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Dissertation title: **DESIGN OF HYBRID HARMONICS POWER FILTERS FOR NON-LINEAR LOAD**
CASE STUDY: IMANA STEEL RWANDA

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Date: October, 2022

DECLARATION

I, the undersigned, declare that this dissertation is my original work, and has not been presented for a degree at the University of Rwanda or any other university. All sources of materials used in the work have been fully acknowledged in the correct academic format.

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Signature :

This thesis dissertation has been submitted for examination with my approval as a university advisor.

JVM Bikorimana, PhD.

Thesis Advisor



Signature

Date: 21, October, 2022

DEDICATION

I dedicate this dissertation:

To my parents and friends.

To my supervisor **JVM Bikorimana, PhD.**

To my department of Renewable Energy Engineering (REE).

To the African Center of Excellence in Energy studies for sustainable development (ACE-ESD).

To all University of Rwanda authorities.

To all those who contributed to carrying out my research.

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First and foremost, I want to express my gratitude to my Almighty God, who has been at my side the entire way, from the beginning to the end. This research would hardly exist without the Lord's ongoing oversight and protection, just like other dreams do.

I would especially want to thank my **PhD advisor, JMV Bikorimana**. He has been my partner in addition to serving as my academic counselor. He carefully guided me through each phase of my study, encouraging me to do my best work.

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ABSTRACT

Due to the fact that today's power systems are increasingly based on the use of power electronics, harmonics are one of the frequent problems that have an impact on the network's ability to improve power quality in industrial power systems. These problems typically have an impact on the performance of electrical equipment like transformers, electrical machines, and electronic equipment. Therefore, some steps must be made to mitigate such problems that may lead to a variety of power quality concerns in the network in order to improve power quality there. This dissertation discusses the design of a hybrid power filter for harmonic compensation caused by nonlinear loads linked to the power system, indicating that more research is required to address this issue. A hybrid harmonic power filter was designed for IMANA Steel Rwanda to reduce the total harmonic distortion brought on by the arc furnace. It combines a shunt passive filter, a shunt active filter, and a nonlinear load used in the system in the form of an electric arc furnace. The total harmonic distortion of the system was determined using a Fast Fourier transfer (FFT) algorithm. This study aimed to analyze the contribution of hybrid harmonics power filters on a power system, analyze the power system behavior with nonlinear loads versus a power system grid and improve power quality by reducing the harmonics (THD) caused by non-linear loads to the recommended value of IEEE 519 -1992 harmonic standards. The suggested topology was simulated using MATLAB/ Simulink software to fulfill the research goal.

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List of abbreviations

EAF: Electric Arc Furnaces

THD: Total Harmonic Distortion

IEEE: Institute of Electrical and Electronic Engineering

DC: Direct Current

AC: Alternative Current

PF: Power Factor

HPF: Hybrid Power Filter

PEC: Power Electronic Converters

PWM: Pulse Width Modulator

SRF: Synchronous Reference Frame

PI: Proportional-Integral

PID: Proportional-Integral and Derivative

FLC: Fuzzy Logic Controller

HSA: Harmony Search Algorithm

STPF: Single-Tuned Passive Filter

SAPF: Shunt Active Power Filter

RLS: Recursive Least Square

PSHFP: Passive three-phase Series Hybrid Power Filter

CPT: Conservative Power Theory

RT: Real-Time

REI: Renewable Energy Integration

CPIDC: Conventional PID Controller

PSO: Particle Swarm Optimization-

GWO: Grey Wolf Optimization

FOPIDC: Fractional Order Proportional-Integral-Derivative controller

DA: Dragonfly Algorithm

HP: Harmonic Pollution

REI: Renewable Energy Integration

Chapter 1: INTRODUCTION

1.1. Background

Non-linear loads have been continuously connected to power networks as society and technology have progressed. Harmonic pollution is generated by non-linear loads in two ways: harmonic current sources and harmonic voltage sources. The capacitor will cause extra power loss as a result of harmonics, the load's power factor (PF) will decline, and the power system loss will continue to rise. Power consumers are increasingly demanding power quality due to the widespread use of sensitive equipment and devices. Adjustable speed drives, high voltage DC transmission systems, energy storage systems, and the penetration of renewable energy (REI) into the primary grid are just a few of the applications that solid-state controllers are used for in the power and energy industries. In addition to reactive power, these controllers inject a large amount of harmonic current into the power system. They result in poor distribution system utilization, electromagnetic interference noise, radio frequency interference, distorted voltage, and other problems that impair the power system. Filtering devices are currently the most common method of reducing harmonics in the power system. Active power filters, passive power filters, and hybrid power filters are all standard filtering devices used to mitigate harmonics in the system.

Because passive filters, which are employed in classical harmonics and reactive power correction, have a simple structure, need little equipment, and have low running costs, they are frequently utilized in power systems[1]. However, there are drawbacks, such as greater harmonics and low filtering efficiency. It is especially ineffective in mitigating harmonics when the harmonic distortion changes dynamically. Many power system standards, such as the IEEE 519-1992 harmonic standard and others, have been set in response to the rise in power quality issues, and customers, manufacturers, and utilities are required to obey these standards. As a result of the combination of passive and active power filters, the hybrid harmonic power filter (HPF) is a novel form of power electronic filtering equipment with high response speed and flexible management. It can also dynamically adjust harmonics whose size and frequency change and overcome the limitations of existing power filters. Its main goal is to mitigate several power-quality issues of loads with nonlinear characteristics, such as sag, voltage fluctuation, voltage harmonics, and current-based power quality issues such as unbalanced current, reactive power, harmonic distortion of current, neutral current, and current fluctuations at both the consumer and supply end. As a result, it offers sinusoidal balanced currents at the supply end, with DC bus voltage control working in tandem with a series-connected filter in a universal active filter

and a shunt passive filter to produce a hybrid. Because of the growing concern and apprehension about power quality issues, hybrid power filters are needed to reduce total harmonic distortion (THD) caused by nonlinear loads in the power system to the recommended level of harmonic standard value.

1.2. Problem Statement

In today's electrical energy distribution systems, power quality is a difficult problem to solve. In other words, low power quality resulted in a significant financial loss. Overheating in power devices and transformers, overcurrent on equipment neutral connection loads, voltage waveform distortion, reduction of insulation lifespan, and electromagnetic interference problems in electrical power networks are all caused by the increasing usage of power electronic converters (PEC) and other non-linear loads.

1.3. Objectives

1.3.1. Major Objectives

The main objective of this thesis is to design hybrid harmonics power filter for a non-linear load.

1.3.2. The Specific Objective

To achieve the main objective of the thesis the specific objectives are proposed:

- i) To analyze the contribution of hybrid harmonics power filters on a power system.
- ii) To analyze the power system behavior with nonlinear loads versus a power system grid
- iii) Design and simulation of hybrid harmonic filters system by using Matlab/Simulink tool
- iv) To reduce the harmonics (THD) caused by non-linear loads to the recommended value of IEEE 519 -1992 harmonic standards.

1.4. Scope of study

The design and simulation of hybrid harmonic power filters using the MATLAB/Simulink tool are the exclusive focus of this thesis to reduce total harmonic distortion (THD) brought on by the non-linear load in the system. IMANA Steel Rwanda is picked as a case study since it is one of the industries in Rwanda that produces steel in arc furnaces and is close to me, making it simpler to visit. The main objective of the case study is the data collection and analysis of the characteristics of the employed EAF for industrial power systems, such as frequency response, current, and voltage characteristics, which enable the research of EAF's static and dynamic properties in the design.

1.5 Contribution

By taking into account both the current and voltage harmonic distortion flowing in the power system from the source, this dissertation helps to compensate for the total harmonic distortion caused by non-linear loads in the system, which is very important for improving the power quality in the power system.

1.6. Thesis organization

The thesis is divided into six main chapters, including the introduction in chapter 1, literature review in chapter 2, methodology in chapter 3, a hybrid harmonic power filter is designed and calculated for the IMANA Steel Rwanda Company in Chapter 4, a power filter simulation is shown in Chapter 5, conclusion and recommendation presented in chapter 6, then reference and appendixes.

Chapter 2: LITERATURE REVIEW ON POWER FILTERS

2.0 Introduction

This chapter focuses on the discussion of fundamental ideas, as well as the many types of electrical power filters, application scenarios, and electrical filter technologies, by acknowledging the efforts of those researchers, pointing out the gaps that need to be filled in their publications, and providing a summary of earlier research on electric power filters for harmonic compensation.

2.1. Types of electric power filter technology

Active filters, passive filters, special transformers, and hybrid harmonic filter techniques are the four most widely used methods for harmonic correction in power system networks.

i) Active power filter technique

This method aims to employ an Active power filter that doesn't need a storage element and needs fewer harmonic compensation devices. As a result, the design's size, weight, and cost can be decreased. Additionally, utilizing this filter can assist in compensating a non-linear load's 5th and 7th harmonic current.

ii) Passive power filter technique

To correct THD for the current and voltage, passive filters are made up of three passive factors: capacitance, inductance, and resistance. These three passive characteristics can be employed as low-pass and high-pass filters, respectively. As a result, harmonic current can be kept out of the rest of the system by using an SPF with low impedance.

iii) Special transformer technique

This is an additional method for correcting harmonic distortions in the power system network. The key limitation of this method is that it can only be used with the stated load and that only triple harmonics may be removed.

iv) Hybrid harmonic filter technique

For harmonic compensation in the power system, this method combines many filters. As a result, compared to other technologies, this one provides good harmonic mitigation performance at a reduced price. This is because such filters don't share any of the drawbacks of earlier filtering methods. As a result of the many shortcomings of conventional technologies for harmonic compensation, a variety of hybrid filter topologies have emerged as viable options for the economical compensation of

harmonic distortion brought on by nonlinear loads. It has been discovered that hybrid filters work better at completely compensating for different kinds of nonlinear loads.

2.2. Classification of filters existing in a power system

There are three main classifications of filters in power systems such as shunt active power filter (SAPF), shunt passive power filter (SPF), and hybrid power filter (HPF) which can be used in several ways to mitigate harmonics at different levels accordingly.

i. Shunt active filter

Non-linear loads are connected in parallel with active shunt filters. It can correct harmonic current distortion by injecting an equal and opposite compensatory current into the grid [2]. Additionally, shunt active filters have features like a current source that injects harmonic components produced by the load with a 180° phase shift.

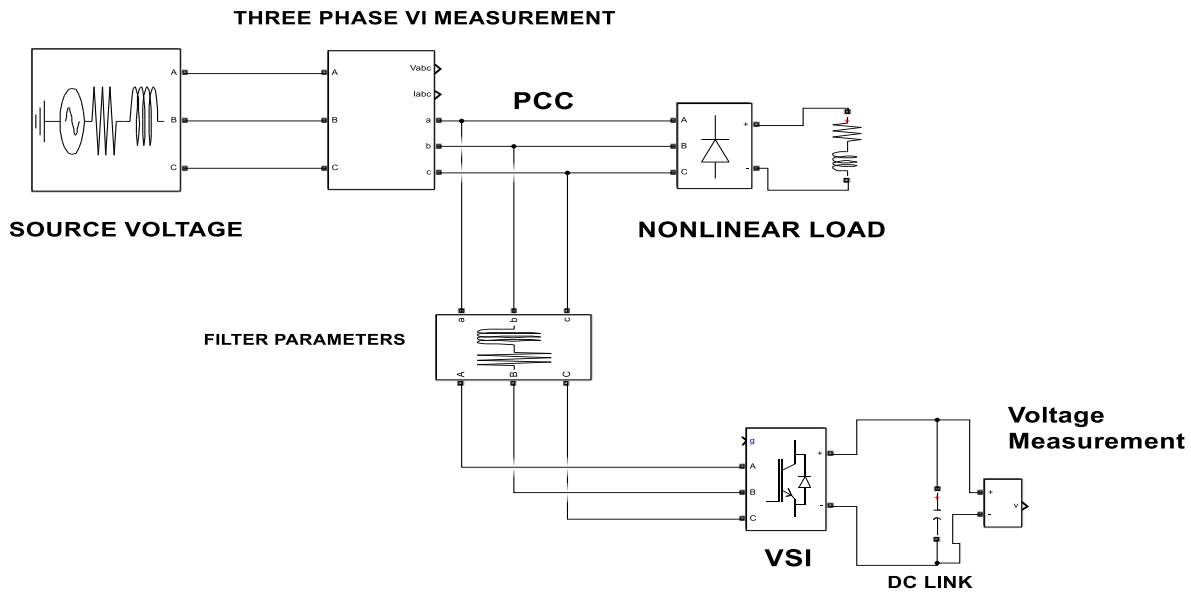


Fig. 1: Shunt active filter topology

ii. Shunt passive filter

Capacitors, reactors, and resistors are common components of passive harmonic filters, which offer harmonic currents an alternate impedance channel and reduce the harmonic impedance profile. High-pass and low-pass filters can adjust THD to the necessary minimum by coupling those passive characteristics. It is linked in parallel to the grid and the nonlinear load through the common coupling

point (PCC), hence the name "shunt passive," to compensate for the distortion of the network's current and voltage harmonics caused by the nonlinear load.

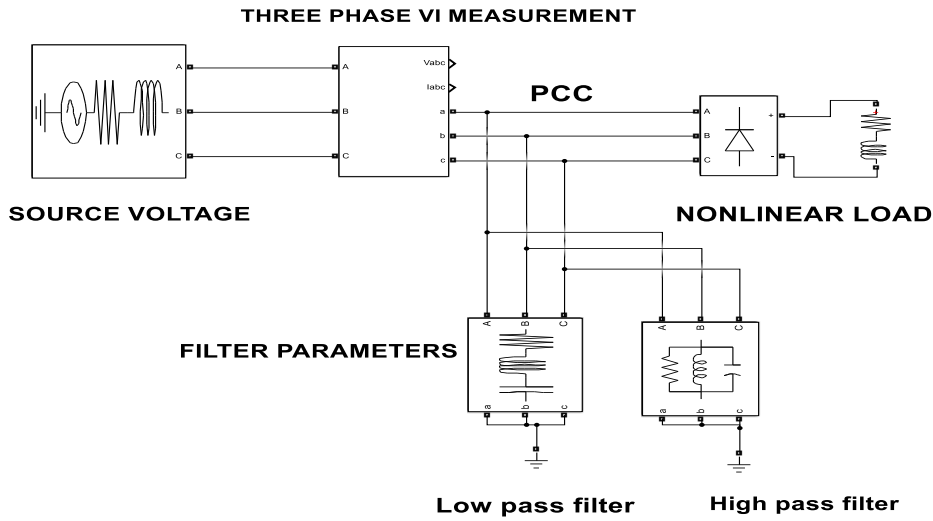


Fig. 2: Shunt passive filter topology

iii. Hybrid power filter

Hybrid filters combine several passive and/or active filters, and they can have a structure with a parallel, series, or hybrid topology. In single-phase, three-phase three-wire, and three-phase four-wire distortion systems, can be installed [3] .

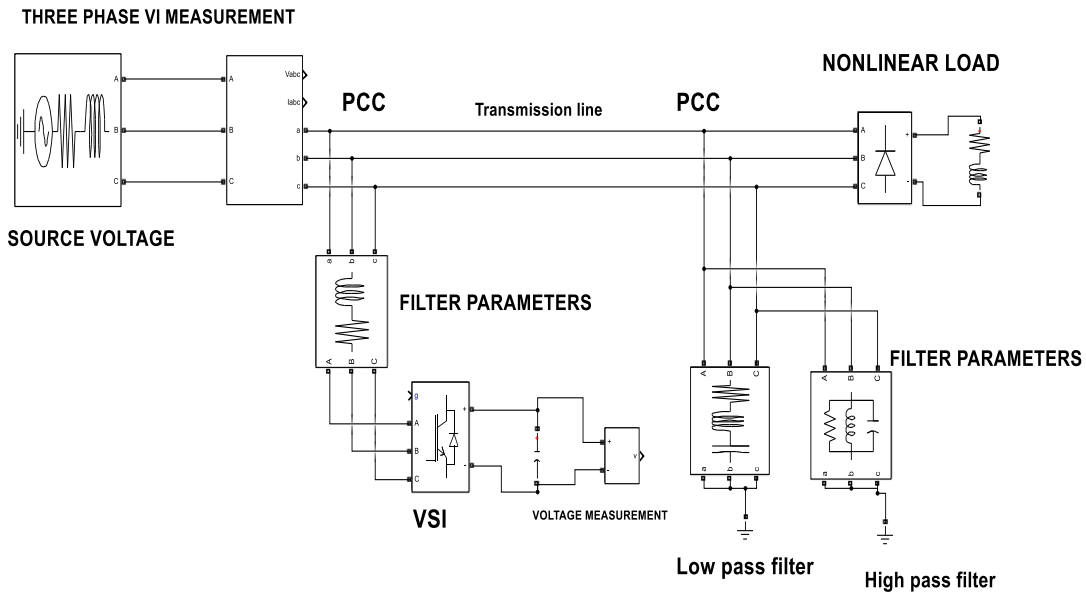


Fig. 3: Hybrid power filter topology

2.3. Mathematical formulas which must be used in the design of power filters

This section gives different formulas to design power filters including low pass filters, high pass filters and hybrid power filters.

i. Single-tuned filter (Low pass filter)

Impedance of low pass filter must be calculated using equation 2.2.

$$Z = R + j \left(2\pi h f L - \frac{1}{2\pi h f c} \right) \quad (2.2)$$

Where Z is an impedance of low pass filter, L is an inductor, R is resistance and h is harmonic order

The calculated impedance of inductive and capacitive reactive is from eq. (2.3)

$$X_C = \frac{V^2 P_h}{Q_F n} \quad , \quad X_L = \frac{X_C}{n^2} \quad (2.3)$$

Where QF stands for the necessary reactive power and n for the filter's harmonic number.

A quality factor of a low pass filter design must be calculated using equation 2.4.

$$Q_L = \frac{X_L}{R} \quad (2.4)$$

Where Q_L is quality factor of a low-pass filter , X_L is inductor reactance and R is resistance

A resonance frequency of a low pass filter must be calculated using equation 2.5

$$f_o = \frac{1}{2\pi\sqrt{LC}} \quad (2.5)$$

Where f_o is a resonance frequency of a filter

L is an inductor and C is a capacitor

ii. Second-order high-pass (High pass filter)

A capacitor in a high pass filter must be calculated using equation 2.9

$$C = \frac{Q_F}{2\pi f V_{Ph}^2} \quad (2.9)$$

Where C is a capacitor of a second-order high-pass filter

f is a fundamental frequency

V_{ph} is a phase voltage

Inductor in high pass filter design must be calculated using equation 2.10

$$L_h = \frac{1}{C(2\pi hf)^2} \quad (2.10)$$

Where L_h is inductor, C is capacitor, h is harmonic order and f is fundamental frequency

Resistance used in high pass filter design can be calculated using equation 2.11

$$R_h = \frac{2\pi fnL_h}{Q_L} \quad (2.11)$$

Equation 2.12 must be used to calculate an impedance of a high pass filter.

$$Z = \frac{1}{j2\pi nfc} + \left(\frac{1}{R} + \frac{1}{j2\pi nL} \right)^{-1} \quad (2.12)$$

Where Z is an impedance of high pass filter, L is an inductor, R is resistance and n is harmonic order

A quality factor of high pass filter must be calculated using equation 2.7

$$Q_H = \frac{L}{R^2C} \quad (2.7)$$

Where Q_H is a quality factor of a high pass filter, R is resistance, C is a capacitor and L is inductor.

The resonant frequency f_0 of a high-pass filter must be calculated using equation 2.8

$$f_0 = \frac{1}{2\pi nCR} \quad (2.8)$$

Where f_0 is resonance frequency of high pass filter, R is resistance and C is capacitor

Resistance (R_h) used in the design must be calculated using equation 2.12:

$$R_h = \frac{1}{2\pi Cfn} \quad (2.12)$$

Where C is a design capacitor, f is a fundamental frequency and n is harmonic order

Inductor used in a high pass filter design must be calculated using equation 2.13:

$$L_h = \frac{C R_n^2}{Q_H} \quad (2.13)$$

Where L is an inductor, C is capacitor, R is resistance and Q_H is high pass quality factor.

Resistance must be taken into consideration when designing the high-pass filter in addition to inductance and capacitance. Also, reactive power compensation must be taken into account during design since nonlinear loads depend on it. As a result, an equation (2.14) must be employed to increase the power factor (Pf) from 0.8 to 0.95 for the industry.

$$Q_C = P(\tan\varphi_1 - \tan\varphi_2) \quad (2.14)$$

Where, Q_C is reactive power and P is real power.

iii. Hybrid power filters

In the hybrid power filters, the voltage total harmonic distortion must be calculated using equation 2.15:

$$VTHD = \frac{\sqrt{\sum_{k \geq 1} V_{LK}^2}}{V_{L1}} \quad (2.15)$$

Where VTHD is voltage total harmonic distortion, VLK is nonlinear load voltage at harmonic order K and K is harmonic order

Total harmonic distortion for source current must be calculated using equation 2.16:

$$ITHD = \frac{\sqrt{\sum_{k \geq 1} I_{SK}^2}}{I_{S1}} \quad (2.16)$$

Where ITHD is current total harmonic distortion, I_{SK} is compensated line current at harmonic number K and K is harmonic order.

2.4 Important of active and passive filters in a power system

Their impedances stifle harmonic currents and keep them out of the power system. On the dc side of the rectifier, these filters also help to lessen ripple in current and voltage. They are inexpensive, simple to install, and have been used to reduce harmonics brought on by large loads like Electric Arc Furnaces, which, are properly sized [4], guarantee compliance with IEEE 519-1992, provide VAR currents, improve system power factor, and mitigate harmonics from the second to the fiftieth harmonics.

2.5 Demerits of passive and active filters

Even though it has been demonstrated above that active and passive filters play a significant role in compensating harmonic distortion in power systems for the enhancement of power quality, these filters do have some drawbacks, however, they are bearable in comparison to alternative approaches like Due to the high-performance control and power portions, the circuit may be larger and more expensive. There is also a chance of passband signal loss when using inductors because there is no separation between the input and output.

2.6 Other methods for harmonic compensation

Other approaches to harmonic compensation for non-linear loads in the power system, besides active and passive filters, include line reactor, 12-pulse distribution, 12-pulse converters, harmonic trap filters, broadband filters, Clean power (18-pulse converters), and DC choke. However, most of them fall short of the IEEE 519-1992 criteria for harmonic reduction and are less protective than active and passive filters. The cost may be low or high depending on implementation, could result in leading power factors at lightly loaded conditions, care is needed in application to ensure that the filter won't become overloaded, larger and heavier magnetics, high-performance control, and power sections, the potential for high levels of harmonic current and voltage distortion.

2.7 Importance Hybrid harmonic power filter

Although active power filters are less dependent on changes to the power system and provide superior compensatory features, their main drawback is the expensive cost of power electronic inverters, particularly for large power ratings. To improve power quality in the power system, one harmonic mitigation option that can be employed is the hybrid harmonic power filter [5]. Where gadgets combine the benefits of shunt passive and shunt active filtering systems. Additionally, they don't share any of the disadvantages of the prior filtering techniques. In addition to being substantially less expensive than active filters, the hybrid offers independence from grid factors, good efficiency, and effective current harmonics suppression. Shunt active and shunt passive filters are a good combination for a hybrid because they offer good harmonic mitigation performance for a lower cost than other solutions, and a separate connection to the grid of both filters is advantageous in cases where the harmonic mitigation performance of a traditional passive power filter or a pure active solution needs to be improved.

Such a topology doesn't call for any adjustments to the components of the system or the devices since both passive and active filters are separately connected to the grid. Most of the harmonic current is sunk by the passive filter, which creates favorable conditions for the active filter to increase compensation accuracy but with a lower power rating than a pure active solution operating alone. Lower-order harmonics are compensated for by the shunt active filter, whereas higher-order harmonics are eliminated by the shunt passive power filter, which consists of a high-pass filter. Therefore, by using this way, the active power filter main circuit's devices can switch off less frequently. However, when using this device, harmonic channels exist between the active filter and the power grid as well as between the active shunt filter and the shunt passive power filter, particularly the latter, which could cause the harmonics injected by the active power filter to flow into the passive power filter or power grid system. The withstand voltage level of the switching device cannot be decreased even though the active power filter's capacity is reduced since it still carries all of the fundamental voltage.

The multi-group single-tuned filters (low-pass filter) and high-pass filter make up the shunt passive power filter in a hybrid harmonic power filter design. The high-pass filter, even 23rd, and 25th-tuned filters, and 11th and 13th-tuned filters make up the shunt passive power filter for the harmonic source of the three-phase bridge rectifier [5]. Shunt passive power filters have a higher proportion of harmonics filtered. Only the harmonics that LC filters are unable to reduce the need to be removed by the shunt active power filter. Since just a little compensatory current is required in the design, the active power filter's rating is higher than when a shunt active power filter is employed alone.

2.8 Review of previous work on hybrid harmonics power filters for nonlinear loads

This section recognizes the contribution of many types of research done by past researchers on hybrid harmonic power filters by appreciating their findings and identifying the research gaps of these researchers to be addressed in the thesis

Manoj Hans, et al (2019) [6] suggested PWM methodology and triangle comparison method were used to compare the results of a study on the design and modeling of a series active power filters for minimizing voltage harmonics in non-linear loads. The harmonic component (THD) on input was found to be 11.89 percent based on simulation findings. This value is higher than the IEEE 519-1992 harmonic standard's recommended value of less than or equal to 5% THD of the system. However, this study only looked at a series of Active Power filters and did not take into account other types of filters such as passive harmonic filters or shunt active filters with shunt passive filters. Also, in terms of the techniques to be employed for active power filters, this research did not only investigate PWM

but also PID controllers, which are responsible for switching semiconductor devices suitably so that harmonic currents are canceled, resulting in THD below 5%.

Banishree Misra, et al (2016) [7] investigated the strategies employed to get the result where the connection of a shunt active filter by employing a voltage source inverter, a series inductor on the AC side, and a capacitor on the DC side for the design of Hybrid filters. The total harmonic distortion (THD) was 9.61 percent and 5.92 percent, respectively, which is higher than the IEEE 519-1992 harmonic norm. However, this study only considered a shunt active filter with a series passive filter, ignoring the other connections that can provide good THD results of less than or equal to 5%, as specified by the IEEE 519-1992 harmonic standard.

Rajkumar Jhapte et al (2017) [8] the suggested study focuses on employing a controlled technique for extracting the voltage and current harmonics from arc furnace load using hybrid active power filters, and the result was obtained with the help of MATLAB Simulink. This study solely looked at connecting a shunt hybrid active power filter to a furnace load using a normal PI controller and an optimum controller adjusted with the harmony search algorithm (HSA). This technique compares the results of the PI controller with the optimized PI utilizing HSA for current and voltage THD percentages to get the total harmonic distortion (THD) result. However, this study did not take into account PID controllers or hybrid harmonic power filters, which are a combination of active and passive filters that can provide high nonlinear load performance in a power system network.

Vijeta V. Barathe et al (2018) [9] worked on the synchronous reference frame (SRF) theory as a control approach used to retrieve the design's reference signal, and it was studied in the design and modeling of a hybrid filter for power quality improvement. Even though the result obtained by this research shows that the total harmonic distortion decreased from 33.49 percent to 0.33 percent, which is within the range of IEEE 519-1992 harmonic standard, the system simulation runs in MATLAB/Simulink tool was presented to verify the performance of the hybrid power filter composed by the connection of the shunt passive filter and shunt active filter. However, the sensitivity of the system compared to single active or passive filters was not considered in this study. To address this, the system should have made use of sensitivity analysis to increase system response.

C. Boonseng et al (2019) [10] investigated hybrid power filters, which combine active and passive power filters to attenuate the 3rd and 5th current harmonics and increase the power quality of the system, which were studied for 3rd harmonic current and power quality improvements in data centers. Also, to

raise the high neutral current and high power quality problem on the distribution network, the system considered parallel-connected switch mode power supplies on the same bus and transformer. The system can minimize the 3rd harmonic current in the neutral line by around 11%, according to the results. For power factor approaches to unity, overall harmonic distortion of voltage and current is reduced to less than 1.3 percent and 4.87 percent, respectively. However, even if the results obtained are within the range of the IEEE 519-1992 harmonic standard, this study did not consider the system's feasibility, and there was no specification of the filter connection, where series active and shunt passive filters can be a good connection of hybrid to mitigate harmonic for nonlinear loads and improve the system's response.

Prakash K. Ray et al (2018) [11] studied hybrid power filters based on a robust extended Kalman filter that was employed in the distribution network to compensate for reactive power at the load end and decrease total harmonic distortion (THD) to improve power quality. The dc-link voltage of the inverter in the system was controlled using a proportional-integral (PI) or fuzzy logic controller (FLC). In this system voltage source inverter was used as the power source, the result was stimulated by the use of MATLAB/ Simulink, the corresponding total harmonic distortion value is found 28.38 percent, and the simulation of the different control strategies was implemented by the use of d-q theory using the proportional-integral controller and fuzzy logic controller. However, this study only looked at the hybrid active filter, with certain limitations in terms of decreasing overall harmonic distortion to the IEEE 519-1992 harmonic standard's needed level. Because the results of the study show that the current method cannot meet the required harmonic standard, the study should consider other types of hybrids, such as a hybrid harmonic power filter that uses a combination of a shunt passive filter and series active filter to reduce THD and improve power quality in the power system.

Madhu B. R et al (2018) [12] suggested different techniques to obtain results such as the use of a voltage source inverter responsible for producing reverse harmonic current based on Clarke's transformation, tuned RLC circuit, and control technique, and this control was simulated using Matlab/Simulink to obtain the desired result. However, this study did not consider other hybrid connections, such as the combination of a shunt passive filter and series active filter, which performs well in response and improves the power quality. Additionally, this study did not consider the system's feasibility, instead focusing solely on reducing the total harmonic distortion (THD) of source current from 30.35 percent to 3.25 percent.

N. F. Adan et al (2017) [13] investigate a hybrid filter that was developed to reduce harmonics induced by nonlinear loads as well as resonance caused by the power factor adjustment capacitor. To reduce total harmonic distortion (THD), multiple strategies were utilized in this study, including a combination of shunt active power filter (SAPF) and single-tuned passive filter (STPF), p-q theory, and the system was simulated using PSCAD/EMTDC software. The total harmonic distortion (THD) and total demand distortion (THD) for the current are equal to 2.93 percent and 9.84 percent, respectively, according to the results. However, this study only considered a shunt active with a series passive filter, which is not more accurate in system response than a combination of shunt passive and series active filters to mitigate harmonics, referring only to firing angles up to 400 to achieve the desired result, and neglected to consider the hybrid's feasibility.

Soumya Ranjan Das et al (2017) [14] worked on hybrid power filters based on the RLS Algorithm was investigated to improve power quality. The d-q and p-q theories were employed as current control approaches in this study, and the final result was reached by comparing these theories to the recursive least square (RLS) harmonic estimating technique. However, the strategies used in this study, such as d-q and p-q theories with a PI controller, are insufficient to reduce the system's overall harmonics distortion. To get a good signal as an output, it should use a combination of a shunt passive filter, series active filter, and PWM inverter. Because these techniques are more accurate in response to the system using RLS Algorithm, and even the THD can be obtained within the IEEE 519-1992 harmonic standard value, they are preferred.

Akhilesh Kumar Panigrahi et al (2016) [15] studied the combination of an active filter and a passive filter utilized to reduce the total harmonic distortion (THD) of the system. The new hybrid filter for harmonic elimination in low-tension power distribution systems was examined to achieve the desired result. However, the current controller of the system and its responsiveness to improve the power quality of the hybrid power filter were not considered in this study.

Francesco Grasso et al (2017) [16] suggested a three-phase series hybrid passive filter was used to improve power quality and efficiency in electrical facilities. A passive three-phase series hybrid power filter (PSHPF) is built and implemented in a commercial facility to reduce harmonics and distorted power generated by unbalanced linear/nonlinear loads in this study the result was obtained by using simulation of the system. However, this study only considers passive filters, which are not capable of accurately eliminating the system's harmonic current. A combination of passive and active filters, on

the other hand, is one of the filters that more accurately and quickly responds to the system's total harmonic distortion caused by nonlinear loads in the power system.

Alok Kumar Mishra et al (2020) [17] studied power quality improvements, a PSO-GWO optimized fractional-order PID-based hybrid shunt active power filter was investigated. P-q theory, conventional PID controller (CPIDC), particle swarm Optimization-Grey wolf optimization (PSO-GWO), and fractional-order proportional-integral-derivative controller were employed in this study to achieve the required results (FOPIDC). Hybrid is created in a real-time experimental setup using MATLAB/Simulink. However, this study ignored the system's feasibility, as well as a mix of passive and active filters that is more precise in mitigating THD produced by nonlinear loads and operates more effectively than a hybrid Shunt active power filter to improve power quality.

Wanxuan Dai et al (2020) [1] to maximize the design of a hybrid power active filter, researchers investigated an updated dragonfly algorithm with a stronger exploitation capacity. Several strategies were employed in this study to achieve the required results for minimizing harmonic pollution (HP) in the power system, including an upgraded dragonfly algorithm (DA), global optimization, and a new technology called IEDA for parameter optimization of hybrid power active filters. However, the contribution of the filter to mitigate the total harmonic distortion of the system was not demonstrated in this study, and the simulation tool used to simulate the result was not specified. Additionally, the current controller is not present, the system's feasibility and the system response were not specified in the study, and a hybrid with only an active filter is not more accurate to mitigate THD caused by nonlinear loads in the power system.

Partha P Biswas et al (2017) [18] worked on the ideal design of a hybrid active power filter using differential evolution was investigated for decreasing harmonic distortion in power systems. Where techniques such as the evolution (DE) algorithm called L-SHADE were used to form a single objective function consisting of both total current harmonic distortion and total voltage harmonic distortion, with both non-linear sources and non-linear loads, and the output results of the L-SHADE algorithm were compared with the results of a previous study to minimize the system's harmonic pollution (HP). Even though the obtained result of this research shows that harmonic pollution caused by nonlinear loads is closer to the recommended value of the IEEE 519-1992 harmonic standard, it is not as effective as a hybrid of active and passive filters to mitigate THD caused by nonlinear loads, and it is more accurate in response and feasibility than a hybrid active power filter.

Sasan Yousefi et al (2015) [19] studied the design of a new hybrid filter structure to reduce 25 kV AC harmonics. In this study, a novel hybrid filter structure was built to adjust reactive power and reduce total harmonics to achieve the acceptable harmonic level as specified by the IEEE 519-1992 harmonic standard, and the model was based on the p-q theory. The developed hybrid model was then applied to a harmonic model of an electric railway using the Matlab/Simulink tool. The results reveal that not only did the designed model reduce total harmonic distortion, but it also compensated for the required reactive power at the start of railway movement. This model, however, only considered a medium voltage of 25 kV and a low frequency of 50 HZ, ignoring high voltage and high-frequency systems to reduce THD to the recommended % standard harmonic value.

Jie Gong et al (2021) [5] conducted a comprehensive review of enhancing power quality using active power filters. Several strategies were employed in this review article to achieve the main purpose, including a review of topology viewpoints, application scenarios, operating principles, and limitations and advantages, which served as a reference point for the study work. As a result of the simulation, the shortcomings of the current industrialized active power filter have been identified, as well as other existing issues such as background harmonics, supra-harmonics, and the multifunction power quality controller. This research also describes the future development trend of active power filters to minimize harmonics in the power system to achieve the desired result. The findings suggest that active power filters are becoming more significant in improving power quality in power systems and are evolving in a variety of ways. Active power filters are also developing in a multi-functional direction, such as voltage regulation, background harmonic isolation, power flow management, fault current limiting, and reactive power compensation, rather than being limited to a single purpose, such as harmonic suppression. However, this review only looked at active power filters to mitigate harmonics in power systems, but the working principle of APFs shows that they have some drawbacks when it comes to mitigating harmonics caused by non-linear loads in power systems, which can be handled by harmonic power filters to mitigate THD in the power system efficiently.

Venkata Subrahmanya Raghavendra Varaprasad Oruganti et al (2017) [20] investigated an industrial power system, real-time control of a hybrid active power filter utilizing conservative power theory. Conservative power theory (CPT)-based hybrid active power filter with type-II current controller for harmonic and reactive power compensation was used in this study, where the type-II controller is designed for current control operation and conservative power theory was used as a harmonic reference generator. The hybrid system was simulated in the MATLAB/Simulink

environment and implemented in real-time (RT) with the help of the OPAL-RT-based RT simulator. The findings produced with the hybrid active power filter are exceptionally efficient and provide the highest performance for retrofitting an industrial power system, as it compensates for distorted current, removes harmonics, and reduces imbalance and reactive power. However, this study only considers hybrid active power filters, which are ineffective in mitigating total harmonics caused by nonlinear loads in the system when compared to hybrids composed of both active and passive power filters. Not only that, but this study also fails to show the rate at which hybrid systems mitigate harmonics caused by nonlinear loads in the power system.

Anand Panchbhai et al (2017) [21] studied shunt active power filter (SAPF) using P-Q theory for harmonic and reactive power correction was investigated. The MATLAB/Simulink tool was used to obtain the results of the research. After integrating the shunt active filter in the system, overall harmonic distortion is reduced from 30.39 percent to 0.91 percent, and the reactive power supplied by the source is compensated. However, even if the results obtained are within the range of the IEEE 519 harmonic standard, this study did not take into account the system's feasibility, real-time reaction, or system controller to minimize total harmonics induced by nonlinear loads.

David Lumbreras et al (2020) [22] investigated trends in power quality, harmonic mitigation, and standards for light and heavy industries. The primary types of filters used to attenuate harmonics induced by non-linear loads in the system and improve power quality in the power system are discussed in this study. The active power filters were deployed in three distinct grid configurations to demonstrate their contributions to improving power quality in the grid, such as a stadium with a large number of light-emitter diodes and an office building. The findings of this review study were acquired by comparing the influence of active power filters on grid quality to the other primary types of filters used to minimize current harmonics in industrial applications. The findings reveal that active power filters help to increase grid power by reducing voltage total harmonics distortion to a more suitable harmonic standard value. However, this study focused on the comparison of active power filters and active power filters to compensate voltage total harmonic distortion in the industrial sector and did not consider the feasibility of hybrid filters, which can contribute significantly to power quality improvement in the power grid and mitigate harmonics caused by non-linear loads in the system more than active power filters.

Dheeraj Sharma et al (2017) [23] researched on the performance of hybrid filters for harmonic mitigation. To mitigate harmonics induced by non-linear loads in the system, several passive and shunt

active filters were investigated in this study. To meet the research's goal, the hybrid was simulated using the Matlab/Simulink tool. Without the filtering stage, source current and voltage harmonics are 25.44 percent and 2.81 percent, respectively, while source current harmonics rise to 3.05 percent and source voltage harmonics fall to 0.43 percent. However, the research focused solely on compensating for harmonics induced by non-linear loads in the system, ignoring the feasibility and response of the hybrid system, as well as the controller's role in the hybrid's design.

2.9 Chapter Conclusion

According to the reading of earlier studies, some researchers made significant contributions to the development of hybrid harmonic power filters for harmonic compensation, despite some gaps in their research. This chapter explained the formulation of the problem, and also the mathematical model that can assist the energy designer in creating a topology with a suitable hybrid filter system. Shunt active and passive filters are two examples of two filters that can be combined using a hybrid filter design concept. The model provides a mathematical solution to reduce the THD of nonlinear load by using FFT analysis for a hybrid power filter system constructed, with different parameters associated with each filter technology by referring to collected data from the case study.

Chapter 3: METHODOLOGY

To carry out successfully this research a series of steps have been considered to achieve the objectives. These steps include documentation, data collection, design, and simulation. In addition to this, a conceptual framework of the present work is provided.

3.1 Methodology steps

Step 1: The documentation: is all about reviewing the earlier literature on power filters by reading the books and articles that have been published on the topic of compensating for harmonic distortion in power systems, brought on by non-linear loads to obtain the findings and some gaps that need to be filled in the thesis.

Step 2: The data collection: is about to compile all data on an electric arc furnace from IMANA Steel Rwanda, such as the rated voltage, power, current, capacity (tone per hour), duty cycle, and operating frequency to be used in thesis design.

Step 3: Design and simulation: this section is about using all information from the case study to design the hybrid harmonic filters topology and simulation by the use of Matlab/Simulink tool so that analyzing the contribution of hybrid harmonics power filter, by compensating harmonic distortions to the standard value as recommended by IEEE 519-1992 in power system.

3.2. Conceptual framework of the research

Fig.4, shows the conceptual framework of hybrid harmonic power filters. This framework formulates the order of ideas of the thesis as well as the activities to be done step by step to achieve the objective of the thesis. As it is shown in Fig.4, begins with a review of recent update trending to enhance power quality technologies in power systems, a review of previous research papers about hybrid power filters technologies followed by problem formulation of the system, feasible methodology applied to the problem formed, and the design and simulation of hybrid harmonic power filters system by the use of MATLAB/Simulink tool.

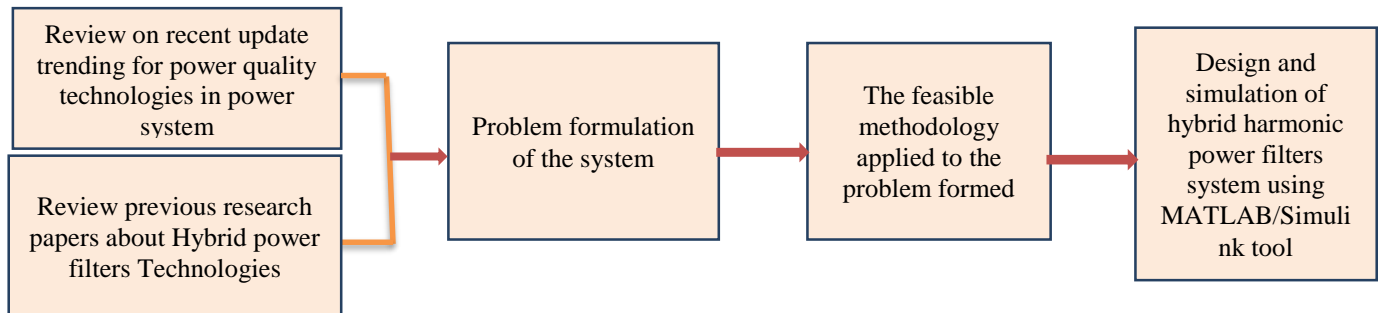


Fig. 4. Conceptual framework of hybrid harmonic power filters

3. 3. Data collection results

3.3.1 Description of IMANA steel company

i. Technical characteristics

Table I provides a summary of the information gathered from IMANA Steel Rwanda for all parameters used in the current harmonic correction filter approach.

Table 1: An overview of the technical information gathered from IMANA Steel Rwanda

Used parameters	Used values
Frequency	50
DC link capacitance	$1\mu F$
Reference DC voltage	680
Source resistance	1Ω
Source inductance	$1e-6$ H
Phase-to-phase voltage (Source voltage)	440 V
Electric arc Furnace (Nonlinear load)	318 and 10Ω

ii. Types of machines

There are several types of machines at IMANA steel Rwanda:

At IMANA Steel Rwanda steel is melted using an electric arc furnace or an electric induction furnace, a grinding machine to give steel a smoother, more touchable surface by shaving off a very little amount of material along its surface, and AC motors which are responsible for the process of roll bending and roll shifting in hot steel mill finishing, coil handling in down coilers, and other necessary steps for the finished steel product.

iii. Application and characteristics of the electric arc furnace

Electric arc furnaces (EAF) transform electrical energy into thermal energy and are commonly used in the iron and steel industry to melt metal. Electric Arc Furnace now provides 40% of all steel produced, and this percentage is predicted to increase to 50% by 2050 [24]. Aside from Electric Arc Furnaces, the electrical energy business is used by the majority of elements. As a result, one of the

most pressing issues in nowadays world is the efficient use of energy in Electric Arc Furnaces systems.

The electric arc furnace is characterized by its ability to control the chemical composition of steel, stability and high alloy recovery rates, high heat efficiency, and a controllable atmosphere. It can also remove chemical impurities like phosphorus, oxygen, sulfur, and others to improve steel quality. The equipment is also simple and quick to operate in terms of technical processes, and the smelting temperature is flexible to be controlled. Additionally, it satisfies the operator's need for various steel-grade manufacturing.

iv. Existing types of filters

At IMANA Steel Rwanda, they currently use an active filter to compensate the current harmonics distorted by the arc furnace to melt steel.

3.3.2 Challenges of power quality at IMANA Steel Company

IMANA Steel Rwanda faces two main issues about the power quality problem, including the ineffective filtering technique that they are currently using and the reactive power compensation for their working machines.

3.3.3 Existing problem related to the employed filters

IMANA Steel Rwanda does not have an electrical substation, which prevents them from designing an efficient power filter topology that can compensate for the harmonic distortion of the arc furnace that is used to melt steel. Because of this, they chose to use shunt active filters parallel to the supply transform line to compensate for harmonics that the arc furnace had distorted. However, in industrial power systems, shunt active filters are unable to do so at the level required by IEEE 519-1992 because some harmonics remain in the network after the filtering process and must be eliminated using other filtering techniques, such as hybrid filters.

3.3.4 Plans to improve IMANA Steel Rwanda's power quality

They intend to build their substation so they can create inexpensive filtering techniques that are effective at reducing the total harmonic distortions caused by the arc furnace as well as reactive power, which occasionally results in Rwanda Energy Group (REG) penalizing them for their reactive power consumption from the grid.

Chapter 4. DESIGN AND CALCULATION OF A HYBRID HARMONIC POWER FILTER FOR IMANA STEEL RWANDA COMPANY

4.0 Introduction

The design has considered the data from the IMANA steel company. This section describes the system for a hybrid power filter designed for the IMANA steel Rwanda company in detail.

4.1. System design

The system design is composed of the shunt active and passive parameters to be used to mitigate harmonic distortion to the acceptable value as recommended by harmonic IEEE 519-1992 standards level in power systems. Therefore, hybrid power filters must be designed to enable harmonic compensation at the AC mains connected to crucial nonlinear loads.

The overall block diagram of the system design is shown in Fig.5 below.

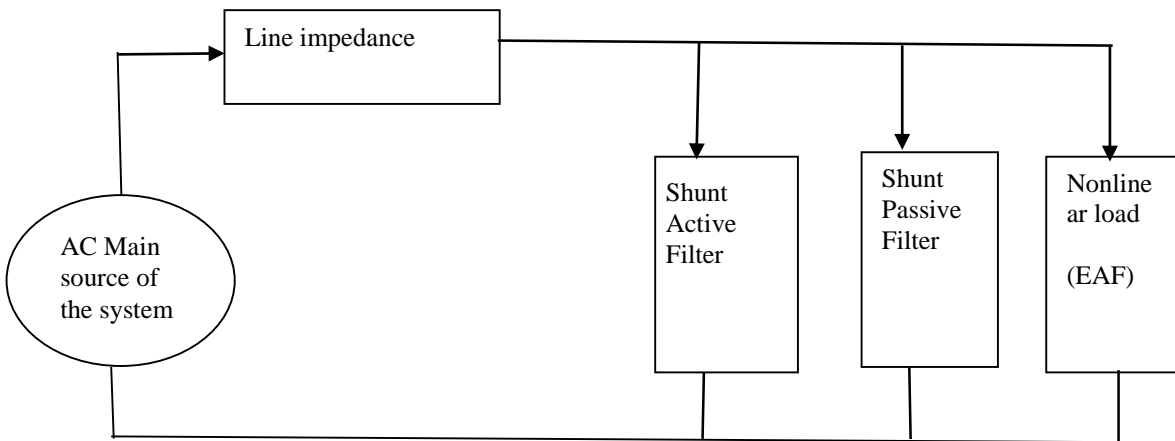


Fig. 5. Block diagram of the system design

4.1.1 Shunt active power filter design at IMANA Steel Rwanda Company.

During designing a shunt active filter for IMANA Steel Company, two components (resistance and inductor) were linked in series for a low pass filter as shown in Fig.7. After analyzing the collected data from the field visit which are tabulated in Table 1, the research aimed at designing a shunt active filter based on the data collected. These data are used as well in the design of hybrid power filter to achieve the objectives of the present thesis.

i. Mathematical Modelling of Shunt Active Filter designed by using PQ theorem

IMANA Steel Company is supplied by a three-phase system therefore a filter must be a three phase system as well. To design a three-phase filter system require some specific techniques like instantaneous real and reactive power known as PQ theory and Alpha, Beta transform techniques. Many researchers have been using this method because is easier to develop, has a control application, smooths signals, and is accurate in estimating error in vectors. The following section gives mathematical model of an Alpha, Beta and zero frame transform.

ii. Alpha (α) and Beta (β) transform

$\alpha\beta 0$ transformation is used to describe the three phase a, b and c voltage and current into two axes (phasor diagram) $\alpha\beta$ for V/I representation so that to eliminate zero sequence components from phase components of a, b and c as it is shown on the graphical representation of $\alpha\beta 0$ transformation reference frame below . Therefore, Inverse Clarke transformation is used to get actual three phase compensated voltage and current at IMANA Steel Rwanda.

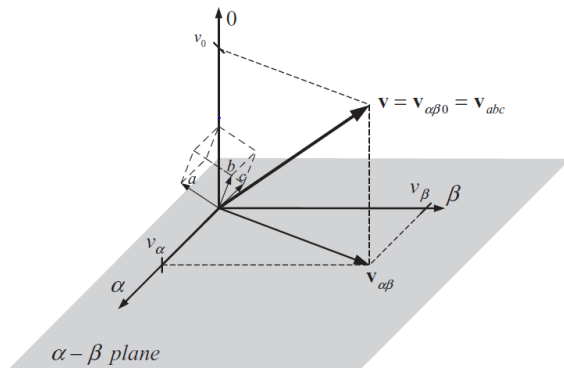


Fig. 6: Graphical representation of $\alpha\beta 0$ reference frame [25].

As it is shown on the figure above the three phases at IMANA Steel Rwanda : a, b and c are spaced apart by 120 degrees for each and $\alpha\beta 0$ at right angle for each , this contribute allot to eliminate zero sequence component of three phases to control and analyze the three phase at IMNANA Steel Company .

The transformation of phase voltage in $\alpha\beta 0$ transform (direct Clarke transformation) is calculated using equation 4.1.

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (4.1)$$

Where V_α is phasor uncompensated alpha voltage, V_β is phasor uncompensated beta voltage and V_a , b and c are uncompensated actual three phases voltage at IMANA Steel Rwanda.

The transformation of line current in $\alpha\beta 0$ transform (direct Clarke transformation) is calculated using equation 4.2.

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (4.2)$$

Where i_0 , i_α and i_β are phasor uncompensated line current in alpha and beta and i_a , b and c are uncompensated actual three phases current at IMANA Steel Rwanda.

iii. Active power (P) and reactive power (Q) calculation using Alpha and Beta transform

PQ theory play important in monitoring and regulation of instantaneous real power and reactive power at IMANA Steel Rwanda.

Instantaneous real power in form of a, b, c coordinate system expressions.

$$P = V_\alpha i_\alpha + V_\beta i_\beta + V_0 i_0 \quad (4.3)$$

Where P is instantaneous power, V are three phase voltages, i are instantaneous currents

Matrix form of instantaneous real power is calculated using equation 4.4.

$$\begin{bmatrix} p_0 \\ p_\alpha \\ q_\beta \end{bmatrix} = \begin{bmatrix} V_0 & 0 & 0 \\ 0 & V_\alpha & V_\beta \\ 0 & V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (4.4)$$

Instantaneous imaginal power is calculated using the following equation.

Where $P_{0\alpha}$ is phasor instantaneous real power and $q\beta$ is phasor reactive power.

$$S = (V_\alpha i_\alpha + V_\beta i_\beta) + j(-V_\beta i_\alpha + jV_\alpha i_\beta) \quad (4.5)$$

The voltage (e) and current (i) vector are calculated using equation 4.6.

$$e = V_\alpha + jV_\beta \quad (4.6)$$

Where e is voltage in vector form and $V_{\alpha\beta}$ is phasor voltages.

Multiplied design of instantaneous power in alpha Beta coordinate system.

$$i = i_\alpha - ji_\beta \quad (4.7)$$

Where i is alpha and beta components in instantaneous current vector form

The complex power is calculated by:

$$S^* = (e * i)^* = ((V_\alpha + jV_\beta)(i_\alpha - ji_\beta))^* \quad (4.8)$$

p^* and q^* consist of feedback power and the power which consist of harmonic complex is calculated using equation 4.9.

$$p^* = p_f + p_h \quad (4.9)$$

Loss of power across dc-link capacitor calculated using equation 4.10

$$p_{loss} = V_{dc} * i_{dc-ref} \quad (4.10)$$

Where p is power loss, V_{dc} is DC link voltage and i_{dc} is DC reference current

iv. Reference compensating current calculations

The instantaneous power represented in equations (4.8), (4.9), and (4.10) is used to estimate the current compensation that is used to reduce/mitigate the harmonic components in the current (4.11).

$$\begin{bmatrix} i_{c_\alpha}^* \\ i_{c_\beta}^* \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} p^* + p_{loss} \\ q^* \end{bmatrix} \quad (4.11)$$

Where $i_{c_\alpha}^*$, $i_{c_\beta}^*$ are alpha and beta compensated and V is phase voltage

By employing the inverse clack transformation approach, compensated current and voltage at IMANA Steel Rwanda are obtained in a, b, and c coordinate system as actual currents and voltage in equations 4.12 and 4.13 respectively.

$$\begin{bmatrix} i_{c_a}^* \\ i_{c_b}^* \\ i_{c_c}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c_0}^* \\ i_{c_\alpha}^* \\ i_{c_\beta}^* \end{bmatrix} \quad (4.12)$$

Where $i_{c_a}^*$, $i_{c_b}^*$ and $i_{c_c}^*$ are actual compensated currents and $i_{c_\alpha}^*$, $i_{c_\beta}^*$ are phasor alpha and beta compensated currents.

$$\begin{bmatrix} V_{c_a}^* \\ V_{c_b}^* \\ V_{c_c}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{c_0}^* \\ V_{c_\alpha}^* \\ V_{c_\beta}^* \end{bmatrix} \quad (4.13)$$

Where $V_{c_a}^*$, $V_{c_b}^*$ and $V_{c_c}^*$ are actual compensated Voltages at IMANA Steel Rwanda and $V_{c_0}^*$, $V_{c_\alpha}^*$ and $V_{c_\beta}^*$ are phasor alpha and beta compensated voltages.

v. RL low pass filter circuit of the designed shunt active filter for IMANA Steel Rwanda

Low pass filter composed by RL circuit was designed in which resistance and inductor are connected in series in the circuit. The purpose of this circuit was to ground high-frequency signals while allowing the low-frequency signals to flow through in the circuit. Therefore, In the design topology, the inductor permits the passage of low-frequency signals into the circuit while obstructing the passage of high-frequency signals. Additionally, a resistor enables both high- and low-frequency impulses to enter the circuit. Low pass filter it was used to smooth the signals which were distorted by nonlinear load in the system.

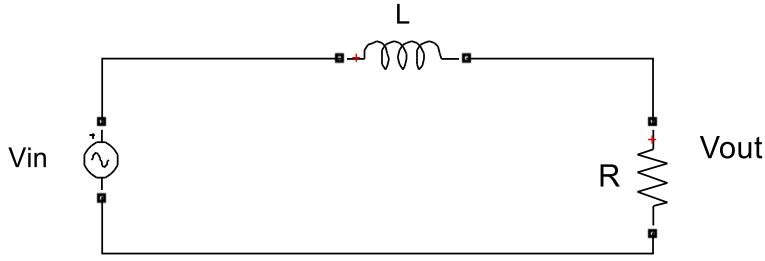


Fig. 7: RL circuit of designed low pass filter

Cutoff frequency of shunt active filter in RL circuit is calculated using equation 4.14.

$$f_c = \frac{R}{2\pi L} \quad (4.14)$$

Where f_c is cutoff frequency of low pass filter, R is resistance and L is inductor.

In this case, the resistance has a straight relationship with the cutoff frequency while the inductor has an inverse relationship with the cutoff frequency. Therefore, the low pass filter designed at IMANA Steel Rwanda Company the output voltage will increase once both frequency and inductive reactance decreases in the system. The increase in the inductive reactance can cause the phase shift between the output and input voltage in the circuit, this reason why inductive resistance must be smaller than resistance in the circuit to reduce voltage drop at IMANA Steel Rwanda.

S domain transfer function of low pass filter at IMANA Steel Rwanda is calculated using equation 4.15.

$$H(S) = \frac{R}{R+LS} \quad (4.15)$$

Where H(S) is transfer function in S domain, L is inductor and R is resistor.

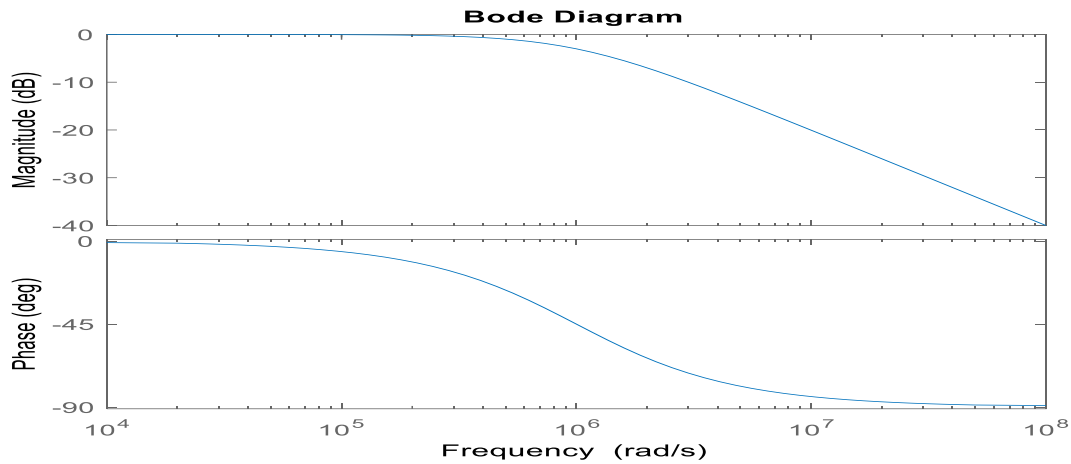


Fig. 8: Bode plot of low pass filter at IMANA Steel Rwanda company.

Referring to Fig.8 it is clear that the shunt active filter at IMANA Steel Rwanda will allow the signals with a frequency less than 10^5 rad/s and block that of higher than 10^5 rad/s to pass through in the circuit, to smooth the signals which are distorted by the nonlinear load.

4.1.2 Shunt passive filter design for IMANA Steel Rwanda Company.

Based on the data collected from IMANA steel Rwanda, as it is tabulated in table 1, and the comparison of obtained results of a designed filter in table 3, a shunt passive filter designed to compensate the remaining THD in a system by calculating suitable parameters to use in the design such as an inductor, capacitor, and resistance which are used in low pass filter and a high pass filter to minimize total harmonic distortion as it is shown in Fig.24. The calculated values of those parameters are tabulated in table 2. Shunt passive filter at IMANA Steel Rwanda is designed with band-pass and band-stop filters to reduce harmonic distortion in the line. The design topology consists of resistance, an inductor, and a capacitor coupled in two different ways parallel and series. Therefore, band-pass filters permit signals of the medium frequency (fm) to enter the circuit but prevent signals of low frequency (fl) and high frequency (fh) from passing in circuit system. Whereas a band-stop filter stops medium-frequency signals while allowing low- and high-frequency ones to enter into the circuit.

4.1.2.1 Design parameters of shunt passive filter were calculated using the following equations

i. Single-tuned filter (Low pass filter)

Low pass filter was designed using RLC circuit where resistor, inductor and capacitor all were connected in series.

Design impedance of low pass filter is calculated using equation 4.16.

$$Z = R + j \left(2\pi n f L - \frac{1}{2\pi n f c} \right) \quad (4.16)$$

Where Z is low pass filter impedance, R is resistance, f is fundamental frequency, n is harmonic order, L is inductor and C is capacitor.

Harmonic order of a shunt passive filter is calculated using equation 4.17.

$$n = \frac{1}{w_s \sqrt{LC}} \quad (4.17)$$

Where n is harmonic order of filter, L is inductor, C is capacitor and w is filter angular frequency.

Resistance of low pass filter is calculated using equation 4.18.

$$R_l = \frac{2\pi f n L_l}{Q_L} \quad (4.18)$$

Where R_l is low pass filter resistance, f is fundamental frequency, L is inductor and Q_L quality factor.

Inductor of low pass filter is calculated using equation 4.19.

$$L = \frac{1}{C(2\pi n f)^2} \quad (4.19)$$

Where L is inductor, C is capacitor, f is fundamental frequency and n is harmonic order.

The inductive reactance and capacitive reactance is calculated using equation 4.20.

$$X_C = \frac{V^2 P_h}{Q_F n} \quad , \quad X_L = \frac{X_C}{n^2} \quad (4.20)$$

Where QF is reactive power, n is harmonic number, X_C is capacitive reactance, X_L is inductive reactance and V_{ph} is phase voltage.

A quality factor of a low pass filter design is calculated using equation 4.21.

$$Q_L = \frac{X_L}{R} \quad (4.21)$$

Where Q_L is quality factor of a low-pass filter, X_L is inductor reactance and R is resistance

Used capacitor design was calculated using equation 4.22.

$$C = \frac{Q_F}{2\pi f V_{Ph}^2} \quad (4.22)$$

Where C is capacitor, QF is reactive power, V_P is phase voltage and f is fundamental frequency.

ii. Series RLC band-stop filters of a designed shunt passive filter topology

Band stop RLC circuit at IMANA Steel Rwanda is designed in which resistance, inductor, and capacitor are connected in series in the circuit. The purpose of this circuit is to ground the medium-frequency signals while allowing the high-frequency and low-frequency signals to flow through in the circuit, so that to be used in parallel RLC band-pass circuit to generate low resistance as well as to have high output voltage of designed shunt passive filter.

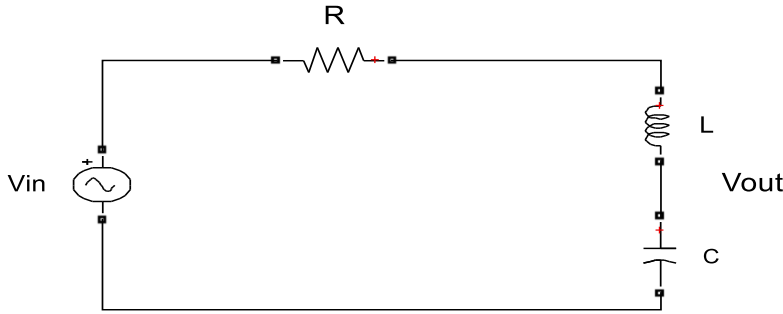


Fig. 9: Series RLC circuit of designed band stop low pass filter

S domain transfer function of bandstop filter at IMANA Steel Rwanda is calculated using equation 4.23.

$$H(S) = \frac{S^2 + \frac{1}{CL}}{S^2 + \frac{RS}{L} + \frac{1}{CL}} \tag{4.23}$$

Where H(S) is transfer function in S domain, C is capacitor, L is inductor and R is inductor.

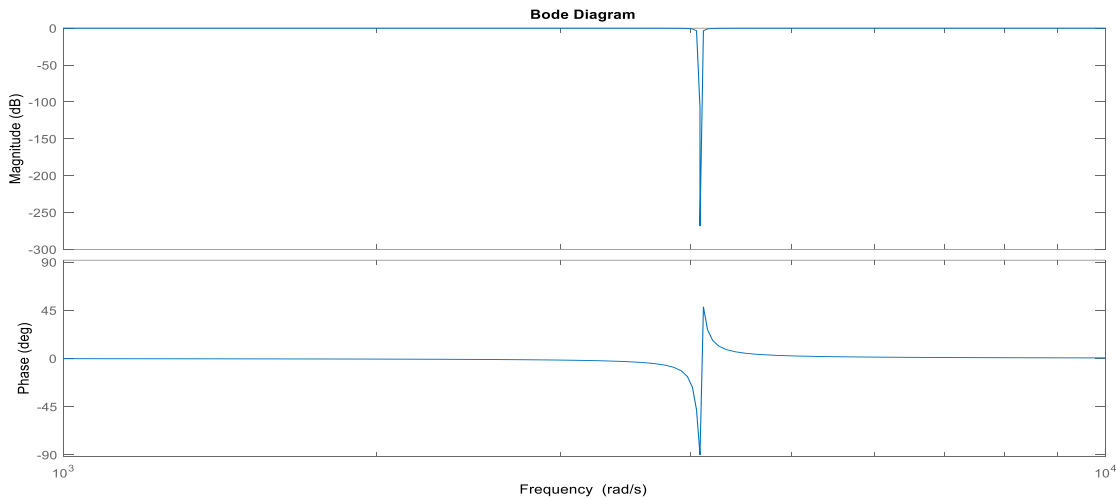


Fig. 10 :Bode plot of bandstop filter at IMANA Steel Rwanda company.

As can be seen in Fig.10 shunt passive filter at IMANA Steel Rwanda allows signals with low and high frequencies between 10^2 rad/s and 10^4 rad/s to pass through in the circuit while blocking (ground) that of medium frequencies in the middle point of 10^2 rad/s and 10^4 rad/s.

iii. Second-order high-pass (High pass filter)

High pass filter is designed at IMANA Steel Rwanda using RLC circuit where resistor, inductor and capacitor all were connected in parallel.

Design impedance of high pass filter is calculated using equation 4.24

$$Z = \frac{1}{j2\pi nfc} + \left(\frac{1}{R} + \frac{1}{j2\pi n fL} \right)^{-1} \quad (4.24)$$

Where Z is an impedance of high pass filter, L is an inductor, R is resistance and n is harmonic order.

Resistance of high pass filter is calculated using equation 4.25.

$$R_h = \frac{1}{2\pi Cfn} \quad (4.25)$$

Where R is high pass filter resistance, C is a design capacitor, f is a fundamental frequency and n is harmonic order.

Inductor of high pass filter is calculated using equation 4.26.

$$L_h = \frac{C R_h^2}{Q_H} \quad (4.26)$$

Where L is high pass filter inductor, C is shunt passive filter capacitor, R is resistance and Q_H is high pass quality factor

A quality factor of high pass filter is calculated using equation 4.27.

$$Q_H = \frac{L}{R^2C} \quad (4.27)$$

Where Q_H is a quality factor of high pass filter, R is resistance and C is capacitor.

4.1.2.2 Parallel RLC band-pass filter circuit of a designed shunt passive filter topology

The resistance, inductor, and capacitor are connected in parallel in the circuit. The medium frequency of the circuit has the highest output voltage in a circuit shown in Fig11, while the low-level frequency signal has the lowest output voltage due to the inductor and the high-level frequency has the lowest output voltage due to the capacitor. As a result, the shunt passive filter reduces the impedance of a system to compensate the residual harmonic distortion in the hybrid power filter design.

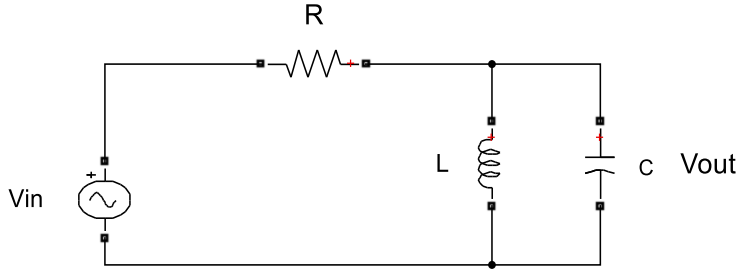


Fig. 11: Parallel RLC band-pass filters circuit

The resonance frequency of a system is calculated using a mathematical equation 4.28.

$$f_R = \frac{1}{2\pi\sqrt{LC}} \quad (4.28)$$

Where f_R is resonance frequency, L is inductor and C is capacitor.

S domain transfer function of bandpass filter at IMANA Steel Rwanda is calculated using equation 4.29.

$$H(S) = \frac{RSC}{CLS^2 + RSC + 1} \quad (4.29)$$

Where H(S) is transfer function in S domain, C is capacitor, L is inductor and R is resistance.

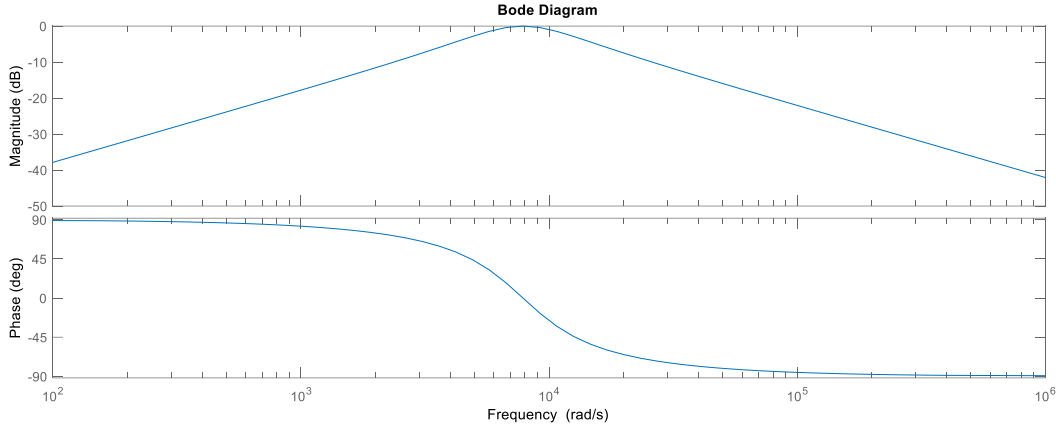


Fig. 12: Bode plot of bandpass filter at IMANA Steel Rwanda company.

The shunt passive filter is designed to absorb harmonics with high order and low order like 11th, 13th, 23rd, and 25th because it gives low impedance to compensate that of the shunt active filter in the system as it is shown in Fig.24. Therefore, the low impedance is intended to make up for any harmonic distortion that remains in the system after connecting the shunt active filter. As it is shown in Fig.12 shunt passive filter allows the signals with medium frequency closer to 10⁴ rad/s to pass through in a circuit while blocking that of high and low frequencies.

The calculated parameters used for the shunt passive filter design are listed in table 2.

Table 2 : Parameters calculated for the SPF model

Capacitor (C) : μF	Low-pass filter for 11 th harmonic		Low-pass filter for 13 th harmonic		H-pass filter for 23 rd harmonic		H-pass filter for 25 th harmonic	
	L (mH)	R (Ω)	L (mH)	R (Ω)	L (mH)	R (Ω)	L (mH)	R (Ω)
5.42	15.460	1.068	11.069	0.765	3.540	25.550	2.990	23.580

4.1.3 Hybrid power filter design

i. Introduction

A designed hybrid harmonic power filter combines both shunt active filter and shunt passive filter connected in parallel with the line system through a point of common coupling (PCC) to reduce total harmonic distorted by nonlinear load at IMANA Steel Rwanda and it is shown in Fig.29.

The objective function of a designed hybrid power filter is to minimize the total harmonic distortion of the source current and the total harmonic distortion of the nonlinear load voltage at IMANA Steel Rwanda. A constraint is to maintain the IEEE 519-1992 recommended range of $0\% \leq \text{THD} \leq 5\%$ for the total harmonic distortion at a point of common coupling, which is between the source and the non-linear load.

ii. Formulas used in a design topology of hybrid power filter at IMANA Steel Rwanda.

The voltage total harmonic distortion of a hybrid power filter is calculated using equation 4.30.

$$VTHD = \frac{\sqrt{\sum_{k \geq 1} V_{LK}^2}}{V_{L1}} \quad (4.30)$$

Where VTHD is voltage total harmonic distortion, V_{LK} is nonlinear load voltage at harmonic order K, K is harmonic order and V_{L1} is load voltage.

The current total harmonic distortion of a hybrid power filter is calculated using equation 4.31.

$$ITHD = \frac{\sqrt{\sum_{k \geq 1} I_{SK}^2}}{I_{S1}} \quad (4.31)$$

Where ITHD is current total harmonic distortion, I_{SK} is source current at harmonic order K, K is harmonic number and I_{S1} is a source current.

To get transfer function of hybrid power filter at IMANA Steel Rwanda Company, research combines all the three transfer functions of low pass, bandstop and band pass filters.

S domain transfer function of hybrid power filter at IMANA Steel Rwanda is calculated using equation 4.32.

$$H(S) = \frac{R}{R+LS} + \frac{S^2 + \frac{1}{CL}}{S^2 + \frac{RS}{L} + \frac{1}{CL}} + \frac{RSC}{CLS^2 + RSC + 1} \quad (4.32)$$

Where H(S) is transfer function in S domain, C is capacitor, L is inductor and R is resistance.

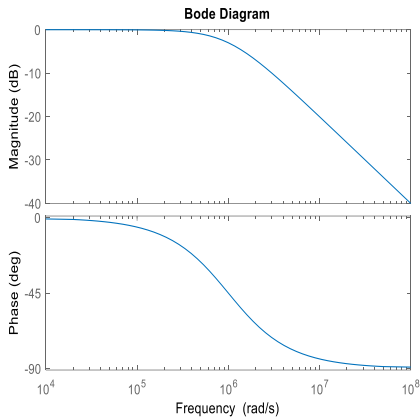


Fig.8: Bode plot of low pass filter

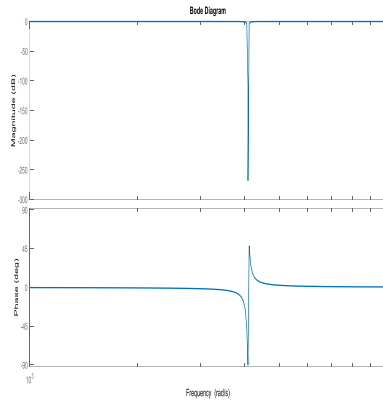


Fig.10: Bode plot of bandstop filter

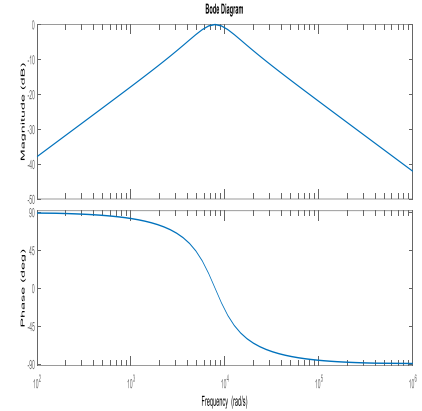


Fig. 12: Bode plot of bandpass filter

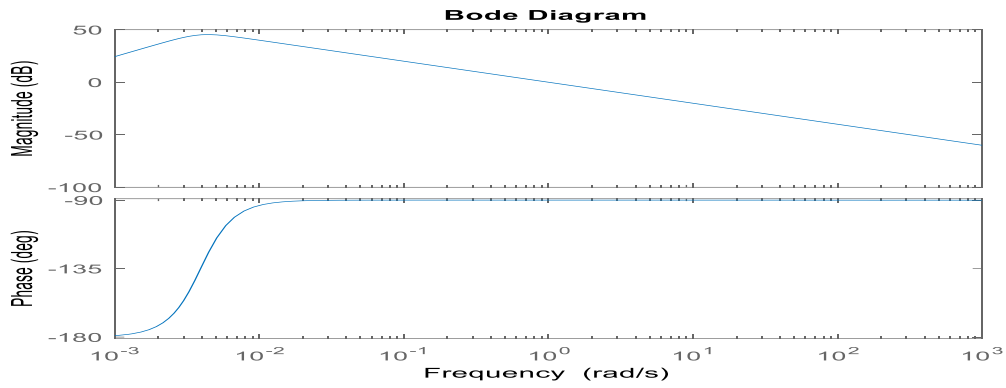


Fig. 13: Bode plot of hybrid power filter at IMANA Steel Rwanda Company.

As can be seen in Fig.13 a designed hybrid power filter bode plot it has similarity with that of a low pass filter, meaning that a designed hybrid power filter at IMANA Steel Rwanda is there to smooth voltage and current waves distorted by a nonlinear load by allowing the signals with frequencies less than 10^2 rad/s and rejecting the signals with frequencies higher than 10^2 rad/s to pass through a circuit so that to minimize the total harmonics distortion to a level that is accepted by IEEE 519-1992 in the power system.

CHAPTER 5. POWER FILTER SIMULATION AT IMANA STEEL RWANDA

5.0 Introduction

This chapter's discussion of the effectiveness of shunt active and shunt passive filters, simulation of a developed hybrid harmonic to reduce the total harmonic distortion at IMANA Steel Rwanda Company, and results analysis are its main points. Also, this section includes simulation models for both compensated and uncompensated topologies. Matlab/Simulink software uses a 440V voltage source for both models. All technics were simulated to show up the feasibility of a hybrid power filter to rectify harmonics present in a source current and voltage. Also, Total harmonic distortion (THD) was calculated using FFT analysis algorithm.

5.1 Simulation of a system without a power filter

Fig.14 depicts a simulation model of a circuit with source current and voltage harmonics. The circuit's major part is an electric arc furnace as a nonlinear load. As a result of the system's connection to an electric arc furnace, source current and voltage harmonics are observed, as depicted in Fig.15 and Fig. 16, respectively. The source current total harmonic distortion (THD) is found to be 26.71% and a source voltage is found to be 4.71%, as illustrated in Fig.17 and Fig. 18, respectively, based on the findings of a Fast Fourier Transformation (FFT).

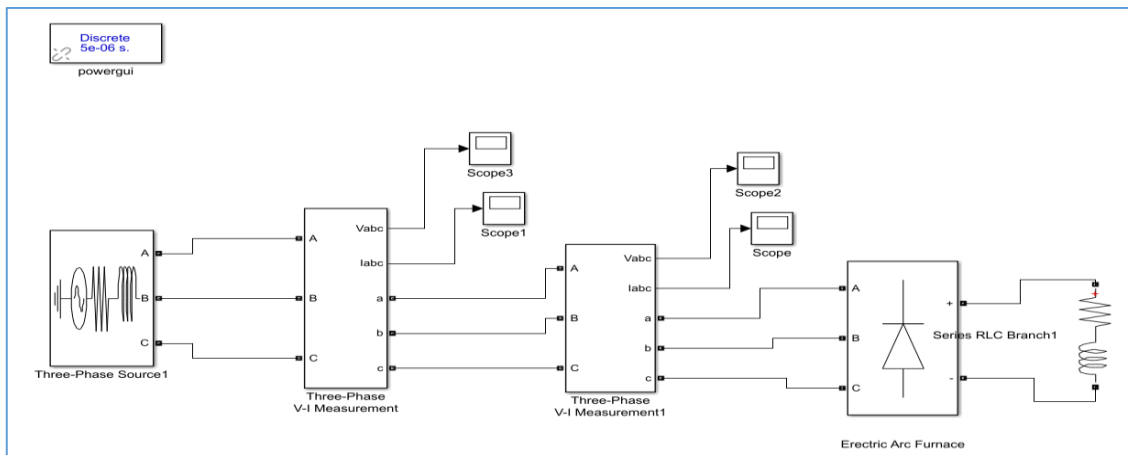


Fig. 14 Model for uncompensated simulation

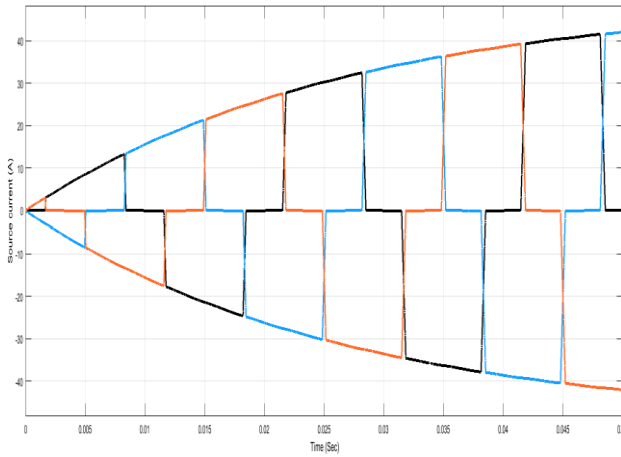


Fig. 15 Waveform of uncompensated source current

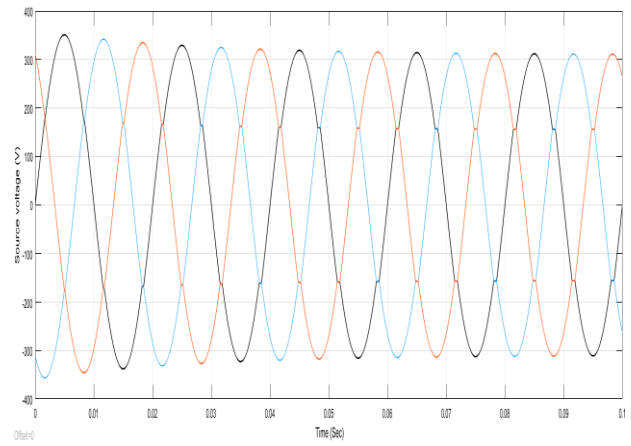


Fig. 16 Uncompensated source voltage waveform

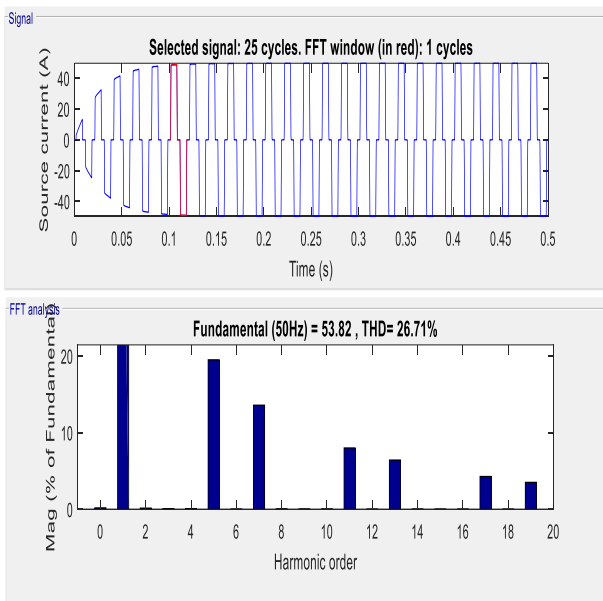


Fig. 17 THD FFT analysis for the uncompensated model's source current

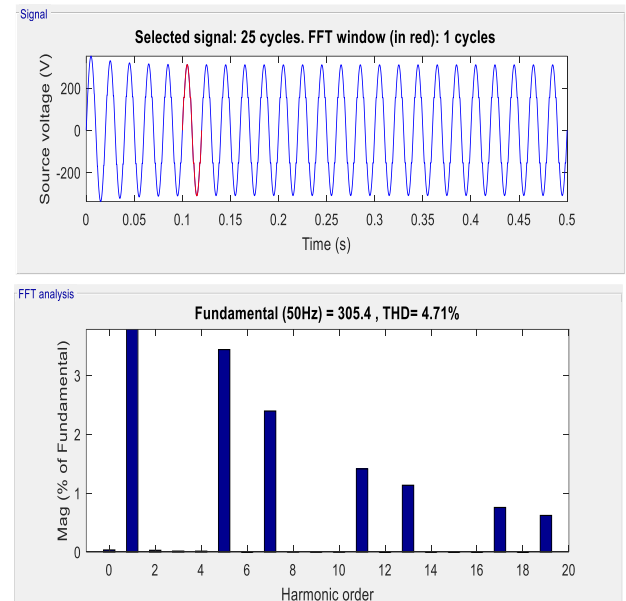


Fig. 18 THD FFT analysis for the uncompensated model's source voltage

5.2 Simulation of a shunt active filter at IMANA Steel Rwanda Company.

This section demonstrates the precise outcomes of the compensated simulation model with an active shunt filter shown in Fig.19. This model is created using an ac three-phase source line, three-phase V-I measurements, a non-linear load (an electric arc furnace), proportional integrator (PI) controller, VSI with DC link, and PQ theory. The design is based on the corrected data from IMANA Steel Rwanda as summarized in table 1. Additionally, other parameters are calculated using formulas as shown in chapter 4.

According to Fig.15 and Fig.16, which depict the uncompensated model's harmonic distortion for source current and source voltage waveforms respectively, it is determined to be significantly higher than the IEEE 519-1992 harmonic standard level limitations. The PQ theory is used to design a shunt active filter that can lower the percentage level of the total harmonic distortion in source current and voltage to achieve an acceptable level as it is specified by IEEE 519-1992 standard regulations. According to FFT analysis, the obtained result of compensated source current is lowered from 26.71% to 12.90% at 0.1 seconds, as shown in Fig.17 and Fig.22. The total harmonic distortion of the source current decreased at a specific level. However, according to FFT analysis the source voltage's THD, increased from 4.71% to 16.99% as shown in table 3. This result is due to the shunt active filters only correcting the 5th and 7th harmonic current of a non-linear load [26] . Also according to the voltage-current characteristics of an electric arc furnace as one of the nonlinear loads, the voltage decreases as the arc current increases which can be only limited by the impedance of the power system [27].

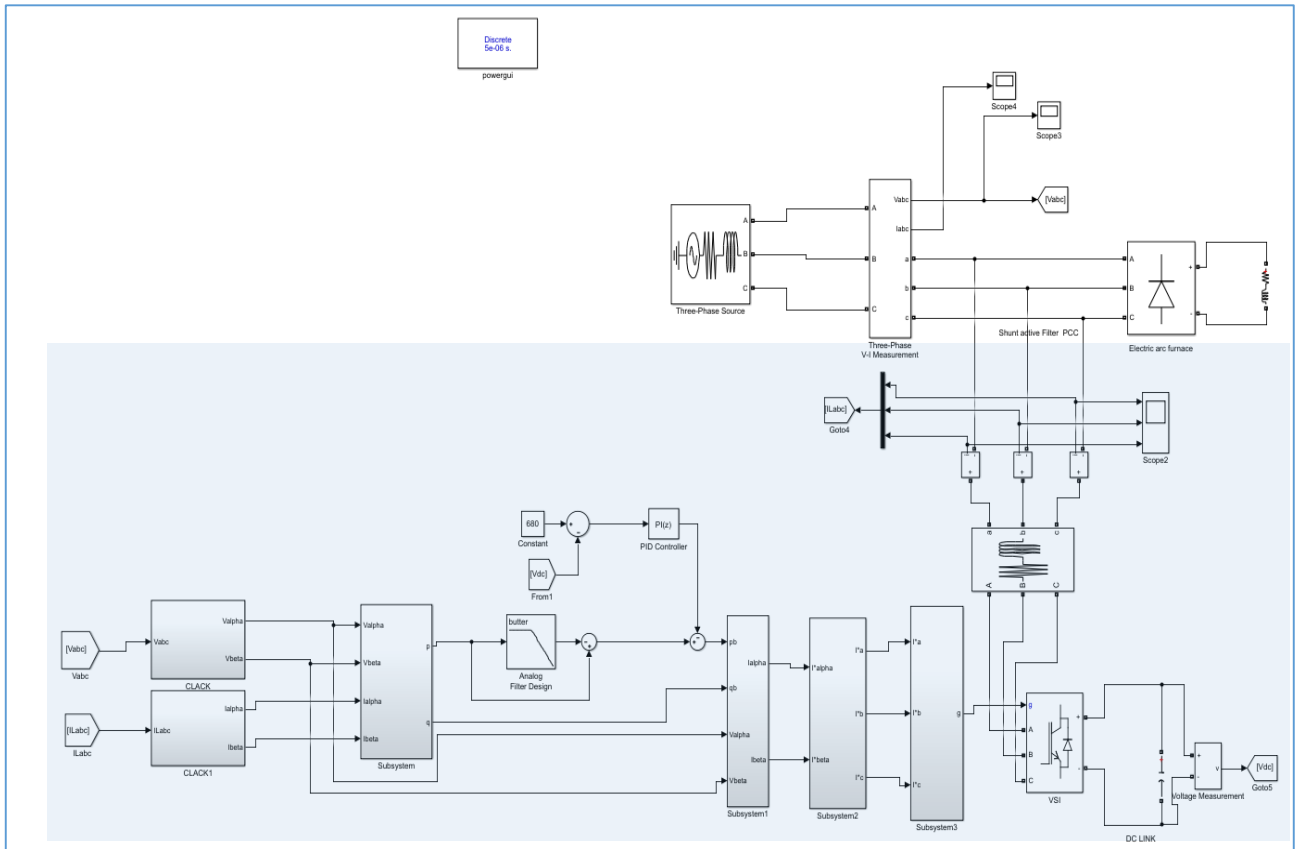


Fig. 19 A compensated Simulation model with Shunt Active filter (SAF)

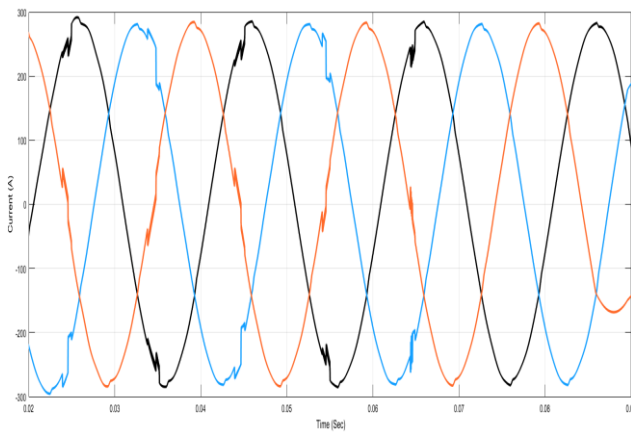


Fig. 20 Source current wave of a compensated model with SAF

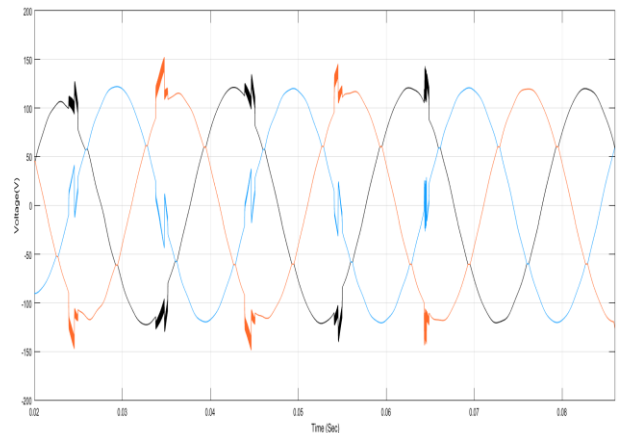


Fig. 21 Source voltage wave of a compensated model with SAF

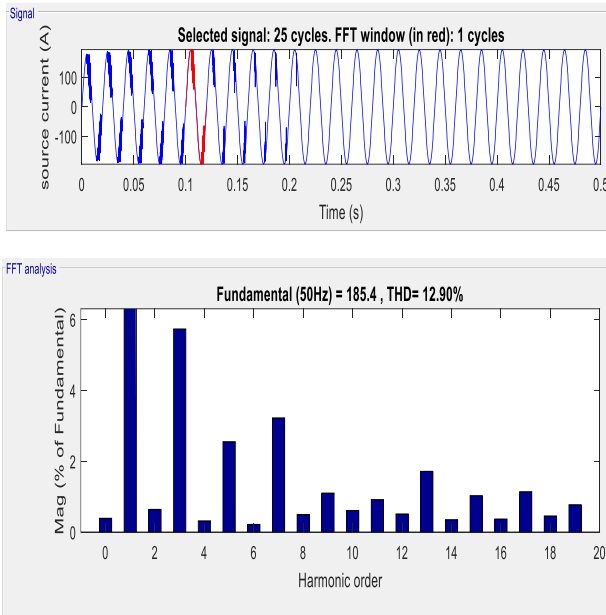


Fig.22 FFT analysis of THD for source current of a compensated model with SAF

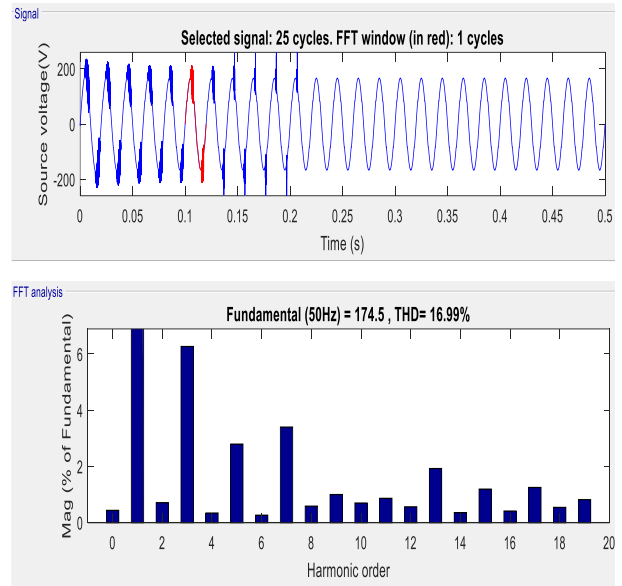


Fig. 23 FFT analysis of THD for source voltage of compensated model with SAF

Table 3 : Comparison of obtained results with uncompensated

Parameters	THD for uncompensated	THD for Compensated with SAF
Current	26.71%	12.90%
Voltage	4.71%	16.99%

5.2 Shunt passive filter simulation at IMANA Steel Rwanda Company.

A designed shunt passive filter simulated in MATLAB to reduce harmonics distorted by a non-linear load like 11th, 13th, 23rd, and 25th. Shunt passive filter reduce those harmonics by using a low pass filter and a high pass filter to adjust THD for the current and voltage of an electric arc furnace at IMANA Steel Company to an acceptable percentage level as recommended by IEEE 519-1992 harmonic standard in power system, and it is highlighted in Fig.24.

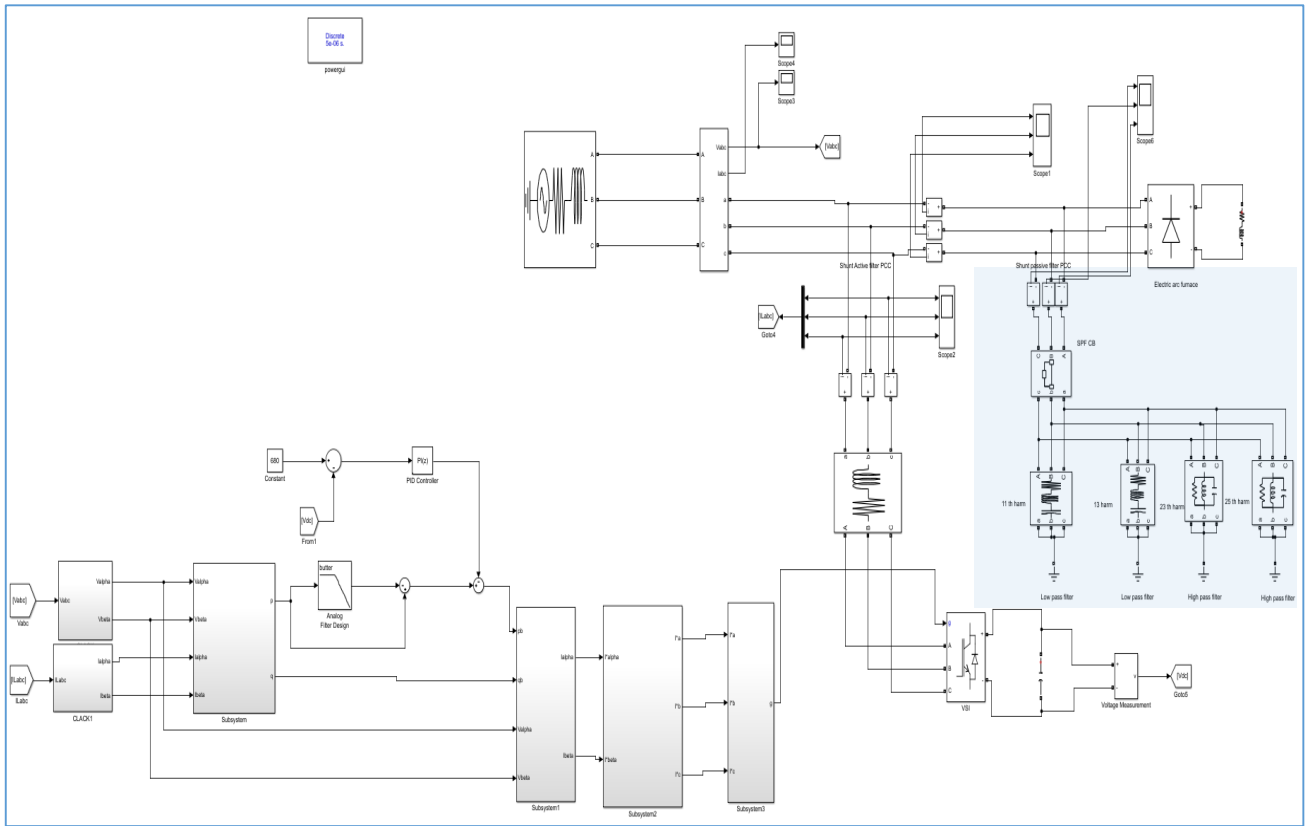


Fig. 24 Shunt passive filter (SPF) design topology

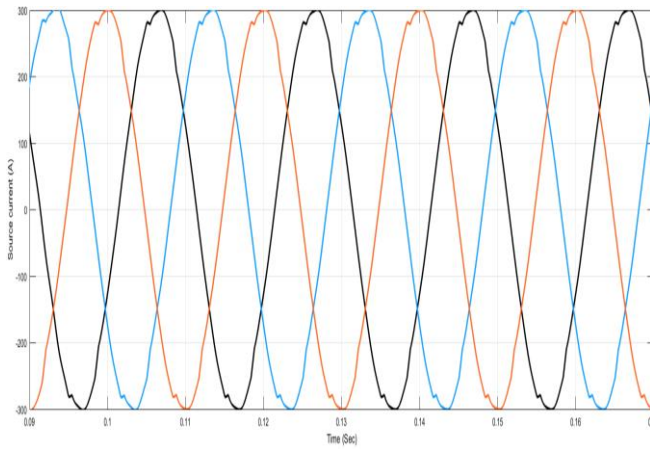


Fig. 25 current waveform of shunt passive filter

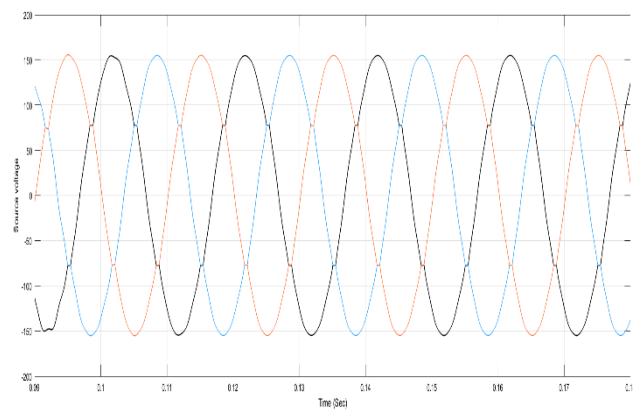


Fig. 26 voltage waveform of shunt passive filter

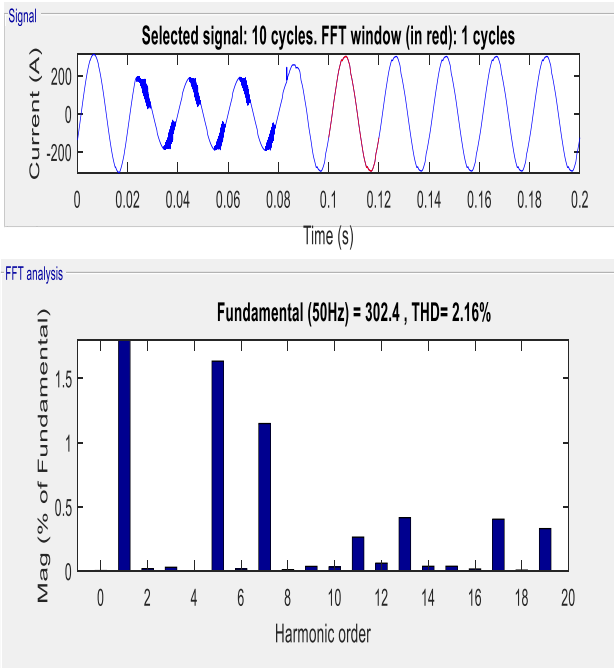


Fig. 27 Total harmonic distortion FFT analysis of current waveform

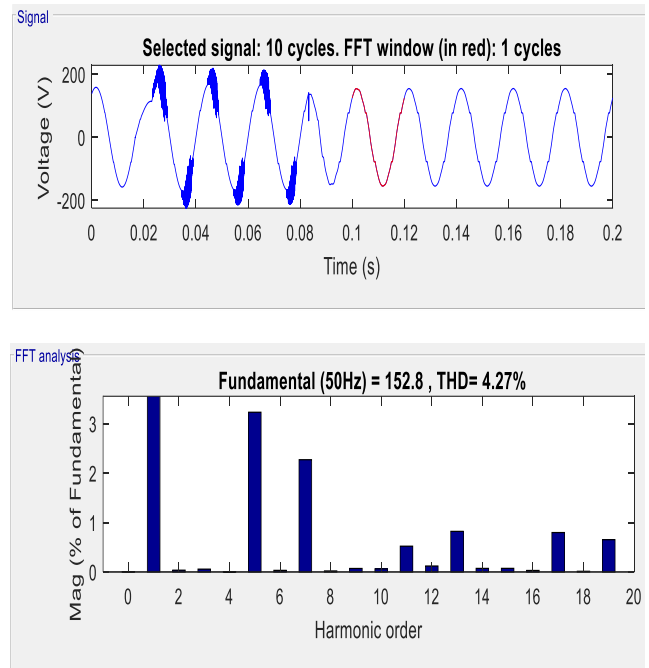


Fig. 28 Total harmonic distortion FFT analysis of voltage waveform

Table 4 : Comparison of obtained results with uncompensated

Parameters	THD for uncompensated	THD for Compensated with SPF
Current	26.71%	2.16%
Voltage	4.71%	4.27%

5.3 Hybrid power filter simulation at IMANA Steel Rwanda.

As it is simulated in this section, it is clear that the use of both a low pass and a high pass filter reduce the remaining THD in the system's current and voltage, as shown in Table 7, is made possible by the combination of shunt active and shunt passive filters, as shown in Fig.29, which allows research to use the active filter as a damper for a shunt passive filter against potential resonances. Furthermore, because HPF is a commercial filter design, it is used at IMANA Steel Rwanda Company as a controllable reactive power filter to reduce overall harmonic distortion in an industrial power system to a suitable harmonic level.

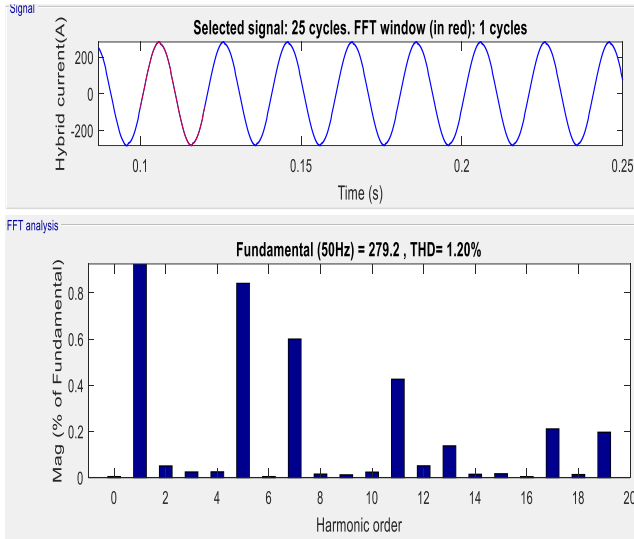


Fig. 32. THD FFT analysis for the hybrid filter design model's current

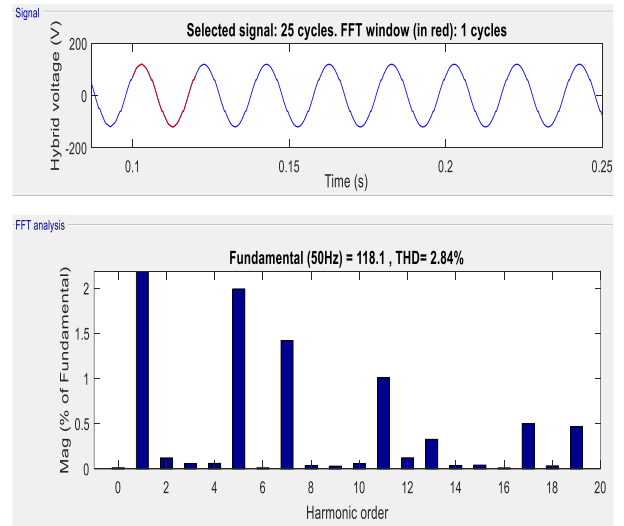


Fig. 33. FFT analysis of the voltage THD for the hybrid filter design model

It is clear that the designed hybrid power filter reduced IMANA Steel Rwanda company's overall harmonic distortion of both current and voltage to level permitted by the IEEE 519-1992 standard and it is one of best filtering technics that can be used for reducing harmonic distortion in industrial power system.

5.4. Results and analysis

5.4.1 The power system behavior with nonlinear loads versus a power system grid

Table 5 : Gotten outcomes for a nonlinear load system

Parameters	THD for uncompensated system
Current	26.71%
Voltage	4.71%

It is obvious from the results that nonlinear loads introduce harmonic distortion into the power system grid (table 5). This is because, according to IEEE 519-1992's recommendations for the harmonic percentage level in the power system network, the harmonic level for both current and voltage is at a high level and is not within the permitted range.

5.4.2 The comparison of obtained simulation results for SAF and SPF

Table 6 : THD comparison of the system compensated with SAF and SPF

Parameter	Total Harmonic Distortion (THD) of a system	
	Compensated with SAF	Compensated with SPF
Current	12.90%	2.16%
Voltage	16.99%	4.27%

It is clear that a design of shunt passive filter at IMANA Steel Company with low pass and high pass filters reduces the harmonic current from 26.71% to 2.16% and the harmonic voltage from 4.71% to 4.27% in the system rather than that of shunt active filter with highest values of THD not within the acceptable level as recommended by IEEE 519-1992 standard harmonic level.

5.4.3 The contribution of hybrid harmonics power filter on a power system.

Table 7 : THD comparison of the system with and without a hybrid power filter

Parameters	Total Harmonic Distortion (THD) of a system			
	Uncompensated system	Compensated with SAF	Compensated with SPF	compensated with HPF
Current	26.71%	12.90%	2.16%	1.20%
Voltage	4.71%	16.99%	4.27%	2.84%

Table 7 shows that the voltage total harmonic distortion at IMANA Steel Rwanda Company decreased from 16.99% to 2.84% after a passive shunt filter was added to a system model that was previously created, and the current total harmonic distortion decreased from 12.90% to 1.20% after the design process of a hybrid power filter to a level that is acceptable by IEEE 519-1992 harmonic percentage standard level. It demonstrates that the overall harmonic distortion at a point of common coupling (PCC) is achieved and is within allowable limits. The results unequivocally demonstrate that, following IEEE 519-1992 recommendations, the nonlinear load harmonic distortion is adjusted at an acceptable standard level in the system with a hybrid power filter. As a result, the harmonic compensation in the power system is greatly helped by the developed hybrid power filter, which also improves the power quality in the power system network.

Chapter 6. CONCLUSION AND RECOMMENDATION

6.1 Conclusion

To mitigate the growth of power electronics in power systems, the problem of power quality must be addressed in a variety of power system scenarios, such as harmonic distortion. To improve the power quality of the power system while taking into consideration both current and voltage, this thesis presents a complete description of the design topology of a hybrid harmonic power filter at IMANA Steel Rwanda.

The design takes into account an electric arc furnace as one of the non-linear loads at IMANA Steel Rwanda Company, passive filters, such as single-tuned and high-pass filters, as well as instantaneous active and passive/PQ theory to eliminate harmonic distortion in shunt active filters and reactive power compensation was also taken into account in research.

However, hybrid power filter design in this dissertation was about combination of shunt passive and shunt active filters to reduce harmonics distorted by an electric arc furnace taking into account IMANA Steel Rwanda Company as case study of research design.

Before adjusting a hybrid power filter at IMANA Steel Rwanda Company, the THD for the current was 26.71% and for voltage, it was 4.71%. Overall harmonic distortion for current and voltage was measured at 1.20% and 2.84%, respectively, with the use of a hybrid power filter. Thus research discussed about a power system behavior with nonlinear loads versus a power system grid and contribution of hybrid harmonics power filter on a power system at IMANA Steel Rwanda Company. Therefore, results showed that THD for current and voltage are both corrected by FFT analysis to fall under the IEEE 519-1992 allowable suggested harmonic levels standard of less than 5% for both types of THD.

6.2 Recommendation

After reviewing the research's findings at IMANA Steel Rwanda Company, it is necessary to make some recommendations for readers and prospective electrical power quality enhancement researchers. Power quality problems in industries can be resolved with hybrid filters for industrial power systems.

- i. I would like to urge that academics and decision-makers in the energy sector to implement this project by working on the prototype of this research and developing some innovations based on anticipated future technical advancements to improve the quality of the power in the power system.

- ii. In this study, a hybrid power filter system was created to reduce total harmonic distortion brought on by nonlinear loads and enhance the quality of the power in industrial power systems, but the concept also required financial backing. However, I would like to encourage upcoming scholars to focus on this study's cost optimization.
- iii. However, I would like to encourage future researchers to work on other algorithms which can be used to compensate THD at minimum values closer to zero percent because it would be preferable to have zero total harmonic distortion in the power system for power quality improvement in the network. The algorithm used, determine the total harmonic distortion caused by the non-linear load to improve power quality at IMANA Steel Rwanda Company.

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APPENDIX OF RESEARCH

The images below were taken during the site visit at IMANA Steel Rwanda Company.

Appendix 1. Site electric arc furnace

An electric arc furnace used at IMANA Steel Rwanda to melt scrap metal to produce steel is depicted in figure 1 below.

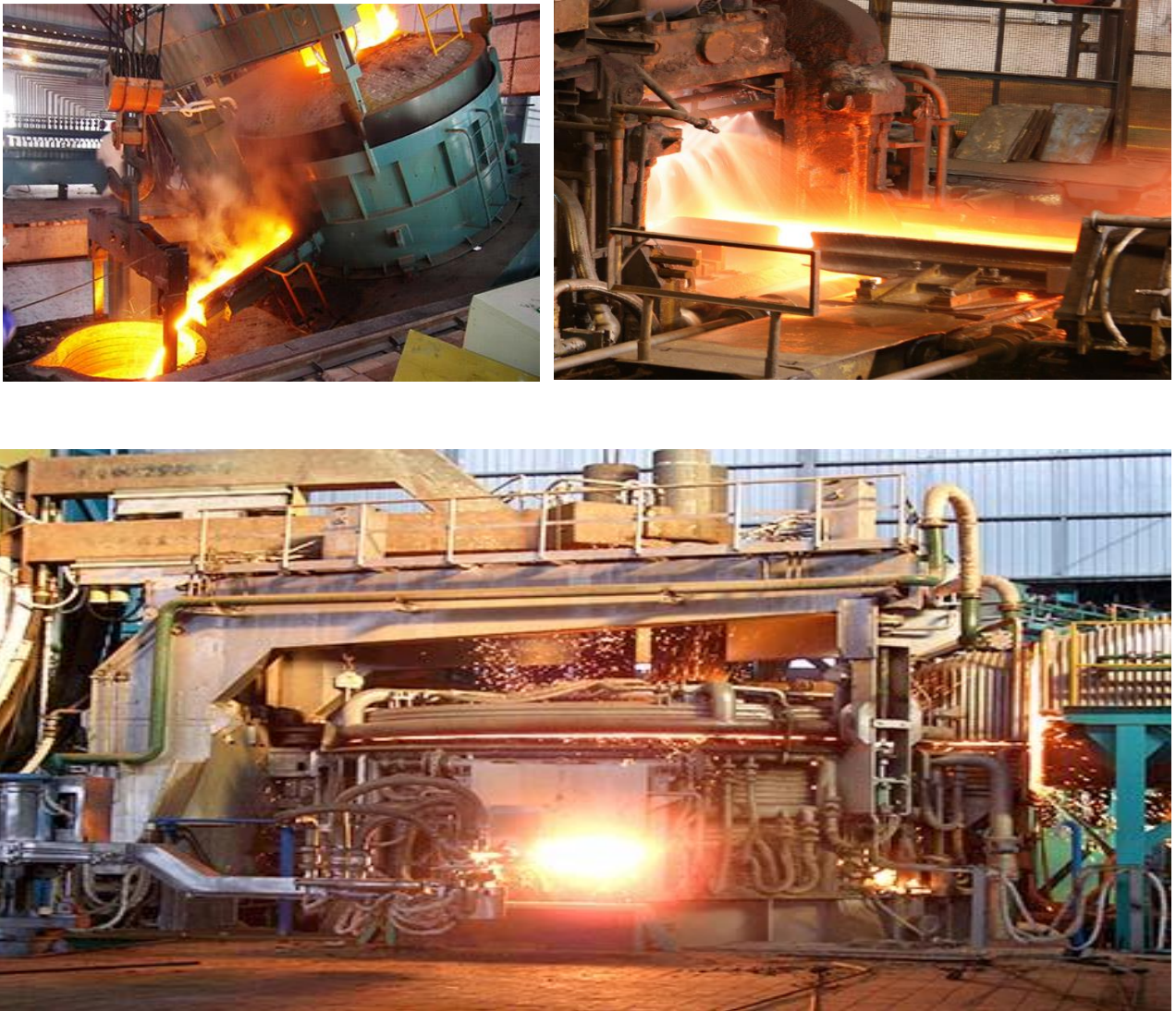


Figure 1. An arc furnace melting metal scraps.

Appendix 2. Site Mild steel

As the industry's final product, steel is depicted in figure 2 below.



Figure 2. Mild Steel