Harmonic Analysis of Power System and Comparative Study of It's Mitigation Technique

A Project and Thesis submitted in partial fulfillment of the requirements for the Award of Degree of Bachelor of Science in Electrical and Electronic Engineering

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Certification

This is to certify that this project and thesis entitled "**Harmonic Analysis of Power System and Comparative Study of It's Mitigation Technique**" is done by the following student under my direct supervision and this work has been carried out by them in the laboratories of the Department of Electrical and Electronic Engineering under the Faculty of Engineering of Daffodil International University in partial fulfillment of the requirements for the degree of Bachelor of Science in Electrical and Electronic Engineering.

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The project and thesis entitled " Harmonic Analysis of Power System and Comparative Study of It's Mitigation Technique**,"** submitted by **Name: Esha Khaled Utsho, ID No:182-33-714, Name: Jahed Ibne Karim, ID No: 182-33-766** Session: Spring 2022 has been accepted as satisfactory in partial fulfillment of the requirements for the degree of **Bachelor of Science in Electrical and Electronic Engineering** .

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LIST OF ABBREVIATIONS

APF	Active Power Filter
ST	Single tuned
HPF	High Pass Filter
RLC	Resistance Inductance Capacitance
AC	Alternating current
DC	Dirrect Current
SAPF	Shunt Active Power Filter
SMPS	Switch Mode Power Supply
ASD	Adjustable Speed Drives
RMS	Root Mean Square
THD	Total Harmonic Distortion
THD_I	Total Harmonic Distortion of Current
THD_V	Total Harmonic Distortion of Voltage
DF	Distortion Factor
FFT	Fast Furiuer Transformation
CFL	Compact Fluorescence Light
PHF	Passive Harmonic Filter

LIST OF SYMBOLS

f_0	**Fundamental Frequency**
Ω	**Ohm**
R	**Resistance**
L	**Inductance**
C	**Capacitance**
kW	**Kilo-Watt**
VAR	**Volt –Ampere Reactive**

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ABSTRACT

Modern load equipment and power electronic devices, which are controlled by microprocessors, are an important source of concern for the power quality issue of electrical grids. A conventional electrical grid must produce sinusoidal voltages and currents that are unaffected by amplitude or frequency fluctuation. But the sinusoidal voltage and current waveform could not be maintained distortion free when harmonics appear due the loading of non-linear load. The harmonics mainly generate from loading of non-linear load and also there are many other reasons which are further discussed in this paper. Harmonics in load currents can have a number of negative effects, including low power factor, conductor loss, eddy current loss in transformers, etc. Harmonics cannot be totally eliminated from the grid but that can be mitigate in admissible limit. IEEE 519-2014 has given limit of THD for current and voltage distortion for various range of voltages and current. Finding a way to reduce harmonics is therefore crucial for maintaining the ideal nature of a power grid or the source. Harmonics can be mitigated by various technique which are discussed in this paper but among them the mitigating harmonics by passive, active or by hybrid filters are popular. Depending on THD of the system and current rating on have to choose the right and affordable solution for the system. In this paper we did a comparative study on passive filters types by simulating them in Matlab/Simulink. Then for overall THD reduction of a simulated 3 phase power system with nonlinear load connected we tried passive filters, active filters and hybrid filter to see the best performance. The current harmonic distortion values obtained with active and hybrid filters were well within the permissible threshold suggested by IEEE 519-2014.

CHAPTER-1
INTRODUCTION

1.1 Introduction

Technology advancement has resulted in a large number of nonlinear loads in industrial plants as well in domestic use, primarily power electronics devices like variable speed motor drives (VSDs), computers, LED driver, light dimmers, and power converters used in conjunction with compressor, fans, and industrial pumps, as well as air-conditioning hardwire. The combined impact of those nonlinear loads has the potential to cause significant harmonic distortion levels. Both voltage and current might experience the distortion. This is an indication of low power quality. The major impacts of harmonics in power distribution systems include excessive heat in equipment, component aging and capacity decline, failure of protection and measurement devices, reduced power factor and, as a result, decreased power system efficiency owing to increased losses. As a result, when harmonics are formed, they must be reduced for the system's performance to improve.

Many various strategies have been presented to deal with harmonic difficulties. The most basic harmonic filtering strategy was to utilize RLC components in the form of filter banks that were set to provide a short circuit or low impedance for the frequencies of harmonics to be cancelled. These filters are built in such a manner that the primary frequency has a high impedance (fundamental frequency). Because these filters are made entirely of passive parts, they are referred to as passive filters.

These types of filters are a useful strategy in the condition of stable static systems with little fluctuations. Passive filters may not be useful in dynamic non-predictable systems due to their static behavior, which means they cannot adapt to changes in the load. There is also the possibility that they will induce resonance with certain frequencies, causing stability issues.

Active filter is another technology that is based on a power electronics device. Active filters were first developed in the 1980s. They are dynamic systems that dynamically correct for harmonic currents and voltages. They can respond rapidly to load and system changes without requiring any interruptions. Shunt Active Power Filter's primary role is to cancel harmonic currents in power networks. The SAPF idea is to create harmonic currents that are similar in amplitude and opposite in phase to cancel harmonic from grid .

Active power filter is divided into several categories, some of which address voltage control and voltage harmonics abatement. Another sort of active filter can be used to filter currents and eliminate harmonics. Voltage control is accomplished by the employment of series active power filters. Shunt active filters, on the other hand, were proposed for current harmonics and reactive power adjustment. Although there are other varieties of Active power filters, the Shunt APF is the most common and widely utilized.

Another popular configuration is Hybrid Active power filter .In this design we use both Shunt and passive filter to mitigate harmonics and reactive power .Main advantage of this HAPF is that active filter rating were reduces means cost reduce with good quality of filtering.

1.2 Problem statement

An ideal alternating current generator with finely distributed stator and field windings provides hypothetical pure sinusoidal voltage. Voltage waveform distortions are produced in a real AC machine because neither the winding distribution nor the magnetic field are homogeneous. However, the distortion at the moment of creation is quite modest (approximately 1% to 2%), yet it occurs.

When the sinusoidal voltage is applied to a linear load (time-invariant) current through it is also sinusoidal. Because current follow the voltage. But in case of non-linear (time-variant) loads, such as an VFD the applied voltage and current is no more to be in sinusoidal nature. In this case the distortion produce is known as harmonics distortion. These distortion has various effect on other loads as harmonics tries follow in low impedance path .So in this way it can find the source as low impedance path and it will appear in source bus. Then it will appear in every -where of power system including transformer. In generators, transformers, and induction motors, harmonic currents increase hysteresis, eddy current, and core losses. Line losses in conductors and cables multiplied by higher frequencies can cause circuit breakers, protection relays, fuses, and control systems to fail.

To maintain the power grid clean, we must prevent harmonics from traveling from load towards power grid. Harmonics solutions are included into the system for this purpose.

The goal of our study is to identify the best approach for eliminating harmonic currents and compensating for the reactive power at the fundamental frequency. Matlab Simulink was used to model the considerations.

1.3 Objectives

The objective of this thesis are ,

i. To investigate Power system harmonics
ii. To study how does harmonics generate and what are the solution of it
iii. To apply harmonics mitigation techniques
iv. To design different harmonics filters and comparison of it.

1.4 Research Methodology

The research technique relied on an analytical and experimental strategy. The following are the most essential points:

a. To understand and gain proper knowledge of harmonics, harmonics effect on equipment, mitigation technique from literature analysis.
b. Design different harmonics passive and active filter for different non-linear loads in Matlab/Simulink.
c. Comparison of passive filter with existing Active filter.
d. Testing different types of filter by loading different types of non-linear load.
e. Analysis and investigation on experimental results.
f. Finding the best optimal solution for harmonic mitigation.

1.5 Thesis Outline

This Project/thesis is organized as follows:

Chapter 1 include a broad overview of power quality, passive and active power filters It also involves thesis research methodology.

Chapter 2 investigates the literature the main topics covered here are harmonics history, harmonic sources, the effect of harmonic distortion, three phase non-linear load, and harmonic minimization method and harmonic filter design .

Chapter 3 deals with simulation of different types of non-linear loads and harmonic filter design.

Chapter 4 presents the result and its discussions.

Chapter 5 Final thoughts, future direction, and references.

CHAPTER-2
LITERATURE REVIEWS

2.1 Introduction

This chapter has gone into detail about power quality, harmonic distortions, and various harmonic distortion mitigation strategies. Previous research projects on improving the quality of power supplies are investigated. Articles on harmonic distortion are reviewed. The characteristics of a nonlinear load and the power factor when a harmonic is present in the system are explored. To mitigate or eliminate harmonic from system there are several types of solution which are discussed in detail.

2.2 Harmonics Background Information

It is believed that Steinmetz's study of harmonics in a three-phase power system in 1916 is what sparked the first investigation into harmonic pollution in the electrical network[1]. To stop the 3rd harmonic current from returning to the power source, he advised using delta windings. Harmonics difficulties were temporarily solved until the 1940s, when rural electrification and telephones were introduced. Due to inductive coupling between power line harmonic frequencies and nearby open wire telephone circuits, audible telephone interference resulted. Twisted pair cables, cable burying, and the introduction of fiber optics were all used to tackle this problem. However, with the advancement of electronic devices that draw non-sinusoidal currents in the form of pulses, the power system of the 1980s and 1990s was exposed to non-sinusoidal currents, which interacted with system impedance, creating voltage distortions and severe parallel resonance. The quantity and kind of harmonics-generating loads are increasing rapidly and will continue to do so [2]. This is why various research projects are being conducted to address the present harmonics emitted by both residential and industrial modern nonlinear loads. As mentioned in [3]there are some harmonic phenomena that require to mitigate from system:

i. Harmonic production can be high when the load have multiple nonlinear loads with comparable electrical properties
ii. Travelling of harmonics through long transmission line can generate voltage distortion as well as telephone interference.
iii. The system response impedance amplifies one or more frequencies, resulting in parallel or series resonance.

In this aspect, given the recent increase in the number of distribution transformers prematurely failing, it is worthwhile to do significant research to determine the impacts of harmonic distortions on power system component and create an effective mitigation method.

2.2.1 Harmonic Limits.

IEEE 519-2014 prescribes the maximum THD for current and voltage distortion over a wide range of voltages and currents. For bellow 1kV power lines THD for voltage is limited to 8% with each individual harmonic limited to 5%, as per this standard.

Current harmonic limits vary depending on the short circuit strength of the system into which they are injected.

Table 2.1: Harmonic Voltage Limits, IEEE Std 519-2014 **[4]**.

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
V ≤ 1.0 kV	5.0	8.0
1 kV < V ≤ 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
161 kV < V	1.0	1.5*

Table 2.2: Distortion limits of current for system rated 120V through 69 kV **[4]**.

ISC/IL	Harmonic limits a,b 3 ≤ h < 11	Harmonic limits a,b 11 ≤ h < 17	Harmonic limits a,b 17 ≤ h < 23	Harmonic limits a,b 23 ≤ h < 35	Harmonic limits a,b 35 ≤ h ≤ 50	TDD Required
<20c	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

Here,
Isc=maximum short-circuit current at PCC
I_L=maximum demand load current (fundamental frequency component) at PCC under normal operating conditions.

2.3 Characteristic of Modern Nonlinear Loads

In order to understand harmonic generation in power system It is necessary to discuss the general characteristics of nonlinear loads. Nonlinear loads inject harmonic currents or voltages into the network even though they are supplied by a sinusoidal voltage or current generating source. There are two types of nonlinear loads:

1. Loads that produce current distortion;
2. Loads that produce voltage distortion;

Harmonic current source loads include those that are controlled by thyristors, such as dc drives and current-source inverters (CSIs). Similar to induction motors, which require reactive currents, these loads produce harmonic currents on the ac supply side of the rectifier in order to function. Contrarily, harmonic voltage source type loads are diode rectifiers with capacitors on the dc side of the device. These loads, which need voltages on the ac side of the rectifier to operate, are becoming more widespread as a result of their usage in household electronics, variable speed drives (VSDs), and other devices.

In residential houses, the majority of modern electronic gadgets are nonlinear loads with SMPS that don't conduct current over the complete cycle of the applied voltage in AC circuits, as shown in Figure 2.1(b).

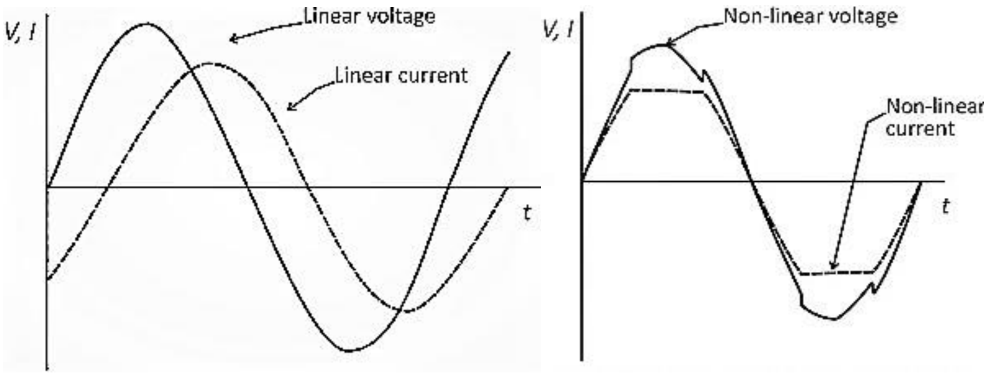


Figure 2.1: (a) nonlinear load, (b) linear load .

Waveforms for a linear and nonlinear single phase load are shown in Figure 2.1. Despite the supply voltage being close to a sinusoidal waveform, it is seen that the nonlinear load draws a non-sinusoidal current waveform (including both fundamental and harmonic frequencies) (contains only fundamental signal). This nonlinear load property is desired to boost energy consumption effectiveness and, as a result, lower electricity bills for power end users. Additionally, it enables the use of less expensive generators, such as geothermal and hydro generators, which are less expensive to operate. Additionally, when there are more nonlinear loads, electricity providers invest less in infrastructure and equipment. The main issue with a linear load is that it consumes more energy by using full cycle current, as seen in figure 2.1(a).

This is the rationale for constructing electrical appliances that do not continually draw electricity to conserve energy. According to study by[5], using efficient nonlinear loads with SMPS allowed California to save 240 GWh of energy annually. On the other hand, the author of [6] claimed that harmonic aberrations are now commonplace in electrical power systems as a result of SMPS. Reference [6] listed the following as the primary justifications for looking into power utility supply quality:

i. Users of power provided by power utilities are becoming more concerned about the quality of the power. Voltage sag, swell, power interruptions, transients, and frequency variations are examples of power quality problems that customers are becoming more aware of since they can result in expensive legal disputes.

ii. Utilization of more energy-efficient and low-power-consumption equipment such compact fluorescent light (CFL) bulbs, SMPS, or adjustable speed drives (ASD), but which results in an increase in harmonics levels that have a detrimental influence on the power quality.

2.4 Definition of harmonics and its characteristics.

2.4.1 Definition of harmonics.

Non fundamental component of any periodic waveform are harmonic .This non fundamental component has a frequency that is an integral multiple of the frequency of a reference signal or wave. Or we can say it is the ratio of non-fundamental frequency to the frequency of the fundamental wave [7].

The first, harmonic is the fundamental frequency or initial wave. After that following component of other high frequency are named as 2^{nd}, 3^{rd}, 5^{th} ……. Harmonics and so on.

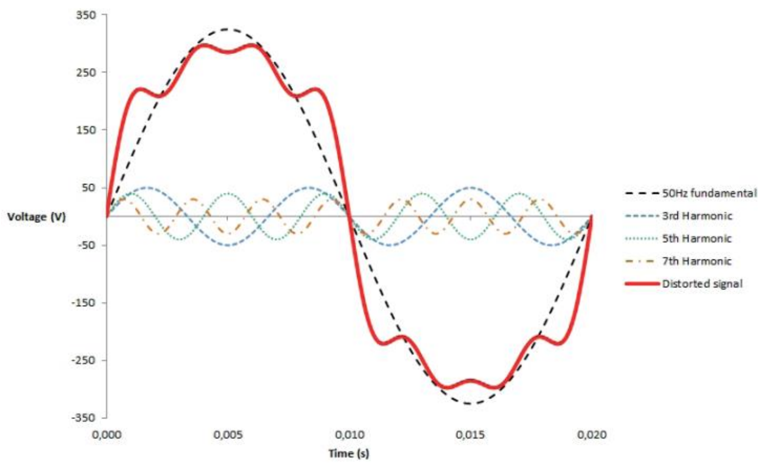


Figure2.2: Harmonics component of a distorted waveform .

Even harmonics: Even harmonics of a distorted (non-sinusoidal) periodic signal are harmonics whose frequency is a non-zero even integer multiple of the distorted signal's fundamental frequency. Because of the symmetry between the positive and negative half of a cycle, they cancel each other so even harmonics do not generally exist in power systems [7].

Odd harmonics: Odd harmonics of a distorted (non-sinusoidal) periodic signal are harmonics whose frequency is an odd integer multiple of the distorted signal's fundamental frequency [7].

2.4.2 Harmonic distortion characteristics

The properties of harmonic distortions are described in [7] and [8]. The following important traits of harmonic distortions are listed below:

i. Higher harmonic levels are typically anticipated because of the inverse relationship between harmonics' lower amplitude and higher harmonic order level.

ii. Half-wave symmetric distortion is observed to be caused by odd harmonics, whereas half-wave unsymmetrical distortion is observed to be caused by even harmonics and the DC component. While non-linear circuits produce asymmetrical current waves, rotating machinery like an induction motor produce similar positive and negative half-cycles.

iii. All neutral current results from triple-n harmonics, which generate inter-harmonic distortion that is asymmetrical across periods (zero sequence harmonics).

iv. While all odd multiples of the fundamental frequency are produced by single-phase electronic loads, the majority harmonics are triple-n (homo-polar) harmonics.

v. When a single-phase circuit with linear (passive) components (such as a resistor, inductor, or capacitor) is subjected to an alternating voltage with harmonics, the resultant current likewise includes harmonic content.

2.6 Different harmonic measures

There are several approaches for assessing and quantifying harmonic contamination in power networks. Total harmonic distortion THD, the distortion factor, and the displacement factor are some of these approaches or numbers.

2.6.1 Total harmonic distortion

The total harmonic distortion is the most often used harmonic measure (THD). It is used for both voltage and current.

THDs for voltage and current [8],

$$\mathrm{THD_v} = \left(\sqrt{\sum_{h>1}^{h_{max}} V_{h,rms}^2}\right)/V_1 = \frac{\sqrt{V_{2,rms}^2 + V_{3,rms}^2 \cdots V_{h_{max},rms}^2}}{V_1} \dots\dots\dots\dots\dots (2.1)$$

$$\mathrm{THD_i} = \frac{\left(\sqrt{\sum_{h>1}^{h_{max}} I_{h,rms}^2}\right)}{I_1} = \frac{\sqrt{I_{2,rms}^2 + I_{3,rms}^2 \cdots I_{h_{max},rms}^2}}{I_1} \dots\dots\dots\dots\dots\dots\dots\dots\dots (2.2)$$

Distortion Power:

In a linear load the active power (P),

$$P = \frac{V_1 I_1}{2}\cos\,\theta_1 = V_{1rms} I_{1rms} \cos\,\theta_1 = S\cos\,\theta_1 \dots\dots\dots\dots\dots\dots\dots\dots (2.3)$$

Reactive power,

$$Q = \frac{V_1 I_1}{2}\sin\,\theta_1 = VI_{1rms} I_{1rms} \sin\,\theta_1 = S\sin\,\theta_1 \dots\dots\dots\dots\dots\dots\dots\dots (2.4)$$

And the apparent power (S) providing the fundamental and harmonics is given by

$$S = V_{rms} \times I_{rms} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.5)$$

Active and reactive components are also present in harmonic voltages and currents. It is referred to as distortion power to distinguish it from typical inductive or capacitive reactive powers (D). We are denoting harmonic distortion as (VAd) are used in this study. By relating active, reactive, and apparent abilities to distortion power we are getting [8].

$$D = \sqrt{S^2 - P^2 - Q^2} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.6)$$

2.6.2 Distortion factor

It is a another term related to harmonic distortion, known as ratio between the fundamental and the root mean squared value of a signal. The degree of harmonics increases as the ratio decreases [8].

$$DF = \frac{I_{1,rms}}{I_{rms}} \dots\dots\dots\dots (2.7)$$

2.6.3 Harmonics and Power Factor

When harmonics present in the system the power factor cannot treated as normal harmonics free system. For a harmonics free system active power P and reactive power Q are defined as:

$$P = \frac{V_1 I_1}{2} \cos\ \theta_1 = V_{1rms} I_{1rms} \cos\ \theta_1 = S\cos\ \theta_1 \dots\dots\dots\dots (2.8)$$

$$Q = \frac{V_1 I_1}{2} \sin\ \theta_1 = VI_{1rms} I_{1rms} \sin\ \theta_1 = S\sin\ \theta_1 \dots\dots\dots\dots (2.9)$$

As a result, the power factor will be:

$$PF = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} \dots\dots\dots\dots (2.10)$$

However, if the system generates harmonics to the power grid, an additional distorted power would arise, causing further losses. This can be defined as follows:

$$D = \sqrt{S^2 - P^2 - Q^2} \dots\dots\dots\dots (2.11)$$

So, apparent power and the power factor will be defined by:

$$S = \sqrt{P^2 + Q^2 + D^2} \dots\dots\dots\dots (2.12)$$

$$PF = \frac{P}{\sqrt{P^2 + Q^2 + D^2}} \dots\dots\dots\dots (2.13)$$

The new power factor formula clearly shows that the power factor in the presence of harmonics is smaller than the power factor in a harmonic free system. It may be established that the presence of harmonics increases power losses and places additional strain on power transformers and transmission lines [8].

2.7 Methods for Reducing Harmonic Distortions

Several approaches have been proposed to prevent or mitigate the negative effects of harmonics in power system bellow acceptable limits as specified in power quality standards. The common approaches offered by researchers for mitigating the impacts of harmonic distortions are as follows. Each recommended mitigation method's downsides are mentioned.

2.7.1 Passive Harmonic Filter

One of the traditional techniques used to remove or minimize the harmonics at the source is the PHF. One of the earliest (conventional) methods for reducing harmonics at the source caused by nonlinear loads is PHF. The PHF uses capacitors, inductors, and resistors as passive electrical components. Typically, they are linked in series or shunt. While the shunt arrangement diverts the flow of harmonic currents coming from nonlinear loads by providing a low-impedance channel parallel to the ground, the series configuration provides high impedance to voltage harmonics, preventing/blocking them from reaching the connected loads. The PHF has the disadvantage of creating resonance circumstances in the network circuit in which it is deployed. This is affected by the dynamics of the source impedance and the power distribution system's frequency fluctuations, which have an impact on their filtering properties. For instance, a tuned filter needs a thorough system study to avoid resonance issues. PHF are also less expensive and simpler to install, despite being massive and requiring a wide installation area.

A series line reactor is another popular kind of passive filter and a practical way to raise the source impedance. According to study, the current harmonic distortions may be minimized by up to 60% when using the series line reactor [9]. The fact that a series line reactor must carry the whole load current drawn by the associated loads is one of its principal drawbacks; as a result, the maximum load must be established beforehand to permit correct inductor sizing. Finding the maximum loads at system conception for proper line reactor sizing is a hurdle as a result. Furthermore, because the system is always dynamic, the series reactor could need to be changed if the loads rise above the inductor's rating. Other PHF kinds include tuned harmonic filters, resonant filters with parallel and series connections, and filters that employ neutral current to prevent triple-n frequencies. Passive filters' major drawback is that because of the unique harmonic orders for which they are intended, they may result in resonance issues in the power system [8]. The usage of a hybrid harmonic filter, which combines both passive and active harmonic filters, is a strategy to get around some of the problems created by passive filters. Hybrid harmonic filters aren't frequently utilized since they are pricey.

2.7.2 Phase shifting winding method

Shifting of the windings was suggested by the authors of [10] as a means of reducing harmonic distortions in the power distribution system. In order to do this, the electrical supply must be divided into two or even more outputs. To get rid of the harmonic pairs, each output is phase-shifted in relation to one another at the proper angle. The idea is to move the harmonic current pairs such that they experience an 180^0 phase shift and cancel one another out. In [11], the specifics of phase shifting are thoroughly detailed.

In order to cancel the harmonic distortions, the single line diagram (SLD) approach is utilized in Figure 2.3 to mitigate the 5th and 7th harmonic distortions, which are the most prevalent harmonic orders in three phase nonlinear loads with PMW of 6 pulses. According to Figure 2.3, nonlinear loads are supplied by two distinct step-down distribution transformers, one with zero phase shift and the other with 30^0 phase shift, respectively. As a result of the 5th and 7th harmonics canceling each other, the resulting waveform at the common bus approaches a sinusoidal waveform.

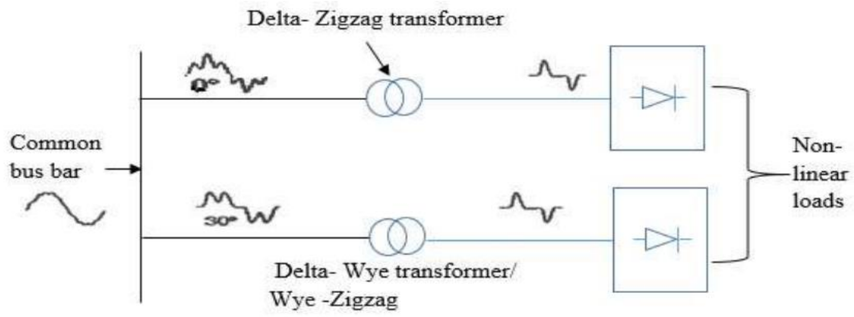


Figure 2.3: Diagram of a single line used to reduce the 5th and 7th harmonic .

To mitigate different order harmonic the Table 2.3 displays the necessary phase shift in a transformer's windings.

Table 2.3: Phase shifting required for harmonic mitigation or cancellation

S/No.	Harmonic order	Sequence	Phase shift required	Solution mode
1	3	Zero	180^0	Cancellation
2	5	-	30^0	Mitigation
3	7	+	30^0	Mitigation
4	9	Zero	180^0	Cancellation
5	11	-	15^0	Mitigation
6	13	+	15^0	Mitigation
7	15	Zero	180^0	Cancellation

Table 2.3 makes it abundantly evident that utilizing the phase-shifting methodology, homopolar harmonics may be entirely removed while other harmonic orders can be neutralized or lowered inside the transformer. As more than one transformer is needed, this technology is costly and nearly impractical to deploy on an LV voltage distribution network. It works well in settings that are business and industrial. In order to reduce harmonic distortions on low voltage distribution systems, a better technique must be developed.

2.7.3 Zigzag transformers

As shown in Figure 2.4, the transformer contains three windings on each limb of the core, one on the primary side and two on the secondary side.

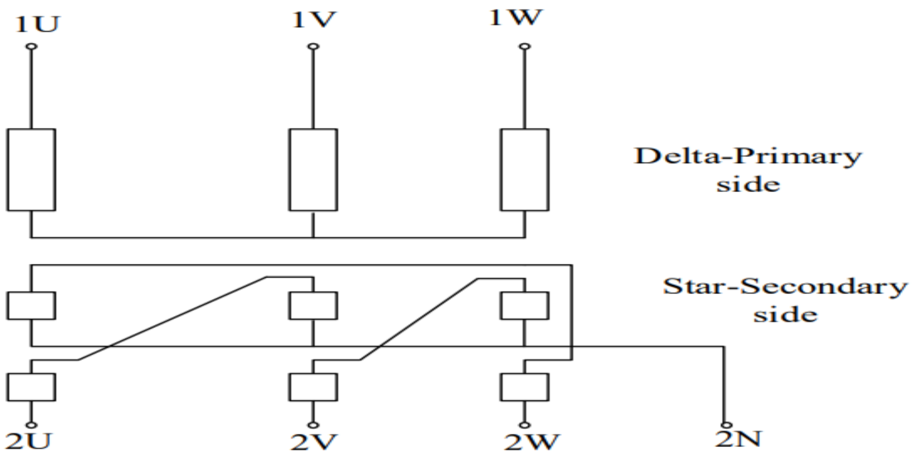


Figure 2.4: Zigzag transformer windings connection

On the secondary side, there are two equal-turn windings that are wound in opposition to one another. This results in a zero-phase displacement between the primary and secondary windings, meaning that they are in phase. The grounding of the neutral wire to an earth reference point is made possible by using this sort of transformer to cancel triple-n harmonics and create the missing neutral connection from an ungrounded three-phase system. The primary flaw in this approach is that it only cancels homo-polar harmonic frequencies, leaving behind other harmonics produced by nonlinear loads that might lead to system resonance.

2.7.4 Use of K-factor transformers

The distribution transformers with K-factor ratings are made to withstand the heating effect of current harmonic distortions, as described in [12]. The word K-factor is used to describe how many harmonics are generated by a specific load. For instance, a K-4 transformer shows that it can handle 4 times as much eddy current losses as a K-4 transformer (i.e., a K-4 transformer can tolerate a load up to 100% at 50 Hz, 16% of 3rd harmonic, 10% of 5th harmonic, 7% of 7th harmonic, and 5.5% of 9th harmonic). Since there are more harmonics present with a larger "factor," the transformer must be built to withstand the thermal stress brought on by electrical pollution.

K-Factor for a linear load is 1. A transformer's capacity to withstand the extra heat produced by the harmonic current increases with increasing K-Factor. It is important to note that K-Factor transformers can withstand the thermal stress brought on by harmonics present at the secondary side of the transformer and neutral wire but do not attenuate harmonics. The following is a list of some K-Factor transformers and applications, as provided by transformer manufacturer Claude Lyons Group;

i. K-1: Resistance heating, motors, control transformers (mostly linear loads)
ii. K-4: Welders, induction heaters, fluorescent lighting, load with solid-state controls.
iii. K-13: Telecommunications equipment
iv. K-20: Mainframe computers, variable speed drives, sub circuits with loads of data processing equipment, and desktop computers.

A Transformers with a high K-Factor have distinguishing qualities. The problems caused by harmonic distortions in the distribution system cannot all be solved by using K-factor transformers. Voltage and current resonance, as well as neutral conductor overload caused by zero sequence harmonic orders, are some of the problems that a K-factor transformer cannot solve. Transformers with a K-factor are pricey. Therefore, a workable mitigation strategy for the LV distribution network must be developed.

2.7.5 Increase of converter pulses

According to [8], converter circuits are increasingly being used with greater pulse counts. To get rid of the lower order harmonic distortions, converter circuits with 12-pulse, 18-pulse, and 24-pulse rectifiers must be designed. The finding is that the prominent harmonics are successively 121, 181, and 241. The amount of overall harmonic distortion decreases as the number of converter pulses increases. This is mostly due to the elimination of low harmonic frequencies, which often have significant magnitudes (3rd, 5th, etc.). According to research, a 6-pulse rectifier will generate around 25% THD_i, a 12-pulse rectifier will generate about 12% THD_i, and an 18-pulse rectifier would generate about 5% THD_i. The biggest disadvantage of raising converter pulses is an increase in converter price. Additionally, boosting the device's converter pulses won't stop current harmonics from returning to the power utility service wires.

2.7.6 Electronic devices with low harmonics

For AC/DC power conversion, low harmonics level electronic devices use front-end rectifiers instead of diodes or thyristors (also known as natural commutation devices), which use forced commutation (pulse width modulated) devices like IGBTs, MOSFETs, GTO, and IEGT (Injected-Enhanced Gate Transistor). According to research, devices with an IGBT or IEGT at the front-end rectifier have less harmonic current distortion than those with a diode [8].

2.7.7 Active Harmonic Filter

According to [8], the active harmonic filter, also known as an active power filter (APF) or an active power line conditioner (APLC), was proposed as early as the 1970s. However, it remained in the laboratory (simulation) stage since technology was not yet mature enough to execute the compensating concept realistically. With the introduction of fast switching devices such as the Bipolar Junction Transistor (BJT), Insulated Gate Bipolar Transistor (IGBT), and Gate Turn-On (GTO) thyristor, there has been a surge of interest in the research of shunt and series active power line conditioners for reactive power and harmonics compensation. The first shunt active conditioner, consisting of a current source PWM inverter employing a GTO thyristor, was used for harmonics correction in 1982.

The controller is the heart of AHF. The control approach is crucial in improving the filter's performance and stability. The control techniques used are of two types:

i. The fast Fourier transform, which computes the amplitude and angle of each harmonic order.
ii. Time domain that performs full spectrum cancellation by extracting the fundamental frequency component (fundamental frequency 50 Hz) first, and

then "directing" the voltage source inverter (VSI) to inject the inverse of the harmonic waveforms.

(p - q) theory, deadbeat controller, neural network, adaptive control, wavelet, fuzzy, delta-sigma modulation, sliding mode control, vector control, repeated control, synchronous reference frame, and SFX control are some typical time domain reference current extraction approaches. The AHF is equipped with two controllers: a reference current harmonic extraction controller and a PWM current controller. The latter is used to create gating pulses, whilst the former is used to retrieve harmonic features caused by nonlinear load.

The key reason that AHF is becoming the preferred choice in most installations is that it does not generate damaging resonance with the power distribution system impedance and installed feeder shunt capacitor used for reactive compensation. The cost of AHF, on the other hand, remains very high and is mostly determined by filter rating [13]. A single phase active harmonic filter, on the other hand, is less expensive and less complicated than a three phase AHF. The technique of connection at the PCC distinguishes the active power filters. The configuration is determined by the inductor or transformer used to interface. There are several types of active filter available ,categories are shown in Figure 2.4 [14].

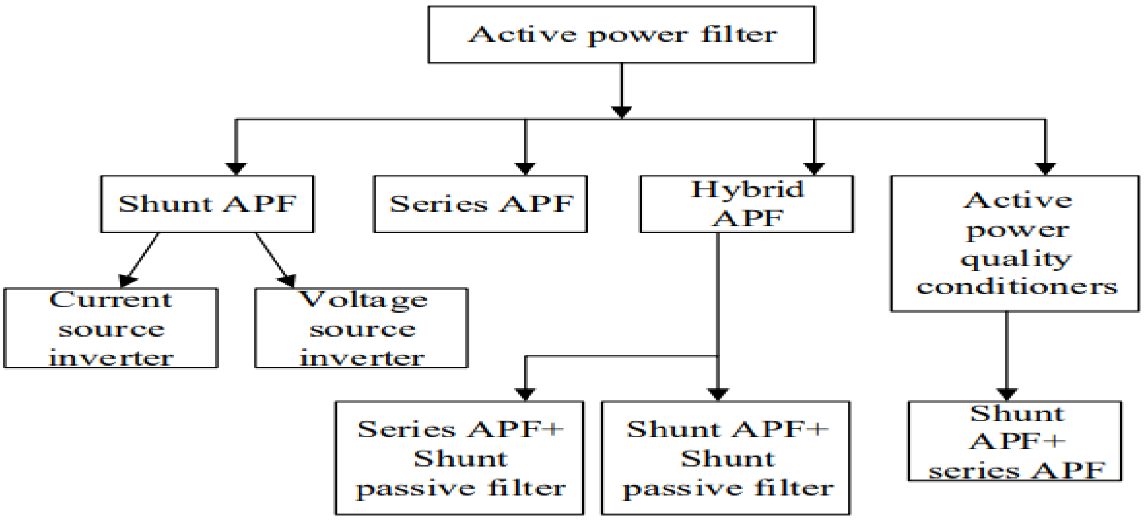


Figure 2.5: Different types of connection of active harmonic filter.

2.8 Characteristics of Passive Harmonics filter

Passive filters are the most common type harmonics filter. It has great popularity for industrial and domestic usages .So for designing specific filters for specific harmonic it is necessary to understand different types of passive harmonics filter characteristic.

2.8.1 Single-tuned filter

Figure illustrates the single-tuned filter diagram together with its impedance curve as a function of frequency. By using the equation, the impedance curve is generated.

$$Z_f(s) = \frac{LCs^2 + RCs + 1}{Cs}$$

Figure 2.6: Impedance curve of a single-tuned filter **[15]**.

The filter is adjusted to a certain frequency where a notch in the impedance curve may be seen in order to remove the particular harmonic component. The impedance curve has a tiny notch in its form. The frequency of the notch is determined by

$$f = \frac{1}{2\pi\sqrt{LC}}$$

The quality factor Q, which is,

$$Q = \frac{\sqrt{L/C}}{R}$$

The impedance curve can be significantly shifted by such changes in component values since the notch frequency is sensitive to inductance and capacitance parameter variation. This may result in the desired harmonic being amplified rather than being suppressed. The impedance curve of the filter and the power system as seen from the harmonic source is shown in Figure 2.6 to highlight this concern. A parallel- and series resonance point are discernible. Since the impedance is low at the series-resonance point, harmonic voltage distortion at adjacent frequencies is also minimal. Severe impedance and harmonic currents result in high voltage distortion at parallel-resonance point. The point of parallel resonance for inductive systems with a single STF is given by,

$$f = \frac{1}{2\pi\sqrt{(L_s + L)C}}$$

Ls stands for series source inductance. A lower frequency than the series-resonance point is where the parallel-resonance always occurs. Detuning the filter to a frequency lower than the intended harmonic prevents harmonic amplification as a result. The target harmonic will always sit at or above the point of series resonance in this method, at least if the parameter variation is within the predicted range. Thus, dangerous harmonic amplification is avoided.

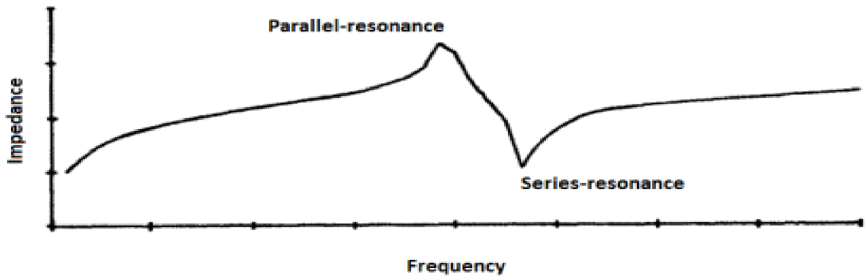


Figure 2.7: Filter and system Impedance Curve **[15]**.

2.8.2 First-order high-pass filter

Equation of impedance curve for first order filter is,

$$Z_f(s) = \frac{RCs + 1}{Cs}$$

This kind of filter is appropriate for a shunt-filter architecture because it may offer a low impedance route to ground for harmonics just above tuning frequency. There is no quality factor since the filter circuit simply contains capacitance and not inductance.

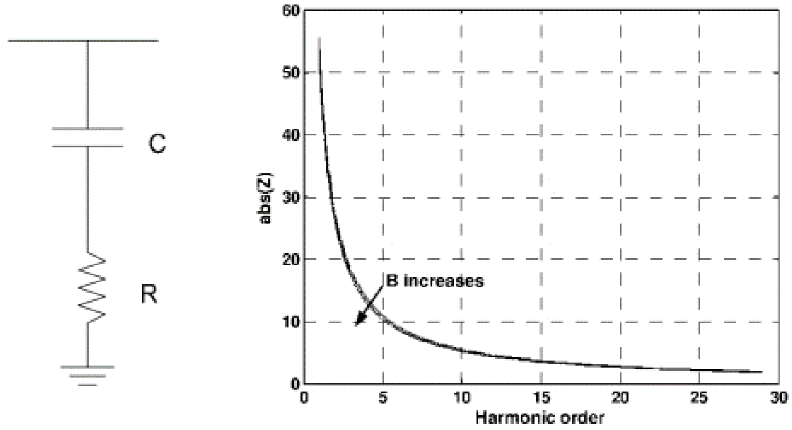


Figure 2.8: Impedance curve of a first-order high-pass filter **[15]**.

Due to the nearly pure resistive resistance at the fundamental frequency, this filter suffers from large losses at that frequency. Another drawback is the large capacity filter rating required to attenuate the broad harmonic spectrum. These two drawbacks are the main reasons why this filter architecture is not widely used [15].

2.8.3 Second-order high-pass filter

The Figure 2.7.1 curve is determined by the equation ,

$$Z_f(s) = \frac{RLCs^2 + Ls + R}{s(CLs + CR)}$$

The shallow notch of this topology as opposed to the single tuned filter is one of its main benefits.

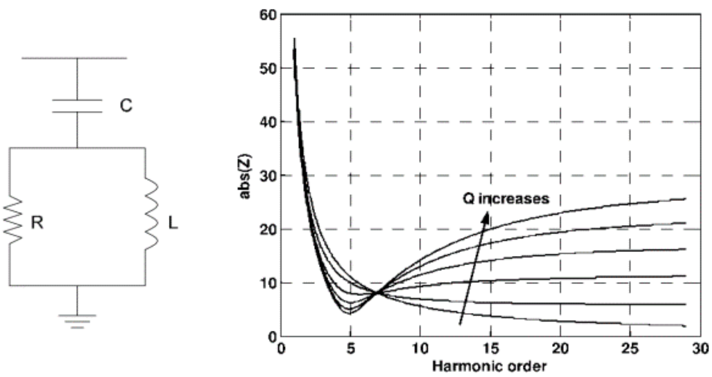


Figure 2.9: Impedance curve of a second-order high-pass filter **[15]**.

This is the rationale for the usage of this filter for a number of high-order harmonics. Additionally, it leads to a lesser sensitivity to parameter variation. It has fewer fundamental losses than the first-order high-pass filter. Due to these excellent qualities, the HP2nd filter architecture is a favorite for industrial uses such high power VSDs [15].

2.8.4 Third-order high-pass filter

The third-order high-pass filter topology and its impedance curve as a function of frequency is shown in Figure 2.8. The impedance curve is determined by,

$$Z_f(s) = \frac{RLC_1C_2s^3 + (C_1 + C_2)Ls^2 + C_2Rs + 1}{sC_1(C_2Ls^2 + C_2Rs + 1)}$$

The third-order high-pass filter has even lower losses than the HPF2nd.

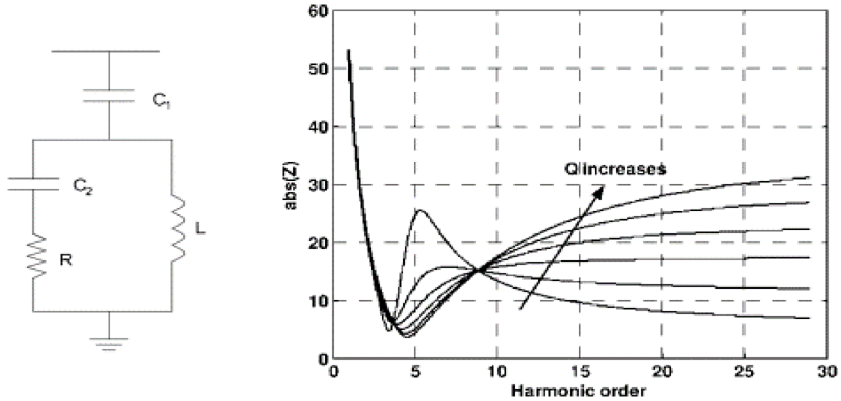


Figure 2.10: Impedance curve of a third-order high-pass filter **[15]**.

Due to the extra capacitor C2, which raises the resistive branch's impedance at low frequencies and reduces losses at the fundamental frequency compared to the HPF2nd, the third-order high-pass filter experiences even lower losses. Nevertheless, compared to the second-order kind, it is less successful at filtering high-order harmonics. It is rarely employed in industry due to the high cost and complexity of the solution [17].

2.8.5 C-type filter

Figure 2.9 shows the c-type filter structure and its impedance curve as a function of frequency.

$$Z_f(s) = \frac{LRC_1C_2s^3 + LC_2s^2 + (C_1 + C_2)Rs + 1}{sC_1(LC_2s^2 + RC_2s + 1)}.$$

The C-type filter has additional auxiliary capacitor C2 added in series with the inductance. The auxiliary capacitor is set to have a low impedance branch for the fundamental current, preventing excessive losses in the resistive branch, while compensating for the inductive reactance at the fundamental frequency.

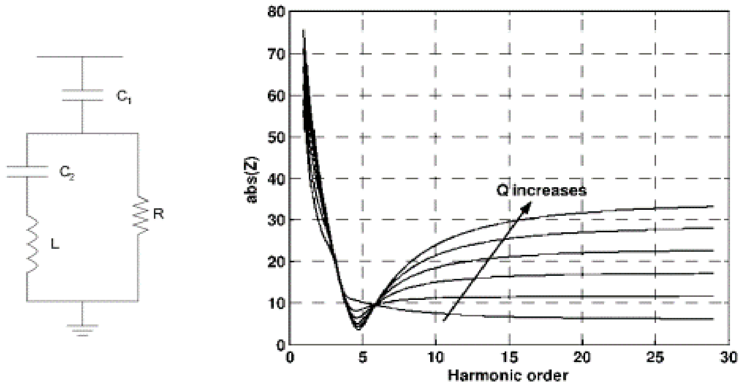


Figure 2.11: Impedance curve and a high-pass C-Type filter **[15]**.

The primary benefit of C-type filters is their minimal fundamental losses. In addition, compared to high-pass filters, a better harmonic attenuation at the tuned frequency is achieved. In comparison to high-pass filters, C-type filters may be set to lower harmonic orders [16]. However, compared to second-order high-pass filters, it is less successful in harmonic attenuation at high-order frequencies. Thus, it can be said that the C-type filter generally exhibits behavior that is between that of second- and third-order high-pass filters. In general, industry applications typically use SFT, HPF2nd, and parallel combinations of the two types. Most commonly utilized in mitigation at the transmission system level are the type C filter and third-order high-pass filters.

2.9 Passive filter design

Before design passive filter we need to know some system parameter like power factor , THD ,line voltage etc. Then for designing filter some step need to flow which are given bellow,

1) Input data
   Calculations of the system's power factor and harmonic current spectrum are required. It is necessary to model the pertinent components and specify the target system.
2) Define min and max capacitor size
   As it was mentioned in, reactive power can be provided via shunt harmonic filters to raise the load's power factor. When the power factor is enough, a filter that merely fulfills harmonic standards must be created; this is known as a minimal filter. The necessary reactive power is determined as follows when the filter is made to increase the power factor.

$$Q = P(\tan\theta_1 - \tan\theta_2)$$

Where Q is the reactive power that the filter must provide. The capacitor reactance is computed using the bus voltage as follows.

$$X_c = \frac{kV^2}{Q}$$

3) Start with C-type topology

   As we know lower order harmonic are greater in magnitude so choosing a lossless filter design is recommended. We know compared to the single-tuned version, the C-type, high-pass filter has lower losses at the fundamental frequency, because the capacitor and inductor are parallel with the resistor.

4) Decide on detuning

   To avoid harmonic amplification designer must keep in mind to detune them to 1-10% below the intended frequency [16].

5) Select minimal capacitor size

6) Filters parameter can be calculated from the given table 2.4,

Table2.4: Values of RCL Filter Components **[17]**.

	Single-Tuned	Double-Tuned	Second-Order, High-Pass	C-type, High-Pass
R	$\frac{1}{2\pi f_0 C Q_f}$	$2\pi f_m L_2 Q_f$	$2\pi n f_0 L Q_f$	$Q_f(2\pi\, n\, f_0\, L_2)$
L	$\frac{1}{C(2\pi n f_0)^2}$	$\frac{V^2}{Q_r \pi f_0 (n_1^2 + n_2^2 - 2)}$	$\frac{1}{C(2\pi n f_0)^2}$	None
C	$\frac{Q_r}{2\pi f_0 V^2} \cdot \frac{n^2 - 1}{n^2}$	$\frac{Q_r}{4\pi f_0 V^2}\left(\frac{n_1^2 - 1}{n_1^2} + \frac{n_2^2 - 1}{n_2^2}\right)$	$\frac{Q_r}{2\pi f_0 V^2} \cdot \frac{n^2 - 1}{n^2}$	$\frac{Q_r}{2\pi f_0 V^2}$
L_2	None	$\frac{\left(1 - \frac{f_1^2}{f_s^2}\right)\left(1 - \frac{f_1^2}{f_p^2}\right)}{C(2\pi f_1)}$ where $f_s = \frac{1}{2\pi\sqrt{LC}}, f_p = \frac{f_1 f_2}{f_s}$	None	$\frac{1}{C_2(2\pi n f_0)^2}$
C_2	None	$\frac{1}{L_2(2\pi f_p)^2}$	None	$C(n^2 - 1)$

Conduct a harmonic analysis after choosing the right settings to determine the voltages and currents of the filter's component parts. In order to evaluate various designs, it is necessary to determine whether another topology or tuning frequency has to be looked into if the harmonic criterion is met.

It is important to take into account filter costs and loss in addition to harmonic performance and component stress.

2.10 Summary

Many studies on harmonics have been discussed in this chapter. We have covered the properties of many types of loads that cause harmonics. This chapter introduced and discussed the harmonic problem, which is one of the most important concerns in power grids. Harmonic standard and the impact of harmonics were discussed. This chapter contains harmonics calculations such as THD, DF, active power, eeactive power, and True power factor. The various approaches of voltage and current harmonics treatment were given and debated. The methods discussed were the classic passive filters based on RLC circuits connected to provide low impedance in order to reduce harmonics. The merits and cons of these passive filters were also discussed. The main drawback of passive filters was their inability to be dynamically adjusted in response to changes in the load and grid. This chapter also discussed and demonstrated the most recent active and hybrid filters

CHAPTER-3
ANALYSIS AND SIMULATION

3.1 Introduction

To understand power system characteristics and to analysis voltage, current, impedance, active power and reactive power, we can simulate the system in computer based software like Matlab Simulink. In this study, The MATLAB/Simulink platform is used to study and create various filter types. The shunt active filter that we are going to introduce in this study were designed by the author of [18].

3.2 Harmonic Order and Their Effect

Harmonic order and their magnitude decides how it going to impact on the load ,source and power lines. Higher order harmonics are less of an issue than lower order harmonics. Current harmonics are the default definition of harmonics. We know most the equipment we use mostly inductive and so their impedance ‘$Z= R+jwL$’, where $w=2\pi f$. As a result, the equation shows that the offered impedance is directly proportional to frequency. Because of this, higher order harmonics have less of a magnitude than lower order harmonics because as harmonic order grows, their effective impedance increases. Therefore, the higher order harmonics are blocked by the device's or the circuit's resistance. Hence the filters are designed mostly for lower order harmonics.

Harmonic order can be define by the equation like 3n ,(3n+2),(3n-2) where n=1,3,5,7…in between them 3n or more specifically 3^{rd} harmonic is most dangerous in power system .

The triplen harmonic is present in single phase system and there phase system with neutral conductor. But in three phase without neutral conductor important are fifth and seventh harmonics.

3.2.1 Triplen Harmonic

When a three phase system is balanced we know there is no current flow through neutral wire because the phase currents are 120 degrees out of phase with one another so the current can return to the source without neutral wire. But in case of unbalanced condition and 3n harmonic present in current the neutral wire is used to return current back to the source. Neutral wire is not so thick as compared to other phase conductor so current must be keep limited, in order to not blow the neutral conductor. The 3n harmonics currents are 360 (or zero) degrees out of phase so there is no phase difference between them .That’s why they add up to a very large magnitude current and flow through the neutral wire and therefore cause overheating of the neutral conductor.

In order to understand 3n current harmonics effect on neutral conductor better we can simulate it on Matlab by some simple coding,

```
Command Window
>> Im=20;
f=50;
fs=10^5;
t=0:1/fs:1/50;
w=2*pi*f;

% Balanced 3phase current fundamental component

Ir=Im*sin(w*t);
Iy=Im*sin(w*t-2*pi/3);
Ib=Im*sin(w*t+2*pi/3);

plot(t,Ir,t,Iy,t,Ib,'LineWidth',2)

I=Ir+Iy+Ib;

figure
plot(t,I)
axis([0 1/50 -10 10])

% 3n  harmonics

I3r=Im*sin(3*w*t);
I3y=Im*sin(3*w*t-3*2*pi/3);
I3b=Im*sin(3*w*t+3*2*pi/3);

plot(t,I3r,t,I3y,t,I3b,'LineWidth',2)

subplot(3,1,1), plot(t,I3r,'r')
subplot(3,1,2), plot(t,I3y,'g')
subplot(3,1,3), plot(t,I3b,'b')

figure
I3=I3r+I3y+I3b;
plot(t,I3,'LineWidth',2)
```

Figure 3.1: Matlab code to generate balanced 3phase wave and 3n harmonic.

In figure 3.1 we showed the code to generate 3phase balanced current and 3n harmonic resultant current waveform which are shown in figure 3.2, 3.3, 3.4.

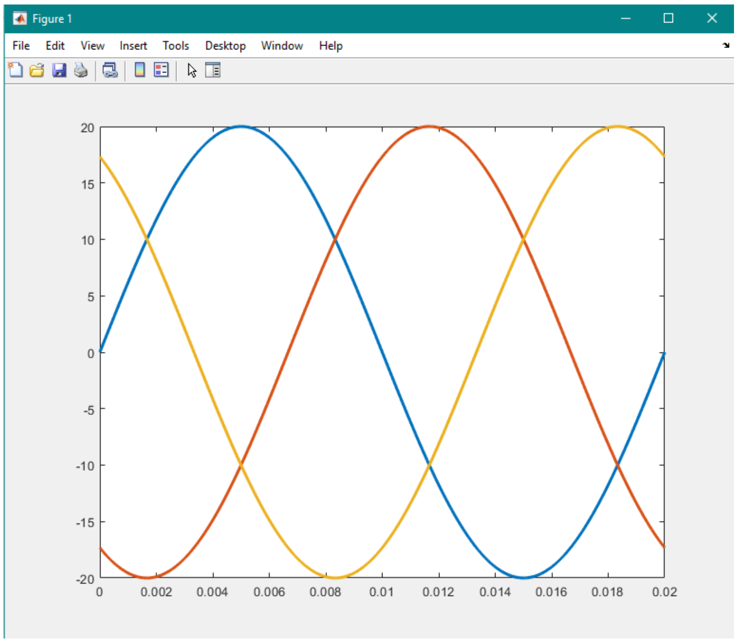


Figure 3.2: Balanced 3phase sinusoidal current wave.

This figure 3.2 shows the balanced current waveform with 120* phase difference and 20A of peak current. For this no neutral wire is required.

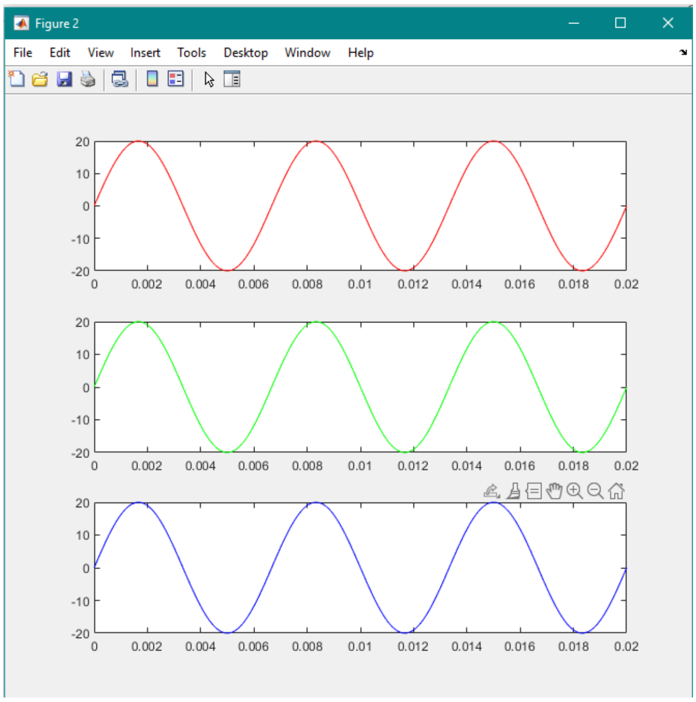


Figure 3.3: Phase current with zero phase difference.

But in figure 3.3 we can clearly see there is no phase difference in the phases because in 3n harmonics the frequency of each phase are multiplied by 3n time which making them zero phase difference (0*3=0 , 120*3=360 or 0 , -120*3=-360 or 0).That means they will be in phase .

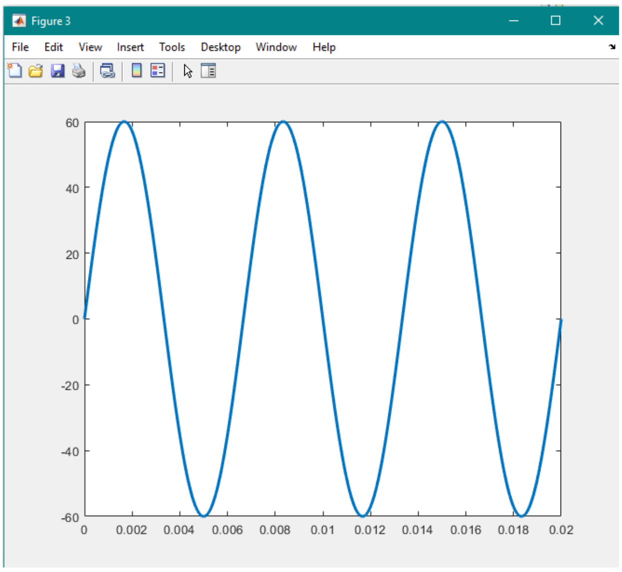


Figure 3.4: Resultant current waveform due to 3n harmonic.

We can see in figure 3.4 the resultant waveform due to 3n harmonic are add up to 3time peak the maximum current .If there is neutral path available (star grounded) this 3n harmonic current will flow through the neutral wire, hence this will cause overloading the neutral wire and heat up.

The negative effects of 3^{rd} harmonic on sensitive equipment is huge if they are not filtered at the proper locations. Third and all triplen harmonics can be prevented from propagating in power systems using power transformers because the delta windings of transformers trap them at the points of common coupling (PCC) with the rest of the power grid.

3.3 Passive Filter Comparison

RLC circuits are used to build band pass passive filters. Different types of RLC topologies to form passive filter are available in market. Depending on the harmonic order magnitude the topology can be selected. As we studied from different research paper the c-type filter has great acceptance in market due their low power losses at fundamental frequency. To justify this we will test every passive filter topologies to check their performance in Simulink.

3.3.1 Simulation with Three Phase Non-Linear Load:

To compare our 4 types of harmonic filter we designed a simple 3phase power system circuit in Matlab Simulink. Three are there 3 bus in our design. We will connect deferent types of load at bus 3.As we know harmonic wave try to propagate from load to source so our main concern will be at bus 2 and bus 1.Our target is to stop harmonic before it reach at bus 2.So to trap or bypassing the harmonic wave we need to create low impedance path using filters .That's why we are going to connect our designed filter in between bus 2 and bus3. For this purpose our scopes are connected at bus 2 to see voltage and current wave shape and THD of bus 2 .The system does not include any transformer or other equipment for the shake of simplicity. The system parameter are shown in Table 3.1,

Table-3.1: System Parameters.

System parameter	Value
Voltage (L-L)	220V
frequency	50Hz
L_l	$0.05*10^{-3}$ H
R_l	0.01Ω
Nonlinear load + Linear load	3ohm(3phase diode)+(100W+30VAR)

At first we run our system normally and we can see the non-liner load(3phase diode rectifier) consuming 72.19A of current ,which is shown in Figure 3.5 . At Bus 2 if we look at our Voltage and current waveform (Figure 3.6) we can see current wave shape is badly distorted by harmonics.

At Bus 2 we can see our real and reactive power demand at fundamental frequency is respectively 26.62kW and 6.367kVAR (Figure 3.7).

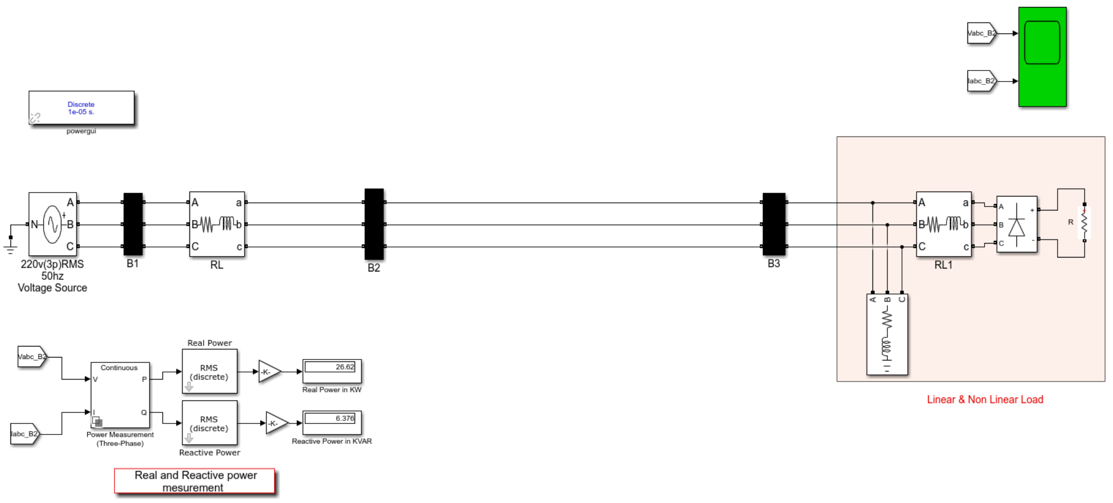


Figure3.5: Circuit of our designed system without any filter.

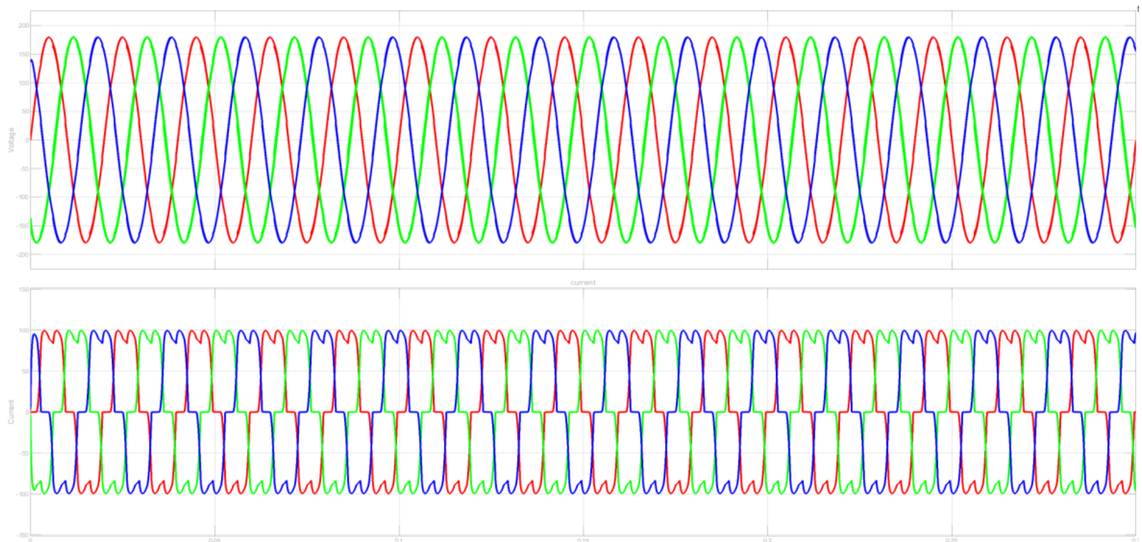


Figure3.6: Bus 2 (load) voltage and current waveform.

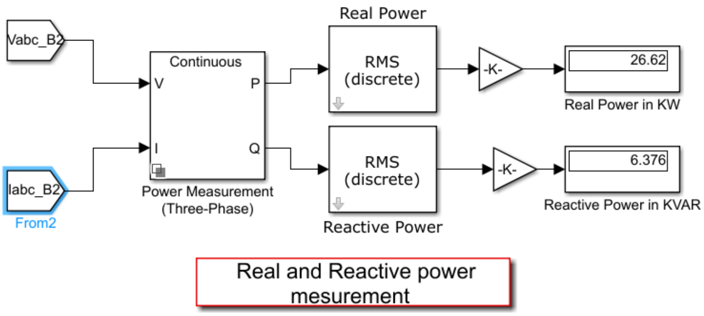
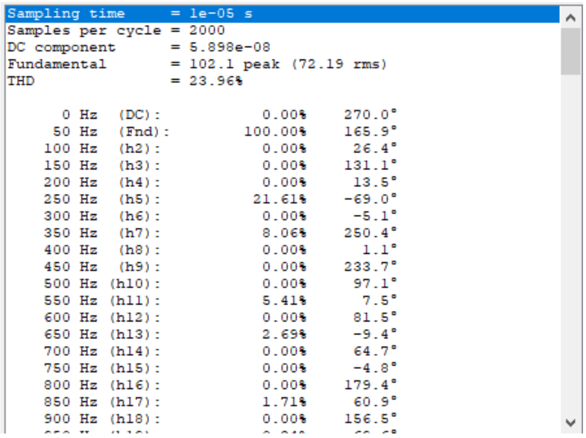


Figure3.7: Real and Reactive power consumed by load at fundamental frequency.



```
Sampling time      = 1e-05 s
Samples per cycle = 2000
DC component       = 5.898e-08
Fundamental        = 102.1 peak (72.19 rms)
THD                = 23.96%

    0 Hz  (DC):          0.00%    270.0°
   50 Hz  (Fnd):       100.00%    165.9°
  100 Hz  (h2):          0.00%     26.4°
  150 Hz  (h3):          0.00%    131.1°
  200 Hz  (h4):          0.00%     13.5°
  250 Hz  (h5):         21.61%    -69.0°
  300 Hz  (h6):          0.00%     -5.1°
  350 Hz  (h7):          8.06%    250.4°
  400 Hz  (h8):          0.00%      1.1°
  450 Hz  (h9):          0.00%    233.7°
  500 Hz (h10):          0.00%     97.1°
  550 Hz (h11):          5.41%      7.5°
  600 Hz (h12):          0.00%     81.5°
  650 Hz (h13):          2.69%     -9.4°
  700 Hz (h14):          0.00%     64.7°
  750 Hz (h15):          0.00%     -4.8°
  800 Hz (h16):          0.00%    179.4°
  850 Hz (h17):          1.71%     60.9°
  900 Hz (h18):          0.00%    156.5°
```

Figure3.8: system FFT Analysis.

Now From FFT Analysis (Figure3.8) we can see total harmonic distortion due to non-linear load is 23.96%. Also the dominating harmonics components are 5^{th}, 7^{th}, 11^{th}, 13^{th} and 17^{th} and their respective magnitudes are, 21.61%, 8%, 5.41%, 2.69% and 1.71%. Now our goal is to find the suitable filter design for reducing the THD to standard limit. For this we are using built in filter of Simulink shown in Figure 3.9.

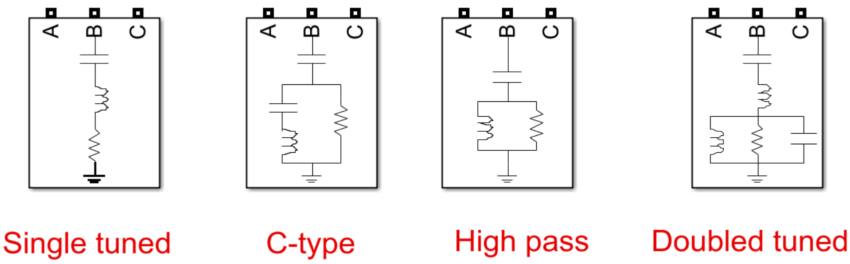


Figure3.9: Passive filters.

From FFT analysis we have seen 5th harmonic is most dominating harmonic component in our system ,so gonna test our all filters that are tuned at 5*50=250Hz. And find which is best for low order harmonics.

Single tuned filter to mitigate 5th order harmonic:

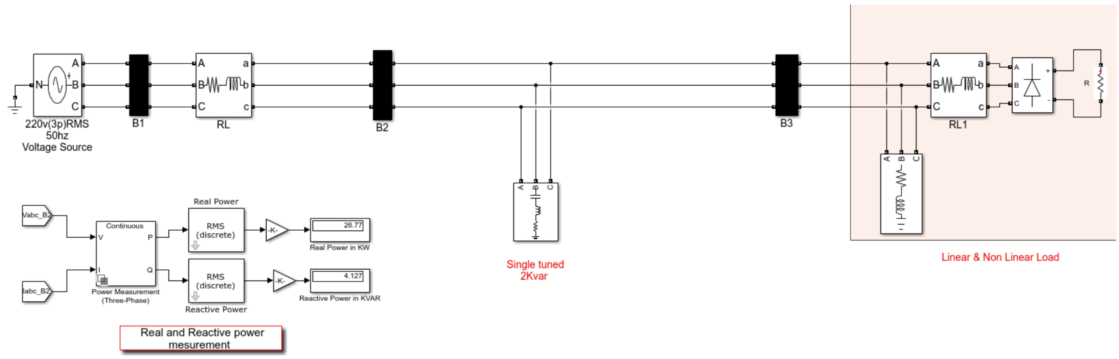


Figure 3.10: Single tuned 5th fifth order harmonic filter connected to system.

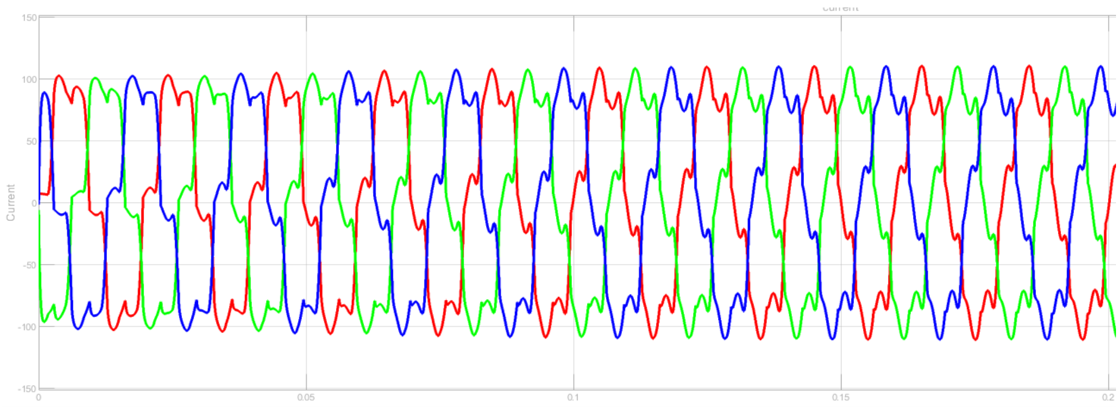


Figure 3.11: Current waveform after adding 5th order filter.

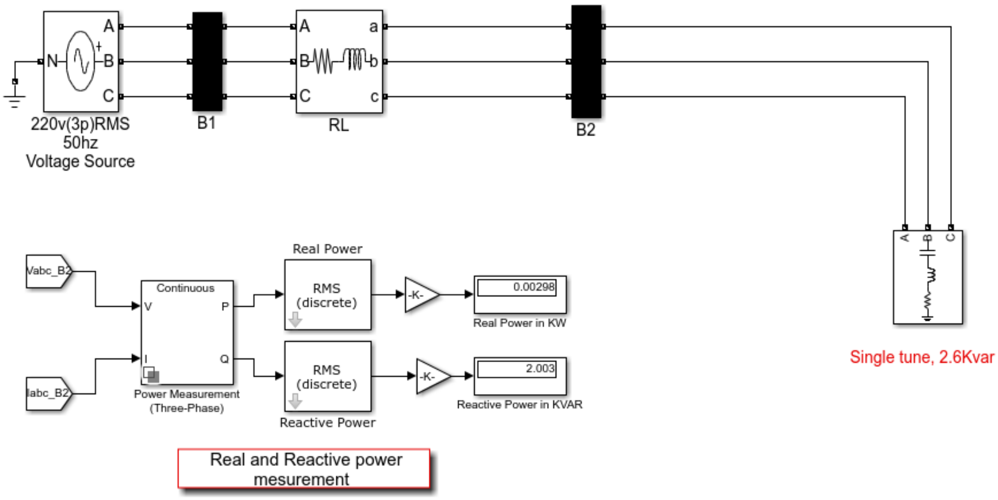
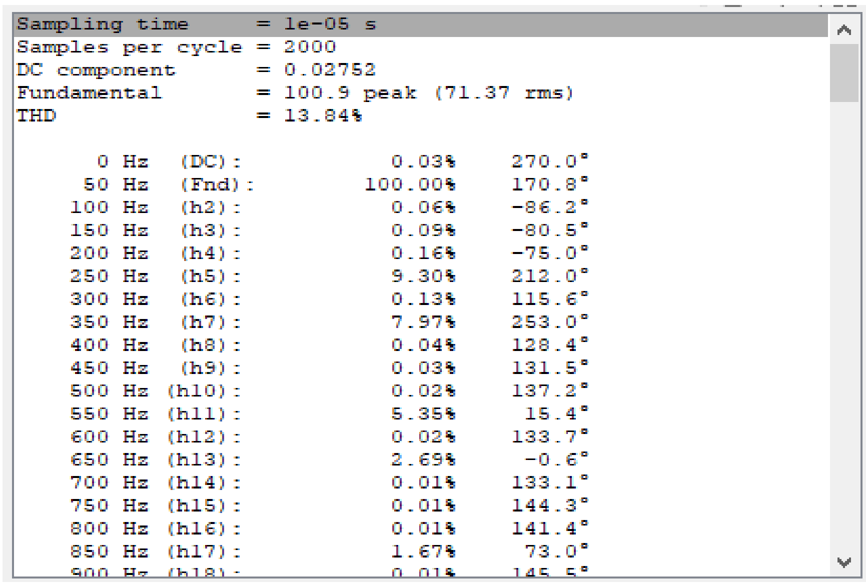


Figure 3.12: Single tuned filter real power consumption from source.



```
Sampling time      = 1e-05 s
Samples per cycle  = 2000
DC component       = 0.02752
Fundamental        = 100.9 peak (71.37 rms)
THD                = 13.84%

    0 Hz  (DC):        0.03%    270.0°
   50 Hz  (Fnd):     100.00%    170.8°
  100 Hz  (h2):        0.06%    -86.2°
  150 Hz  (h3):        0.09%    -80.5°
  200 Hz  (h4):        0.16%    -75.0°
  250 Hz  (h5):        9.30%    212.0°
  300 Hz  (h6):        0.13%    115.6°
  350 Hz  (h7):        7.97%    253.0°
  400 Hz  (h8):        0.04%    128.4°
  450 Hz  (h9):        0.03%    131.5°
  500 Hz (h10):        0.02%    137.2°
  550 Hz (h11):        5.35%     15.4°
  600 Hz (h12):        0.02%    133.7°
  650 Hz (h13):        2.69%     -0.6°
  700 Hz (h14):        0.01%    133.1°
  750 Hz (h15):        0.01%    144.3°
  800 Hz (h16):        0.01%    141.4°
  850 Hz (h17):        1.67%     73.0°
  900 Hz (h18):        0.01%    145.5°
```

Figure 3.13: FFT analysis after adding single tuned filter.

Figure 3.10 showing that only single tuned filter 2kVAR is connected between source and Load. After adding this the current wave form look like figure 3.11.

Figure 3.12 showing that the filter is consuming 0.00298kW of real power and producing 2kVAR reactive power .5th harmonic has reduced to 9.30% and overall THD down to 13.84% (Figure3.13).

High Pass passive filter to mitigate 5th order harmonic:

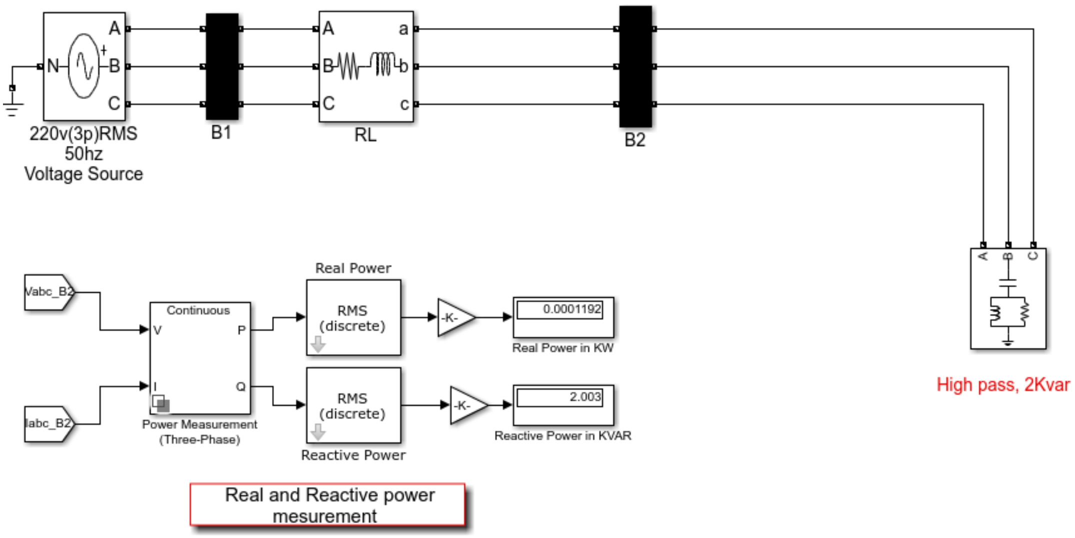


Figure3.14: High pass filter real power consumption from source.

```
Sampling time      = 1e-05 s
Samples per cycle = 2000
DC component       = 0.02805
Fundamental        = 100.9 peak (71.36 rms)
THD                = 13.89%

      0 Hz   (DC):          0.03%    270.0°
     50 Hz  (Fnd):        100.00%    170.8°
    100 Hz   (h2):          0.07%    -86.1°
    150 Hz   (h3):          0.09%    -79.7°
    200 Hz   (h4):          0.17%    -74.7°
    250 Hz   (h5):          9.36%    211.3°
    300 Hz   (h6):          0.13%    115.9°
    350 Hz   (h7):          7.97%    253.0°
    400 Hz   (h8):          0.04%    128.8°
    450 Hz   (h9):          0.03%    131.1°
    500 Hz  (h10):          0.02%    137.5°
    550 Hz  (h11):          5.35%     15.4°
    600 Hz  (h12):          0.02%    134.2°
    650 Hz  (h13):          2.69%     -0.6°
    700 Hz  (h14):          0.01%    133.4°
    750 Hz  (h15):          0.01%    145.4°
    800 Hz  (h16):          0.01%    142.1°
    850 Hz  (h17):          1.67%     73.1°
    900 Hz  (h18):          0.01%    145.7°
```

Figure3.15: FFT analysis after adding High Pass filter.

Figure 3.14 showing that the filter is consuming 0.0001192kW of real power and producing 2kVAR reactive power. 5th harmonic has reduced to 9.36% and overall THD down to 13.89% (Figure3.15).

C-type filter to mitigate 5th order harmonic:

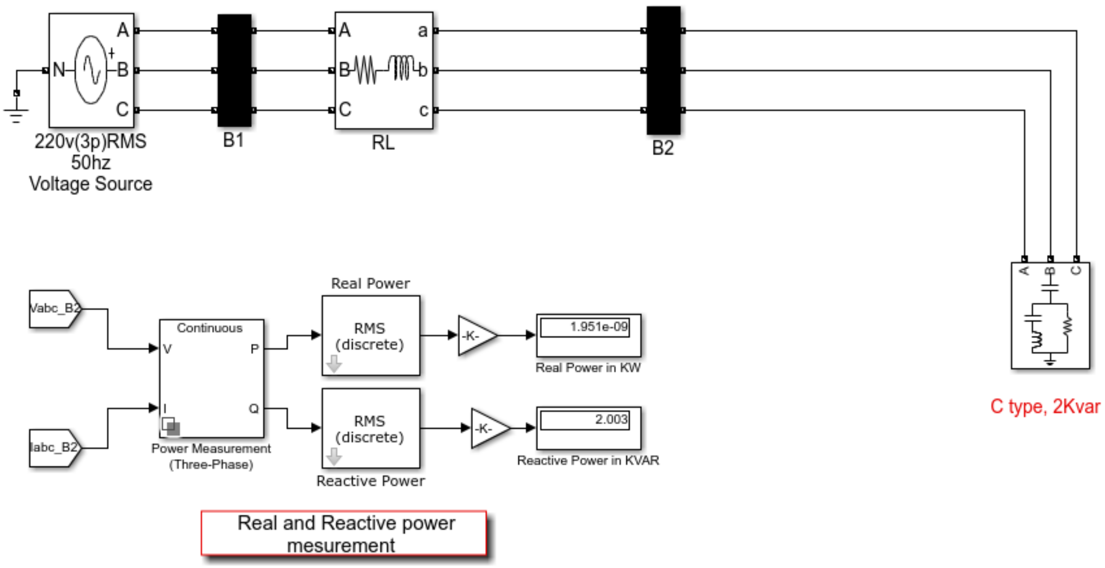
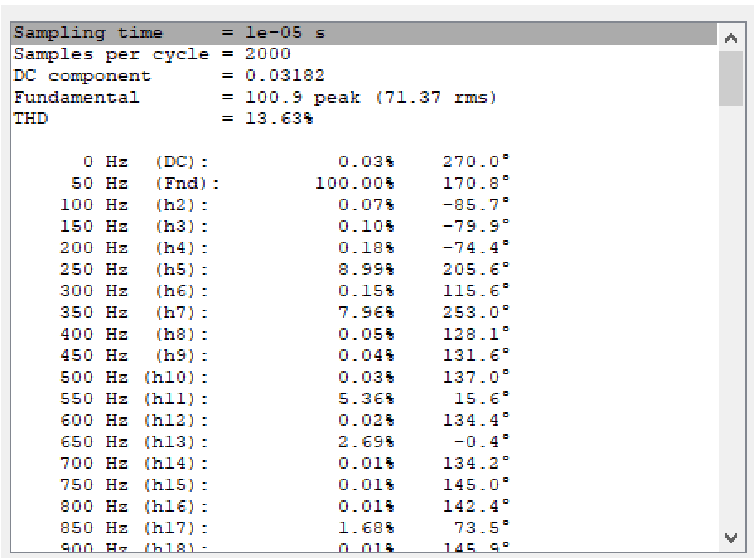


Figure3.16: C-Type filter real power consumption from source.



```
Sampling time      = 1e-05 s
Samples per cycle = 2000
DC component       = 0.03182
Fundamental        = 100.9 peak (71.37 rms)
THD                = 13.63%

     0 Hz  (DC):         0.03%    270.0°
    50 Hz  (Fnd):      100.00%    170.8°
   100 Hz  (h2):         0.07%    -85.7°
   150 Hz  (h3):         0.10%    -79.9°
   200 Hz  (h4):         0.18%    -74.4°
   250 Hz  (h5):         8.99%    205.6°
   300 Hz  (h6):         0.15%    115.6°
   350 Hz  (h7):         7.96%    253.0°
   400 Hz  (h8):         0.05%    128.1°
   450 Hz  (h9):         0.04%    131.6°
   500 Hz (h10):         0.03%    137.0°
   550 Hz (h11):         5.36%     15.6°
   600 Hz (h12):         0.02%    134.4°
   650 Hz (h13):         2.69%     -0.4°
   700 Hz (h14):         0.01%    134.2°
   750 Hz (h15):         0.01%    145.0°
   800 Hz (h16):         0.01%    142.4°
   850 Hz (h17):         1.68%     73.5°
   900 Hz (h18):         0.01%    145.9°
```

Figure3.17: FFT analysis after adding C-Type filter.

Figure 3.16 showing that the filter is consuming almost zero real power and producing 2kVAR reactive power. 5th harmonic has reduced to 8.99% and overall THD down to 13.69% (Figure3.17).

3.4. Harmonic Distortion mitigation to standard limit Using Passive filter Combination:

To reduce harmonic current distortion to minimum, we will use several filters depending upon the order of harmonic component which are higher in magnitude. From FFT analysis we know for our system total current distortion is around 23.96% and the 5^{th}, 7^{th}, 11^{th} and 13^{th} order harmonic component magnitude are dominating in nature .So we will use four filter which are tuned at those dominating component frequencies. The value of passive component and filter types which we calculated using table 2.4 are given in table 3.2.

Table3.2: Passive filters parameters.

Filter type	Harmonic Order	Nominal Reactive power (kVAR)	R(Ohm)	C(uf)	L(mH)	C2(uf)	L2(H)
C type	5^{Th}	2	21.72	171	×	4103.8	9.88e-5
	7^{th}	2	30.40	239.4	×	5745.32	8.97e-5
Single tuned	11^{th}	1	0.488	65.22	1.28	×	×
	13^{th}	1	0.472	65.37	0.97	×	×

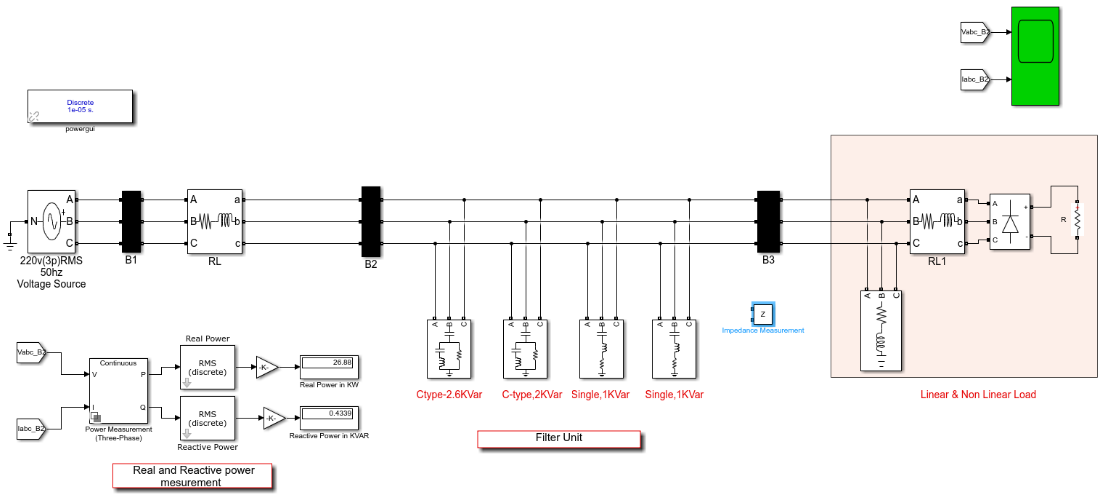


Figure3.18: Overall THD reduction by passive filters

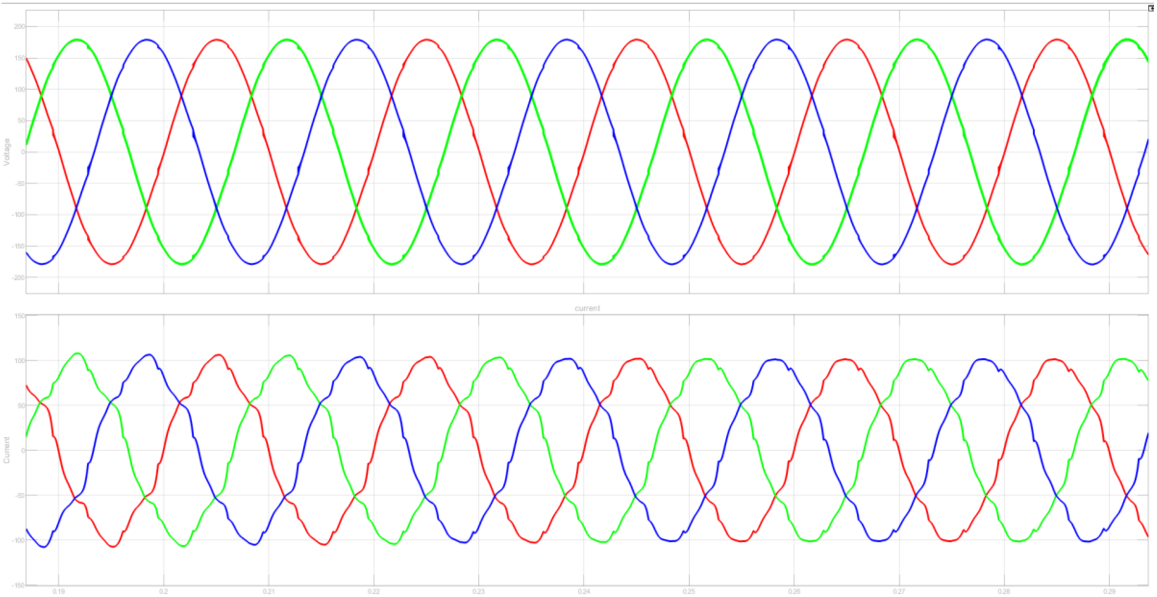


Figure3.19: Voltage and current wave form after adding passive filters

We have connected the filter in between bus 2 and bus 3 in parallel to the load (Figure3.18). From figure 3.19 we can see voltage and current waveform after filtering which is closely sinusoidal and from FFT analysis we can see THD_i reduced to 4.79% and dominating harmonic components were in admissible limit (figure3.20).

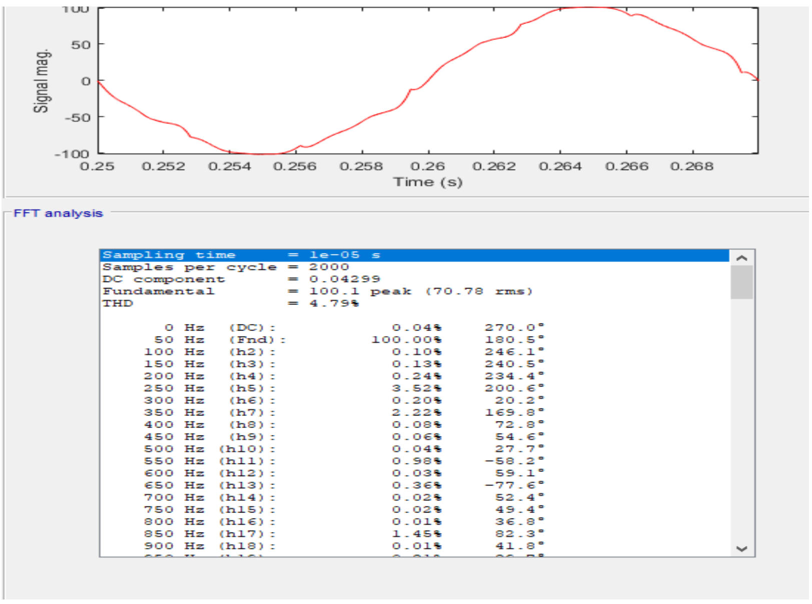


Figure3.20: THD_i after adding passive filters.

3.4.1 New type of load connected to existing system:

In the above simulation we have used 3phase diode as a non-linear load .Now we will change our load type so that we can see how our existing filter will react with new type load. We are denoting this load as load-2.

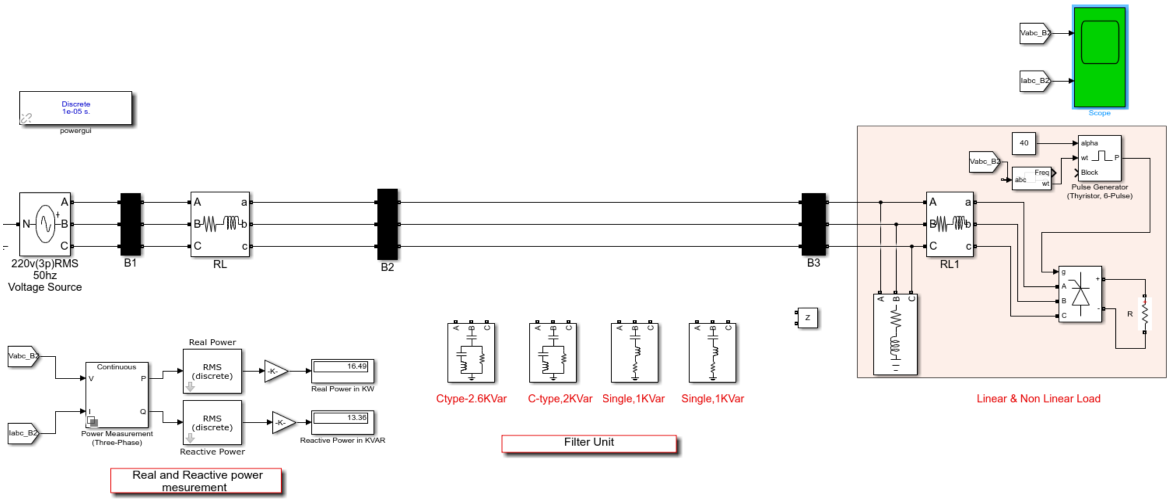


Figure3.21: 6-pulse thyrestor based load (load-2) connected at bus-3.

At bus 3 we have connected a new type of load which will produce different harmonic pollution to system and then we will check our filters performance (figure3.21).

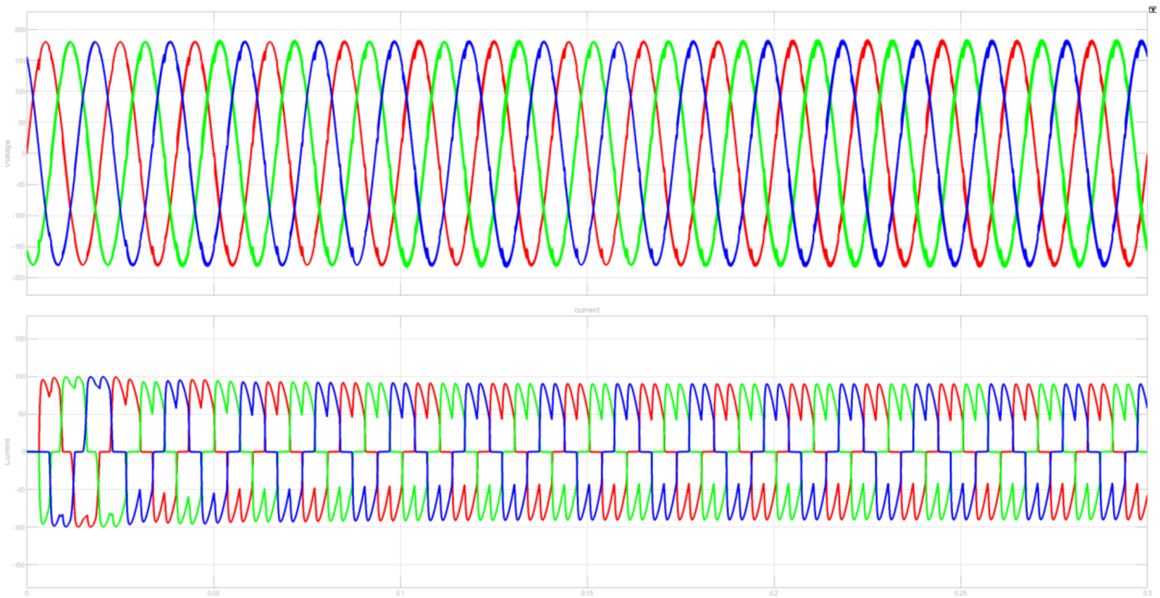


Figure3.22: Voltage and current waveform without any filter for load-2.

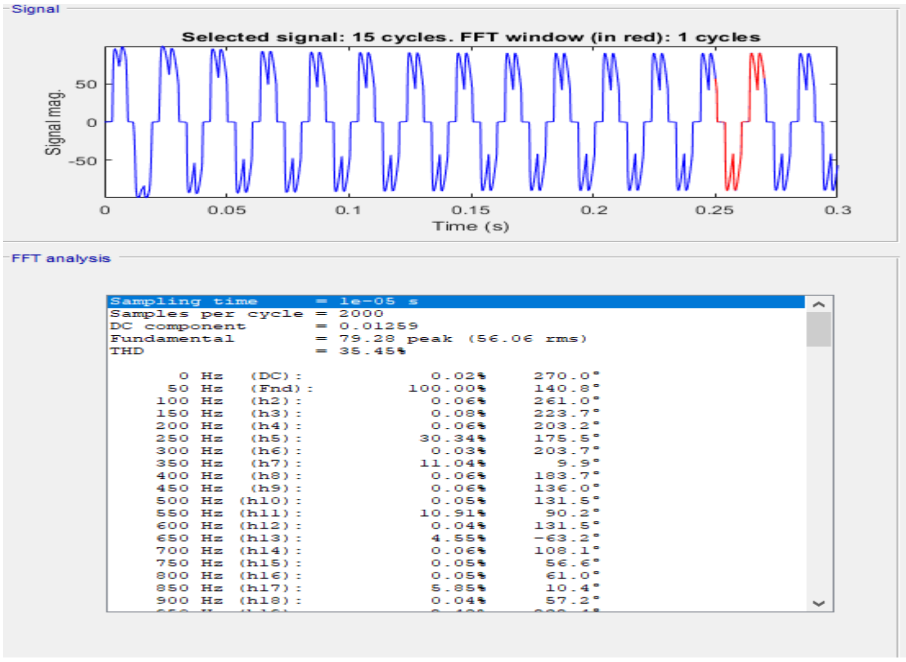


Figure3.23: THD$_i$ for load 2.

In figure 3.22 and 3.23, that we can see current waveform and FFT analysis result is completely different from load-1.THD$_i$ is around 35.45% and 17th and 19th order dominating harmonics were produced .

Now we have connected our passive filter from previously designed system to our new load2 in figure 3.24.

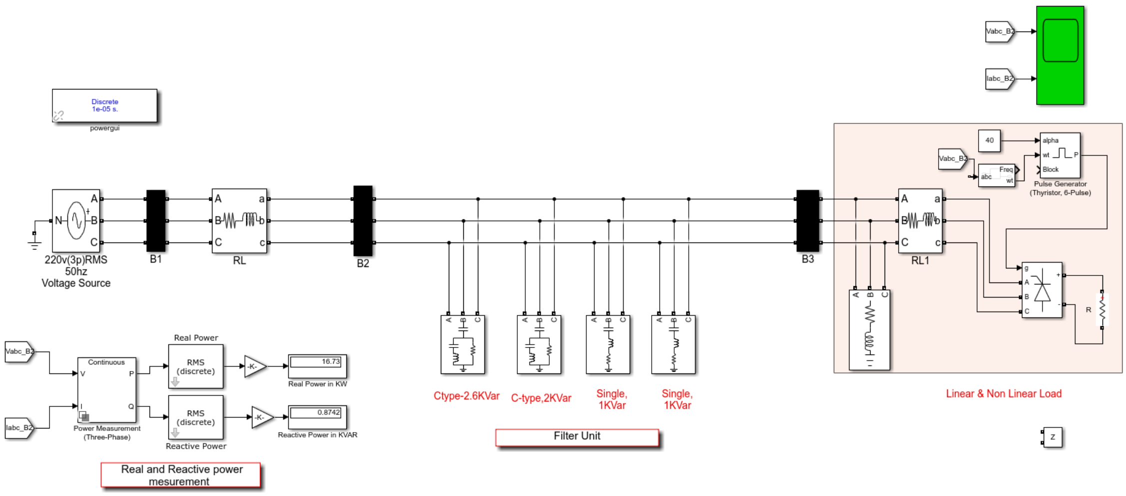


Figure3.24: Pre designed passive filter connected for load type2.

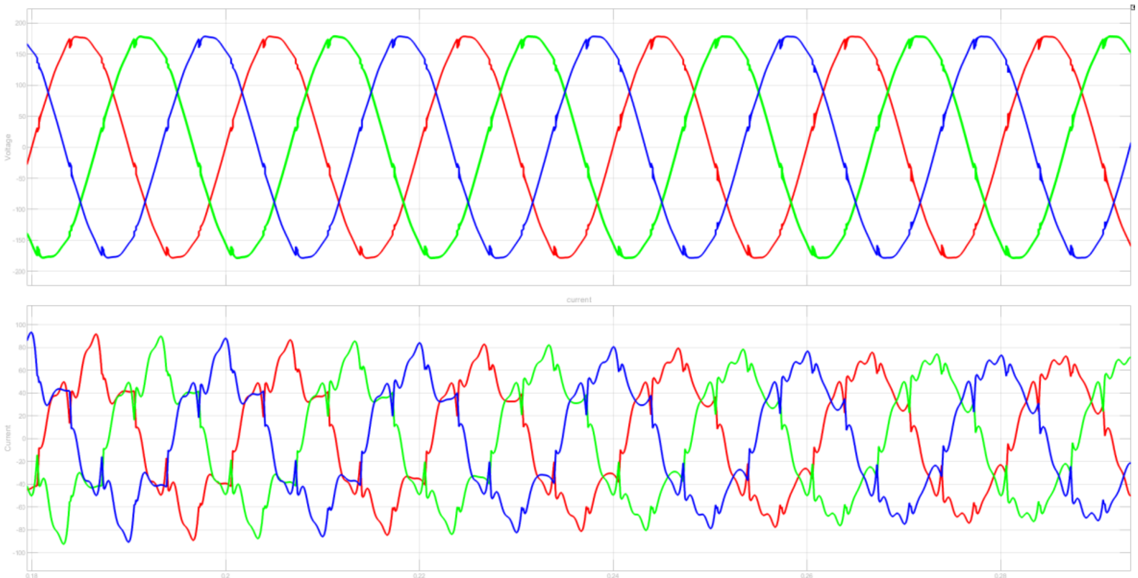


Figure3.25: Voltage and current waveform after adding passive filter (load-2).

The current waveform after filtering is still distorted badly shown in figure3.21.The FFT analysis showing THD is around 15.69% and also higher order harmonics component are increased in magnitude after adding filters in figure 3.26.

```
Sampling time     = 1e-05 s
Samples per cycle = 2000
DC component      = 0.07143
Fundamental       = 67.1 peak (47.44 rms)
THD               = 15.69%

    0 Hz   (DC):        0.11%     90.0°
   50 Hz  (Fnd):      100.00%    157.4°
  100 Hz   (h2):        0.29%    122.4°
  150 Hz   (h3):        0.45%    136.1°
  200 Hz   (h4):        0.89%    135.9°
  250 Hz   (h5):       11.48%     29.4°
  300 Hz   (h6):        0.47%    -54.8°
  350 Hz   (h7):        5.11%    -27.4°
  400 Hz   (h8):        0.57%    -19.5°
  450 Hz   (h9):        0.33%    -21.2°
  500 Hz  (h10):        0.24%    -41.0°
  550 Hz  (h11):        2.96%     17.4°
  600 Hz  (h12):        0.28%    -19.0°
  650 Hz  (h13):        0.53%    210.6°
  700 Hz  (h14):        0.18%      8.9°
  750 Hz  (h15):        0.18%      6.2°
  800 Hz  (h16):        0.15%      1.6°
  850 Hz  (h17):        5.82%     11.2°
  900 Hz  (h18):        0.13%     -1.0°
```

```
  450 Hz   (h9):        0.33%    -21.2°
  500 Hz  (h10):        0.24%    -41.0°
  550 Hz  (h11):        2.96%     17.4°
  600 Hz  (h12):        0.28%    -19.0°
  650 Hz  (h13):        0.53%    210.6°
  700 Hz  (h14):        0.18%      8.9°
  750 Hz  (h15):        0.18%      6.2°
  800 Hz  (h16):        0.15%      1.6°
  850 Hz  (h17):        5.82%     11.2°
  900 Hz  (h18):        0.13%     -1.0°
  950 Hz  (h19):        2.47%    232.1°
 1000 Hz  (h20):        0.11%     -1.5°
 1050 Hz  (h21):        0.11%    -10.4°
 1100 Hz  (h22):        0.10%     -1.7°
 1150 Hz  (h23):        3.78%    -63.5°
 1200 Hz  (h24):        0.09%     -0.9°
 1250 Hz  (h25):        1.66%    167.9°
 1300 Hz  (h26):        0.08%      0.4°
 1350 Hz  (h27):        0.06%     -4.1°
 1400 Hz  (h28):        0.07%     -0.3°
 1450 Hz  (h29):        2.50%    221.9°
 1500 Hz  (h30):        0.07%      0.8°
 1550 Hz  (h31):        1.32%    103.2°
 1600 Hz  (h32):        0.06%      1.4°
 1650 Hz  (h33):        0.06%     12.2°
```

Figure3.26: THD_i after adding passive filter for of load 2.

3.5 Shunt Active filter: Case1

In this case we will simulate our system from figure 3.5 with shunt active filter. At the load end we have tried our first 3phase diode rectifier load .For shake of simplicity we have used pre designed model of shunt filter from the website of Mathworks [18].

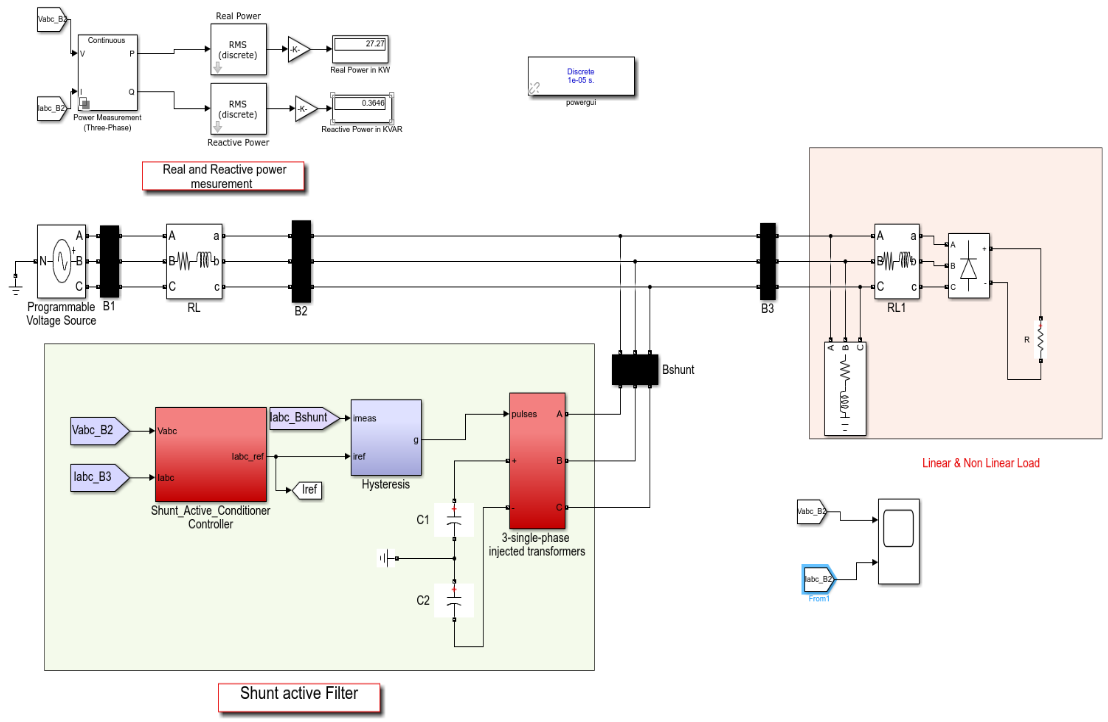


Figure 3.27: Shunt Active filter connected to grid (load 1).

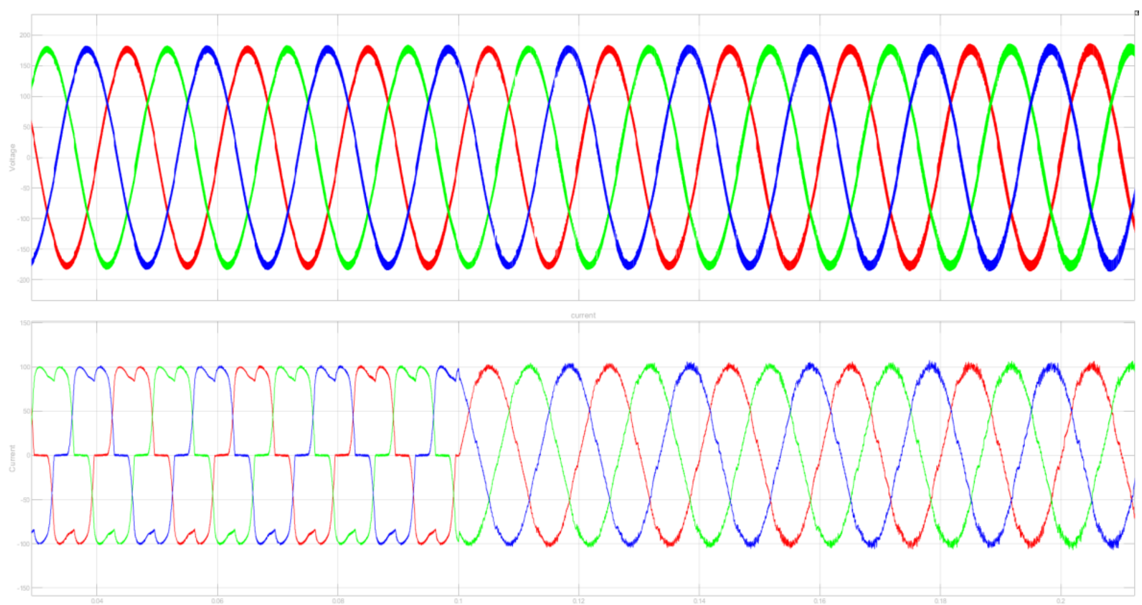


Figure 3.28: Voltage and current waveform before and after connecting SAPF (load 1).

The figure 3.28 showing that volatage and current waveform are before and after starting the shunt active filter. The current waveform is decent after filter action start .The FFT analysis is shown in figure 3.29.

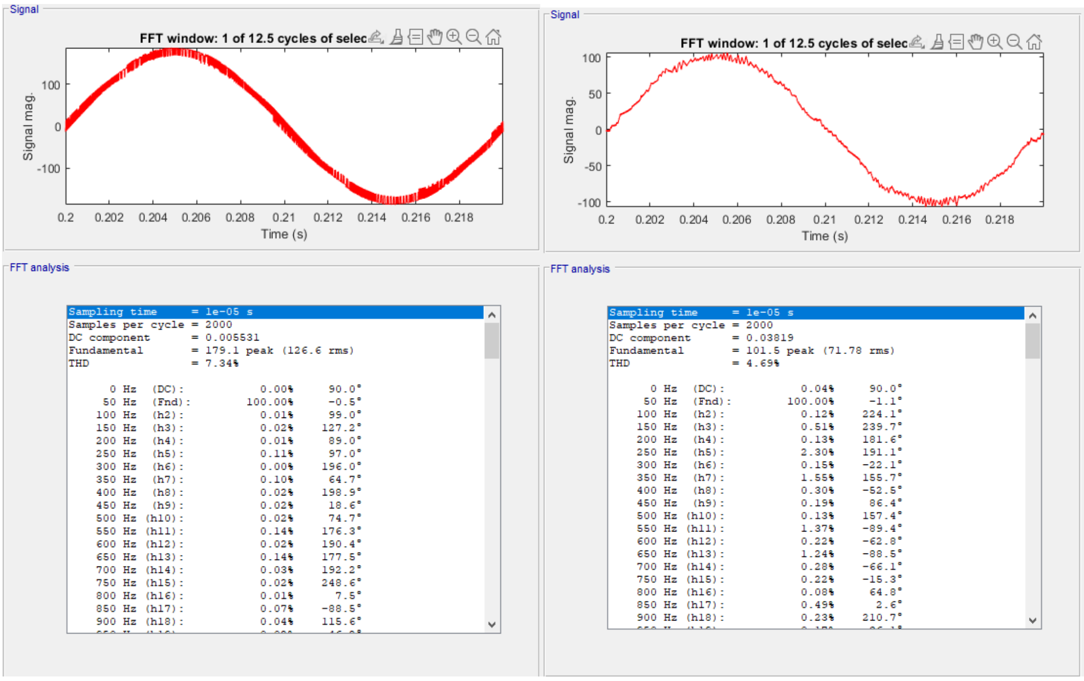


Figure 3.29 : THD_v and THD_i of voltage and current after adding SAPF.

3.5.1 Shunt Active filter : Case2

Now we changed our load to 6-pulse thyristors based load shown in figure 3.30.

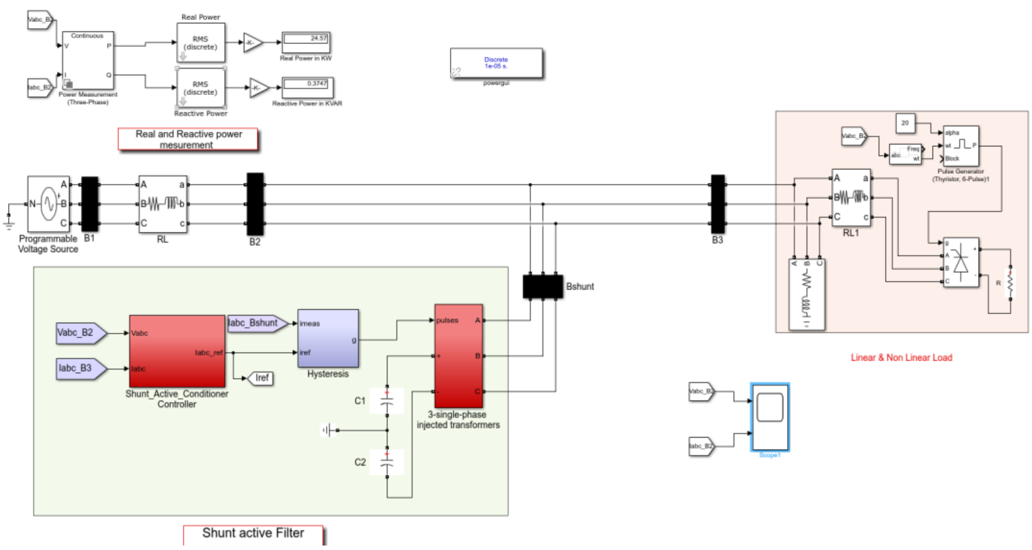


Figure 3.30: Shunt Active filter connected to grid (load 2).

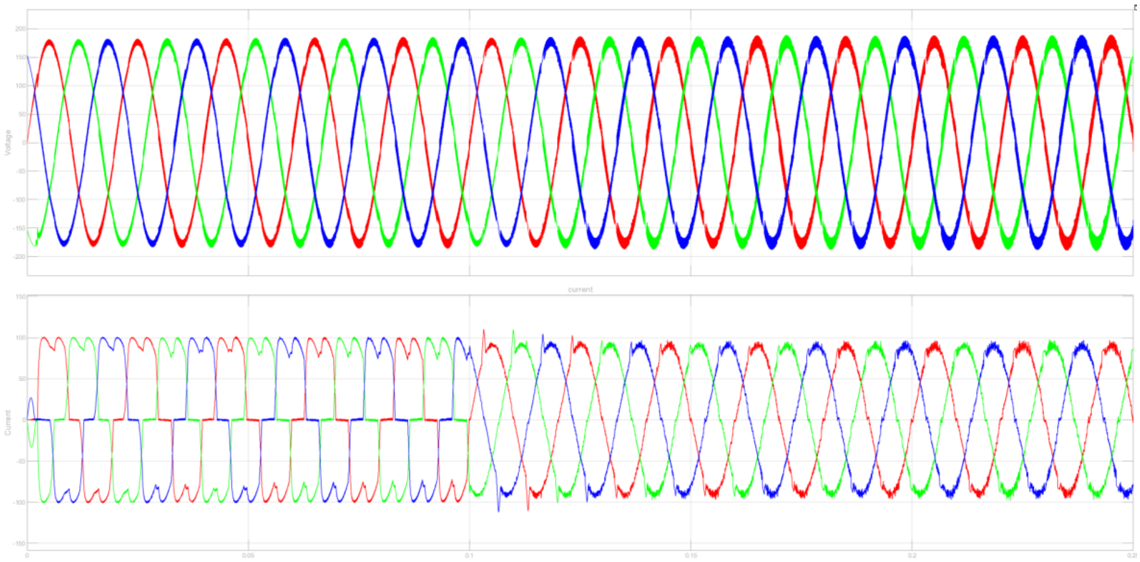


Figure 3.31: Voltage and current waveform before and after connecting SAPF (load 2).

The voltage and current waveform after changing the load type still good close to sinusoidal (Figure3.31). Although THD value is increased than before. Shown in figure 3.32.

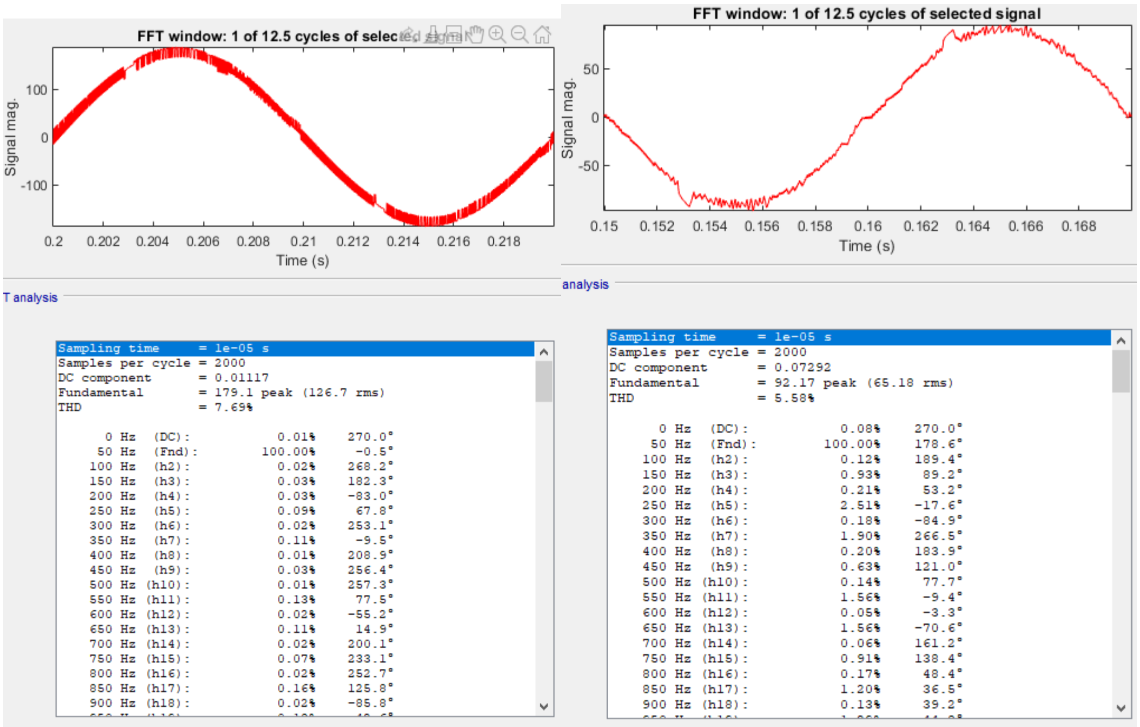


Figure 3.32: THD of voltage and current after adding SAPF for load -2.

3.6 Hybrid filter (SAPF + Passive filter):

Now to get better result we will combine two solution which is known as hybrid filter .from figure 3.32 we have seen that voltage distortion was around 7.69% and very high frequency harmonic were present in voltage waveform. So for this we will use a line reactor to block very high frequency travelling from load to grid. And to improve current THD more we gonna add a single tuned filter of 2kVAR tuned at 250Hz (5th harmonic).

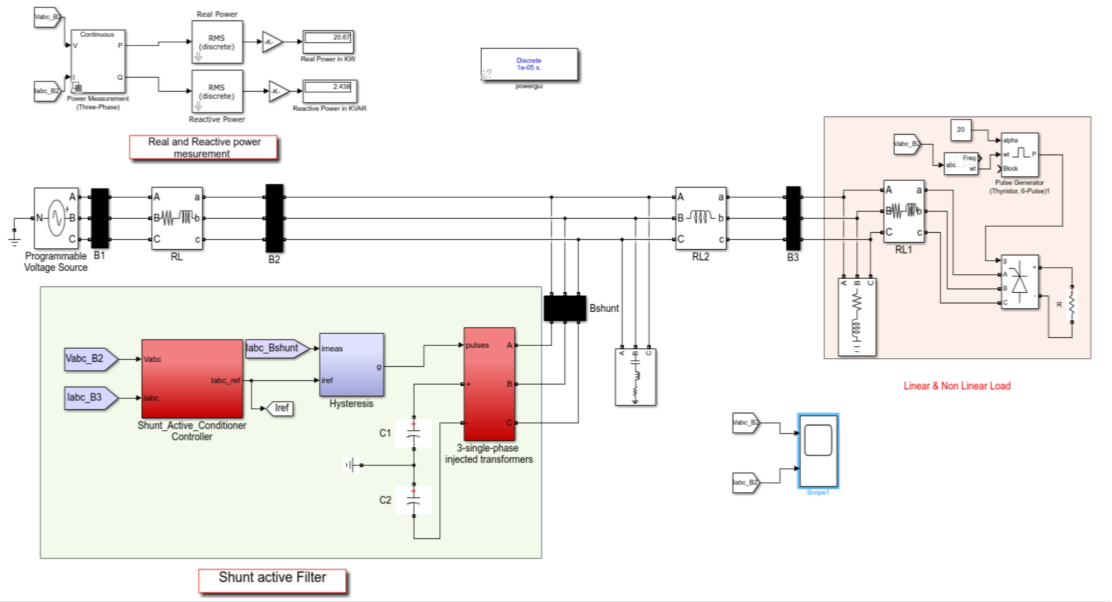


Figure 3.33: Shunt +passive Active filter connected to grid (load 2).

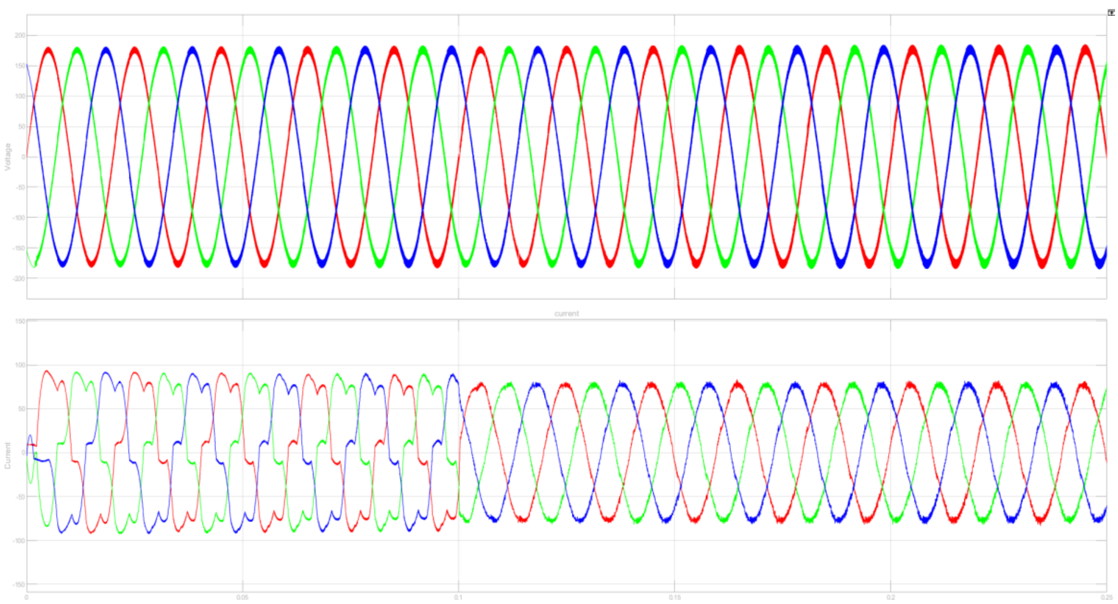


Figure 3.34: Voltage and current waveform before and after connecting Hybrid filter (load 2).

We can see the voltage and current wave form are very close to sinusoidal (figure 3.34). And FFT analysis (figure 3.35) showing that THD_v and THD_i has significantly reduced .

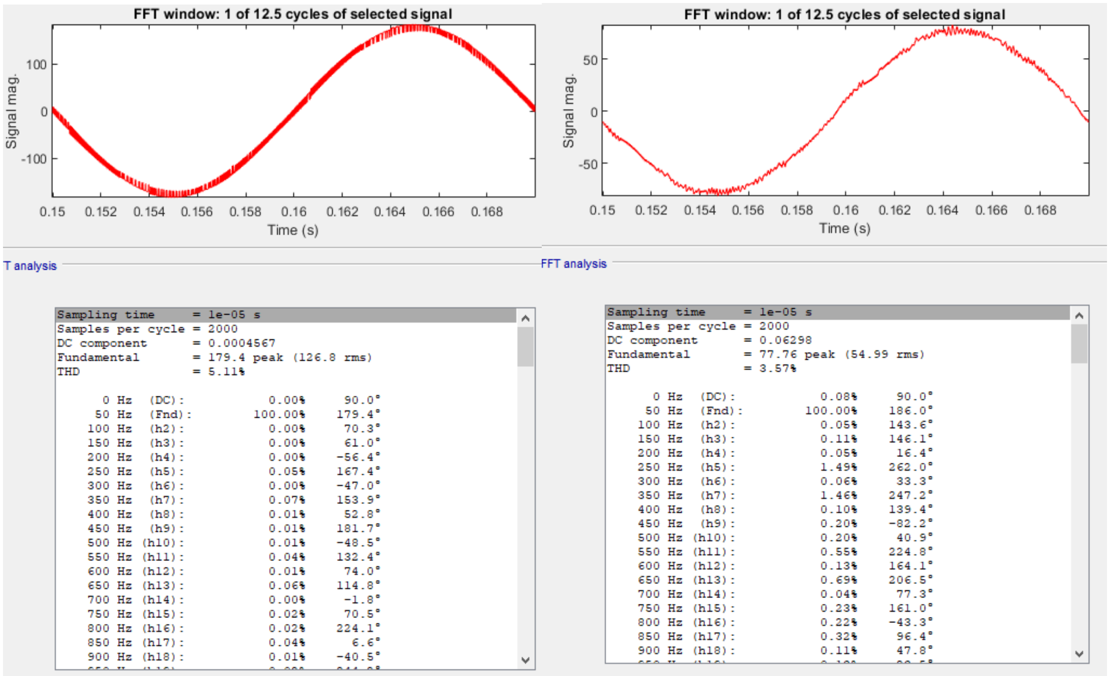


Figure 3.35: THD of Voltage and current after hybrid filter connection.

3.7 Summary

In this chapter we have tried show our simulation result for harmonic analysis and its mitigation using different types of filter. For this simulation we have used Matlab/Simulink. The passive filter performance for lower order harmonic, overall harmonic reduction for two different types of loads using combine passive filter, active shunt filter, hybrid filters was our main intention to simulate.

CHAPTER-4
RESULTS AND DISCUSSIONS

4.1 Introduction

We shall explain our simulation results in this chapter. In chapter 3 we have tested different type of passive filter for 5^{th} harmonic mitigation .Then for complete THD reduction we have simulate our system by connected combined passive filters, shunt active filters and hybrid filter and gathered test results .

4.2 Simulation results for Passive filters comparison for low order harmonic mitigation

As we know we have various design of shunt passive filter, so choosing the compatible filters for right order harmonic is necessary. For this we can see in table 4.1. We can see the C-type filter is very good choice among the other filter. It has the minimum losses of active power at fundamental frequency. Though $\%THD_i$ reduction was almost same for every filter. As we know low order harmonics are always bigger in magnitude of distortion so C-type filters are suitable.

Table 4.1: Passive harmonic filter comparison based on 5^{th} order harmonic component mitigation (Load 1).

Filter type	**Active power (At fundamental Frequency 50Hz) (kW)**	**Reactive power (At fundamental Frequency 50Hz) (kVAR)**	**%H5 component (magnitude)**	**%THD**
No filter	26.62	6.376	21.61%	23.96%
Single tuned	0.00298	2.00	9.30%	13.84%
High pass	0.0001192	2.00	9.36%	13.89%
C type	$1.9*10^{-9}$	2.00	8.99%	13.63%
Doubled tuned	×	×	×	×

4.3 Simulation results for overall THD reduction for load 1

In our first system we had use three phase diode based nonlinear load .Before filtering at bus 2 THD was 23.96%. Then we attached passive filter into the system in shunt configuration. And we were capable of reducing the THD (current) to 4.79% by maintaining the current rating and reactive power demand. After that we tried our system with shunt active filter. And THD (current) was reduced to 4.69%. The test result are shown in table 4.2 .Both were showing almost similar result except active and reactive power. Active power consumption was high for Shunt active filter. Hybrid topology was not tested for load type 1 as passive and active system was showing good result.

Table 4.2: Comparison between Passive and Shunt Active filter for load 1.

Filter type	**Active power (kW)**	**Reactive power (kVAR)**	**%THD$_V$**	**%THD$_I$**
No filter	26.62	6.376	1.7%	23.96%
Passive filter	26.88	0.4339	1.8%	4.79%
Shunt Active filter	27.27	0.3646	7.34%	4.69%
Hybrid	Not tested	Not tested	Not tested	Not tested

4.3.1Simulation results for overall THD reduction for load 2

Now table 4.3 these result we got when we used 6pulse thyristor based load at receiving end . The passive filter was designed for previous load so It didn't work like before, THD_i is now 15.69%. Next we tried shunt active filter with load 2 ,and the result was much better than passive filter 5.58% .But voltage distortion was arise to 7.69%. So in order to get better performance we tried hybrid combination of these two type filter. And the result was improved . Both voltage and current reduced to 5.11 and 3.57 % respectively.

Table 4.3: Comparison between Passive and Shunt Active filter for load 2.

Filter type	Active power (kW)	Reactive power (kVAR)	$\%THD_V$	$\%THD_I$
No filter	16.49	13.36	1.8%	35.45%
Passive filter	16.73	0.8742	2%	15.69%
Shunt Active filter	17.27	0.3747	7.69%	5.58%
Hybrid	20.67	2.438	5.11	3.57

Table 4.4: A comparison of the key characteristics of hybrid filters, active filters, and passive filters for enhancing grid quality.

Feature	**Passive filter**	**Active filter**	**Hybrid filter**
Harmonic filtering	yes	yes	yes
Reactive power correction	yes	yes	yes
Phase balancing	no	yes	yes
Applicability	**Passive filter**	**Active filter**	**Hybrid filter**
Principal benefits	The most economical	Dynamic property to compensate any order harmonic .Better harmonic mitigation	Same as APFs ,less stress on switches . Better harmonic mitigation
Main disadvantages	Not suitable for variables loads ,Can cause resonance with the system ,Design depends on system	Complex, Expensive	Complex, Expensive
Optimum application	Single load	Low power	High power
Costs	**Passive filter**	**Active filter**	**Hybrid filter**
Overall Cost	Low	Medium high	Medium High

4.4 Summary

In this section we tried to show our Matlab simulation result in tabular form. We have compared different types of filters by THD level .The passive filters are very economical and available solution for fixed static type load but not for dynamic load. Shunt filters are very good for dynamic type loads and Hybrid filter are the best solution for any system. The combination of shunt active filter with passive filter can reduce the ratings of active filter in order to save cost.

CHAPTER 5

CONCLUSIONS

Our conclusion through this study of harmonics and its mitigation techniques are discussed below.

5.1 Conclusions

Investigation, analysis, and reduction of the impacts of harmonics were all part of this study. As is well known, there is a rising daily need for power. The most crucial concern with the power system was the power quality issue. The issues with power quality can be alleviated by reducing harmonics and enhancing power factor. This project discusses harmonic reduction using several types of filters. The following inferences are made from the analysis of various harmonic solutions.

- Passive series filters are not commonly employed because of their size and need to control the entire load's current.
- 3n harmonics are the worst harmonic as they are dominating is nature .
- For small or medium-sized non-linear loads, line reactors are preferred because they reduce system losses while causing a voltage drop.
- The K-factor transformer can handle the heat associated with eddy current losses, which are K times greater than a non K-factor transformer, but they are costly.
- Because they can improve the power factor of the system and reduce harmonic distortion, passive shunt harmonic filters are a good system solution.
- Passive solution are cheaper compared to active solution.
- For low order harmonics like bellow 7^{th}, C-type harmonic filters are suitable .As C-type filters have low losses at fundamental frequency.
- Passive solution are not suitable for dynamic load .If the load characteristic changes then the existing passive filters can resonant and can cause more harmonic distortion.
- Active filters are modern solution with good efficiency and reliability.
- For variable compensation, the SAPF is linked in parallel to the load.
- Shunt active filters are suitable for compensating current harmonics and series are for voltage harmonics.
- Under different load condition we have tried our SAPF which shows better result than passive shunt filter.
- Hybrid solution are the best for complete THD reduction

5.2 Future Scopes of the Work

With a few upgrades, the work already done could be expanded. Like

a. Better performance shunt active filter can be implement
b. Series active filters could be implemented in order to reduce THD level

REFERENCES

[1] V. Khatavkar and S. Chaphekar, “Study of Harmonics in Industries A Power Quality Aspect,” Electr. INDIA, vol. 46, no. 11, p. 188, 2006.

[2] S. Santoso, M. F. McGranaghan, R. C. Dugan, and H. W. Beaty, Electrical power systems quality. McGraw-Hill Education, 2012.

[3] M.-Y. Chan, K. K. Lee, and M. W. Fung, “A case study survey of harmonic currents generated from a computer centre in an office building,” Archit. Sci. Rev., vol. 50, no. 3, pp. 274–280, 2007.

[4] “IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems,” IEEE Std 519-2014 Revis. IEEE Std 519-1992, pp. 1–29, Jun. 2014, doi: 10.1109/IEEESTD.2014.6826459.

[5] H. Su, G. Chang, S. Ranade, and H. Lu, “Modeling and simulation of an ac microgrid for harmonics study,” 2012, pp. 668–672.

[6] S. T. Jan, R. Afzal, and A. Z. Khan, “Transformer failures, causes & impact,” 2015, pp. 49–52.

[7] “Harmonic . - Wikipedia.” https://en.wikipedia.org/wiki/Harmonic_. (accessed Sep. 03, 2022).

[8] A. Kalair, N. Abas, A. Kalair, Z. Saleem, and N. Khan, “Review of harmonic analysis, modeling and mitigation techniques,” Renew. Sustain. Energy Rev., vol. 78, pp. 1152–1187, 2017.

[9] C. S. Kumar and D. V. Gopalakrishnan, “Investigation of harmonic detection techniques for shunt active power filter,” J. Electron. Commun. Eng., pp. 68–73, 2013.

[10] M. Sunitha and B. Kartheek, “Elimination of harmonics using active power filter based on DQ reference frame theory,” Int. J. Eng. Trends Technol., vol. 4, no. 4, p. 781, 2013.

[11] S. M. Ghulbet, P. Hinga, and J. Nderu, “An Investigation on Harmonic Problems for N-1 Contingency in Industrial Distribution and Its Mitigation Using Fuzzy Controlled Hybrid Filter,” Int. J. Appl. Eng. Res., vol. 12, no. 20, pp. 10284–10297, 2017.

[12] M. Davudi, S. Torabzad, and B. Ojaghi, "Analysis of harmonics and harmonic mitigation methods in distribution systems," Aust. J. Basic Appl. Sci., vol. 5, no. 11, pp. 996–1005, 2011.

[13] S. Kerrouche and F. Krim, "Three-phase active power filter based on fuzzy logic controller," Int. J. Sci. Tech. Autom. Control Comput. Eng., vol. 3, no. 1, pp. 942–955, 2009.

[14] M. S. Witherden, R. Rayudu, and R. Rigo-Mariani, "The influence of nonlinear loads on the power quality of the New Zealand low voltage electrical power distribution network," 2010, pp. 1–6.

[15] A. B. Nassif and W. Xu, "Passive harmonic filters for medium-voltage industrial systems: Practical considerations and topology analysis," 2007, pp. 301–307.

[16] D. A. Gonzalez and J. C. Mccall, "Design of filters to reduce harmonic distortion in industrial power systems," IEEE Trans. Ind. Appl., no. 3, pp. 504–511, 1987.

[17] "Harmonic current filter - MATLAB." https://www.mathworks.com/help/physmod/sps/ref/passiveharmonicfilterthreephase.html (accessed Sep. 07, 2022).

[18] "220V, 50 Hz, Shunt Active Filter." https://www.mathworks.com/matlabcentral/fileexchange/80248-220v-50-hz-shunt-active-filter (accessed Sep. 03, 2022).