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DEVELOPMENT OF HYBRID ACTIVE POWER FILTER FOR THE MITIGATION OF HARMONICS

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ABSTRACT

This research project proposes an innovative Hybrid Active Power Filter (HAPF) designed to alleviate harmonic distortion in power systems attributable to non-linear loads. By integrating solar energy as a sustainable and renewable power source, the system synergistically combines active and passive filtering methodologies to adaptively mitigate harmonic components. Initially, the system exhibited substantial harmonic distortion, with a Total Harmonic Distortion (THD) of **35.66%**. However, upon implementation of the HAPF, THD was significantly reduced to **3.08%.** The HAPF's efficacy is attributable to key subsystems, including the PI Controller, PQ and I Compensation Calculation, Hysteresis Controller, and PQ Measurement, which collectively facilitate precise compensating currents and optimal system performance. This groundbreaking approach underscores the potential for solar-powered systems to provide high-quality power while minimizing environmental impact, reducing dependence on fossil fuels, and enhancing energy independence.

KEYWORDS: *SAPF, HAPF, FFT, MPPT, PQ, DQ, MBC, THD, APF, VSI*

INTRODUCTION

Power Quality, refers to the condition of voltage and current in a power system, assessed by voltage stability, supply continuity, and waveform similarity to a pure sine wave [11]. Poor power quality can cause financial losses, including equipment damage, downtime, service disruptions, and increased repair costs, as well as reduce device efficiency and increase energy consumption, raising operational expenses. Disturbances in power quality arise from factors like voltage fluctuations (sags, swells, transients), harmonic distortion, frequency deviations, and phase imbalance [8]. To ensure power quality, strict standards such as IEEE 519, IEEE 1159, the IEC 61000 series, and EN 50160 have been established for industrial and residential settings, defining voltage and current limits to reduce equipment malfunctions, damage, and safety risks. Compliance with these guidelines is essential, and as industries and infrastructure continue to evolve, the importance of effective power quality analysis and improvement grows.

LITRATURE REVIEW

Power quality disturbances, including voltage sags, swells, transients, harmonic distortion, frequency deviations, and phase imbalances, stem from a variety of underlying factors and often present identifiable symptoms depending on the specific nature of the issue [8]. These manifestations may include phenomena such as lamp flickering, recurrent power outages, frequent disruptions in the operation of sensitive equipment, unexpected voltage presence relative to the ground, interference in communication systems, and excessive heating of electrical components or devices [1]. Among these, harmonic distortion is a significant concern, arising from non-linear loads such as modern electronic devices that disturb the smooth sinusoidal waveform characteristic of alternating current systems. Harmonics, which are current or voltage waveforms occurring at frequencies that are integer multiples of the fundamental frequency, can extend to higher orders, with those between the 3rd and 25th being most commonly observed.

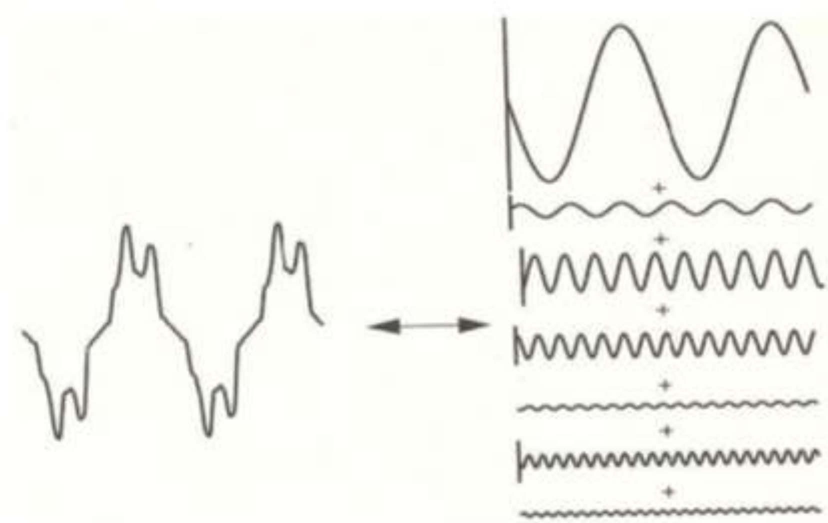


Figure 1. The harmonic distortion produced in sinusoidal wave

To quantify the extent of harmonic distortion, Total Harmonic Distortion (THD) serves as a critical metric, offering insights into waveform deviations by comparing the magnitudes of harmonic frequencies to the fundamental [2]. Expressed as a ratio or percentage, THD highlights the presence and severity of harmonic content within a system, with higher values indicating greater distortion, leading to diminished efficiency and potential operational issues. The formula for calculating THD involves determining the root mean square of the harmonic components relative to the fundamental, providing a nuanced understanding of power quality within the system.

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots I_n^2}}{I_1}$$

Where:

I_1 is the amplitude of the fundamental current.

I_2, I_3, I_4, ……. I_n are the amplitudes of the harmonic components of current at frequencies $2f$, $3f$, $4f$, …….nf respectively.

The international standards IEC 61000.3.6 and IEEE 519 set guidelines for acceptable levels of harmonic voltages in power systems. According to these standards, Total Harmonic Distortion (THD) limits for current and voltage are generally specified within the range of 5% to 8% for total harmonic current, while individual harmonic components are typically required to remain at or below 6%. These thresholds are critical for maintaining power quality and ensuring the efficient operation of electrical systems.

Power Filter:

Harmonic filters are specialized electrical circuits specifically designed to eliminate distortion and interference in electrical currents and voltages caused by harmonic frequencies. These filters are crucial for maintaining power quality and come in three primary categories: passive, active, and hybrid filters[3].

Passive filters are designed using a combination of passive components such as resistors, capacitor and/or inductors with the intention of either directing the undesirable components through a different path and/or by providing a high impedance path for undesirable components to block it [6].

Active filters make use of power electronic devices and appropriate control techniques to feed the harmonic current required by the load so that only the clean current is drawn by the load [13].

Passive Power Filter:

Passive filters are extensively utilized as an effective solution for mitigating power system harmonics. These filters are available in various topologies, each characterized by unique frequency response attributes [9],[6]. Constructed using passive components such as resistors, capacitors, and inductors, passive filters function by selectively allowing certain frequencies to pass while attenuating others. Unlike their active counterparts, passive filters operate without the need for external power sources or amplification components, relying instead on the intrinsic impedance characteristics of their elements. Capacitors exhibit low impedance at higher frequencies, whereas inductors demonstrate the inverse behaviour, facilitating the design of filter configurations such as low-pass, high-pass, band-pass, and band-stop filters. Widely employed in audio systems, communication networks, and power circuits, passive filters are valued for their simplicity, reliability, and efficiency, despite their relatively lower precision compared to active filters.

Types of Passive Filters:

1. **Single-Tuned Filters**: Single-tuned filters, also known as notch filters, are a type of passive filter specifically designed to target and mitigate individual harmonic frequencies. They consist of a combination of inductors (L) and capacitors © arranged in a series or parallel configuration, tuned to resonate at a specific harmonic frequency. When

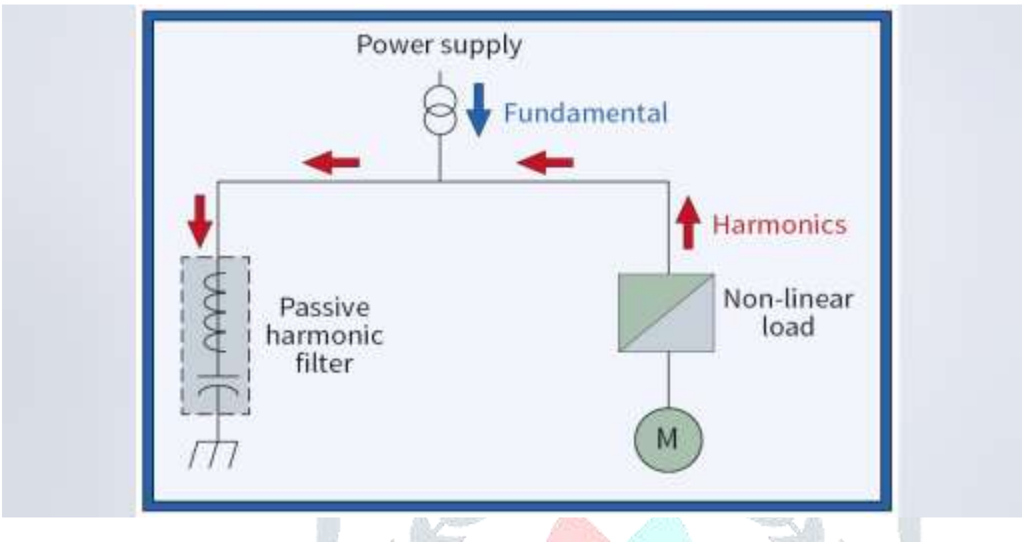


Figure 2. Harmonic Mitigation Techniques Passive Filter

harmonic currents at the tuned frequency flow through the filter, the filter provides a low-impedance path, effectively trapping and dissipating these currents. This prevents the harmonic currents from flowing into the rest of the power system.

The resonant frequency (f_r) of a single-tuned filter is given by the following expression:

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

Where:

- L is the inductance of the filter,
- C is the capacitance of the filter,
- f_r is the harmonic frequency at which the filter is tuned.
- Single-tuned filters are typically used to mitigate low-order harmonics, such as the 3rd, 5th, 7th, 11th, or 13th harmonics, as these harmonics are the most prevalent in power systems with non-linear loads.

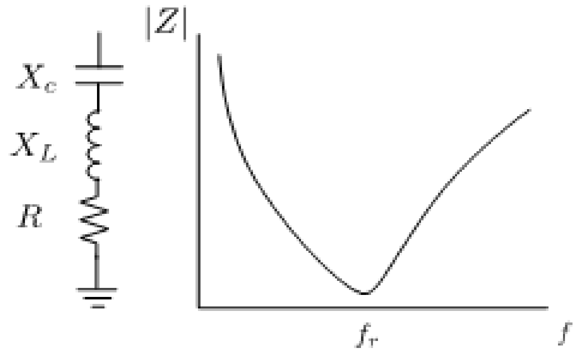


Figure 3. Series (Single-Tuned) Filter

2. **Broadband Filters**: Designed to accommodate a wide frequency spectrum, broadband filters include the following configurations:

   a. **Low-Pass Filters**: Allow frequencies below a predefined cutoff to pass through.

   b. **High-Pass Filters**: Permit frequencies above a certain cutoff while attenuating lower frequencies.

   c. **Band-Pass Filters**: Enable a defined range of frequencies to pass while blocking others.

   d. **Band-Stop Filters**: Suppress a specific frequency range while allowing others to pass.

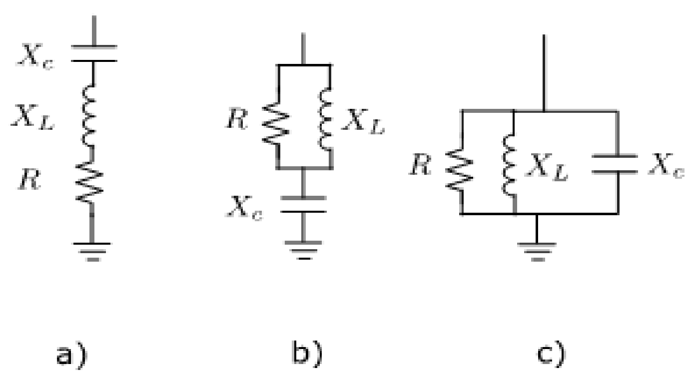


Figure 4. Filter Configurations. a) Series, b) High-Pass, c) Band-Pass

Active power filter:

Active filters were developed as a solution to the limitations of passive filters, offering enhanced effectiveness in harmonic compensation and improved overall performance [5]. In active methods, harmonic distortion is mitigated by introducing a current or voltage distortion of the same magnitude but opposite phase at the Point of Common Coupling (PCC). Active power filters are widely used to reduce harmonic distortion within the thresholds specified by the IEEE-519 standard. They serve as a viable alternative for managing harmonic levels in power systems due to several advantages over passive filters, such as adaptability to load variations, selective harmonic compensation, reactive power compensation, and the elimination of resonance issues [12]. The operation of active filters involves generating a reference current that is the inverse of the extracted harmonic current and injecting this reference current at the PCC through power electronic switching to neutralize individual harmonics.

Shunt Active Power Filter (SAPF):

A Shunt Active Power Filter (SAPF) is a power electronic device used to improve power quality by mitigating harmonic distortion, compensating reactive power, and enhancing system stability. It achieves this by injecting compensating currents into the system, calculated based on measured load current and voltage. The SAPF comprises components such as power electronic switches, a DC bus capacitor, current and voltage sensors, and a control unit. Common configurations include Voltage Source Inverter (VSI)-based, Current Source Inverter (CSI)-based, and Multilevel Inverter-based SAPFs. While SAPFs offer benefits like effective harmonic suppression, improved power factor, reduced Total Harmonic Distortion (THD), and compact design, they also face challenges such as high cost, complex control algorithms, switching losses, and electromagnetic interference.

Control strategies for SAPFs include Instantaneous Reactive Power (p-q) Theory, Synchronous Reference Frame (SRF) Theory, Adaptive Filter Theory, and Model Predictive Control (MPC). Design considerations involve selecting appropriate filter ratings, optimizing the DC bus capacitor, managing switching frequency, refining control algorithms, and mitigating electromagnetic interference. SAPFs are widely applied in industrial and commercial systems, renewable energy setups, distribution networks, and electric vehicle charging stations. Key controllable components in SAPFs include harmonic detection, voltage regulation, and current control. Techniques like p-q theory and d-q theory are commonly used for harmonic detection, Proportional-Integral (PI) control is preferred for voltage regulation [7], and hysteresis-based control is widely adopted for current control.

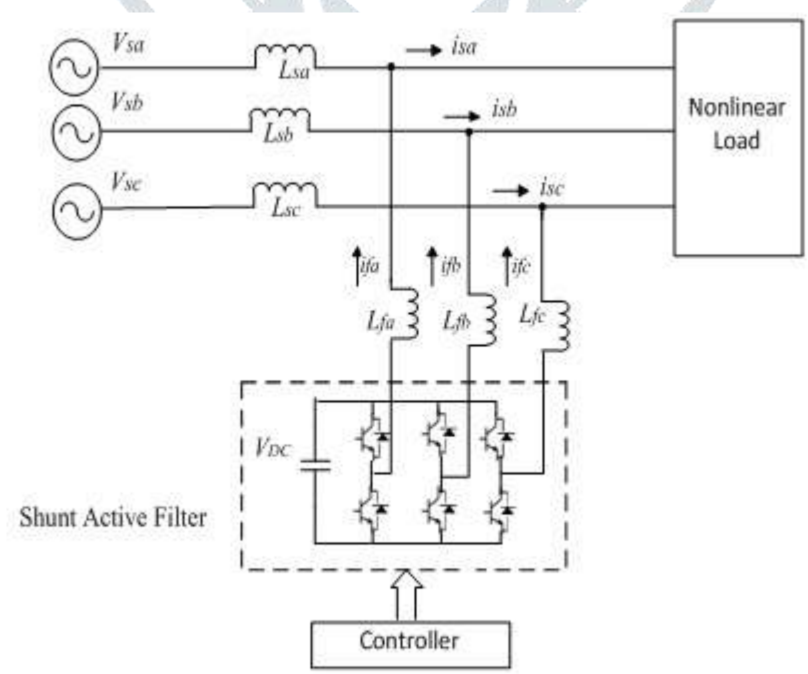


Figure 5. Shunt active power filter block diagram

Series Active Power Filter (SAPF):

The Voltage Source Inverter (VSI) of a Series Active Power Filter (SAPF) generates a Pulse Width Modulation (PWM) output, injecting a voltage in series between the source and load to effectively eliminate harmonic components in the circuit. The generation of the reference voltage is guided by a current control method, where the harmonic and reactive components of the current drawn by the load are extracted by the series compensator [10].

The Series Active Power Filter is connected in a series configuration within the power system, with its primary role being the protection of sensitive loads from voltage disturbances such as sags, swells, and transients. Unlike shunt filters, which address current waveform distortions, the series filter compensates for voltage irregularities by injecting a controlled voltage to neutralize distortions in the supply voltage. This ensures a clean and stable voltage supply for sensitive equipment, making Series Active Power Filters particularly advantageous in environments where voltage stability is critical for the reliable operation of sensitive systems.

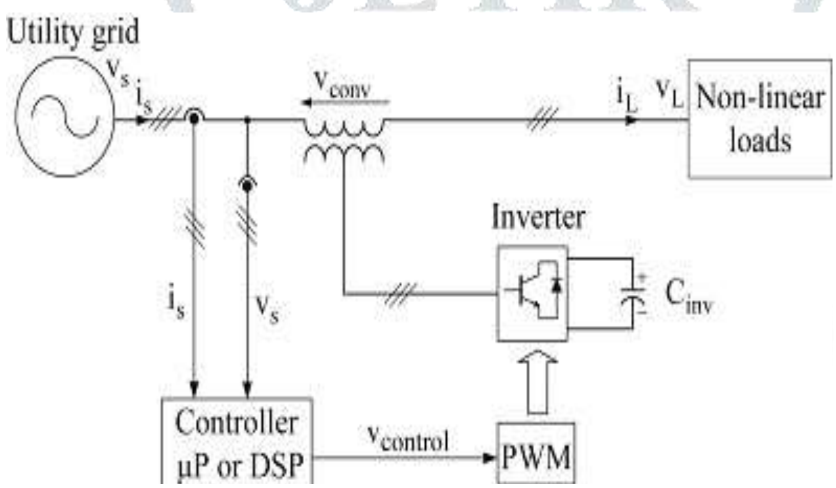


Figure 6. Series Active Filter

Hybrid Active Power Filter (HAPF):

Hybrid Active Power Filters (HAPFs) offer an efficient and versatile solution for mitigating harmonic distortion in modern power systems. By integrating the strengths of passive and active filtering techniques, HAPFs enhance power quality while maintaining cost-effectiveness and operational efficiency. The passive filter is responsible for addressing low-order harmonics, while the active power filter (APF) compensates for higher-order harmonics and dynamically adapts to changes in the harmonic profile. When designed and implemented effectively, HAPFs can significantly reduce Total Harmonic Distortion (THD), improve power factor, and ensure reliable electrical system performance across diverse applications.

Hybrid filters combine passive and active components to optimize harmonic mitigation, leveraging the advantages of both approaches while minimizing their limitations. Typically, the passive filter targets low-order harmonics, while the active filter handles higher-order harmonics and provides real-time compensation. This complementary interaction ensures robust harmonic suppression and improved system stability.

The instantaneous active and reactive power theory, also referred to as pq0 theory in three-phase four-wire systems, forms the foundation of SHAPF control strategies. This theory begins with the Clarke transformation, which converts three-phase load currents (i_{La}, i_{Lb},i_{Lc}) and source voltages (V_{Sa}, V_{Sb}, V_{Sc}) from abc coordinates to αβ0 coordinates. The pq0 theory is then employed to generate the required harmonic reference currents (i_{ra}, i_{rb}, i_{rc}), enabling effective harmonic compensation [4].

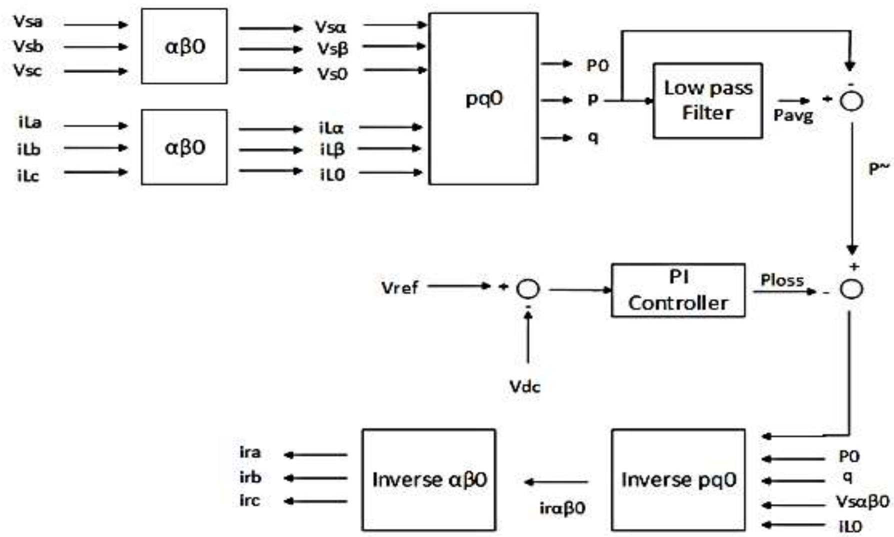


Figure 7. p-q theory-based harmonic detection in SHAPF

PROBLEM IDENTIFICATION

This MATLAB simulation conducts an in-depth investigation into the operational dynamics of a solar-powered electrical distribution system, incorporating a photovoltaic source as the primary energy provider and a trio of diverse loads, namely a Three phase unbalanced load, a Three phase rectifier, and a Three phase induction motor. The complex interplay between these system components necessitates a thorough examination of the potential challenges and limitations inherent in such a configuration.

The integration of nonlinear loads into solar power systems introduces significant performance hurdles, triggering a range of problems. These issues encompass harmonic distortion, power factor deterioration, voltage instability, and excessive thermal loading, ultimately jeopardizing system reliability and efficiency.

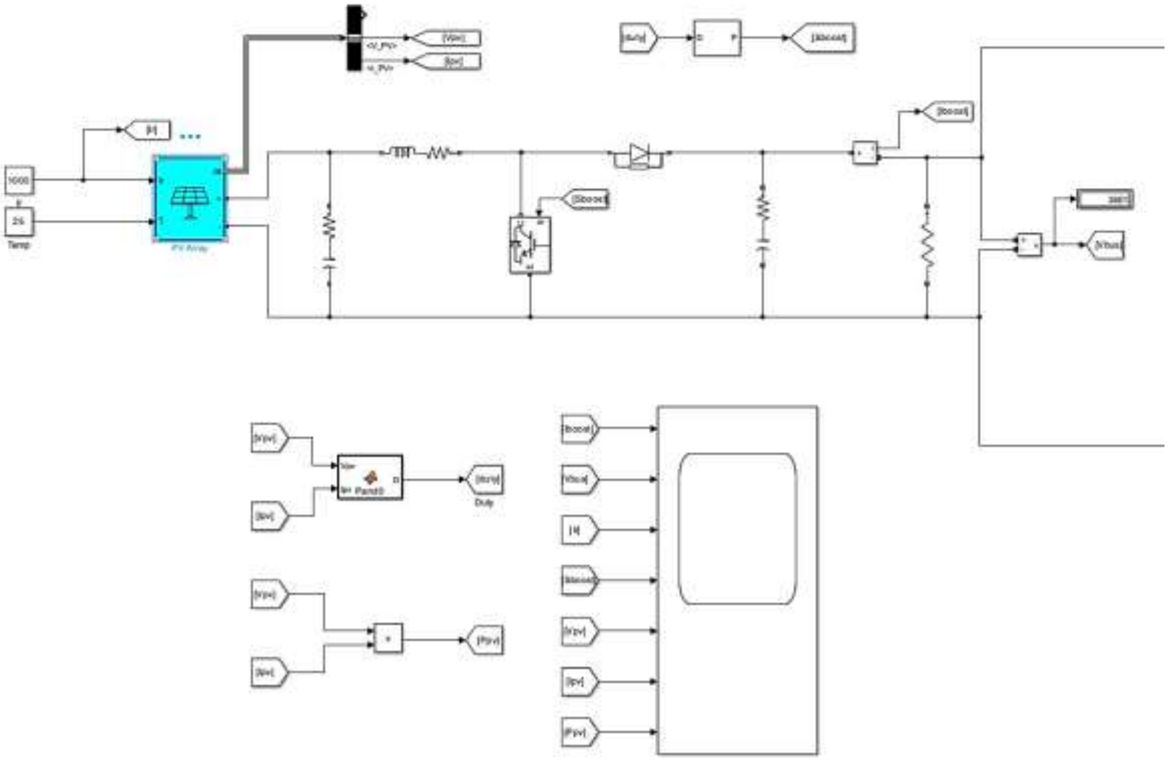


Figure 9. Three phase Inverter with SPWM and three phase LC filter

Figure 8. Solar source with P&O MPPT and Boost converter

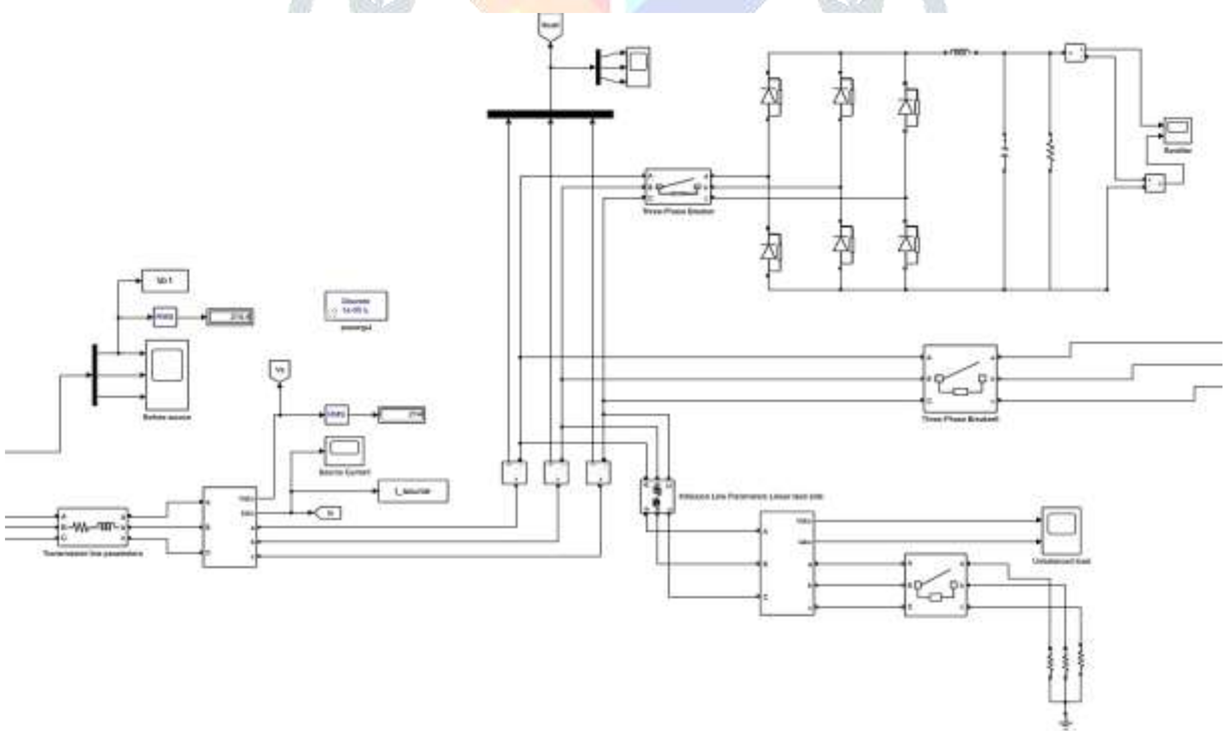


Figure 10. Rectifier and three phase unbalanced load

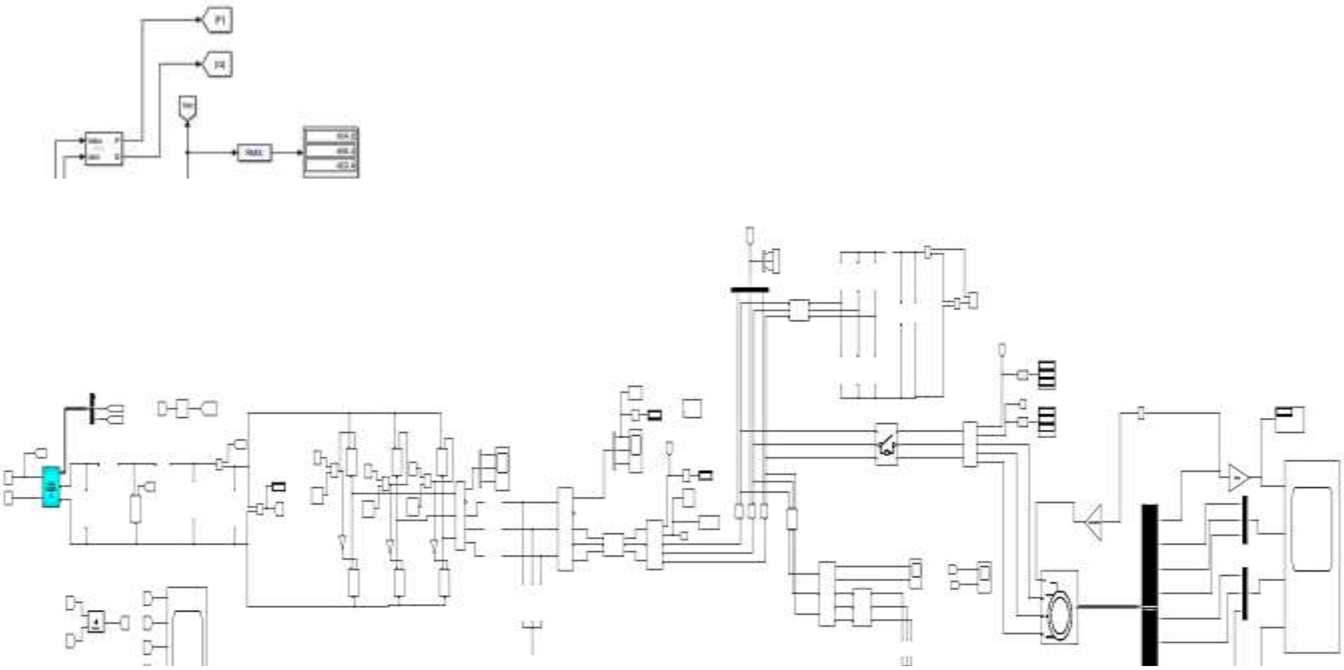


Figure 11. Induction Motor with Asynchronous load

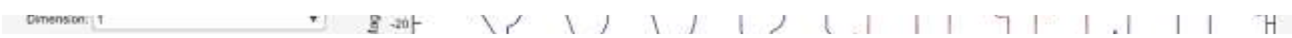


Figure 12. Simulation

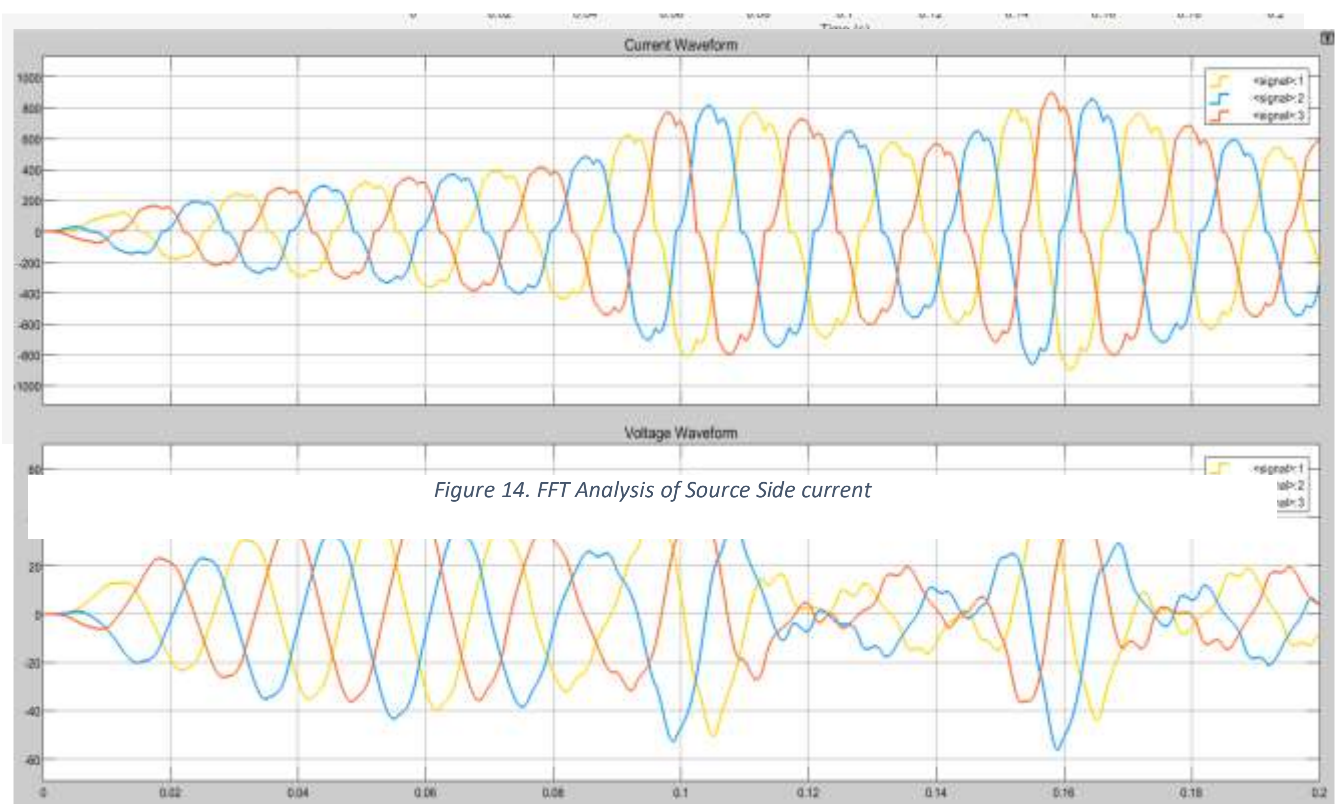


Figure 14. FFT Analysis of Source Side current

Nonlinear loads, increasingly prevalent in residential and industrial settings, distort current waveforms due to non-

Figure 13. Current and Voltage waveform of source side

proportional current-voltage relationships. Devices such as computers and variable frequency drives generate high-crest-factor pulse waveforms, compromising power quality and potentially leading to device malfunctions, lighting flicker, and premature equipment failure. Effective control and mitigation strategies are crucial to maintaining consistent power quality, as nonlinear loads can introduce harmonic distortion, degrade power factor, cause voltage instability, and increase thermal loading, emphasizing the need for advanced solutions to ensure reliable and efficient electricity distribution.

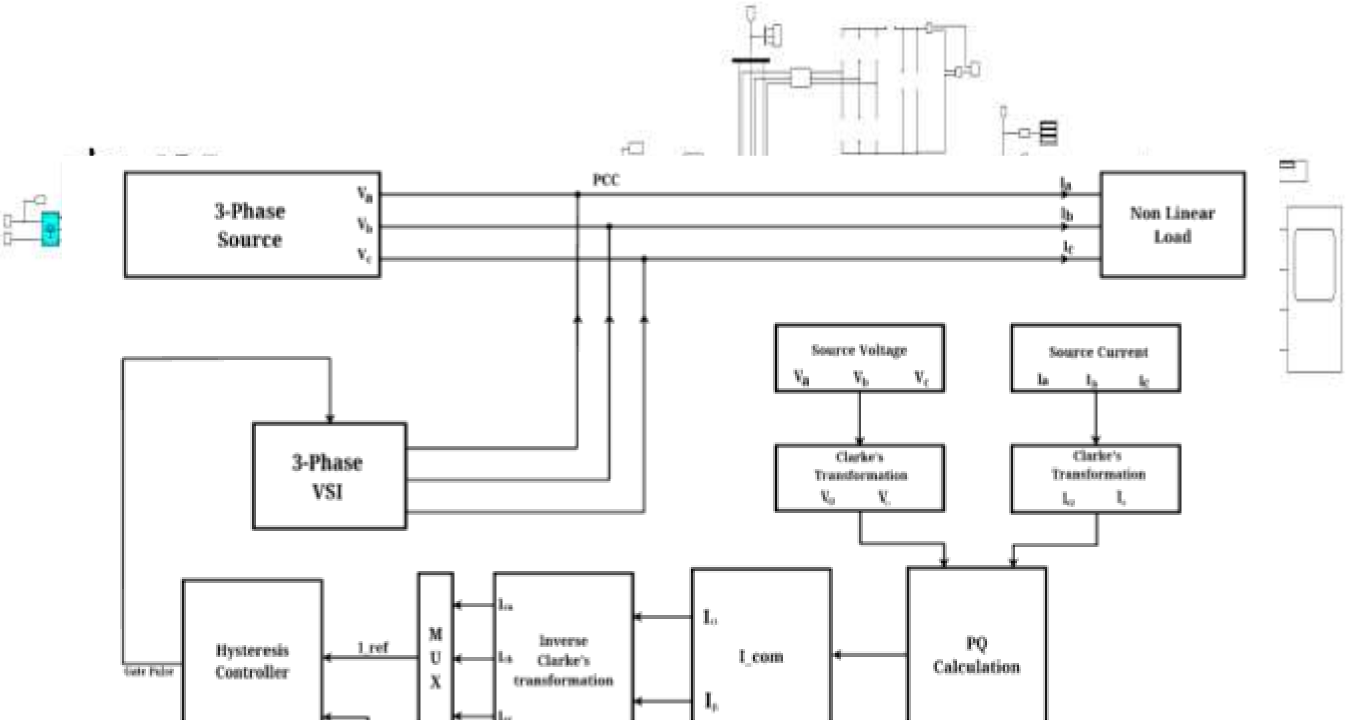
It is evident from the above waveforms that the source current after performing the FFT analysis we get a measurement of the harmonic distortion present in the source current waveform in terms of THD.

The presence of harmonics, primarily triggered by nonlinear loads, is widely acknowledged as the primary culprit behind power quality degradation. These undesirable electrical distortions can have far-reaching, detrimental consequences on electrical systems, including overheating and reduced lifespan of equipment, malfunctions and premature failure of sensitive devices, increased energy losses, decreased system efficiency, interference with communication and control systems, and voltage instability. Additionally, harmonics can lead to capacitor overheating, transformer degradation, motor vibration, and power factor degradation, resulting in penalty charges. Therefore, mitigating harmonic distortion is crucial for ensuring reliable, efficient, and safe operation of electrical system.

PROPOSED METHODOLOGY

The SAPF is designed to produce compensating currents that neutralize harmonic currents generated by non-linear loads such as variable-speed drives, rectifiers, and other power electronic devices frequently utilized in industrial and commercial settings. The SAPF subsystem, which constitutes the central component of the proposed approach, is composed of four modules: the Proportional-Integral (PI) Controller, the PQ and Current Compensation Calculation, the Hysteresis Controller, and the PQ Measurement subsystem.

The effective operation of the SAPF depends on its ability to precisely identify the harmonic components present in the load current. In the proposed solution, the Instantaneous Reactive Power Theory (pq Theory) is employed to extract the harmonic currents.



The

Figure 15. Simulation with SAPF

Figure 16. Block diagram of proposed system

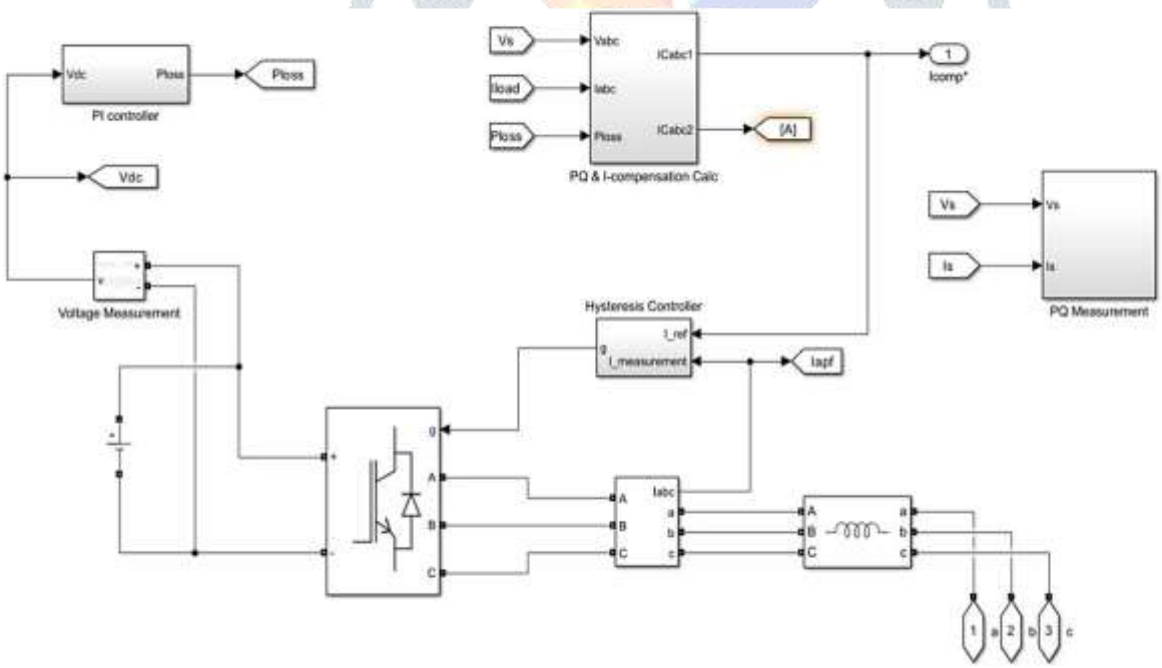


Figure 17. SAPF

Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits also known as instantaneous power theory, or p-q theory. It is based on instantaneous values in three-phase power system with or without neutral wire and is valid for steady-state or transitory operations, as well as for generic voltage and current waveforms.

The method uses the transformation of distorted currents from three phase frame ABC into bi-phase stationary frame αβ. The basic idea is that the harmonic currents caused by nonlinear loads in the power system can be compensated with other nonlinear controlled loads. The p-q theory is based on a set of instantaneous powers defined in the time domain. The three-phase supply voltages (V_a, V_b, V_c) and currents (i_a, i_b, i_c) are transformed using the Clarke (or α-β) transformation into a different coordinate system yielding instantaneous active and reactive power components. This transformation may be viewed as a projection of the three-phase quantities onto a stationary two-axis reference frame.

The Clarke transformation for the voltage variables is given by:-

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \times \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (5.1)$$

Similarly the Clarke transformation for the current variables is given by:-

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \times \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (5.2)$$

The value of instantaneous active and reactive powers are then calculated using the equation:-

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (5.3)$$

This is passed through a low pass filter to remove any AC part present in them.

Then they are used for the calculation of compensation current using :-

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{{V_\alpha}^2 + {V_\beta}^2} \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} \tilde{P} \\ \tilde{Q} \end{bmatrix} \quad (5.4)$$

$$\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} \quad (5.5)$$

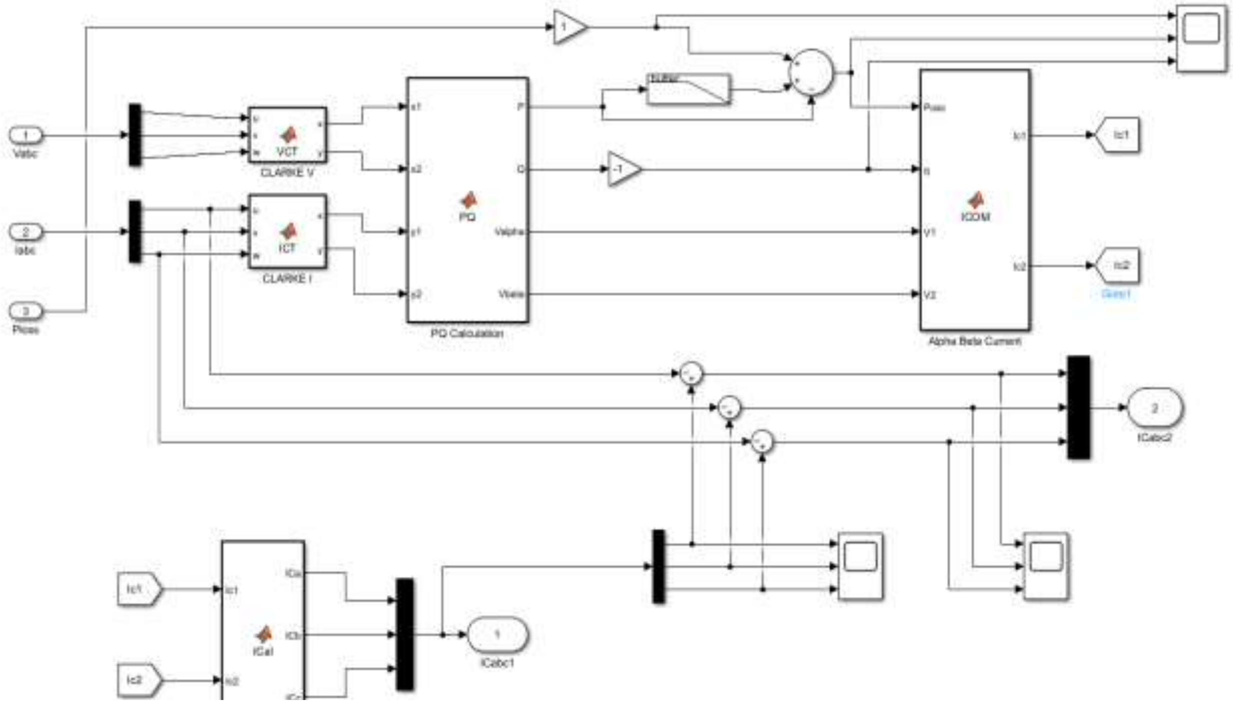


Figure 18. Input configuration of PQ and I

The actual value of current in the system is then compared with this value in the hysteresis controller to generate the PWM pulse required to control the operation of VSI and generate the compensating current to be injected in the system.

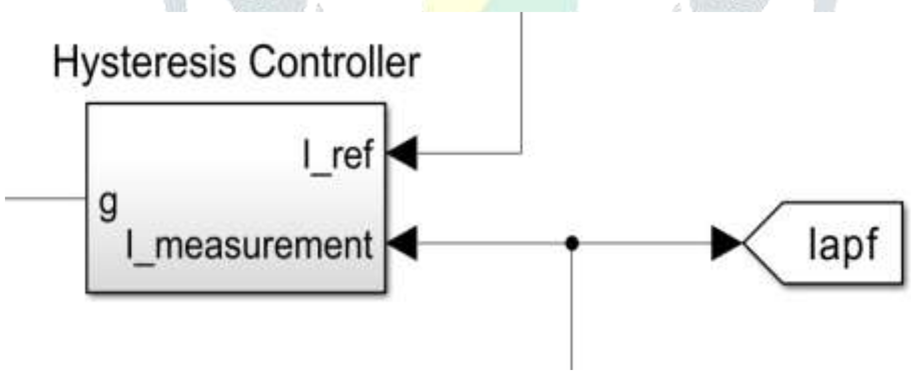


Figure 19. Hysteresis Controller

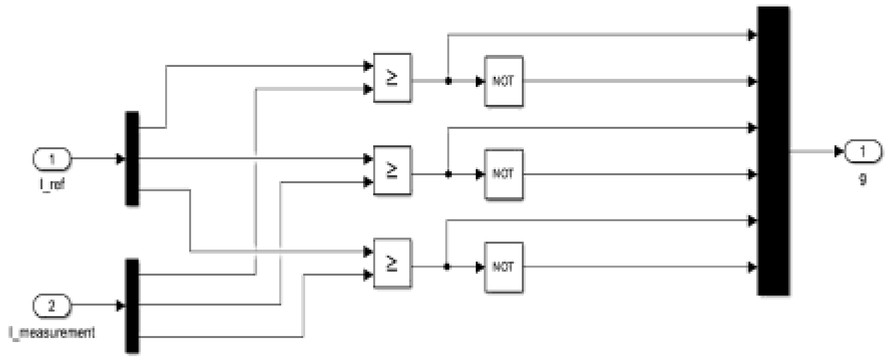


Figure 20. Input Configuration of Hysteresis Controller

RESULT

The FFT analysis of the system after integrating the Hybrid Active Power Filter is presented below:-

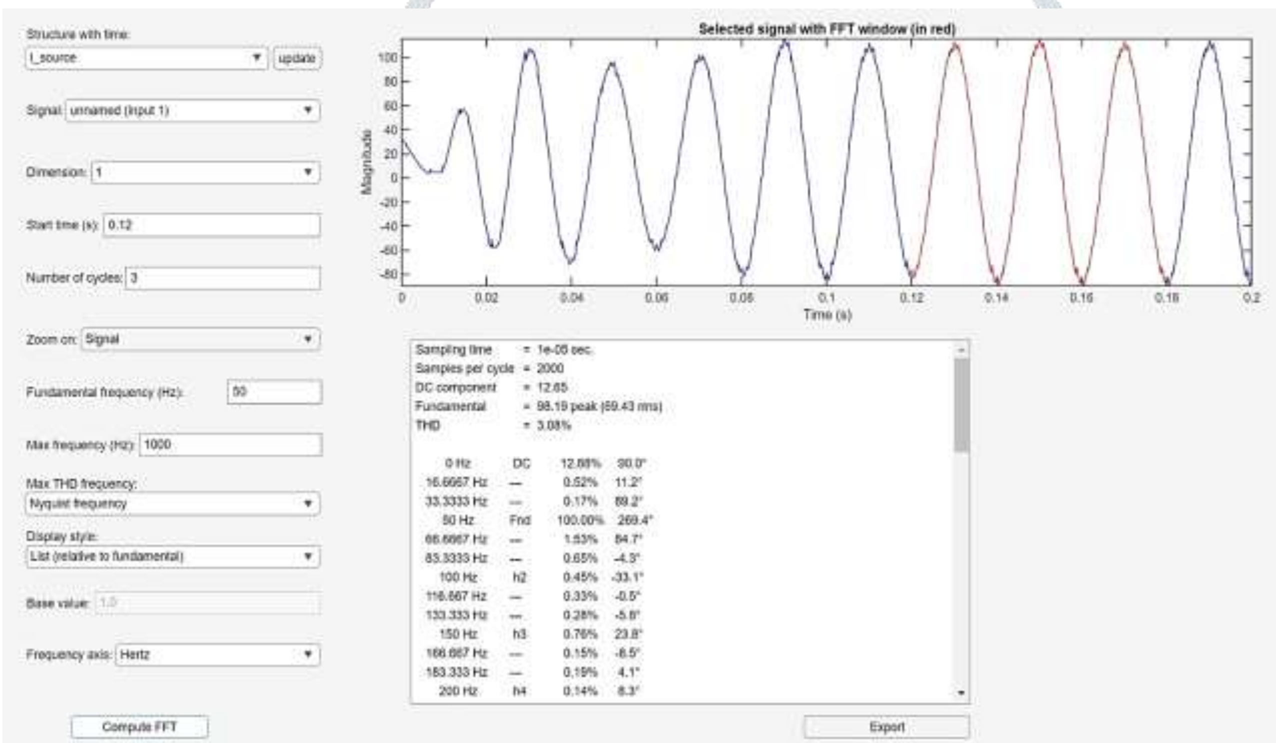


Figure 21. Source Current waveform and THD after implementing HAPF

After using HAPF, the THD was reduced to 3.08%.

After the shunt active power filter was connected at the point of common coupling in parallel with the nonlinear load, the source and load current waveforms were filtered. As shown in Figure, FFT analysis indicates that the Total Harmonic Distortion (THD) decreased by 91.36%, dropping from 35.66% to 3.08% of the fundamental value.

Following is the comparative analysis of Source Current without SAPF and with HAPF:-

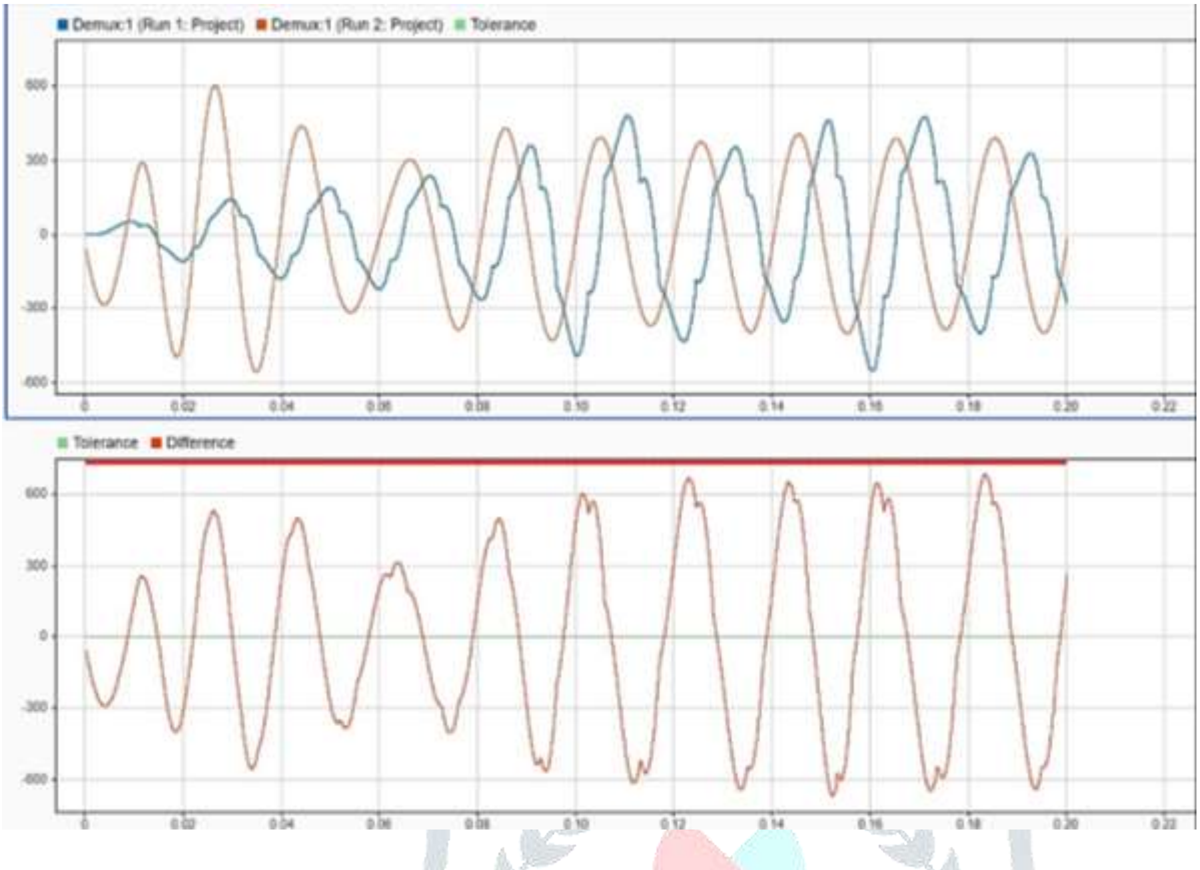


Figure 22. Comparative Analysis of simulation without SAPF and with HAPF

A comparative analysis of THD, illustrated in the graph, reveals a significant decrease in THD from **35.66%** to **3.08%** highlights the SAPF's effectiveness in improving power quality by reducing harmonics. This outcome confirms that the SAPF has effectively fulfilled its intended objective.

Following 2D graph shows the relation between Frequency and THD when SAPF is not connected:-

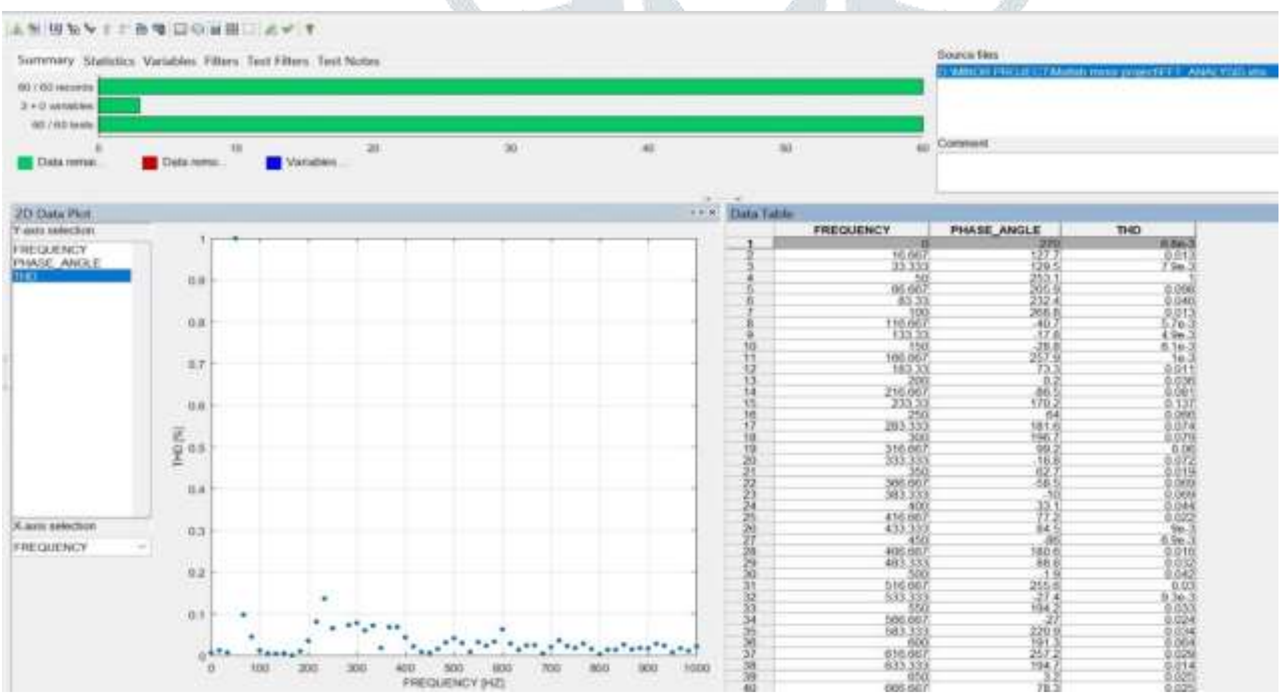


Figure 23. Relation between Frequency and THD when SAPF is not connected

Following 2D graph shows the relation between Frequency and THD when HAPF was connected:-

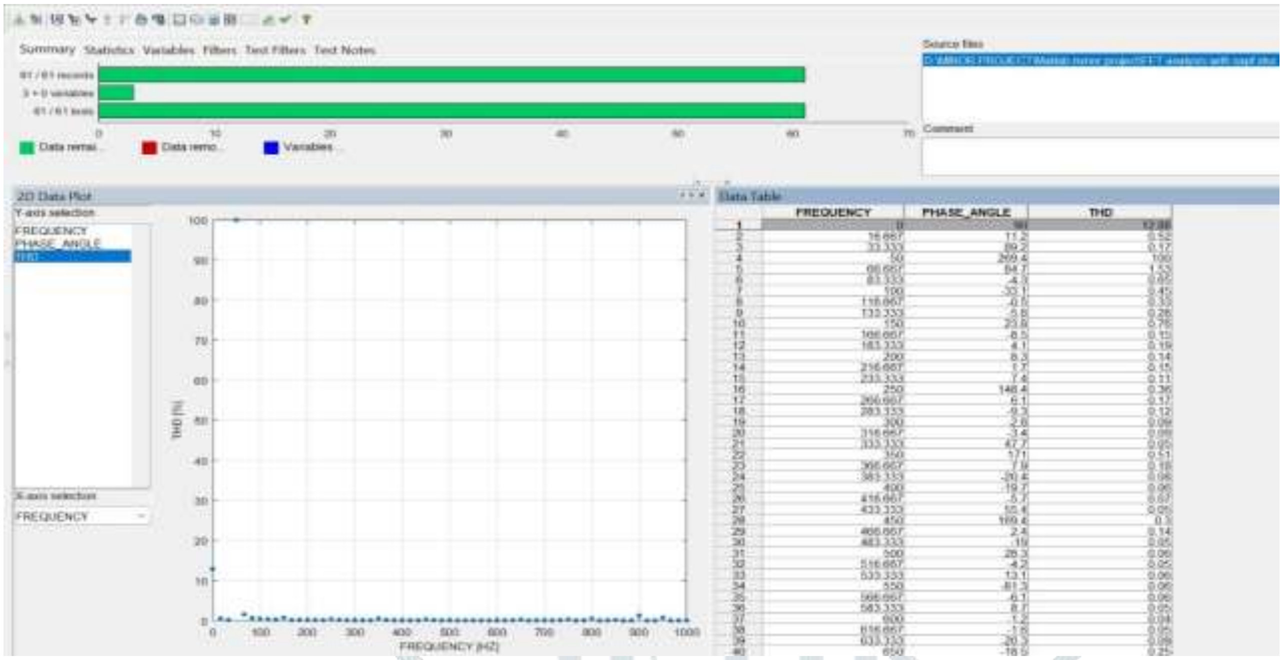


Figure 24. Relation between Frequency and THD when HAPF is connected

Following 3D graph shows the relation between Frequency, THD and Phase Angle when SAPF is not connected:-

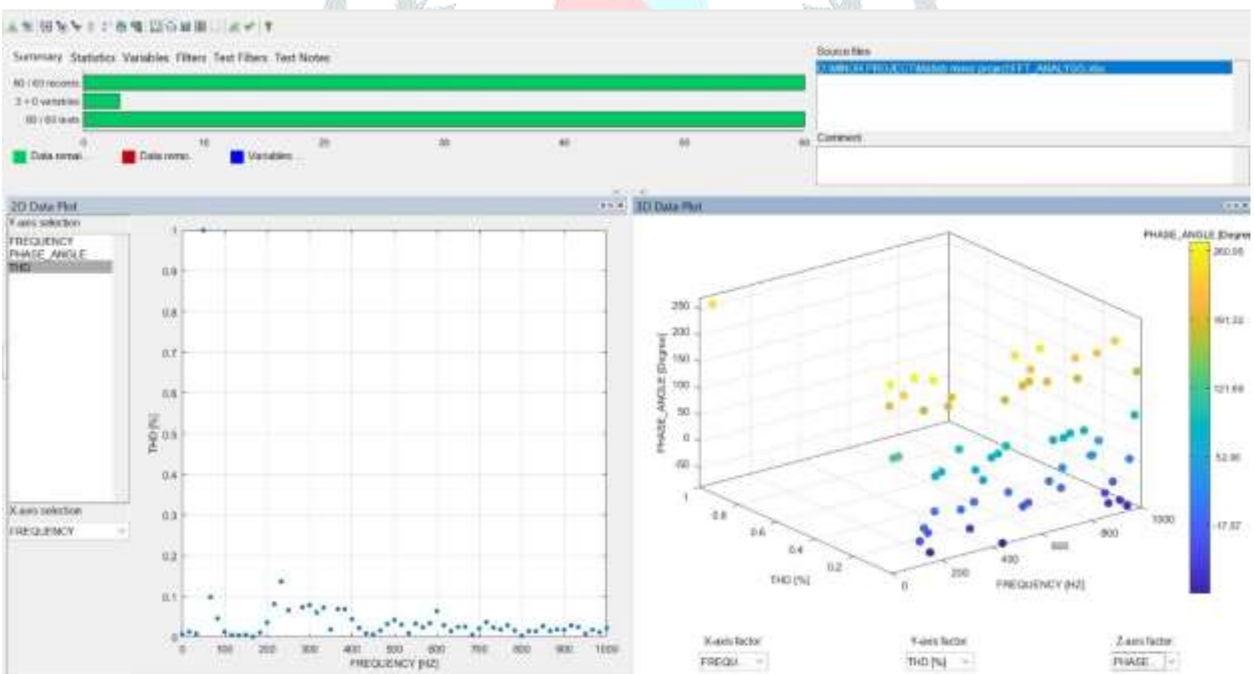


Figure 25. Relation between Frequency, THD and Phase Angle when SAPF is not connected

Following 3D graph shows the relation between Frequency, THD and Phase Angle when HAPF is connected:-

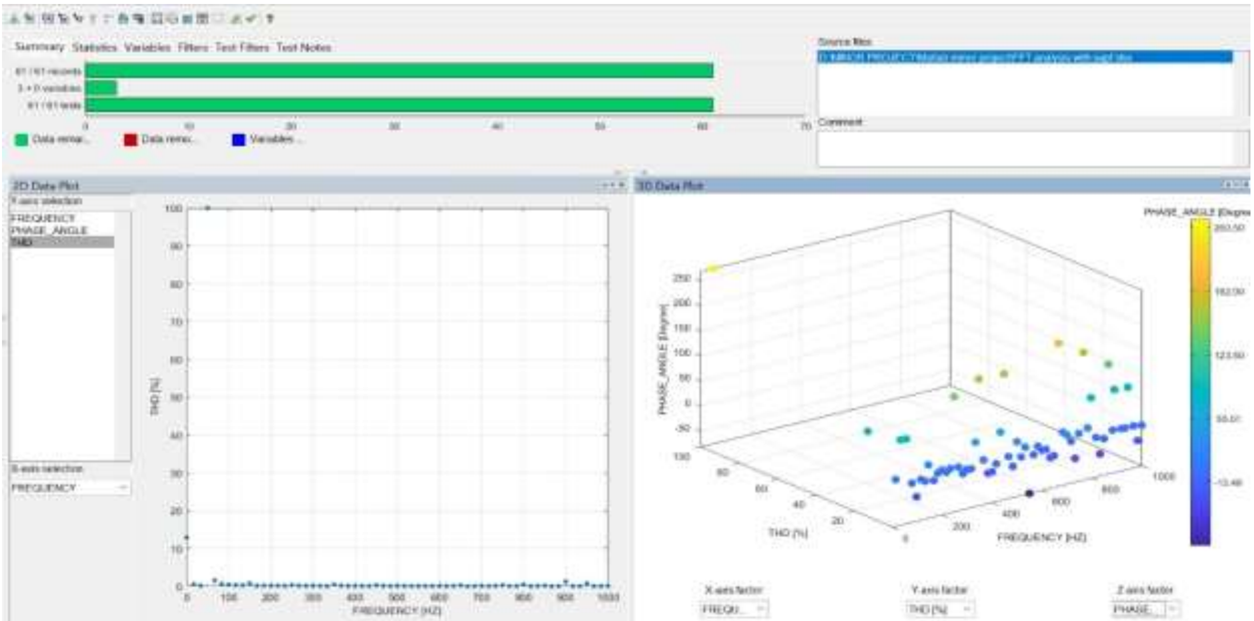


Figure 26. Relation between Frequency, THD and Phase Angle when HAPF is connected

Comparison of THD in Simulation

Without SAPF

Sampling time = 1e-05 sec.
Samples per cycle = 2000
DC component = 0.4827
Fundamental = 70.85 peak (50.1 rms)
THD = 35.66%

0 Hz	DC	0.68%	270.0°
16.6667 Hz	---	1.27%	127.7°
33.3333 Hz	---	0.79%	129.5°
50 Hz	Fnd	100.00%	253.1°
66.6667 Hz	---	9.82%	205.9°
83.3333 Hz	---	4.65%	232.4°
100 Hz	h2	1.29%	268.8°
116.667 Hz	---	0.57%	-40.7°
133.333 Hz	---	0.49%	-17.8°
150 Hz	h3	0.61%	-28.8°
166.667 Hz	---	0.10%	257.9°
183.333 Hz	---	1.10%	73.3°
200 Hz	h4	3.58%	0.2°

With SAPF

Sampling time = 1e-05 sec.
Samples per cycle = 2000
DC component = 1.182
Fundamental = 77.66 peak (54.91 rms)
THD = 4.55%

0 Hz	DC	1.52%	270.0°
16.6667 Hz	---	0.33%	159.1°
33.3333 Hz	---	0.63%	154.9°
50 Hz	Fnd	100.00%	269.9°
66.6667 Hz	---	0.76%	10.6°
83.3333 Hz	---	0.42%	4.2°
100 Hz	h2	0.33%	-59.9°
116.667 Hz	---	0.23%	0.7°
133.333 Hz	---	0.19%	0.1°
150 Hz	h3	0.15%	13.0°
166.667 Hz	---	0.15%	-0.5°
183.333 Hz	---	0.13%	-1.1°

With HAPF

Sampling time = 1e-05 sec.
Samples per cycle = 2000
DC component = 12.65
Fundamental = 98.19 peak (69.43 rms)
THD = 3.08%

0 Hz	DC	12.88%	90.0°
16.6667 Hz	---	0.52%	11.2°
33.3333 Hz	---	0.17%	89.2°
50 Hz	Fnd	100.00%	269.4°
66.6667 Hz	---	1.53%	84.7°
83.3333 Hz	---	0.65%	-4.3°
100 Hz	h2	0.45%	-33.1°
116.667 Hz	---	0.33%	-0.5°
133.333 Hz	---	0.28%	-5.8°
150 Hz	h3	0.76%	23.8°
166.667 Hz	---	0.15%	-8.5°
183.333 Hz	---	0.19%	4.1°
200 Hz	h4	0.14%	8.3°

Figure 27. Comparison of THD

CONCLUSION

The implementation of the Hybrid Active Power Filter (HAPF) has proven to be an effective solution for mitigating harmonics, improving power quality, and ensuring compliance with international power quality standards. By utilizing advanced control algorithms and efficient power electronics, the SAPF effectively compensates for current harmonics, reactive power, and load unbalances in real-time. This research demonstrates the feasibility of HAPF in various industrial and commercial applications, highlighting its ability to enhance system stability, reduce energy losses, and ensure reliable power delivery. Future work can focus on further optimizing control strategies and integrating renewable energy sources to enhance the overall efficiency and sustainability of HAPF systems.

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