INVESTIGATION ON HARMONIC PROBLEMS FOR N-1 CONTINGENCY IN INDUSTRIAL DISTRIBUTION AND MITIGATION USING FUZZY CONTROLLED HYBRID FILTER

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Investigation on Harmonic Problems for N-1 Contingency in Industrial Distribution and Mitigation Using Fuzzy Controlled Hybrid Filter

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DECLARATION

This thesis is my original work and has not been submitted to any other university for examination.

Signature:... Date:........................

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This thesis report has been submitted for examination with our approval as University supervisors.

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DEDICATION

To my family for their unrelenting support and encouragement all through the course of my education.

ABSTRACT

The electric distribution structure of modern industries is rapidly changing and becomes complex and complex as a result of an increase in demand and market competition. Effective nonlinear electronic devices were introduced recently to increase productivity and efficiency. However, installing devices such as; Programmable Logic Controllers (PLCs), Adjustable-Speed Drives (ASD), energy efficient motors and other power electronic devices are creating a power quality related problem namely harmonic distortion. Harmonic means the multiple of fundamental frequencies resulting in excessive current flow on lines due to power electronic devices, short circuits, and other contingency effect. This has a great threat to industrial consumers, results in equipment damages, poor power factor, and excessive neutral currents. Considering the economic consequence of harmonic problems due to damaging of electric equipment and an increase of electric bill due to poor power factor in Industries, this research project presents the modeling of an industrial distribution named Red Sea Bottlers Share Company in Eritrea using Matlab Simulink for an investigation of harmonic distortion level. To carry out the investigation, firstly the industrial network and loads were modeled. Specifically, the substation, transformer, transmission lines, variable frequency drive motors, induction motors, switch mode power supply were modeled using Matlab Simulink for harmonic study. After that, the modeled system was simulated to carry out the spectral analysis. Then harmonic distortion level at both Point of Common Coupling (PCC) and In Plant Coupling (IPC) were computed for normal operating conditions as well as for N-1 contingency cases. The result was compared with the IEEE 519-2 and IEC 61000-2-4 for class 2 standards and found don’t comply with the standards. A fuzzy logic controlled hybrid filter was designed to reduce the harmonic distortion level up to the threshold that satisfies the above-stated standards. To verify the whether the harmonic distortion level is within the stipulated limits the overall modeled industrial plant was simulated after the introduction of the designed hybrid filter. The harmonic distortion level was measured at both Point of Common Coupling (PCC) and In Plant Coupling (IPC) for the normal operating condition as well as N-1 contingency conditions. Then the result was compared IEEE 519-2 and IEC 61000-2-4 for class 2 standards. It was found out that the designed filter can able maintain the harmonic distortion level within the recommended limits as per the IEEE 519-2 and IEC 61000-2-4 for class 2 standards regardless of the operating conditions of the industrial plant.

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LIST OF ABBREVIATIONS

RMS - Root Mean Square

TDD - Total Demand Distortion

THD -Total Harmonic Distortion

THDI - Current Total Harmonic Distortion

THDV - Voltage Total Harmonic Distortion

ASD - Adjustable Speed Drive

VFD -Variable frequency drive

UPS - Uninterruptable power supply

PCC-Point of common coupling

IPC- In Plant Coupling

IEEE-Institute of Electrical and Electronics Engineering

IEC-International Electro technical Commission

PLCs- Programmable Logic Controllers

PPF - Passive Power Filter

APF - Active Power Filter

HVDC-High Voltage Direct Current

CFL -Compact Fluorescent Lamp

SMPS-Switch Mode Power Supply

AC-Alternating Current

DC-Direct Current

SRF- Synchronous Reference Frame Method

PWM-Pulse Width Modulation

FLC-Fuzzy Logic Controller

PID-Proportional Integral deferential

CHAPTER ONE

1. Introduction

1.1. Background of the Study

The modern industries are constantly exposed to power quality related problems results in an unscheduled plant shutdown[1]. Power quality of a system expresses to which degree a practical supply system resembles the ideal supply system. The term is used to describe electric power that drives an electrical load and the load's ability to function properly. Any deviation of electrical supply from its perfect sinusoidal waveform that can result in failure of customer equipment is called power quality problem. For instance, voltage sags or swells, transients, harmonic distortion, electrical noise, flickering lights, and voltage notching are some of the power quality related disturbances[2]. From all those power quality related disturbances, harmonic distortion is critical as it represents the steady-state problem. It is always available as long as the harmonic producing equipment is there[3].

In the 19th century, it was found out that electrical machines and transformers were the main sources of harmonic distortion. Until recently, the electric equipment could work satisfactorily within the expected range of deviation in voltage and frequency[4].However, in this information technology era, the structure of modern industrial distribution has completely changed and brought its own impact to the power system disturbance. Even though the incorporations of Programmable Logic Controllers (PLCs), Adjustable-Speed Drives (ASD), energy efficient motors and other power electronic devices in an automated industries have improved the production process by increasing productivity and efficiency; they are the main contributors to harmonic distortion and producing great destruction in industrial companies worldwide [5].

A modern industrial distribution system is fully automated, equipped with nonlinear devices such as Programmable Logic Controllers (PLCs), Adjustable-Speed Drives (ASD), energy efficient motors and other electronic devices. These nonlinear loads are the type of loads that change their impedance with the voltage applied. Hence, the current they draw is non-sinusoidal in nature. This distorted current propagates through all the impedance between the load and power source. It causes voltage drops for each harmonic frequency based on ohms law and thereby producing total voltage distortion at the Point of Common Coupling (PCC) due to the vector sum of the individual voltage drops. This Harmonic distortion is quantified by Total Harmonic Distortion(THD) which is a function of the impedance between the power source and the load[6]. If any change happens in the impedance due to any sort of fault in the distribution system such as pure wiring practice, geographical or weather conditions, and effect of neighboring customers, it thus affects the THD[3].In general, the THD at the PCC depends upon load, type of load, Configuration (resonances depending on the capacitive or inductive character of the elements in the network),network impedance and the fault level [7][8][9][10]. Therefore the study focuses on an investigation of harmonic distortion at the PCC of an industry considering contingency and its mitigation techniques.

1.2. Statement of the Problem

The nonlinear loads such as PLC, Adjustable Speed Drives(ASD),electrical machines and other electronic sensors are part and parcel of a modern industry. They were introduced to improve the productivity and efficiency of industrial systems. Unfortunately, these electronic equipment suffers from harmonic problems that they produced and affects the performance of the industry in general. Some of the harmonic problems experienced in an industry are ;motor heating, stoppage of PLC operation, undesirable tripping of breakers or relays without overload, wire insulation breakdown, and malfunctioning of lighting systems .Hence, they create great production financial loss Moreover, they reduce the power factor which results in increasing electric bill. Understanding these problems, different researchers have made a contribution to an investigation and mitigation of harmonics based on the hybrid filter using different control strategies. However, the majority of them designed a power filter based on fixed load condition, or for a small range of load variations. They didn’t consider the complex nature of power system distribution in which it is exposed to various types of faults that result in changing the load and the harmonic distortion level greatly. Moreover, almost all researchers have used power quality analyzers to quantify the harmonic distortion level at different bus and designed suitable filters accordingly. These methods are expensive and time-consuming as they need to take harmonic measurements systematically. They also only consider the circumstances in which they were taken, because what measure today is not equal to what we measure tomorrow, thus can’t be guaranteed to reflect the worst possible conditions of a system. Therefore, there is a need of developing a model which gives relative flexibility to investigate Harmonic distortion at PCC considering various operating conditions of the plant and designing a fuzzy logic controlled hybrid filter that can maintain the THD well within IEEE standards taking contingency under consideration, so that it can effectively mitigate the harmonic levels even in the worst case operation of the plant.

1.3. Motivations

The harmonic producing loads i.e. nonlinear devices have been introduced in automated factories recently to improve the overall performance of the industry. Due to their tremendous advantage in improving productivity and efficiency, they are expected to increase in future. Consequently,the harmonic distortion level in an industrial distribution system will likely increase and create a great economic loss for the industry.

1.4. Objective of the Study

The main objective is to investigate harmonic problems for N-1 contingency in an industrial distribution and designing of a fuzzy logic based controlled hybrid filter to mitigate the harmonic distortion.

1.4.1. Specific Objectives

- To model an industrial distribution network for harmonic study
- To calculate harmonic voltage and current distortion factors at the point of common coupling and compare with the standards.

- To design and model,a fuzzy logic controlled hybrid filter and simulate the result to see the impact after the introduction of hybrid filter.

1.5. Significance of the Study

Harmonic problems have become a bottleneck for industries to maximize its profit. Indeed for any company to maximize its profit it has to reduce the production, operation, and maintenance cost. For instance; the cost of replacement for damaged equipment, the penalty imposed due to low power factor, the power loss of inefficient devices and loss of production. The designed filter will minimize the harmonic problems. The production, operation, and maintenance cost will be reduced and thereby maximizes the total profit.

1.6. Research Scope

In this research, an industrial distribution network wasmodeled for harmonic study. An investigation of harmonic distortion level at PCC as well as at the IPC of the distribution system has been carried out for normal operating conditions and for N-1 contingency cases using Matlab Simulink. In both normal operating condition of the industry and N-1 contingency case, it was found out that the harmonic distortion level doesn't comply with both the IEEE 519-2 and IEC 61000-2-4 for class 2 standards. Afterward, a fuzzy logic controlled hybrid filter were designed and inserted to eliminate the harmonics. Finally, the harmonic analysiswas carried out to verify the harmonic distortion level at PCC, as well as IPC which satisfies the IEEE 519-2 and IEC 61000-2-4 for class 2 standards respectively.

1.7. Thesis Organization

The thesis comprised of five chapters arranged as follows

Chapter one

This chapter discusses the introduction part which consists of background of the study, statement of the problem, motivation, the objective of the study, and the significance of the study and research scope.

Chapter two

This chapter discusses the literature review that covers power quality phenomena, the majority of power quality related issues experienced by industries such as voltage sag, transients, and harmonics. Specifically, it addresses about harmonics, Power quality indices and power quantities under nonsinusoidal situations, Cause of harmonic effect in industrial distribution, Source of harmonics, their production and the conventional methods of harmonic mitigation techniques such as passive filter, active filter and hybrid filter with their configuration. It also reviews about the different types of reference current extraction techniques and their control methods. It also presents the main components of hybrid filter briefly. Finally, fuzzy and their advantage fuzzy logic control over convention techniques is reviewed.

Chapter three

This chapter focus on developing the overall model of the industrial distribution network for harmonic study and the design of hybrid filter to mitigate the harmonic distortion level. The former specifically one addresses on the modeling of the utility substation, transformer modeling, transmission line and modeling of some of the industrial loads such as variable frequency VFD modeling, switch mode power supply modeling (SMPS) and induction motor modeling. Whereas, the former one discusses on the proposed control mechanism of the active filter, design of DC link capacitor and AC link inductor of the active filter, design of passive filter and design of fuzzy logic based DC voltage control

Chapter four

This chapter covers the results and analysis of the research. It discusses the spectral result of the variable frequency drive, switch mode power supply and the spectral analysis of the whole industrial network before compensation, after compensation, and for N-1 contingency case.

Chapter five

This chapter discusses the conclusion and future scope of the research

CHAPTER TWO

2. Literature Review

2.1. Power Quality

Power quality of a system expresses to which degree a practical supply system resembles the ideal supply system. The term is used to describe electric power that drives an electrical load and the load's ability to function properly. Any deviation of electrical supply from its perfect sinusoidal waveform that can result in failure of customer equipment is called power quality problem. Some of the power quality issues related to fluctuations in the electrical supply are voltage sags or swells, under voltages, overvoltage, transients, harmonic distortion, interruptions, DC offsets, notching, noise, voltage fluctuations, and frequency variations. However, the vast majority of power quality related issues experienced by industrial customers can be attributed to voltage sags, harmonics, and transients. Though all these types of Power quality related disturbance affect the performance of an industry in several ways, harmonic distortion is critical as it represents the steady-state problem. It is always available as long as the harmonic producing equipments are there [2][3].Moreover, in industries harmonics comes first even during switching on and off of large loads there is maximum fluctuation of current which results in harmonics.

2.2. Voltage Sag

Voltage sags are the reduction of an RMS voltage by at least10% of the nominal voltage that lasts between half a cycle and a minute. The frequent cause of voltage sags in industries is the switching on and off of large motors. If a motor is started using direct online starter, the current it draws can be more than six times or more of its normal operating current. This heavy and sudden current draw causes a voltage drop in the downstream. Moreover, weather factors, such as lightning, wind, and ice, and other faults in the transmission line are also responsible for voltage sag.

2.2.1. Causes of Voltage Sag

Programmable Logic Controllers (PLC) and other industrial computers can be very susceptible to voltage sags. All computing equipment requires a power supply to provide a low DC voltage in order to operate. Without sufficient ride through capability, computing equipment can be disrupted during sags, severely impacting industrial controls and causing data corruption. Moreover, if using digital I/O, a logical “high” can be read by the PLC as a logical “low” if the input voltage drops significantly, potentially causing process disruption. Voltage sags can be solved using soft starters for motors[2].

2.3. Transients

A transient is defined in IEEE 1100-1999 as a sub-cycle disturbance in the AC waveform that is evidenced by a sharp, brief discontinuity of the waveform. Transients can be categorized as either impulsive or oscillatory. Lightning surges are the most common cause of impulsive transients on the utility system. Capacitor switching is the most common cause of oscillatory transients. Both types of transients can affect industrial equipment because all electronic equipment works on low voltage, a voltage above their rating harm them[5].

2.4. Harmonics

A sinusoidal voltage or current having frequencies that are integral multiples of the power frequency.

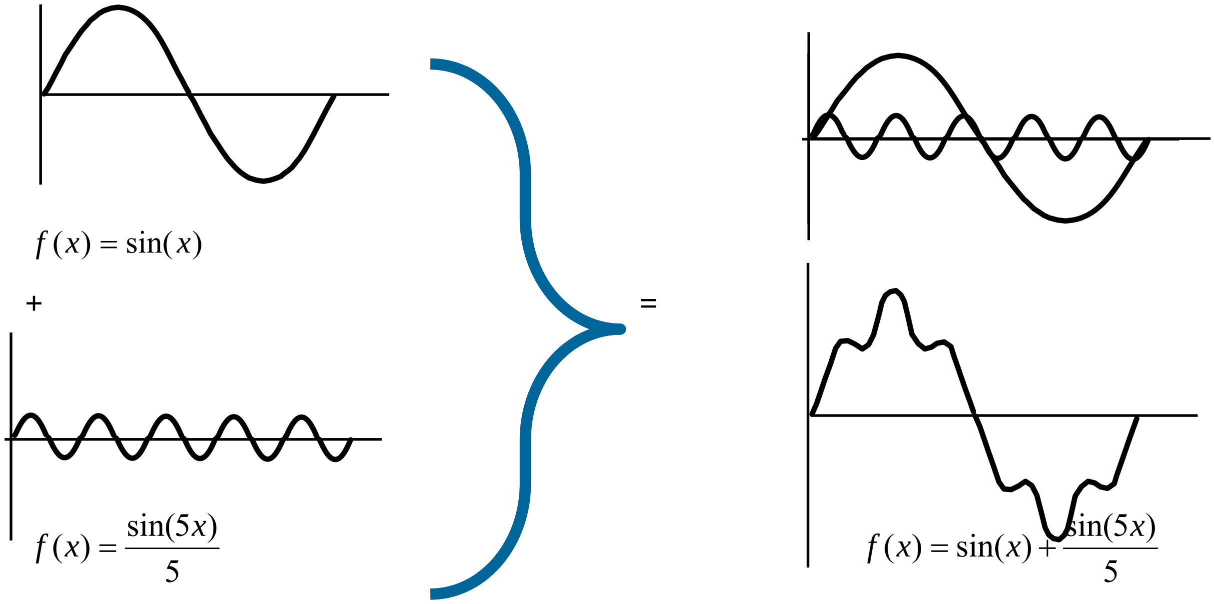

Figure 2-1:Harmonics

2.4.1. Power Quality Indices and Power Quantities Under Nonsinusoidal Situations

2.4.1.1. Total Harmonic Distortion (THD)

The most common method used to quantify for harmonics is total harmonic distortion (THD) or Distortion Factor. It is applied to both voltage and current.THD is defined as the RMS value of the harmonics above fundamental, divided by the rms value of the fundamental. DC is ignored. Thus, for current

$$THD_I = \frac{\sqrt{\sum_{k=2}^{\infty}\left(\frac{I_k}{\sqrt{2}}\right)^2}}{\frac{I_1}{\sqrt{2}}} \qquad (2\text{-}1)$$

Similarly, the same equation applies to the voltage *THDV*.

THD and rms are directly linked. Note that since

$$I_{rms}^2 = \frac{1}{2}\sum_{k=1}^{\infty} I_k^2 \qquad (2\text{-}2)$$

And since

$$THD_I^2 = \frac{\frac{1}{2}\sum_{k=2}^{\infty} I_k^2}{\frac{I_1^2}{2}} = \frac{\left(\sum_{k=1}^{\infty} I_k^2\right) - I_1^2}{I_1^2} \tag{2-3}$$

Then rewriting gives

$$\sum_{k=1}^{\infty} I_k^2 = I_1^2(1 + THD_I^2) \tag{2-4}$$

So that

$$\frac{1}{2}\sum_{k=1}^{\infty} I_k^2 = \frac{1}{2} I_1^2(1+THD_I^2) \tag{2-5}$$

Comparing equation (2-5) with equation (2-2)

$$I_{rms}^2 = \frac{1}{2}\sum_{k=1}^{\infty} I_k^2 = \frac{1}{2} I_1^2(1+THD_I^2) = I_{1,rms}^2\left(1+THD_I^2\right) \tag{2-6}$$

Thus the equation linking THD and rms is

$$I_{rms} = I_{1,rms}\sqrt{1+THD_I^2} \tag{2-7}$$

As observed from the mathematical relation the losses are proportional to the square of rms current (and sometimes increase more rapidly due to the resistive skin effect).Therefore, the rms increases with harmonics, then line losses increases in accordance with the level of harmonics that are present[11].

2.4.1.2. Active, Reactive and Apparent Power

The rate of flow of electric energy, the instantaneous power, has two type of components:

1**. Active Powers**: these are components that have an average value, flow in a unidirectional way from sources to loads and are measured in watts.

2. **NonactivePower**s: these components have a nil mean value and oscillate between sources and loads. Do not cause a net transfer of energy. So far their unit is the var[12].

For single phase linear loads and systems where both voltage and current are sinusoidal, the active power (P), reactive power (Q) and apparent power (S) can be expressed by the familiar equations:

$$P = UI\cos\theta \tag{2-8}$$

$$Q = UI\sin\theta \tag{2-9}$$

$$S = UI = \sqrt{P^2 + Q^2} \tag{2-10}$$

Where *U* and *I* are the root-mean-square (RMS) values of voltage and current and θ is the phase difference between voltage and current.

Similarly for symmetrical three-phase linear systems

Phase Voltages

$$\begin{aligned} v_a &= U_1\cos(w_1 t) \\ v_b &= U_1\cos(w_1(t-\frac{T}{3})) \\ v_C &= U_1\cos(w_1(t+\frac{T}{3})) \end{aligned} \tag{2-11}$$

Phase currents

$$\begin{aligned} i_a &= I_1\cos(w_1 t-\theta_1) \\ i_b &= I_1\cos(w_1(t-\frac{T}{3})-\theta_1) \\ i_c &= I_1\cos(w_1(t+\frac{T}{3})-\theta_1) \end{aligned} \tag{2-12}$$

Instantaneous power

$$\begin{aligned} p(t) = u_a i_a + u_b i_b + u_c i &= \frac{P}{3}(1+\cos 2w_1 t) + \frac{Q}{3}\sin 2w_1 t \\ &+ \frac{P}{3}(1+\cos 2w_1(t-\frac{T}{3})) + \frac{Q}{3}\sin 2w_1(t-\frac{T}{3}) \\ &+ \frac{P}{3}(1+\cos 2w_1(t+\frac{T}{3})) + \frac{Q}{3}\sin 2w_1(t+\frac{T}{3}) \end{aligned} \tag{2-13}$$

$$p(t) = \frac{P}{3}(1+\cos 2w_1 t) + \frac{P}{3}(1+\cos 2w_1(t-\frac{T}{3})) + \frac{P}{3}(1+\cos 2w_1(t+\frac{T}{3})) = 3\frac{P}{3} = P \tag{2-14}$$

$$P = \frac{3}{2} U_1 * I_1 \cos\theta_1$$
$$Q = \frac{3}{2} U_1 * I_1 \sin\theta_1 \qquad (2\text{-}15)$$

At nonsinusoidalconditions, there is, more or less, a general agreement for using $S = UI$. So for a periodic nonsinusoidal signal, the apparent power is equal to

$$S = \sqrt{\sum_n U_n^2 \sum_n I_n^2} \qquad (2\text{-}16)$$

There are various definitions for reactive power in non-sinusoidal conditions; based on the physical phenomena of electrical power and energy, for instance,Budeanu's definition, Fryze's definition, Kimbark's definition, Kusters and Moore's definition, Shepherd and Zakikhani's definition, Sharon's definition and Czarnecki's definition. From all these definitions, Fryze's definition satisfies the characteristics of the reactive power in sinusoidal conditions[11].Some of the various definition of reactive power in non-sinusoidal conditions are explained as shown below[13]

Budeanu'sDefinition

The Budeanu's power decomposition is shown in the following equations

$$P = \sum_n U_n I_n \cos(\phi_n)$$
$$Q = \sum_n U_n I_n \sin(\phi_n) \qquad (2\text{-}17)$$
$$D^2 = S^2 - P^2 - Q^2$$

Where ϕ_n is the phase difference between voltage and current of the n'th harmonic. P is the active power, Q is the reactive power, S is the apparent power and D is the distortion power

2.4.1.3. Kimbark's Definition

The kimbark's power decomposition is shown in the following equations

$$Q = U_1 I_1 \sin(\phi_1) \qquad (2\text{-}18)$$

Where U_1 and I_1 are the RMS values of the fundamental harmonic of voltage and current and ϕ_1 is the phase difference between them.

$$\begin{aligned} P &= UI\cos\phi \\ S &= UI = \sqrt{P^2+Q^2} \end{aligned} \tag{2-19}$$

$$D = \sqrt{S^2 - P^2 - Q^2} \tag{2-20}$$

2.4.1.4. Kusters and Moore's Definition Kusters

Kusters and Moore provide the power system operator to determine if the possibility of improving power factor by means of shunt capacitance or inductance exists and to identify the proper value required to realize the maximum benefit. The current components are as follows:

The first part is defined similarly to Fryze's active current:

$$i_p = \frac{P}{U^2}u \tag{2-21}$$

The capacitive reactive current is the current component which can be compensated by the capacitance; and in the case of capacitive load is defined as equation

$$i_{qc} = \dot{u}\frac{\frac{1}{T}\int_T (\dot{u})(i)dt}{\dot{U}^2} \tag{2-22}$$

$\dot{u}$ denotes the periodic part of derivative of the instantaneous voltage and $\dot{U}$ denotes the RMS value of the derivative of the instantaneous voltage.

The inductive reactive current is the current component, which can be compensated by the inductive defined as equation below

$$i_{ql} = u_{\text{int}}\frac{\frac{1}{T}\int_T (u_{\text{int}})(i)dt}{U_{\text{int}}^{\ 2}} \tag{2-23}$$

u_{int} denotes the periodic part of the integration of instantaneous voltage and U_{int} denotes the RMS value of integration of instantaneous voltage.

Capacitive and inductive reactive currents are determined by equations below

$$\begin{aligned} i_{qcr} &= i - i_p - i_{qc} \\ i_{qlr} &= i - i_p - i_{ql} \end{aligned} \tag{2-24}$$

*P*is the same as Fryze's could be written as

$$P = UI_p \tag{2-25}$$

Terms Q_c and Q_l can be determined by the equations below

$$\begin{aligned} Q_c &= UI_{qc} \\ Q_l &= UI_{ql} \end{aligned} \tag{2-26}$$

Q_c and Q_l reactive powers obtained from the above equations can be positive or negative: the sign specifies whether a load is of inductive or capacitive type.

If Q_c or Q_l is negative signed, the load is capacitive or inductive respectively and the required reactive power for compensation is equal to Q_c or Q_l respectively.

So the sign of Q_c is like the conventional sign of the capacitive load reactive power in sinusoidal situations while the Q_l will have opposite sign of the conventional inductive load reactive power.

The rest terms Q_{cr} and Q_{lr}

$$Q_{cr} = \sqrt{S^2 - P^2 - Q_c^{\;2}} \tag{2-27}$$

$$Q_{lr} = \sqrt{S^2 - P^2 - Q_l^{2}} \tag{2-28}$$

2.4.1.5. Shepherd and Zakikhani's Definition

The Shepherd and Zakikhani's power decomposition is shown in the following equation

$$S_R = \sqrt{\sum_{n\in N} U_n{}^2 \sum_{n\in N} I_n{}^2 \cos^2(\phi_n)} \tag{2-29}$$

S_R is the active apparent power. U_n and I_n are the root-mean-square (RMS) values of voltage and current and ϕ_n the phase difference between voltage and current. Whereas N is the set of all common harmonic orders of voltage and current; when a nonlinear load connected to an ideal source results in current harmonics that do not have any corresponding voltage harmonics, the current and voltage harmonics are divided into common and non-common harmonics. For the common harmonic order of n, both U_n and I_n are nonzero, while for the non-common harmonic of order n only one of U_n and I_n is nonzero. Active apparent power (S_R) is different from the active power (*P)*.So this decomposition does not provide any information leading to the determination of power factor.

Reactive apparent power is defined as

$$S_x = \sqrt{\sum_{n\in N} U_n{}^2 \sum_{n\in N} I_n{}^2 \sin^2(\phi_n)} \tag{2-30}$$

The reactive apparent power may be far from Budeanu's definition even if the voltage is close to sinusoidal and also it could not be directly used to determine the power of optimum compensation capacitance.

The rest term, named distortion apparent power, is equal to S_D :

$$S_D = \sqrt{S^2 - S_R{}^2 - S_x{}^2} \tag{2-31}$$

2.4.1.6. Sharon’s Definition

Sharon proposed new decomposition in which the average power (*P*) is the same as Fryze’s definition and the reactive apparent power (S_Q) is defined in the equation below.

$$S_Q = U.\sqrt{\sum_{n\in N} I_n{}^2 \sin^2(\phi_n)} \tag{2-32}$$

N is the set of common harmonics of voltage and current.

The rest term in the equation $S^2 = P^2 + S_Q{}^2 + S_C{}^2$ named complementary apparent power will be:

$$S_c = \sqrt{S^2 - P^2 - S_Q{}^2} \tag{2-33}$$

2.4.1.7. Czarnecki’s Definition

The Czarnecki’s power decomposition is a frequency domain definition. The instantaneous value of a periodic voltage and current expressed as a complex Fourier series with *n* harmonics as an equation.

$$\begin{aligned} u &= \sqrt{2}\,\mathrm{Re}\sum_n U_n e^{jnw_1 t} \\ i &= \sqrt{2}\,\mathrm{Re}\sum_n I_n e^{jnw_1 t} \end{aligned} \tag{2-34}$$

Where w_1 the fundamental angular frequency and *n* is the harmonic order. In this definition *P* is the average power, same as Fryze’s definition.

The load admittance corresponding to n’th harmonic can be written as:

$$Y_n = \frac{I_n}{U_n} = G_n + jB_n \tag{2-35}$$

Where G_n and B_n are the conductance and susceptance corresponding to n’th harmonic of load respectively.

The reactive power and distortion power of Czarnecki's definition is written as shown below.

$$Q_r = U\sqrt{\sum_n B_n^2 I_n^2}$$
$$D_s = \sqrt{S^2 - P^2 - Q_r^2} \qquad (2\text{-}36)$$

Therefore the Fryze's definition that satisfies the above characteristics is defined as shown below [13]

2.4.1.8. Fryze'sDefinition

The Fryze's power decomposition is shown by the following equations

$$i_a = \frac{P}{U^2}u \qquad (2\text{-}37)$$

i_a is the purely resistive part of the load current and has the same wave-shape and phase angle as the voltage. The second part of the current is a residual term named ir .It is determined by the equation below

$$i_r = i - i_a \qquad (2\text{-}38)$$

Active power can be derived as

$$P = UI_a \qquad (2\text{-}39)$$

And the reactive power according to Fryze is written by:

$$Q = UI_r \qquad (2\text{-}40)$$

I_a,I_r, and U are the RMS values of i_a,i_r and u .Fryze's definition doesn't have any distortion power (D), so when the reactive power is reduced to zero the power factor will be unity[13].

2.4.1.9. Reactive Power Characteristics at Sinusoidal Conditions

The most important reactive power characteristics at completely sinusoidal conditions are as follows[13]:

(i) If the reactive power is reduced to zero, the power factor will be unity.

(ii) The reactive power completes the power triangle, $S = \sqrt{P^2 + Q^2}$

(iii) Reactive power can be positive or negative (the sign specifies whether a load is of inductive or capacitive type).

(iv) Reactive power can be reduced to zero by inserting inductive or capacitive components.

(v) The reactive power can be calculated from the time domain waveforms of voltage and current

2.5. Cause of Harmonic Effect in Industrial Distribution

2.5.1. Capacitor Bank

Voltage distortion creates an extra power loss in capacitors. Series and parallel resonances between the capacitors and the rest of the system can also raise the voltage and current of the capacitor which consequently leads to increase in power loss and the total destruction of the capacitor.

2.5.2. Effect of Harmonics on Rotating Machines

The presence of harmonics increases the iron and copper loss and heating of both synchronous and induction motors results in reducing their efficiency. Positive sequence harmonics develop shaft torques that aid shaft rotation; negative sequence harmonics have the opposite effect that results in oscillating motor torque[14].

2.5.3. Transmission Lines and Cable

Harmonics develops heat in cables and transmission lines due to skin and proximity effects which are a function of frequency; consequently, the dielectric breakdown of insulatedcables happens and R_{ac} increases, therefore ($I^2 * R_{ac}$) losses increase[15].

2.5.4. Transformers and Reactors

(a) winding stray (eddy-current) losses due to non-sinusoidal load currents rise in proportion to the square of the load current and the square of the frequency;

(b) Hysteresis losses increase;

(c) Possible resonance may occur between the transformer inductance and the line capacitance[15].

2.5.5. Effects on Power Measurements

Since measurement instruments are initially calibrated on pure sinusoidal alternating currents, measurement errors will be introduced if they are used on a distorted power supply; For instance, when using a wattmeter to measure the power consumed by a device, the magnitude and direction of power flow are the key elements in power consumption calculations.

In general, the influence of harmonics upon the accuracy of meters is manifested in three

a. The meters are frequency sensitive, with negative error increasing with the frequency one can see from the fact that the inductance of the voltage coil is increased, that the magnetic field and the driving torque are decreased.
b. The magnetic fields of the voltage coil of a meter are not linear and contain some harmonic components due to compensation devices. It is believed that some additional torque will develop anyway, even though there aren't harmonics of voltage and current in the distribution network. These errors are negative.
c. The meters do not measure the component of energy due to the DC [16].

2.5.6. Equipment Misoperation

Circuit breakers, adjustable speed drives (ASDS), programmable logic controllers, and other equipment employ control circuits that may not operate correctly in a distorted environment. Distortion of the equipment supply voltage may cause inaccurate measurement of control input signals. It can produce multiple zero crossings per cycle of the input signal waveform, causing crossing detectors to malfunction. Typical problems include clocks running fast, hunting and oscillation in motor speed control systems, and circuit breaker failure to trip or nuisance trips. Voltage distortion can also reduce the ability of electronic equipment to withstand momentary voltage sags and interruptions[17].

2.5.7. Overloading of Neutral Conductors

In three-phase 4-wire circuits serving single-phase electronic power supply loads. Triplen harmonic currents from each phase add in the neutral. Though balancing loads among the phases will eliminate fundamental current in the neutral, this is not true for the triples. Neutral current can be approximately 70% higher than phase conductor current for circuits serving balanced computer loads[17][i].

2.6. Source of Harmonics

Harmonic distortion in power system is generally due to the widespread use of nonlinear loads. The sources of harmonics can be broadly classified as follows:

A) Harmonic originated at high voltages by supply authorities.

1. HVDC systems
2. Back to back systems
3. Static VAR compensation system.
4. Wind and solar power converters with interconnection.

B) Harmonics originated at medium voltages by large industrial loads like Traction equipment, variable speed drives, Thyristor controlled drives, Induction Heaters, Arc furnaces, Arc welding, Capacitor bank, electronic energy controllers.

C) Harmonic originated at low voltages by consumer end like single phase loadings, uninterrupted power supplier, semiconducting devices, CFL, Solid state devices, domestic appliances and accessories using electric devices, electronic fluorescent chokes, electronic fan regulator, light dimmers [18].

2.7. How Harmonics is Produced

All Static power converters use power semiconductor devices for power conversion from AC to DC, DC to DC, DC to AC and AC to AC; and constitute the largest nonlinear loads connected to the electric power systems in industrial distributions. These converters are used for various purposes in the industry, such as adjustable speed (or variable frequency) drives, uninterruptible power supplies, switch-mode power supplies etc. These static power converters used in a variety of applications draw non-linear (i.e. non-sinusoidal) currents and distort the supply voltage waveform at the point of common coupling (PCC)[6][19].

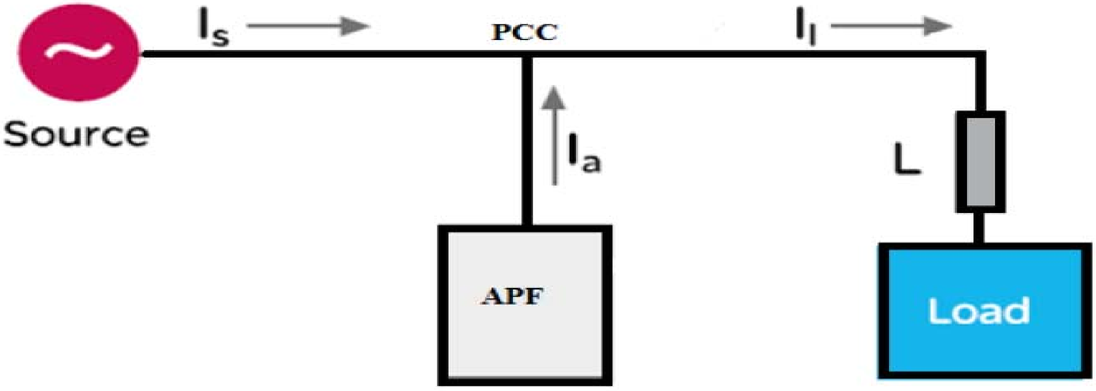

Figure 2-2: Connection of APF at the PCC [20]

2.8. Methods of Solving Harmonic Distortion

The problem of harmonics can be solved by installing a filter at the point of common coupling. Installation of Passive Power Filters(PPF) has been practiced sincethe mid-1940s because of their low cost and simplicity [21]. However, they have so many shortcomings such as; large size, limited lifetime, resonance, and fixed compensation [21][22]. In 1976 the researcher called L. Gyugyi [7] developed an Active Power filter (APF) that can alleviate the shortcomings of Passive Power Filter, but their installation and operational costs are high, as a result of the cost associated with semiconductor switching device with its controller. Moreover, the DC-link operating voltage of APF is higher than the load voltage in order to efficiently eliminate higher order of harmonics. Consequently, it increases its cost and power loss. Later, Hybrid filters were developed to effectively mitigate the drawbacks of a passive and an active filter in order to provide cost-effective harmonic compensation, particularly for high-power nonlinear loads [21][23].

2.9. Types of Filters Mitigating Harmonic Distortion at PCC

2.9.1. Passive Filter

Passive harmonic filters are combination of capacitors, inductors, and resistors. They are categorized as a tuned filter and a high pass filter

(i) Tuned Filter

They are the type of filters that filter particular types of frequency. The filter at Figure (2-3) separates single frequency where the filter at the figure the filter in Figure (2-4) provides a low impedance to two harmonics

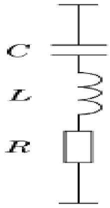

Figure 2-3: Single tuned filter

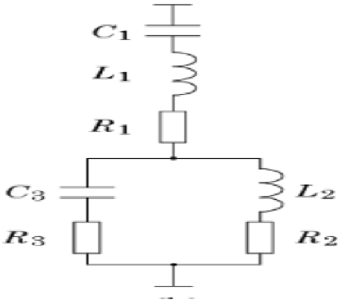

Figure 2-4: Double tuned filter

(ii) High Pass Filter

High pass filter provides a low impedance to high frequency .their configuration is shown in the Figure 2-5

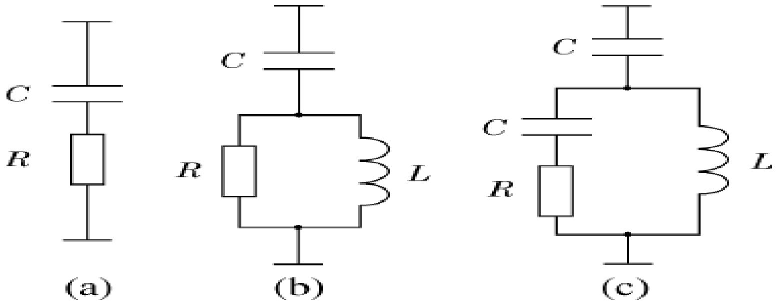

Figure 2-5 Types of high pass filters

The passive filter is installed in parallel with nonlinear loads such as diode/thyristor rectifiers, ac electric arc furnaces, and so on. The purpose of their installation is to provide low impedance pass for specific harmonic frequencies, thus absorbing the harmonic out of the load[24].

2.9.2. Active Filter

Active filter injects equal but opposite current or voltage distortion into the network, thereby canceling the original distortion[25]

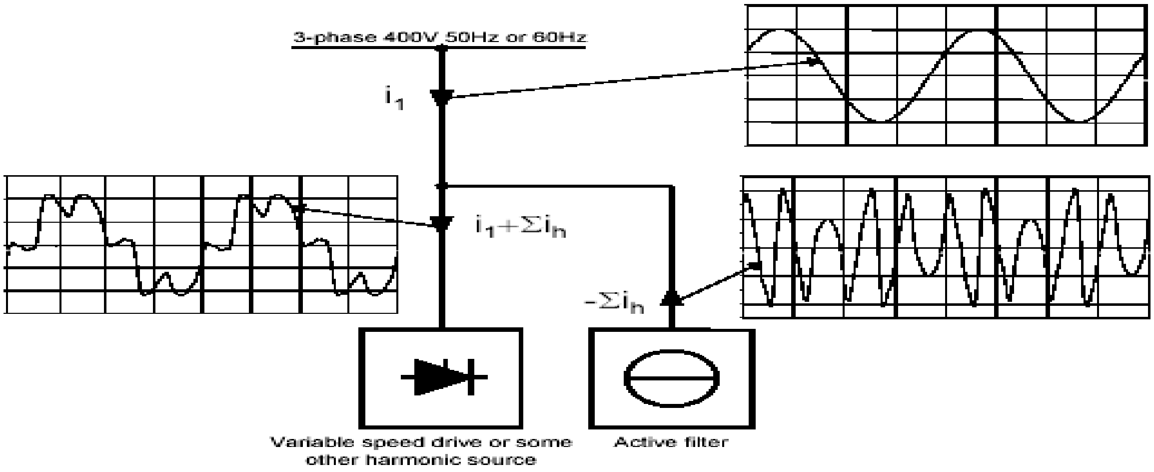

Figure 2-6Active filters

Active power filters are categorized as Shunt (parallel) active filters and Series active filters according to their circuit configuration.

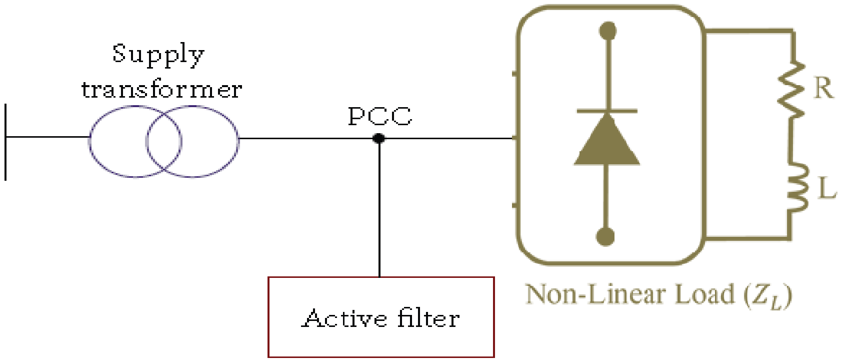

Figure 2-7 Shunt active filter circuit configuration [16]

Shunt active filter injects equal but opposite current to cancel out the harmonic current, active power filter draws compensating current from utility supply. The filter is operated to cancel out the load harmonic currents leaving the supply current free from any harmonic distortion. Parallel filters have the advantage of carrying the load harmonic current components only and not the full load current of the circuit[25].

This type of active harmonic filter can be controlled on the basis of the following methods:

(i) The controller detects the instantaneous load current iL,

(ii) The AHF extracts the harmonic current iL□ from the detected load current $iL$by means of digital signal processing,

(iii) The AHF draws the compensating current $iAF(=-iL$□$)$ from the utility supply voltage $v$sso as to cancel out the harmonic current iL□[24].

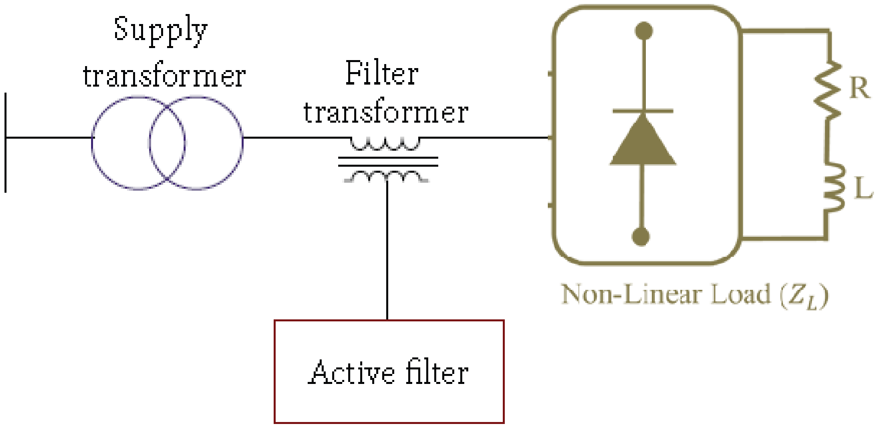

Figure 2-8 Series active filter circuit configuration

The idea here is to eliminate voltage harmonic distortions and improve the quality of the voltage applied to the load. This is achieved by producing a sinusoidal pulse width modulated (PWM) voltage waveform across the connection transformer, which is added to the supply voltage to counter the distortion across the supply impedance and present a sinusoidal voltage across the load. Series AHF has to carry the full load current increasing their current ratings and I^2R losses compared with parallel filters, especially across the secondary side of the coupling transformer.

Therefore Unlike the shunt AHF, the series AHF is controlled on the basis of the following methods:

(i) The controller detects the instantaneous supply current i_S,

(ii) The AHF extracts the harmonic current $i_S$from the detected supply current by means of digital signal processing,

(iii)The active filter applies the compensating voltage vAF $(=-Ki_{S\square})$ across the primary of the transformer. This will result in a significant reduction in the supply harmonic current $(i_{S\square})$, when the feedback gain K is set to be high enough[24]

The active filteristypically sized based on how much harmonic current the filter can produce, normally in amperage increments of 50Amps. The proper amperage of AHF can be chosen after determining the amount of harmonic cancellation current. Essentially, the filter consists of a VSD with a special electronic controller which injects the harmonic current onto the system180 out of phase to the system or drive harmonics. This results in harmonics cancellation [25].

2.9.3. Hybrid Filter

Hybrid filter is a combination of both passive filter and active filter. Hybrid filter is classified as

The series connection of an active filter and a passive filter and Combination of the series active filter and shunt passive filter. The passive filters absorb all the harmonics in the load current, while the series/shunt active filters combination decouples the utility from the load and the passive filters at the harmonic frequencies, and enhance the filtering capabilities of passive filters respectively, besides eliminating the resonance[26][27].

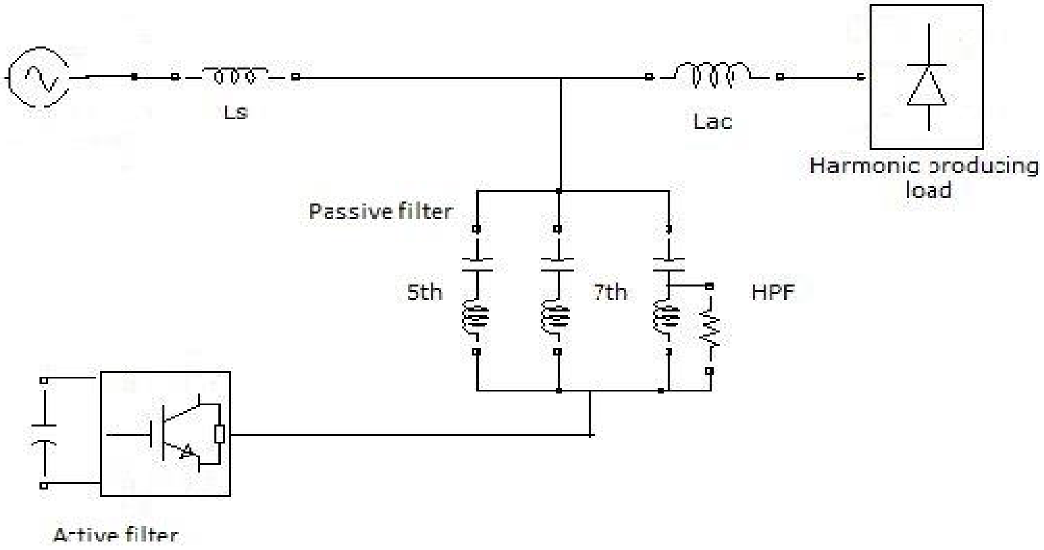

Figure 2-9 Series connection of an active filter and a passive filter [27]

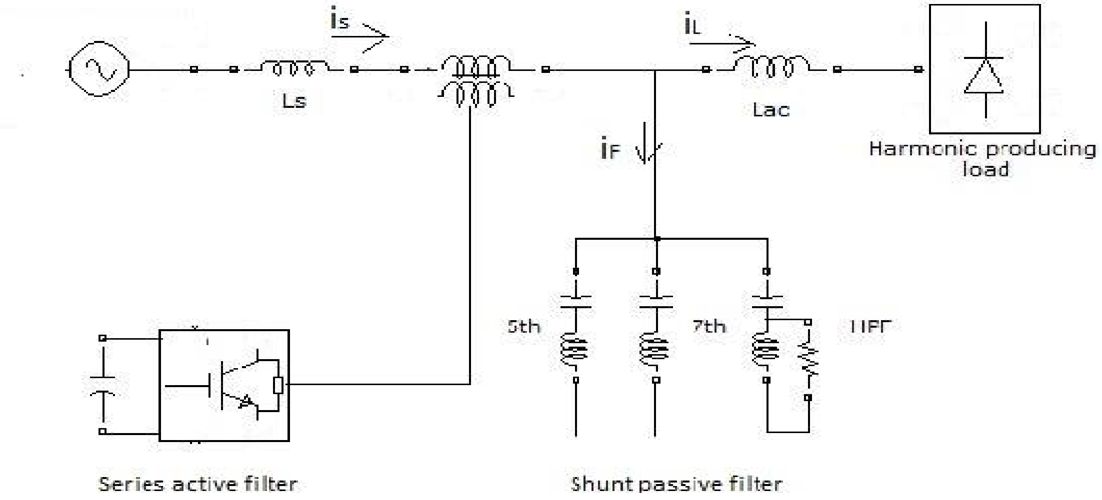

Figure 2-10 Combination of series active filter and shunt passive filter[27]

2.9.4. Main Components of Hybrid Filter

The heart hybrid filter is Reference current generator, Gating signal generator ,and DC voltage control

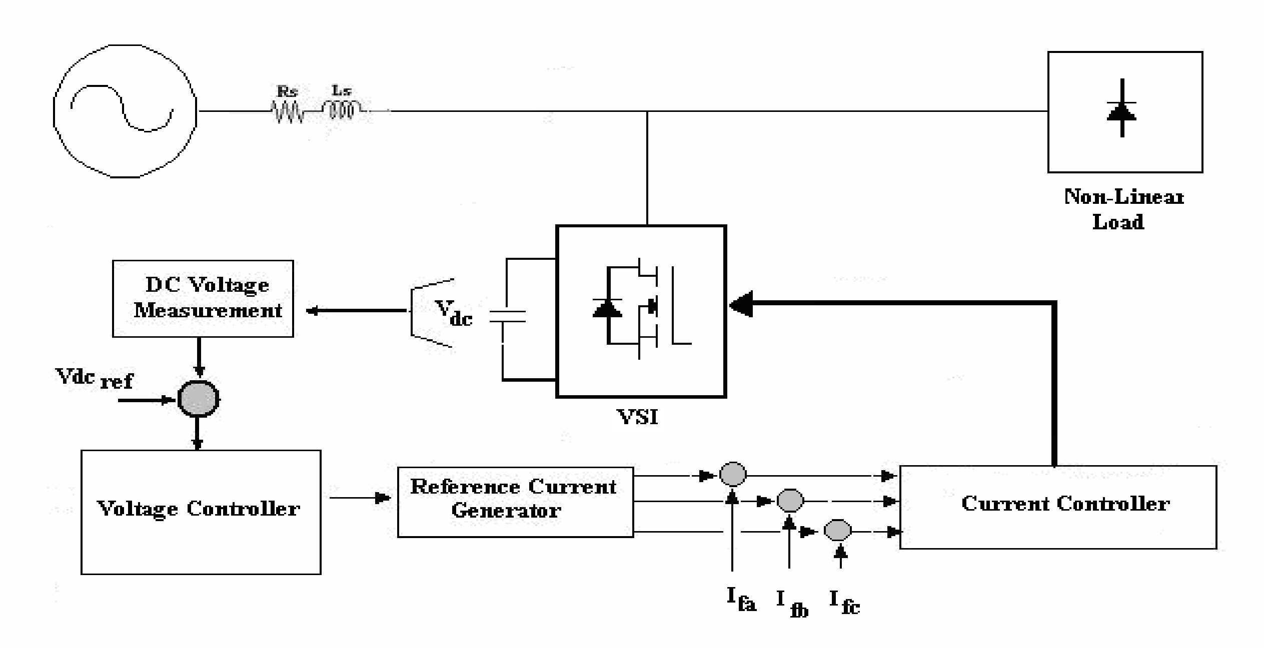

Figure 2-11 Block diagram of hybrid filter with its control system [28]

2.9.4.1. Reference Current Generator

Reference current generator is used to generate a signal having the desired amplitude and phase of compensation. It is classified as Time domain Techniques and Frequency Domain Techniques. Harmonic extraction methods in the time domain are based on the instantaneous derivation of compensating signals in the form of either voltage or current signals from distorted and harmonic polluted voltage or current signals. Some of the specific control techniques under this category are p-q Method, d-q Method, Synchronous Reference Fame Method (SRF),Current Hysteresis Control and Triangle-Comparison PWM Control [29][30].Some control strategies using Frequency Domain Techniques also developed, even though they are not practically used due to a large number of calculation required for their operation. But in this research, we use generalized fryze current control strategy due to its simplicity, concise and requires less computational efforts[28].

2.9.4.2. Gating Signal Generator

The function of APF control is to produce appropriate gating signals for the switching devices based on the estimated compensation reference signal. APF uses different control techniques to generate gating signals. Therefore performance an APF is influenced as per the selection of particular control technique. Some of the control strategies are Linear Control Technique and Hysteresis Current Control Technique[31].

2.9.4.3. DC Bus Voltage Control

The DC bus voltage must be kept at a constant value otherwise the source current will change and distorted from the sinusoidal waveform. Various types of controllers like Proportional-Integral (PI), adaptive, Neuro and Fuzzy Logic Controller (FLC) for DC bus voltage regulation are well presented in different kinds of literature. PI, PID, fuzzy logic based controllers are used for DC bus voltage control of shunt active power filter[32].

2.10. Fuzzy Logic Controller

2.10.1. What is Fuzzy Logic Controller

The fuzzy logic controller (FLC) is a technique that imitateshuman-like thinking. It belongs to the class of “intelligent control,” “knowledge-based control,” or “expert control. It uses knowledge-based decision-making employing techniques of fuzzy logic in determining the control actions[33].

2.10.2. Fuzzy Algorithm

In a fuzzy logic controller, the control action is determined from the evaluation of a set of simple linguistic rules. The development of the rules requires a thorough understanding of the process to be controlled, but it does not require a mathematical model of the system. The internal structure of the fuzzy controller is shown below [34].

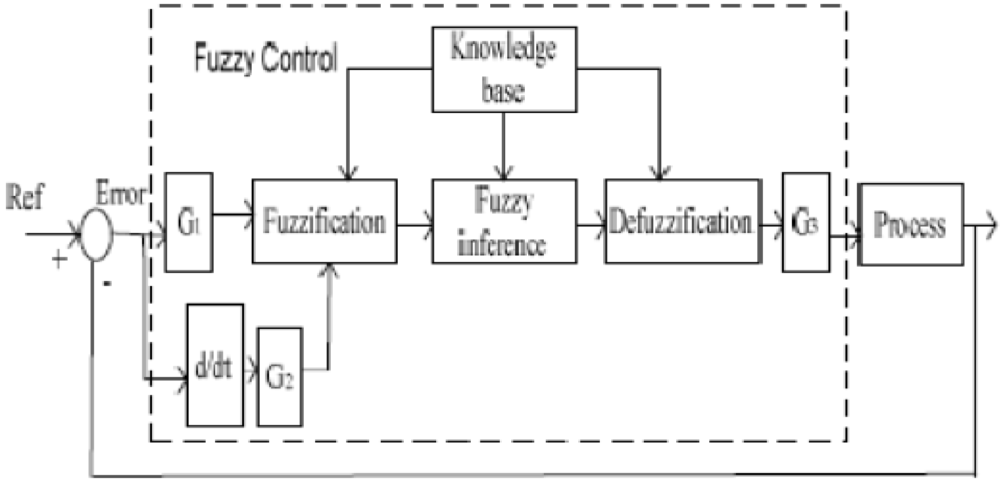

Figure 2-12 Structure of fuzzy controller [35]

A fuzzy inference system (or fuzzy system) basically consists of a formulation of the mapping from a given input set to an output set using fuzzy logic. This mapping process provides the basis from which the inference or conclusion can be made. A fuzzy inference process consists of the following steps:

Step 1: Fuzzification of the variables

- Develop a set of linguistic control rules (protocols) that contain fuzzy variables as conditions (process outputs) and actions (control inputs to the process).
- Obtain a set of membership functions for process output variables and control input variables.

Step 2: Application of fuzzy operator (AND, OR, NOT) in the If (antecedent) part of the rule

- Using the "fuzzy AND" operation (typically, *min*) and the "fuzzy implication" operation (typically, *min*) on each rule in Step 1, and using Step 2, obtain the multivariable rule base function *Ri* (a multidimensional array of membership values in the discrete case) for that rule.

Step 4: Aggregation of the consequents across the rules

- Combine (aggregate) the relations *Ri* using the fuzzy connectives ELSE (fuzzy OR; typically, *max*) to obtain the overall fuzzy rule base (relation) *R* (a multidimensional array in the discrete case).

Step 5: Defuzzification

In general, the control actions may be determined in real time as follows:

1. Fuzzify the measured (crisp) process variables (for example, a fuzzy singleton may be obtained by reading the grade value of the corresponding membership function at the measured value of the variable).
2. Match the fuzzy measurements obtained in Step 1 with the membership function (array in the discrete case) of the fuzzy rule base (obtained in previous Step 4), using the compositional rule of inference.
3. Defuzzify the control inference obtained in Step 2 (for example, the mean of maxima method or the centroid method may be used here).

These steps reflect the formal procedure in FLC [33][34].

2.10.3. Advantage of Fuzzy Logic Controller

It has many advantages over the conventional control techniques. It doesn't need the accurate mathematical model and can work in the nonlinear system. More importantly, it has short settling time and very low steady-state error that reduces the ripples in the DC capacitor voltage. Therefore it reduces the THD at PCC better than PID[36][37].

2.11. Work Done by Other Researchers

Various researchers have made a contribution to an investigation and mitigation of harmonic problems based on the hybrid filter using different control strategies. For instance, the authors referred[38]developed a fuzzy logic controlled based hybrid filter. It was a combination of series Active filter and shunt passive filter. In their report, they stated that they have designed the power filter based on fixed RL and RC loads to reduce the harmonic and improve the power factor.

The research referred[39] has developed fuzzy logic control of shunt active power filter for power quality improvement. They simulated their model under steady state and transient condition using fixed RL load conditions. The designed filter can able to reduce the harmonic distortion level to standard harmonic limits as specified by IEEE 519[39].

The researchers [40] developed hybrid active power filter dc bus control based on fuzzy PID control aiming to reduce the problem of overshoot and static error. They simulated the result using fixed RC load conditions and they conclude that the designed fuzzy controlled hybrid filter can able to reduce the overshoot and static error greatly.

The researchers [41] designed a fuzzy logic controller for three-level series active power filter to compensate voltage harmonics. In their work, they present principles of operation and design of a fuzzy logic control algorithm to control the harmonic voltages. The viability of the proposed algorithm is validated with computer simulation under fixed RL load conditions. The obtained results showed that source voltage is sinusoidal and in phase with source current as well as a reduced total harmonic distortion.

Others researchers[42]have designed a cost-effectivehybrid power filter. It was a combination of shunt Active power filter and passive filter based on constant RL load. Those proponents stated that they can able to provide a cost-effective, efficient and reliable hybrid filter that can damp out the resonance created between the line impedance and passive filter.

Some other researchers[43]also developed a hybrid filter. The designed a hybrid filter was a combination of a shunt passive filter connected in series with an active power filter. They have used Hysteresis control mechanism and P-Q theorem to track the harmonic currents in their design. They validate their design using small and slowly varying resistance load.

The researcher referred[44] had developed an efficient control scheme for five level shunt active power filters based on fuzzy control approaches In their paper, five-level (NPC) shunt active filter using synchronous current detection method based on fuzzy logic control approaches is proposed to mitigate current harmonics and compensate reactive power. The performances of the proposed
Shunt APF is evaluated through computer simulations for transient and steady-state conditions using Matlab-Simulink program and SimPowerSystem toolbox under fixe RL load condition.

Some other researchers referred in [45][46][47]developed a hybrid filter using different control mechanisms based on fixed or some used small variation of loads.

As per the report of various researchers, the majority of the work done on the design of power filter is based on fixed load conditions, or for a small range of load variations. But in practical life apart from small load variation due to the activities of customers, power system distribution is exposed to various types of faults. Hence, it changes the loads greatly. Consequently, it exacerbates the harmonic distortion level. Moreover, many researchers as referred[48][49] have used power quality analyzers to quantify the harmonic level at different bus and designed suitable filters accordingly. These methods are expensive and time-consuming as they need to take harmonic measurements systematically. They only consider the circumstances in which they were taken, therefore can't be guaranteed to reflect the worst possible conditions of a system. Measurements can also be inaccurate due to measuring errors or flawed use of instruments[50]. Therefore, there is a need of developing a model which gives relative flexibility to investigate Harmonic distortion at PCC considering various operating conditions of the plant and designing a fuzzy logic controlled hybrid filter that can maintain the THD well within IEEE standards taking contingency under consideration so that it can effectively mitigate the harmonic levels even in the worst case operation of the plant.

CHAPTER THREE

3. Methodology

3.1. General Background of the Industry

The red sea bottlers share company receives the electric power from the Denden substation which is 4km of far. The 15kv incoming line is connected to the 630 KVA step-down transformer which converts the voltage to 400V. The outgoing section of the transformer has two feeders that distribute power to the two sections named the bottling section and utility section. The bottling section has seven subsections bottle washer, filling machine, bottle conveyer, crate conveyer, crate washer, packing machine and paramix. In all these subsections there are several motors performing different duties. For the case of utility failure, the company is equipped with two diesel generator (Perkins generator) 550KVA, 440KW, 0.8PF, 1500RPM and Caterpillar type generator 725KVA,580KW,0.8PF,1000RPM Caterpillar type generator 725KVA, 580KW.0.8PF,1000RPM ratings. The caterpillar type generator switched on during utility failure using Automatic Transfer Switch (ATM) whereas the other standby generator named Perkins switched on manually if the caterpillar fails. Both generators have the capacity to supply to all loads of the industry

3.2. Developing the Model of the Industrial Distribution

3.2.1. The Utility or Substation

The data needed is the line to line voltage (VLL), short-circuit MVA (SC MVA), and X/R. Obtaining the voltage is simple enough. SC MVA is the power available at a bolted three-phase fault. Bolted means all three phases connected together with no added impedance. X/R is the ratio of reactance to resistance in the supply. SC MVA and X/R may need to be derived from other data [51].

$$SCMVA = \sqrt{3} * I_{SC} * V_{LL}, \tag{3-1}$$

Where $I_{sc}$is expressed in KA and V_{LL} –in KV

$$X/R = \tan(\cos^{-1} PF) \qquad (3\text{-}2)$$

3.2.2. Transformer Modelling

Transformers are specified by output voltage (V), KVA rating, percent impedance (%Z), and X/R ratio. All this information apart from X/R is usually available on the transformer nameplate. If the X/R is not specified 4.9 can be used for calculations. Therefore the impedance(Z) can be calculated from V,KVA, and %Z[52].

$$Z = \frac{Z * V^2}{kVA * 100{,}000} \quad \text{Or} \quad Z = \frac{Z}{100} * \frac{V^2}{VA} \qquad (3\text{-}3)$$

3.2.3. Transformer Impedance

Z%=4% S=630KVA Secondary voltage =V_s=400v f=50hz

Since

$$Z_t^{\,2} = R_t^{\,2} + X_t^{\,2}$$
$$Z = \frac{V_s^{\,2}}{SKVA} * Z\% = \frac{400^2}{630*10^3} * 0.04 = 0.01\Omega \qquad (3\text{-}4)$$

Assuming $\frac{X_t}{R_t} = 4.9$

Therefore $R_t = 4.12*10^{-3}\Omega$ and $X_t = 0.02\Omega$ then

$$L_t = \frac{X_t}{2 * \Pi * 50} = \frac{0.02}{2 * \Pi * 50} = 63.7\,\mu\Omega$$

The transformer data for modeling is

$R_t = 4.12*10^{-3}\Omega$ $X_t = 0.02\Omega$ $L_t = 63.7\mu\Omega$

3.2.4. Computing of the Transmission Line Parameters

The transmission line extends 3728 meters from the substation to the factory transformer. It is 95mm^2 aluminum type conductor.

The resistance of the cable can be calculated as follows

The resistivity of aluminum is $\rho = 2.65 * 10^{-8} \Omega m$

$$R_C = \rho \frac{l}{A} = 2.65 * 10^{-8} \frac{3728}{95} = 1.04\Omega \tag{3-5}$$

Similarly, the inductance can be calculated

$$L = 2l[2.303 \log(4l/d) - 1 + \mu/4 + (d/2l)] \text{ Or } L = 2l[\ln(2l/r) - 0.75]nH \tag{3-6}$$

In the above equation, L is the inductance in nH (10^{-9}Henry), $l$is the length and d is the diameter of the wire/rod (both in cm). μ is the permeability of the material (=1.0, except for iron and other ferromagnetic materials) [53].

Thus, L=9969188 nH

Therefore the inductive reactance would be

$$X_L = 2 * \Pi * f * L = 2 * \Pi * 50 * 0.009969 = 3.13$$

3.3. Modeling of Loads

3.3.1. VFD Modeling

A Variable Frequency Drive (VFD) is a type of motor controller that drives an electric motor by varying the frequency and voltage supplied to the electric motor. Hence, the VFD consists of three major components; the first is the front end, which is usually a 6 or 12 pulse rectifier. The second is the inverter stage that converts the generated DC voltage to controllable frequency AC voltage to control the speed of the motor. The last stage is the DC link (shunt capacitor) that couples the two main stages and help in reducing the ripples of the DC voltage in case of VSI and PWM topologies. The DC link capacitor in case of VSI can block the propagation of the harmonics generated from the inverter side from entering the AC system. This conclusion calls for a simple representation of the converter and the motor collectively by a DC current source instead of a harmonic current source. The most common rectifier circuit in three-phase PWM drives, 6-pulse VFD uses six-pulse diode rectifier. A 6-pulse rectifier is a most robust and cost-effective solution in the VFD industry as of today, even though input current contains some amount of low order harmonics. The capacitor and resistor dependupon the active power of the inverter. It can be modeled as shown in the Figure(3-1)[54][55][56][57][58].

Since the capacitive reactance affects the THD [59]

As a general rule $\omega R_L C = 1, \approx [12\%], \omega R_L C = 2, \approx [6\%], \omega R_L C = 3, \approx [4\%]$ (3-8)

Assuming the lowest distortion

The capacitance value would be

$$\omega R_L C = 3, \approx [4\%] \tag{3-9}$$

The general formula is

$$C_x = \frac{Q_T}{2\Pi f(R_L)}, \text{ where } 1 < Q_T < 3 \tag{3-10}$$

$$R_L = \frac{(V_{DC}{}^2)}{P_{out}} \tag{3-11}$$

Where $V_{DC} =$ 1.35 $V_{DC} = 1.35 V_{LL}$

Therefore for VFD motor having apower rating of 15KW, the capacitance value would be

$$R_L = \frac{(400*1,35)^2}{15000} = 19.44$$ Thus the capacitance value would

$$C_x = \frac{3}{2*\Pi*50*19.44} = 49mF$$

Therefore it can be modeled as shown in the Figure 3-1

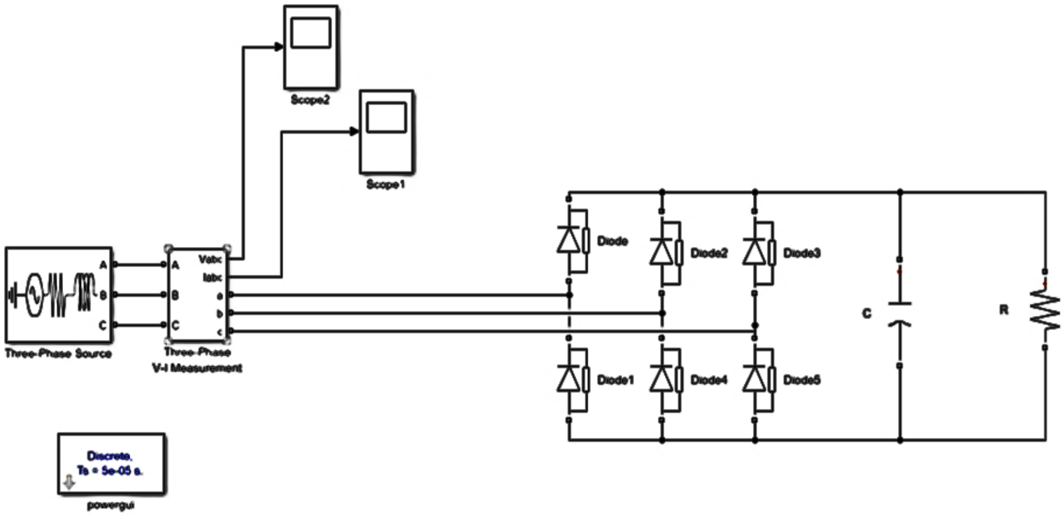

Figure 3-1: Six pulse variable frequency drive (VFD*)*

Similarly, all the VFD available in the industry can modeled following the same procedure

3.3.2. Switched-Mode Power Supply (SMPS)

These power supplies are the "front-end" of single-phase 120V loads such as PCs and home entertainment equipment. Typically, they have a full-wave diode rectifier connected to the AC supply system and a capacitor, and the capacitor serves as a low-ripple “battery” for the DC load. Unfortunately, low ripple means that the AC system charges the capacitor for only a fraction of each half-cycle, yielding an AC waveform that is highly peaked[60]

The capacitor and resistor can found out using the following formulas[61].

$R = \frac{V_{dc}^2}{P_{rated}}$ Where V_{dc} the instantaneous value of the DC is link voltage and P_{rated} is the rated power of the modeled SMPS device.

Similarly, the capacitor value can be computed as shown below

$$Rf = \frac{1}{\left[\sqrt{2}\left(2 * f_r * RC - 1\right)\right]} \text{[62][63]} \qquad (3\text{-}12)$$

Where Rf the ripple is afactor and f_r is the ripple frequency.

Therefore the Switch mode power supplies (SMPS) can be modeled as shown below in Figure (3-2)

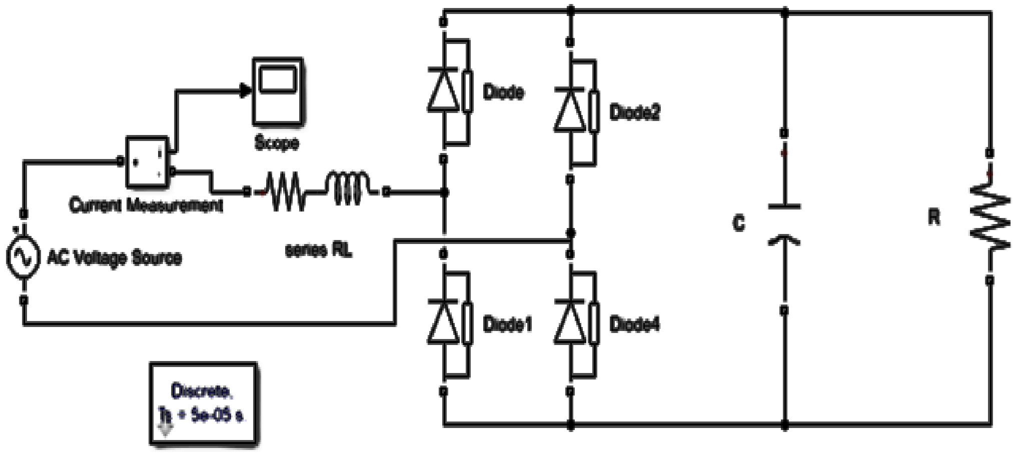

Figure 3-2: Switch mode power supply (SMPS)

3.3.3. Modeling of Induction Motors

The normal induction motors are modeled as a constant RL load being assumed as linear passive loadsbecause an Induction motor is basically a large inductor in which the current doesn't change very fast as per the inductive property[64][65][66].Therefore the parameters can be computed as follows.

$$Z_n = \sqrt{3}\frac{V_n}{I_n} \tag{3-13}$$

$$R_n = Z_n * \cos\varphi \tag{3-14}$$

$$L_n = \frac{Z_n * \sin\varphi}{2\pi f} \tag{3-15}$$

Or

$$R = \frac{V^2}{P} \tag{3-16}$$

$$L = \frac{\left(\frac{V^2}{Q}\right)}{2\pi f} \tag{3-17}$$

Therefore for normal induction motor P=0.75KW /2.1A and 400V and power factor 0.8, the impedance can be calculated as follows.

$$Z_n = \sqrt{3}\frac{400}{2.1} = 329.9\Omega, \quad R_n = 329.9 * 0.8 = 263.9, \quad L_n = \frac{329.9 * 0.6}{2 * \pi * 50} = 0.63$$

Similarly, the impedance of other inductor motors can be computed using the same procedure. However, to reduce the computational effort, the induction motors available in a particular department were lumped first, based on the direct addition of their power rating since they are connected in parallel.

3.4. Model of the Whole Industrial Network for Harmonic Study

The overall model of the industrial distribution is developed considering the following assumption. The induction motor of each department is lumped, whereas the VFD motors are preferred not to be lumped because the harmonics generated by each VFD drives has a canceling property that reduces the overall harmonic distortion at the PCC. Hence, considering the above-stated cases the overall model of the plant with both active and passive filter is as shown below in Figure (3-3).

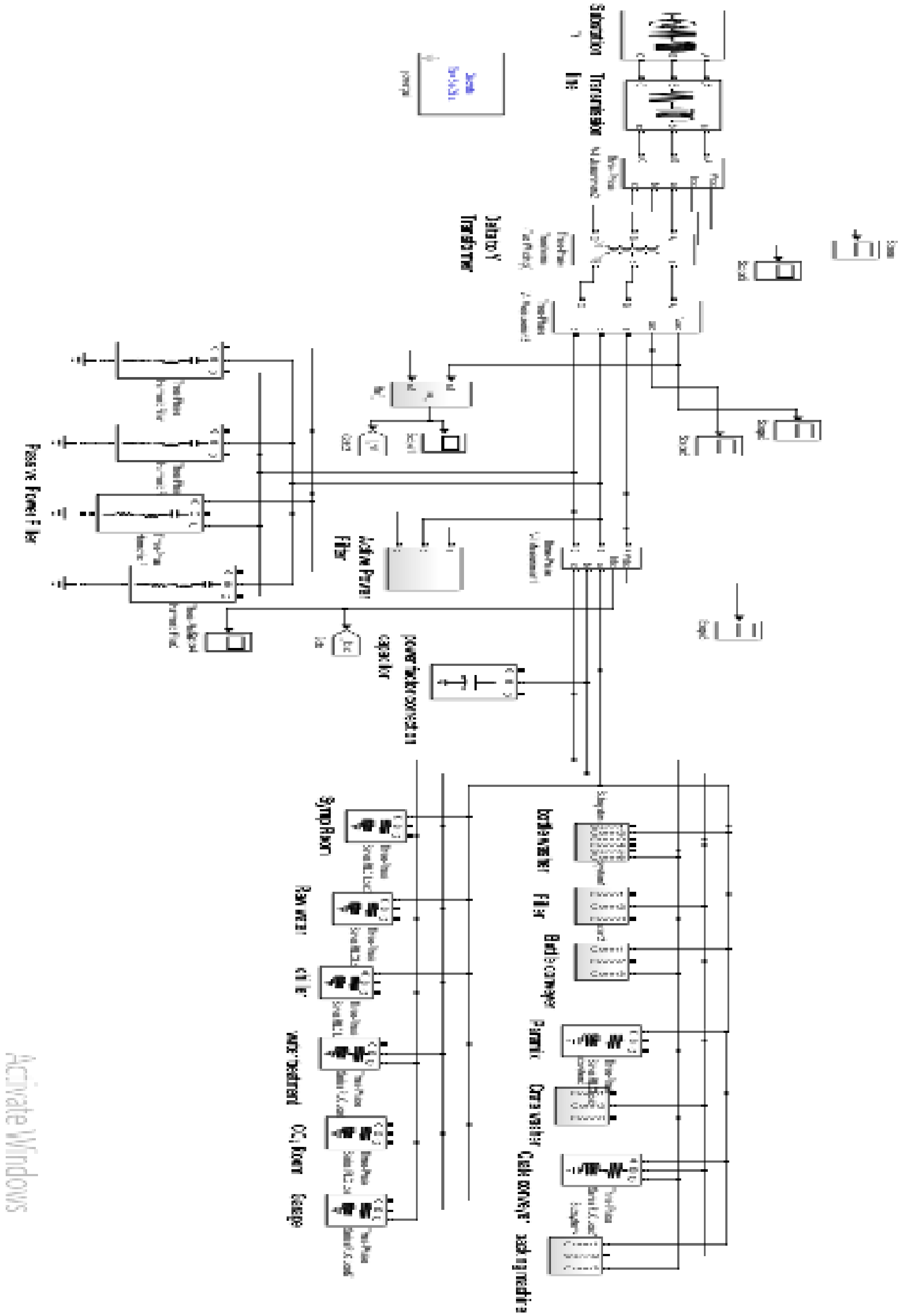

Figure 3-3: Model of the whole industrial network

3.5. Proposed Control Algorism

The control algorism used in this research is generalized fryze current control strategy. This strategy is concise and requires less computational efforts since it deals directly with the abc phase voltages and line currents. The elimination of the Clark transformation makes this control strategy simple [67]

The hybrid filter generates appropriate compensating currents based on the load currents, DC bus voltage and a peak voltage of AC source (Vsm).

The instantaneous voltages of AC source can be represented as in equation below.

$$\begin{aligned} V_{sa}(t) &= V_{sm}\cos(wt) \\ V_{sb}(t) &= V_{sm}\cos(wt-120) \\ V_{sc}(t) &= V_{sm}\cos(wt-240) \end{aligned} \tag{3-18}$$

The ultimate role of the proposed hybrid filter is to eliminate harmonics and compensate the current unbalance and reactive power of the load. After compensation, the AC source feeds the fundamental active power component of load current and loss of inverter for regulating the DC capacitor voltage. Hence the peak of source reference current I_{sm} has two components. The first part derived from the average load active power and the second component is derived from the DC capacitor voltage regulator [67].

The instantaneous apparent power is given by

$$p(t) = \sum_{k=1}^{m} v_k(t) i_k(t) \tag{3-19}$$

By definition, the active power P_{DC} equals the average value (DC components) over one period T of the instantaneous power $p(t)$.

$$P_{DC} == \frac{1}{T}\int_0^T p(t)dt = \frac{1}{T}\int_0^T v(t)i(t)dt = V_{RMS} I_{RMS} \cos\theta \tag{3-20}$$

This average power can be obtained by passing $p(t)$ through the low pass filter or moving average filter.

Considering the unity power factor the average active power of the of the AC source can be represented as below

$$P_s = 3/2 V_{sm} I_{smp} = P_{DC} \tag{3-21}$$

Where V_{sm} is the maximum amplitude voltage source and can be calculated at sampling frequency fs from the source phase voltages V_{sa}, V_{sb}, V_{sc} ,at each sampling instant, it can be expressed as shown below

$$V_{sm} = \sqrt{2/3\left(V_{sa}^2 + V_{sb}^2 + V_{sc}^2\right)}, \tag{3-22}$$

From this equation, the first part of AC side current can be derived

$$I_{smp} = 2/3 * (P_{DC} / V_{sm}) \tag{3-23}$$

The second component of AC current source is obtained from DC link capacitor

The reference stored energy on the DC link capacitor is given by

$$E_{dcn} = \frac{1}{2} C V_{dcn}^2 \tag{3-24}$$

Where is the reference or nominal voltage across the capacitor C.

When the capacitor is charged with a V_{dc} voltage the energy unbalance in the DC link capacitor is [68]

$$\Delta E_{dc} = \frac{1}{2} C\left(V_{dcn}^2 - V_{dc}^2\right) \tag{3-25}$$

This energy unbalances must be supplied by the AC source. Imposing a sinusoidal input current, the change in the capacitor energy must satisfy

$$\Delta E_{dc} = \int_0^T \left[\sum_{i=0}^{2} V_{sm} \sin\left(\omega_s t - \frac{2\Pi}{3} i \right) I_{smd} sin\left(\omega_s t - \frac{2\Pi}{3} i \right) dt \right] \tag{3-26}$$

The I_{smd} is the active current supplied to the DC link capacitor.

So the reference current to maintain the DC voltage is given by

$$I_{smd} = \frac{2}{3} \frac{\Delta E_{dc}}{TV_{sm}} = C \frac{V_{dcn}^2 - V_{dc}^2}{3TV_{sm}} \tag{3-27}$$

The desired peak current of AC source is then obtained using the equation below.

$$I_{sm} = I_{smp} + I_{smd} \tag{3-28}$$

If the total harmonic and reactive power of the load is supplied by the Active power filter then there will not be any harmonic in the source current. Then AC source current will be sinusoidal and in-phase with source voltages. Therefore the desired currents of AC source can be calculated by multiplying peak source current with unity sinusoidal signal and these unity signals. Therefore the desired or reference source current can be obtained by the using equations below.

$$I_{ref\_a} = I_{sm} * \left(\frac{V_a}{V_{mag}}) \right)$$

$$I_{ref\_b} = I_{sm} * \left(\frac{V_b}{V_{mag}}) \right) \tag{3-29}$$

$$I_{ref\_c} = I_{sm} * \left(\frac{V_c}{V_{mag}}) \right)$$

Finally, the reference currents of the hybrid filter can be obtained by subtracting the reference source current from load current as shown below.

$$i_{ca} = I_{la} - I_{ref\_a}$$

$$i_{cb} = I_{lb} - I_{ref\_b} \tag{3-30}$$

$$i_{cc} = I_{lc} - I_{ref\_c}$$

These reference currents i_{ca}, i_{cb}, i_{cc} will be fed to the switching circuit of carrier-less hysteresis controller for producing the necessary PWM pulse to the voltage source inverter. So the voltage source inverter with the closed loop system acts as a controlled current source and produces the exact reference waveform at the output. This output of the shunt active filter compensates the line harmonics and the line current becomes sinusoidal.

3.6. Design of DC Link Capacitor and AC Link Inductor

The selection of DC link capacitor and AC link inductor affects the performance of the active filter. Therefore they have to be properly selected to get the best result.

3.6.1. AC Link Inductor

The standard inductor differential equation is given by

$$\frac{di}{dt} = \frac{\Delta V}{L_{flter}} \tag{3-31}$$

The maximum possible inductance should be used to achieve the lowest average switching frequency

Therefore the maximum value of the inductor can be obtained using the equation below

$$L_{filter} = \frac{\Delta V}{\max\left(\frac{di}{dt}\right)} \tag{3-32}$$

The maximum $\frac{di}{dt}$ of the actual compensating current has to be determined for each harmonic component based on its amplitude and frequency. Hence the maximum value of the inductor to be considered is as shown below

$$L_{filter} = \frac{\left(\frac{V_{dc}}{\sqrt{2}}\right) - \left(\frac{V_{line}}{\sqrt{2}}\right)}{n * \omega * I_n} \tag{3-33}$$

Where $\omega = 2 * \Pi * f$ (f is the fundamental frequency and I_n is the current of nth harmonic order.

The inductor should allow the flow of compensating current which includes the harmonic components of load current simultaneously it should block the high-frequency signals generated by the switching inverter to the supply[69].

The table below shows the amplitude of each harmonic in the FFT of load current. Neglecting Tripelen and third harmonics up to 19th order are considered for inductor design.

Table 3-1: Amplitude of different orders of harmonics

Order of harmonics	Amplitude
5th	0.013
7th	0.0033
11th	0.0029
13th	0.0012
17th	0.0011
19th	0.0003

Other Important parameters for the design are

$I_L = 438.7A$ and $V_{line} = 400V$

$V_{dc} = \sqrt{2} * V_{line} = \sqrt{2} * 400 = 565.7$, Therefore V_{dc} can be considered 600

$$I_L = \frac{\frac{600}{\sqrt{2}} - \frac{400}{\sqrt{2}}}{\begin{pmatrix} 5*2\Pi*50*0.013*438.7+7*2\Pi*50*0.0033*438.7+11*2\Pi*50*0.0029*438.7+ \\ 13*2\Pi*50*0.0012*438.7+17*2\Pi*50*0.0011*438.7+19*2\Pi*50*0.0003*438.7 \\ \end{pmatrix}} = 6.4mH$$

3.6.2. Design of DC Link Capacitor

$$C = \frac{P*T}{\frac{1}{2}\left(V_{dc}{}^2\right)}; \text{ Where } P = \frac{V_{line}}{\sqrt{2}} * I \qquad (3\text{-}34)$$

Therefore the capacitor value would be

$$C = \frac{124083*40*10^{-3}}{\frac{1}{2}\left(V_{dc}\right)^2} = 27574\mu\text{F}$$

3.7. Design of the Passive Filter

The capacitive reactance needed to improve power factor with θ_1 to power factor with θ_2 is defined by

$$\text{VARs} = \text{P} (\tan\theta_2 - \tan\theta_1) \qquad (3\text{-}35)$$

Where

$$\text{P} = (\text{V})(\text{I})\cos\theta_2 \qquad (3\text{-}36)$$

The capacitive reactance would be calculated using the equation below

$$X_C = \frac{V^2}{VARs} \qquad (3\text{-}37)$$

The capacitor value will be [70]

$$C = \frac{Q_C}{V^2 w} \frac{n^2 - 1}{n^2} \tag{3-38}$$

Similarly, the inductance formula is

$L = \frac{1}{h^2 w_1^2 c}$, and $R = \frac{X_L}{Q_f}$ where the Q_f is the quality factor (3-39)

Using the above formulas the computed parameters of the passive filter are as shown below

Table 3-2: Passive filter parameters

Filter type	R(mΩ)	L(μH)	C(mF)
5th single tuned	41	4.88	83
7th single tuned	55.8	4.06	50.9
11th single tuned	52.5	2.43	34.4
13th single tuned	89.3	3.5	17.2

3.8. Design of Fuzzy Logic Based DC Voltage Control

The equation (3-40) derived from the energy stored in the capacitor is used to design FLC controller as shown in the Figure (3-4).

$$I_{smd} = C \frac{V_{dcn}^2 - V_{dc}^2}{3TV_{sm}} \tag{3-40}$$

From the equation (3-40) the block diagram of the control system is

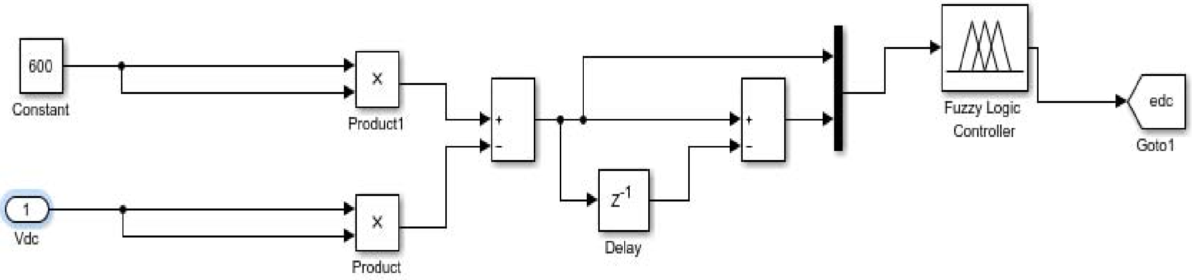

Figure 3-4: Design of the control system

Where the output of the controller is $edc = V_{dcn}^2 - V_{dc}^2 = 600^2 - V_{dc}^2$ (3-41)

3.9. Membership Function

Triangular membership function was chosen from other membership functions because it has a different degree of conformity at different points.

The graph shown in the Figure 3-5 is input error in a triangular membership function.

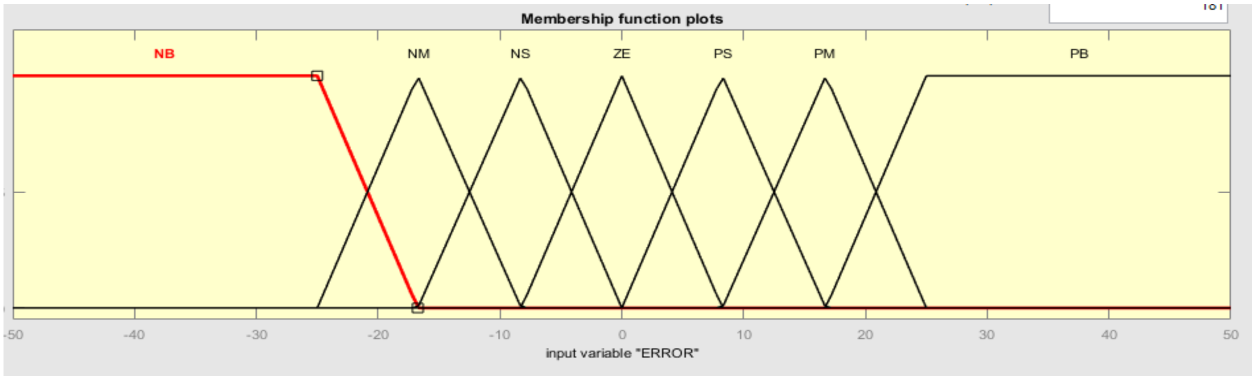

Figure 3-5: Input error membership function

The graph shown in the Figure 3-6 is input change of error in a triangular membership function.

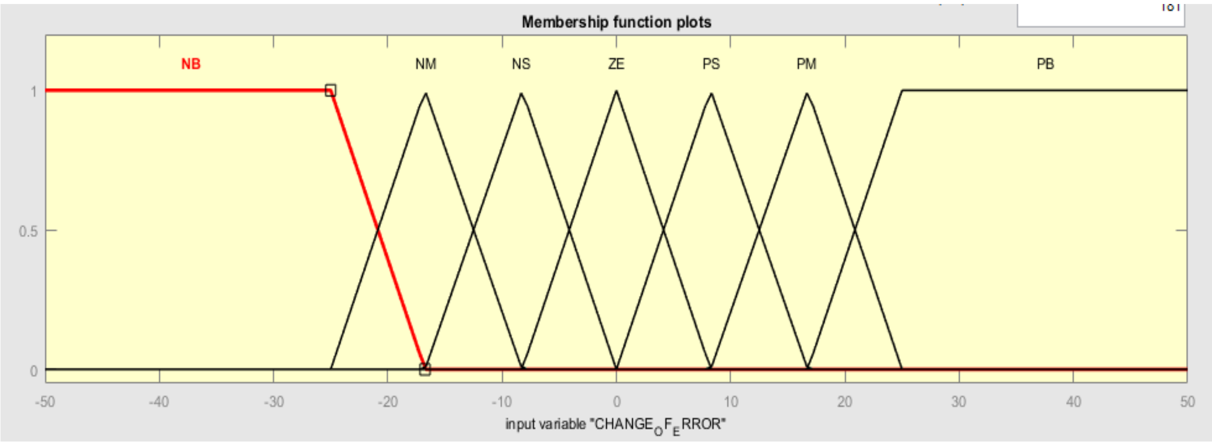

Figure 3-6: Input change of error membership function

Similarly, the output membership function of the controller is in triangular membership function is shown in Figure 3-7.

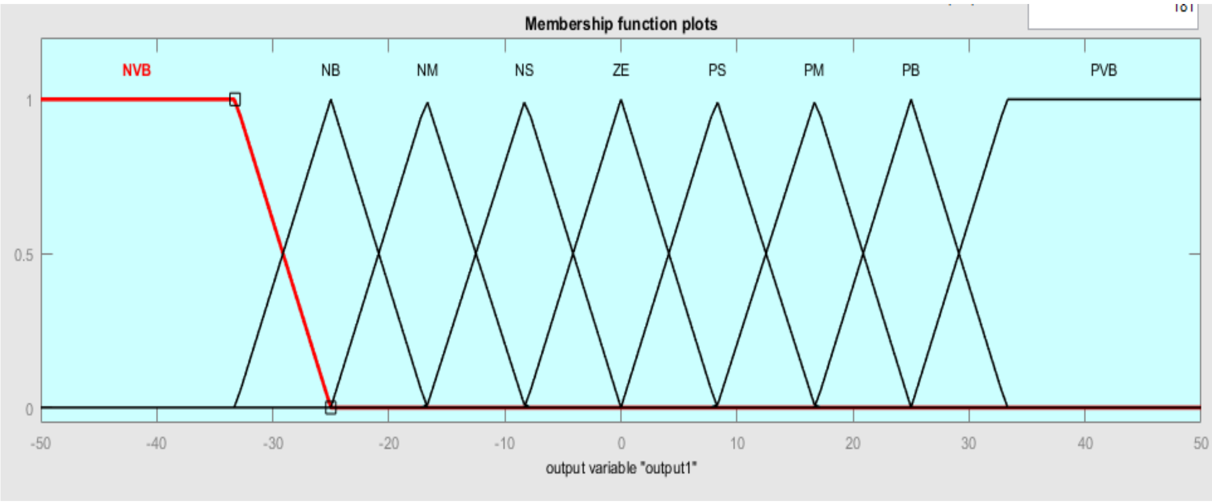

Figure 3-7: Output membership function

3.10. The Rule Base

The rule is constructed based on the concept shown below

$e_c = e_p + \Delta e$, where e_c=current error, e_p = previous error and Δe=change of error

The output of the controller (Δu) is directly proportional to the current error (e_c).

Therefore $\Delta u = e_p + \Delta e$ which implies the output of the controller is the summation of both e_p and Δe .if the inputs are defined as follows .the rule base can be generated using simple addition.

Table 3-3: Membership table

e	NB	NM	NS	Z	PS	PM	PB
Δe							
NB	NVB	NVB	NVB	NB	NM	NS	Z
NM	NVB	NVB	NB	NM	NS	Z	PS
NS	NVB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PVB
PM	NS	Z	PS	PM	PB	PVB	PVB
PB	Z	PS	PM	PB	PVB	PVB	PVB

Where

NVB is negative very big

NB is negative big

NM is negative medium

NS is negative small

Z is zero

PS is Positive small

PM is Positive medium

PB is Positive big

PVB is positive very big

CHAPTER FOUR

4. Results and Analysis

4.1. An Overview

This chapter presents the spectral result of the main harmonic producing equipment's i.e Variable Frequency Drive (VFD) and Switch Mode Power Supply (SMPS) first. The purpose of this analysis is to view the types of harmonics generated by Variable Frequency Drive (VFD) and Switch Mode Power Supply (SMPS).The definition and working principle of Variable Frequency Drive (VFD) and Switch Mode Power Supply (SMPS) are well presented in chapter three, under methodology, in the development of modeling. Then, at last, the spectral result of the overall model of the industrial plant when all the loads including Variable Frequency Drive (VFD) and Switch Mode Power Supply (SMPS) were integrated is followed. The spectral result revealed that the type of the harmonics generated by the overall loads of the plant as well as the harmonic distortion level at both Point of Common Coupling (PCC) and In Plant Coupling (IPC) as seen in the subsequent titles.

4.2. Variable Frequency Drive (VFD) Spectral Result

The simulation result of variable frequency drive is shown in Figure 4-1

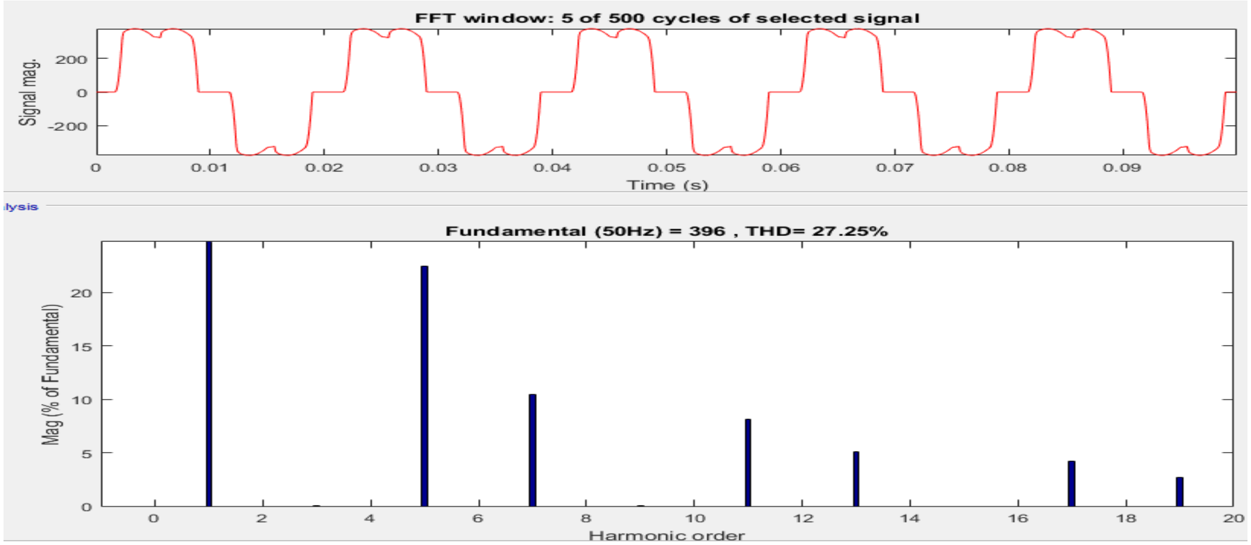

Figure 4-1: The spectral analysis of phase input current of VFD

As observed the spectral analysis of phase input current of the VFD. It has the value of THDI 27.25%.The current contains 5th, 7th, 11th, 13th ,17th ,19thetc harmonic. It can be derived that the six pulse rectifier which is the front of VFD creates harmonics with theorder

$h = 6n \pm 1$

(4-1)

Where

n 0,1,2,3,4…..

h is theharmonic order

4.3. Switch Mode Power Supply (SMPS) Spectral Result

The spectral result of the switch mode power supply (SMPS) is shown in the Figure 4-2.

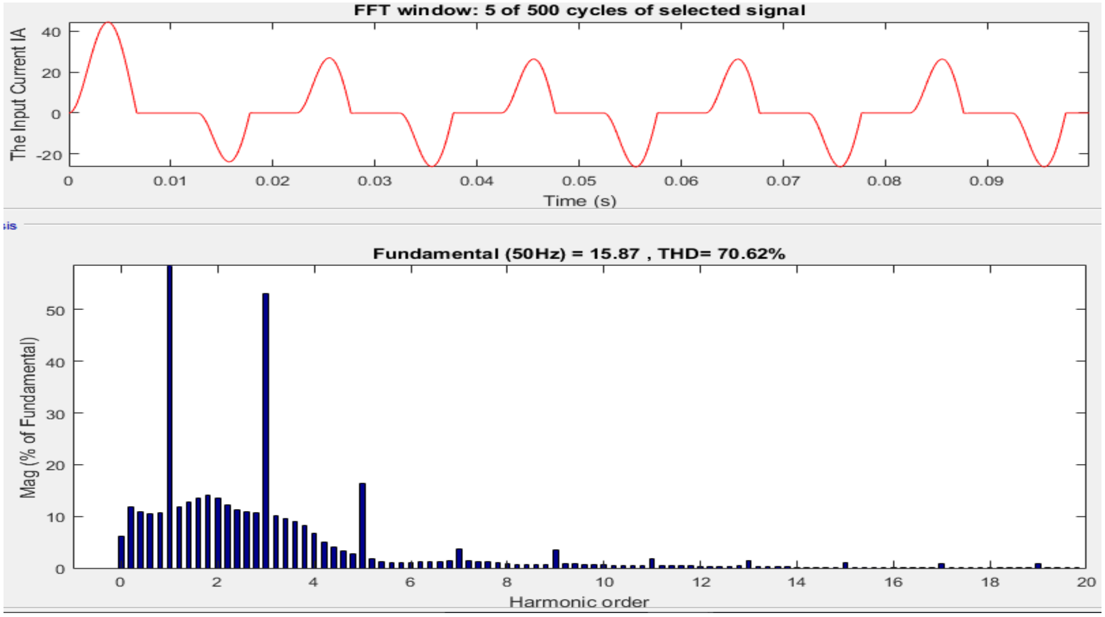

Figure 4-2: The spectral analysis of phase input current of SMPS

As seen the spectral result of the input current of the switch mode power supply. The current contains only odd harmonics and THDI is 70.62%

4.4. The Spectral Result of the Whole Industrial Network

4.4.1. Spectral Analysis Before Compensation

Considering all the loads are working and loaded 100%, the measured THDV and THDI at the point both PCC and IPC before compensation is as shown below.

4.4.1.1. THDV at PCC Before Compensation

As observed in the voltage waveform at PCC in Figure 4-3, it is distorted from its sinusoidal form and resembles trapezoidal waveform due to the presence of harmonics. From the spectral result, the voltage contains 5th, 7th ,11th ,13th ,17th ,19th harmonics etc. Moreover, the THDV is 14.87% which is much greater than the recommended limit. As per the IEEE 519-2 standard, it should be lower than 5%

[71].Therefore a filter is required to reduce the voltage harmonic distortion to the recommended standard limits.

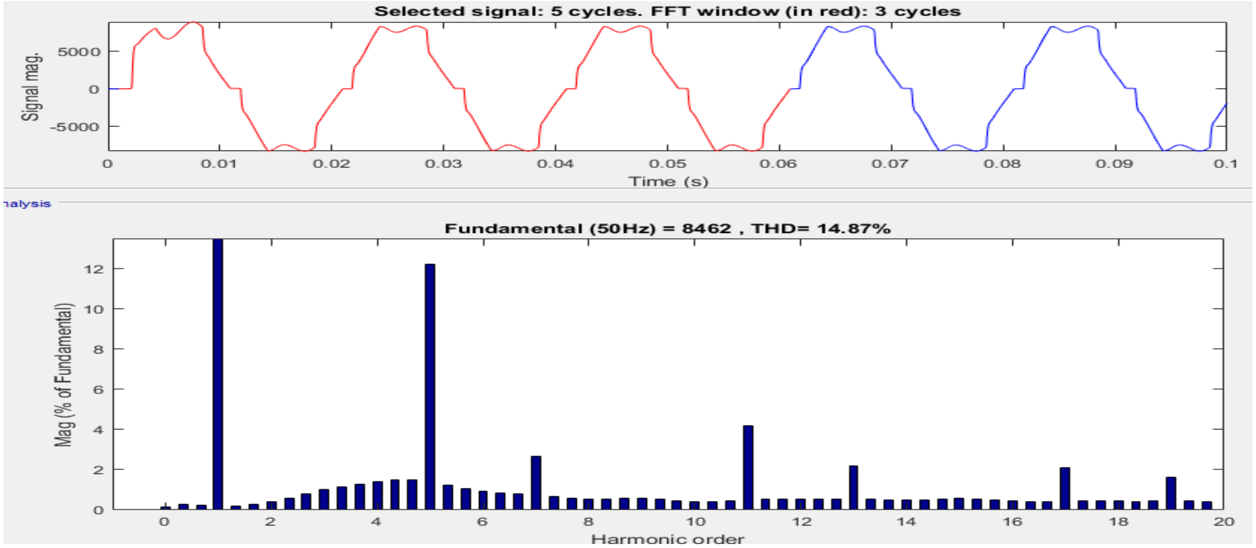

Figure 4-3: Voltage distortion at the PCC before compensation

4.4.1.2. THDV at PCC Before Compensation

As we observe the waveform below Figure 4-4. The current waveform is not pure sinusoidal as it is required. It contains 5th, 7^{th} ,11^{th} ,13^{th} ,17^{th} ,19^{th} harmonics etc that makes the signal to be distorted. The THDI as per the spectral result is 4.75%.To verify whether the total current harmonic distortion (THDI) is within the limit as per defined by IEEE 519-2[71].we have to calculate the short circuit ratio at the PCC of the primary side of the transformer.

Computing the short-circuit ratio $\frac{I_{sc}}{I_L}$

I_{sc} can be calculated from the utility information based on this formula

$$I_{sc} = \frac{KVA_{sc} * 1000}{V_{LL} * \sqrt{3}} = \frac{6000000 * 1000}{15000 * \sqrt{3}} = 230940A \qquad (4\text{-}1)$$

Whereas I_L can be computed using this formula

$$I_L = \frac{Kw}{PF * \sqrt{3} * kV} \tag{4-2}$$

Where PF is the power factor and KW is the average power demand that can be found out from the billing information for over the recent 12 months [72]

$$\text{Average power demand=KW=}\frac{\text{kwh consumed in the period}}{\text{hours in the period}} \tag{4-3}$$

Assuming the maximum power consumption 70500KWH during the month of December

This month has 31 days therefore

The average power $KW = \frac{70500KWH}{24*31} = 94.76KW$

therefore $I_L = \frac{94.76KW}{0.8*\sqrt{3}*400} = 170.97$

Therefore $\frac{I_{sc}}{I_L} = \frac{230940}{170.97} = 1350.76$

As per defined by IEEE 519-2 THDI should not exceed the limit 20%, therefore, the THDI is within the limit.

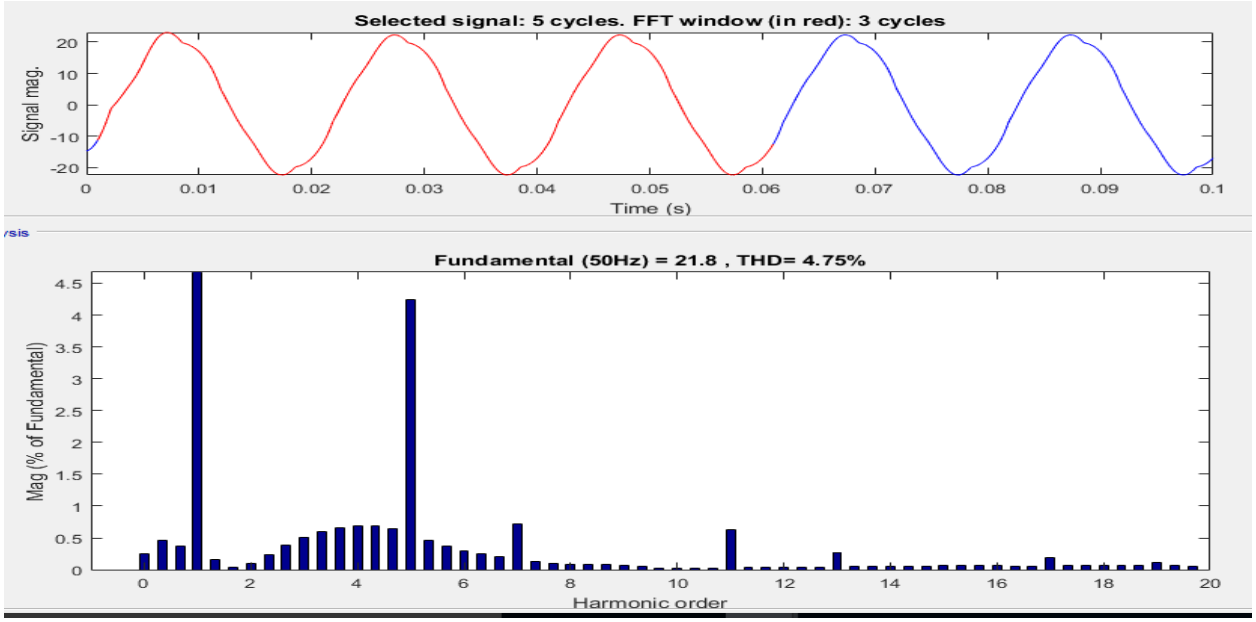

Figure 4-4: Current distortion at the PCC before compensation

4.4.1.3. THDV at IPC Before Compensation

As observed the voltage waveform at PCC in Figure 4-5, it is distorted from its sinusoidal form and resembles triangular waveform due to the presence of harmonics. From the spectral result, the voltage contains 5th, 7th ,11th ,13th ,17th ,19th harmonics etc. Moreover, the THDV is 14.60% which is much greater than the recommended limit. As per the IEC 61000-2-4 for class 2 standards it should be lower than 8%[73][74].

Since $\mathrm{THDV}_{\mathrm{IPC}} \geq \mathrm{THDV}_{\mathrm{IPC\_Permitted}}$

$14.60\% \geq 8\%$

Therefore a filter is required to reduce the voltage harmonic distortion to the recommended standard limits.

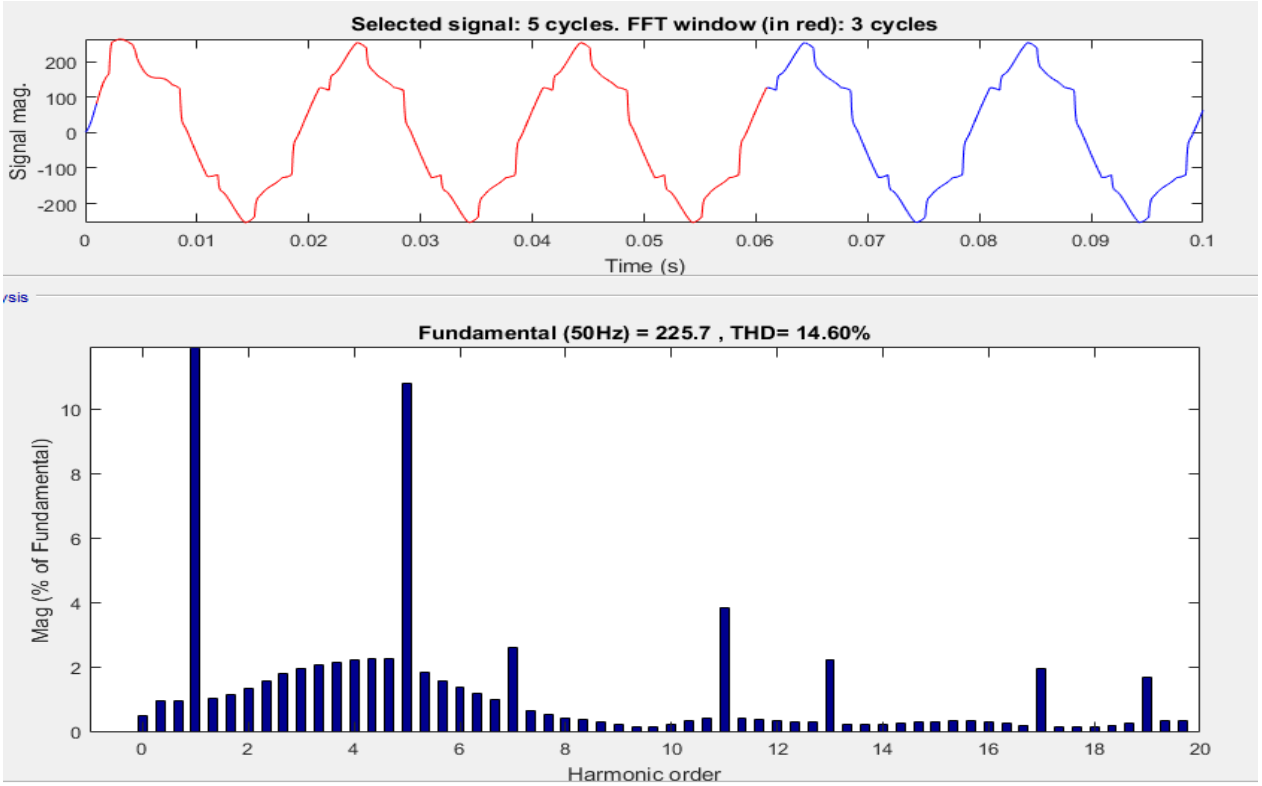

Figure 4-5: Voltage distortion at the IPC before compensation

4.4.1.4. THDI at IPC Before Compensation

As observed the waveform below Figure 4-6. The current waveform is not pure sinusoidal as it is required. It contains 5th, 7th , 11th , 13th harmonics etc that makes the signal to be distorted. The THDI as per the spectral result is 5.59%. The current distortion is within the limit as per defined by IEC 61000-2-4 for class 2 standards.

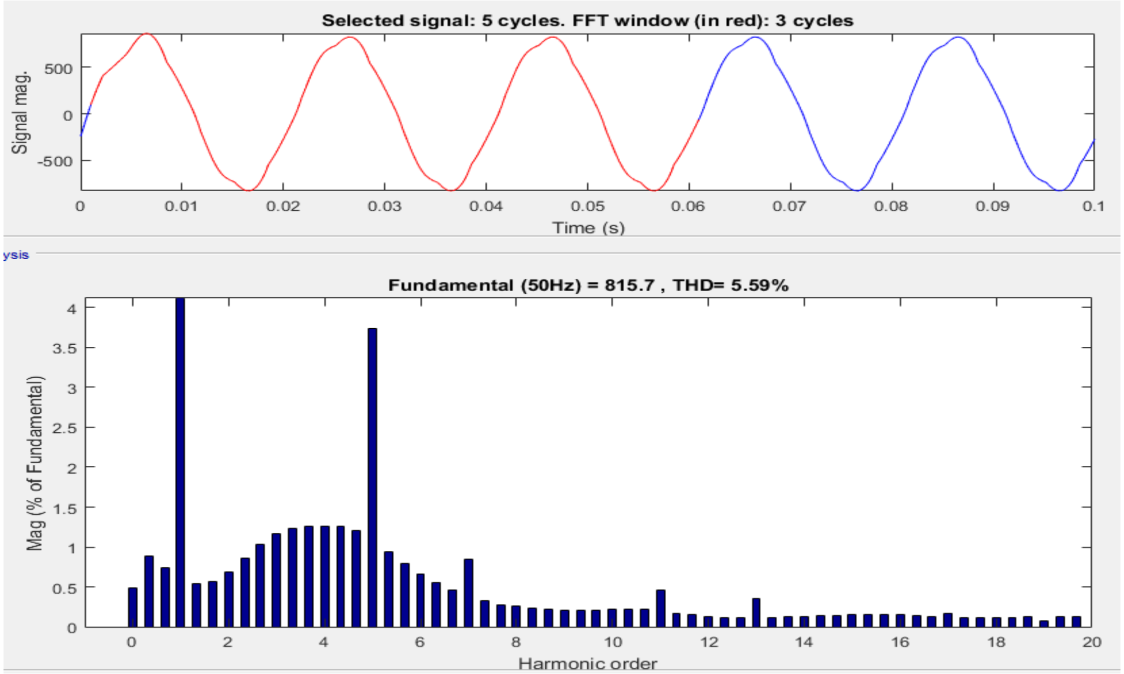

Figure 4-6: Current distortion at the IPC before compensation

In brief, the spectral result before compensation is summarized in a tabulated form is as shown below in Table 4-1.

Table 4-1: The Spectral Result Before Compensation

Point	THDV (%)	THDI (%)
PCC	14.87	4.75
IPC	14.60	5.59

4.4.2. The Spectral Result After Compensation

4.4.2.1. THDV at PCC After Compensation

As observed in the voltage waveform at PCC in Figure 4-7, The designed hybrid filter can able to reduce the harmonic distortion level consequently the voltage waveform is almost sinusoidal. The THDV is 4.58% that satisfies the IEEE 519-2 recommended limits.

The spectral results after compensation are shown below.

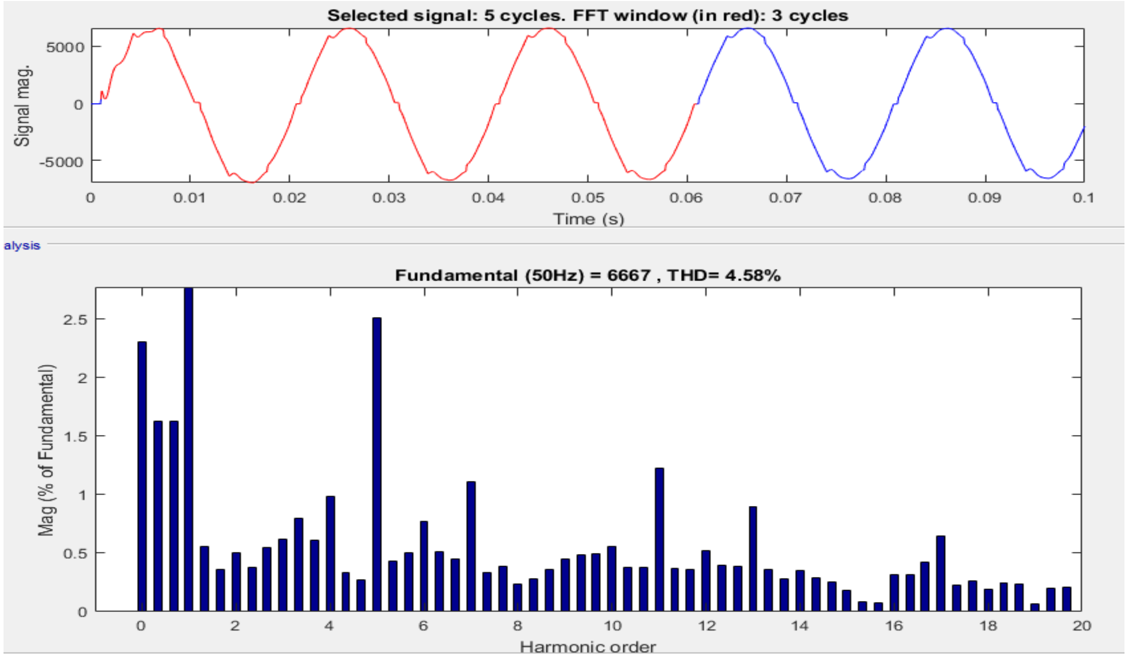

Figure 4-7 : Voltage distortion at the PCC after compensation

4.4.2.2. THDI at PCC After Compensation

As seen the current waveform at the Figure 4-8.It is almost pure sinusoidal. As per the spectral result the presence of harmonics is negligible. The designed hybrid filter can able to eliminate all the harmonics and the THDI is 4.83% within the safe zone of the recommended standard limit of IEEE 519-2.

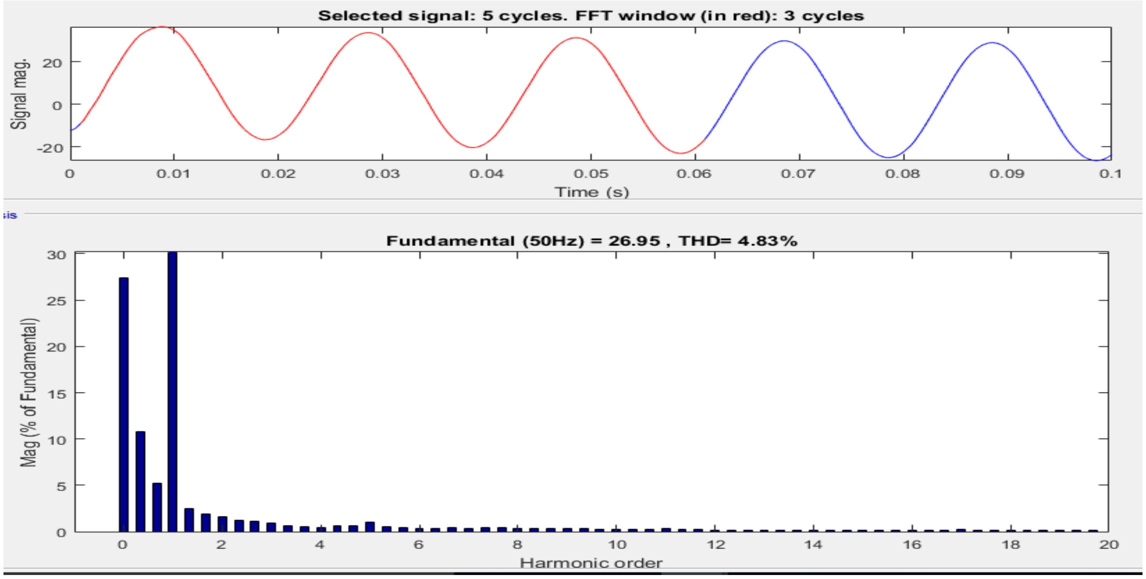

Figure 4-8 : Current distortion at the PCC after compensation

4.4.2.3. THDV at IPC After Compensation

As seen the voltage wave form at the Figure 4-9. The designed filter can able to change the distortion wave form from its triangular shape to the almost pure sinusoidal waveform. It has also reduces the THDV from 14.6% to 4.26% that satisfies the standard recommended limit of IEC 61000-2-4 for class 2.

As per IEC 61000-2-4 for class 2

$THDV_{IPC} \leq 8\%$ Therefore the THDV =4.26% is within the safe zone of the standard stipulation

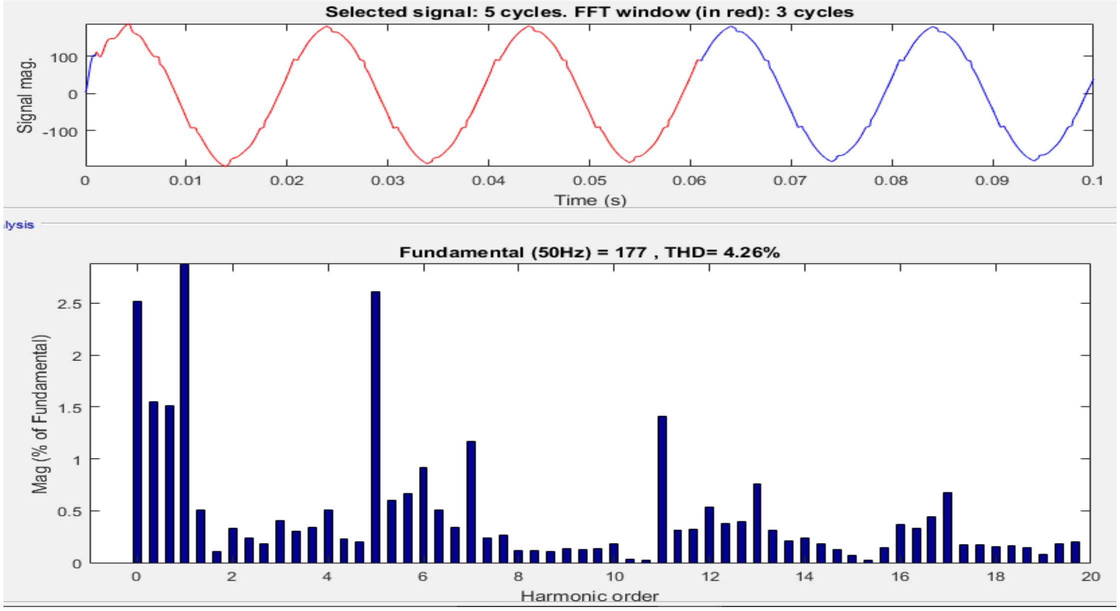

Figure 4-9 : Voltage distortion at the IPC after compensation

4.4.2.4. THDI at IPC After Compensation

As observed the current wave form at the Figure 4-10.The designed filter can able to reduce the harmonic distortion level consequently the current wave form at the IPC becomes sinusoidal. The THDI is 4.72% within the recommended limits.

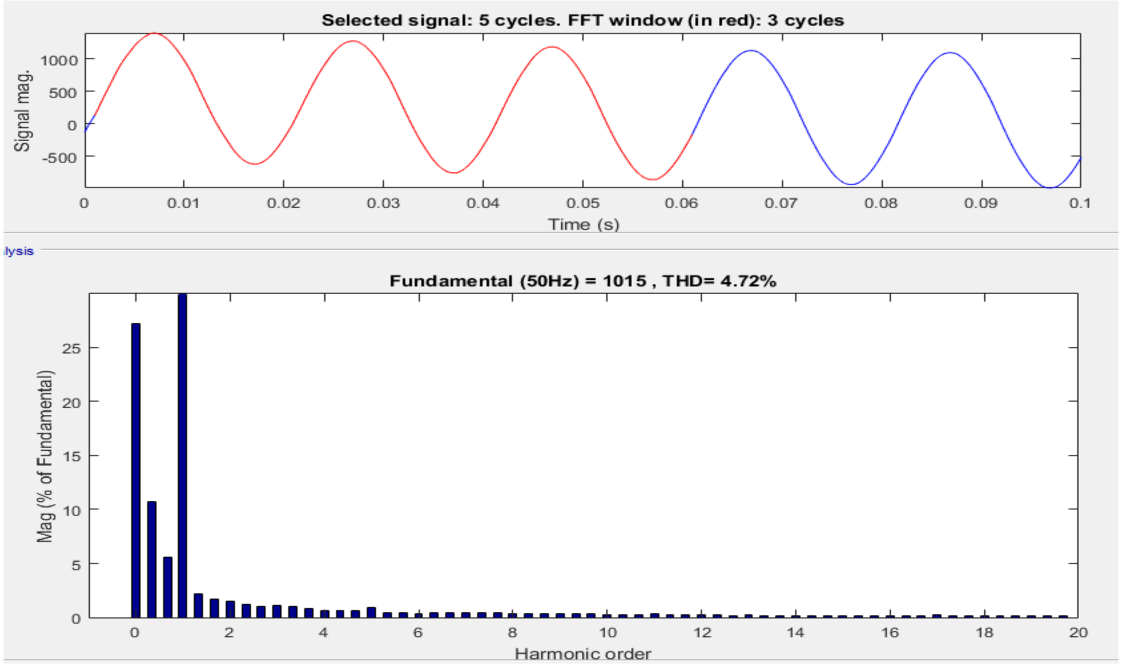

Figure 4-10 : Current distortion at the IPC after compensation

The harmonic distortion result after compensation in a tabulated form is as shown below

Table 4-2: The Spectral Result After Compensation

Point	THDV (%)	THDI (%)
PCC	4.58	4.83
IPC	4.26	4.72

4.4.3. The Spectral Result for Considering N-1 Contingency Case

The aim of this analysis to see what will happen when any department which involves alarge amount of linear load is isolated due to either fault or maintenance. The linear loads have damping effect to the harmonics. If large amount of linear load isolated for any type of reason the harmonic distortion level increase tremendously.

For this study, the worse scenario was considered i.e. aCo_2 room that hasa large number of induction motors were isolated. Consequently the harmonic distortion level increase as expected. However, the designed filter can still able to reduce the harmonic distortion level to the threshold that complies the standards with this condition. The spectral results are as shown below.

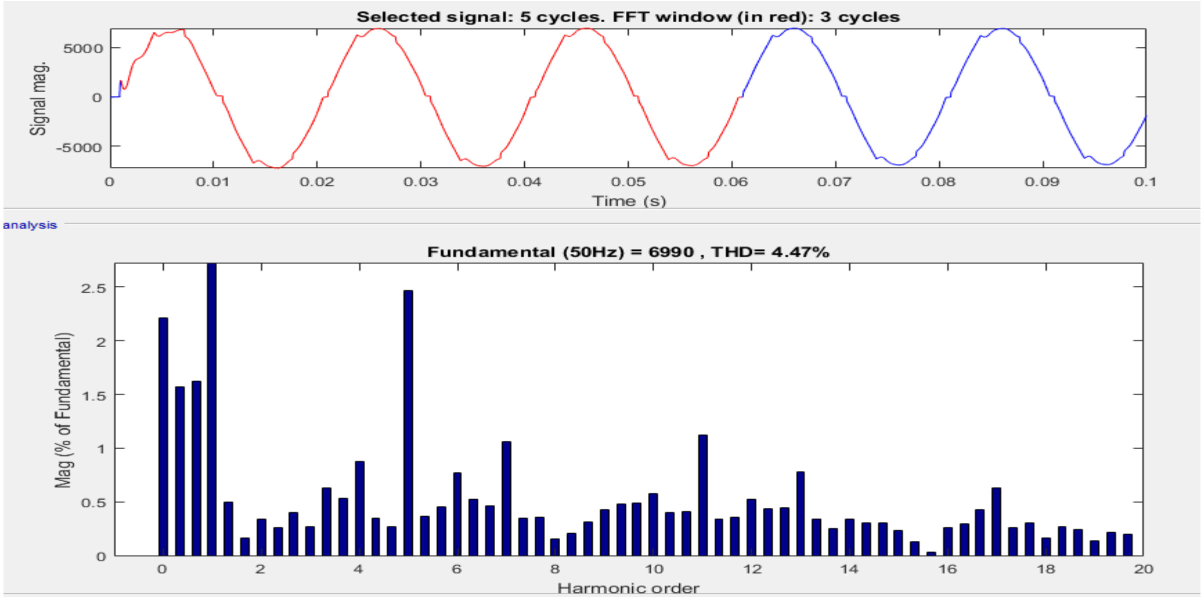

Figure 4-11 : Voltage distortion at the PCC after compensation for N-1 contingency

4.4.3.1. THDV at PCC After Compensation for N-1 Contingency

As noticed the voltage wave form at the Figure 4-11.The designed hybrid filter can still be able to change to the distorted trapezoidal wave form to almost pure sinusoidal wave form even under the worst possible operation of the plant. The THDV at the PCC is 4.47% that satisfies the standard IEEE 519-2 recommended limit.

4.4.3.2. THDI at PCC After Compensation for N-1 Contingency

As observed the current wave form at the Figure 4-12. The filter can able to minimize the harmonic distortion level consequently the current waveform is sinusoidal. The THDI 5.91% is within the recommended IEEE519-2.

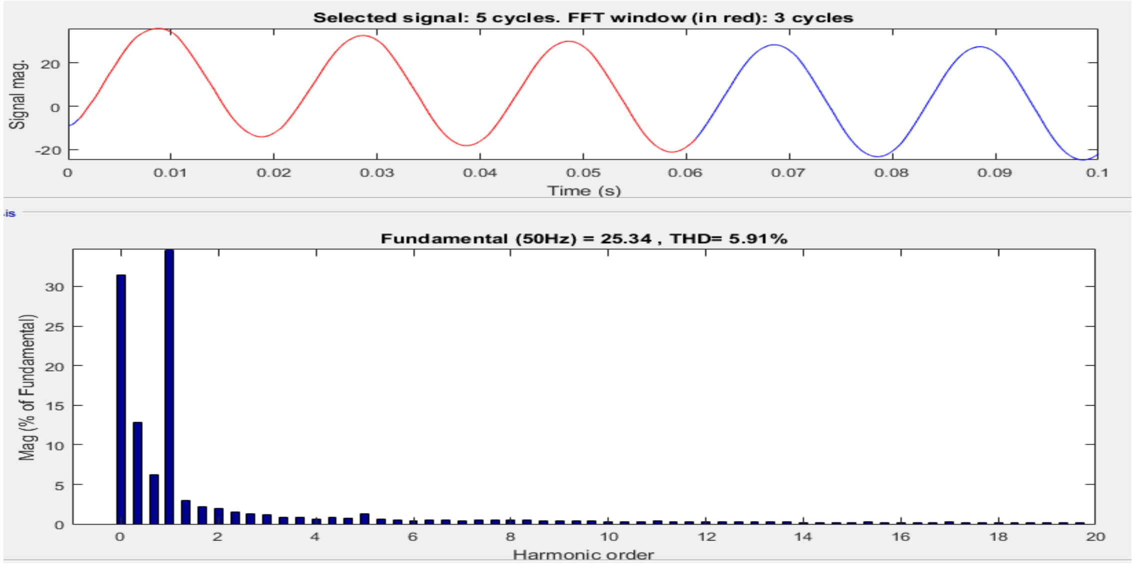

Figure 4-12 : Current distortion at the PCC after compensation

4.4.3.3. THDV at IPC After Compensation Considering N-1 Contingency

As seen the voltage wave form at the Figure 4-13. The designed hybrid filter can able to change the distortion wave form from its triangular shape to the almost pure sinusoidal waveform even under worse possible operation of the plant i.e. considering N-1 contingency. It has also reduces the THDV to 4.42%, As per IEC 61000-2-4 for class 2

$THDV_{IPC} \leq 8\%$ Therefore the THDV =4.42% is within the safe zone of the standard stipulation.

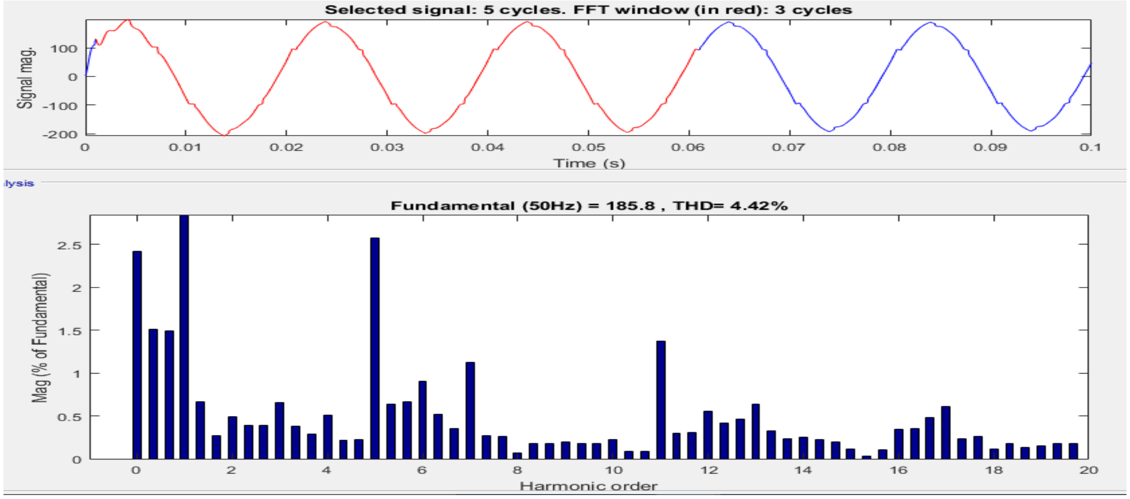

Figure 4-13 : Voltage distortion at the IPC after compensation

4.4.3.4. THDI at IPC After Compensation Considering N-1 Contingency

As seen the current waveform at the IPC as shown in the Figure 4-14.the designed filter eliminates the harmonic distortion and produce a signal of pure sinusoidal even under the worst possible operation of the plant. As per the spectral result there are no presence harmonics.

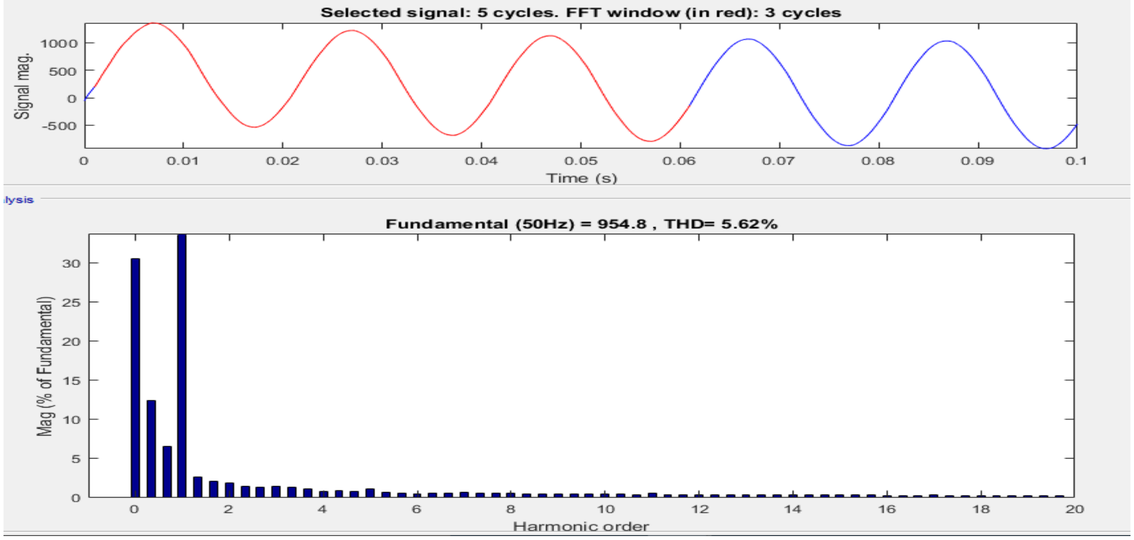

Figure 4-14 : Current distortion at the IPC after compensation

In Brief and summarized form, the spectral result in a tabulated form is shown below

Table 4-3: The Spectral Result for N-1 Contingency Case

Point	THDV (%)		THDI (%)
PCC	4.47		5.91
IPC	4.42		5.62

CHAPTER FIVE

5. Conclusion and Recommendation for Future Work

5.1. Conclusion

The research focused on an investigation of harmonics distortion level in an industrial network and designing a fuzzy controlled hybrid filter as a solution. To carry out the investigation, firstly the industrial network and loads were modeled. Specifically, the substation, transformer, transmission lines, variable frequency drive motors, induction motors, switch mode power supply were modeled using Matlab Simulink for harmonic study. The overall modeled industrial network was simulated for spectral analysis. The spectral result was compared with both standards IEC 61000-4-2 for class 2 and IEEE-519. It was explored the harmonic distortion level do not comply with both standards.

To reduce the harmonic distortion to the standard limits a fuzzy controlled hybrid filter were designed. The designed hybrid filter was able to maintain the distortion within the standards in both normal operating conditions and N-1 contingency cases of the plant

5.2. Recommendation

In this research, modeling of thefluorescent lampwas not included due to the fact that the harmonic currents injected by a fluorescent lamp are negligible because of its low power. Moreover, these fluorescent lamps are scattered within the plant which makes them difficult to lump and incorporate into the overall model of the plant. Though exclusivity of the fluorescent lamps does not invalidate the spectral result if someone considers these lumps the overall models would have become more accurate. Furthermore, to validate and to make the modeled systems more feasible, other researchers can use the simulation result of the modeled system and compare it with the measured results taken using power quality analyzers in future.

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APPENDICES

A. Standards

IEC 61000-2-4 specifies the voltage characteristics. It defines three classes of electromagnetic environment[75]

Class 1

This class applies to protected supplies, having compatibility levels which are lower than for public grids. It refers to the operation of equipment which response in a very sensitive manner to disturbances in the power supply, for example, the electrical equipment of technical laboratories, certain automation and protection gear, certain data processing facilities etc.

Class 2

This class generally applies to points of common coupling (PCC) with the public grid and for in-plant points of coupling (IPC) with industrial and other non-public power supply networks. The compatibility levels for this class are generally identical with those applying to public grids. Therefore, components which were developed for use in public grids can also be employed in this class for industrial environments.

Class 3

This class only applies to in-plant points of coupling (IPC) in industrial environments. For some disturbances, it comprises higher compatibility levels than those in Class 2. This class should be considered, for example, if one of the following conditions is true.

- A major load share is fed by the power converters
- Welding machines exist
- Large motors are frequently started
- Loads vary quickly

Table A-1Compatibility Limits: Voltage Harmonics (U_n %) in Industrial LV Networks (IEC-61000-2-4)[74]

Harmonic order	**Class 1 Un %**	**Class 2 Un %**	**Class 3 Un %**
2	2	2	3
3	3	5	6
4	1	1	1.5
5	3	6	8
6	0.5	0.5	1
7	3	5	7
8	0.5	0.5	1
9	1.5	1.5	2.5
10	0.5	0.5	1
>10 mult. of 2	0.2	0.2	1
11	3	3.5	5
13	3	3	3.5
15	0.3	0.3	2
17	2	2	4
19	1.5	1.5	4
21	0.2	0.2	1.75
>21 mult. Of 3	0.2	0.2	1
23	1.5	1.5	3.5
25	1.5	1.5	3.5
>25 not multiples of 2 or 3	0.2+12.5/h	0.2+12.5/h	$5*\sqrt{11/h}$
THD(V)	5%	8%	10%

As shown above,IEC-61000-2-4standard does not state standard limits for current distortion in public connected grids and industrial plants. To meet the voltage harmonic distortion level within the standard it is enough to refer the IEC-61000-2-4as a yardstick**.**

However, in apractical situation, it might happen when the voltage distortion level is within the standard limits whereas the current distortion is out of the limit. This condition is undesirable because it can cause serious problems. To avoid this undesirable condition it is important to keep the current distortion as per defined in IEEE-519-92 shown below[71].

Table A-2IEEE- 519 Current Distortion Limits for General Distribution System (120 V through 69000 V

Maximum Harmonic Current Distortion in Percent of I_LIndividual						
Individual Harmonic Order (Odd Harmonics)						
I_{SC}/I_L	<11	11<h<17	17<h<23	23<h<35	35<h	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed

*All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L

Where

I_{SC} = maximum short-circuit current at PCC. I_L, = maximum demand load current (fundamental frequency component) at PCC.

The IEEE-519-92 standard stipulated for both current and harmonic distortion limits .the voltage distortion limits is shown below[71]

Table A-3IEEE 519 Voltage Distortion Limits

Bus voltage a PCC	Individual voltage distortion (%)	THDU (%)
69 kV and below	3	5
69001 through 161 kV	1.5	2.5
161000 kV and above	1	1.5
