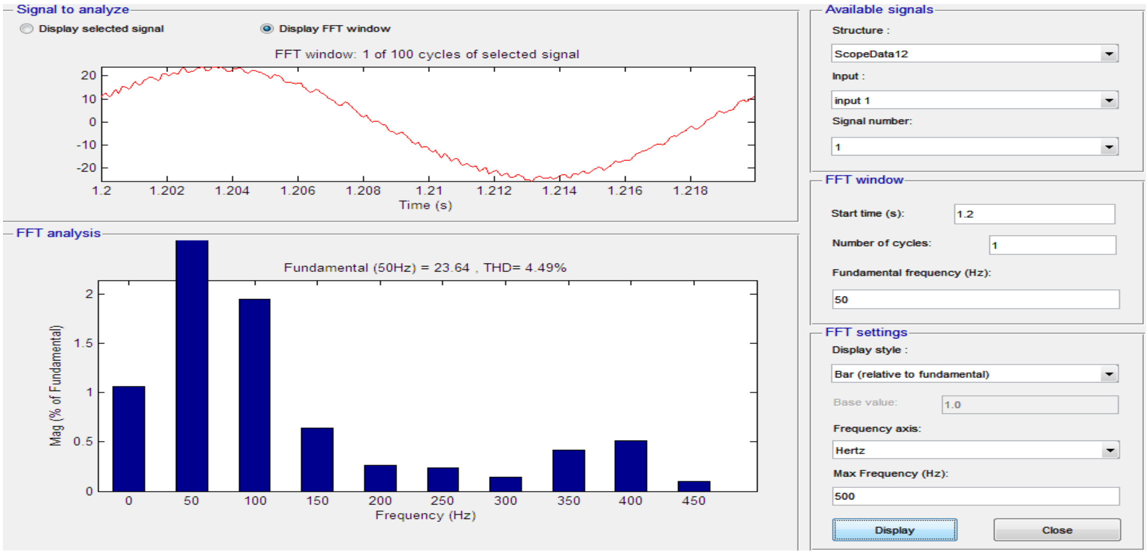


Figure: 5.9 Current waves with SAPF

The above figure shows the waveform of three phase line current. The THD of the line current is reduced to permissible limit (below 5%) after using the SAPF. The THD figure of the FFT window is shown below.



Signal to analyze

○ Display selected signal ● Display FFT window

FFT window: 1 of 100 cycles of selected signal

FFT analysis

Fundamental (50Hz) = 23.64 , THD= 4.49%

Available signals

Structure : ScopeData12

Input : input 1

Signal number: 1

FFT window

Start time (s): 1.2

Number of cycles: 1

Fundamental frequency (Hz): 50

FFT settings

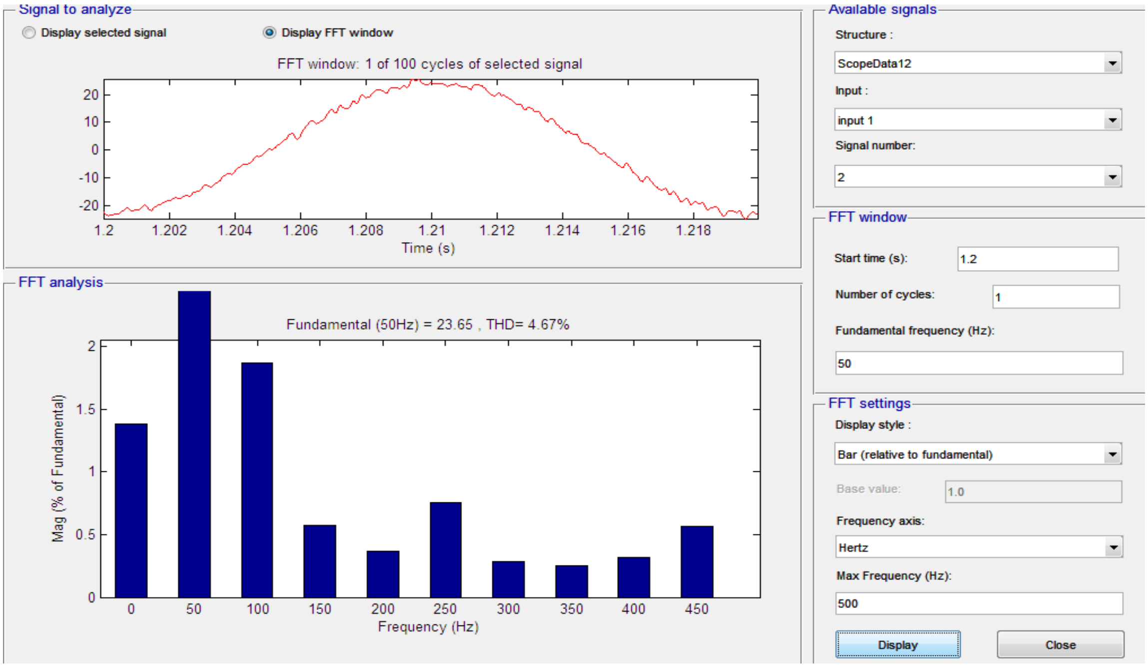
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 500

Figure: 5.10 THD of phase a with SAPF



Signal to analyze

○ Display selected signal ● Display FFT window

FFT window: 1 of 100 cycles of selected signal

FFT analysis

Fundamental (50Hz) = 23.65 , THD= 4.67%

Available signals

Structure : ScopeData12

Input : input 1

Signal number: 2

FFT window

Start time (s): 1.2

Number of cycles: 1

Fundamental frequency (Hz): 50

FFT settings

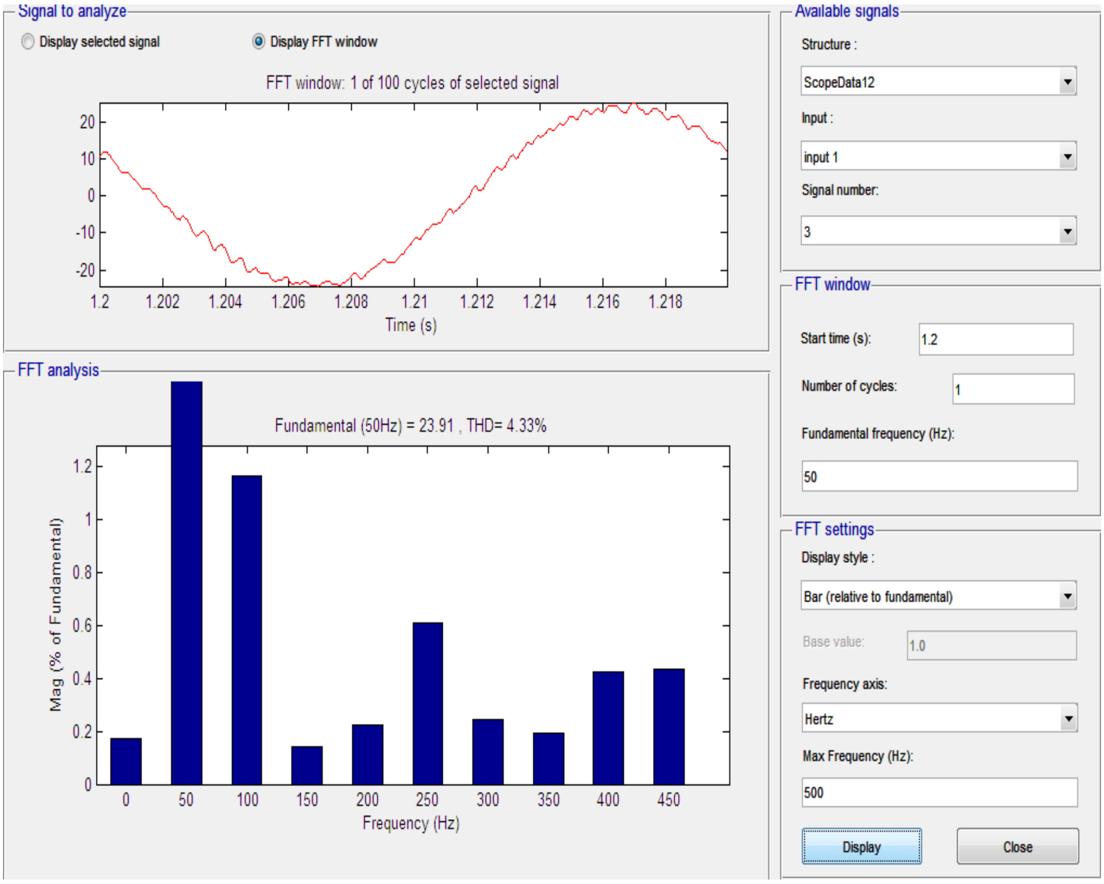
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 500

Figure: 5.11 THD of phase b with SAPF



Signal to analyze

○ Display selected signal ● Display FFT window

FFT window: 1 of 100 cycles of selected signal

FFT analysis

Fundamental (50Hz) = 23.91 , THD= 4.33%

Available signals

Structure : ScopeData12

Input : input 1

Signal number: 3

FFT window

Start time (s): 1.2

Number of cycles: 1

Fundamental frequency (Hz): 50

FFT settings

Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 500

Figure: 5.12 THD of phase c with SAPF

From above figure we see that the THD of line current of all three phases is very much reduced below desired level (below5%). The Shunt Active Power Filter can do this in a very efficient way. By reducing the THD it also reduces the neutral current and make the power factor unity.

CHAPTER 6

6.1Conclusion

This dissertation work presents to improve power quality in distribution system. This work has presented a novel control of an existing grid interfacing inverter to improve the quality of power at PCC for a3-phase 4-wire system. It has been shown that the grid-interfacing inverter can be effectively utilized for power conditioning without affecting its normal operation of real power transfer.

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