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Design and Implementation of Two Level Shunt Active Power Filter

Presented By:

- **DEKARI Cherif**
- **DAHMANI Seifeddine**

Supervisor:

Prof. KHELDOUN Aissa

Co-Supervisor:

Dr. AMMAR Abdelkrime

Registration Number:……../2019

Dedication

In the name of Allah the most Merciful and Beneficent.

This thesis is dedicated to my Grandmother. She was constant source of inspiration to my life. Although she is not here to give me strength and support I always feel her presence that used to urge me to strive to achieve my goals in life.

To My great parents, who were real supports, without forgetting my beloved brothers, my sister and all my family.

I wish to express my sincere appreciation to Dahmani Seifeddine, Bot Mohamed and all my friends who encourage and support me from in or out the institute.

To all the staff of IGEE for the great journey of five years.

THANK you ALL

DEKARI Cherif.

Dedication

First of all we thank the almighty God for guiding us to the right way

*I dedicate this project to my **beloved Mother**. Without her, I would never reach that far.*

Also to my Father, and all my family members.

To my friend, DEKARI Cherif , I thank him for working me to complete this Final Project.

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DAHMANI Seifeddine

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Abstract

Power quality has become of utmost importance for the power systems owners, where, the power electronics systems are found nowadays in all systems, such as industrial applications, appliances and telecommunications. These systems, which use power switching devices, are source of harmonics and consequently deteriorate the quality of voltage and current in the grid utilities. For this reason, the passive filters can be used to eliminate some of these harmonics; however, they are not enough to improve the quality being required by standards. Therefore, shunt active power filter is proposed for study in this project. A two-level inverter configuration is proposed and control system will be designed and implemented to satisfy the required quality. MATLAB/Simulink with STM32f4 microcontroller will be employed to carry out the simulation and the experimental implementation of this project. The results will be analyzed and discussed.

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Abbreviations

APF	Active Power Filter
SAPF	Shunt Active Power Filter
AC	Alternating Current
DC	Direct Current
Id-Iq	Instantaneous active and reactive currents
PI	Proportional Integrator
p-q	Instantaneous active and reactive power
PCC	Point of Common Coupling
TDD	Total Demand Distortion
RMS	Root Mean Square
IEEE	Institute of Electrical and Electronics Engineers
BIPV	Building Integrated Photovoltaic
KCL	Kirchhoff's Current Law
UPQC	Unified Power Quality Conditioner
CSI	Current Source Inverter
LPF	Low-Pass Filter
PLL	Phase Locked Loop
SRF	Synchronous Reference Frame
HCC	Hysteresis Current Controller
THB	Total Hysteresis Band
VSI	Voltage Source Inverter
V/f	voltage/ frequency
PWM	Pulse Width Modulation
EMI	Electro-Magnetic Interference
HD	Harmonic Distortion
THD	Total Harmonic Distortion
PF	Power Factor
DPF	Displacement Power Factor
DF	Distortion Power Factor
UPS	Uninterruptible Power Supplies
IGBT	Insulated Gate Bipolar Transistor
SSG	static synchronous generator

ESD	Electrostatic discharge
SRG	Signal reference ground
SCR	semi-conductor rectifier
LHF	Line harmonic filters
VAR	Volt-Ampere reactive

General Introduction

General Introduction

Nowadays, an enormous portion of our electrical energy usage involves power electronics. Power electronic based hardware such as uninterruptible power supplies, adjustable speed drives, personal computers and more have all enhanced our daily lives by providing an efficient and reliable way of utilizing the electrical energy [1].

At the time of fast work and quick response output, we are selecting electronics equipment based on their switching properties which make them a better solution for our applications. However, there is a drawback of power electronics equipments that generate harmonics; these harmonics are responsible for input voltage distortion at point of common coupling. Harmonics can be defined as “a sinusoidal component of a periodic wave or quantity which having a frequency that is an integral multiple of the fundamental supply frequency” [2]. These harmonics are caused by a certain type of loads known as nonlinear loads. To reduce and eliminate these effects in electrical distribution system, different types of compensators have been proposed, one of these compensators is the active power filter (APF). Active power filter is applied in order to protect the electrical equipments from getting damaged due to harmonic current distortion. They can also be used for the compensation of power quality problems such as reactive power control, harmonic filtering, load balancing, voltage regulation and flicker reduction [3, 4].

Our report consists of four chapters: the first chapter affords a general background of power quality. The second chapter presents the active power filter theories. The third one deal with different active power filters simulations. The last chapter exhibits and discusses the obtained results from the implementation of our project. The report ends up with a general conclusion and some suggestions for future works.

CHAPTER I
Power Quality

1.1 Introduction

Recently, power quality has become an important subject and area of research because of its increasing sensitivityand impacts on the consumers, manufacturers, and utilities. As power quality problems are increasing, the research and development in mitigation techniques for power quality problems is becoming relevant and important to limit the pollution of the supply system [9]. In such a situation, it is quite important to study the causes, effects, and mitigation techniques for power quality problems. All of these concepts will be discussed in details within this chapter.

1.2-Power quality in power system

The term electric power quality (PQ) is generally used to assess and to maintain the good quality of power at the level of generation, transmission, distribution, and utilization of AC electrical power[5]. There are different definitions for power quality:

According to Utility, power quality is reliability.

According to load aspect, it is defined as the power supplied for satisfactory performance of all equipment i.e., all sensitive equipment.

In IEEE dictionary, power quality is defined as “the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment”. IEC (International Electrotechnical Commission), it is defined as, “ set of parameters defining the properties of the power supply as delivered to the user in normal operating conditions in terms of continuity of supply and characteristics of voltage (magnitude, frequency, waveform) [6].

1.3-Power Quality Problems

The proliferation of microelectronics processors in a wide range of equipments, from home VCRs and digital clocks to automated industrial assembly lines and hospital diagnostics systems, has increased the sensitivity of such equipment to power quality problems. These problems include a variety of electrical disturbances, which may result in several ways and have different effects on various kinds of sensitive loads. What were once considered minor variations in power, usually unnoticed in the operation of conventional equipment, may now bring whole factories to standstill. As a result of this vulnerability, increasing numbers of industrial and commercial facilities are trying to protect themselves by investing in more sophisticate equipment to improve power quality [7].

Power qualityis a simple term, yet it describes a multitude of issues that are found in any electrical power system. The concept of good and bad power depends on the end user. If a piece of equipment functions satisfactorily, the user feels that the power is good. If the equipment does not function as intended or fails prematurely, there is a feeling that the power is bad. In between these limits, several grades or layers of power quality may exist, depending on the perspective of the power user. Understanding power quality issues is a good starting point for solving any power quality problem.**Fig 1.1** provides an overview of the power quality issues that will be discussed in this chapter.

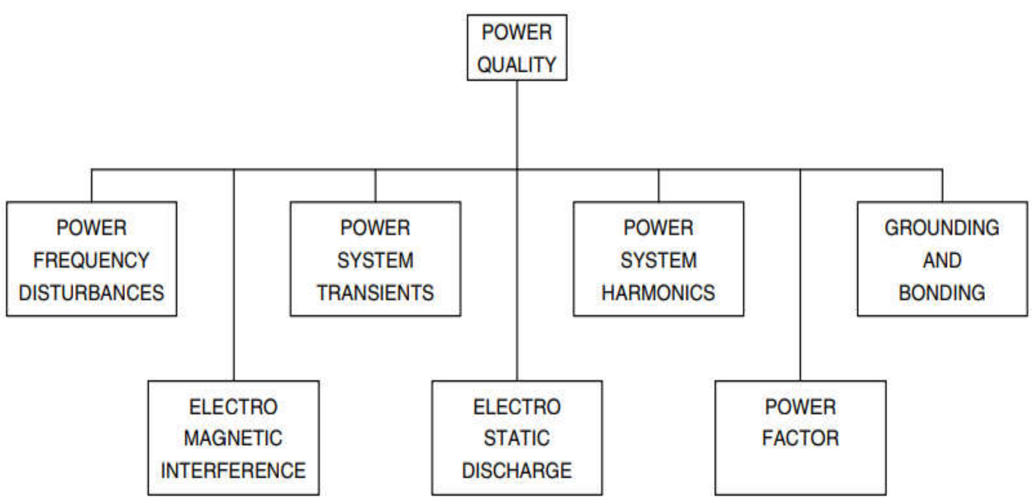


Figure 1.1: Power quality concerns

Power frequency disturbancesare low-frequency phenomena that result in voltage sags or swells as shown in **Fig.1.2** and **1.3**. These may be source or load generated due to faults or switching operations in a power system.

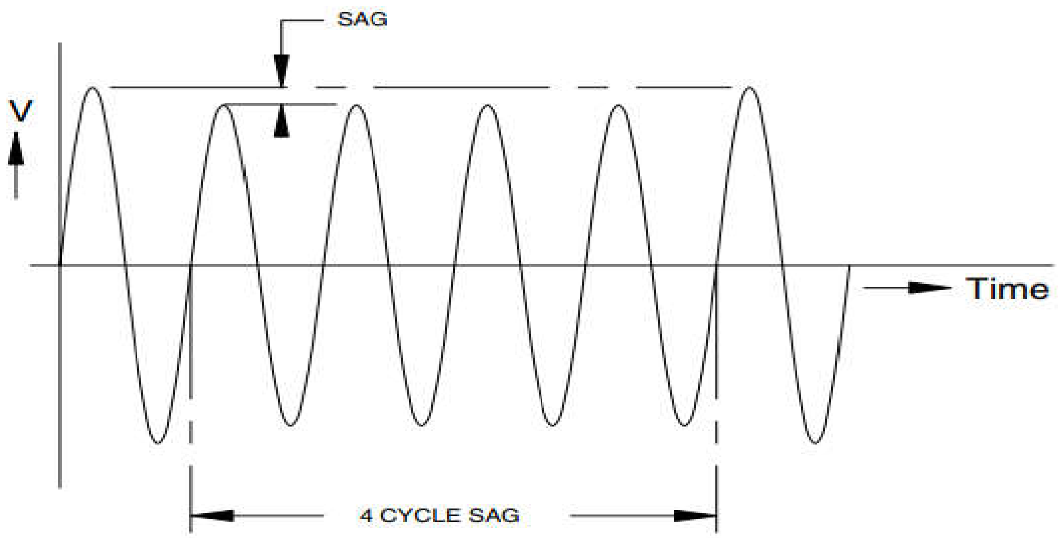


Figure 1.2 Voltage sag

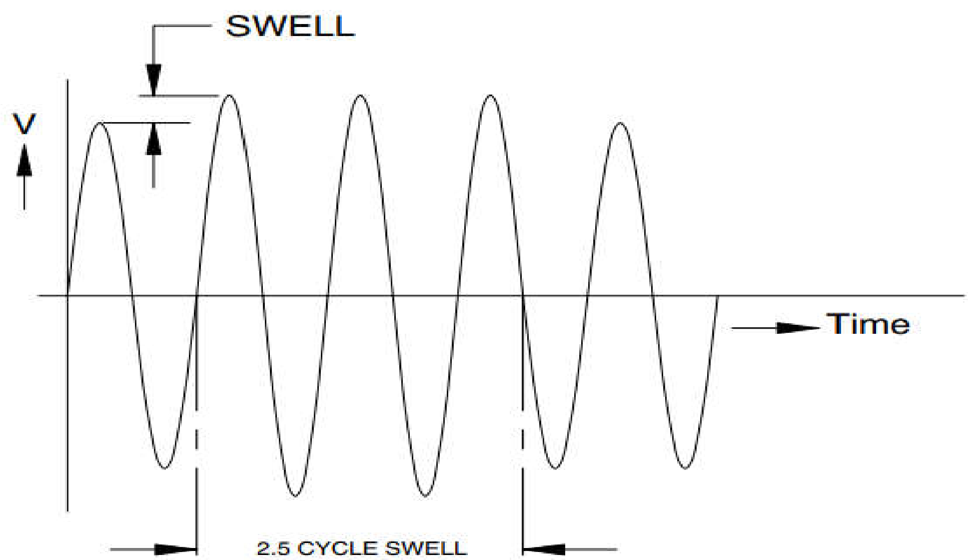


Figure 1.3: Voltage swell

Power system transientsare fast, short-duration events that produce distortions such as notching, ringing, and impulse. The mechanisms by which transient energy is propagated in power lines, transferred to otherelectrical circuits, and eventually dissipated are different from the factors that affectpower frequency disturbances.

Power system harmonicsare low-frequency phenomena characterized by waveform distortion, which introduces harmonic frequency components. Voltage and current harmonics have undesirable effects on power system operation and power system components. In some instances, interaction between the harmonics and the power system parameters (*R*–*L*–*C*) can cause harmonics to multiply with severe consequences.

The subject of ***grounding and bonding***is one of the more critical issues in power quality studies. Grounding is done for three reasons. The fundamental objective of grounding is safety, and nothing that is done in an electrical system should compromise the safety of people who work in the environment; in the U.S., safety grounding is mandated by the National Electrical Code (NEC®). The second objective of grounding and bonding is to provide a low-impedance path for the flow of fault current in case of a ground fault so that the protective device could isolate the faulted circuit from the power source. The third use of grounding is to create a ground reference plane for sensitive electrical equipment. This is known as the signal reference ground (SRG).

Electromagnetic interference **(EMI)** refers to the interaction between electric and magnetic fields and sensitive electronic circuits and devices. EMI is predominantly a high-frequency phenomenon. The mechanism of coupling EMI to sensitive devices is different from that for power frequency disturbances and electrical transients.

Electrostatic discharge (ESD) is a very familiar and unpleasant occurrence. In our day-to-day lives, ESD is an uncomfortable nuisance we are subjected to when we open the door of a car or the refrigerated case in the supermarket. But, at high levels, ESD is harmful to electronic equipment, causing malfunction and damage.

Finally**,** low ***Power factor***is responsible for equipment damage due to component overload. For the most part, power factor is an economic issue in the operation of a power system. As utilities are increasingly faced with power demands that exceed generation capability, the penalty for low power factor is expected to increase. An understanding of the power factor and how to remedy low power factor conditions is not any less important than understanding other factors that determine the health of a power system[8].

Effects of Power Quality on Users:

The power quality problems affect all concerned utilities, customers, and manufacturers directly or indirectly in terms of major financial losses due to interruption of process, equipment damage, production loss, wastage of raw material, loss of important data, and so on. There are many instances and applications such as automated industrial processes, namely, semiconductor manufacturing, pharmaceutical industries, and banking, where even a small voltage dip/sag causes interruption of process for several hours, wastage of raw material, and so on.

Some power quality problems affect the protection systems and result in mal-operation of protective devices. These interrupt many operations and processes in the industries and other establishments. These also affect many types of measuring instruments and metering of the various quantities such as voltage, current, power, and energy. Moreover, these problems affect the monitoring systems in much critical, important, emergency, vital, and costly equipment.

Harmonic currents increase losses in a number of electrical equipment and distribution systems and cause wastage of energy, poor utilization of utilities' assets such as transformers and feeders, overloading of power capacitors, noise and vibrations in electrical machines, and disturbance and interference to electronics appliances and communication networks[9].

1.3Basic of Harmonics

In an AC circuit, a resistance behaves in exactly the same way as it does in a DC circuit. That is, the current flowing through the resistance is proportional to the voltage across it. This is because a resistor is a linear device and if the voltage applied to it is a sine wave, the current flowing through it is also a sine wave,and the phase difference between the two sinusoids is zero. But this is not always the case, in an electrical or electronic device or circuit that has a voltage-current characteristic which is not linear, that is, the current flowing through it is not proportional to the applied voltage. The alternating waveforms associated with the device will be different to a greater or lesser extent to those of an ideal sinusoidal waveform. These types of waveforms are commonly referred to as non-sinusoidal or complex waveforms that are represented in **Fig.1.4**.

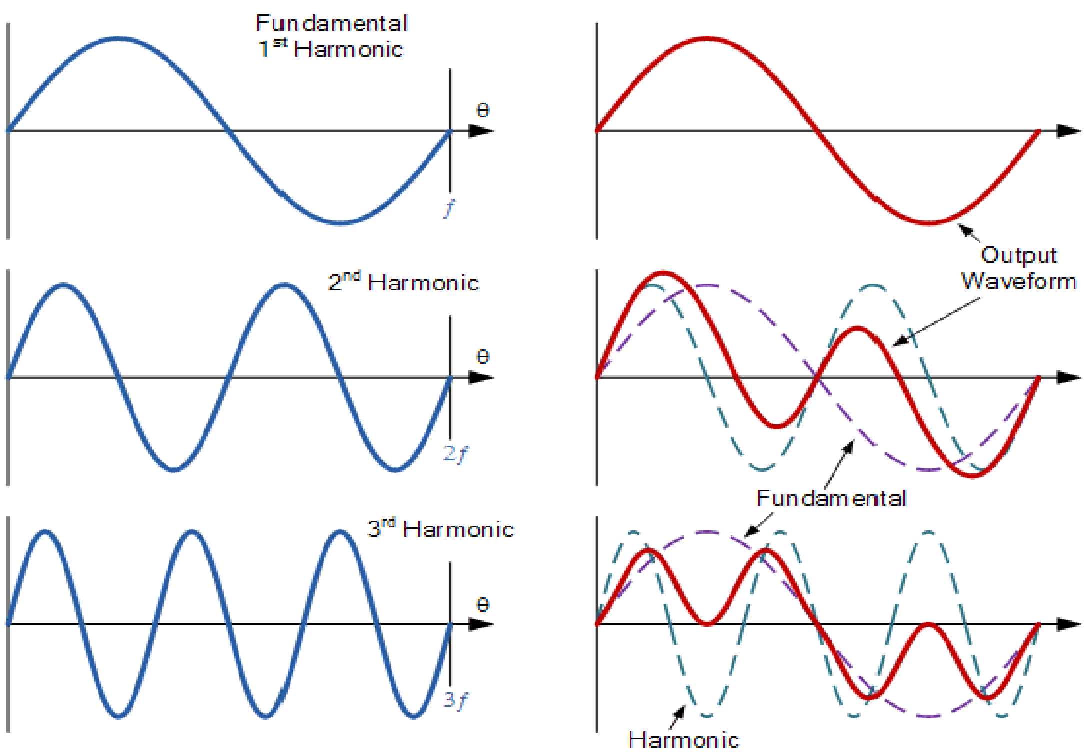


Figure 1.4: Output Waveform of Sinewave before and after adding 2nd and 3rd Harminics

Thus, Harmonics are defined as unwanted higher frequencies which superimposed on the fundamental waveform creating a distorted wave pattern. In other word, Harmonics are voltages or currents that operate at a frequency that is an integer (whole-number) multiple of the fundamental frequency.

Also most electronic power supply switching circuits such as rectifiers, silicon controlled rectifier (SCR's), power transistors, power converters and other such solid state switches which cut and chop the power supplies sinusoidal waveform to control motor power, or to convert the sinusoidal AC supply to DC. Theses switching circuits tend to draw current only at the peak values of the AC supply and since the switching current waveform is non-sinusoidal the resulting load current is said contain Harmonics**.**Non sinusoidal complex waveforms are constructed by "adding" together a series of sine wave frequencies known as "Harmonics". Harmonics is the generalized term used to describe the distortion of a sinusoidal waveform by waveforms of different frequencies.

Then whatever its shape, a complex waveform can be split up mathematically into its individual components called the fundamental frequency and a number of "harmonic frequencies" [16].

A sinusoidal voltage or current function that is dependent on time *t* may be represented by the following expressions:

$$v(t) = V\sin(wt) \quad (1.1)$$

$$i(t) = I\sin(wt \pm \theta) \quad (1.2)$$

where $\omega = 2 \times \pi \times f$ is known as the angular velocity of the periodic waveform and θ is the difference in phase angle between the voltage and the current waveforms referred to as a common axis.

Fourier analysis permits a periodic distorted waveform to be decomposed into a series containing dc, fundamental frequency (e.g. 50Hz), second harmonic (e.g. 100Hz), third harmonic (e.g. 150Hz), and so on. The Fourier series can be expressed as follows:

$$i(t)=I_{avg} + \sum_{n=1}^{\infty} I_n \,.\, sin(n\omega t + \theta_n) \quad (1.3)$$

I_{avg} is the average (often referred to as the "DC" valueI_{dc}). I_n are peak magnitudes of the individual harmonics, ω is the fundamental frequency (in radians per second), and θ_n are the harmonic phase angles[10].

1.4Total Harmonic Distortion (THD)

Total harmonic distortion (THD) is a term used to describe the net deviation of a nonlinear waveform from ideal sine waveform characteristics. Total harmonic distortion is the ratio between the RMS value of the harmonics and the RMS value of the fundamental. For example, if a nonlinear current has a fundamental component of I_1 and harmonic components of I_2, I_3, I_4, I_5, I_6, I_7, …, then the RMS value of the harmonics is:

$$I_h = \sqrt{(I_2^2 + I_3^2 + I_4^2 + I_5^2 + I_6^2 + I_7^2 + \cdots} \qquad (1.4)$$

$$THD = \frac{I_h}{I_1} \times 100\% \qquad (1.5)$$

THD is important in several types of systems, including power systems, where a low THD means higher power factor, lower peak currents, and higher efficiency; audio systems, where low THD means that the audio signal is a more faithful reproduction of the original recording; and communication systems, also low THD means less interference with other devices and higher transmit power for the signal of interest[8].

1.5Causes, Effects and Sources of Harmonics

1.5.1Cause of Harmonics

Harmonics are caused by non-linear loads, that is, the loads that draw a non-sinusoidal current from a sinusoidal voltage source. Some examples of harmonic producing loads are electric arc furnaces, static VAR compensators, inverters, DC converters, switch-mode power supplies, and AC or DC motor drives. In the case of a motor drive, the AC current at the input to the rectifier looks more like a square wave than a sine wave.

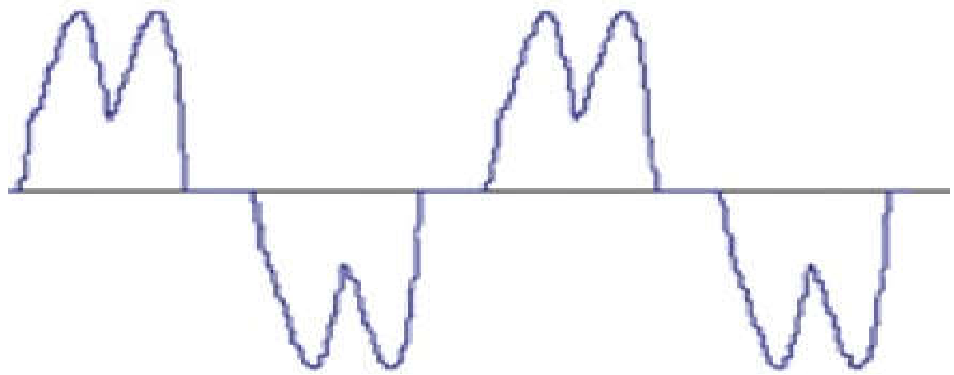


Figure 1.5 Typical 6-Pulse Rectifier Input Current Waveform

The rectifier can be thought of as a harmonic current source and produces roughly the same amount of harmonic current over a wide range of power system impedances. The characteristic current harmonics that are produced by a rectifier are determined by the pulse number. The following equation allows determination of the characteristic harmonics for a given pulse number:

$$h = kq \pm 1 \qquad (1.6)$$

Where:

h is the harmonic number (integer multiple of the fundamental).

k is any positive integer.

q is the pulse number of the converter.

This means that a 6-pulse (or 3-phase) rectifier will exhibit harmonics at the 5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th, etc. multiples of the fundamental. As a rough rule of thumb, the magnitudes of the harmonic currents will be the fundamental current divided by the harmonic number (e.g. the magnitude of the 5th harmonic would be about 1/5th of the fundamental current). A 12-pulse (or 6-phase rectifier) will, in theory, produce harmonic currents at the 11th, 13th, 23rd, 25th, etc. multiples. In reality, a small amount of the 5th, 7th, 17th and 19th harmonics will be present with a 12-pulse system (typically the magnitudes will be on the order of about 10 percent of those for a 6-pulse drive).

Variable frequency drives also produce harmonic currents at the output of the inverter which are seen by the motor. Most of these harmonics are integer multiples of the inverter operating frequency and not the power supply frequency, but little generalization can be made about their magnitude since this varies greatly with the type of drive and the switching algorithm for the inverter semiconductors. Some "interharmonic" currents may also be present at the input or the output of the drive. Interharmonics do not fit the classical definition of harmonics since they do not necessarily occur at integer multiples of the power supply or inverter fundamental frequency. Harmonics can occur on the input at the power system frequency plus or minus the inverter operating frequency[11].

1.5.2 Effects of Harmonics

Voltage distortion is generally very harmful because it can increase the effective peak value and also the RMS current in some devices connected to the network. For a capacitor, impedance decreases drastically as it is inversely proportional to the frequency. Under normal circumstances the voltage distortion in primary electrical distribution network is minimal and can usually be ignored from a practical point of view. On the other hand distortion of current wave shape is common particularly when electronic equipment is connected to the network or when non-linear loads are connected. Current distortion, in general, causes overheating due to increase in the losses and affects all electrical machines, transformers etc. These harmonics currents degrade the power system performance and reliability and could also cause safety problem [12].

a) Transformers

The effects of the harmonic currents on Transformer are:

- ***Core loss:*** Harmonic voltage increases the hysteresis and eddy current losses in the lamination. The amount of the core loss depends on harmonic present in supply voltage design parameter of core materials and magnetic circuit.

- ***Copper loss:*** Harmonic current increases copper loss. The loss mainly depends on the harmonics present in the load and effective ac resistance of the winding. Copper loss increase temperature and create hot spots in that transformer. The effect is prominent in the case of converter transformers these transformers do not benefit from the presence of filters as filter are normally connected on the AC. system side.
- ***Stress:*** Voltage harmonics increase stresses of the insulation,
- ***Core vibration:*** Current and voltage harmonics increase small core vibrations.
- ***Saturation problem:*** Sometimes additional harmonic voltage causes core Saturation.

b) Rotating machines

The effects of the harmonic currents on Rotating Machines are:

- ***Harmonic losses:*** Harmonic voltages or currents increase losses in the stator windings, rotor circuit, and stator and rotor lamination. Normally the losses in the stator and rotor conductors of A.C. machines are greater than those associated with the D.C. resistances due to the presence of eddy current and skin effect in ac circuit. Harmonics increase both copper loss and core loss. This results in overheating and reduction of the efficiency of a machine.
- ***Harmonic torque:*** Harmonic currents present in the stator of an AC. machine produce induction motoring action (i.e. positive harmonic slips Sn), which gives rise to shaft torques in the same direction as the harmonic field velocities in such a way that all positive sequence harmonic will develop shaft torques aiding shaft rotation whereas negative sequence harmonics will have the opposite effect.

- ***Speed torque characteristics:*** Each harmonic component contributes to the magnetic force. The presence of harmonics has effect on speed/torque characteristics.

- ***Cogging:*** Cogging is the failure of an induction motor to run up to normal speed due to a stable operating point occurring at a lower frequency.
- ***High capacitive current:*** The presence of harmonics increases capacitive current through the stray capacitance in ASD-fed electric motors which is one of the reasons for their failure.
- ***Voltage stress on insulation:*** Harmonic voltages increase the stress on insulating materials.

c) Capacitors

- The life expectancy decreases due to increased dielectric losses that cause additional heating, reactive power increases due to harmonic voltages.
- Over voltage can occur and resonance may occur resulting in harmonic magnification.

d) Cables

- Additional heating occurs in cables due to harmonic currents because of skin and proximity effects which are function of frequency.
- The I^2R losses increase.

e) Switchgear

- Changing the rate of rise of transient recovery voltage.
- Affects the operation of the blowout.

f) Relays

- Affects the time delay characteristics,
- False tripping may occurs[13].

g) Measuring instruments

- ***Error:*** Measuring instruments are calibrated on purely sinusoidal alternating current but they are used on a distorted electricity supply. This introduces error in measurement.

- ***Sign of error:*** Sign of error depends on the magnitude and the direction of the harmonic power.
- ***Harmonic torque:*** Torque produced by harmonics greatly affects operation of instruments.
- Any DC power supplied to or generated by the customer will cause an error proportional to the harmonic-fundamental power ratio, with the error sign related to the direction of power flow.
- Harmonic voltages or currents not only produce torques, but also degrade the capability of a meter to measure fundamental frequency power.
- The kilowatt-hour meter, based on the Ferraris (eddy current) motor principle, show generally appreciably high readings with a consumer generating harmonics through thyristor-controlled variable speed equipment particularly where even harmonics and DC are involved. By this way, consumers that generate harmonics are automatically penalized by higher apparent electricity consumption. This may well offset the supply authority's additional losses. It is therefore in the consumer's own interest to reduce harmonic generation to the greatest possible extent.

1.5.3Sources of Harmonics

Conventional electromagnetic devices as well as semiconductor applications act as sources of harmonics. Conventional electromagnetic devices include stationary transformer as well as rotating machines. Harmonic generation in these machine depends on the properties of the materials used to construct them, different design constraints and considerations, operating principle and of course load environment. Beside these arcing devices produces considerable amount of harmonics. Other than conventional devices, semiconductor based power supplies, phase controllers, reactors, etc are used enormously in modern power system network and they are contributing huge amount of harmonics to the power system. In electric power system, main sources of harmonics may be classified as follows:

- Magnetization non-linearities of transformer
- Rotating machines

- Arcing devices
- Semiconductor based power supply system
- Inverter fed A.C. drives
- Thyristor controlled reactors
- Phase controllers
- A.C. regulators

a) Magnetization non-linearities of transformer

Transformer magnetic material characteristic is non linear. This non linearity is the main reason for harmonics during excitation. Sources of harmonics in transformer may be classified into four categories as follows:

1-Normal Excitation: Normal excitation current of a transformer is non sinusoidal. The distortion is mainly caused by zero sequence triplen harmonics and particularly the third present in the excitation current. Presence of the electric path like air, oil or tank for zero sequence components can be used to reduce those harmonics. Their high reluctance tends to reduce them. Delta connection of poly-phase transformer is very effective to reduce triplen harmonics provided the three phase voltages are balanced.

2- Symmetrical Over Excitation: Transformers are designed to make good use of the magnetic properties of the core material. When such transformers are subjected to a rise in voltage, the cores face a considerable rise in magnetic flux density, which often causes considerable saturation. This saturation with symmetrical magnetizing current generates all the odd harmonics. The fundamental component is not a problem and all triplen harmonics can be absorbed by delta connection in balanced system. The harmonics generated by symmetrical over excitation are odd harmonics (like 5, 7, 11, 13, 17, 19. . . . etc) i.e. those of orders $6k\pm1$, where k is an integer.

3-Inrush Current Harmonics: When a transformer is switched off, sometimes there exists a residual flux density in the core. When the transformer is re-energized the flux density can reach peak levels of twice the maximum flux density or more. It produces high ampere-turns in the core. This causes magnetizing currents to reach up to 5–10 per unit of the rated value, which is very high as compared to the normal values of a few percentage points. This is known as inrush current. This causes generation of enormous second order harmonic component in the transformer current.

4-D.C. Magnetization: Under magnetic imbalance, the shape of the magnetizing characteristics and the excitation currents are different from those under no load conditions. When the flux is unbalanced, the core contains an average value of flux (φdc), which is equivalent to a direct component of excitation current of the transformer. Under such unbalance conditions, the transformer excitation current contains both odd and even harmonic components.

b) Rotating machines

Rotating machines also act as source of harmonics in power system. Causes of harmonics generation in rotating electrical machines are classified into following categories:

1-Magnetic Nonlinearities Of The Core Matrial: is a nonlinear magnetization characteristics of the core material causes harmonic generation.

2-Non Uniform Flux Distribution In Air Gap: often it is assumed that the air-gap flux distribution is uniform and the operating principles of rotating machines are discussed based on this assumption. But in most of the rotating machines, flux distribution in air-gap is not uniform which leads to harmonics production.

4-Slot Harmonics: slots are inevitable in rotating machines. Alternate presence of slot and teeth changes the reluctance of the magnetic flux varies in similar type of alternating fashion. This variation acts as a reason for harmonic generation. Harmonics produced due to pitch factor and distribution factor.

5-Mass Unbalance:with the aging, mass unbalance is observed specially in the rotor side. This refers to the core property and adds in harmonic generation.

6-**Unsymmetrical Fault:**unsymmetrical fault is also a reason for harmonic generation related to negative sequence components.

c) Semiconductor based power supply system

Semiconductor based power supply systems are the main sources of harmonics. Harmonics generated in power supply include integer harmonics, inter harmonics and sub harmonics. Frequencies and magnitudes of the harmonics depend on the type ofsemiconductor devices used in the power supplies, operating point, nature of load variation, etc.

1-Inverter fed A.C. drives

Application of AC drives has increased to a great extent, most of which are inverter fed AC drives. They use switching circuits using semiconductor devices like GTO, IGBT, etc. Pulse width modulation (PWM) has got very popularity in AC drive application. All these drives are sources of integer as well as fractional harmonics.

2-Thyristor controlled reactors

VAR compensators used in power system network are also source of harmonics. Different types of thyristor controlled reactors are used in power system like series controller, shunt controller, static VAR compensator (SVC), fixed capacitor thyristor controlled reactor (FCTCR), thyristor switched capacitor thyristor controlled reactor (TSCTCR). All these circuits are sources of harmonics in power system. Use of static synchronous generator (SSG), voltage source STATCOM, current source STATCOM, etc in power system are increasing rapidly. All these contribute harmonics of both integer and fractional type in power system. For example, SVC produces odd harmonics. Under perfectly symmetrical voltage conditions, triplen harmonics are kept out of the line by delta connection.

3-A.C. regulators

AC regulators used in power system apply both off line and on line control technique for voltage regulation which result in harmonic generation. On line regulation technique distorts wave-shape more than off line regulation along with other power system disturbances like transients, DC offset, flicker etc. Thyristor controlled single phase or poly phase regulators using half wave, full wave or integral cycle control technique produce sub-harmonics and inter-harmonics in power system [14].

1.6Harmonic mitigation methods

a) Line Reactors

Line Reactors are the simplest and lowest cost means of attenuating harmonics. They connect in series with an individual non-linear load such as an ASD. By inserting series inductive reactance into the circuit, they attenuate harmonics as well as absorb voltage transients that may otherwise cause a voltage source ASD to trip on over-voltage. The magnitude of harmonic distortion and the actual spectrum of harmonics depend on the effective impedance that the reactor represents in relation to the load.

Advantages:

1. It cost low.
2. It can provide moderate but significant reduction in voltage and current harmonics.
3. It is available in various values of percent impedances.

Disadvantages:

1. It causes a voltage drop.
2. It increases system losses.
3. The normal impedance value of line reactor don’t achieve current distortion levels much below 35% THD-I.

b) Isolation Transformers

Since input circuit reactance is a major determining factor for the magnitude of harmonics that will be present and flowing to an individual load, isolation transformers can be used effectively to reduce harmonic distortion. The leakage inductance of isolation transformers can offer appropriate values of circuit impedance so that harmonics are attenuated. The typical configuration of isolation transformer for power quality purposes is delta primary and wye secondary.

Advantages:

1. It can reduce both common mode and normal mode disturbances as well as provide circuit isolation.

Disadvantages:

1. It can achieve effective harmonic attenuation with only proper physical size. It should be sized as close as possible to the rated load current and has their impedance based on load current and voltage.

2. It causes more circuit losses and cost as compared to line reactor.

c) Tuned Harmonic Filter

It is a device with basic elements as inductive and capacitive reactance. These reactive elements are connected in series to form a tuned LC circuit. It is connected as a shunt device in power system. It is a resonant circuit at the tuning frequency, at which it offer very low impedance. This makes it to become the source of the tuned frequency harmonic energy demanded by the loads. It means that, at tuning frequency, the filter offer very low resistances and the greater amount of harmonic current flows through it. The total harmonic current distortion decreases.

Advantages:

1. It improves the displacement power factor due to capacitive behavior at low frequencies.

2. It improves distortion power factor by reducing total harmonic current distortion. The ultimate result is improved total power factor.

Disadvantages:

1. The capacitance of tuned filter may cause a resonance problem if initial THD-I is less than 20%.

2. It doesn't eliminate the tuned harmonics, but it only mitigates it.

d) IGBT Based Fast Switched Harmonic Filters

The changes in Reactive power over time can be achieved by an automatic filter. But automatic filter will not respond quickly enough to meet requirement of reactive power. Also, acceptable power factor and harmonic distortion level are to be maintained. That's why, fast switching harmonic filter with IGBT (Isolated Gate Bipolar Transistors) is used. It can be switched without discharging the capacitor at switching rates up to 60 times per second.

Advantage:

1. This filter has the capability to switch without transient and to respond in real time, to dynamically changing load conditions.

2. The total harmonic current distortion can be achieved is from 3% to 12%.

e) 12 & 18 Pulse Rectifier

It involves a special type of rectifier and transformer configuration. In case of 12 pulse and 18 pulse system, the transformers have two and three, respectively, separate secondary windings. The degrees of phase shift between each secondary are 360 divided by the number of rectifier pulses.

Advantages:

1. 12-pulse rectifier system can achieve input current distortion levels from 10% to 20 % THD-I. 18-pulse rectifier system can achieve input current distortion levels from 5 % to 10 % THD-I at full load conditions.

Disadvantages:

1. THD-I increases with decrease in load.

2. The current drawn by each rectifier bridge and the source voltages for all phases are balanced. If not, it can cause to flow triplen harmonics and increase the residual harmonic current distortion.

f) Active Filter

These filtering techniques can be applied either as a standalone harmonics filter or by incorporating the technology into the rectifier stage of a drive, UPS or other power electronics equipment. It will monitor the load current. It filters out the fundamental frequency current and analyse the frequency and magnitude content of the remaining current. Then, it injects the appropriate inverse currents to cancel the individual harmonics. It uses fast switching transistors (IGBT).

Advantages:

1. It cancels harmonics up to about 50th harmonics.
2. It can achieve harmonic distortion level up to 5% THD-I or even less.

Disadvantages:

1. It may perform low due to high level of pre-existing voltage distortion.
2. It requires more maintenance due to use of power electronic circuitry.
3. It costs high and also losses are greater than passive filters [15].

1.7 Conclusion

In this chapter, we have discussed concepts that are relevant to Power Quality. These are Harmonics, THD, causes, effects, and sources of Harmonics. Then we have seen the different Harmonic mitigation methods that are used nowadays in order to limit the pollution of the Utilities. The next chapter will cover the main types of filters, active and passive filters. And more about active filters, its configurations and its control techniques.

CHAPTER II
Active Filter Components and Control

2.1Introduction

Passive filters have been among the popular solution for reducing the effect of harmonic pollution. However, under variable load conditions, they are not optimal as they are tuned for specific frequencies. Shunt active power filters (SAPFs) have offered a good solution to solve this problem caused by non-linear loads.[32] This chapter will focus on the SAPFs, their configurations and their different control techniques.

2.2 Active and passive Filters

2.2.1 Passive Filters

Passive filter is an electronic filterto filter out the harmonics present in a system and in this filter designing we are using passive elements. Passive elements such as R, L and C are being used to overcome the complexity of system. The combined of these three elements did not depend on external power supply and called passive filter. The capacitor passing highfrequency signals and blocking low-frequency signals, the inductor do the just opposite of it. As we combine these components, we can allow only the fundamental component to pass into the utility grid.

In passive filters, it can be found low-pass filters, high-pass filters or band pass filters. In the low-pass filters, the inductor passes signals while the capacitor grounds them. The reverse action of capacitor and inductor called high-pass filter. The resistors have no frequency selection assets but they are used to determine the time constants of both inductors and capacitors. These latter are the reactive elements of the filter. The number of used elements in the circuit determines the order of the filter [19].However, these passive components are often bulky, heavy and expensive which make it difficult to modify and adapt for system design variations.

2.2.2 Active Filters

In order to avoid the passive elements which are heavy and take lot of space,a new technology of semiconductors switching devices has been introduced[20].The harmonic suppression become easier and with more precision using the switching devices known as active filters.

Active filters are filters that use active component, in other words no inductors are needed. They are developed with PWM converters (current source or voltage source inverters). The current-fed PWM inverter bridge structure behaves as a non-sinusoidal current source to meet the harmonic current requirement of the non-linear load. Besides, it has a self-supported dc reactor that ensures the continuous circulation of the dc current. They present good reliability, but have important losses and require higher values of parallel capacitor filters at the ac terminals to remove unwanted current harmonics.

By comparing the two types of filters based on the cost, Active filters are much cheaper than the passive filters duo to the absence of costly inductors. In term of the frequency, the active filter can deal with the very low frequencies and it is also easier to adjust, while the passive filter adjustment requires passive component replacement [33].

2.3 Active Filter Configurations:

Active power filters can be classified based on the type of converter, configuration, control scheme, and compensation characteristics. The most popular classification is based on the configuration. The main configurations of the active filter are: shunt, series or hybrid. The hybrid configuration is a combination of shunt and seriesconfigurations. As shown in **Fig.2.1.**

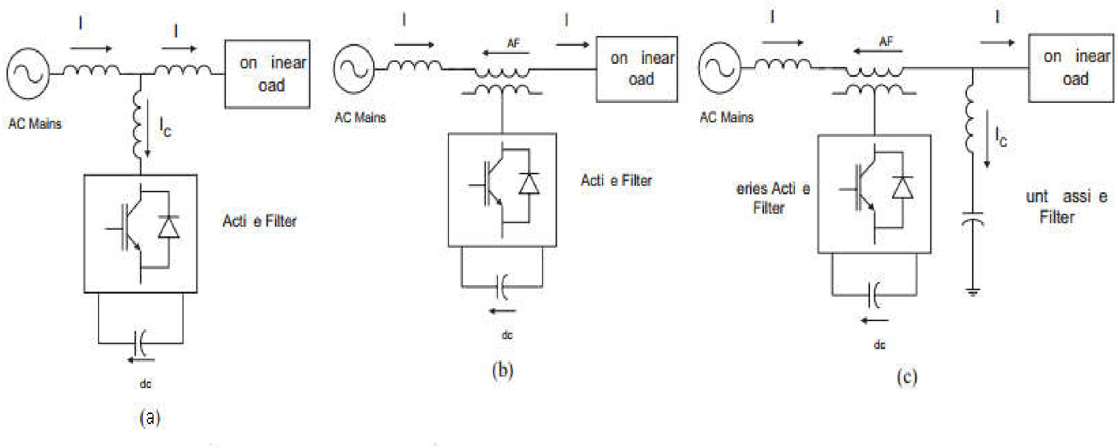


Figure 2.1 Active power filter topologies implemented with VSI. (a) Shunt active power filter. (b) Series active power filter. (c) Hybrid active power filter

Shunt active power filters are widely used tocompensate current harmonics, reactive power and load current unbalanced. It can also be used as a static VARgenerator in power system networks for stabilizing and improving voltage profile.

Series active power filters are usually connected before the load in series with the acmains, through a coupling transformer to eliminate voltage harmonics and to balance and regulate the terminal voltage of the load or line.

The hybrid configuration is a combination of series active filter and passive shunt filter. This topology is very convenient for the compensation of highpower systems, because the rated power of the active filter issignificantly reduced (about 10% of the load size)[21],Since themajor part of the hybrid filter consists of the passive shunt LCfilter, it used to compensate lower-order current harmonics andreactive power.

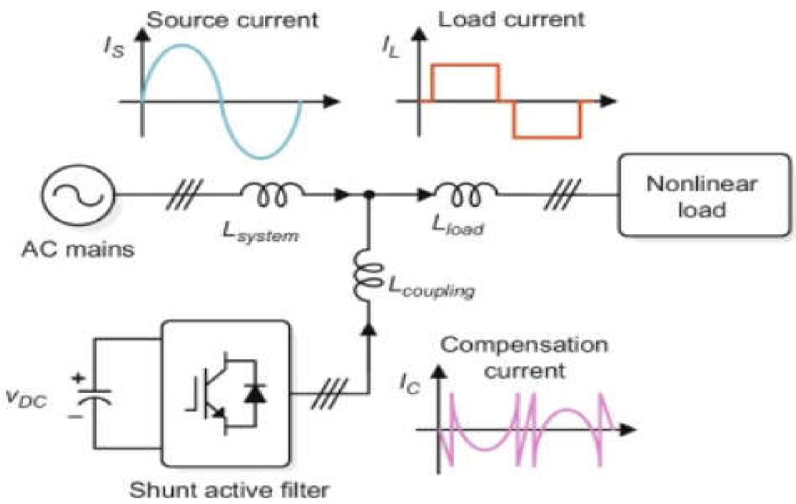


Figure 2.2: Shunt Active Power Filter Scheme

To implement the SAPF, different converter topologies may be used. **Fig.2.3** shows two three-phase, three-wire power converters. **Fig.2.3a** shows a pulsewidth modulation (PWM) voltage source converter (VSC) with a capacitor as energystorage element. **Fig.2.3b**shows a PWM current source converter (CSC) with an inductor as energy storage element.

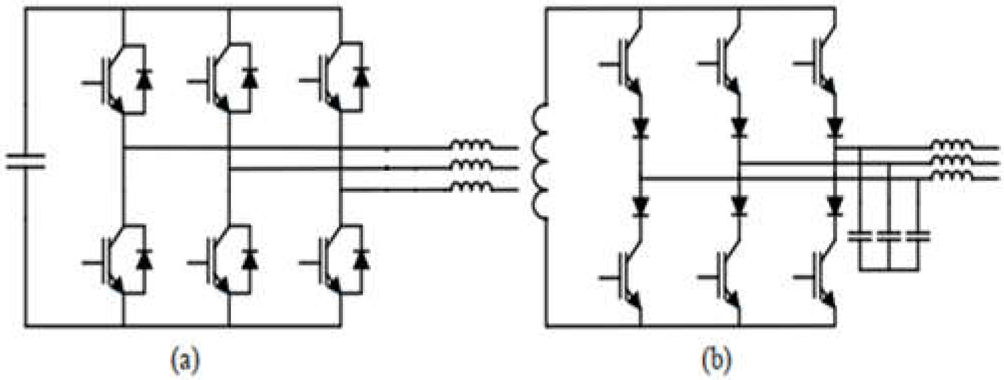


Figure 2.3:scheme of a shunt active filter

Due to efficiency, size and reliability VSCs are preferred to work with[22].

2.4 Control Techniques of Shunt Active Power Filter

Shunt active power filters compensate current harmonics by injecting equal butopposite harmonic compensating current. Active power filters use PWM controlled power electronic converters to generate currents from the point of common coupling that are opposite in phase to the harmonic currents drawn by the load, such that the resulting currents into the grid are distortion-free, sinusoidal waveforms.

Since the development of APF, many control techniques have been proposed. Among them, three techniques have been well presented in literature. Instantaneous active and reactive power (p-q) scheme, modified Instantaneous active and reactive power (modified p-q) scheme and Instantaneous active and reactive current component (d-q) scheme.

2.4.1 Instantaneous active and reactive power (p-q) scheme

The instantaneous p-q theory is the most popular theory used for the control ofshuntAPFs, where, undesirable powers canbe selected and compensated conveniently.In addition,it offers a very precise reference compensation currenttemplate and allows obtaining a clear difference between instantaneous active andreactive powers. However, it is criticized under non-ideal supplyconditions [23].The control block diagram for the p-q theory is shown in **Fig.2.4.**

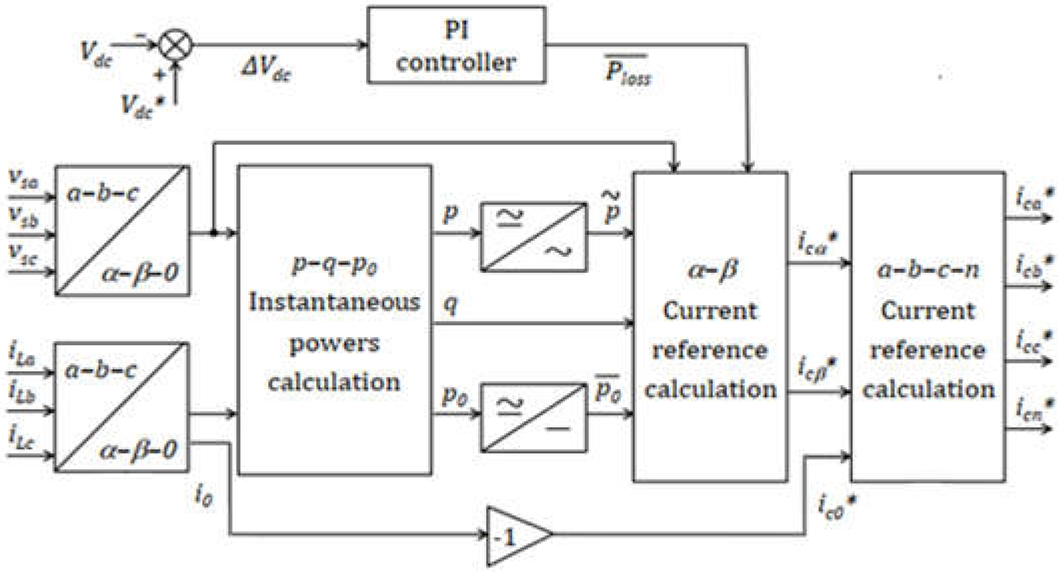


Figure 2.4: Control block diagram for p-q scheme

Using sensors, source voltages (V_{sa},V_{sb},V_{sc}) and load currents (I_{La},I_{Lb},I_{Lc}) are measured .As shown in the **Fig2.4**,Clarck transformation is applied to the voltages and currents in order to obtain the active and reactive power.

The Clarck transformation matrix for the voltages, from (a,b,c) sequence to (α,β,0) is defined as:

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{2.1}$$

The inverse Clarck transformation matrix is given by:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} \tag{2.2}$$

Similarly for the three phase currents:

$$\begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{2.3}$$

And the inverse:

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} \qquad (2.4)$$

The zero-sequence current (I_0),or voltage (V_0) exists only in three-phase four-wire power systems [24].Therefore, to simplify the calculations,both(I_0) and (V_0) can be neglected when the p-q theory isapplied to three-phase three-wire systems.

In order to obtain the instantaneous active power (p), reactive power (q) and zero sequence power (p_0), we multiply the instantaneous α,β,0 components of currents and voltages as:

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} V_0 & 0 & 0 \\ 0 & V_\alpha & V_\beta \\ 0 & V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} \qquad (2.5)$$

Where p,q and p_0 have DC components ($\bar{p}, \bar{q}, \bar{p}_0$) and AC components ($\tilde{p}, \tilde{q}, \tilde{p}_0$).

As shown in the scheme of p-q method, the entire reactive power (q) and oscillating component of active power ($\tilde{p}$) are utilized for calculation of reference filter currents in α,β coordinates using:

$$\begin{bmatrix} I_{c\alpha^*} \\ I_{c\beta^*} \end{bmatrix} = \frac{1}{\sqrt{{V_\alpha}^2+{V_\beta}^2}} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} + \Delta\bar{p} \\ -q \end{bmatrix} \qquad (2.6)$$

The zero-sequence reference compensation current (I_{c0}*) should be same as the zero-sequence component detected in load current (I_0), but in opposite sign; so that it canprovide the required zero-sequence current compensation[24]i.e.:

$$I_{c0}* = - I_0. \qquad (2.7)$$

Several methods for separating the average power $\bar{p}$ from the power $p$exist, where low-pass filters (LPFs) is a common method.

The term $\Delta\bar{p}$ refers to the power losses occurring inside the VSIdue to the switching of semiconductor devices, the VSI requires some powerfrom the grid [25].A DC voltage controller is used for calculating p_{loss}. If losses are more than what is supplied to the VSI the DC link voltage would fall, and rise if the losses areless than what is supplied[29]. For proper operation the DC voltage should be maintained ata fixed reference value by a controller, the controller does not need to have a fast response[26]. Using a PI controller as in Figure 2.4, the term $p_{loss}$is given by:

$$P_{loss} = K_p . \Delta V_{dc} + K_i \int \Delta V_{dc}.dt. \quad (2.8)$$

$$\text{Where:} \Delta V_{dc} = V_{ref} - V_{dc}. \quad (2.9)$$

Once reference currents ($I_{\alpha\beta0}^{*}$)are obtained, one can transform them into (I_{abc}^{*})using the inverse Clarke transformation.

$$\begin{bmatrix} I_{ca^*} \\ I_{cb^*} \\ I_{cc^*} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{c0^*} \\ I_{c\alpha^*} \\ I_{c\beta^*} \end{bmatrix} \quad (2.10)$$

Because of the multiplication of instantaneous load currents and voltages while calculating the instantaneous active and reactive powers, an amplification of harmonic content is occurred.Another method has been developed in 2005 to reduce this kind of harmonics. This method is known asthe modified Instantaneous active and reactive power (modified p-q)[24].

2.4.2 Modified instantaneous active and reactive power (p-q) scheme

Kale and Ozdemir, in 2005 proposed a modification to theconventional scheme. By using a low pass filter to the source voltages we make them sinusoidal [24]. Before utilizing the same calculation for theinstantaneous active and reactive powerscheme.The control block diagram for the modified p-q theory is shown in **Fig.2.5**.

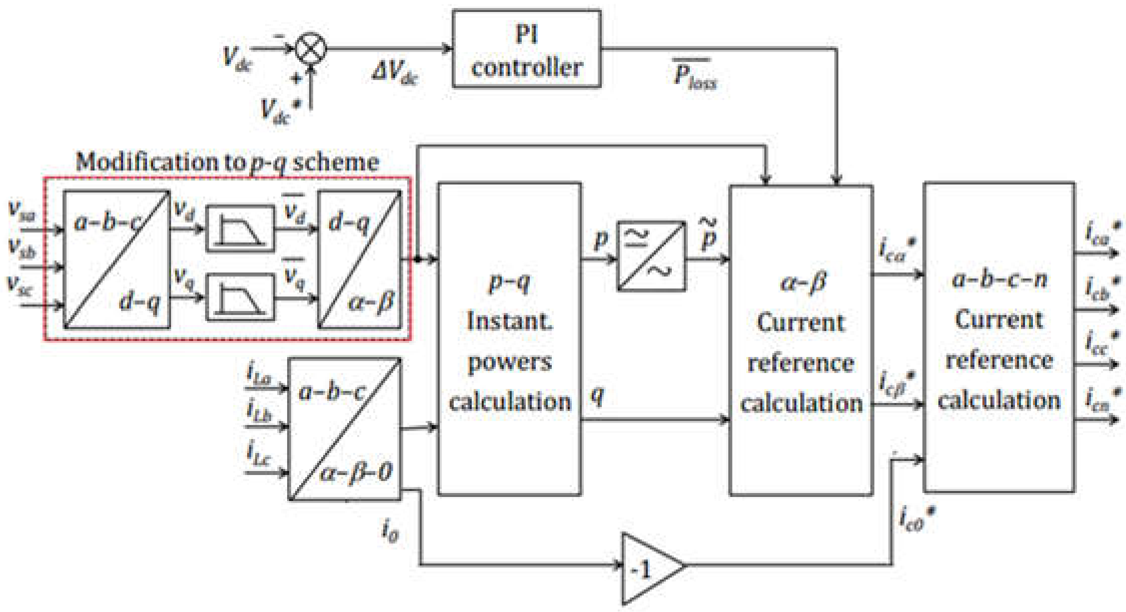


Figure 2.5: Control block diagram for the modified p-q scheme

The filters are used in the d-q coordinates as shown in **fig.2.5**, we transfer the tracked voltages (V_{sa},V_{sb} and V_{sc}) into ($V_d$and V_q) using the Park transformation:

$$\begin{bmatrix} Vd \\ Vq \\ V0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\omega t & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ -\sin\omega t & -\sin(\omega t - \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} Vsa \\ Vsb \\ Vsc \end{bmatrix} \quad (2.11)$$

Here ω represents the rotational speed of synchronously rotating axes. The voltages $V_d$and V_q thus obtained are then subjected to harmonic filtering using of 5th order lowpass filters with cut-off frequency of 50 Hz each. Voltage harmonic filtering is done inthis control scheme in order to filter out the harmonics in source voltage thereby makingit balanced and sinusoidal. Since, the zero-sequence voltage component is filtered out[24]; thezero-sequence power (p_0) is always zero. The outputs of harmonic voltage filtering,$\bar{V}_d$and$\bar{V}_q$ are then transformed into α,β coordinates using:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} \cos\omega t & \sin\omega t \\ -\sin\omega t & \cos\omega t \end{bmatrix}\begin{bmatrix} \overline{V_d} \\ \overline{V_q} \end{bmatrix} \quad (2.12)$$

Once the α,β coordinates of the filtered voltages are obtained, the same procedure of reference compensation current of conventional p-q method is followed.

2.4.3 The Instantaneous active and reactive current component (d-q) scheme

Unlike the first two methods, in this method, the phase locked loop (PLL)is required in order to track the rotational speed of the three phase voltages.After sensing the source voltages and the load currents, they will be transferred to the d-qreference frame by Park transformation.Therefore, the angular speed ωt is needed.

The instantaneous q-d axes currents can be driven as:

$$\begin{bmatrix} I_{ld} \\ I_{lq} \end{bmatrix} = \frac{1}{\sqrt{V_{s\alpha}^2 + V_{s\beta}^2}} \begin{bmatrix} V_{s\alpha} & V_{s\beta} \\ -V_{s\beta} & V_{s\alpha} \end{bmatrix} \begin{bmatrix} I_{l\alpha} \\ I_{l\beta} \end{bmatrix} \quad (2.13)$$

Here the currents $I_{ld}$and I_{lq}consist of a DC and AC components and can be written as:

$$\begin{bmatrix} I_{ld} \\ I_{lq} \end{bmatrix} = \begin{bmatrix} I_{ld1\text{h}} + I_{ldn\text{h}} \\ I_{lq1\text{h}} + I_{lqn\text{h}} \end{bmatrix} \quad (2.14)$$

Where I_{ld1h} and I_{lq1h} represent the fundamental frequency components. And $I_{ldnh}$with I_{lqnh} are the components to be filtered in this process.

The total active current required to maintain a constant DC-link capacitor voltage and tocompensate the power losses occurring inside the APF is represented by I_{ld1h}[24]. This is theoutput signal of PI controller used to minimize the DC-link voltage error ΔV_{dc}.

$$I_{ld1h} = K_p.\ \Delta V_{dc} + K_i \int \Delta V_{dc}.dt, \quad (2.15)$$

$$\text{Where}\ \Delta V_{dc} = V_{ref} - V_{dc}. \quad (2.16)$$

In this control strategy the currentsI_{ldnh} andI_{lqnh} along withI_{ld1h} are utilized to generate reference filter currentsI_{cd}^* andI_{cq}^* in d-q coordinates[24].

$$I_{cd}^* = -I_{ldnh} + I_{ld1h}. \quad (2.17)$$

$$I_{cq}^* = -\ I_{lqnh}. \quad (2.18)$$

Once I_{cd}^* and I_{cq}^* are defined, the a,b,c coordinate of current I_{ca}^*, I_{cb}^* and I_{cc}^* can be found using the inverse Park's transformationas:

$$\begin{bmatrix} I_{ca^*} \\ I_{cb^*} \\ I_{cc^*} \end{bmatrix} = \begin{bmatrix} \cos\omega t & -\sin\omega t & 1 \\ \cos(\omega t - \frac{2\pi}{3}) & -\sin(\omega t - \frac{2\pi}{3}) & 1 \\ \cos(\omega t + \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} I_{cd^*} \\ I_{cq^*} \\ I_{c0^*} \end{bmatrix} \quad (2.19)$$

With I_{c0}^* is just $-I_0$.

$(I_{c0}^* = -I_0)$. (2.20)

The block diagram for the d-q control scheme is:

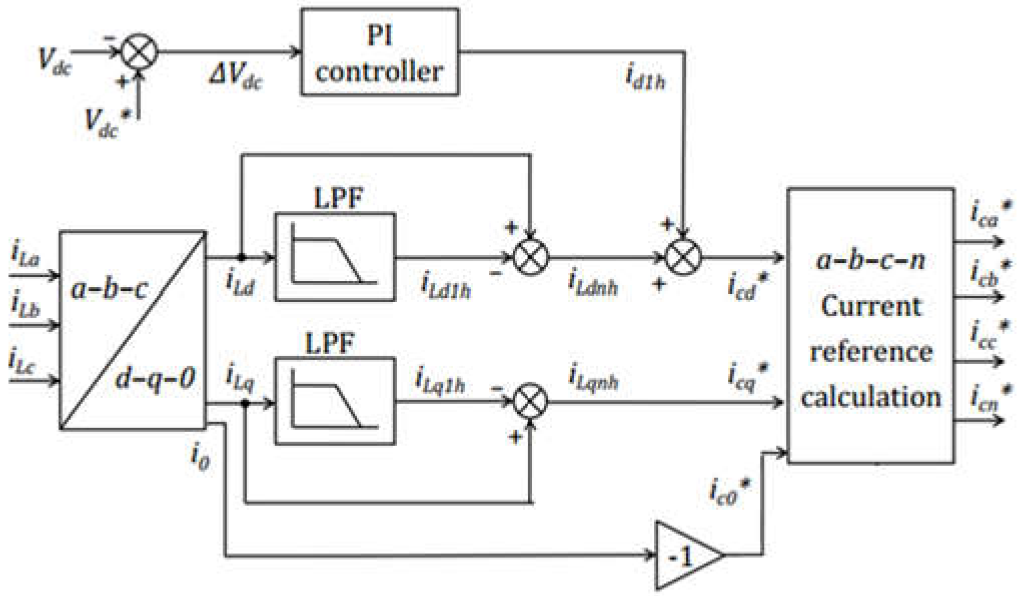


Figure 2.6: Control block diagram for the Instantaneous active and reactive current component (d-q) scheme

In this method, the harmonics caused by the multiplication on currents and voltage can be illuminated. However, the PLL is required in order to obtain the frequency of the system as explained before.

2.5 Hysteresis Current Controller

The next step after getting the reference currents (I_{abc}^*) is to compare them to the filter actual currents using a specified control technique. Among various PWM current control strategies for shunt APFs, the hysteresis currentcontroller (HCC) is a simple, robust and high bandwidth method used for generating theswitching patterns for the VSI. The main drawback is its varying switching frequency[27, 28]. The HCC maintains the compensation current within a desired hysteresis band(HB). The HB directly affects the switching frequency, a lower value of *HB* gives less ripplebut higher average switching frequency and vice versa. The switching logic in **Fig.2.7**for leg *A* is given by:

If $i_{ca}<(i_{ca,ref}- HB)$ (2.21)

The upper switch is *off* and the lower switch is *on*.

If $i_{ca}>(i_{ca,ref}+ HB)$ (2.22)

The upper switch is *on* and the lower switch is *off*.

Where $i_{ca}$and $i_{ca,ref}$are the measured and reference line currents respectively for the leg *A*.The current and voltage waveforms for phase *a* is shown in **Fig.2.8**, similarwaveformsand switching logic also applies to phase *b* and phase *c* but shifted in time[27].

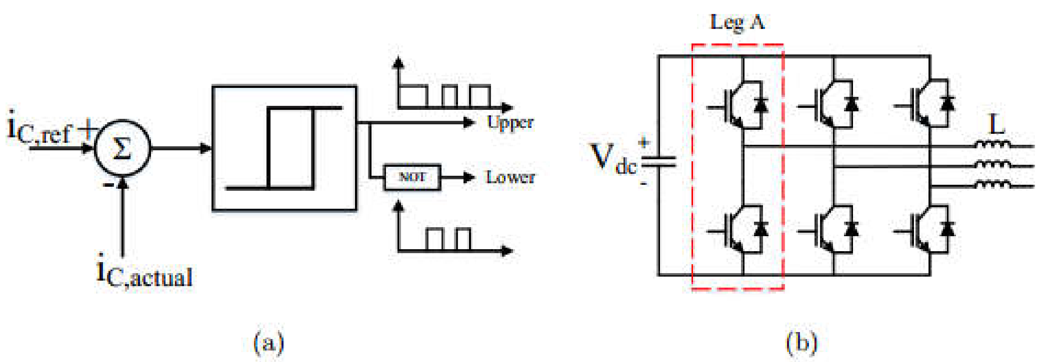


Figure 2.7:(a) Hysteresis current controller,(b) Voltage source converter

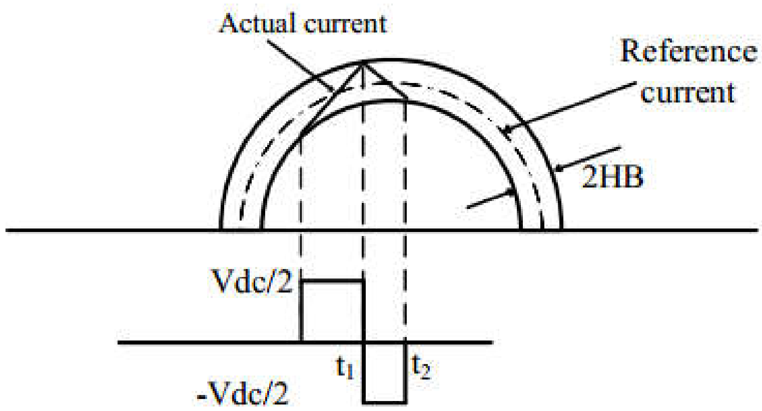


Figure 2.8: Principle of the hysteresis current controller

The final output signal of the hysteresis controllers is driven into the 6 IGBTs gates of the converters.

2.6 DC-link Capacitor

The main role of the DC-side capacitor is to serve two major purposes : a) Maintains a constant DC voltage with small ripples in the steady state. b) Compensates the real power difference between the load and the source during the transient state.

During steady state, real power supplied by the source is equal to the real power demandof the loads plus a small power to compensate the losses occurring inside APF. Thus, theDC-link voltage can be maintained at a constant reference value. However, during loadvariation the real power balance between the mains and the load is disturbed. This realpower difference is compensated by the charging/discharging of DC-link capacitor. If theDC-link capacitor voltage is recovered and it attains the reference voltage; real powersupplied by the source again becomes equal to that consumed by the load [24].

The DC bus capacitor can be designed by taking into account the rated filter current ($I_{c,\ rated}$)and the peak-to-peak voltage ripple inV_{dc} ($V_{dc,\ max,\ rip\ (P\text{-}P)}$) as per[30]

$$C_{dc}=\frac{\pi\times Ic,rated}{\sqrt{3}\omega\times Vdc,max,rip\ (P-P)} \tag{2.23}$$

The reference value (V_{dc}^{*})is set to (2.5 x V_s). For proper operation, the voltage reference should be greater than at leasttwice the value of the utility voltage [31].

2.7Conclusion

The beginning of this chapter is devoted for the main types of filters (i.e. active and passive filters). Then it presented different configurations and control techniques dedicated to the active filters.Finally, it focused more on the theory of thethree control techniquesfor the SAPF.

The next chapter investigates the design of these techniques using MATLAB/Simulink and comparing of their results.

CHAPTER III

Simulation of Shunt Active Power Filter

3.1 Introduction

Nowadays, simulation has become an important and powerful tool during development and to study the behavior of various systems. It allows gaining time and cost.

Out of the three explained control methods of the shunt active power filter, in this chapter we will cover with the MATLAB/Simulink simulation of two of them. The Instantaneous active and reactive power (p-q) and the Instantaneous active and reactive current component (d-q) control techniques in order to evaluate their performances.

MATLAB provides a simulation platform with its different tools, from the network build to the analysis of the obtained results using the FFT box. By the end of this chapter, simulation results and we be obtained and a comparison based on these results will be performed.

3.2 The system configuration

The overall system model of the shunt active power filter based either on the p-q theorem or the d-q theorem containing the power source, the APF and the nonlinear load is shown in **Fig3.1**:

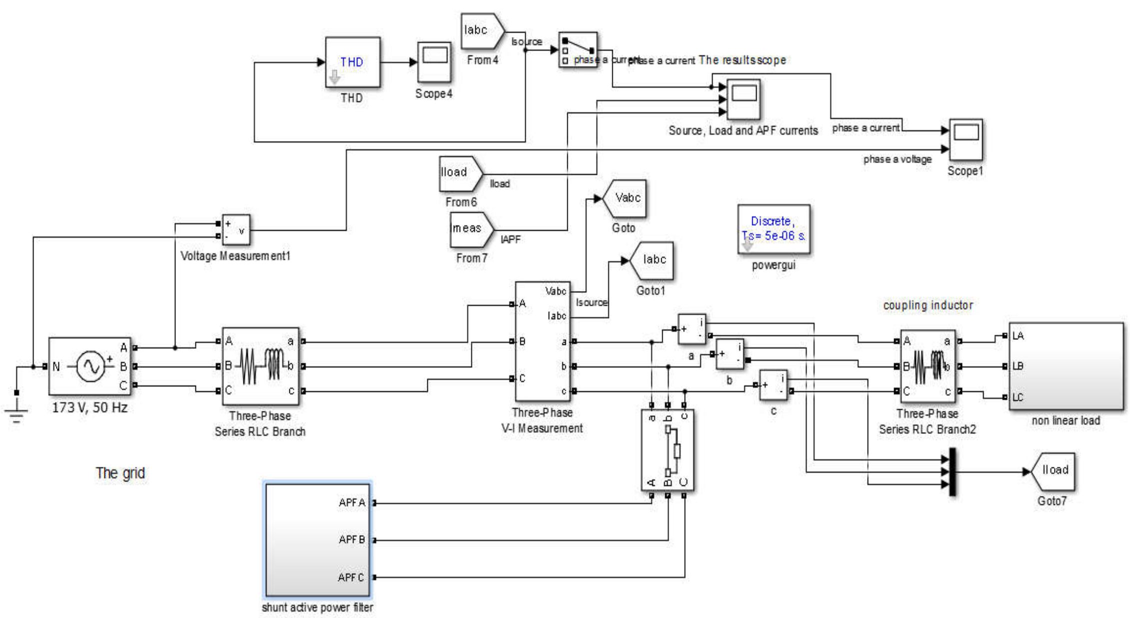


Figure 3.1: SAPF scheme

The shunt active power filter block shown in **Fig3.1** will represent the two methods; the difference between them will be discussed later on.

3.3 MATLAB modeling of SAPF

In addition to the shunt active power filter block shown in **Fig3.1**.Two other blocks are connected to the PCC, the first block is the power source and the second one represents the non linear load block.

3.3.1 The Power source

It represents the grid of our system, a three-phase voltage source with programmable time variation of amplitude, phase, frequency, and harmonics can be found in the Fundamental Blocks/Electrical Sources library.

This block is used to generate a three-phase sinusoidal voltage with time-varying parameters.

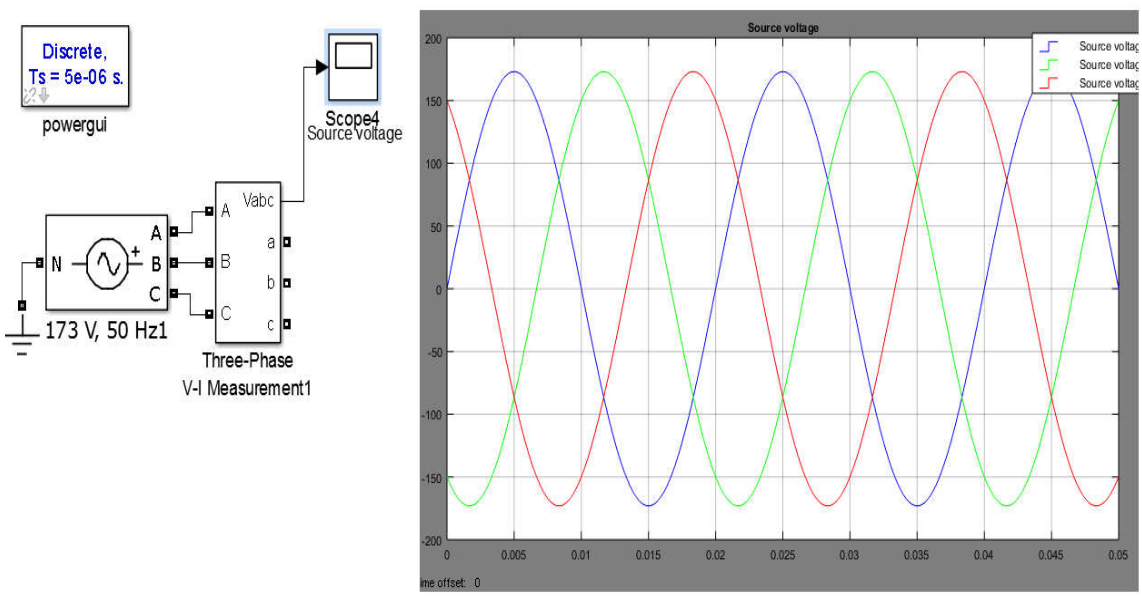


Figure 3.2: The supply model with its corresponding wave form

3.3.2 Load modeling

A non linear load has been implemented in MATLAB/Simulink using three phase full wave rectifier with an RL branch.

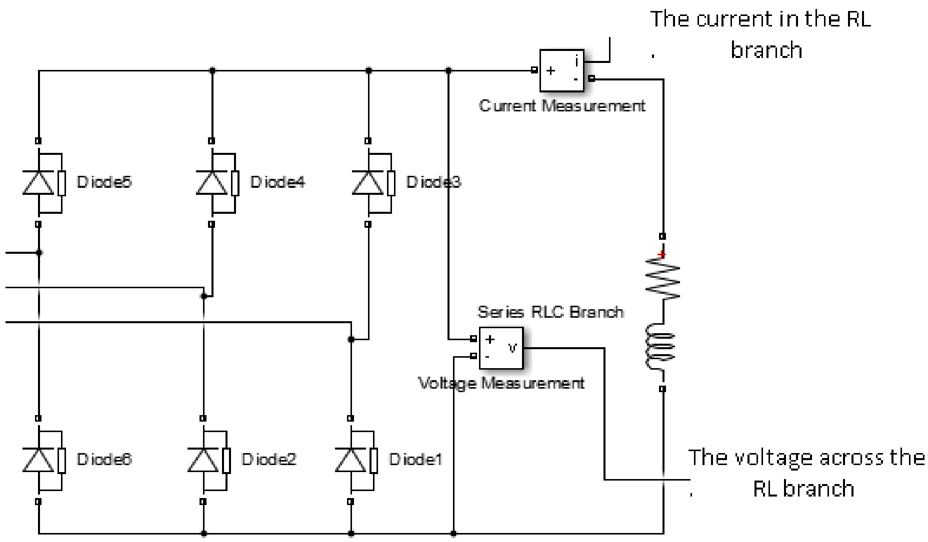


Figure 3.3: The non-linear load model

3.4: Simulation of SAPF based on p-q theorem

The inside of the Active Power Filter block shown in **Fig3.1** includes two subsystems, reference current calculation and the inverter controllers. The inverter controller subsystems are composed of:

-The DC link capacitor.
-The six IGBTs.
And the reference currents calculation subsystem is composed of:
-The instantaneous power block.
-The compensating currents block.
-The pulse generator block

The DC side capacitor was chosen to have the value of *Capf* = 2200 μF, based on similar active power filters in article [36] and slightly modified by trial and error to give adequate performance (e.g. energy storage capability and voltage ripple) for this particular system. The capacitor initial voltage is set to 450V to avoid large start up currents.

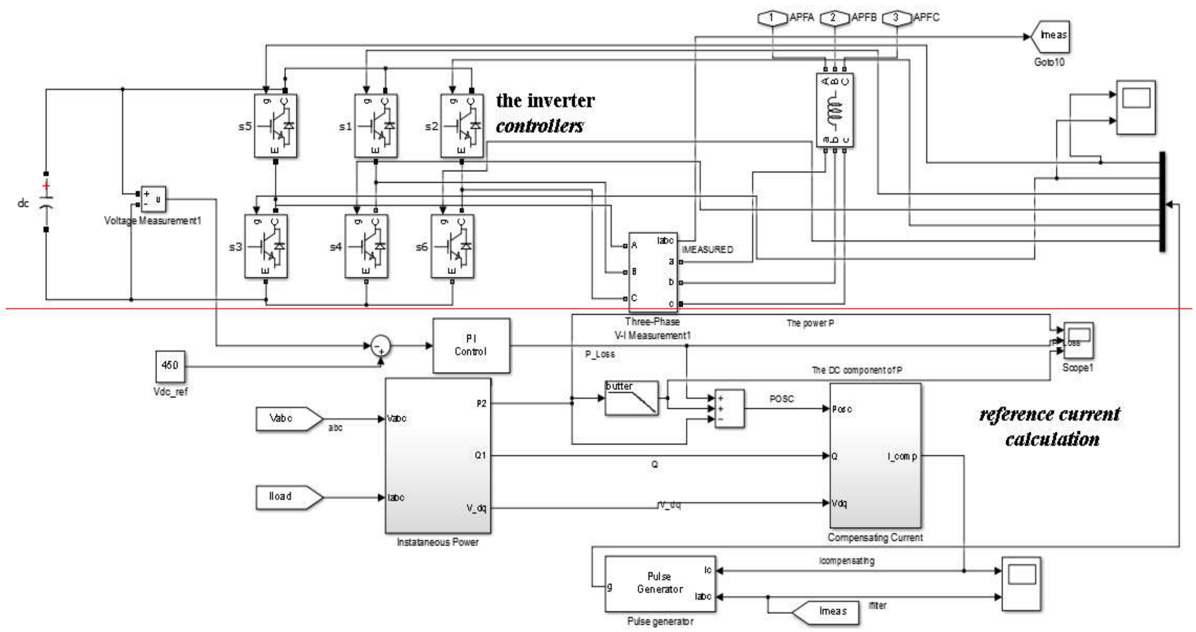


Figure 3.4: The shunt active power filter scheme for p-q theorem

The block used to obtain the instantaneous active power (p), reactive power (q) is:

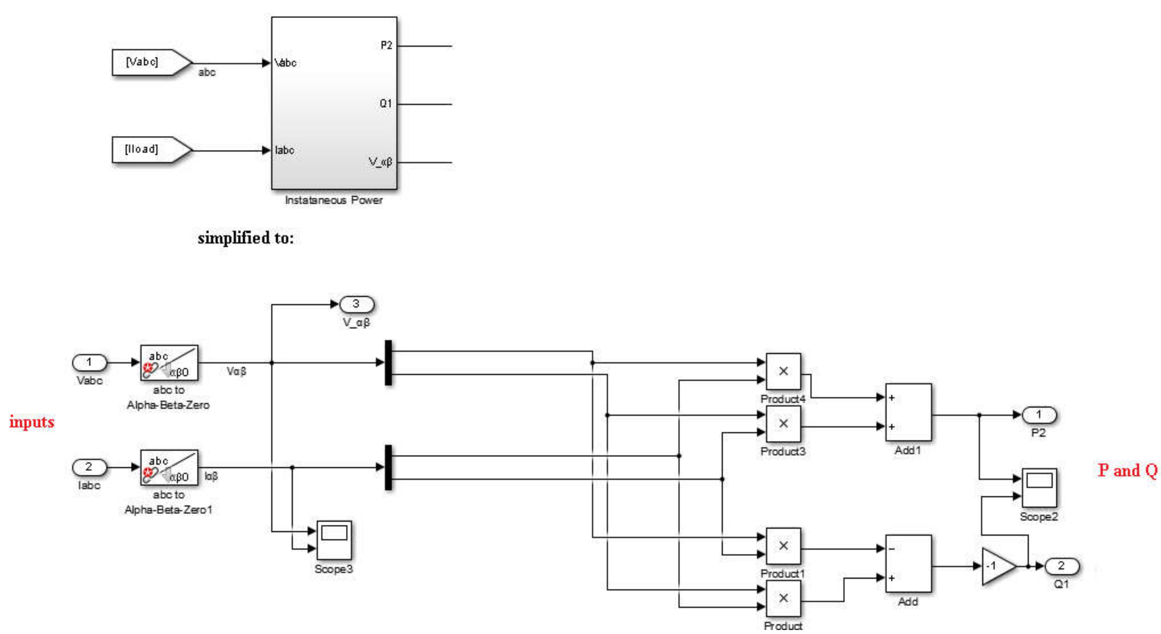


Figure 3.5: Instantaneous power calculation scheme

As discussed in the previous chapter, the inputs of this block diagram are the source voltages and the load currents. These inputs are used to calculate P and Q to construct the reference currents.

The fundamental active power is removed from the total active power P in order to get the harmonic active power to be compensated. After that, the power losses occurring inside the VSI is added to compensate for switching losses of semiconductor devices.

The resulting power Posc with the reactive power Q and the $V\alpha\beta$ are the inputs of the compensating currents calculation block shown in the next figure.

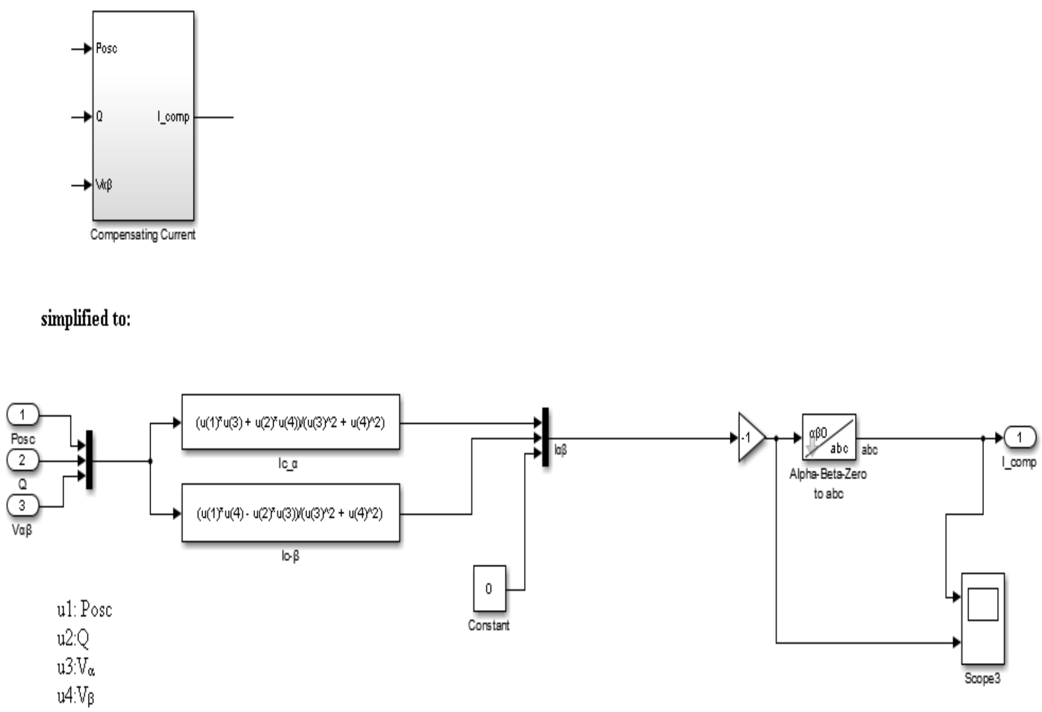


Figure 3.6: Compensating currents calculation block

Once the compensating currents are obtained, they are compared to the reference currents with a hysteresis band. In order to construct the control signals to the gates of the 6 IGBTs. The block diagram of the pulses generator is:

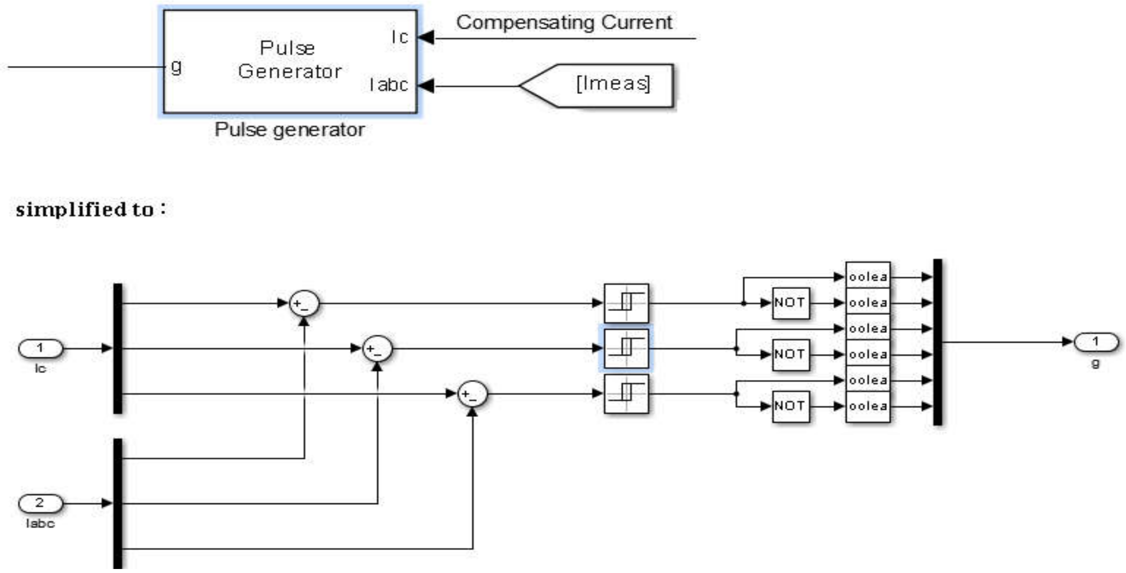


Figure 3.7: Pulse generator scheme

These control signal as shown in **Fig3.7**, allow generation the filtered currents that compensate the unwanted harmonics.

3.5: Simulation of SAPF based on d-q theorem

Similarly to the previous model of the shunt active power filter that was based on the Instantaneous active and reactive power (p-q) theorem, this part will cover the second method which is based on the Instantaneous active and reactive current component (d-q) theorem.

The overall scheme on the SAPF in this case is shown in **Fig3.8**, its internal blocks are described in details in the following sections.

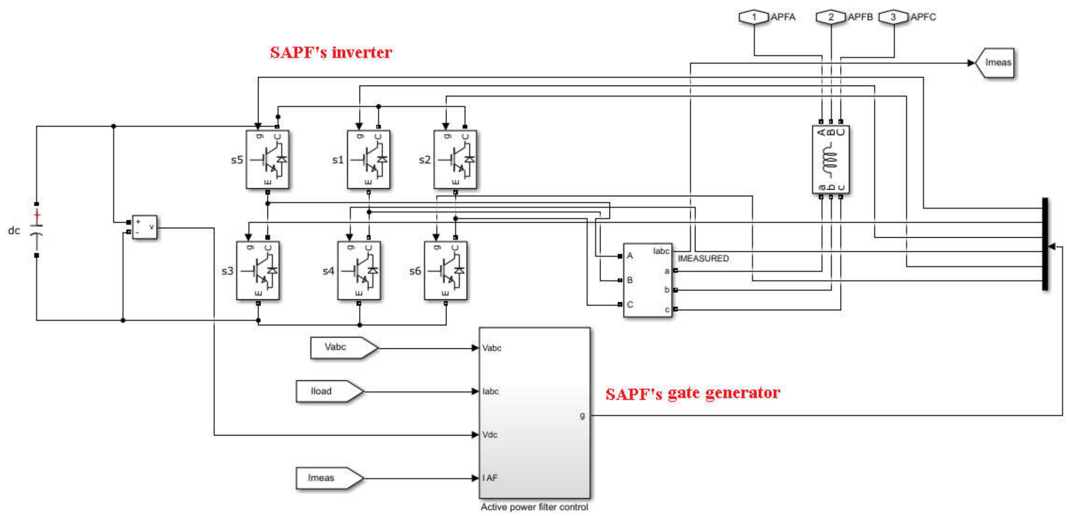


Figure 3.8: The shunt active power filter scheme based on dq theorem

Where V_{abc} represents the source voltages, I_{load} is the load currents and I_{meas} is the output filter currents.

The block 'active power filter control' is shown in **Fig3.9** to demonstrate the process followed to generate the gate signals that are used to control the inverter which will generate the desired compensation currents.

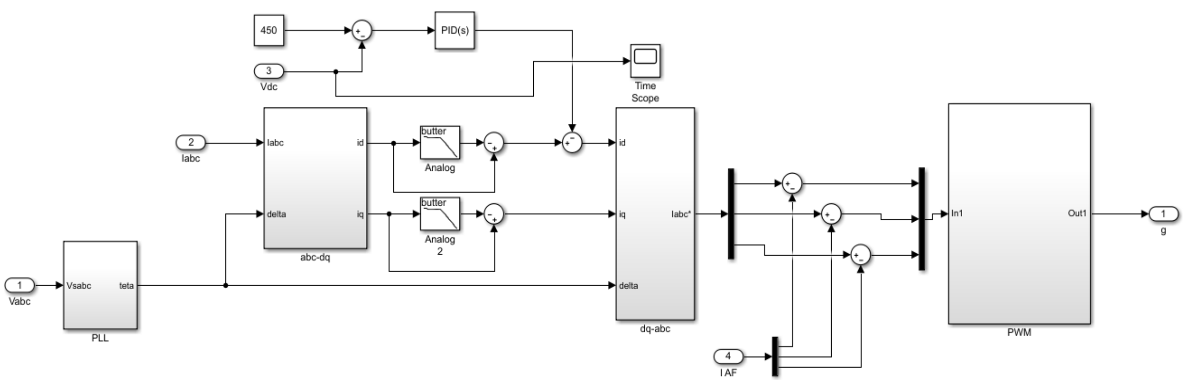


Figure 3.9: The shunt active power filter scheme based on d-q theorem

As we can see the two methods used the same inputs (V_{abc}, I_{abc}), but the control techniques are totally different as explained in chapter 2.

The block used in the following figure will describe how the d-q components of the load are obtained from its abc components as shown in equation (2.11):

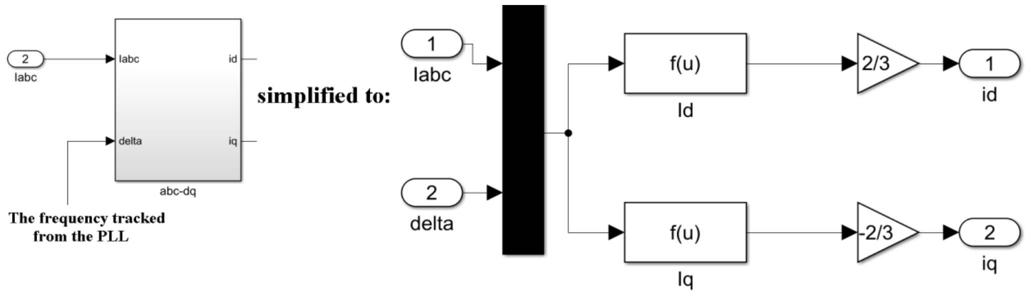


Figure 3.10: d-q current calculation scheme

After filtering the d-q currents and adding the total active current required to maintain a constant DC-link capacitor voltage and to compensate the power losses occurring inside the APF (I_{d1h}), we come back to the abc frame in order to subtract the filter current. **Fig3.11** represents the d-q to abc transformation block based on equation (2.19).

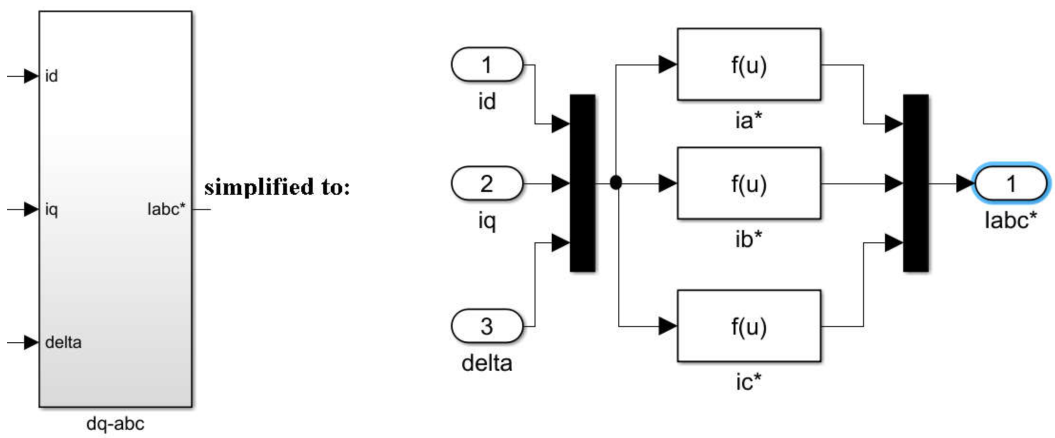


Figure3.11: d-q to abc transformation scheme

Using the obtained reference currents, one can use the pulse width modulators with an external carrier signal to generate the control signals to the gates of the 6 IGBTs. The block diagram of the pulses generator is:

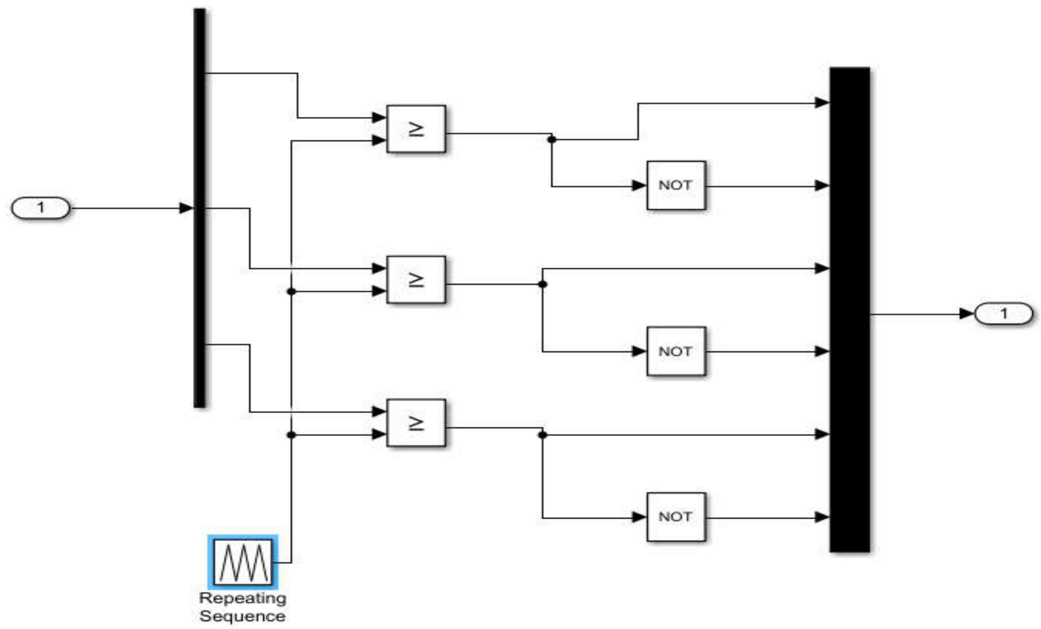


Figure 3.12: PWM generator to the 6 gates of the IGBTs

The previous method (p-q) uses the hysteresis controllers. In this method, the PWM with an external carrier is used. The main advantage of using the PWM is the control the switching frequency. However it is not as easy to implement as the hysteresis controllers.[38].

3.6 Results and discussion

After studying the SAPF theoretically, a simulation is constructed in order to compare the theoretical background with the simulating results. The system without any filtering process is shown first then the system with an operating shunt active power filter is analyzed. The obtained results are compared and discussed.

3.6.1 System parameters

The system parameters used in the simulation model for both control techniques (p-q and d-q theorems) are listed below, where $\mathrm{Vs}, \mathrm{fs}, \mathrm{Rs}, \mathrm{Ls}, \mathrm{Capf}, \mathrm{Vdc-ref}$ and Lf are grid voltage, system frequency, source resistance, source inductance, DC-link capacitance, Vdc reference and inductance of the inductors connected between the shunt APF and PCC respectively. This values of $\mathrm{Vs}, \mathrm{Capf}$ and Lf were chosen based on related-paper [36][37], and then modified slightly to give an adequate performance.

Table 3.1 : System parameters for SAPF based on p-q and d-q theorems

Vs	fs	Rs	Ls	Capf	Lf	Vdc-ref
173v $Vp_{.ph-ph}$	50hz	0.0001Ω	0.15mh	2200µf	15mh	450v

The measuring DC capacitor voltage will be subtracted from the desired DC voltage (Vref), the resulting error signal will be controlled by a PI controller to generate the active power losses (Ploss) needed to be compensated by the SAPF.

The PI controller values (Kp and Ki) are chosen based on the best THD as:

Kp = 0.91 and Ki = 42 for p-q scheme.

Kp = 0.5 and Ki = 50 for d-q scheme.

More values were obtained by trial and error using simulation as shown in **tables 3.2 and 3.3**:

Tableau 3.2: THD for different Kp and Ki with p-q scheme.

Case:	Kp	Ki	THD (%)
1	0.25	7.3	4.16
2	0.47	11.3	3.75
3	**0.91**	**42**	**1.62**
4	1	60	1.74

Tableau 3.3:THD for different Kp and Ki with d-q scheme.

Case:	Kp	Ki	THD(%)
1	0.28	25	3.37
2	**0.5**	**50**	**1.05**
3	0.95	44	2.58
4	0.78	28	1.87

3.6.2 System without any operating filter

At first the system s simulated without an operating shunt active power filter. In order to do that, the breakers between the SAPF and the point of common coupling (PCC) are opened. In this way the SAPF is not supplying any currents to the PCC.

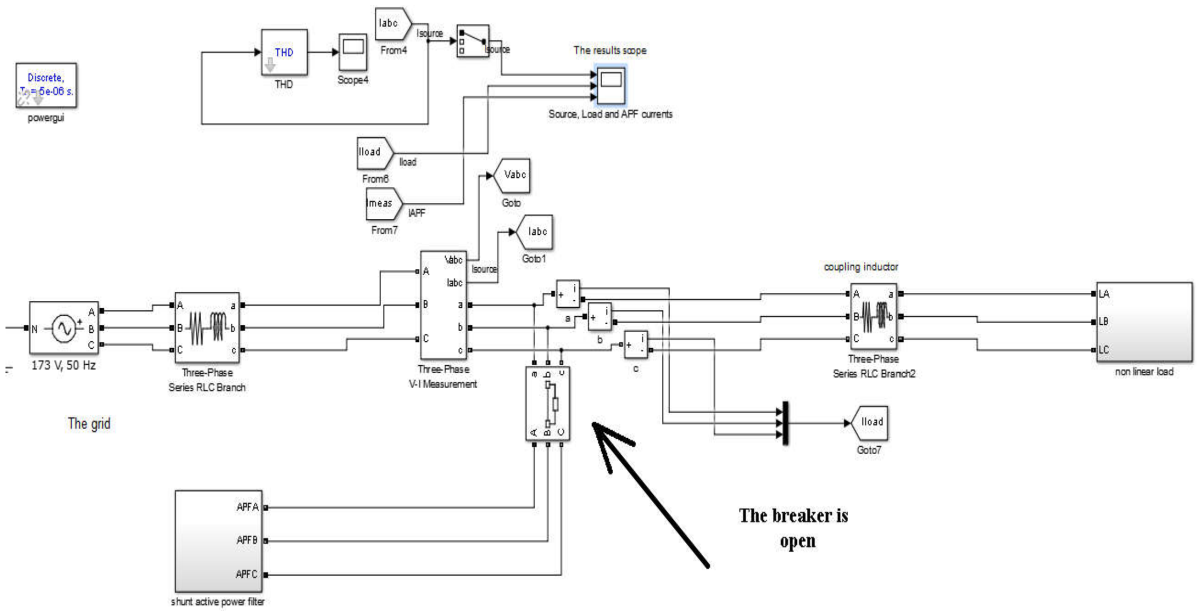


Figure 3.13: Simulation of case a: system without APF

The grid voltage shown in **Fig3.2** was sinusoidal, and since the load is not linear load we obtain the following results.

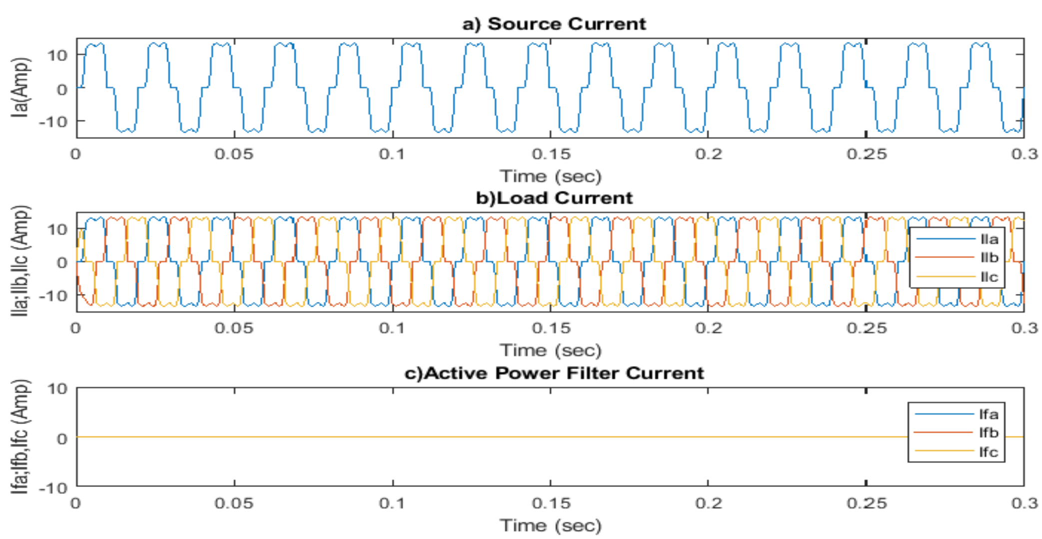


Figure 3.14: A-The source, B- load and C- APF currents with an open breaker

As can be seen, **Fig3.14A** represents one phase from the grid current. The source current shape is the same in **Fig3.14B** which is the Load current. They are in phase and have the same amplitude and period since the active power filter is not operating yet as shown in **Fig3.14C**.

We can see the total harmonic distortion of the source currents using the FFT provided by powergui block. After setting the fundamental frequency to 50 Hz, with the proper start time and number of cycles. The following results are obtained:

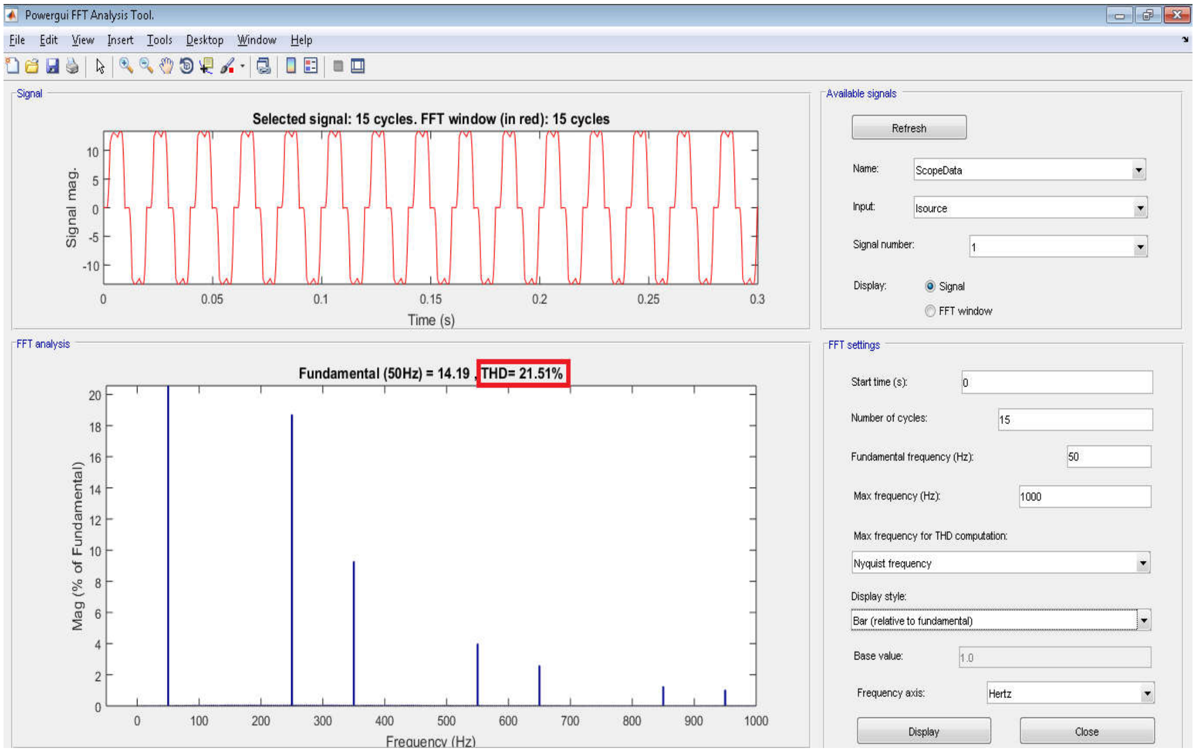


Figure 3.2: FFT analysis tool for the source currents without an APF operating

The THD is 21.51% which is high as it should be because of the non linearity of the load. Our goal is to obtain a THD of the source current less than 5% according to IEEE 519-1992.

The breakers between the SAPF and the PCC are closed now in order to see the effect of the SAPF block for both control techniques p-q and d-q.

3.6.3 System with SAPF based on p-q method

The breakers are closed at t=0.05s and the filter's currents are supplied to the point of common coupling. It is expected to get more sinusoidal source currents and that will result in lower THD.

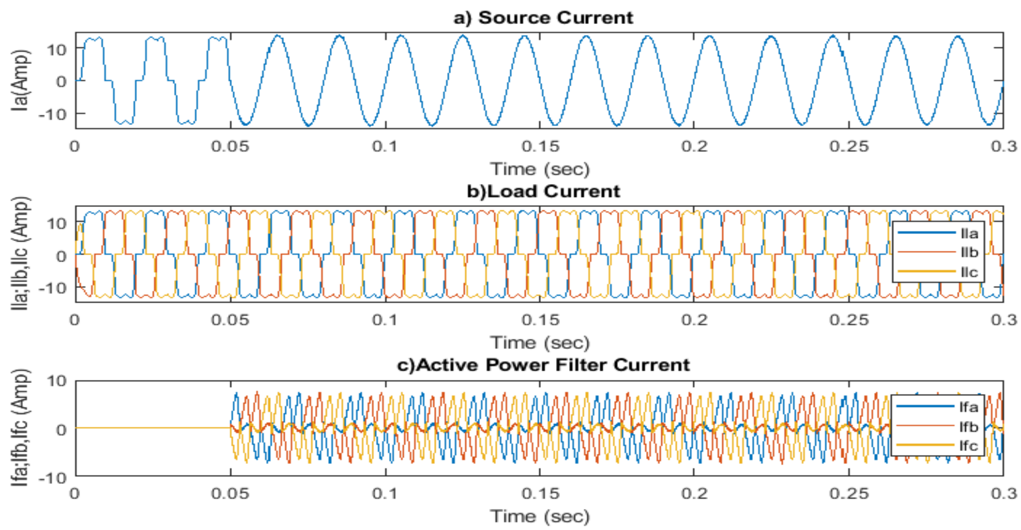


Figure 3.3: A-The source, B- load and C- APF based on p-q theorem currents with a closed breaker

Unlike the first case, in this case the active power filter is operating starting at t=0.05 seconds. It injects the inverse of the harmonic currents at the point of common coupling resulting sinusoidal source currents as expected.

The load currents are composed of the fundamental currents and the harmonic currents, and can be written as:

$$\text{Iload} = \text{Ifundamental} + \text{Iharmonics}. \tag{3.1}$$

And the source currents by applying the Kirchhoff's current low (KCL) at the PCC are the load currents minus the filter currents:

$$\text{Isource} = \text{Iload} - \text{Ifilter} = \text{Ifundamental} + \text{Iharmonics} - \text{Iharmonics} \tag{3.2}$$

That is: $\text{Isource} = \text{Ifundamental}$ (3.3)

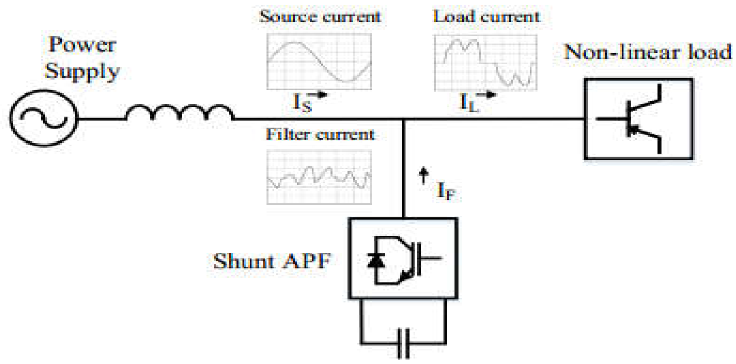


Figure 3.4: Shunt active power filter currents direction

The total harmonic distortion of the source currents using the FFT as done for case a. After setting the fundamental frequency to 50 Hz, the start time in this case is set to be the same time of closing the breaker. The following results are obtained:

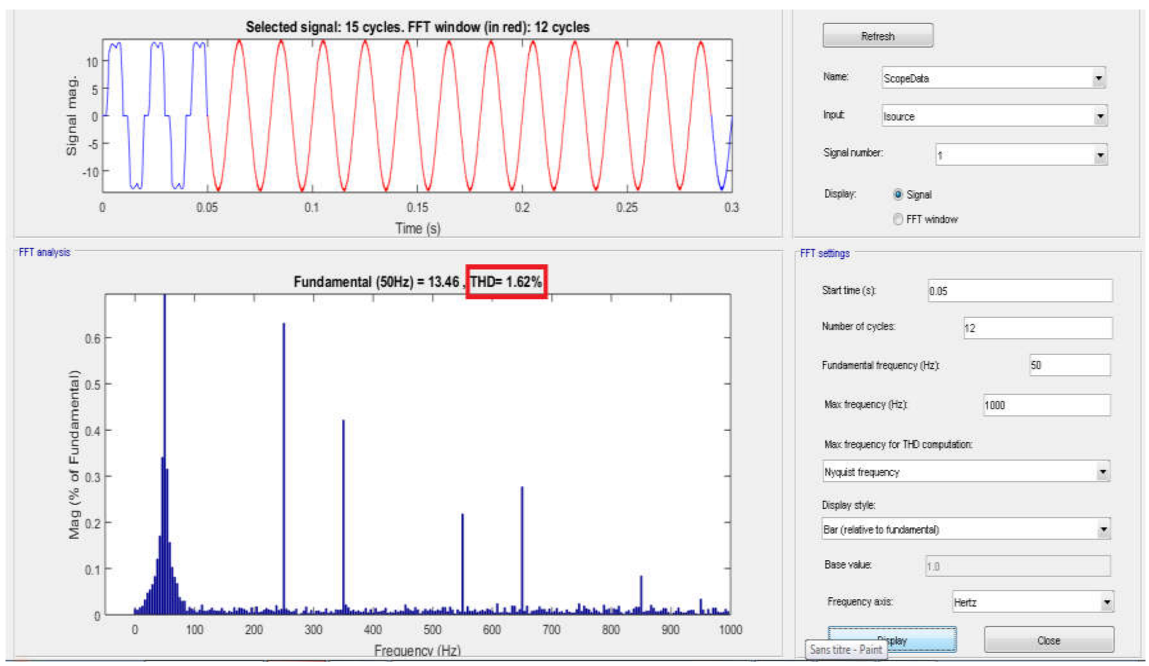


Figure 3.5: FFT analysis tool for the source currents with an operating APF based on p-q theorem

The shunt APF is turned on at t = 0.05s and the source currents become sinusoidal, balanced and in-phase with its respective phase voltage as shown in **Fig3.19** the THD of the phase A current before compensation is equal to 21.*51*% and after compensation equal to 1.62%.

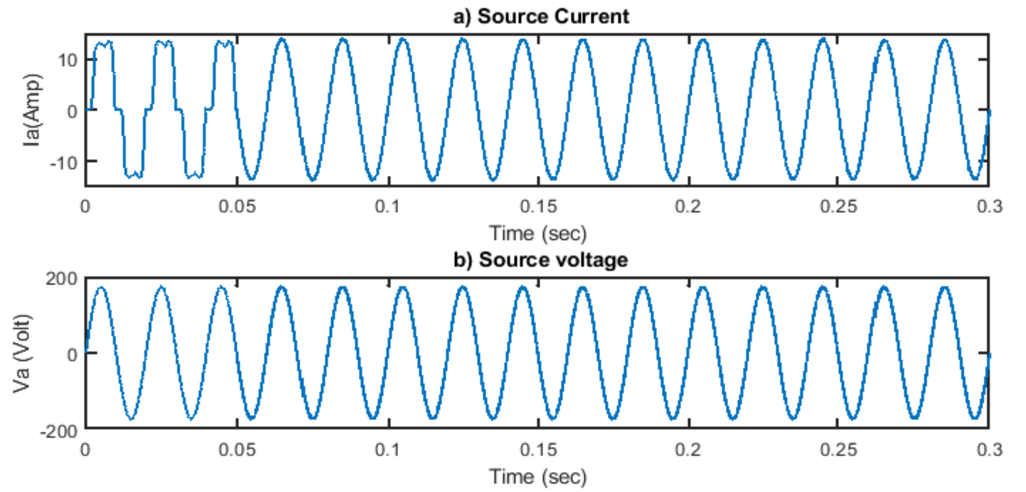


Figure 3.19: Phase A voltage and current before and after the compensation

The power of the system P shown in **Fig3.20A** is filtered with a low pass filter with a pass band of 50 Hz, the resulting fundamental P shown in **Fig3.20B** in order to get the active power needed to be compensated by the SAPF.

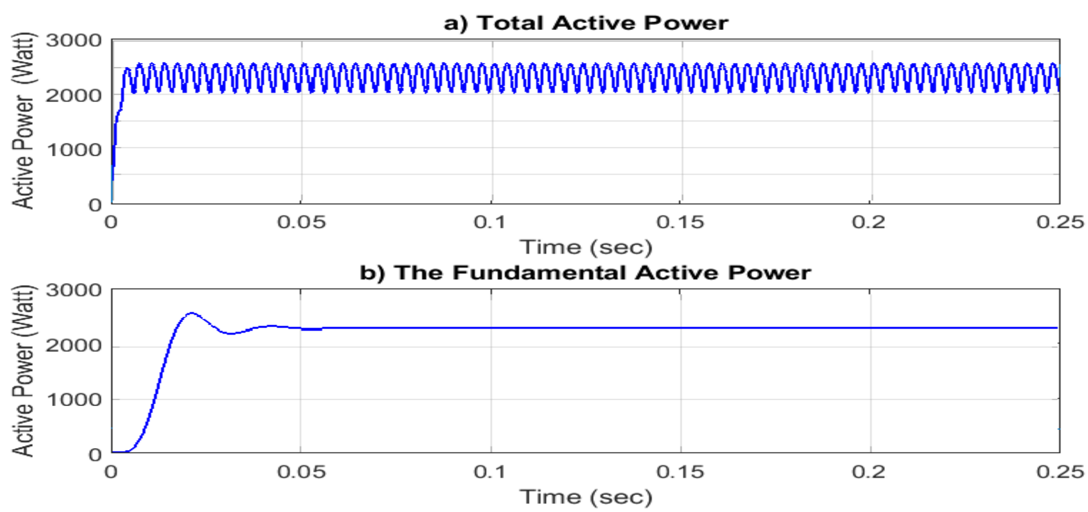


Figure 3.6: A- The total active power. B- The fundamental active power based on p-q theorem

3.6.4 System with an operating APF based on d-q method

Similarly the breaker is closed at t=0.05s and the filter's currents supplied to the point of common coupling can be seen. The resulting graphs are shown in **Fig3.21**.

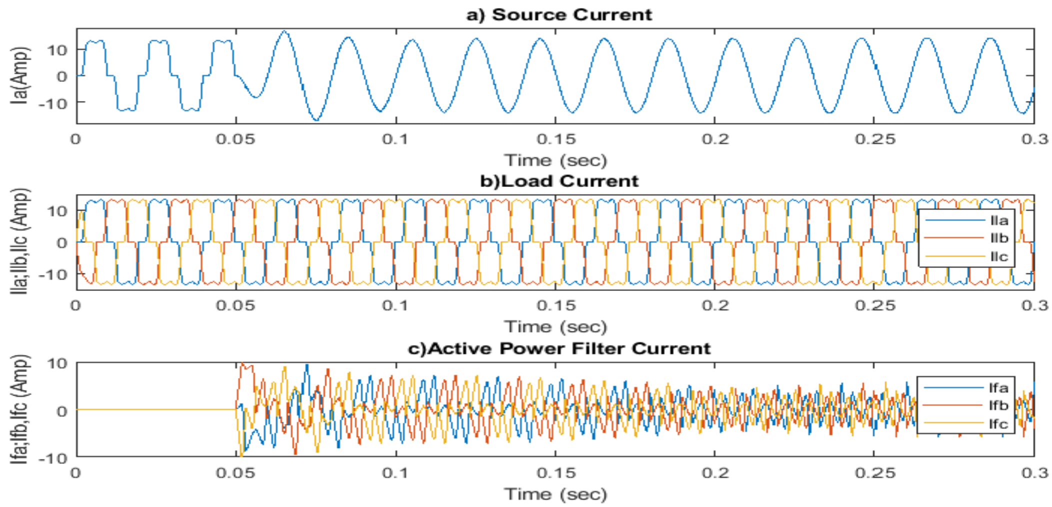


Figure 3.7:A-The source, B- load and C- APF based on d-q theorem currents with a closed breaker

As we can see the filter start supplying currents at t=0.05s, and the source currents is becoming sinusoidal. We expect the THD to be less than 21.51% which was before closing the breakers.

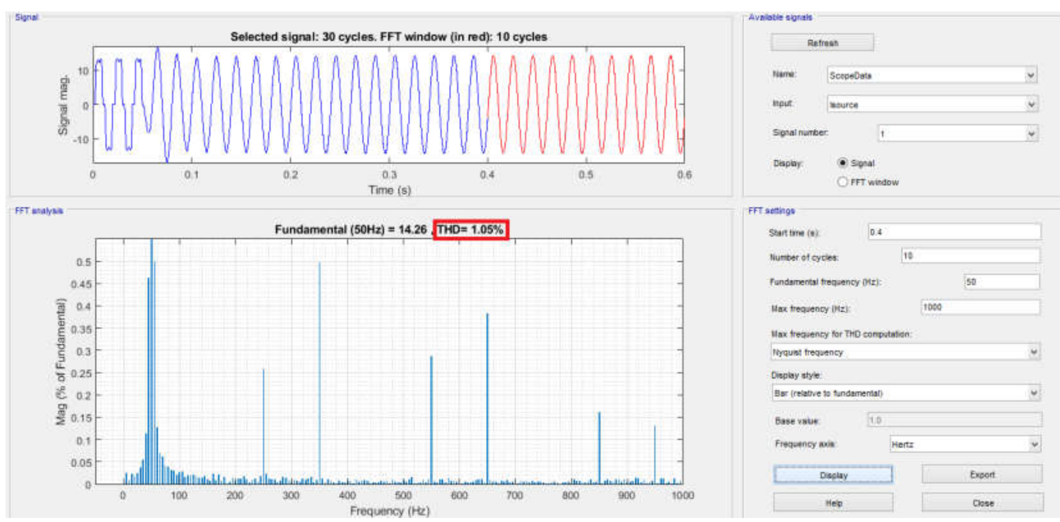


Figure 3.8: FFT analysis for the source currents with an operating APF based on d-q theorem

The THD in this case is lower than the THD before closing the breakers (THD = 1.05%). The dc link capacitor voltage graph is shown the effect of the PI controller after selecting the appropriate Kp and Ki which are 0.5 and 50 respectively.

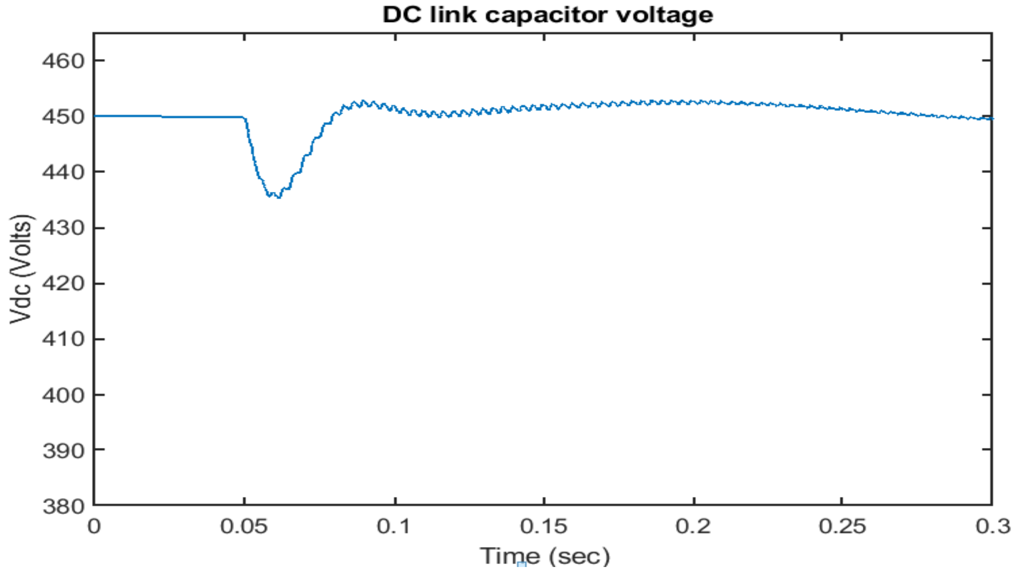


Figure 3.23: DC link capacitor voltage of the SAPF based on the d-q theorem

3.6.5 Results discussion:

The THD of the SAPF based on p-q theorem before and after compensation of phase A was 21.51% and then reduced to 1.61%. Most of the harmonic currents are compensated but high frequency components have been introduced in the source current, which can be seen in **Fig3.18**. Similarly the THD of the SAPF based on d-q theorem was reduced below even the THD of p-q theorem and found to be equal to 1.05% however there still be some high frequency components that can't be filtered out as shown in **Fig3.22**. As a result, the two methods found to be successful in lowering down the THDs in the source currents well below 5%.

3.7 Conclusion

A simulation model for a three-phase three-wire shunt APF using two control methods. The instantaneous power theory (p-q) and the Instantaneous active and reactive current component (d-q) theory have been investigated in this chapter. The control algorithm was implemented in MATLAB/Simulink studying the operation of the shunt active power filter and its effect on the THD on the source current.

The shunt APF with a hysteresis current controller was able to almost instantaneously compensate for the harmonic currents and reactive power during the tests. The source currents became sinusoidal and the THD was reduced below 5%. The theoretical results of the previous chapter were achieved.

The implementation of the shunt active power filter is the subject of the next chapter for purpose of validation.

CHAPTER IV
Implementation of Shunt Active Power Filter

4.1 Introduction

It has been noticed that the simulation results of the active power perfectly match the theoretical expectations. Following these results, the implementation of the shunt active power filter can be done.

Out of the two simulated control methods of the shunt active power filter, in this chapter the Instantaneous active and reactive power (p-q) theory is implemented, it's the simplest one, no phase locked loop is needed which will reduce the errors during the implementation.

The first part of the chapter will cover the whole system set up; it will be followed by a description to each subsystem. At the end of this chapter, experimental results will be compared to the theoretical ones for purpose of validation.

4.2 System set-up

To transfer our simulation of the shunt active power filter into an implementation, many tools are needed. **Fig4.1** describes the full system set up.

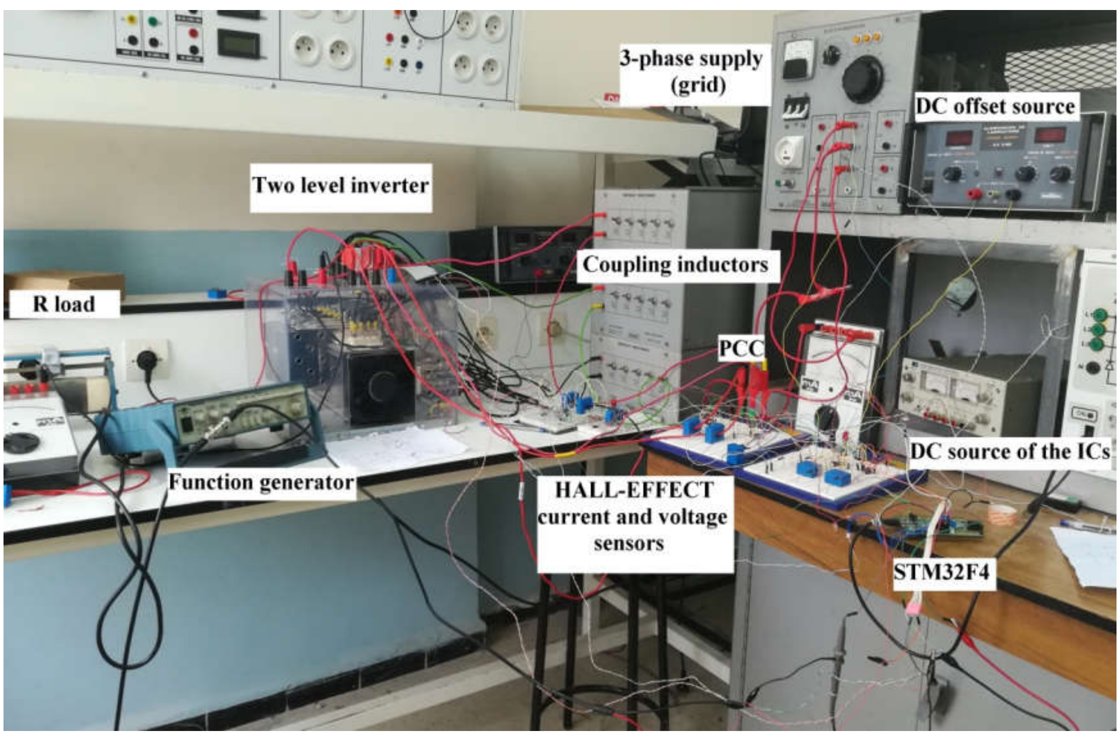


Figure 4.1: Hardware setup of the shunt active power filter

The system is composed of many components, they can be classified into different types: power sources, the sensors, the microcontroller and the two levels inverter. In addition to that we used a coupling inductor and a resistive load is connected to the 3 phase full wave rectifier.

4.3 Tools used for the implementation

The tools used for implementing the shunt active power filter are:

4.3.1 The STM32f4 microcontroller:

STM32 is a family of 32-bit microcontroller integrated circuits by STMicroelectronics. The STM32 chips are grouped into related series that are based around the same 32-bit ARM processor core, such as the Cortex-M7F, Cortex-M4F, Cortex-M3, Cortex-M0+, or Cortex-M0. Internally, each microcontroller consists of the processor core, static RAM, flash memory, debugging interface, and various peripherals [39].

STM32f4 is the microcontroller used in this implementation in order to process our measured signals, and to generate the gates control signal. It has up to 80 fast I/Os with up to 140 MHz [40]. STM is programmable by C, C++, pascal and java. In our case, instead of writing hundreds of coding lines, simulink provides and automatically generated C and HDL code. Once the program is simulated, it can be uploaded to the STM32f4 [41].

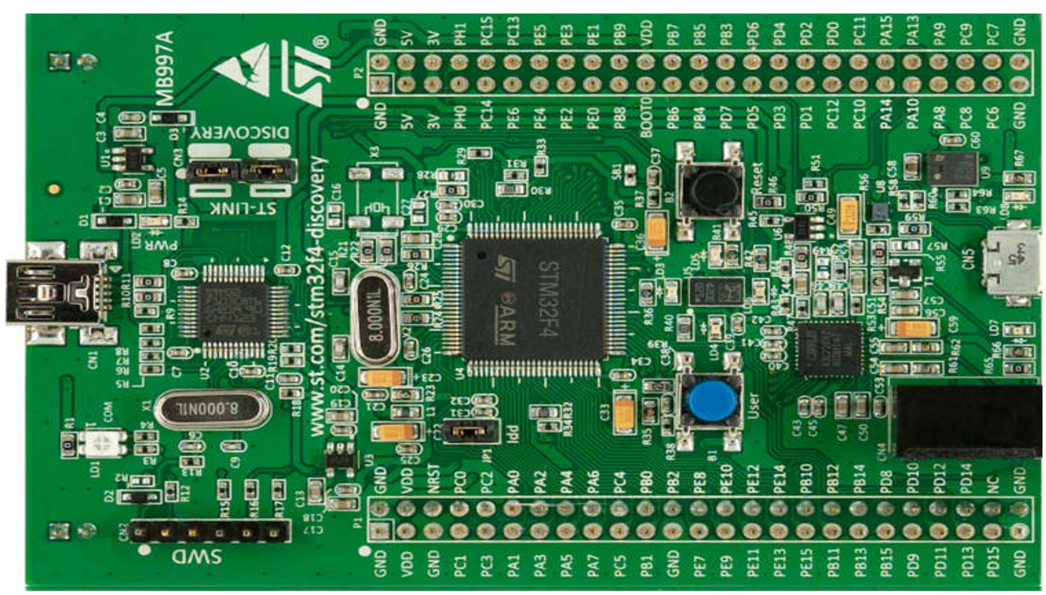


Figure 4.2: STM32f4 microcontroller

4.3.2 Interfacing system

As mentioned earlier, this simulation is based on stm32f4 microcontroller programmed with MATLAB/Simulink. The library of the microcontroller is shown in **Fig4.3**

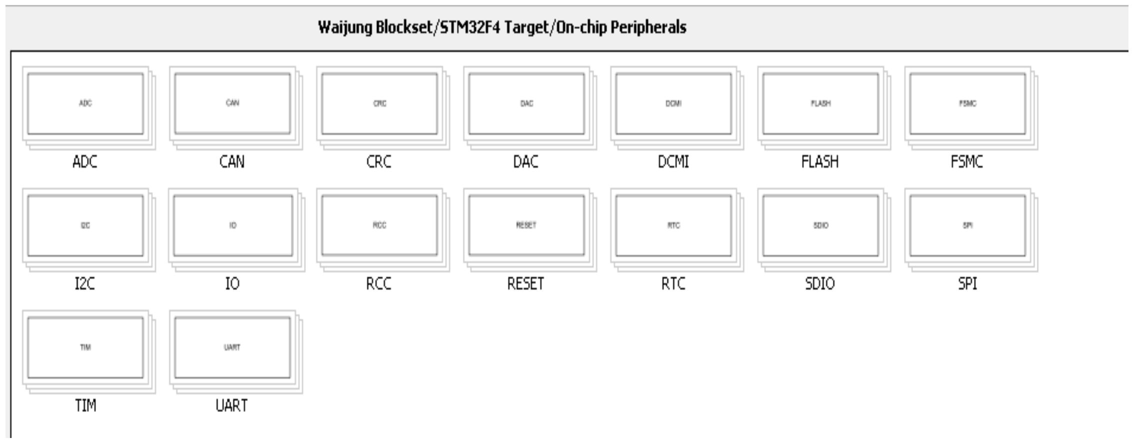


Figure 4.3: STM32f4 library on simulink matlab

A new simulation is constructed, in which there are only the active filter's components. It has inputs and outputs. The inputs are the measured currents and voltages and the outputs are the six control signals to the gates of the IGBTs, as shown in **Fig4.4:**

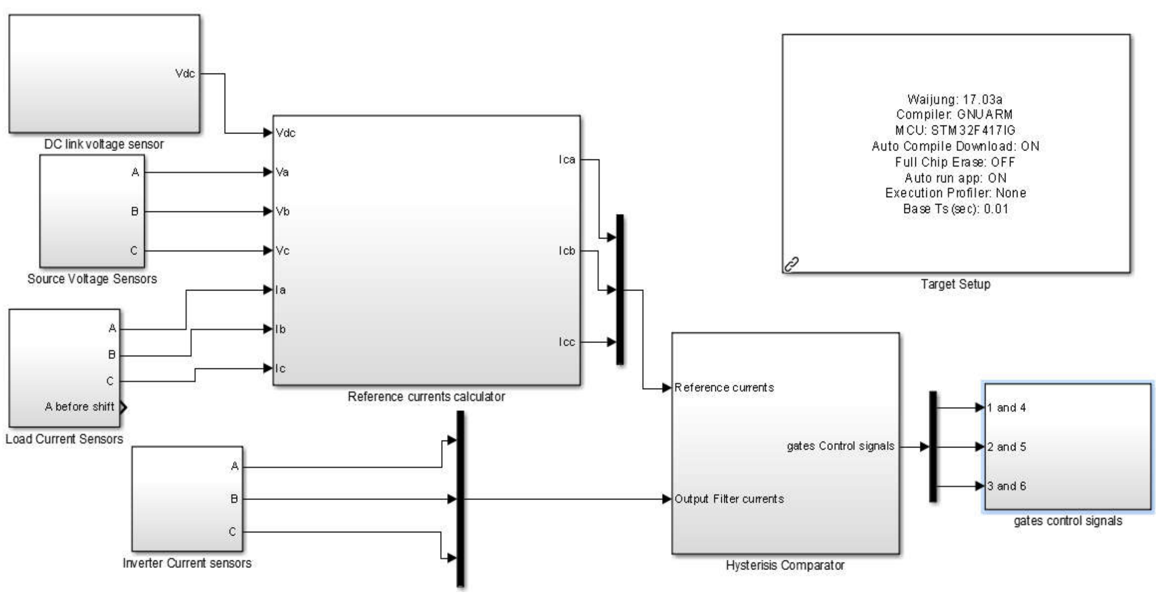


Figure 4.4: Active power filter.

4.3.2 Three phases supply

It represents the grid, and generates 3phase symmetrical voltages of adjustable amplitude with fixed frequency of 50 Hz. It is shown in **Fig4.5**.

4.3.3 Power modules

The DC sources are used to:

-Supply the integrated circuits (op-amps) and the Hall Effect sensors with +/-12volts.

-Generate the DC offset needed to be used to shift the reading value of the AC sensors before entering them to the ADC of the STM32f4 board.

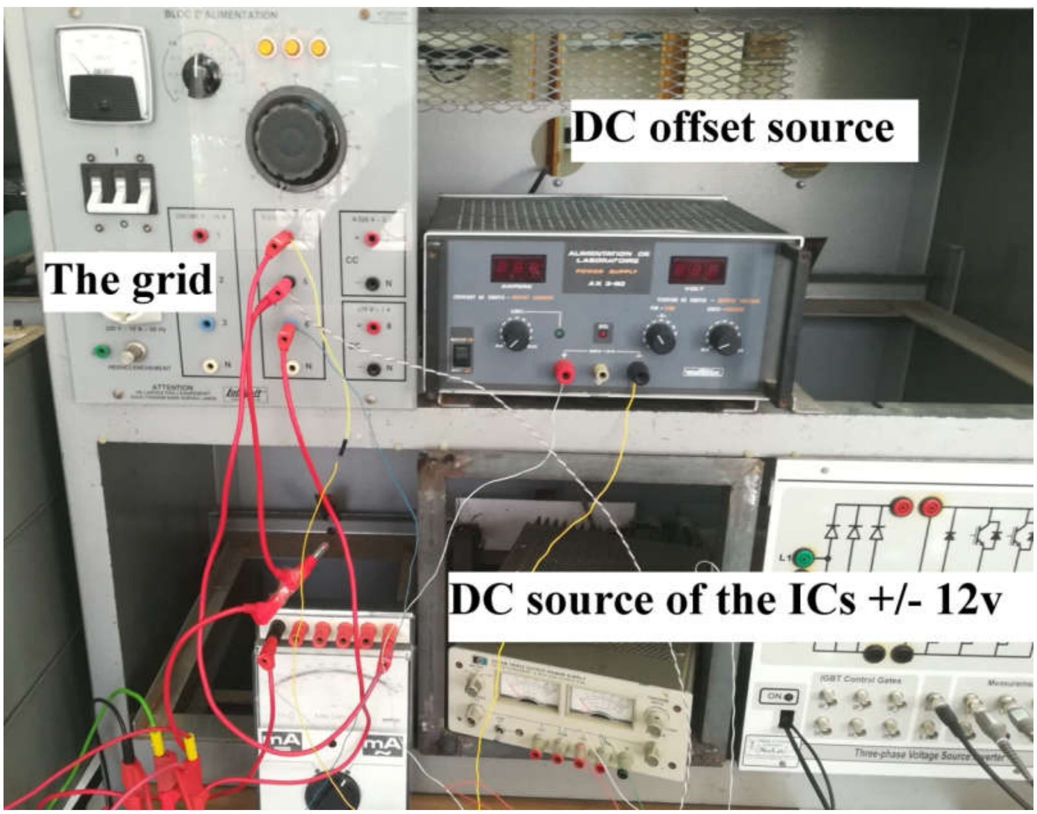


Figure 4.5: The different AC and DC sources used

4.3.4 The Hall Effect current and voltage sensors

8 sensors are used, 5 for sensing the currents and 3 for the voltages. As noticed from the simulation, one needs to sense the 3 phase load currents, 3 phase source voltages, the 3 phase APF currents. In addition to the DC link capacitor voltage. For the load currents, since the system is balanced; only two phase currents are sensed. The third one is constructed as $Ic = -(Ia + Ib)$. This can be done for the source voltages as well i.e. $Vc = -(Va + Vb)$

The ADC pins of the STM32f4 can read analog signals and convert them into digital signals. The STM can only read positive analog signals and we have sinusoidal reading signals that contain negative values. To solve this problem, one needs to introduce a DC shift taking into account that the reading value must not exceed 3.3 Volts which is the nominal value of the input of the ADC theoretically. But experimentally we have faced that the reading values of the input ADC of the STM can't read more than 2.8 V.

The ADC read an analog value from 0 to 2.8 and converts it to a digital value from 0 to 4096. To recover the real analog measured values we need to multiply the reading signal by:

$$Gain = the\ digital\ value\ \frac{2.8}{4096} \tag{4.1}$$

HALL EFFECT current sensors LA25 and the Hall Effect voltage sensors LV55 are employed and can be found in Appendix A and Appendix B.

For the AC voltage sensors, resistors of Rm = 58Ω and Rv = 18kΩ are used. In order to get a reading of 100Vpeak/0.81 Vpeak. Given that:

$$K_v = \frac{2.8}{\frac{2500}{1000}\times 4095}\frac{R_v}{R_m} \tag{4.2}$$

Where Kvis the voltage gain, Rv and Rm are represented in **Fig.4.6**

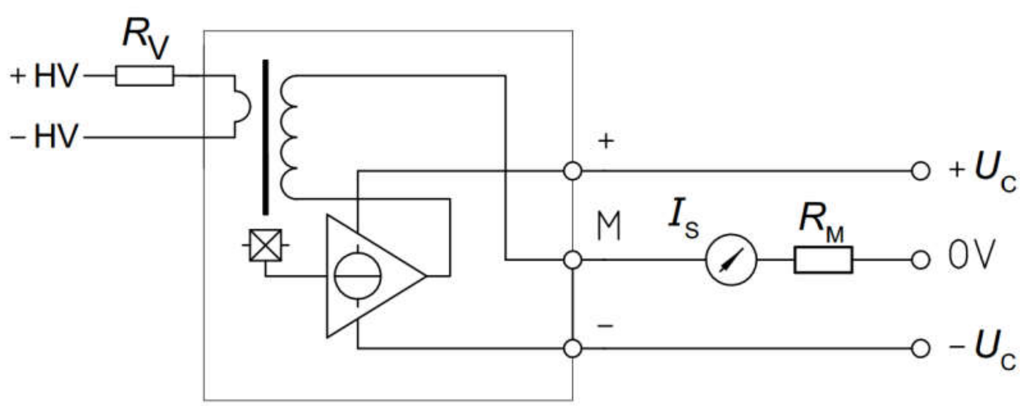


Figure 4.6: The Hall Effect Voltage sensor scheme

For the DC voltage sensors, resistors of Rm = 75Ω and Rv = 18kΩ are used. In order to get a reading of 100Vpeak/1 Vpeak.

For the current sensors a resistor with resistance of $Rm = 94\Omega$. The Current gain is given by: $K_i = \frac{1000}{R_m}\frac{2.8}{4095}$ (4.3)

Gives a reading of $10.63A/1v$ with the represented Rm in **Fig.4.7.**

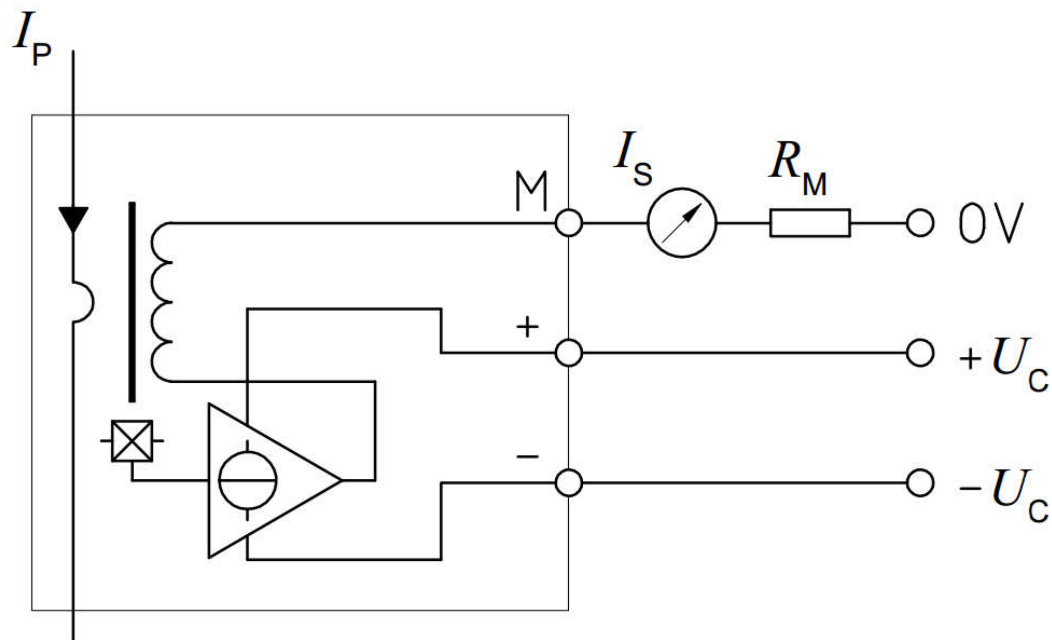


Figure 4.7: The Hall Effect current sensor scheme

Once the reading value is obtained from the Hall Effect sensor, a DC shift is added to it such that:

- $1.15V$ for voltage sensors.
- $0.224V$ for current sensors.

Remember that the reading values must be shifted back by the same DC offset multiplied by $\frac{4096}{2.8}$ in the program of the STM.

The hardware shift circuit is based on the summing and the inverting op amps as shown in **Fig.4.8.**

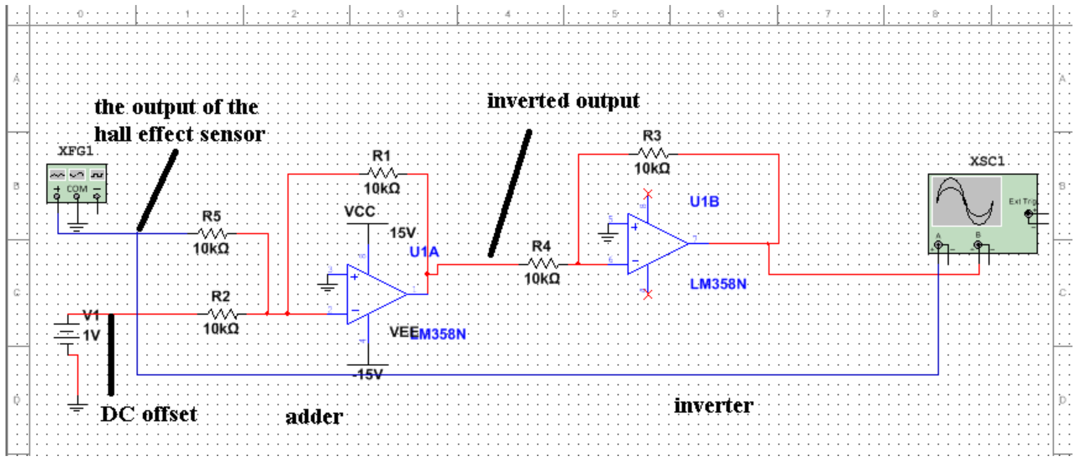


Figure 4.8:A summer and inverter circuit diagram for the sensing circuits

One can notice a minus sign at the output of the first op amp, another inverting op amp is needed to eliminate the minus sign.

The circuit of the current sensors shift is simulated using multisim14.0, the op amps used are LM358 and the gain was always 1 to simplify the calculation when the signals from the Hall Effect sensors are recovered.

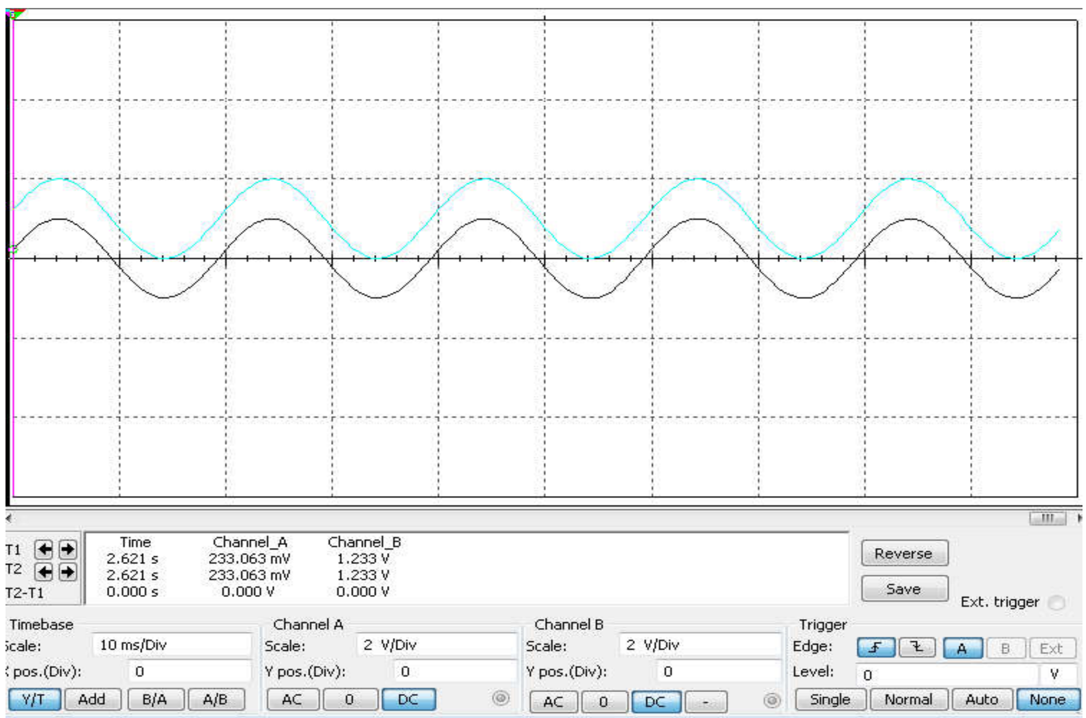


Figure 4.9: the output of the Hall Effect sensor before and after the shift

In **Fig.4.9** the obtained signal after the shift is shown in blue color, while the black one is the output of the Hall Effect sensor before the shift.

Now the measured signals can be entered to the ADC of the STM32f4 board and complete the process in order to generate the control signals of the inverter.

4.3.5 Three phases inverter

Semikron module which is a Multi-function IGBT converter, it contains a 4 legs inverter, a DC capacitor and a three phase full wave rectifier as shown in **Fig.4.10**. Its datasheet can be found in Appendix C.

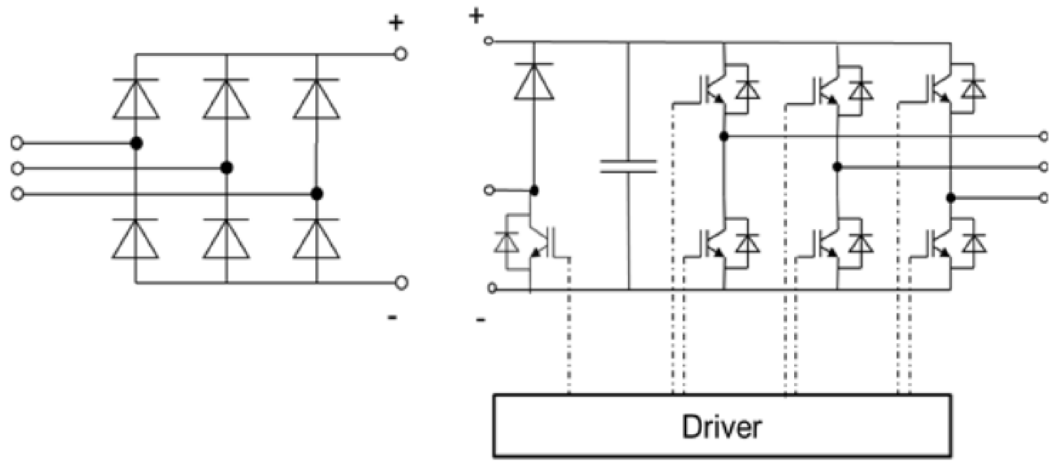


Figure 4.10: The full wave rectifier and four legs inverter

4.3.6 Coupling inductors

Coupling inductors located between the SAPF and the PCC, are used in order to filter the current ripples out from the SAPF. A proper selection of the coupling inductor is very important for the APF, since it directly affects the output filtering and harmonic tracking capability [42]. The simulation value was about 15mH, when it comes to hardware implementation, very limited choices in lab are available. At first, an inductor of 0.4mH has been used but it caused a high short circuit current according to:

$$V_{source} = L\frac{di}{dt} \tag{4.4}$$

With dt is the sampling time Ts and di is the variation in current can be written as Δi, which gives:

$$V_{source} = L\frac{\Delta i}{Ts} \tag{4.5}$$

The variation of the current can be computed as follows:

$$\Delta i = \frac{V_{source} \times Ts}{L} \qquad (4.6)$$

For $L = 0.4\text{mH}$ and $Ts = 2 \times 10^{-4} s$, Δi is equal to: 35.36 Amp which is very high and the circuit can't work properly. To solve this problem, one needs to raise the inductance L, but as mentioned previously, proper values are not available. The second inductor used in this simulation has a much higher inductance than the first one that was about 121mH.

Theoretically through simulation this filter will supply some currents, but it is not ideal. Δi in this case is less than 0.2 Amp.

4.3.7 The interfacing board

To minimize the outputs of the STM, three of the six gates signals can be eliminated. They are simply their complements. This task is done by this interfacing board located between the STM32F4 and the Semikron inverter. It also maps the gates signals from 2.8V which is the maximum voltage of the STM up to 15V such that they can control the 6 gates of the inverter.

4.3.8 The load

As simulated before, the load is composed of a full wave rectifier with resistor of 70Ω . The three phase full wave rectifier of the Semikron inverter has been used.

4.4 Results and discussion

The system parameters used for the implementation are listed in table 4.1:

Table 4.1: The system parameters used for the implementation

Vs	fs	Capf	Lf	Vdc-ref
100v $Vrms._{ph-ph}$	50hz	2200µf	121mh	150v

The program in MATLAB/Simulink is built in order to be uploaded to the STMf4 board. Source voltages, the load currents and the DC link capacitor voltage are sensed. The source voltages sensors block is shown in **Fig.4.11.**

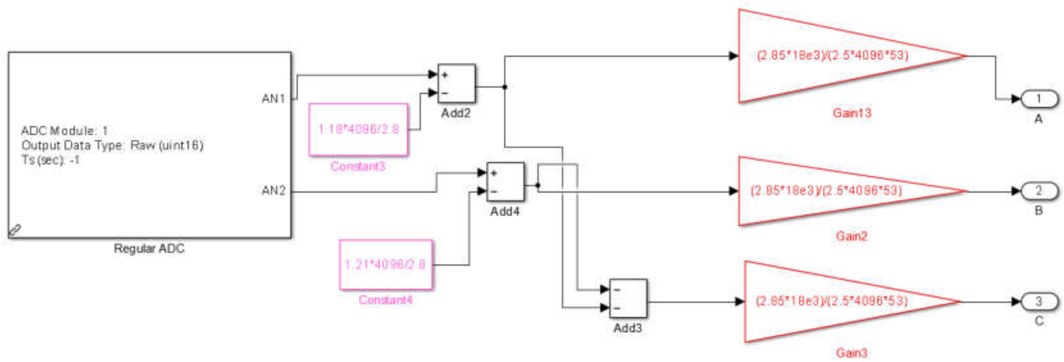


Figure 4.11: The source voltages sensors block.

The source voltage tracked by the Hall Effect sensors is shown in **Fig.4.12.**

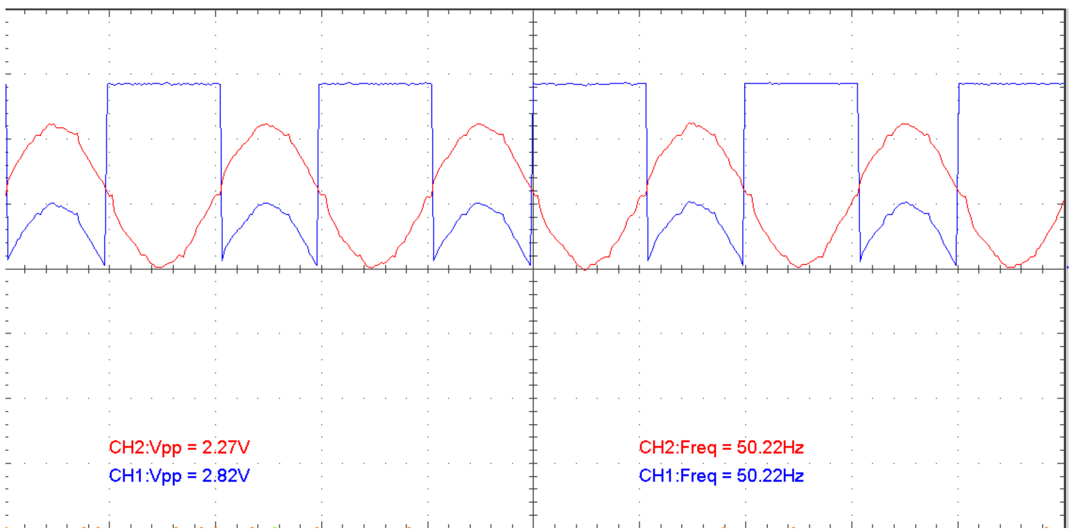


Figure 4.12: The source voltage of phase a tracked by the Hall Effect sensor

Channel 1 shown in blue color represents the source voltage before the DC shift and Channel 2 shown in red color represents the source voltage of phase a after the up shift.

All the sensor blocks are similar to this one; for example the load current of phase a is shown in figure 4.13 before and after the DC shift. An example of the circuit explained earlier is demonstrated in **Fig.4.13**:

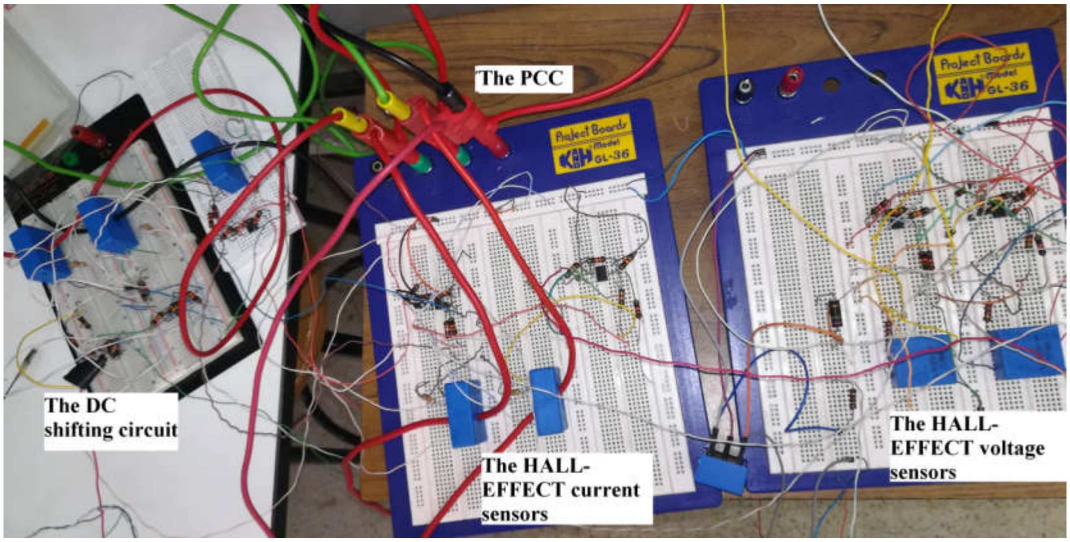


Figure 4.13: The HALL-EFFECT sensors with their shifting circuit

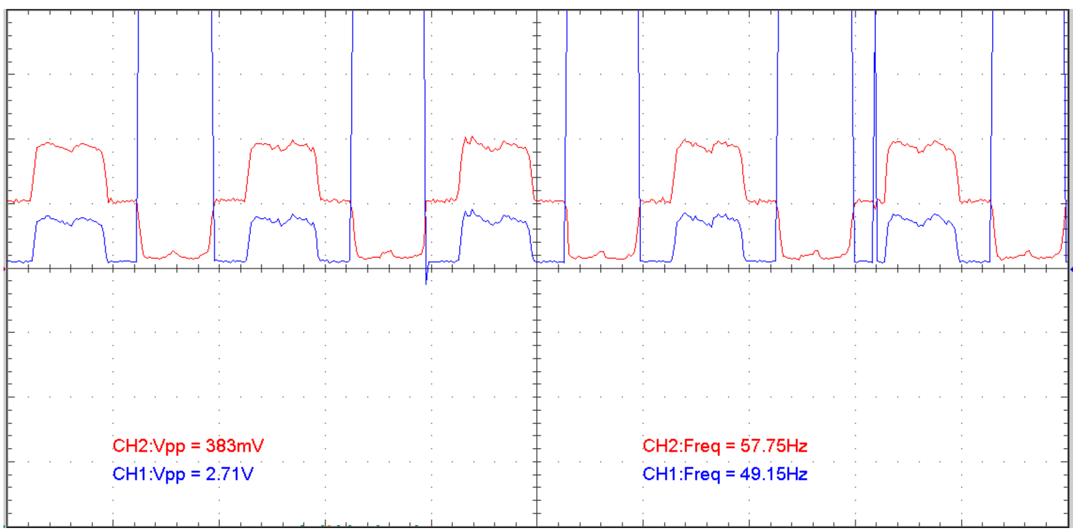


Figure 4.14: The load current of phase a tracked by the Hall Effect sensor

The next block is the reference currents calculator block, shown in **Fig.4.15**. That is identical to the simulation one. MATLAB functions are used instead of Simulink blocks so that the STM32f4 can function properly.

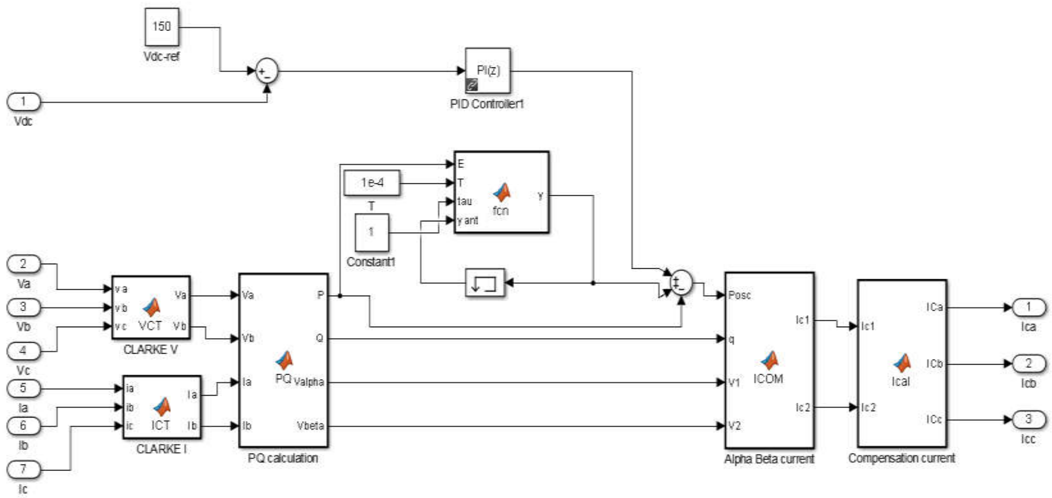


Figure 4.15: the reference currents calculator block

As done earlier, after calculating the compensation currents. These currents are compared to the filter currents with a hysteresis band, and the output is driven out to the 6 gates of the IGBTs of the inverter through the digital outputs of the STM32f4 as shown in **Fig.4.16**.

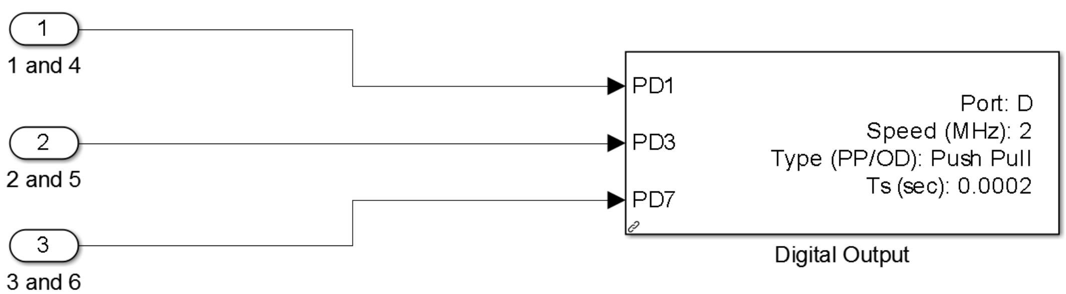


Figure 4.16: The IGBTs gates control signals

The system is tested without filter. The resulting source currents shown in **Fig.4.17** are non sinusoidal and they are exactly the same as the load currents because the SAPF is not operating yet.

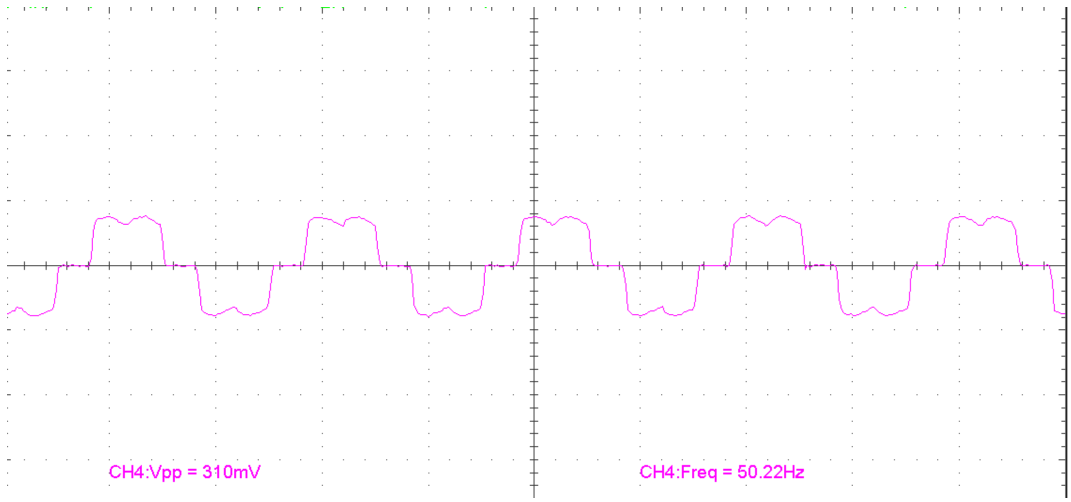


Figure 4.17: The source currents without an operating SAPF

To test the filter, the interfacing board is switched on and all the control signals are applied to the gates of the 6 IGBTs. The following results are obtained. The source current of phase a is shown in **Fig.4.18**:

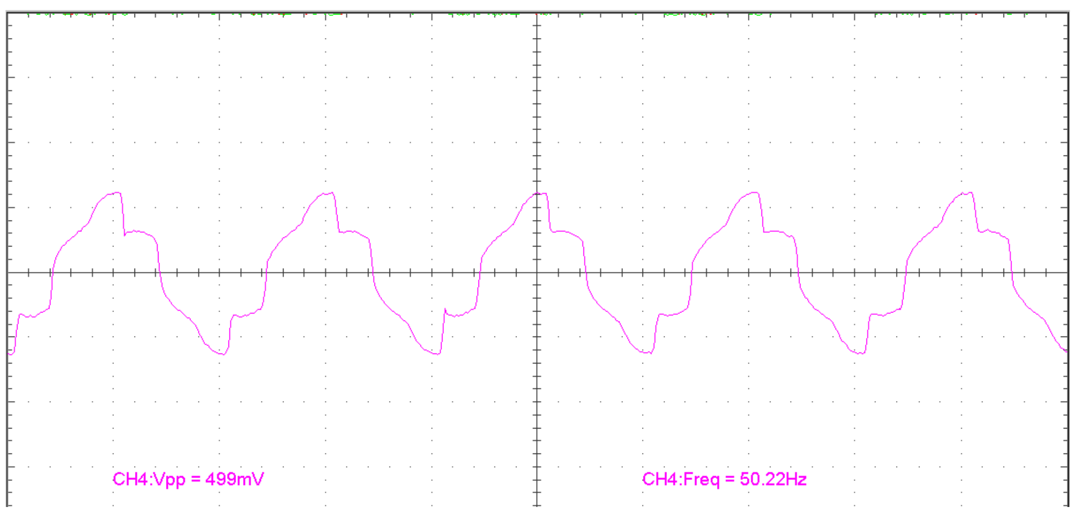


Figure 4.18: The source current of phase a with an operating SAPF

This current shape is not 100% sinusoidal but we can say that it is better than the upper one before we start the filter. In order to know the approximately value of the THD of this current, a MATLAB/Simulink simulation based on the values of the implementation is built. One found that the THD is about 17% with the inductance of 121mH. **Fig.4.19** shows the THD of the source current in this case.

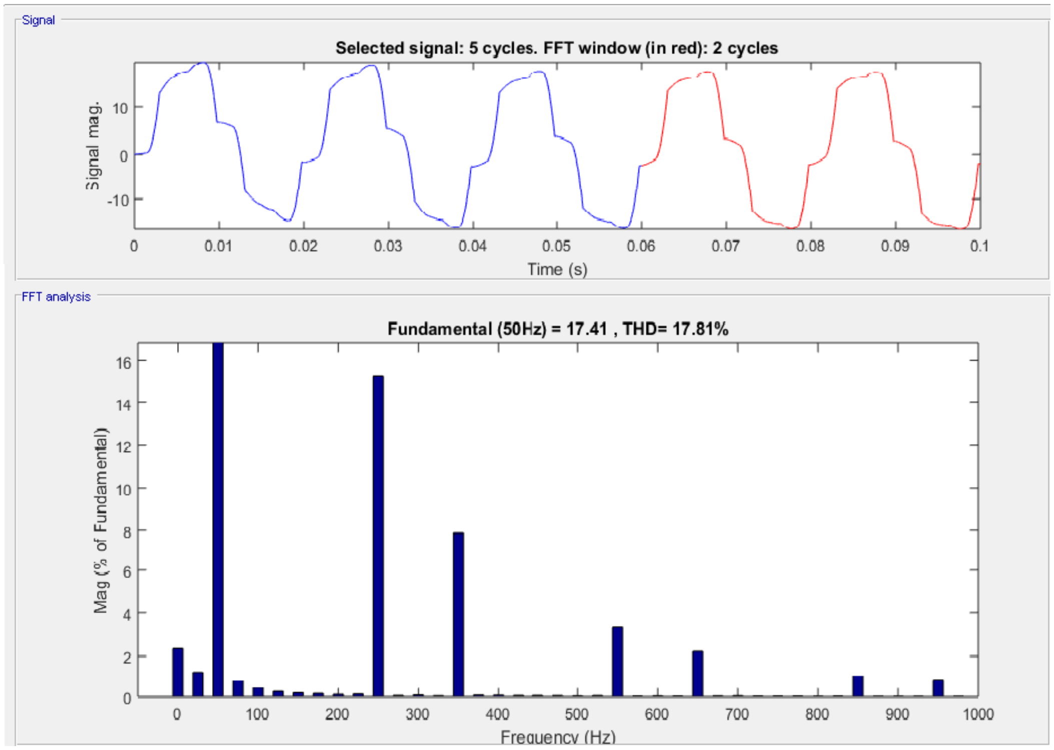


Figure 4.19: The THD of the source current of the hardware implementation

In order to see the filter's currents by using the Hall Effect sensors. A pure sinusoidal currents with small amplitude is obtained, the filter current of phase a is shown in **Fig.4.20**. By checking them in the simulation, the same results are found.

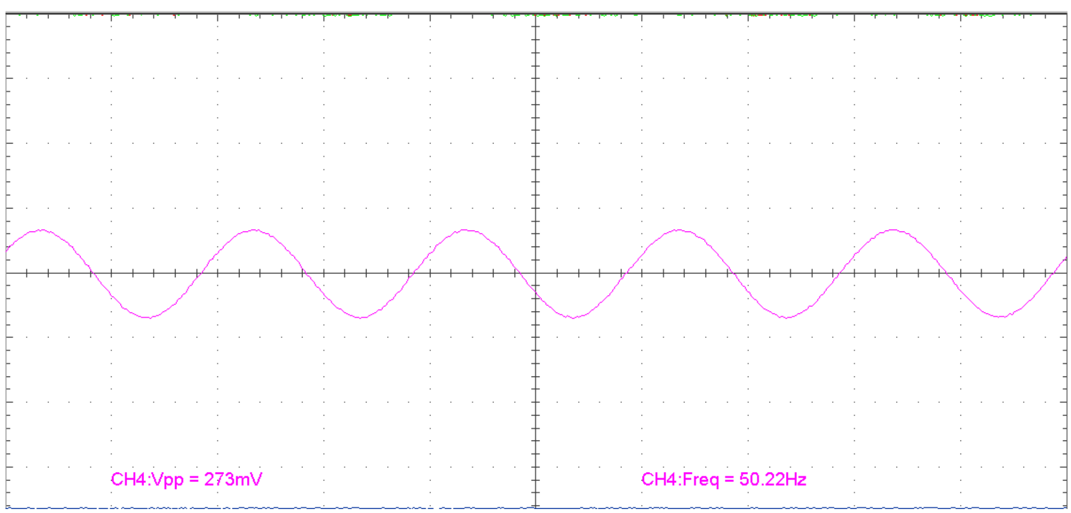


Figure 4.20: The filter current of phase A

The filter current with a proper coupling inductors as were in the previous chapter had a high frequency. Now by working with a high inductance, the filter currents can't change as fast as they should be because this inductance is slowing them down. That's what caused sinusoidal filter currents. Also when the source current of phase a is subtracted from the load current of the same phase, a sinusoidal result is obtained.

3.5 Conclusion

An implementation of the shunt active power filter based on the instantaneous power theory (p-q) is built in this chapter in order to see how close we can match the results obtained in the simulation part. The implementation in based on the STM32f4 microcontroller and the Semikron.

Based on the obtained results the implementation has shown that the SAPF can reduce the THD of a non linear load affecting the source currents, however, due to the lack of the exact components, the overall implementation results were as expected. Moreover, using proper value of coupling inductor will provide better results.

General Conclusion and Further Work

General Conclusion and Future Work

The sole aim of carrying out the design, the construction and the implementation of shunt active power filter has been achieved. In this project, the research studies start with an introduction to power quality theories. The role of passive power filters in harmonics elimination is discussed. However, the research work deals with the use of APFs due to the several inevitable drawbacks associated with passive filters. Performances of p-q, modified p-q and d-q strategies are evaluated by comparing the THDs in compensated source currents under the ideal conditions during the simulation, and then during the non ideality of the experimental building. Based on these results, it can be concluded that the SAPF can be used to mitigate the harmonics caused by the non linear loads. It can be built with the most cost effectiveness as done is this project using the STM microcontroller.

For further works, we suggest:

- To implement the SAPF using other PWM techniques.
- To design an LC/LCL output filter in order to reduce the current ripples.
- Three phase three wire system can be extended to three phase four wire system with different conditions like considering the zero sequence voltage present in the system.
- Renewable energy sources maybe investigated and combined with the SAPF.
- We used a two level inverter, while this work can be done using a three level inverter to obtain more precise results.

Appendix A

LEM

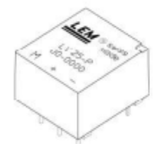
Voltage Transducer LV 25-P

I_{PN} = 10 mA
V_{PN} = 10 .. 500 V

For the electronic measurement of voltages : DC, AC, pulsed..., with a galvanic isolation between the primary circuit (high voltage) and the secondary circuit (electronic circuit).

LEM TRANSDUCERS 5 YEARS WARRANTY

CE



Electrical data

I_{PN}	Primary nominal r.m.s. current		10		mA
I_P	Primary current, measuring range		0 .. ± 14		mA
R_M	Measuring resistance		$R_{M\,min}$	$R_{M\,max}$	
	with ± 12 V	@ ± 10 mA $_{max}$	30	190	Ω
		@ ± 14 mA $_{max}$	30	100	Ω
	with ± 15 V	@ ± 10 mA $_{max}$	100	350	Ω
		@ ± 14 mA $_{max}$	100	190	Ω
I_{SN}	Secondary nominal r.m.s. current		25		mA
K_N	Conversion ratio		2500 : 1000		
V_C	Supply voltage (± 5 %)		± 12 .. 15		V
I_C	Current consumption		10 (@±15 V)+I_S		mA
V_d	R.m.s. voltage for AC isolation test [1], 50 Hz, 1 mn		2.5		kV

Accuracy - Dynamic performance data

X_G	Overall Accuracy @ I_{PN} , T_A = 25°C	@ ± 12 .. 15 V	± 0.9		%
		@ ± 15 V (± 5 %)	± 0.8		%
ε_L	Linearity		< 0.2		%
			Typ	Max	
I_O	Offset current @ I_P = 0, T_A = 25°C			± 0.15	mA
I_{OT}	Thermal drift of I_O	0°C .. + 25°C	± 0.06	± 0.25	mA
		+ 25°C .. + 70°C	± 0.10	± 0.35	mA
t_r	Response time [2] @ 90 % of $V_{P\,max}$		40		μs

General data

T_A	Ambient operating temperature	0 .. + 70	°C
T_S	Ambient storage temperature	- 25 .. + 85	°C
R_P	Primary coil resistance @ T_A = 70°C	250	Ω
R_S	Secondary coil resistance @ T_A = 70°C	110	Ω
m	Mass	22	g
	Standards [3]	EN 50178	

Notes : [1] Between primary and secondary
[2] R_1 = 25 kΩ (L/R constant, produced by the resistance and inductance of the primary circuit)
[3] A list of corresponding tests is available

Features

- Closed loop (compensated) voltage transducer using the Hall effect
- Insulated plastic case recognized according to UL 94-V0.

Principle of use

- For voltage measurements, a current proportional to the measured voltage must be passed through an external resistor R_1 which is selected by the user and installed in series with the primary circuit of the transducer.

Advantages

- Excellent accuracy
- Very good linearity
- Low thermal drift
- Low response time
- High bandwidth
- High immunity to external interference
- Low disturbance in common mode.

Applications

- AC variable speed drives and servo motor drives
- Static converters for DC motor drives
- Battery supplied applications
- Uninterruptible Power Supplies (UPS)
- Power supplies for welding applications.

981125/14

LEM Components www.lem.com

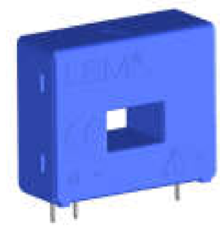
Appendix B

Current Transducer LA 55-P

I_{PN} = 50 A

For the electronic measurement of currents: DC, AC, pulsed..., with galvanic separation between the primary circuit and the secondary circuit.

CE cULus RoHS



Electrical data

I_{PN}	Primary nominal RMS current		50				A
I_{PM}	Primary current, measuring range		0 ... ±70				A
R_M	Measuring resistance		@ T_A = 70 °C		T_A = 85 °C		
			$R_{M\,min}$	$R_{M\,max}$	$R_{M\,min}$	$R_{M\,max}$	
	with ±12 V	@ ±50 A_{max}	10	100	60	95	Ω
		@ ±70 A_{max}	10	50	60 [1]	60 [1]	Ω
	with ±15 V	@ ±50 A_{max}	50	160	135	155	Ω
		@ ±70 A_{max}	50	90	135 [2]	135 [2]	Ω
I_{SN}	Secondary nominal RMS current		50				mA
N_P/N_S	Turns ratio		1 : 1000				
U_C	Supply voltage (±5 %)		±12 ... 15				V
I_C	Current consumption (±2)		10 (@ ±15 V) + I_S				mA

Accuracy - Dynamic performance data

ε	Error @ I_{PN}, T_A = 25 °C	@ ±15 V (±5 %)	±0.65		%
		@ ±12 ... 15 V (±5 %)	±0.90		%
ε_L	Linearity error		< 0.15		%
			Typ	Max	
I_O	Offset current @ I_P = 0, T_A = 25 °C			±0.2	mA
I_{OM}	Magnetic offset current [3] @ I_P = 0 and specified R_M, after an overload of 3 × I_{PN}			±0.3	mA
I_{OT}	Temperature variation of I_O	−25 °C ... +85 °C	±0.1	±0.6	mA
		−40 °C ... −25 °C	±0.2	±1.0	mA
$t_{D\,10}$	Delay time @ 10 % of I_{PN}		< 500		ns
$t_{D\,90}$	Delay time to 90 % of I_{PN} [4]		< 1		µs
BW	Frequency bandwidth (−1 dB)		DC ... 200		kHz

General data

T_A	Ambient operating temperature		−40 ... +85	°C
T_S	Ambient storage temperature		−40 ... +90	°C
R_S	Resistance of secondary winding	@ T_A = 70 °C	80	Ω
		@ T_A = 85 °C	85	Ω
m	Mass		18	g
	Standards		EN 50178: 1997 UL 508: 2010	

Notes: [1] Measuring range limited to ±60 A_{max}
[2] Measuring range limited to ±55 A_{max}
[3] Result of the coercive field of the magnetic circuit
[4] For a di/dt = 200 A/µs.

Features

- Closed loop (compensated) current transducer using the Hall effect
- Insulating plastic case recognized according to UL 94-V0.

Advantages

- Excellent accuracy
- Very good linearity
- Low temperature drift
- Optimized response time
- Wide frequency bandwidth
- No insertion losses
- High immunity to external interference
- Current overload capability.

Applications

- AC variable speed drives and servo motor drives
- Static converters for DC motor drives
- Battery supplied applications
- Uninterruptible Power Supplies (UPS)
- Switched Mode Power Supplies (SMPS)
- Power supplies for welding applications.

Application domain

- Industrial.

Appendix C

SEMITEACH IGBT

IGBT Module stack

SEMITEACH - IGBT
3-phase retifier + IGBT inverter + brake chopper

datasheet

Ordering No. 08753450
Description SEMITEACH IGBT
SKM50GB12T4, SKHI22A, SKD51/14

Features
- Multi-function IGBT converter
- IP2x protection for safety hazards
- Transparent enclosure to allow visualisation of internal part
- External connector for easy wiring
- Built in isolated IGBT driver and IGBT protection
- Forced-air cooled heatsink

Typical Applications

- Education : various converter configuration possible :
- 3-phase inverter+brake chopper
- Buck or boost converter
- single phase inverter
- single or 3-phase rectifier

Footnotes

1) The user shall ensure air ventilation for proper cooling

Remarks

This technical information specifies semiconductor devices but promises no characteristics. No warranty or guarantee, expressed or implied is made regarding delivery, performance or suitability.

Absolute maximum ratings

Symbol	Conditions	Values	Unit
$I_{OUT\ MAX}$	Maximum permanent output current	30	A_{RMS}
$I_{IN\ MAX}$	Maximum permanent input current	30	A_{DC}
$V_{OUT\ MAX}$	Maximum output voltage	400	V_{AC}
$V_{BUS\ MAX}$	Maximum DC bus voltage	750	V_{DC}
f_{OUT}	Maximum inverter output frequency	500	Hz
f_{SW}	Maximum switching frequency	50	kHz

Electrical characteristics / Typical application *$T_{AIR\ COOLING\ 1)}$ = 30℃ unless otherwise specified*

Symbol	Conditions		min	typ	max	Unit
Ratings						
$I_{OUT\ RATED}$	Rated output current	No overload, tamb = 30℃ Chip junction T°< 150℃, (Max junction temperature = 175℃) With SEMIKRON axial fan assembly		30		A_{RMS}
V_{OUT}	Rated output voltage			400		V_{AC}
PF	Power factor			1		-
P_{OUT}	Rated output power			20		kW
f_{SW}	Inverter switching frequency			5		kHz
f_{OUT}	Output frequency			50		Hz
V_{BUS}	Rated DC voltage			750		V_{DC}
$P_{LOSS\ INV}$	Total power losses			700		W
η	Inverter efficiency			-		%

Protection & measurement

Symbol	Conditions	min	typ	max	Unit
Thermal trip	Temperature trip level (Normally Open type: NO)		71		℃
Temperature sensing $T_{analogue\ OUT}$	Scaling over 30℃…110℃ temperature range				$mV.°C^{-1}$
	Linear temperature range	30		110	℃
	Accuracy of analogue signal over 65℃…110℃ range	-1,5		1,5	℃
	Max. output current			5	mA
	Max. voltage range	0		10	V_{DC}

Axial fan data

			min	typ	max	Unit
Heatsink fans	V_{SUPPLY}	Heatsink fan DC voltage supply		230		Vac
	P_{FAN}	Rated power at V_{SUPPLY} per fan, PWM 100%			15	W

Filtering characteristics

		min	typ	max	Unit
V_{BUS}	Rated DC voltage applied to the caps bank with switching		540	700	V_{DC}
$V_{DC\ CAP}$	Max DC voltage applied to the caps bank without switching			800	V_{DC}
$\tau_{d5\%}$	Discharge time of the capacitors (5%)		-		s
C_{DC}	Capacitor bank capacity	0,88		1,32	mF
LTE	Calculated LTE of the caps with forced air cooling		-		kH

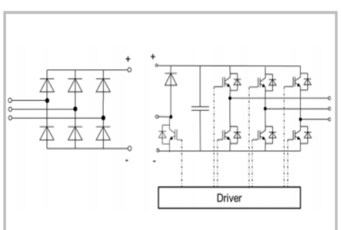
Stack Insulation

		min	typ	max	Unit
V_{ISOL}	Frame / Power stage AC/DC (insulation test voltage AC, 60s)			1 500	V

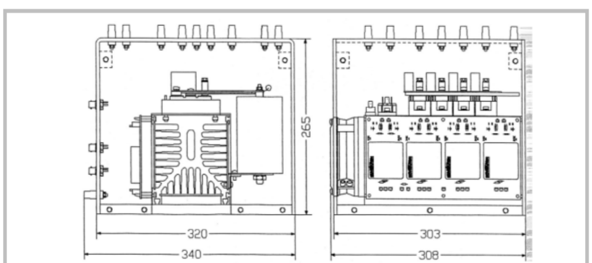
Driver Characteristcs

Symbol	Conditions	min	typ	max	Unit
Driver board data					
V_S	Supply voltage	14,4	15	15,6	Vpc
$I_{VP,\ IDLE}$	Supply primary current (no load)		20		mA
$I_{VP,\ LOAD}$	Max. supply primary current			290	mA
ViT+	input threshold voltage HIGH			12,5	Vpc
ViT-	input threshold voltage LOW	4,5			Vpc
R_{IN}	Input resistance		10		kΩ

Weight	3-phase IGBT inverter	13,3	kg
	3-phase IGBT inverter including fan assembly	14,9	



B6U + B6CI + E1CIKF



General dimensions

References

[1] J. Arrillaga and N. R. Watson, Power system harmonics. John Wiley & Sons, 2004.

[2] "IEEE standard dictionary of electrical and electronics terms," IEEE Standard 100,1984

[3] H.Akagi, “Active harmonic filter,” in Proceedings of IEEE, Vol 93, No 12, Dec 2005.

[4] T.C. Green and J.H. Marks, “Control techniques for activepower filter,” in IEE Proceedings of Electric powerapplications.

[5] Fuchs, Ewald_ Masoum, Mohammad A. S – “Power Quality in Power Systems and Electrical Machines, Second Edition” (2015, Academic Press_Elsevier).

[6] DrRanjan Kumar Jena “Electrical_Power_Quality-PEEL” 8th Semester-Electrical.

[7] M. Rahmani, A. Arora, R. Pfister, P. Huencho, “State of the Art Power Quality Devices and Innovative Concepts”, in VII Seminario de Electrónica de Potencia, Valparaíso, Chile, Abril 1999.

[8] C. Sankaran. – “ Power Quality” (2001)

[9] Al-Haddad, Kamal_ Chandra, Ambrish_ Singh, Bhim – “Power Quality_ Problems and Mitigation Techniques” (12 December 2014, Wiley).

[10] Prof. Mack Grady “Understanding_power_system_harmonics_grady” Dept. of Electrical & Computer Engineering, University of Texas at Austin (april_2012)

[11] G.RobertP.Ellis“ALLEN-BRADLEY SERIES OF ISSUES AND ANSWERS” POWER SYSTEM HARMONICS”. April 2001, printed in Canada

[12] Https://www.electricalindia.in/harmonics-causes-effects access date 25/02/2019

[13] Http://top10electrical.blogspot.com/2015/02/harmonics-effects-on-power-system.html access date 25/02/2019

[14] SOURCES OF HARMONICS ENGINEERING ARTICLES “httptop10electrical.blogspot.com201412sources-of-harmonics.html”

[15] Gonzalo Sandoval, John Houdek,"A Review of Harmonic Mitigation Techniques" 2005

[16] Www.electtronics-tutorials.ws/accircuits/harmonics.html access date 12/02/2019

[17] J. Arrillaga and N. R. Watson, Power system harmonics. John Wiley & Sons, 2004.

[18] H. Özkaya, "Parallel active filter design, control, and implementation," Ph.D. Dissertation, Citeseer, 2007

[19] Voltage Harmonic Reduction Using Passive Filter Shunt Passive-Active Filters For non Linear Load. 2017 7th International Conference on Communication Systems and Network Technologies (CSNT)

[20] Researchgate.net/publication/2985858_The_Future_of_Power_Semiconductor _Device_Technology. 15/05/2019.

[21] Power electronics handbook, Muhammad H.Rashid. Academic press, 2010.

[22] A. Vandermeulenand J. Maurin, "Current source inverter vs. Voltage source inverter topology," Technical Data TD02004004E, Eaton, 2010.

[23] M. Kale and E. Ozdemir, "Harmonic and reactive power compensation with shunt active power filter under non-ideal mains voltage," Electric Power System Research (Elsevier), vol. 77, pp. 363-370, 2005.

[24] SUSHREE SANGITA PATNAIK, Performance Enhancement of Shunt apfsUsing Various Topologies, Control Schemes and Optimization Techniques, 2015

[25] C.-Y. Hsu and H.-Y. Wu, "A new single-phase active power filter with reduced energystorage capacity," IEE Proceedings-Electric Power Applications, vol. 143, no. 1, pp.25–30, 1996.

[26] K. Young and R. Dougal, "Srf-pll with dynamic center frequency for improved phasedetection," in Clean Electrical Power, 2009 International Conference on. IEEE,2009, pp. 212–216.

[27] M. Kale and E. Ozdemir, "An adaptive hysteresis band current controller for shuntactive power filter," Electric power systems research, vol. 73, no. 2, pp. 113–119, 2005.

[28] H. Vahedi, A. Sheikholeslami, M. TavakoliBina, and M. Vahedi, "Review and simulation of fixed and adaptive hysteresis current control considering switching lossesand high-frequency harmonics," Advances in Power Electronics, Hindawi Publishing Corporation, vol. 2011, 2011.

[29] ASBJØRN RYSSTAD, Active Power Filters in Zero Energy Buildings. University of Agder, 2017 Faculty of Engineering and Science

[30] S.K. Jain, P. Agarwal and H. O. Gupta, "Design simulation and experimental investigations on a shunt active power filter for harmonics, and reactive power compensation," Electric Power Components and Systems (Taylor & Francis), vol. 31,no. 7, pp. 671-692, 2003.

[31] T. M. Undeland, W. P. Robbins, and N. Mohan, “Power electronics: converters,applications, and design,” 2003.

[32] Y. S. Prabhu, A. Dharme, and D. Talange, “A three phase shunt active power filter based on instantaneous reactive power theory,” in India Conference (INDICON), 2014 Annual IEEE. IEEE, 2014, pp. 1–5

[33] ASHISH BAGWARI, RAJESHWARI ‘VOLTAGE HARMONIC REDUCTION USING PASSIVE FILTER SHUNTPASSIVE-ACTIVE FILTERS FOR NON-LINEAR LOAD’978-1-5386-1860-8/17/$31.00 ©2017 IEEE

[34] Mathworks.com/help/simulink/, access date 20/05/2019

[35] Powergui MATLAB 2015a documentation.

[36] Y. Tang, P. C. Loh, P. Wang, F. H. Choo, F. Gao, and F. Blaabjerg, “Generalizeddesign of high performance shunt active power filter with output lcl filter,” IEEETransactions on Industrial Electronics, vol. 59, no. 3, pp. 1443–1452, 2012.

[37] S.K. Jain, P. Agarwal and H. O. Gupta, "Design simulation and experimental investigations on a shunt active power filter for harmonics, and reactive power compensation," Electric Power Components and Systems (Taylor & Francis).Vol. 31, no. 7, pp. 671–692, 2003

[38] Http://www.rroij.com/open-access/harmonic-analysis-of-sine-pwm-andhysteresis-current-controller.php?Aid=42511 access date 15/05/2019

[39] Www.st.com/en/microcontrollers-microprocessors/stm32-32-bit-arm-cortex-mcus.htmlaccess date 20/06/2019

[40] STM32F405xx datasheet.

[41] Https://www.mathworks.com/products/simulink.htmlaccess date 21/06/2019

[42] Ning-Yi Dai, Man-Chung Wong, ‘Design Considerations of Coupling Inductance for Active Power Filters ‘Department of Electrical and Electronics

EngineeringUniversity of Macau 2011 6th IEEE Conference on Industrial Electronics and Applications.