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Harmonics Reduction in the Power System using a Shunt Active Power Filter

by

Irum Sheraz Kiyani

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My dissertation work is devoted to My Family, My Teachers, and My Friends. I have a special feeling of gratitude for My beloved parents and brothers. Special thanks to my supervisor whose uncountable confidence enabled me to reach this milestone.

CERTIFICATE OF APPROVAL

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Abstract

As technology advances, our dependency on electricity has increased tremendously. The efficient performance of various electrical devices is closely linked to power quality. Power quality issues manifest as deviations from ideal voltage waveforms or amplitude levels, typically characterized by distortions from a sine wave or deviations from established reference levels. These disturbances involve a wide variety of difficulties, including voltage fluctuations, sags, imbalance, transients, and harmonics, all of which can hurt electrical system performance and dependability.

Harmonics provide a substantial problem in power systems, appearing as a major issue among numerous power quality concerns. The growing use of power electronics equipment has significantly increased harmonic distortions in the power network. Harmonic currents are typically caused by nonlinear loads interacting with the distribution system. These current harmonics have negative consequences such as lower power factor, voltage variations across the power system, poorer overall efficiency, and interference with communication systems. Harmonic currents have become increasingly common in residential, commercial, and industrial installations in recent years, coinciding with the tremendous growth of nonlinear loads.

Active power filtering stands at the forefront of contemporary research, attracting numerous scholars keen on refining power quality. Particularly, active power filters are pivotal for suppressing harmonics and compensating reactive power, elevating overall power quality standards. Among these, Shunt Active Power Filters (SAPF) emerge as a vital tool, strategically positioned in parallel with the load to counteract current harmonics.

The methodology involves a multifaceted approach, commencing with the identification of harmonic components. Subsequently, a reference current is meticulously generated, serving as a benchmark for desired waveform characteristics. Finally, gate pulses are precisely crafted for the power circuit, ensuring seamless integration of the active power filter into the system.

Functionally, an active power filter operates by negating the adverse effects of current harmonics induced by nonlinear loads. This is accomplished by injecting compensatory currents in parallel with the load, effectively sculpting the current waveform into a sinusoidal pattern. As a result, the power system attains enhanced stability and efficiency, aligning with modern power quality standards.

In this research, the use of Instantaneous Real and Reactive Power Theory (p-q theory) for reference current generation and a Hysteresis Current Controller (HCC) for reference current injection were investigated for the implementation of a shunt active power filter (SAPF) aimed at harmonics reduction in power systems. The p-q theory facilitates precise extraction of reference currents by directly considering the real and reactive power components, ensuring effective compensation of harmonic currents. Meanwhile, the HCC ensures rapid response to load variations and disturbances, providing robust and accurate control of the SAPF. The p-q theory provides accurate extraction of reference currents independent of system loading circumstances, whereas the HCC is simple to implement and performs well against system perturbations.

Contents

Author's Declaration iv

Plagiarism Undertaking v

Acknowledgement vi

Abstract vii

List of Figures xi

List of Tables xiii

Abbreviations xiv

1 Introduction 1
- 1.1 Power Quality Issues 1
- 1.2 Power Factor 5
- 1.3 Techniques for Harmonics Mitigation 7
  - 1.3.1 Power Filters 7
    - 1.3.1.1 Passive Filters 8
    - 1.3.1.2 Active Filters 9
- 1.4 Methodology of Shunt Active Filter 11
  - 1.4.1 Reference Current Generation 11
  - 1.4.2 Reference Current Injection 16

2 Literature Review 19
- 2.1 Reference Current Generation 19
- 2.2 Reference Current Injection 25
- 2.3 Critical Analysis 31
  - 2.3.1 Reference Current Generation 31
  - 2.3.2 Reference Current Injection: 31
- 2.4 Problem Statement 32

3 Reference Current Generation 33
- 3.1 Instanteous Reactive Power Theory 33
  - 3.1.1 Clark Transformation 35

3.2 Simulink Model Analysis 38
3.2.1 Simulink Model of Three-Phase Power Systems with Non-Linear Load 38

4 Reference Current Injection 44
4.1 Introduction 44
4.2 Implementation 45
4.2.1 Comparator 46
4.2.2 Hysteresis Band 46
4.2.3 Switching Logic 46
4.2.4 Dead Time Compensation 46
4.2.5 Feedback Circuitry 47
4.2.6 Digital Implementation 48
4.3 Hysteresis Current Controller Block 49
4.4 Three-Phase Inverter 50

5 Implementation and Results 52
5.1 Simulink Model of Three Phase Power System with SAPF 52
5.1.1 Results 54
5.1.1.1 Before Compensation 54
5.1.1.2 After Compensation 55
5.2 Analytical Calculation of Total Harmonic Distortion (THD) Using Fourier Series Analysis 57
5.3 Investigation of SAPF Performance with Dual Full-Wave Rectifier Loads 59
5.3.1 Results 61
5.3.1.1 Before Compensation 61
5.3.1.2 After Compensation 62
5.4 Analytical Calculation of Total Harmonic Distortion (THD) Using Fourier Series Analysis 64
5.5 Comparative Analysis 67

6 Conclusion and Future Work 71
6.1 Conclusion 71
6.2 Future Work 72

7 Appendix 75

Bibliography 77

List of Figures

1.1 Basic Compensation Principle of SAPF [13] 11
1.2 Synchronous Reference Frame Theory - Block Diagram [17] 13

3.1 Block Diagram of pq theory [60] 34
3.2 Power components of P-Q theory [61]. 37
3.3 Three-Phase Power Systems with Non-Linear Load without Compensation 38
3.4 Before compensation (a) Source current (b) Load current 39
3.5 Before compensation Source Current FFT Analysis 40
3.6 Compensation of Three-Phase Power Systems with pq theory 41
3.7 Instantaneous Reactive Power Theory Block 41
3.8 Reference Current 42
3.9 After Compensation (a) Source Current (b) Load Current 42
3.10 After Compensation Source Current FFT Analysis 43

4.1 Hysteresis Current Control Technique 45
4.2 Hysteresis Current Controller Block 49
4.3 Three-phase Inverter 51

5.1 Simulink Model of Three Phase Power System with the Shunt Active Power Filter (SAPF) 53
5.2 Before Compensation (a)Source Current (b) load Current 54
5.3 Before Compensation Source Current FFT Analysis 55
5.4 After Compensation (a)Source Current, (b)Reference current (c)Load Current 56
5.5 After Compensation Source Current: Steady State Response 56
5.6 After Compensation Source Current FFT Analysis 57
5.7 Shunt Active Power Filter with Dual Full-Wave Rectifier Loads . . 60
5.8 Before Compensation (a)Source Current (b) Load Current 61
5.9 Before Compensation Source Current FFT Analysis 62
5.10 After Compensation (a)Source Current, (b)Reference current (c)Load Current 63
5.11 After Compensation Source current FFT Analysis 63
5.12 Comparative Analysis of THD for Single and Dual Bridge Full Wave Rectifiers Before and After Compensation 66
5.13 Source Current Before Compensation 68
5.14 Before Compensation Source Current FFT Analysis 69

5.15 Source Current After Compensation 69
5.16 After Compensation Source Current FFT Analysis 70

List of Tables

2.1 Reference Current Generation Techniques 25
2.2 Current Injection Techniques 30

5.1 System parameters 65
5.2 Comparison of THD Reduction Before and After Compensation Using Different Control Techniques 70

Abbreviations

AC	Alternating Current
AI	Artificial Intelligence
ANN	Artificial Neural Network
DC	Direct Current
DERs	Distributed Energy Resources
DFT	Discrete Fourier Transform
DMC	Delta Modulation Control
ESS	Energy Storage System
HCC	Hysteresis Current Controller
IGBT	Insulated Gate Bipolar Transistor
LMS	Least Mean Squares
ML	Machine Learning
MPC	Model Predictive Control
OCC	One Cycle Control
PQ	Instantaneous Active and Reactive Power Theory
PF	Power Factor
PWM	Pulse Width Modulation
RES	Renewable Energy Sources
RLS	Recursive Least Squares
RMS	Root Mean Square
SAPF	Shunt Active Power Filter
SMC	Sliding Mode Controller
SPWM	Sinusoidal Pulse Width Modulation
STF	Self Tuning Filters

UVTG	Unit Vector Template Generation

Chapter 1

Introduction

Power quality, characterized by stable voltage levels, frequency, and waveform, is crucial for modern electrical systems [1]. High-quality electricity is essential for the reliable operation of electronic equipment, minimizing downtime, and optimizing energy usage [2].

1.1 Power Quality Issues

Voltage sags, also known as dips or short-duration reductions in voltage levels, are characterized by a decrease in voltage magnitude below the nominal value for a short period. They can be caused by various factors such as sudden changes in load, faults in the electrical system, or starting large motors. Voltage sags can disrupt sensitive equipment, causing malfunctions or temporary shutdowns. Devices like computers, sensitive electronic equipment, and manufacturing machinery are particularly susceptible to damage or operational issues during voltage sags.

Voltage swells, on the other hand, refer to short-duration increases in voltage levels above the nominal value. They can occur due to sudden load disconnection, transformer tap changes, or faults in the distribution network. Like voltage sags, voltage swells can also damage or disrupt electrical equipment. Excessive voltage can lead to insulation breakdown, component failure, or incorrect operation of electronic devices. Voltage interruptions, meanwhile, are complete or partial loss of voltage for a short period, often caused by faults in the power system or equipment failures. These interruptions can lead to data loss, equipment damage, or production downtime, depending on the criticality of the affected systems. [3]. Each disturbance will be described individually in the following sections:

1. **Voltage Sags:**

   Temporary drops in the electrical voltage sent to a system or device are referred to as voltage sags, also known as voltage dips or transitory voltage reductions. These short outages may be caused by several reasons, such as power grid malfunctions, sharp spikes in electrical demand, or the operation of heavy machinery. Voltage sags might interfere with the regular operation of delicate machinery and electronic devices, leading to breakdowns or data loss.

2. **Voltage Swells:**

   Voltage swells—also known as over-voltages or voltage spikes—occurs when the electrical voltage supplied to a device or system temporarily exceeds its regular working range. These brief voltage spikes can be caused by electrical grid switching events, power surges, or lightning strikes. If safety precautions like surge protectors are not used, voltage swells can harm delicate electronic equipment, posing a risk to its durability and performance.

3. **Voltage Interruptions:**

   Voltage interruptions are temporary, unexpected disruptions in the flow of electricity that are frequently brought on by problems with the equipment, flaws in the power distribution system, or natural influences like bad weather. These disruptions lead to a complete loss of electrical voltage, affecting the operation of connected systems and devices. Voltage interruptions can cause harm to equipment, loss of information, and decreased productivity for both enterprises and residences, depending on how often and how long they last. To mitigate the negative impacts of voltage interruptions, an uninterruptible power supply (UPS) is frequently used. It provides backup power to ensure continuous operation. These devices ensure continuous power during outages, protecting equipment and maintaining operations.

4. **Frequency Variations:**

   When the conventional electrical frequency of a power grid, which is commonly 50 or 60 Hertz (Hz), deviates from its intended range, it is referred to as a frequency variation or frequency deviation. These variations may be brought on by grid instability, an imbalance between the production and consumption of power, or defective equipment. Electrical machinery and gadgets that depend on precise timing or synchronization can be negatively impacted by frequency changes, sometimes resulting in inadequate functionality or breakdown. To keep the frequency of the electrical grid stable and ensure the steady operation of connected systems, frequency regulation measures have been put in place.

5. **Transients:**

   Electricity transients are quick, abrupt variations in voltage or current that depart from steady-state conditions. Numerous things, including lightning strikes, electrical surges, switching procedures, or defects in the equipment, might result in these transient events. If electronic systems and gadgets are not effectively safeguarded against transients, they may malfunction or experience premature damage. To lessen the effects of transients and guarantee the stable operation of electrical equipment, surge protectors and voltage control devices are frequently used. These devices help in managing unexpected voltage spikes and fluctuations, ensuring the smooth functioning and longevity of the connected electrical systems.

6. **Flickers:**

   The term ”flickers” refers to abrupt, regular changes in voltage or light intensity that can be perceived by the human eye. They are frequently brought on by abrupt changes in electrical demand or voltage fluctuations in the power supply, like the starting or stopping of heavy equipment. Flickering can be especially troublesome in domestic lighting situations. It can also pose significant issues for delicate industrial processes. Both environments require stable illumination for comfort and safety. Voltage regulators and power quality solutions are employed to reduce flicker and ensure constant, stable voltage levels for reliable operation. These systems work together to maintain consistent voltage and improve the overall power quality of the electrical network.

7. **Voltage Unbalance:**

   When the three phases of a three-phase electrical system deviate from their optimal balanced state, voltage unbalance develops. This is evident when the three phases have different voltage magnitudes. They may also have varying phase angles. This imbalance may be caused by several things, such as uneven loads, defective connections, or an uneven allocation of power throughout the phases. Voltage imbalance can cause motors and other three-phase equipment to operate less efficiently and age down more quickly, which could lead to overheating and early breakdown. A stable and effective electrical system requires regular monitoring and remedial actions, such as balancing loads and fixing connection flaws.

8. **Electromagnetic Interference (EMI):**

   The phenomenon of unwanted electromagnetic waves interfering with an electronic system or device's ability to operate properly is known as electromagnetic interference (EMI). It happens when electromagnetic radiation from one source messes with the signals or functionality of nearby electrical or electronic equipment, leading to problems including signal degradation, data loss, or malfunction. To lessen the effects of EMI and preserve the integrity of sensitive electronic systems, mitigation techniques, including shielding and filtering, are used. EMI, arising from sources such as radio frequency emissions from devices like mobile phones and Wi-Fi routers, as well as power surges causing abrupt increases in electrical power, can disrupt the operation of sensitive electronic devices. Employing techniques such as shielding, grounding, and the use of filters or surge protectors effectively mitigates EMI's adverse effects on electronic systems.

9. **Radio-Frequency Interference (RFI):**

   The undesirable electromagnetic interference that radio frequency waves in the surroundings generate is known as radio-frequency interference (RFI). These interfering signals frequently come from a variety of sources, including radios, wireless devices, or electronic equipment. To reduce disturbances and guarantee the consistent operation of electronic equipment, RFI mitigation solutions like shielding, filtering, or frequency allocation laws are needed.

10. **Harmonics:**

    Harmonics are unwanted sinusoidal-shaped waves that have frequencies that are integer multiples of the basic frequency, mostly 50 or 60 Hertz. Non-linear loads such as computers, UPSs, VFDs, LED/CFL lighting, switch-mode power supplies, photocopiers, laser printers, battery chargers, welding machinery, arc furnaces, induction heaters, electric arc welders, and Electric vehicle charging devices produce these harmonics.

Out of all the problems, harmonic is thought to be the most problematic. Harmonics in an electrical system can have a variety of negative effects, including higher energy losses, interference with delicate electronics, and resonance issues. Harmonic currents cause resistive heating in wires and transformers, leading to increased energy losses that shorten the useful lives and efficacy of these types of equipment. Voltage distortion, another consequence of harmonics, compromises system dependability, reduces equipment health and disrupts operation. Moreover, harmonic resonance can happen, amplifying some harmonics and resulting in severe voltage variations as well as wrecking appliances.

1.2 Power Factor

The power factor (PF) measures how effectively electrical power is utilized in a system. The power factor in an AC circuit is determined by dividing the real power, which represents the actual energy consumed by the load, by the apparent power, calculated as the product of RMS voltage and RMS current. This ratio serves as a critical indicator of how efficiently electrical power is utilized within the system. A high power factor not only signifies optimal energy efficiency but also reduces losses and improves the overall stability of the electrical distribution network. It is therefore essential for maintaining the reliable and cost-effective operation of electrical systems.The formula for calculating power factor (PF) is:

$$\mathrm{PF} = \frac{I_{s1}}{I_s} \times \cos(\theta) \tag{1.1}$$

Where:

I_{s1} : This represents the RMS (Root Mean Square) value of the fundamental component of the current. In AC (alternating current) circuits, the current waveform can be decomposed into different frequency components, with the fundamental component being the one with the lowest frequency.
I_s : This represents the RMS value of the total current. It includes all frequency components present in the current waveform, not just the fundamental component.
θ : This represents the phase angle between the voltage and current waveforms. In an AC circuit, the voltage and current waveforms are typically not perfectly aligned due to the presence of inductive or capacitive elements in the circuit. The phase angle represents the time difference between the peaks of the voltage and current waveforms. It indicates the lead or lag relationship between these two signals.

The power factor formula is derived from the ratio of the RMS value of the fundamental current component to the RMS value of the total current. This ratio is then multiplied by the cosine of the phase angle between the voltage and current waveforms. Essentially, it quantifies how effectively a system converts electrical current into useful work. A higher power factor indicates more efficient use of electrical power, reducing wasted energy and improving overall system performance.

In practical terms, achieving a high power factor involves minimizing phase differences between voltage and current waveforms. This alignment ensures that the energy delivered by the power source is fully utilized by the load, without unnecessary losses or inefficiencies. Utilities and industries often aim to maintain a power factor close to unity (1.0), as it optimizes energy distribution and reduces operational costs associated with reactive power. Effective management of power factor not only enhances system efficiency but also supports sustainable energy practices by minimizing environmental impact through reduced energy consumption.

1.3 Techniques for Harmonics Mitigation

Following are some techniques that are applicable to reduce harmonics in power systems like Phase-Shifting Transformers, Line Reactors, Multi-Pulse Converters, Active Front-End Drives, Zigzag Autotransformers, Synchronous Condensers, and Power Filters. Among all the methods, power filter design emerges as a valuable approach for reducing harmonic distortion within power systems. Beyond its role in harmonic mitigation, this filter also serves to compensate for reactive power.

1.3.1 Power Filters

Power filters—which include active and passive harmonic filters—are preferred for harmonic mitigation because they can precisely target particular harmonic frequencies, adapt in real-time, maintain efficiency, call for little maintenance, offer scalability, and work with a variety of electrical devices. In addition to sustaining standards for power quality and reducing voltage drops, they offer an ongoing solution for harmonics reduction [4]. These filters play a crucial role in modern electrical systems, where maintaining high power quality is essential.

Active harmonic filters (AHFs), in particular, are highly regarded for their ability to dynamically monitor and compensate for harmonic distortions by injecting counteracting currents. The capability to adapt in real time ensures that the electrical system sustains efficiency and stability across a spectrum of load variations. This adaptability ensures a consistent and reliable operation by reducing the risks associated with equipment damage and energy losses. It plays a crucial role in maintaining system stability under varying conditions, contributing to enhanced resilience and prolonged operational lifespan. By effectively managing load fluctuations, the system can optimize performance and minimize downtime, supporting sustained efficiency over time.

Passive harmonic filters (PHFs) employ inductors, capacitors, and resistors to reduce harmonics, proving effective in environments characterized by stability and predictability. They are designed to maintain power quality by filtering out unwanted frequencies, ensuring reliable operation of electrical systems. Although they lack the adaptability of active harmonic filters (AHFs), their simplicity and lower cost make them appealing for many applications. Both AHFs and PHFs significantly reduce issues like overheating, equipment malfunction, and power inefficiency. The decision between these options is contingent upon specific system requirements and the varying nature of harmonic profiles. Integrating appropriate filters not only enhances the overall performance of electrical systems but also plays a crucial role in mitigating potential disruptions caused by harmonic distortions. This proactive approach not only improves operational efficiency but also reduces long-term maintenance costs associated with system downtime and component wear. Moreover, by ensuring compliance with stringent power quality standards, organizations can uphold reliability and consistency in their electrical operations. Implementing these measures reflects a commitment to sustainable and reliable electrical infrastructure, supporting seamless operations across diverse industrial and commercial applications.

1.3.1.1 Passive Filters

Passive filters use passive devices like resistors, capacitors, and inductors to create a frequency-dependent impedance that attenuates specific harmonics [5]. Passive filters are known for their simplicity and cost-effectiveness, making them accessible solutions for harmonic mitigation. However, their effectiveness diminishes when dealing with higher-order harmonics. They have the potential to introduce complications such as voltage drops, which could significantly impact the overall performance and reliability of the system.[6].

1.3.1.2 Active Filters

Active filters, on the other hand, use active electronic elements like transistors and operational amplifiers to actively produce compensating currents that cancel out harmonics in real-time [7]. Due to its ability to dynamically adapt to changing harmonic loads, active filters are now more effective, especially at reducing higher-order. Both active and passive elements make up an active filter. The primary objective of the APF is to eradicate the harmonics that are present in the power supply. Active power filters (APFs) come in two different varieties: shunt APFs and series APFs [8].

1. **Series Active Power Filter:**

   The Series Active Power Filter is a device used in power systems to mitigate voltage harmonic distortion and regulate voltage by injecting compensating currents into the system. Series active power filters are connected in series with the load or the grid. The main components of a series active power filter consist of a power electronic converter, often utilizing voltage source converter (VSC) technology, which actively compensates for harmonic currents and reactive power. This converter is intricately managed by a robust control system that monitors grid conditions and adjusts the filter's operation in real time. Together, these components ensure effective mitigation of power quality issues, enhancing the reliability and efficiency of electrical distribution systems. [9].

2. **Shunt Active Power Filter:**

   The shunt active power filter operation can be explained using Figure 1.1. As depicted in the figure, the fundamental current component is denoted by i_{Lf}, while the harmonic current is represented by i_{Lh}. To mitigate load current harmonics, the shunt active power filter injects a compensating current, denoted as i_F, at the point of common coupling (PCC). The compensating current is exactly equal in magnitude to the harmonic current i_{Lh}, yet it opposes it with a phase difference of 180 degrees. This phase relationship cancels out harmonic current, reducing its impact.

Shunt active power filters are linked in parallel with electrical equipment to balance the harmonic currents produced by nonlinear loads such as variable frequency drives, rectifiers, and other electronic devices [10]. The shunt active power filter is integral to maintaining power quality by continuously monitoring voltage and current waveforms at its connection point to the grid. This vigilance allows it to swiftly detect any harmonic distortions that could degrade electrical efficiency and equipment performance. Utilizing advanced algorithms, the filter analyzes these waveforms to accurately pinpoint the frequencies and amplitudes of harmonic components amidst the fundamental voltage or current. This analytical precision enables the filter to differentiate between essential power signals and unwanted harmonics, facilitating targeted corrective measures.

In response to detected harmonics, the shunt active power filter dynamically generates compensatory currents phased 180 degrees out of sync with the identified harmonics. By injecting these currents at the point of common coupling (PCC), the filter effectively neutralizes the harmonic distortions, ensuring that the total current entering the system closely resembles a pure sine wave. This proactive approach not only addresses power quality issues like voltage fluctuations and equipment overheating but also improves system reliability. The shunt active power filter's real-time monitoring, analysis, and mitigation of harmonic distortions highlight its crucial role in ensuring optimal power quality and operational stability in electrical networks. [11]. The shunt active power filter utilizes sophisticated control algorithms to analyze electrical waveforms and detect harmonics. By generating compensatory currents equal in magnitude but opposite in phase to the identified harmonics, the filter effectively cancels out these undesirable components from the electrical signal. This process ensures that the total current in the system closely resembles a pure sine wave, leading to reduced harmonic content and enhanced overall power quality. By effectively canceling out harmonic currents through phase opposition, it contributes to smoother operation and fewer disturbances in electrical networks. This enhancement promotes increased efficiency and reliability across diverse applications, ensuring more stable and predictable operation of electrical systems. By reducing harmonic distortions and optimizing power quality, it helps mitigate potential disruptions and equipment failures, thereby enhancing overall performance and longevity. Such improvements are crucial for maintaining consistent and reliable electrical supply in industrial, commercial, and residential settings alike [12].

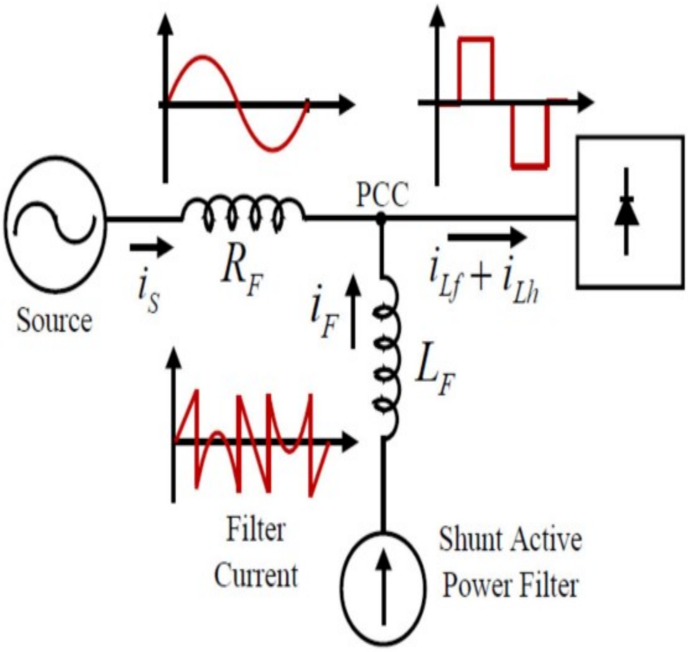


FIGURE 1.1: Basic Compensation Principle of SAPF [13]

1.4 Methodology of Shunt Active Filter

1.4.1 Reference Current Generation

To detect reference current, two techniques are employed. One involves using a time-domain technique that combines Instantaneous Reactive Power Theory (p-q Theory), Synchronous Reference Frame (d-q Transformation), Unit Vector Template Generation (UVTG), and Self Tuning Filters (STF). For a time-domain method, coordinate transformation is necessary. The second technique is the frequency-domain technique that uses the Discrete Fourier Transformation (DFT). In the section that follows, each technique will be described thoroughly.

1 Instantaneous Reactive Power Theory:

The instantaneous active and reactive power theory, sometimes referred to as the p-q theory, is based on instantaneous power calculations. Creating reference currents for the SAPF entails extracting the active and reactive parts of the load current [14]. The p-q theory effectively cancels out harmonic currents, making it suitable for applications where the load characteristics are mostly nonlinear. However, it could have problems when the supply voltages are uneven and distorted. The p-q Theory has some benefits for managing power quality, including its efficiency in reducing harmonic currents, ease of calculation, and adaptability for highly nonlinear loads. Although it can be negatively impacted by supply voltage imbalances, which are sensitive to it, its capacity to make up for imbalanced operating conditions is limited.

2 Synchronous Reference Frame (d-q Transformation):

The d-q theory, sometimes referred to as Park's transformation theory, is crucial in the field of electrical engineering because it provides a comprehensive method for addressing challenging issues in AC systems. The operation of the synchronous reference frame theory is illustrated in detail in the block diagram shown in Figure 1.2. The basic idea behind this theory is to transform a traditional three-phase AC system into a better controllable two-phase orthogonal reference frame, where the d-axis is purposefully aligned with important elements like rotor flux or the instantaneous power component and the q-axis remains orthogonal [15]. This method's capacity to precisely separate the active (actual) and reactive (imaginary) components of current and voltage is what gives it its transforming potential. By doing this, it makes it simpler to control and regulate the flow of power in AC systems. The d-q theory excels in handling unbalanced and distorted supply voltages, addressing issues that often challenge traditional three-phase analytical techniques. Its robust framework makes it particularly effective in these complex scenarios [16]. This theory helps in such circumstances by naturally controlling these complicated variables, making it especially suitable for applications where voltage quality is an issue. Furthermore, the d-q theory has gained popularity for its remarkable ability to handle harmonic deviations, which are common in contemporary electrical systems. Engineers and individuals can separate harmonic components using this innovative approach, making it easier to adopt cutting-edge techniques like active filtering and exact harmonic compensation. This is particularly valuable in situations where harmonics can cause equipment damage, efficiency losses, and problems with power quality. It is also crucial for power electronics applications including motor drives, renewable energy sources, and voltage source inverters, where it helps with accurate and efficient power conversion. In conclusion, the d-q theory stands as an essential tool for streamlining analysis, optimizing control, and ensuring reliable performance in a variety of AC systems and applications because of its transformative powers.

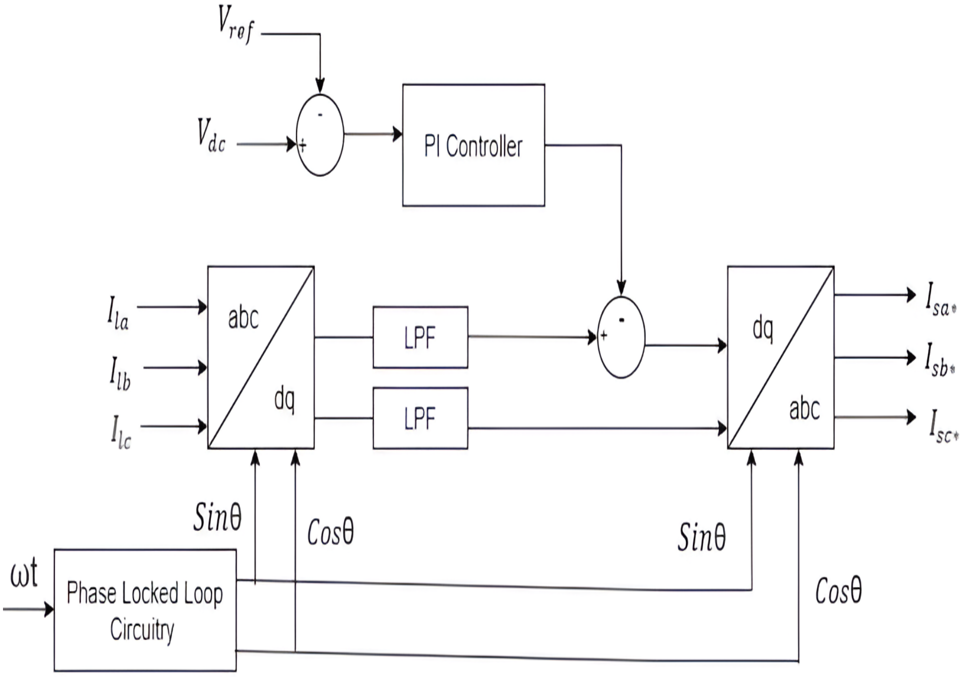


FIGURE 1.2: Synchronous Reference Frame Theory - Block Diagram [17]

3 Unit Vector Template Generation (UVTG)

In the fields of mathematics and physics, unit vector template generation is a key idea because it provides a methodical way to produce vectors with a precise magnitude of one. This procedure acts as the fundamental building block for specifying reference axes or creating a foundation in various mathematical domains [18]. Creating unit vectors often includes taking an existing vector, normalizing it by dividing it by its magnitude, and then creating a new vector with a set length of one unit that still points in the same direction. When it comes to defining vector spaces, transformations, and inner products, this standardized unit vector becomes a basic tool in linear algebra. Unit vectors are essential in physics and engineering in general for precisely expressing directions and orientations in various coordinate systems, including more specialized ones like spherical or cylindrical coordinates. Unit vector template generation serves as a fundamental building block for mathematical modeling, simulations, and problem-solving, and it is used in a wide range of scientific and engineering fields, including computer graphics and celestial navigation, where accuracy in direction and orientation is crucial.

4 Self Tuning Filters (STF):

Self-tuning filters (STF) are a group of adaptive signal processing methods that have been widely used in several fields, such as telecommunications, control systems, and digital signal processing. When the properties of the input signal change, these filters are built to automatically modify their filter coefficients or settings. They can successfully track and filter out undesirable noise, interference, or disturbances while keeping the desired signal components thanks to their versatility. STFs use complex algorithms, frequently built on ideas from adaptive signal processing, to continuously improve their filter settings, assuring the best performance under changing circumstances. Enhancing the robustness and adaptability of systems in real time is one of the main benefits of self-tuning filters. They perform well in conditions where the statistical characteristics of the input signal are vulnerable to unanticipated changes over time. STFs are used for a variety of things, including enhancing the voice and data transmission quality in communication systems and stabilizing industrial process control systems. Additionally, they are used in industries like biomedical signal processing, where precise and adaptive noise reduction is essential for deciphering physiological signals and obtaining valuable information. The fundamental idea behind self-tuning filters is to continuously monitor the input and, through repeated changes, modify the filter coefficients or parameters to reduce the difference between the desired signal and the filtered output. The least mean squares (LMS) and recursive least squares (RLS) algorithms are frequently employed for this purpose. STFs can continuously adapt to changing conditions thanks to these algorithms, which makes them indispensable tools in applications where signal quality and dependability are crucial. In conclusion, self-tuning filters ensure optimal performance in complex and constantly changing contexts by acting as a dynamic and flexible solution for signal amplification and noise reduction.

5 Discrete Fourier Transform (DFT)

The Discrete Fourier Transform (DFT) is an essential computational tool in the realm of signal processing, employed for evaluating and comprehending the frequency components of discrete-time signals or sequences [19]. A finite series of evenly spaced samples of a time-domain signal is transformed into the equivalent frequency-domain representation to make the algorithm function. Through the use of this transformation, we can separate the original signal into a collection of sinusoidal functions, each of which has a distinct frequency-dependent amplitude and phase. The Discrete Fourier Transform (DFT) is a cornerstone of signal processing across a multitude of industries. In audio processing, it enables detailed analysis and manipulation of audio signals, facilitating tasks such as filtering, equalization, and compression. By transforming signals from the time domain to the frequency domain, the DFT provides a comprehensive view of signal spectra, essential for optimizing sound quality in music production, broadcasting, and digital media streaming. In picture processing and digital image analysis, the DFT is indispensable for extracting spatial frequency information from images. This capability supports applications ranging from image enhancement and compression to pattern recognition and feature extraction. The DFT effectively decomposes images into frequency components, offering critical insights into intricate details such as image textures, edges, and structural characteristics. These insights play a pivotal role in fields such as medical imaging, satellite imagery analysis, and advancing computer vision technologies. Telecommunications heavily rely on the DFT for tasks such as spectrum analysis, channel equalization, and modulation techniques.

1.4.2 Reference Current Injection

In shunt active power filters, various techniques are employed for reference current injection, including Hysteresis Current Control, One Cycle Control, Repetitive Control, Delta Modulation Control, ANN Control, Fuzzy Logic Control, and Deadbeat Control. In the section that follows, each technique will be described thoroughly.

1 **Hysteresis Current Control:**

Hysteresis current control is a popular technique due to its simplicity and fast response. It operates by comparing the actual current with a predefined reference hysteresis band. When the actual current deviates from the reference, the control action is triggered to bring it back within the hysteresis band [20]. This control strategy ensures that the current tracking error remains bounded within the hysteresis band. However, it can lead to high-frequency switching of the power semiconductor devices, which may result in increased switching losses and electromagnetic interference.

2 **One Cycle Control:**

One Cycle Control (OCC) is a modulation technique that synchronizes the switching of the power converter with the fundamental cycle of the grid voltage. Unlike traditional PWM techniques, which operate with fixed switching frequencies, OCC ensures that each cycle of the grid voltage is fully utilized for control purposes. Optimized Commutation Control (OCC) achieves minimized harmonic distortion and improved system efficiency by continuously adapting switching instances according to real-time grid voltage conditions. This dynamic adjustment ensures optimal performance of power electronic converters in mitigating harmonic disturbances.

3 Repetitive Control:

Repetitive control is particularly effective for mitigating periodic disturbances or harmonics in power systems. It exploits the periodicity of the grid voltage waveform by generating a control signal that repeats with the same frequency as the disturbance. Through repetitive learning mechanisms, the control algorithm continuously adjusts the output to cancel out the periodic disturbances, thereby achieving improved harmonic compensation.

4 Delta Modulation Control:

Delta modulation control is a type of pulse width modulation (PWM) technique that regulates the output voltage or current by comparing the error between the reference and actual signals. It adjusts the PWM pulse width based on the magnitude and direction of the error signal, aiming to minimize the error over time [21]. Delta modulation control offers advantages such as simplicity, low computational complexity, and fast response, making it suitable for real-time applications.

5 ANN Control (Artificial Neural Network Control):

Artificial Neural Network (ANN) control utilizes neural network models to adaptively adjust the control signals based on input-output mappings learned during the training phase. ANN-based controllers can handle complex and nonlinear relationships between system variables, making them suitable for shunt active power filters operating under varying conditions. By learning from historical data and online measurements, ANN controllers can provide robust and adaptive performance.

6 Fuzzy Logic Control:

Fuzzy logic control employs linguistic variables and fuzzy rules to emulate human-like decision-making processes. Unlike conventional control strategies that rely on precise mathematical models, fuzzy logic control incorporates expert knowledge into the control algorithm through fuzzy rules and membership functions. This allows the controller to handle uncertainties, imprecisions, and nonlinearities in the system effectively. Fuzzy logic control is particularly suitable for shunt active power filters operating in dynamic and uncertain environments.

7 Deadbeat Control:

Deadbeat control is a model-based control strategy that aims to achieve zero steady-state error within a finite number of control steps. It calculates the control input required to drive the system to the desired state in the shortest possible time, ensuring rapid response and precise tracking of the reference signal. Deadbeat control is well-suited for applications where fast transient response and accurate tracking are essential, such as shunt active power filters used for harmonic compensation and power quality improvement.

8 Sinusoidal Pulse Width Modulation (SPWM):

SPWM is a sophisticated technique used in power electronics to efficiently control the voltage or current delivered to loads such as motors or heaters. Unlike traditional PWM methods, which utilize rectangular waveforms, SPWM generates pulses with a sinusoidal shape. This approach minimizes harmonic distortion and reduces electromagnetic interference, leading to smoother output waveforms and improved efficiency. By varying the width of these sinusoidal pulses in proportion to the desired output, SPWM enables precise control over the power delivered to the load, making it an essential tool in applications requiring high-performance voltage or current regulation.

Chapter 2

Literature Review

To gain a deeper comprehension of the research conducted on the topic of Active Power Filters, a comprehensive review of the literature has been conducted in this chapter. This chapter will provide an in-depth awareness of the development, difficulties, and advancements in shunt active power filter technology by analyzing the information and research that currently exists in this area. The creation of the reference current and the injection of current via a voltage source inverter are the two primary components of SAPF. The methods created thus far for the creation of reference compensating current are examined in the first section of the literature study, and the methods created for the synthesis of VSI gate pulses are discussed in the second.

2.1 Reference Current Generation

In [22], Anand Panchbhai, Nikunj Prajapati, and Shreya Parmar proposed a three-phase SAPF. The simulation results show that without SAPF, the THD was very high; however, with SAPF, the THD is minimized and falls within the IEEE guidelines. In this study, two distinct control strategies are used, and both produce better outcomes according to IEEE standards. Both techniques were compared using factors such as reactive power, Total Harmonic Distortion (THD), and power factor. It is also seen that the system's transient behavior has improved. THD was reduced from 30.39% to 0.91% for Instantaneous Reactive Power theory and from 30.39% to 0.90% for Synchronous Reference Frame theory. After SAPF is involved, even the reactive power supplied by the source is compensated. The power factor value is likewise examined for both conditions, and the obtained findings are also satisfactory.

Sagar S. Patil and R. A. Metri suggested a control mechanism for a shunt active filter to eliminate the current harmonic generated by non-linear loads in [23]. The instantaneous reactive (pq) theory is utilized to generate the reference current, and a hysteresis current controller is used to inject the reference current, which is implemented in Simulink and proven through simulation. THD was measured with and without the shunt active filter (SAF) connected. THD without the filter is 36.98 % and 1.31 % for the first non-linear load. Similarly, THD for the second non-linear load decreased from 25.24 % to 0.81 %.

Kilic et al. generated the reference current for a three-phase-active power filter using a predictive filtering technique [24]. He applied the suggested method using a DSP controller. A cascade of digital Chebyshev low-pass filters and digital predictive filters was part of the suggested filtering topology. The predictive filter was utilized to eliminate the time delay introduced by the low pass filter, and the Chebyshev low pass filter was employed to retrieve the fundamental harmonic from the distorted load current waveform. Even with significant amplitude and frequency fluctuations, the predictive filtering structure performed well in extracting the reference current from severely distorted signals without phase shift.

Akkaya recommended a sine function multiplication technique for the extraction of the reference current [25]. In terms of computing time, this technique performed better than the others. To retrieve the reference filter current, Akkaya suggested modifying the sine function multiplication approach in [26]. The addition of a voltage controller made the alteration possible and produced a rapid response time.

Kanjiya and Khadkikar proposed a non-iterative optimization approach for controlling the SAPF [27]. Without using any iterative optimization techniques, the suggested approach generated the reference current by directly calculating the control variables. For the injection of reference current a hysteresis controller was utilized. THD of the source current decreased from 23.5% to 1.4% using the suggested method as compared to 5.19% of the existing method. The response time of the proposed work was 35 μs, while the previous method was 35.3ms.

For the reference current generation, Kadivar employed the Unit Vector Template Generation approach in [28]. Using this method, he obtained the unit vector template signal by multiplying a gain factor by the input source voltages. The peak value of the reference current was determined by regulating the DC bus capacitor voltage of the inverter. The error signal was processed by a PI controller by comparing the voltage of the capacitor with the reference value. The total harmonics distortion of the source current dropped from 30.74% to 7.35%.

In [29] Panigrahi and Subudhi suggested a Kalman filter (KF) based H infinity control strategy for a three-phase SAPF. Kalman filter was used for quick calculation of positive sequence current from the fundamental component of supply current, which produces the reference current by performing signal processing. The H infinity robust controller was utilized for reference current injection. When the experimental findings were compared to those of the PI controller, THD decreased from 25.9% to 2.2%, compared to 3% for the PI controller. The suggested control technique demonstrated superior steady-state and adaptive stability against supply variations in loads.

Shabeer et al developed a shunt active power filter using the PI controller and the Hysteresis current controller (HCC) in the control block [30]. Using a PI controller, the reference current was calculated from the measured DC bus voltage. The Hysteresis Controller was employed to create the gate pulses for the VSI. By applying these templates to generate the reference currents, engineers can effectively mitigate harmonics and achieve smoother operation of the VSI, reducing total harmonic distortion (THD) and enhancing overall power quality. For reference current generation, they employed the unit vector template generation technique. Following compensation using these advanced control techniques, the source current's THD significantly improves, dropping from a highly distorted

17.37% to a much lower 2.90%. This reduction underscores the effectiveness of employing precise control strategies like PI controllers, Hysteresis Controllers, and unit vector template generation in modern power electronic systems. These methods ensure high power quality and improve the reliability, efficiency, and durability of electrical systems in both industrial and commercial settings.

Kadivar used the unit vector template generation technique (UVTG), instantaneous PQ theory, and d-q reference frame theory to calculate the reference compensating current in [31]. The UVTG algorithm performed better under a balanced mains voltage, but it was unable to produce a balanced current when the mains voltage was unbalanced. A satisfactory sinusoidal current was supplied by the instantaneous PQ theory. Under unbalanced supply voltages, the synchronous reference frame approach performed exceptionally well. A total harmonic distortion of 30.17% was present in the load current, which included notable 5th and 7th-order harmonics. The THD was lowered to 2.61% by employing the UVTG approach for harmonics compensation.

Four reference current extraction procedures were put into practice by Topiwala and Mehta [32] which were Perfect Harmonic Cancellation (PHC), Synchronous Reference Frame (d-q), Unity Power Factor (UPF), and Instantaneous Reactive Power Theory (p-q). It was found that all approaches functioned well for an unbalanced load and an ideal source. The transient analysis revealed that the PHC approach responded slowly, while the UPF method responded quickly.

Dian et al. suggested in [33] a three-phase three-wire shunt active power filter with a main circuit based on an H bridge three-level converter and a dc-link voltage control technique focused on the negative sequence current control approach. A unique harmonic detection approach operating in dual d-q axes was presented for reference current generation. This innovative method aims to accurately detect and mitigate harmonic currents by analyzing signals in both d-axis (direct axis) and q-axis (quadrature axis) coordinates. By utilizing dual d-q axes, the approach enhances the precision of harmonic detection and effectively reduces variations in the DC-link voltage caused by negative sequence fundamental components. Maintaining stable operation and minimizing disturbances in power electronic systems is essential to uphold reliable performance and maximize efficiency. This capability ensures consistent functionality across various operational conditions, safeguarding against disruptions and optimizing energy utilization.

Choudary et al. [34] also explored various methods for generating reference currents based on their study of harmonic detection techniques. They evaluated these methods to assess their effectiveness in improving system performance and mitigating harmonic distortions. By comparing and analyzing different approaches, they aimed to optimize the generation of reference currents to achieve optimal operation and enhanced power quality in electrical systems. These efforts underscore the ongoing advancements in control strategies aimed at addressing harmonic issues and ensuring reliable operation across industrial and commercial applications. These methods included Perfect Harmonic Cancellation (PHC), Predictive filtering method (PFM), Instantaneous Reactive Power Theory (p-q), Synchronous Reference Frame (d-q), Unity Power Factor (UPF), and Self Tuning Filter (STF). After calculating the Total Harmonic Distortion (THD) for each strategy, they evaluated how well they performed and discovered that the PHC method was quite successful in lowering the THD.

Sathyan and Chacko employed Artificial Neural Network (ANN) and Synchronous Reference Frame (SRF) as their two methods for generating reference current [35]. They were controlling the voltage source converter of the distribution static compensator (DSTATCOM). It was found that the ANN control technique outperformed SRF in terms of implementation, lowering THD and response time. The simulation results revealed that the SRF technique minimized the %THD of the source current from 27.39% to 1.42% and by employing ANN, the THD of the source current was decreased to 0.42%.

Akagi proposed a theory called Instantaneous Reactive Power theory (i.e., p-q theory) for calculating reference currents for Active Power Filters. Researchers established additional approaches that utilized this theory [36], [37]. Williams' study on p-q theory revealed that it is successful in three-phase systems with no zero-sequence component [38]. However, he highlighted that the theory becomes more complex due to the need for coordinate transformations and the challenges in managing reactive power components under non-ideal conditions. These complexities stem from factors such as varying load conditions, harmonic distortions, and the interaction between different components within the power system.

Srivastava and Tiwari in [39] utilized the Instantaneous Reactive Power theory (p-q theory) to develop reference currents for Active Power Filters (APFs). This theory, known for its ability to dynamically compute reactive power components in real time, played a crucial role in their study aimed at improving power quality. By implementing an APF based on p-q theory, they achieved a remarkable reduction in the Total Harmonic Distortion (THD) of the source current. Specifically, THD dropped to a minimal 0.90% during operation with the APF, highlighting its effectiveness in mitigating harmonic distortions compared to an initial simulation without the APF, where THD was significantly higher at 30.28%.

Leonardo et al suggested alternate and adaptable techniques for the compensation of sequence components (negative, zero, or both) associated with utility currents utilizing SRF-based Controllers in [40]. The zero and negative fundamental sequence components of current were not taken into consideration in the prior work, which only corrected for the load's harmonics and reactive power. The synchronous reference frame (SRF) approach was utilized to create a reference current, and the PI controller was employed to generate the inverter's gate pulses. THD of the source current dropped to 3.66% from 25%.

To construct a three-phase shunt active power, Panigrahi et al. [41] introduced a new reference current estimation approach that combined the model predictive current (MPC) control strategy with the resilient extended complex Kalman filter (RECKF). Predictive control was utilized to inject the reference current model, and the reference current was produced using RECKF. The proposed RECKF-MPC-based SAPF system was compared with PI-MPC in a steady state as well as a transient state. In a steady state, the THD of the source current decreased from 24.9% to 4.46% in comparison with 4.65% for PI-MPC. In the transient state, THD was 4.67% for the proposed technique and 5.32% for existing methods respectively. The flexibility and resilience issues with the fixed-gain PI controller are resolved by the suggested work.

Based on the literature review, Table 2.1 presents an overview of various current generation techniques along with their respective Total Harmonic Reduction (THD) ranges, advantages, and disadvantages.

TABLE 2.1: Reference Current Generation Techniques

Current Generation Techniques	**Total Harmonic Reduction (THD)**	**Advantages**	**Disadvantages**
Instantaneous Reactive Power Theory	0.5% to 2%	Effective in mitigating harmonics for nonlinear loads.	Sensitive to voltage imbalances.
Synchronous Reference Frame (d-q)	1% to 5 %	Robust Compensation under unbalanced and distorted conditions.	Complex mathematical transformations.
Unit Vector Template Generation (UVTG)	1 % to 5%	Precise tracking of reference current waveforms.	Requires accurate knowledge of system parameters.
Self Tuning Filter (STF)	5% to 10%	Adaptive control for varying load conditions.	Complexity in tuning and implementation.
Discrete Fourier Transform	1% to 10%	Provides accurate harmonic analysis.	Limited real-time compensation capability.

2.2 Reference Current Injection

Belonkar and Salodkar proposed two alternative switching signal-generating techniques: Hysteresis Current Control (HCC) and Sinusoidal Pulse Width Modulation (SPWM). HCC utilizes hysteresis bands to generate switching signals based on instantaneous signal comparisons, emphasizing simplicity and rapid response. On the other hand, SPWM synthesizes switching signals using sinusoidal waveforms to achieve precise control over output voltages and harmonic content. [42] In HCC (Hysteresis Current Control), a closed-loop system compares error signals to generate switching signals, ensuring precise current regulation in power electronic systems. Before the compensation, the source current's THD value was 29.85%; however, by utilizing the hysteresis controller, THD was just 2.84%. The triangle wave served as the carrier and the pure sine wave as the reference in sinusoidal PWM. The strategy was a linear control technique that eliminated ripples in the error signal and lower-order frequency using the PI controller. The SPWM approach was used to lower the THD to 2.17%. The following factors were used to analyze performance: %THD, complexity, switching frequency, RMS vector error, and response time.

Patel et al devised a one-cycle control (OCC) approach for controlling inverter gate pulses [43]. One cycle control was easy to deploy, reliable, and offered an immediate response time. Because of these advantages, one-cycle control (OCC) performed exceptionally well. The simulation results demonstrated that employing a single-cycle control strategy resulted in a sinusoidal output current with lower THD. The power factor has also been increased.

Tarisciotti et al. proposed a Modulated Model Predictive Control, a variation to the classical Model Predictive Control algorithm, and its application to active power filters [44]. Model Predictive Control (MPC)'s larger current ripple was significantly decreased by implementing a cost function-based modulation technique without affecting dynamic performance. The proposed controller was demonstrated to be a practical and effective solution for the control of active power compensators, allowing different system variables to be regulated with a single control loop and without the use of grid synchronization devices.

Al-Ogaili et al developed a novel current injection method for active power filters in [45]. This technique was meant to produce better outcomes for high-power applications and simpler circuitry. A current injection network and a current injection device were used to implement this method. Two IGBT Transistors were used in the Current Injection Network. THD was reduced from 32% to 5.5% utilizing this strategy.

Hornik and Zhong implemented a current control approach for switching signal production based on $\mathcal{H}_\infty$ and Repetitive control[46]. This technique effectively manages a broad spectrum of harmonic frequencies simultaneously, addressing multiple harmonics concurrently. It is designed to handle diverse harmonic challenges in electrical systems with comprehensive efficiency. A comparison of different controllers, including the suggested controller, was done, and it was decided that the proposed controller was good at minimizing THD but had the slowest reaction of all.

Acuna et al used a predictive control technique to create an active power filter with a four-leg voltage-source inverter in [47]. A four-leg voltage-source inverter was utilized to compensate for current harmonic components along with unbalanced current produced by single-phase nonlinear loads. Signal processing was carried out using the synchronous reference frame (d-q) technique for reference current generation. For the injection of the reference current, a predictive control method was employed. THD dropped from 27.09% to 4.54% in the experimental data, and the proposed approach had a response time of two cycles. The suggested controller turned out to be a viable alternative to traditional linear control methods.

Bandal and Madurwar [48] used two alternative current control approaches for switching signal generation. The initial technique employed Proportional Integral control to create gate pulses by comparing the current error to a predefined tolerance band. In the second method, they employed the sliding mode control (SMC) approach. THD before compensation was 40.38%. THD decreased to 3.4% after using the PI controller, and 0.91% after employing the SMC. Sliding mode control (SMC) outperformed Proportional Integral control based on total harmonic distortion (THD) and load current balance.

Sreeraj E. S et al suggested a one-cycle control (OCC) shunt harmonic filter capable of correcting only the harmonic components of the load current [49]. By correlating the actual wave to a reference sine wave, the reference current was determined. For the current injection, the Optimal Control Current (OCC) approach was employed. This technique, notable for its absence of phase-locked loops, ensures rapid response times while maintaining a constant switching frequency. By avoiding the complexities associated with phase-locked loops, the OCC (Online Current Control) approach simplifies implementation and enhances the stability of current injection processes in power electronic systems. The method achieves robust performance by directly controlling current, eliminating complex synchronization mechanisms. This ensures reliable operation in diverse conditions and reduces overall system complexity.

Xiao et al suggested a unique control technique for a shunt active power filter (SAPF) in [50], combining adaptive PI control and a dual-repetitive controller (DRC). The predictive harmonic detection approach was developed for the generation of reference current and for injection purposes a blend of adaptive PI control and DRC was employed. The outcomes were compared to the standard single repetitive controller (SRC). SRC reduced THD from 28.74% to 8.93%, whereas the suggested technique produced a THD of 4.62%. When the response times for both strategies were examined, the SRC-based APF took 20.02ms and 29.83ms to turn on and off, in contrast to 5.81ms and 9.81ms for the suggested method.

Zahira et al employed sinusoidal pulse width modulation (SPWM) to generate gate pulses for the inverter in [51]. Because of the constant switching frequency, this approach was used to control the VSI. The SPWM approach performed well in terms of minimizing switching losses and Total Harmonic Distortion. THD of the system without APF was 24.70%, however after applying the SPWM controls approach, THD was reduced to 2.54%.

Swain and Ray presented a sliding mode controller (SMC-2) as a modern control approach for minimizing chattering in classical sliding mode controllers in [52]. The synchronous reference frame (d-q) approach was utilized to generate reference current. The suggested controller was compared to an existing approach that employed instantaneous reactive power theory as a reference generating process and an ideal sliding mode controller with carrier-based PWM (CBPWM) for current injection. In a steady state, the suggested controller reduced THD from 20.14% to 1.62%, compared to 4.16% for the previous technique. The suggested controller reduced the THD of source current from 26.7% to 2.16% during transient load conditions, outperforming the previous technique which achieved 3.25% THD. This enhancement showcases superior harmonic mitigation capabilities, ensuring consistent clean power delivery even under varying load conditions. It underscores robust performance in maintaining stable electrical operation across dynamic scenarios. It ensures robust performance across varying operational states, ensuring stable and efficient electrical operation.

Sarasvathi et al employed two control techniques, PI Control and Fuzzy Logic Control (FLC), to enhance the effectiveness of shunt active power filters [53]. Total Harmonic Distortion (THD) and power factor were employed as performance measures. For decision-making in FLC, the two parameters error and change in error were used. This superiority underscores the fuzzy logic controller's effectiveness in dynamically adapting to different load conditions and optimizing harmonic mitigation in power electronic systems. THD dropped from 31.57% to 0.72% using a fuzzy logic controller, and a power factor of 0.9708 was achieved.

Munazama Ali et al. [54] examined the effectiveness of two alternative current control approaches. One approach was the PI controller and the other approach was the ANN controller. Without the active filter, the Total Harmonic Distortion (THD) of the source current measured 18.79%. The source current THD dropped to 3.06% when SAPF was implemented with a PI controller, and 2.39% when SAPF was implemented with an ANN controller. Both controllers mitigated harmonics, however, the ANN controller outperformed the PI controller significantly.

Hao Yi et al suggested a new control strategy for source current detection that utilized a vector resonant controller [55]. They compared the suggested approach to traditional source current detection control techniques such as the Current-Source-based (CS) and Power-Balance-based (PB) schemes. The actual current was compared to the reference sine wave to generate the reference current and a vector resonant controller was used for the current injection. The THD of the source current decreased from 28% to 8.4% using the CS scheme, 3.5% using the PB system, and 2.9% by implementing the suggested approach. The suggested approach retains the benefits of existing schemes while minimizing their drawbacks, resulting in consistent and transient performance.

Narongrit et al [56] compared the outcomes of three shunt active power filter current control strategies. Hysteresis current control, delta modulation control

(DMC), and carrier-based PWM control were the three strategies employed. Based on simulation findings, the carrier-based PWM control strategy demonstrated a substantial reduction in THD compared to other methodologies. This highlights its effectiveness in improving power quality by minimizing harmonic distortion.

Parthasarathy et al suggested a new current injection methodology [57] that provided improved harmonic filtering performance while using a Boost Converter to significantly minimize THD. A three-phase regulated converter was used as a harmonic source in the suggested method. To manage the injection current, the duty ratio of the boost converter was changed. The size of the injection current was determined by the DC link voltage to decrease the harmonic currents.

Yadav et al [58] presented a sinusoidal current control approach for the Shunt Active Power Filter. The simulations were carried out with both balanced and unbalanced source voltages. The proposed technique performed admirably under both situations of source voltage. The source current's Total Harmonic Distortion (THD) was reduced from 18.85% to 3.65%, while the power factor increased from 0.7 to 0.98.

Tamilarasi and Suganthini described a neural network-based technique for generating switching signals for voltage source inverters [59]. The neural network was trained in the first stage to generate switching angles and patterns for various modulation index values. The simulation results demonstrated that the switching signals generated by the neural network were capable of eliminating all lower-order harmonics. THD decreased from 28.63% to 1.48% utilizing this strategy.

Table 2.2: Current Injection Techniques

Control Method	**Constructional Complexity**	**Speed of Response**
Hysteresis Current Control	Straightforward	$10\,\mu s \rightarrow 1\,ms$
One Cycle Control	Straightforward	$1\,ms \rightarrow 10\,ms$
Repetitive Control	Straightforward	$5\,ms \rightarrow 15\,ms$
Delta Modulation Control	Straightforward	$100\,\mu s \rightarrow 10\,ms$
SPWM	Intermediate	$1\,ms \rightarrow 10\,ms$
ANN Control	Intermediate	$100\,\mu s \rightarrow 1\,ms$
Fuzzy Logic Control	Intermediate	$1\,ms \rightarrow 10\,ms$
Deadbeat Control	Complex	$10\,\mu s \rightarrow 5\,ms$

Based on the literature review, Table 2.2 provides an overview of different current control techniques, detailing their computational complexities and speed of response. This comparison aids in understanding their practical applicability in power electronic systems.

2.3 Critical Analysis

2.3.1 Reference Current Generation

After conducting a literature review on various current generation techniques for harmonic reduction, we found distinct advantages and disadvantages associated with each method. Instantaneous Reactive Power Theory emerged as the most promising approach, offering a Total Harmonic Distortion (THD) ranging from 0.5% to 2%. Its effectiveness in mitigating harmonics for nonlinear loads was highlighted, despite being sensitive to voltage imbalances. Instantaneous Reactive Power Theory requires less computation, shortening the control process. This efficiency enhances overall system performance. This attribute, coupled with its ability to efficiently handle harmonics, led us to choose this method for our adopted model. Other techniques, such as Synchronous Reference Frame (d-q), Unit Vector Template Generation (UVTG), Self Tuning Filter (STF), and Discrete Fourier Transform, while offering their own advantages, exhibited either complexities in implementation, sensitivity to system parameters, or limitations in real-time compensation capability compared to Instantaneous Reactive Power Theory. Therefore, considering our system requirements and the findings of the literature review, Instantaneous Reactive Power Theory emerged as the optimal choice for harmonic mitigation in our adopted model.

2.3.2 Reference Current Injection:

The literature review encompasses an extensive exploration of various reference current injection techniques and it is concluded that. Hysteresis Current Control

(HCC) emerges as a particularly noteworthy technique due to its straightforward computational complexity and impressive speed of response ranging from 10 microseconds to 1 millisecond. This simplicity in computational requirements facilitates rapid execution, making it highly suitable for applications demanding quick response times. In contrast, other techniques such as Deadbeat Control exhibit greater complexity, albeit with faster response times, but not necessarily superior to HCC. Furthermore, while techniques like ANN Control and Fuzzy Logic Control offer intermediate computational complexity and response speeds, they do not consistently outperform HCC in terms of simplicity and speed.

2.4 Problem Statement

Increasing levels of nonlinear loads in power systems lead to excessive harmonic distortion and reactive power issues. To address these power quality problems efficiently, Shunt Active Power Filter (SAPF) is implemented using the instantaneous reactive power theory for the reference current generation and a hysteresis current controller for current injection.

Chapter 3

Reference Current Generation

In Shunt Active Power Filters (SAPF), the generation of reference currents plays a crucial role in achieving effective harmonic mitigation and reactive power compensation. Through a meticulous literature review, various methods for reference current generation have been explored. Among these techniques, Instantaneous Reactive Power Theory (IRPT) has emerged as a preferred approach due to its capability to accurately estimate instantaneous reactive power components and thus generate reference currents that align with the compensation requirements of the system. Consequently, based on our comprehensive literature review, IRPT has been selected as the method of choice for reference current generation in our SAPF implementation.

3.1 Instanteous Reactive Power Theory

This Theory is commonly known as the instantaneous real and imaginary power theory, is a fundamental idea in electrical power management. The detailed operation and principles of the Instantaneous Reactive Power Theory can be better understood concerning the block diagram provided in Figure 3.1. It assists with challenges such as minimizing undesired signals called harmonics, balancing reactive power, and managing power flow in transmission lines. This theory uses the 0-α-β coordinate transformation. This transformation transforms complicated three-phase currents or voltages into less complex 0-α-β coordinates, commonly referred to as a Clarke transformation.

The transformation proves beneficial because it isolates specific components, known as zero sequence components. Using the α and β axes simplifies the analysis by eliminating the complexity for a-b-c coordinates. This transformation allows us to define power with greater clarity in this new coordinate system. The use of this transformation has the significant advantage of simplifying power management. It additionally makes it simpler to analyze and control things like harmonics, reactive power, and how power flows through lines.

This transformation has applications beyond standard power management. It also aids in emerging areas such as integrating renewable energy sources and designing smarter electrical systems. Utilizing the insights obtained from this transformation, engineers and scientists may discover enhanced methods to generate, distribute, and use electricity. This advancement can lead to the development of more efficient power generation technologies, optimized distribution networks, and smarter consumption practices. Ultimately, these improvements ensure that our electrical grids become more reliable, effective, and resilient in meeting future energy demands.

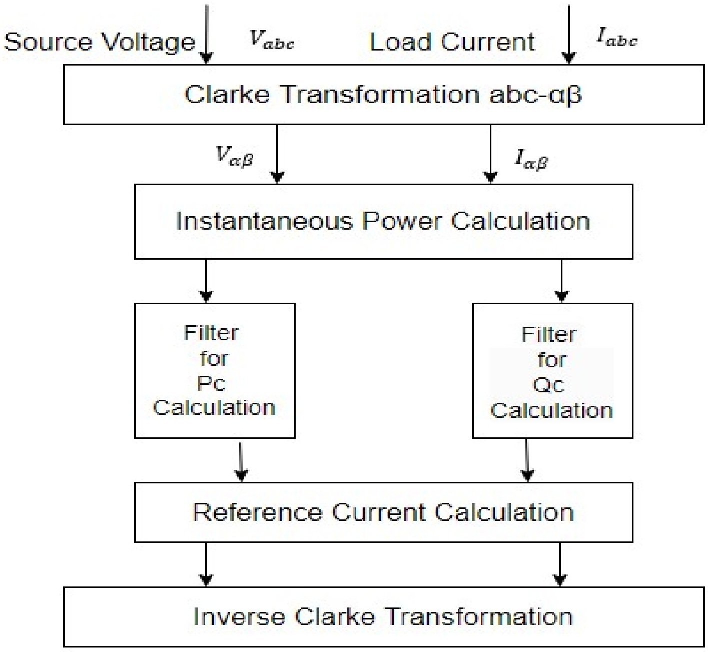


FIGURE 3.1: Block Diagram of pq theory [60]

3.1.1 Clark Transformation

To convert instantaneous voltage from the *a*-*b*-*c* coordinate system (v_a, v_b, v_c) to the 0-α-β coordinate system (v_0, v_α, v_β), we use a transformation matrix. This transformation allows us to simplify the analysis and control of three-phase systems. The matrix form for this transformation is as follows:

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

The 0-α-β coordinate system isolates the zero-sequence component, as the α-β axes do not contribute to this aspect of the voltage. Thus, the zero-sequence component may be eliminated from the above transformation matrix. As a result, the matrix can be modified as follows:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

This modification reflects the exclusion of the zero-sequence component from the transformation, aligning with the objective of the 0-α-β coordinate system to focus solely on the α and β components of the voltage.

Similarly, the transformation matrix of three-phase instantaneous line current from the *a*-*b*-*c* coordinate system (i_a, i_b, i_c) to the 0-α-β coordinate system (i_0, i_α, i_β) is as follows:

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

And by eliminating the zero-sequence component, the above matrix can be expressed as:

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

In an orthogonal coordinate system, the phases are oriented in such a way that they are independent of one another, enabling us to simply determine the power without looking at complex interactions among phases. Because the 3-phase coordinate system (a-b-c) is mutually orthogonal, we can calculate instantaneous power by multiplying the instantaneous currents by the corresponding instantaneous voltages and adding them together. The power in the a-b-c coordinate system is as follows:

In the a-b-c coordinate system, the power is expressed as:

$$P = v_a i_a + v_b i_b + v_c i_c \tag{3.1}$$

While in the 0-α-β coordinate system, the transformation simplifies the computation by removing the zero-sequence component and expressing the power in terms of two orthogonal components (α and β): The power in the 0-α-β coordinate system is expressed as:

$$[P = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0] \tag{3.2}$$

Or

$$P = v_\alpha i_\alpha + v_\beta i_\beta$$

The instantaneous active and reactive power in matrix form may be represented by the following equation:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

When dealing with nonlinear loads, we must split the instantaneous active and reactive power into their AC and DC components, as shown in the following equations. This separation helps in accurately analyzing and compensating for the power components in systems with nonlinear loads. In Figure 3.2, the DC part ($\overline{p}$) of the real power (P) depicts the basic voltage and current components, indicating the power flowing from the source to the load. The AC part ($\tilde{p}$) illustrates the energy exchanged between the source and the load. To extract the DC component of actual power, a high-order low-pass filter is employed. This DC component is the only power that the three-phase AC source needs to provide. The reactive power component (Q), is made up of both fundamental and harmonic components that control the flow of energy between the load's phases.

$$P = \overline{p} + \tilde{p} \tag{3.3}$$

$$Q = \overline{q} + \tilde{q} \tag{3.4}$$

For the generation of harmonic reference currents, the AC component ($\tilde{p}$) of active power and total reactive power (Q) is needed.

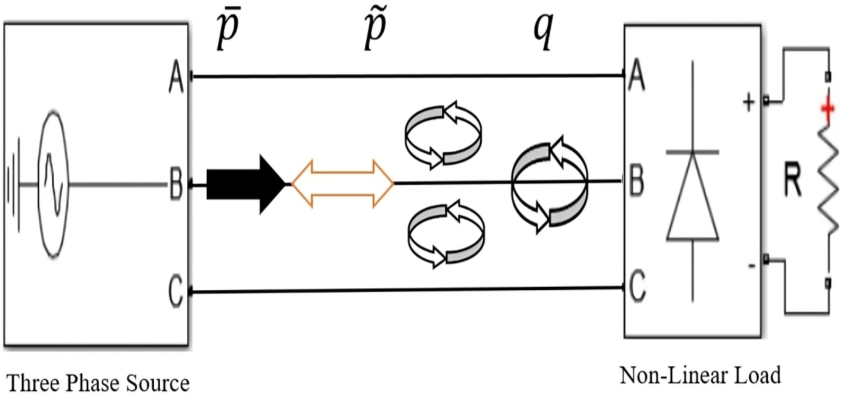


FIGURE 3.2: Power components of P-Q theory [61].

The reference currents in the α-β coordinates are calculated using the following expression:

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ Q \end{bmatrix}$$

These reference currents are then converted back to a-b-c coordinates via an inverse transformation, using the following expression. This procedure ensures that the compensation currents are properly aligned with the initial three-phase system, allowing for effective correction or control:

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix}$$

3.2 Simulink Model Analysis

3.2.1 Simulink Model of Three-Phase Power Systems with Non-Linear Load

The Simulink model presented in Figure 3.3 encapsulates a comprehensive representation of a power system featuring a three-phase power supply interfacing with non-linear load. The model meticulously incorporates the complexities inherent to real-world power systems, notably capturing the presence of harmonics that contribute to significant waveform distortion in both the supply current and load current. By accurately modeling these distortions, the system can better simulate and address the challenges posed by harmonics, ensuring more effective analysis and mitigation strategies for maintaining power quality.

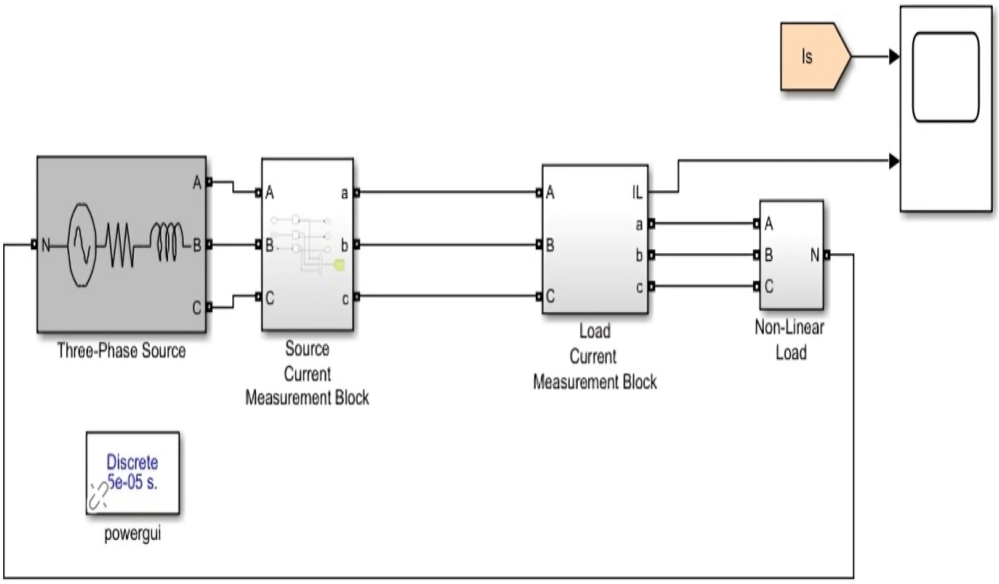


FIGURE 3.3: Three-Phase Power Systems with Non-Linear Load without Compensation

In the context of the provided Simulink model, our research focus will concentrate solely on the analysis and characterization of the steady-state segment of the response. By isolating this component, we aim to delve deeply into the inherent stability, performance, and behavior of the system under conditions where transient effects are negligible. Such an approach will afford us a clearer understanding of the persistent dynamics governing the system, facilitating more precise modeling, analysis, and decision-making processes. The depicted output waveforms of both supply and load currents exhibit pronounced harmonic distortions, as evident from Figure 3.4. These distortions can engender a spectrum of adverse effects, ranging from increased heating in transformers and conductors to interference with communication systems. Recognizing the criticality of preserving power system reliability and efficiency, it becomes imperative to devise mitigation strategies aimed at addressing these challenges.

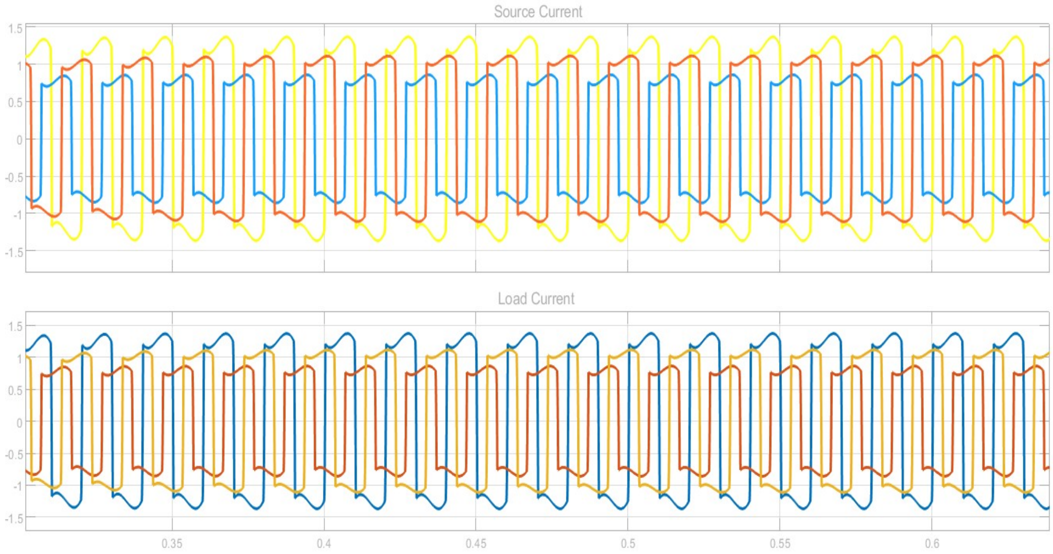


Figure 3.4: Before compensation (a) Source current (b) Load current

Utilizing the Power GUI block within Simulink, a Fast Fourier Transform (FFT) analysis of the source current waveform was conducted, with particular emphasis on the steady-state response, excluding the transient effects as shown in Figure 3.5. Focusing solely on a segment of source current data, Total Harmonic Distortion (THD) calculations were performed. The results revealed a notable concern: both source and load currents exhibited a pronounced THD level of 43.44%, indicative of a substantial presence of harmonics within the system. This finding underscores the criticality of addressing harmonic content to mitigate adverse impacts on power system equipment and overall performance. As illustrated in the accompanying figure, the elevated THD values emphasize the urgency of implementing targeted measures to enhance power quality and ensure the reliability of electrical networks. Addressing these high THD levels is crucial for mitigating waveform distortions and maintaining the efficient and stable operation of power systems.

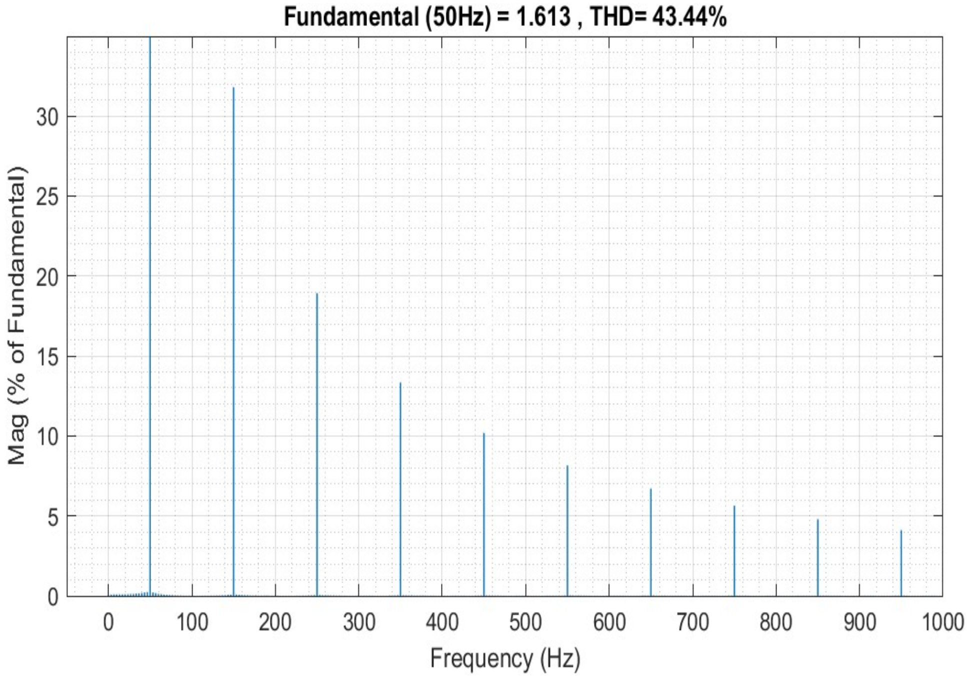


Figure 3.5: Before compensation Source Current FFT Analysis

Addressing harmonic distortion within simulated power systems required a strategic approach, leading to the deployment of Instantaneous $p-q$ Theory methodology. This refined technique, highlighted in Figure 3.6 of the updated model, aims to effectively mitigate harmonic effects. By implementing this method, the model can accurately analyze and counteract harmonic distortions, ensuring improved power quality and system reliability.

The integration of Instantaneous $p-q$ Theory signifies a proactive step towards enhancing power system performance. This methodology enables precise identification and mitigation of harmonics, thereby reducing waveform distortions and optimizing operational efficiency. The updated model in Figure 3.6 illustrates the application of these strategies, demonstrating a focused effort to address and manage harmonic issues in modern power systems.

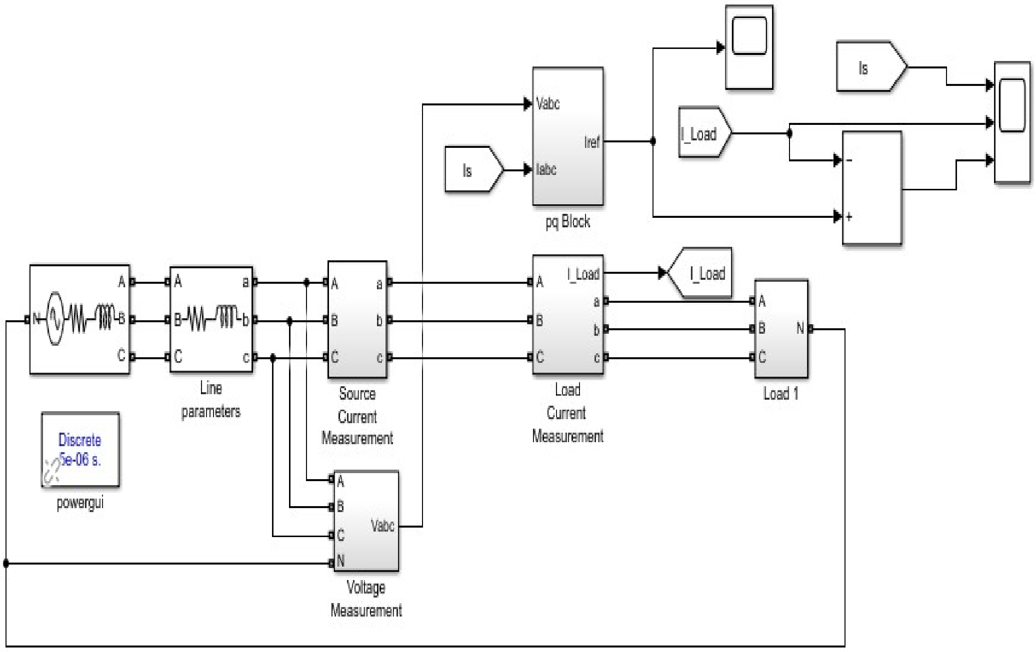


FIGURE 3.6: Compensation of Three-Phase Power Systems with pq theory

Within the adopted Simulink model, the pivotal task of generating reference current is done by the "pq" block shown in Figure 3.7. At the input of this block, three-phase currents and three-phase voltages are supplied.

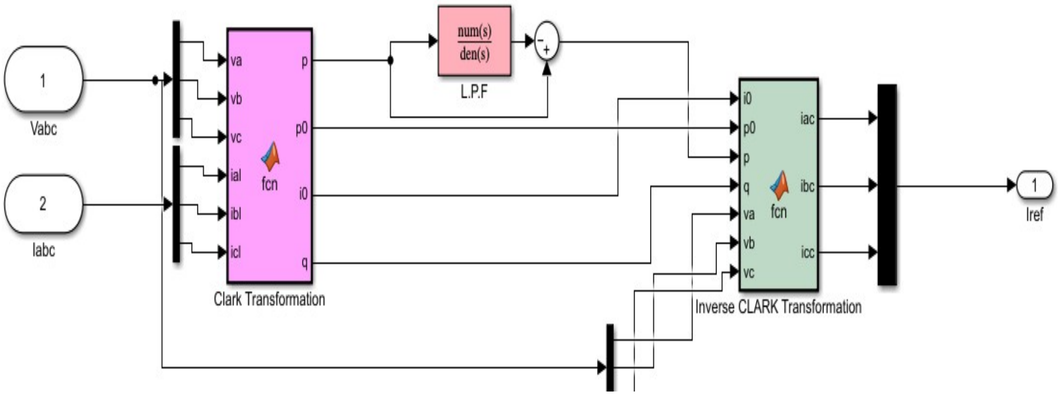


FIGURE 3.7: Instantaneous Reactive Power Theory Block

For the Clark transformation, exemplary data may include converting three-phase currents into a two-dimensional representation in a rotating reference frame. Conversely, for the inverse Clark transformation, pertinent data could involve restoring the transformed variables to their original three-phase form facilitating coherent interpretation and integration within the broader system architecture. The primary output is a harmonic reference current, indicating the magnitude and phase of harmonic current required for compensation. The reference current is shown in Figure 3.8.

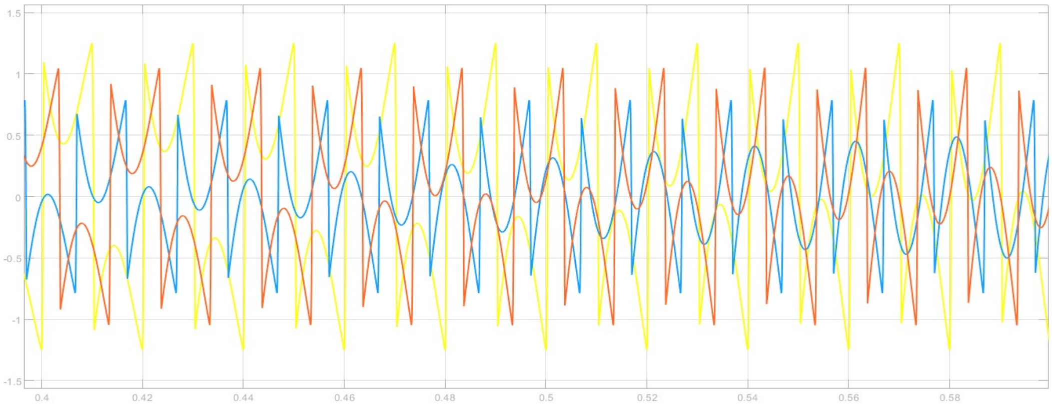


FIGURE 3.8: Reference Current

The Matlab code for Clark transformation and Inverse Clark Transformation utilized in Figure 3.7 is provided in the appendix for reference. The subsequent integration of the reference current with the source current, facilitated by a straightforward addition utilizing a Summer block, has yielded remarkable results. Notably, the source current waveform has transformed, transitioning from its initially distorted state to a sinusoidal profile as shown in Figure 3.9.

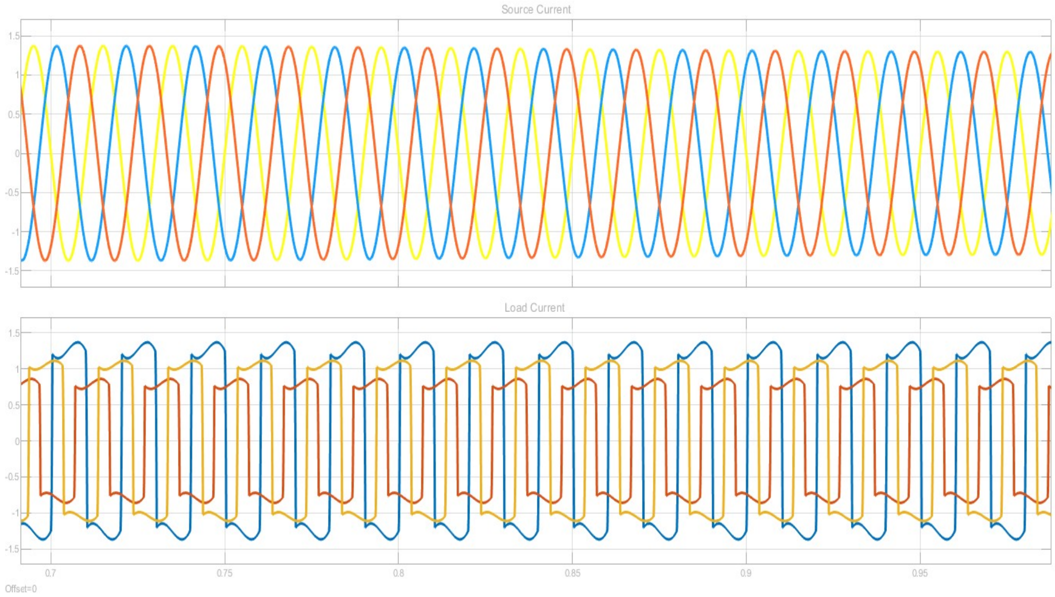


FIGURE 3.9: After Compensation (a) Source Current (b) Load Current

This significant improvement in waveform quality serves as a testament to the efficacy of the p-q Theory in mitigating harmonic distortions within the system. Upon subjecting the resultant output waveform to Total Harmonic Distortion (THD) analysis, the findings underscore a notable enhancement in system performance. Specifically, the THD value has exhibited a substantial reduction, measuring a mere 0.08% as shown in Figure 3.10. This noteworthy reduction in THD attests to the effectiveness of the implemented p-q Theory methodology in rectifying harmonic distortions and improving power quality within the simulated power system. The observed reduction in THD underscores the robustness and reliability of the p-q Theory approach in mitigating harmonic distortions and enhancing overall system stability and efficiency. This outcome signifies a significant milestone in advancing power system engineering practices and underscores the potential for further optimization and refinement in future endeavors.

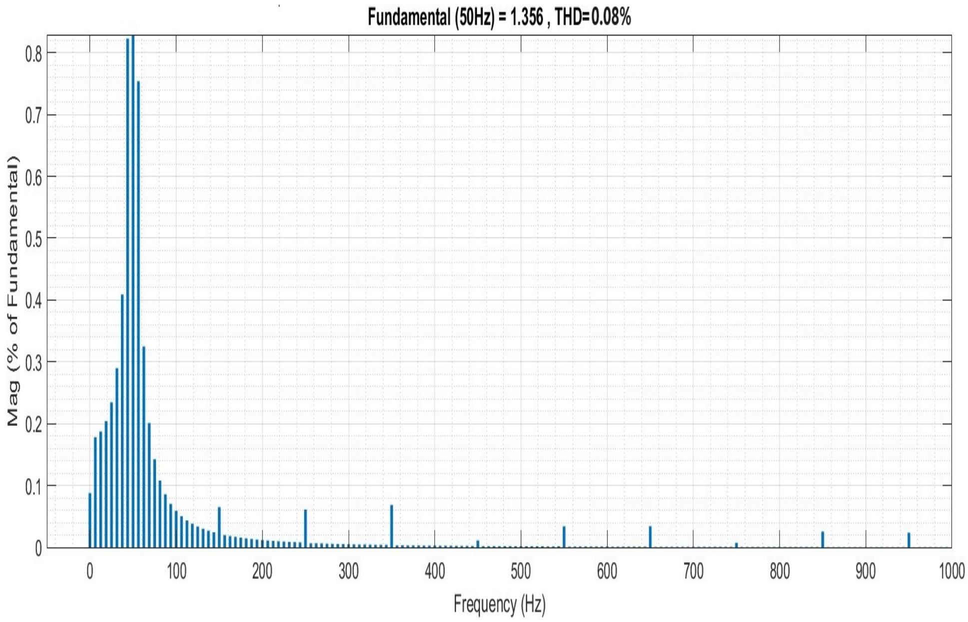


FIGURE 3.10: After Compensation Source Current FFT Analysis

In conclusion, the successful implementation of the Instantaneous Reactive Power Theory (IRPT) offers significant benefits in managing reactive power and mitigating harmonic distortions within electrical systems.

Chapter 4

Reference Current Injection

In the context of Shunt Active Power Filters (SAPF), reference current injection plays a pivotal role in mitigating harmonics and improving power quality. Reference current injection involves generating a reference signal that represents the desired current waveform necessary to compensate for harmonic distortions and reactive power in the electrical system. This reference current is then compared with the actual load current, and the resulting error signal is used to generate control signals for the SAPF. By injecting appropriate compensating currents, the SAPF can effectively cancel out harmonic components and reactive power, thereby improving the overall power quality of the system. Based on our comprehensive literature review and analysis, we have opted to utilize Hysteresis Current Control (HCC) for injecting the reference current. HCC offers a straightforward and efficient approach to current control, aligning well with the requirements of reference current injection in SAPF applications.

4.1 Introduction

Hysteresis current control is a well-known approach in the field of power electronics, providing a reliable way to regulate currents in a wide range of applications such as inverters, motor drives, and power supplies. In hysteresis current control, the current is kept in a predefined band of width, or the hysteresis band (HB), around the reference current, as shown in Figure 4.1. This control approach, based on the fundamental premise of keeping current within a set range around a reference value, works by interacting dynamically with a comparator, hysteresis band, and switching logic. Hysteresis current control maintains intended current levels by repeatedly comparing real current readings to specified thresholds. Its effectiveness stems not only from its ease of implementation but also from its rapid response to transient load fluctuations, making it especially well-suited for circumstances that need quick and precise current control.

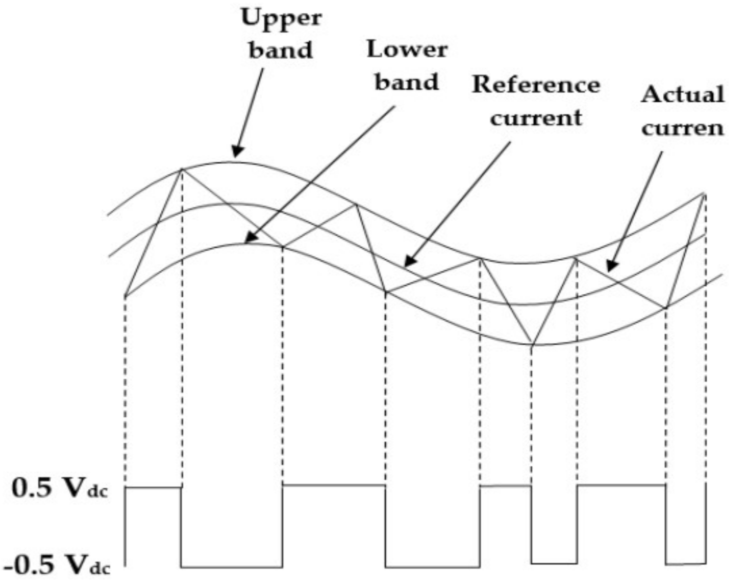


Figure 4.1: Hysteresis Current Control Technique

4.2 Implementation

The major function of the Hysteresis Current Controller in a Shunt Active Power Filter is to keep the current injected into the system within predetermined hysteresis bands. This control approach works by comparing the measured current to a reference value. Implementing hysteresis current control involves integrating numerous critical components and considerations, such as designing precise threshold settings tailored to operational requirements and optimizing efficient switching strategies for power electronic components. This approach ensures effective regulation and stability in managing currents across a wide range of operational conditions, thereby enhancing the reliability and performance of electrical systems.

4.2.1 Comparator

The comparator is the central component of the hysteresis current controller. It compares the actual current to a reference value. When the actual current reaches the upper threshold of the hysteresis band, the comparator outputs a high value, indicating that the current should be lowered. In contrast, when the actual current goes below the lower threshold of the hysteresis band, the comparator produces a low output, suggesting that the current should be raised.

4.2.2 Hysteresis Band

The hysteresis band specifies the range in which the real current should be kept around the reference value. It comprises two thresholds: upper and lower. The width of the hysteresis band specifies the maximum permissible variation of the actual current from the reference value before the correction is done. A broader hysteresis band offers more tolerance to current changes, but it may result in shorter reaction times and bigger overshoots.

4.2.3 Switching Logic

The switching logic selects whether to turn on or off the power devices based on the comparator's output and the hysteresis band. When the output of the comparator changes state, indicating that the actual current is above a threshold, the switching logic performs the necessary step to return the current to the hysteresis band. This activity often consists of turning on or off power devices in the power electronic circuit, such as transistors or thyristors.

4.2.4 Dead Time Compensation

In practical applications, it is critical to account for the dead time caused by the switching characteristics of power devices. Dead time compensation methods are used to alleviate the impacts of dead time while maintaining precise current control. This may involve modifying the hysteresis band or introducing extra delays in the switching logic to compensate for the dead time.

4.2.5 Feedback Circuitry

Feedback circuitry plays a vital role in hysteresis current controllers, enhancing stability and accuracy in controlling the injected current. Here's a detailed expansion on the components and functions typically incorporated into feedback circuitry:

1 **Current Sensors:**

Current sensors are essential components in the feedback circuitry, as they provide real-time measurements of the current flowing through the system. These sensors can be based on various principles such as Hall-effect sensors, current transformers, or shunt resistors. They accurately measure the magnitude and direction of the current, enabling precise control actions.

2 **Filtering Circuits:**

To ensure the reliability and accuracy of the feedback signal, filtering circuits are often employed. These circuits remove noise and unwanted high-frequency components from the measured current signal, improving the signal-to-noise ratio and reducing the likelihood of false triggering of the control system. Common filter types include low-pass filters or band-pass filters tailored to the frequency range of interest.

3 **Amplification Circuits:**

The output signal from the current sensors may require amplification to bring it to a level suitable for further processing and comparison. Amplification circuits boost the signal strength while maintaining its fidelity, ensuring that the feedback signal accurately represents the actual current flowing through the system. Operational amplifiers (op-amps) are widely utilized in these circuits for their capability to achieve precise and reliable signal amplification.

Their versatile nature and ability to integrate with various circuit configurations make them indispensable in applications requiring accurate signal processing. This includes audio equipment, instrumentation, and control systems.

4 **Closed-Loop Control:**

The feedback circuitry forms a closed-loop control system, where the output (the injected current) is continuously monitored and compared with the desired reference value. Any deviations from the desired current are quickly detected by the feedback circuitry, prompting the controller to adjust the switching of the power electronic components to maintain stability and accuracy in current injection.

5 **Calibration and Adjustment:**

Feedback circuitry often incorporates features for calibration and adjustment to compensate for variations in sensor characteristics, component tolerances, and environmental conditions. Calibration procedures ensure that the feedback circuitry operates reliably and accurately over a range of operating conditions, contributing to the overall performance of the hysteresis current controller.

4.2.6 Digital Implementation

In today's power electronic systems, hysteresis current control is often implemented digitally using microcontrollers or digital signal processors (DSPs). This digital approach offers increased versatility, enabling easy adjustment of control parameters and seamless integration with other control algorithms. This flexibility is crucial in dynamic environments where quick response and adaptability are essential for optimal system performance.

However, the digital implementation of hysteresis current control introduces challenges such as sampling and quantization errors. These errors can potentially degrade system performance if not adequately managed. Proper handling of these issues involves careful design of sampling rates, quantization levels, and signal processing algorithms to ensure accurate and reliable operation of the control system. Maintaining high fidelity in digital control systems is essential for achieving stable and efficient operation across a wide range of power electronic applications.

4.3 Hysteresis Current Controller Block

The Hysteresis Current Controller block in the adopted Simulink model of the Shunt Active Power Filter (SAPF), as depicted in Figure 4.2, functions as a crucial component in overseeing the regulation of the reference current injected into the system. By employing a hysteresis band, this controller ensures swift responsiveness to load fluctuations by meticulously managing the load current within a predefined range.

Implementing hysteresis current control involves integrating numerous critical components and considerations, such as designing precise threshold settings tailored to operational requirements and optimizing efficient switching strategies for power electronic components. This approach ensures effective regulation and stability in managing currents across a wide range of operational conditions, thereby enhancing the reliability and performance of electrical systems.

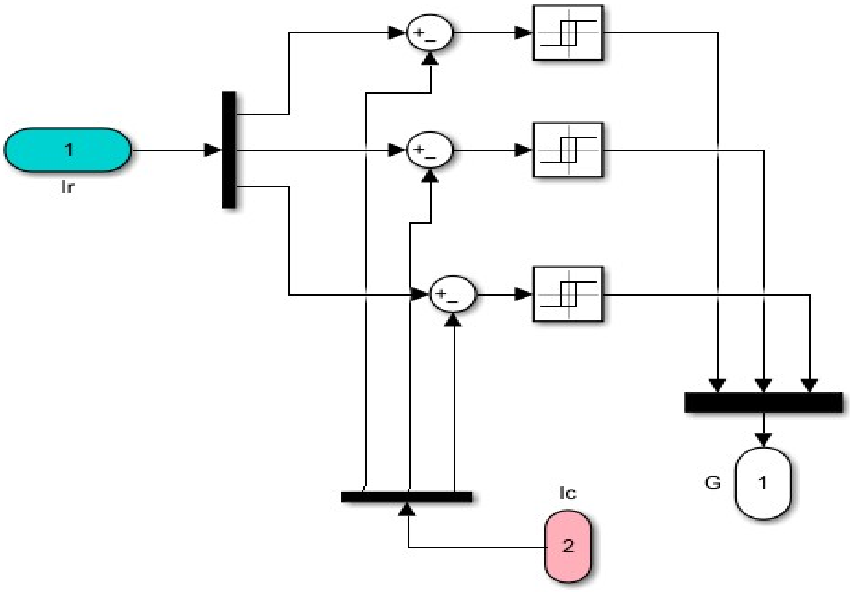


FIGURE 4.2: Hysteresis Current Controller Block

Leveraging this comparison, the Hysteresis Current Controller block effectively governs the switching behavior of the SAPF's control devices, such as Insulated Gate Bipolar Transistors (IGBTs) or other semiconductor switches. By strategically toggling these switches, the controller orchestrates the injection of compensating currents to counteract harmonic distortions and enhance overall power quality. This proactive approach not only mitigates undesirable harmonics but also contributes to stabilizing voltage levels and reducing reactive power flow.

Consequently, the Hysteresis Current Controller block plays an indispensable role in optimizing the performance and efficiency of the SAPF, ensuring the seamless operation of electrical systems even under varying load conditions. The chosen values for the minimum and maximum switching frequencies, 500 Hz and 5 kHz respectively, have been meticulously selected according to our system requirements and load conditions. By carefully selecting these values, our goal is to optimize responsiveness to load fluctuations and ensure overall system stability, achieving optimal performance in power management.

4.4 Three-Phase Inverter

Within the adopted SAPF Simulink model, the three-phase inverter shown in Figure 4.3 serves as a cornerstone element, assuming the pivotal responsibility of injecting corrective currents back into the load current to rectify harmonic distortions. Employing sophisticated control algorithms, the inverter operates with precision to ensure that the injected currents seamlessly align with the load's requirements. This meticulous alignment enables the inverter to effectively reshape the distorted waveform, transforming it from its irregular, non-sinusoidal state into a smooth, sinusoidal profile. This critical functionality emphasizes the pivotal role of the inverter in enhancing power quality throughout the electrical network. It highlights its indispensable contribution to maintaining stable and efficient electrical operation, crucial for supporting reliable performance across various applications. The inverter's capability to manage voltage fluctuations and provide clean power underscores its importance in modern electrical systems.

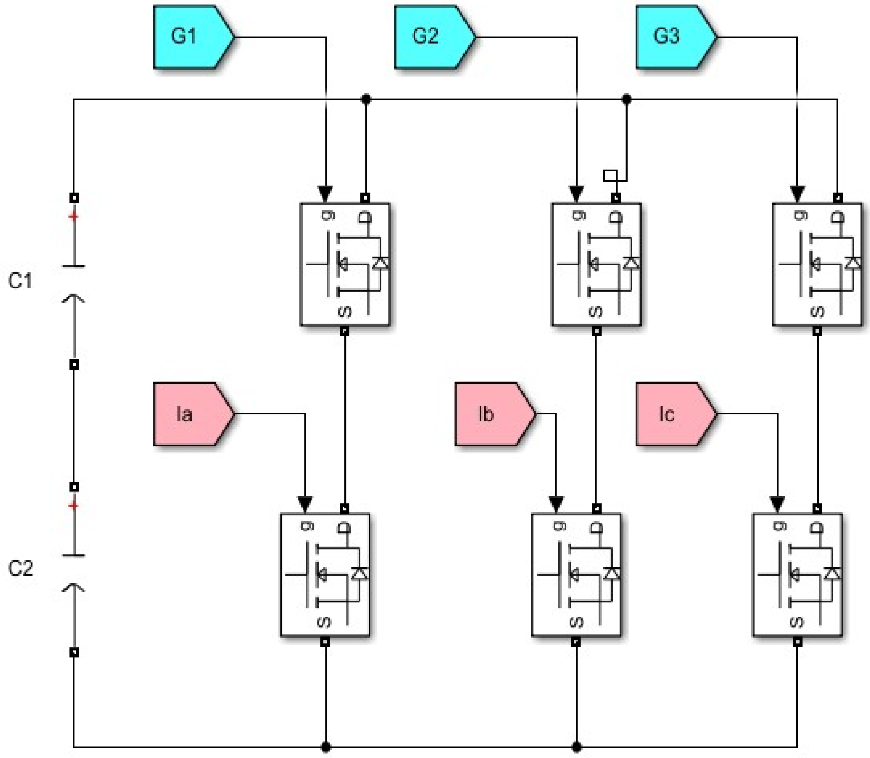


FIGURE 4.3: Three-phase Inverter

By actively mitigating harmonic distortions, the inverter plays a vital role in stabilizing voltage levels, reducing current harmonics, and improving overall system efficiency. Furthermore, the inverter's ability to adapt to dynamic load conditions ensures consistent performance across varying operating scenarios, bolstering the resilience and reliability of the electrical system.

The chosen values for the inverter parameters are a Switching Frequency of 8 kHz and a Modulation Index of 0.7. These values have been selected meticulously based on our system requirements and load conditions. By selecting these values, we aim to achieve the best results in terms of harmonic mitigation and power quality enhancement.This strategic choice aligns with our objective of optimizing power quality and effectively mitigating harmonic distortions, thereby facilitating the seamless operation and reliability of critical electrical infrastructure. It ensures consistent performance under varying conditions, enhancing overall system efficiency and longevity.

Chapter 5

Implementation and Results

This chapter focuses on implementing a Simulink model for deploying a Shunt Active Power Filter (SAPF) using the Instantaneous Reactive Theory for reference current generation. It emphasizes integrating a hysteresis current controller to ensure precise reference current injection, critical for effectively mitigating harmonic distortions in power systems.

The methodology detailed in this chapter outlines the SAPF model's implementation, highlighting essential considerations, design parameters, and simulation techniques employed. It includes a comprehensive analysis of the model's performance in reducing harmonics, accompanied by insightful discussions on the results obtained. Through meticulous implementation and thorough evaluation, this chapter aims to offer valuable insights into applying advanced control strategies to enhance power quality in modern electrical networks.

5.1 Simulink Model of Three Phase Power System with SAPF

In the adopted SAPF, shown in Figure 5.1, the non-linear load is a full-wave bridge rectifier. It is commonly employed as a load in electrical systems,an exhibits distinctive characteristics that can significantly impact system performance.

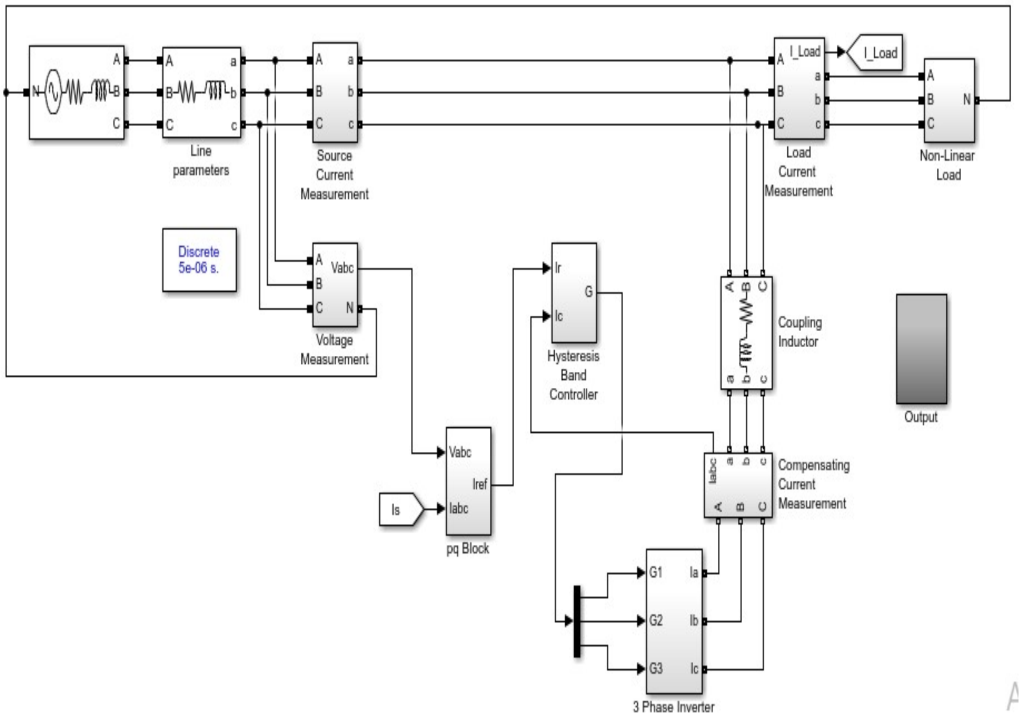


Figure 5.1: Simulink Model of Three Phase Power System with the Shunt Active Power Filter (SAPF)

Operating as a nonlinear load, the bridge rectifier converts alternating current (AC) input into direct current (DC) output, facilitating various applications such as battery charging and power supply systems. However, the operation of the bridge rectifier is inherently non-sinusoidal, leading to the introduction of harmonics into the system. This nonlinearity arises due to the abrupt switching behavior of the diodes within the rectifier circuit, resulting in current waveforms that contain harmonic components.

Specifically, the rectifier load generates odd-order harmonics, including the third, fifth, seventh, and higher-order harmonics, which are superimposed on the fundamental frequency of the AC waveform. Consequently, the presence of these harmonics leads to waveform distortion, increased total harmonic distortion (THD), and degradation of power quality within the electrical system. Moreover, the harmonic currents generated by the rectifier load can propagate through the system, affecting other connected loads and potentially causing issues such as voltage distortion, increased losses, and interference with sensitive equipment. Therefore, understanding the characteristics of the full-wave bridge rectifier as a load is crucial for mitigating harmonic effects and ensuring the reliable operation of the overall electrical system.

5.1.1 Results

5.1.1.1 Before Compensation

Before compensation, the waveforms of both load current and source current as shown in Figure 5.2 exhibit pronounced nonlinearity, characterized by distorted waveforms with significant harmonic content. This nonlinearity is primarily attributed to the presence of harmonics induced by the load, particularly due to the operation of a full bridge rectifier. The rectifier, commonly employed in electrical systems for converting alternating current (AC) to direct current (DC), inherently introduces harmonic distortion into the system's current waveform. The rectifier's nonlinear behaviour, stemming from the abrupt switching action of semiconductor devices such as diodes, leads to the generation of harmonics. Consequently, the distorted current waveforms observed in both the load and source currents can adversely affect power quality, causing increased total harmonic distortion (THD).

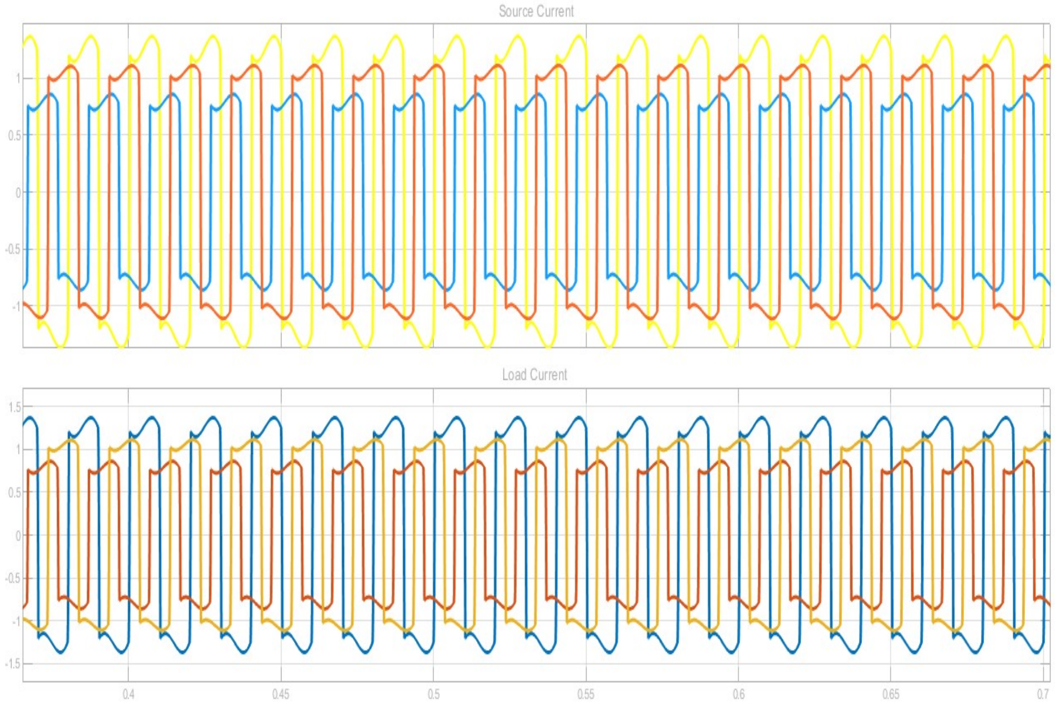


Figure 5.2: Before Compensation (a)Source Current (b) load Current

The Total Harmonic Distortion (THD) value of 43.44%, as shown in Figure 5.3 for the load current waveform before compensation underscores the substantial presence of harmonic distortions within the electrical system. This high THD value indicates that nearly half of the load current waveform comprises harmonic components rather than the fundamental frequency component, illustrating the extent of non linearity and distortion in the current waveform.

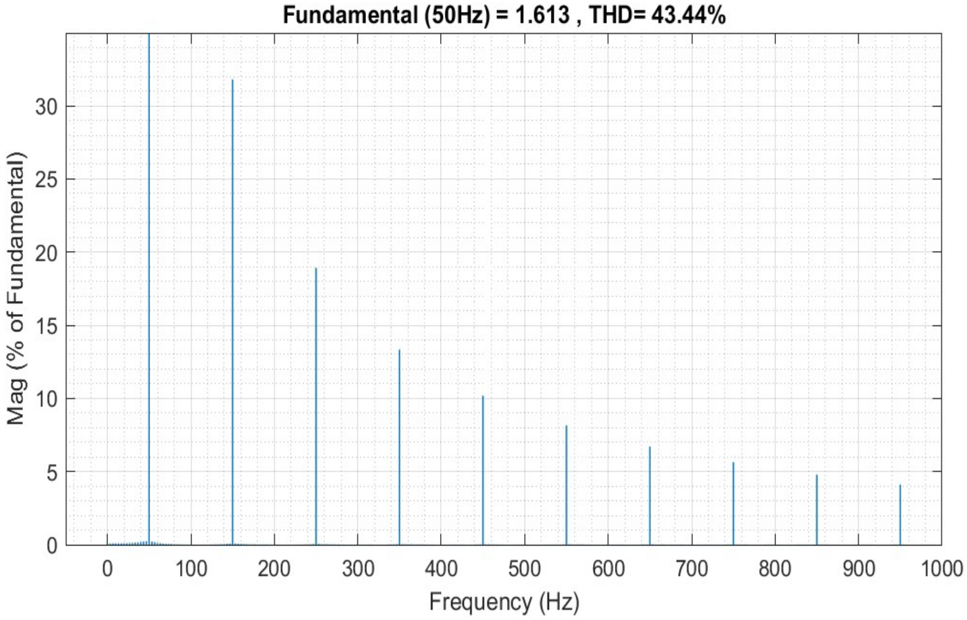


Figure 5.3: Before Compensation Source Current FFT Analysis

5.1.1.2 After Compensation

After the implementation of SAPF, a noticeable transformation is observed in the source current waveform, as depicted in Figure [insert figure number]. This illustrates the effective reduction of harmonic distortions and the improvement in waveform quality achieved by the system 5.4. Previously characterized by pronounced non-sinusoidal features attributed to the presence of harmonic distortions, the waveform now exhibits a markedly smoother and sinusoidal profile. This notable improvement underscores the effectiveness of the compensation strategy in rectifying distortions and restoring the integrity of the source current waveform as shown in Figure 5.5. By mitigating the disruptive influence of harmonics, the compensation measures have effectively minimized irregularities in the waveform, leading to a more stable and predictable electrical output.

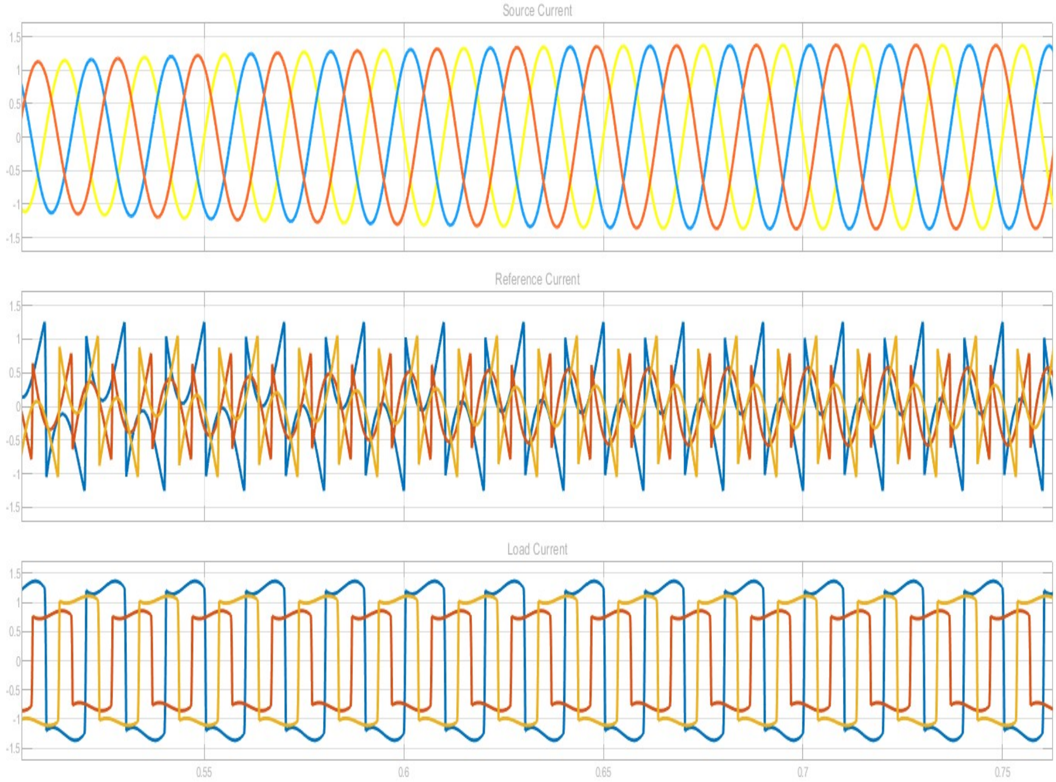


FIGURE 5.4: After Compensation (a)Source Current, (b)Reference current (c)Load Current

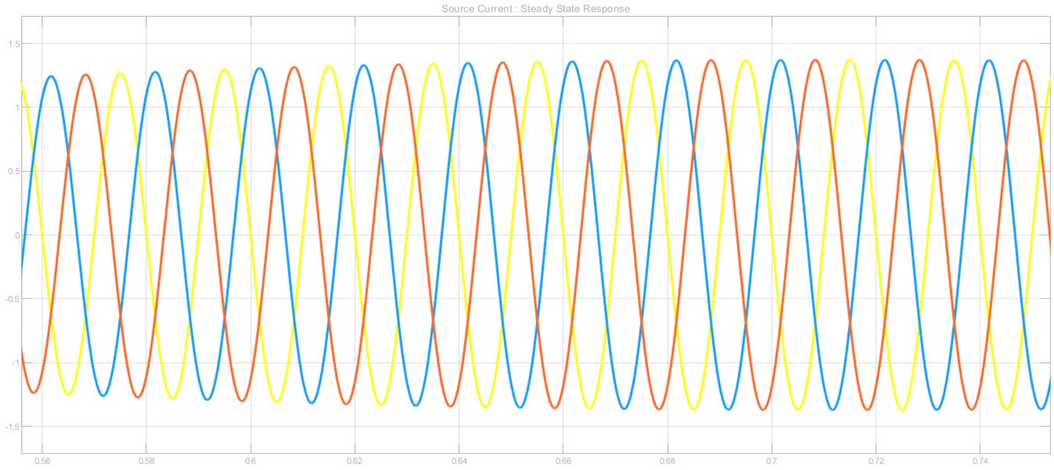


FIGURE 5.5: After Compensation Source Current: Steady State Response

This transition from a non-sinusoidal to a sinusoidal waveform is significant, as it signifies the successful correction of power quality issues within the system. The reduction in harmonic content reflects a more harmonious distribution of power, aligning more closely with the ideal sinusoidal waveform characteristic of a well-regulated electrical system. This improvement not only enhances the aesthetic quality of the waveform but also carries profound implications for the overall efficiency and reliability of the power system. Furthermore, the substantial reduction in Total Harmonic Distortion (THD) from its initial value of 43.43% to a mere 0.84% post-compensation serves as compelling evidence of the efficacy of the compensation strategy as shown in Figure 5.6. This dramatic decrease in THD underscores the effectiveness of the implemented measures in curbing harmonic distortions and optimizing power quality. The resulting waveform, now predominantly sinusoidal, signifies a significant step towards achieving enhanced system stability, improved equipment performance, and a more efficient utilization of electrical energy resources.

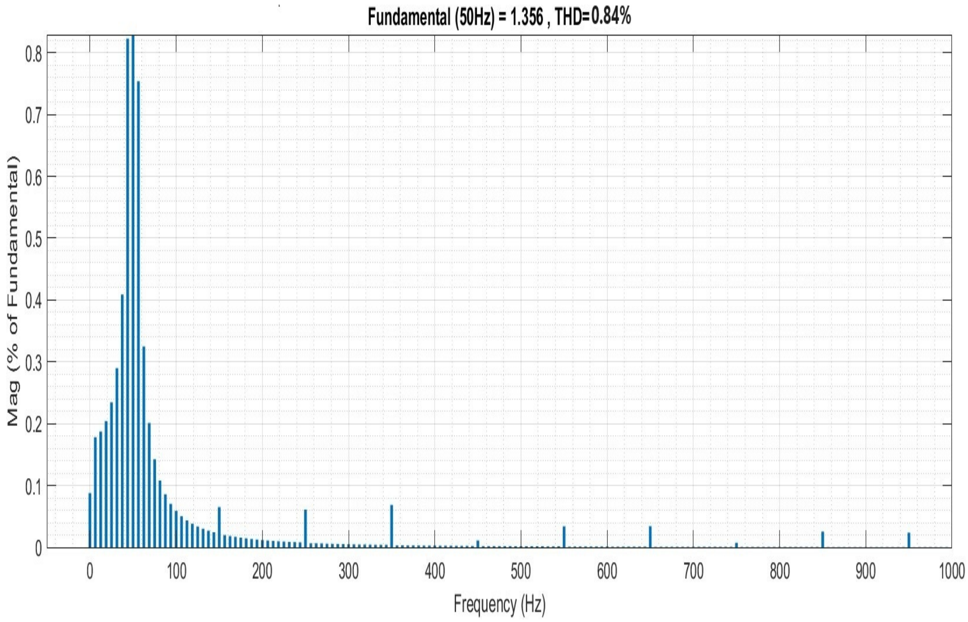


Figure 5.6: After Compensation Source Current FFT Analysis

5.2 Analytical Calculation of Total Harmonic Distortion (THD) Using Fourier Series Analysis

The function of the input source current is defined as:

$$f(t) = \begin{cases} I & 0 \leq t < \frac{\pi}{2} \\ -I & \frac{\pi}{2} \leq t < \pi \end{cases}$$

Fourier Series Representation

The Fourier series representation of a periodic function $i(t)$ with period T is:

$$i(t) = a_0 + \sum_{n=1}^{\infty} \left(a_n \cos\left(\frac{2\pi nt}{T}\right) + b_n \sin\left(\frac{2\pi nt}{T}\right) \right) \tag{5.1}$$

Calculating a_0

$$a_0 = \frac{1}{T_1} \int_0^T i(t)\, dt \tag{5.2}$$

$$a_0 = 0$$

Calculating a_n

The coefficient a_n is given by:

$$a_n = \frac{2}{T} \int_0^T i(t) \cos\left(\frac{2\pi nt}{T}\right)\, dt \tag{5.3}$$

$$a_n = \frac{2}{\pi} \left(\int_0^{\frac{\pi}{2}} I \cos(2nt)\, dt + \int_{\frac{\pi}{2}}^{\pi} (-I) \cos(2nt)\, dt \right) \tag{5.4}$$

$$a_n = 0$$

Calculating b_n

The coefficient b_n is given by:

$$b_n = \frac{2}{T} \int_0^T i(t) \sin\left(\frac{T}{2\pi} nt\right)\, dt \tag{5.5}$$

$$b_n = \frac{2}{\pi} \left(\int_0^{2\pi} I \sin(2nt)\, dt + \int_{2\pi}^{\pi} (-I) \sin(2nt)\, dt \right) \tag{5.6}$$

$$b_n = \frac{2}{\pi n} I$$

By combining all the coefficients i(t) is given as follows:

$$i(t) = \sum_{n=1}^{\infty} \frac{2In}{\pi} \sin(nwt) \tag{5.7}$$

The RMS value of the fundamental component of the source current is

$$I_1 s = \frac{2I}{\pi\sqrt{2}} \tag{5.8}$$

$$I_1 s = 0.45I$$

The RMS value of the source current is:

$$I_s = \left(\frac{2I}{\pi\sqrt{2}}\right) \cdot \sqrt{1 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{5}\right)^2} \tag{5.9}$$

$$I_s = \frac{0.689I}{\sqrt{2m}} \tag{5.10}$$

$$I_s = 0.487I$$

Total Harmonic Distortion

$$THD = \sqrt{\left(\frac{I_s}{I_{s1}}\right)^2 - 1} \tag{5.11}$$

$$THD = \sqrt{\left(\frac{0.487}{0.45}\right)^2 - 1} \tag{5.12}$$

$$THD = 41.8\%$$

5.3 Investigation of SAPF Performance with Dual Full-Wave Rectifier Loads

In the revised simulation model, we have augmented the load configuration by replacing the single full-wave rectifier with two full-wave rectifiers as shown in Figure 5.7. This modification aims to simulate a more representative scenario of real-world electrical systems, where multiple nonlinear loads are commonly encountered. Introducing two rectifiers allows for simulation scenarios that include diverse loads or multiple pieces of equipment operating simultaneously within the system. This setup enables comprehensive testing and evaluation of system performance under realistic operational conditions. This approach helps assess the performance and stability of the system under realistic conditions. This setup enables a comprehensive examination of how increased load complexity influences the performance of the Shunt Active Power Filter (SAPF) and its ability to mitigate harmonic distortions effectively.

Conducting Fast Fourier Transform (FFT) analysis on the resultant waveforms allows for a detailed exploration of the frequency spectra. We anticipate observing notable changes in the frequency content of the waveforms compared to the previous single-rectifier configuration. The addition of a second rectifier introduces additional harmonics into the system, thereby altering the harmonic profile and increasing the complexity of the load current waveform. Consequently, the FFT analysis will reveal shifts in the amplitudes and frequencies of the harmonic components, providing valuable insights into the impact of the augmented load configuration on the overall system behavior.

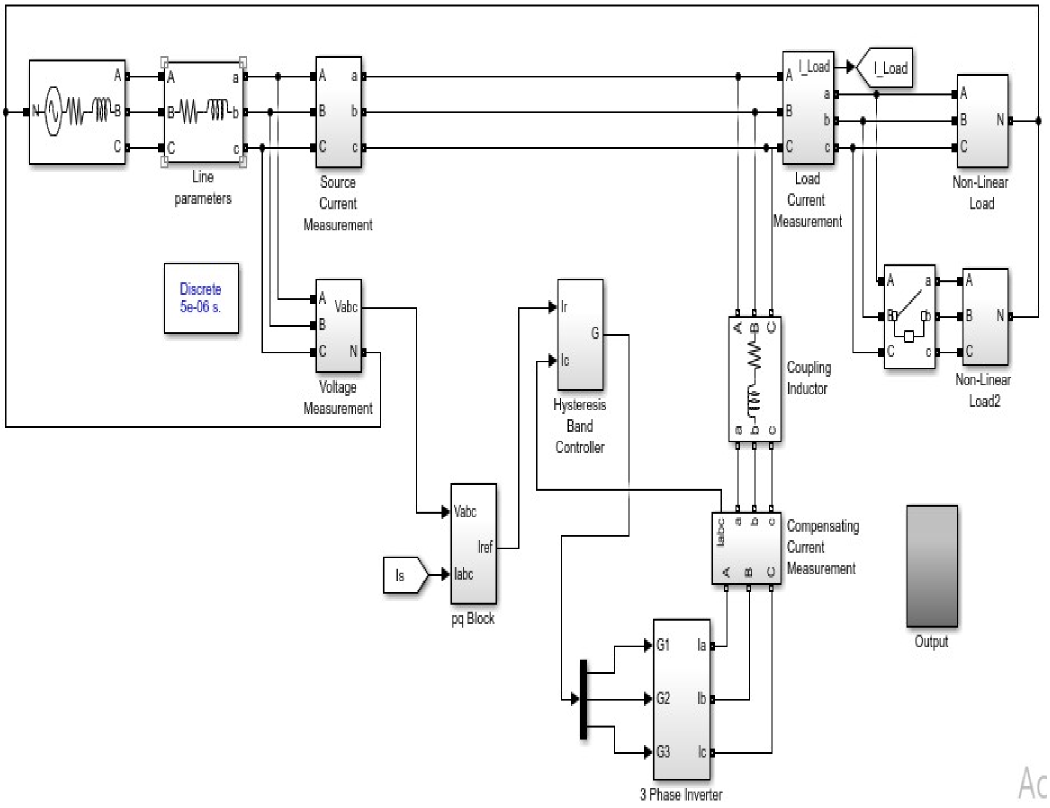


FIGURE 5.7: Shunt Active Power Filter with Dual Full-Wave Rectifier Loads

By scrutinizing the FFT results, we gain a deeper understanding of how the SAPF responds to the heightened harmonic content induced by the multiple rectifiers.

This analysis enables us to evaluate the SAPF's compensation capabilities under more challenging operating conditions and assess its effectiveness in maintaining power quality standards. Insights gleaned from this investigation will inform the refinement of control strategies and parameter optimization techniques to enhance the SAPF's performance in mitigating harmonics and ensuring the reliable operation of the electrical system in practical settings.

5.3.1 Results

5.3.1.1 Before Compensation

Before compensation, the load current and source currents exhibit pronounced nonlinearity due to the presence of two full bridge rectifiers within the electrical system. The operation of these rectifiers introduces significant harmonic distortions into the current waveforms, resulting in distorted and irregular patterns as shown in Figure 5.8.

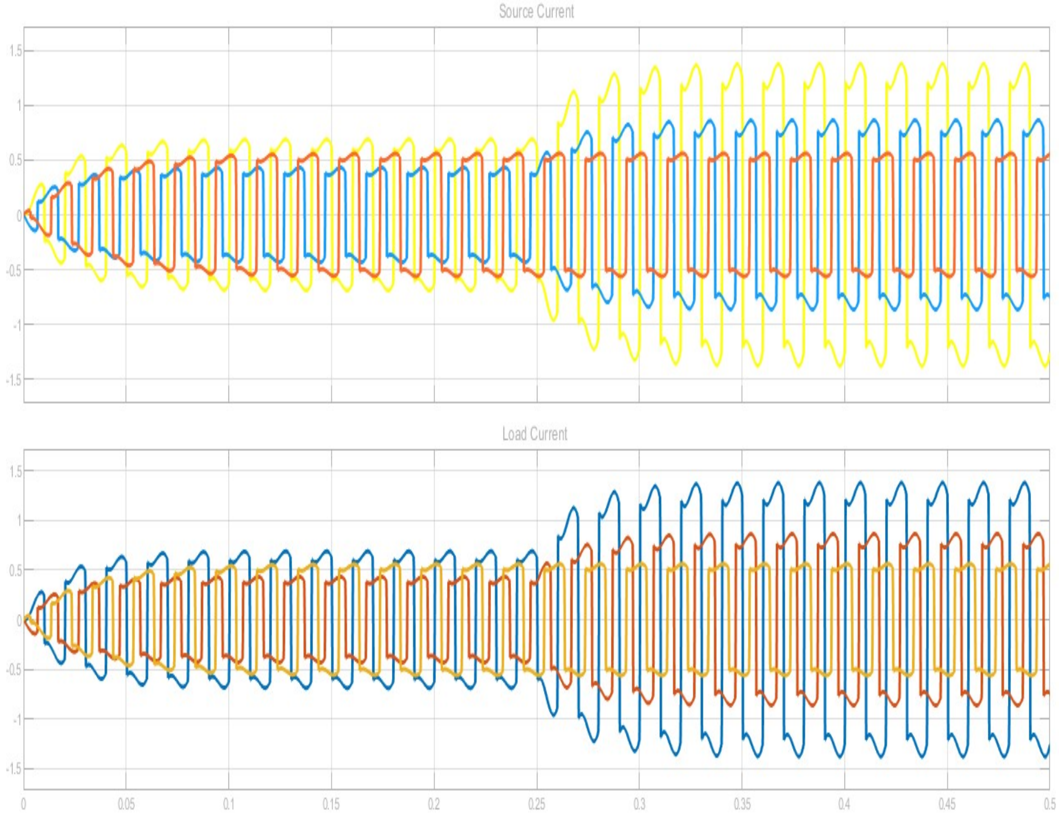


FIGURE 5.8: Before Compensation (a)Source Current (b) Load Current

The results of the Fast Fourier Transform (FFT) analysis indicate a Total Harmonic Distortion (THD) of 50.3% as shown in Figure 5.9, when two full bridge rectifiers are connected at the load, without the application of the Shunt Active Power Filter (SAPF). In contrast, for a single load configuration, the THD without SAPF was recorded at 43.44%. This comparison underscores the significant impact of load complexity on the harmonic content within the system. With the addition of a second rectifier, the harmonic distortion in the current waveform increases noticeably, leading to a higher THD value compared to the single load scenario. The elevated THD underscores the necessity of effective harmonic mitigation strategies to enhance power quality and mitigate the adverse effects of harmonic distortions

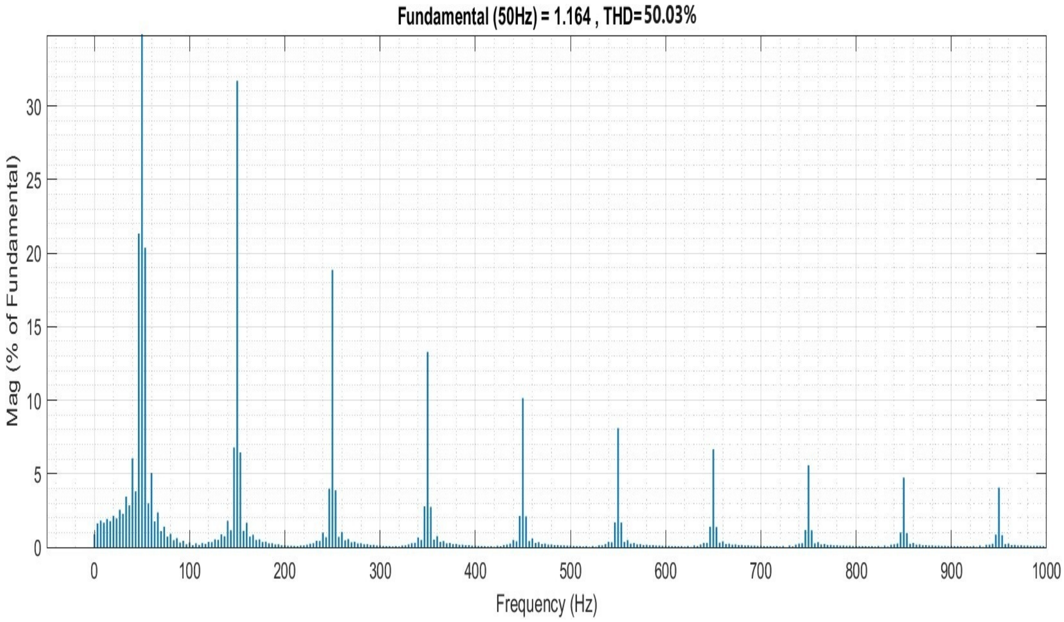


FIGURE 5.9: Before Compensation Source Current FFT Analysis

5.3.1.2 After Compensation

Following the application of the Shunt Active Power Filter (SAPF), a notable transformation was observed in the source current waveform. The previously distorted and non-sinusoidal characteristics of the source current waveform were effectively transformed into a sinusoidal waveform, clearly illustrated in Figure 5.10. This improvement signifies the successful elimination of harmonics by the Shunt Active Power Filter (SAPF), highlighting its capability to enhance power quality and ensure stable electrical operation. This transformation illustrates the SAPF's effective elimination of harmonics, resulting in improved power quality and stable electrical output.

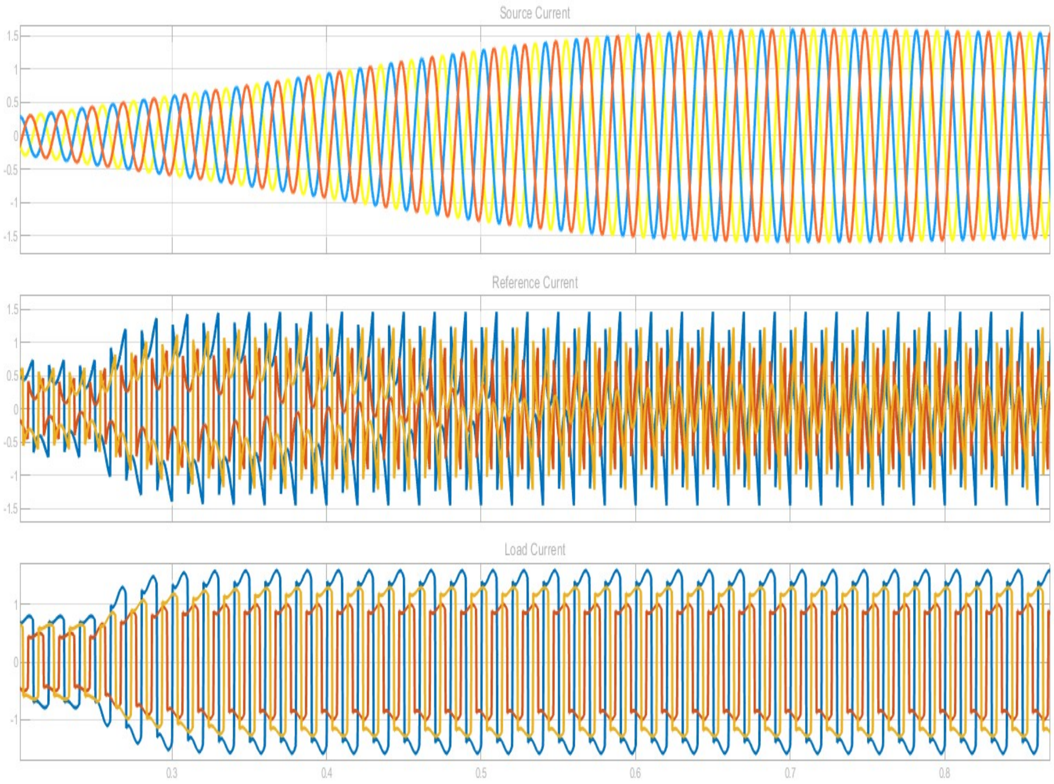


FIGURE 5.10: After Compensation (a)Source Current, (b)Reference current (c)Load Current

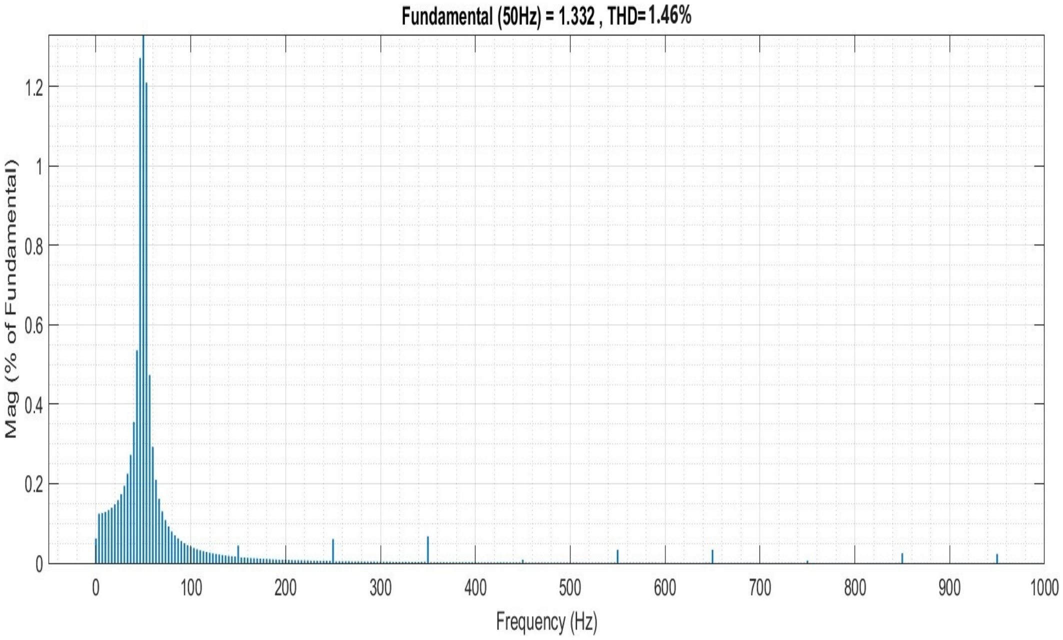


FIGURE 5.11: After Compensation Source current FFT Analysis

The Total Harmonic Distortion (THD) experienced a substantial reduction, plummeting from an initial value of 50.30% to a mere 1.46% as shown in Figure 5.11. This outcome underscores the remarkable success of the SAPF in mitigating harmonic distortions and restoring the load current to a nearly ideal sinusoidal form. The significant reduction in THD reflects the filter's proficiency in dynamically compensating for the non linearity introduced by the dual full bridge rectifiers, thereby enhancing the power quality of the system.

5.4 Analytical Calculation of Total Harmonic Distortion (THD) Using Fourier Series Analysis

The function of the input source current is defined as:

$$i(t) = \begin{cases} I & \text{for } 0 \leq t < 2\pi \end{cases}$$

Fourier Series Representation

The Fourier series representation of a periodic function $i(t)$ with period T is:

$$i(t) = a_0 + \sum_{n=1}^{\infty} \left(a_n \cos\left(\frac{2\pi nt}{T}\right) + b_n \sin\left(\frac{2\pi nt}{T}\right) \right) \tag{5.13}$$

Calculating a_0

$$a_0 = \frac{1}{T_1} \int_0^T i(t)\, dt \tag{5.14}$$

$$a_0 = 0$$

Calculating a_n

$$a_n = \frac{2}{T} \int_0^T i(t) \cos\left(\frac{2\pi nt}{T}\right) dt \tag{5.15}$$

$$a_n = 0$$

Calculating b_n

$$b_n = \frac{2}{T} \int_0^T i(t) \sin\left(\frac{T}{2\pi} nt\right) dt \tag{5.16}$$

$$b_n = \frac{4}{\pi n} I$$

The RMS value of the fundamental component of the source current is

$$I_1 s = \frac{4I}{\pi\sqrt{2}} \tag{5.17}$$

$$I_1 s = 0.91I$$

The RMS value of the source current is

$$I_s = \left(\frac{4I}{\pi\sqrt{2}}\right) \cdot \sqrt{1 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{5}\right)^2} \tag{5.18}$$

$$I_s = I$$

Total Harmonic Distortion

$$THD = \sqrt{\left(\frac{I_s}{I_{s1}}\right)^2 - 1} \tag{5.19}$$

$$THD = \sqrt{\left(\frac{1}{0.90}\right)^2 - 1} \tag{5.20}$$

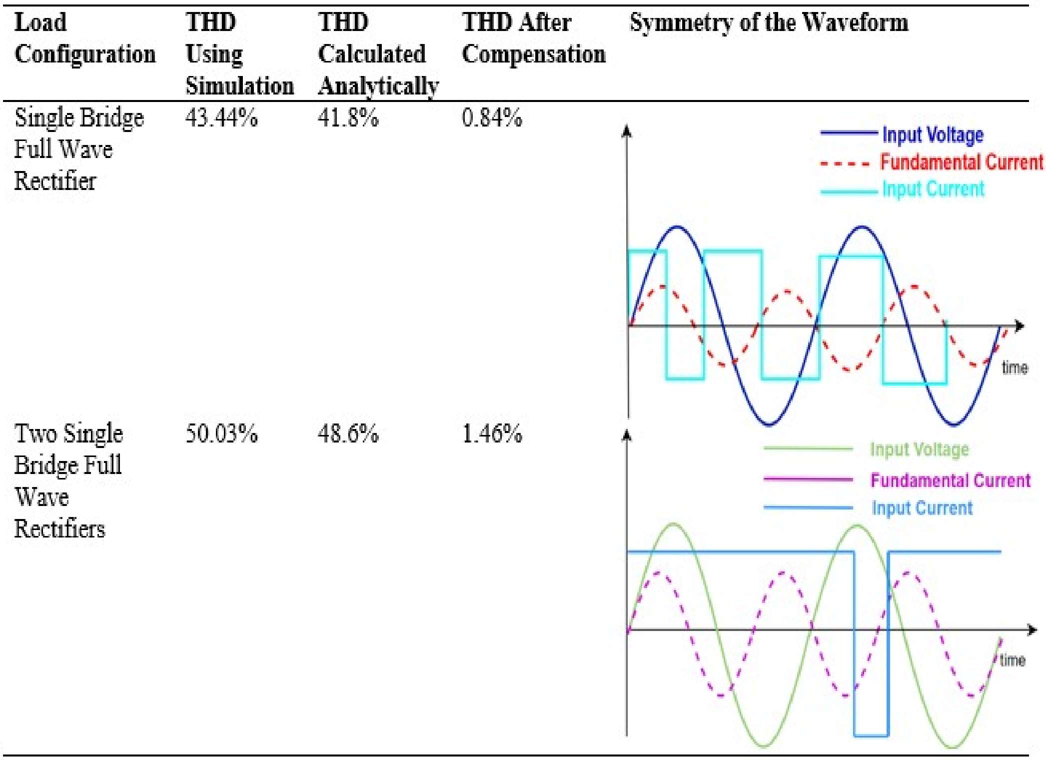
$$THD = 48.86\%$$

Table 5.1 lists the electrical system parameters, including voltage, frequency, resistances, inductances, and capacitance values.

Parameter	**Values**
Line to Line rms voltage	380V
Frequency	50Hz
Source resistance	1mΩ
Line inductance	1μH
Line resistance	1mΩ
DC-link capacitor	500μH

TABLE 5.1: System parameters

The comparison between the two load configurations, each featuring different numbers of single bridge full wave rectifiers as shown in Figure 5.12, reveals compelling insights into the efficacy of the Shunt Active Power Filter (SAPF) in mitigating harmonic distortions. For the single rectifier scenario, the Total Harmonic Distortion (THD) value before the SAPF application stood at 43.44% according to simulation results, while the analytically calculated THD was 41.8%. This indicates significant harmonic content in the load current waveform. However, following compensation, the THD plummeted to a mere 0.84%, signifying a remarkable reduction in harmonic distortions and the successful restoration of the source current waveform to a near-sinusoidal form.



Load Configuration	THD Using Simulation	THD Calculated Analytically	THD After Compensation	Symmetry of the Waveform
Single Bridge Full Wave Rectifier	43.44%	41.8%	0.84%	
Two Single Bridge Full Wave Rectifiers	50.03%	48.6%	1.46%	

FIGURE 5.12: Comparative Analysis of THD for Single and Dual Bridge Full Wave Rectifiers Before and After Compensation

Similarly, in the case of two single bridge rectifiers, the THD before compensation was recorded at 50.30% in simulation, reflecting even higher harmonic content, while the analytically calculated THD was 48.6%. Post-compensation, the THD decreased substantially to 1.46%, underscoring the SAPF's effectiveness in mitigating harmonic distortions even in more complex load configurations. The differences between the analytical and simulation results can be attributed to the consideration of higher-order harmonics in the simulations, which are not accounted for in the analytical calculations. Additionally, the symmetry of the waveform for both single and two single bridge rectifiers has been included, These findings underscore the crucial role of SAPF in enhancing power quality by effectively addressing harmonic distortions, thereby ensuring the reliable and efficient operation of electrical systems.

5.5 Comparative Analysis

In the research paper 'Performance Analysis of Shunt Active Power Filter Using Sliding Mode Control Strategies[48]' two distinct control strategies for a three-phase four-wire shunt active power filter (APF) are presented. These strategies leverage instantaneous reactive power theory to generate reference currents. The primary objective of the APF is to effectively compensate for harmonics, neutral current, and the reactive power demand of nonlinear loads. Post-compensation, the source current becomes sinusoidal, balanced, and in phase with the respective source voltages. The Total Harmonic Distortion (THD) of the line currents is significantly reduced from 40.256%, 41.87%, and 36.48% to 3.86%, 3.90%, and 3.85% respectively using proportional-integral (PI) control, and further reduced to 1.75%, 1.80%, and 1.69% respectively using Sliding Mode Control (SMC).

The research paper considers specific unbalanced load conditions, which are as follows:

- Phase-A: $R = 15\,\Omega$, $L = 60\,\text{mH}$
- Phase-B: $R = 30\,\Omega$, $L = 90\,\text{mH}$
- Phase-C: $R = 45\,\Omega$, $L = 200\,\text{mH}$

In our study, we adopted a similar approach by employing the instantaneous reactive power theory to generate reference currents, ensuring a direct comparison with the results obtained in the referenced research. Additionally, our model uses a Hysteresis current controller for the injection of these reference currents. We implemented the aforementioned unbalanced load conditions in our model and meticulously monitored the source current waveform both before and after compensation. The pre-compensation source current waveform, depicted in Figure 5.13, exhibits significant distortion due to the presence of harmonics. Its frequency spectrum, shown in Figure 5.14, indicates a very high THD, reflective of the unfiltered system's poor power quality. Conversely, the post-compensation source current waveform, illustrated in Figure 5.15, is sinusoidal, demonstrating the successful implementation of the SAPF in mitigating harmonic distortion. The frequency spectrum of the compensated source current, presented in Figure 5.16, shows a very low THD.

Our results indicate a substantial reduction in THD of the line currents after compensation, with values decreasing from 40.256%, 41.87%, and 36.48% to 1.19%, 1.29%, and 1.16% respectively. These results demonstrate that our model achieves superior THD compensation compared to the two techniques presented in the referenced research paper. The combination of instantaneous reactive power theory for reference current generation and the use of a hysteresis current controller for current injection proves to be highly effective in enhancing power quality and achieving significant harmonic mitigation.

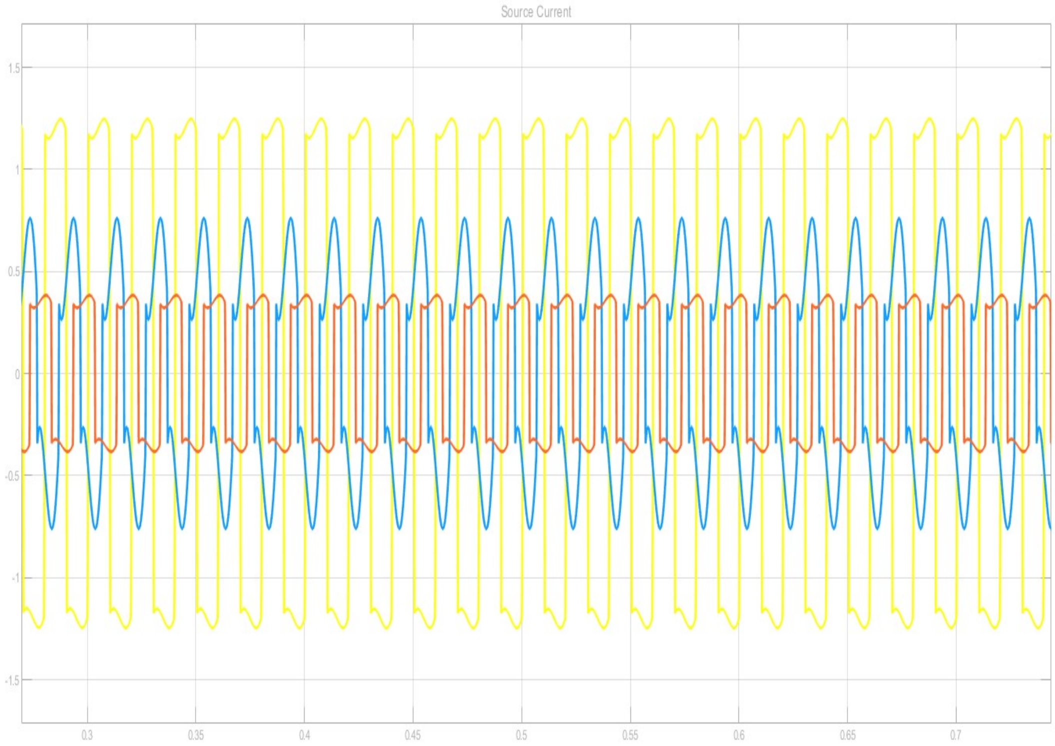


FIGURE 5.13: Source Current Before Compensation

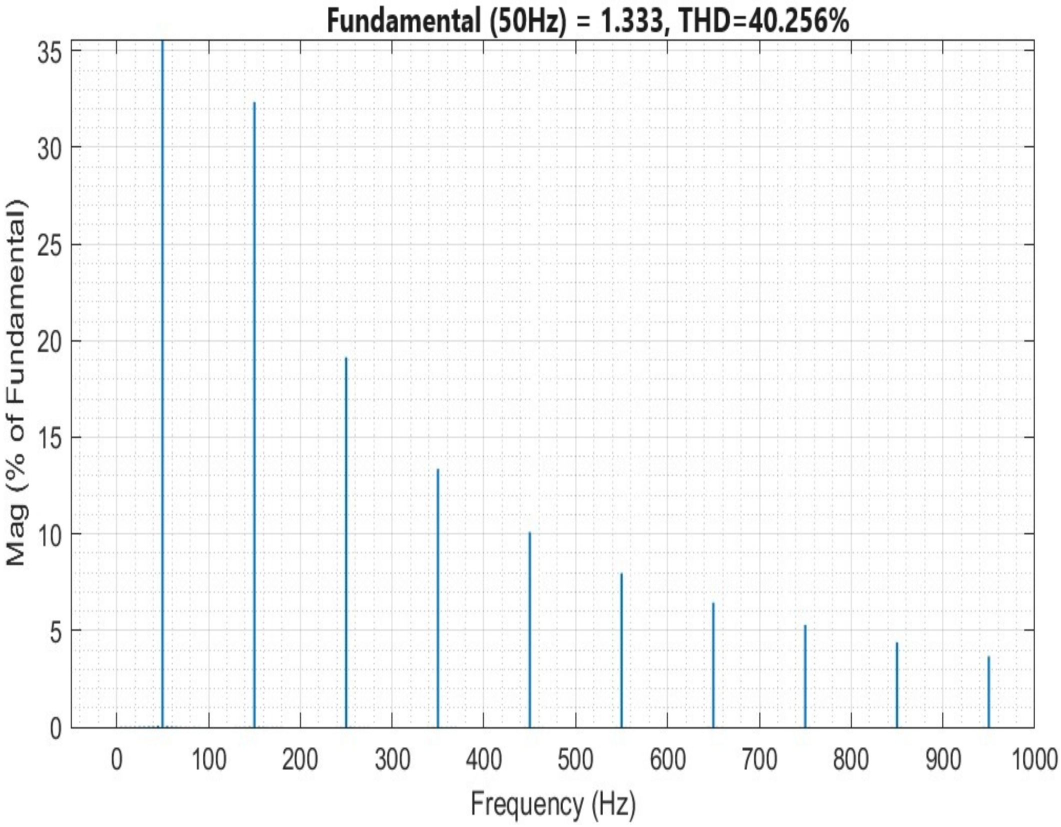


FIGURE 5.14: Before Compensation Source Current FFT Analysis

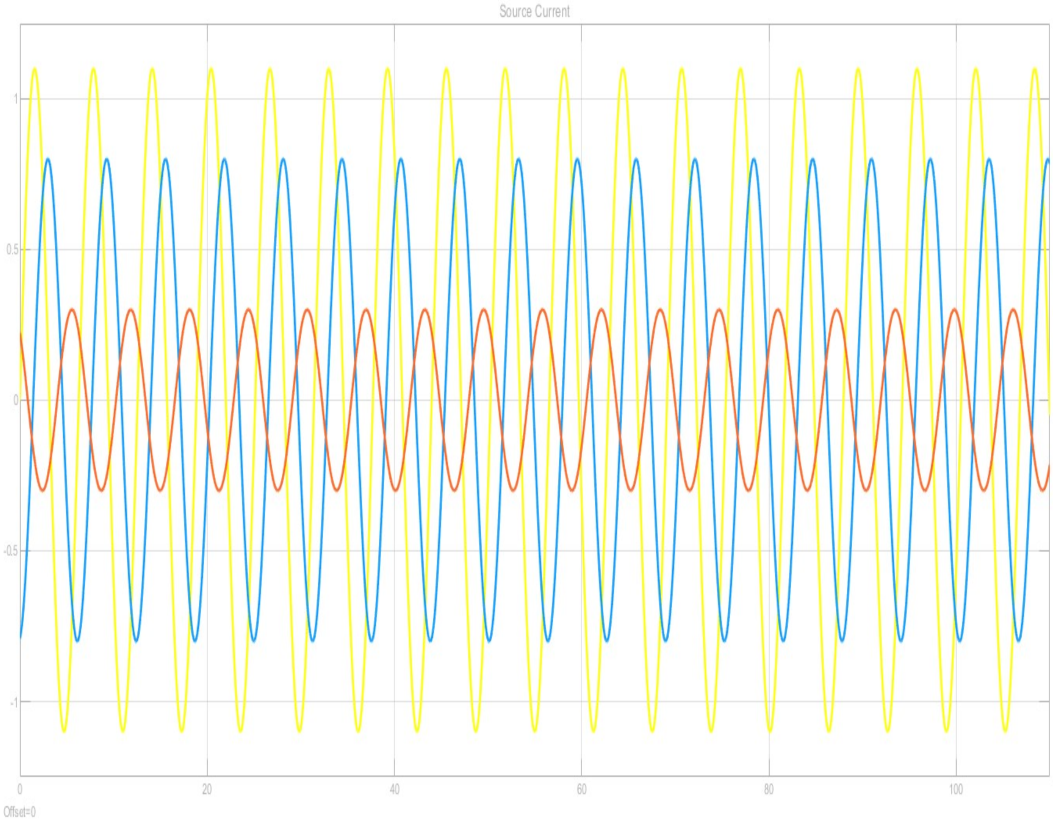


FIGURE 5.15: Source Current After Compensation

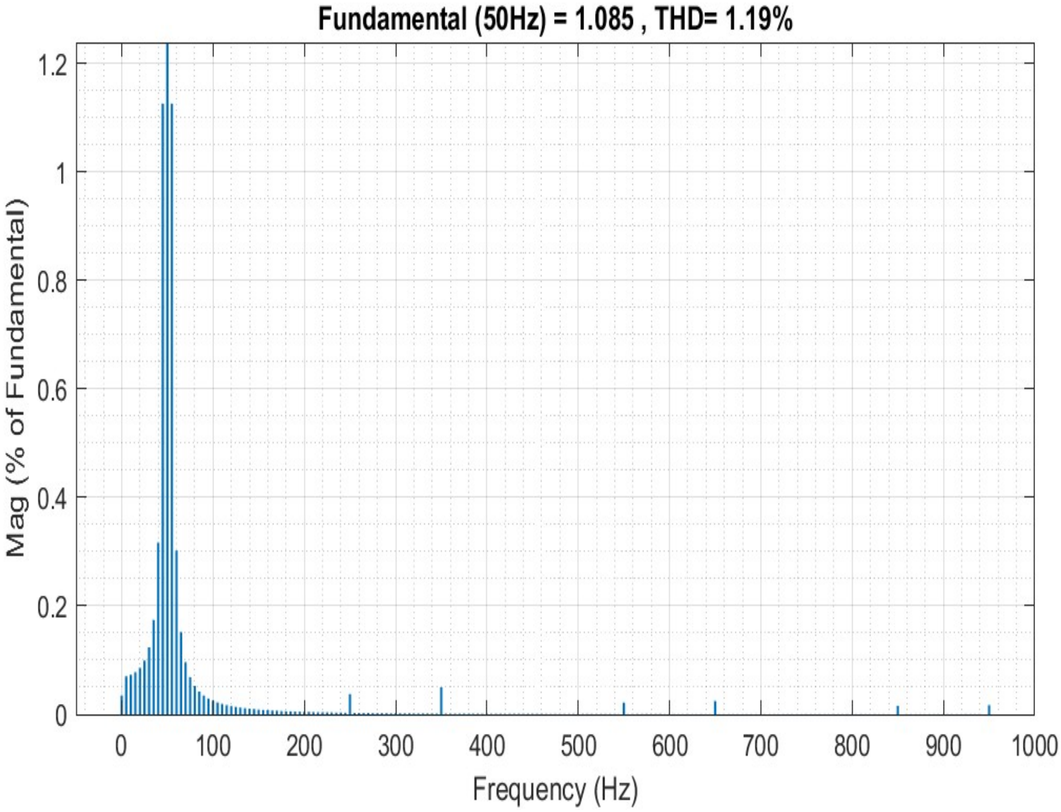


Figure 5.16: After Compensation Source Current FFT Analysis

Technique	**Phase**	**THD Before Compensation (%)**	**THD After Compensation (%)**
PI Controller	Phase-A	40.456	3.86
	Phase-B	41.87	3.90
	Phase-C	36.48	3.85
SMC Controller	Phase-A	40.456	1.75
	Phase-B	41.87	1.80
	Phase-C	36.48	1.69
Hysteresis Current Controller	Phase-A	40.456	1.19
	Phase-B	41.87	1.29
	Phase-C	36.48	1.16

Table 5.2: Comparison of THD Reduction Before and After Compensation Using Different Control Techniques

Chapter 6

Conclusion and Future Work

6.1 Conclusion

In conclusion, our research has highlighted key findings regarding the most effective techniques for power quality improvement:

1. Through a comprehensive literature review of current generation techniques, we have determined that Instantaneous Reactive Power Theory (IRPT) stands out as the most suitable method. Its efficiency lies in its reduced computational complexity, which in turn accelerates the control process, promising enhanced performance in power quality management.
2. Similarly, in our investigation of current injection techniques, the Hysteresis Current Controller has emerged as the optimal choice. Its simplicity in implementation, coupled with its swift response characteristics, make it a highly effective tool for achieving precise current control in power systems.
3. The application of Shunt Active Power Filter (SAPF) has demonstrated remarkable results in mitigating harmonic distortion. In the case of a single rectifier scenario, the Total Harmonic Distortion (THD) was substantially reduced from 43.44% to a mere 0.84% post-compensation, indicating a significant improvement in power quality.

4. Furthermore, our analysis extended to scenarios involving two single bridge rectifiers, where the THD levels prior to compensation were even higher at 50.30%. However, following compensation with SAPF, the THD decreased significantly to 1.46%, underscoring the efficacy of this approach in effectively reducing harmonic content and enhancing power quality standards.

In essence, these findings underscore the importance of employing advanced control and compensation techniques like IRPT, Hysteresis Current Controller, and SAPF in addressing power quality issues, ultimately ensuring more reliable and efficient operation of power systems.

6.2 Future Work

1. **Algorithm Refinement:**

   The optimization and refinement of control algorithms represent a promising avenue for enhancing the performance and efficiency of Shunt Active Power Filters (SAPFs). By further fine-tuning control algorithms, researchers can achieve more accurate harmonic compensation and dynamic response to varying load conditions. This refinement could involve the development of sophisticated control strategies that adaptively adjust parameters in real-time, optimizing SAPF operation under diverse operating conditions.

2. **Integration of Advanced Technologies:**

   Exploring the integration of advanced technologies, such as artificial intelligence (AI) and machine learning (ML) algorithms, holds great potential for advancing SAPF control methodologies. AI and ML algorithms offer the capability for adaptive and autonomous control, enabling SAPFs to learn from operating data and optimize their performance over time. Additionally, these technologies could facilitate real-time fault detection and predictive maintenance strategies, enhancing the reliability and robustness of SAPFs. Enabling proactive maintenance and immediate fault response ensures continuous system performance, minimizing downtime.

3. **Renewable Energy Integration:**

   Investigating the integration of renewable energy sources (RES) and energy storage systems (ESS) with SAPFs presents an opportunity to enhance grid stability and resilience. By coupling SAPFs with RES and ESS technologies, researchers can develop hybrid systems capable of mitigating the intermittency and variability associated with renewable energy generation. This integration could unlock synergistic benefits, such as improved power quality, enhanced grid stability, and increased renewable energy penetration, contributing to a more sustainable and resilient electrical grid.

4. **Grid-Interactive Capabilities:**

   Researching the development of SAPFs with grid-interactive capabilities, such as voltage regulation and power factor correction, could further enhance their versatility and applicability in diverse grid scenarios. By incorporating advanced grid-support functions into SAPFs, such as reactive power injection and voltage control, these devices can actively contribute to grid stability and reliability. Additionally, grid-interactive SAPFs could facilitate the integration of distributed energy resources (DERs) and support the transition towards a more decentralized and flexible grid architecture.

5. **Field Testing and Validation:**

   Conducting extensive field testing and validation studies in real-world grid environments is essential to assess the practical performance and scalability of SAPFs. Field trials allow researchers to evaluate SAPF operation under varying operating conditions, validate control algorithms, and identify potential challenges or limitations. Moreover, field testing provides valuable insights into the interaction between SAPFs and existing grid infrastructure, informing deployment strategies and optimizing system design for real-world applications. Through collaborative efforts with industry partners and utilities, field testing initiatives can accelerate the adoption and deployment of SAPFs, facilitating the transition towards a more resilient and sustainable electrical grid. This collaborative approach will foster innovation and improve grid performance.

In summary, future research endeavors in the field of Shunt Active Power Filters (SAPFs) should focus on algorithm refinement, integration of advanced technologies, renewable energy integration, development of grid-interactive capabilities, and extensive field testing and validation. By addressing these key areas, researchers can further enhance the performance, reliability, and scalability of SAPFs, contributing to the advancement of power quality and grid stability in modern electrical networks.

Chapter 7

Appendix

Clark Transformation

```
function [p, p0, i0, q] = fcn(va, vb, vc, ial, ibl, icl)

v_zero = (va + vb + vc) / sqrt(3);
v_alpha = (va - vb / 2 - vc / 2) * sqrt(2 / 3);
v_beta = (vb - vc) / sqrt(2);

il_zero = (ial + ibl + icl) / sqrt(3);
il_alpha = (ial - ibl / 2 - icl / 2) * sqrt(2 / 3);
il_beta = (ibl - icl) / sqrt(2);
i0 = il_zero;

p0 = v_zero * il_zero;
p = v_alpha * il_alpha + v_beta * il_beta;
q = v_beta * il_alpha - v_alpha * il_beta;
```

Listing 7.1: Clark Transformation Code

Inverse Clark Transformation

```
function [iac, ibc, icc] = fcn(i0, p0, p, q, va, vb, vc)

v_zero = (va + vb + vc) / sqrt(3);
v_alpha = (va - vb / 2 - vc / 2) * sqrt(2 / 3);
v_beta = (vb - vc) / sqrt(2);
i_zero = i0;
i_alpha = (v_alpha .* p + v_beta .* q) / (v_alpha.^2 + v_beta.^2);
i_beta = (v_beta .* p - v_alpha .* q) / (v_alpha.^2 + v_beta.^2);
iac = sqrt(2 / 3) * (i_zero / sqrt(2) + i_alpha);
ibc = sqrt(2 / 3) * (i_zero / sqrt(2) - i_alpha / 2 + sqrt(3) * i_beta / 2);
icc = sqrt(2 / 3) * (i_zero / sqrt(2) - i_alpha / 2 - i_beta * sqrt(3) / 2);
```

Listing 7.2: Inverse Clark Transformation Code

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