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Advanced Power Quality Enhancement using Hybrid Active Power Filters for Harmonic Mitigation

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Abstract: This project focuses on mitigating harmonic distortion in power systems caused by nonlinear loads such as rectifiers and unbalanced loads while also improving unity power factor affected by inductive loads. Harmonics can degrade system efficiency and negatively impact electrical equipment, compromising overall operational reliability. To address these challenges, a Hybrid Active Power Filter (HAPF) was implemented to reduce Total Harmonic Distortion (THD) and achieve unity power factor by generating compensating currents. The integration of the SAPF successfully reduced THD from 30.26% to 8.07%, showcasing its effectiveness in mitigating harmonics. With the subsequent implementation of the HAPF, THD was further minimized to 0.60%, demonstrating a substantial improvement in power quality. The key subsystems involved include the PI Controller, PQ and I Compensation Subsystem, Hysteresis Controller, PQ Measurement Subsystem and Capacitor Bank. These components collectively ensure system stability, precise harmonic compensation, and real-time power quality monitoring, making this combined approach a highly efficient and practical solution for enhancing power system performance.

Keywords: Hybrid Active Power Filter (HAPF), Shunt Active Power Filter (SAPF), Fast Fourier Transform (FFT), Insulated-Gate Bipolar Transistor (IGBT), Point Of Common Coupling (PCC), Total Harmonic Distortion (THD), Non-Linear Loads, Power Quality, PI Controller, Compensating Currents, Hysteresis Controller, PQ Measurement.

I. INTRODUCTION

The increasing prevalence of power quality issues, especially harmonic distortion, has become a critical concern in industrial power systems. Harmonic distortion causes adverse effects such as equipment overheating, vibration, and premature aging, leading to significant economic losses. Traditional passive filters have limitations in mitigating harmonics, prompting the need for innovative solutions. Hybrid Active Filters (HAPFs) have proven to be effective, offering adaptive compensation and improved power factor. This study focuses on harmonic mitigation using HAFs, introducing a novel topology and advanced control strategies. Simulation and experimental results show substantial improvements in power quality, with reduced Total Harmonic Distortion (THD) and better power factor.

II. LITERATURE SURVEY

Narayan Prasad Gupta et al. (2012) [1] in their paper discussed that the increasing reliance on power electronic devices and non-linear loads in industrial, commercial, and residential sectors has led to severe power quality (PQ) issues, primarily due to harmonic distortions. Harmonic currents generated by these non-linear loads degrade system efficiency, increase power losses, and cause malfunctioning of sensitive equipment. To mitigate these problems, various filtering techniques have been developed, including passive filters (PFs), active power filters (APFs), and hybrid active filters (HAFs). Among these, HAFs have emerged as a superior solution due to their ability to provide efficient harmonic mitigation while addressing the shortcomings of standalone passive and active filters.

A. Harmonic Distortion and Power Quality Issues

konala kalyan et al. (2020) [2] mentioned that harmonics are unwanted frequency components that distort the fundamental waveform of electrical signals. The primary sources of harmonics include rectifiers, variable frequency drives, uninterrupted power supplies, and power converters, which result in excessive neutral currents, poor power factor, and increased system resonance.

These issues contribute to various adverse effects, including increased power losses, equipment overheating, electromagnetic interference (EMI), and voltage irregularities. Harmonics lead to higher copper and core losses in transformers and electrical machines, reducing overall efficiency. Nonlinear loads introduce excessive heating in motors, generators, and capacitors, causing premature aging and potential failure. Additionally, high-frequency harmonics create electromagnetic interference (EMI), disrupting communication systems and sensitive electronic equipment. Moreover, harmonics result in voltage sags, flickers, and distortion, leading to irregular voltage fluctuations that affect the stable power supply for industrial and commercial consumers [3].

B. Passive Filters (PFs)

Sanjay et al. (2019) [3] said in their paper, passive filters are widely employed for harmonic suppression due to their simplicity and cost-effectiveness. These filters are designed to provide low-impedance paths for specific harmonic frequencies, reducing their impact on the system.

The key types of filters include single-tuned, double-tuned, and C-type filters. Single-tuned filters are effective in eliminating dominant harmonics such as 5th, 7th, or 11th order harmonics, though they have limited adaptability. Double-tuned filters offer enhanced harmonic attenuation at two distinct frequencies, improving performance without significantly increasing system cost. Meanwhile, C-type filters are specifically designed to mitigate low-order harmonics while maintaining system stability and preventing resonance.

Despite these advantages, passive filters (PFs) have several drawbacks, including fixed compensation, resonance issues, and bulky, costly implementation. They lack adaptability to dynamic load variations, making them less effective for rapidly changing industrial applications. Additionally, improper filter design can lead to parallel or series resonance, which may worsen harmonic levels instead of mitigating them. Furthermore, the use of large inductors and capacitors makes these filters impractical for space constrained installations, adding to their cost and complexity.

C. Active Power Filters (APFs)

Markovska et al. (2017) [4] mentioned in their paper mentioned that the APFs offer a dynamic and flexible solution for harmonic mitigation by injecting compensating currents in phase opposition to the harmonics.

These are categorized into shunt active power filters (APFs), series APFs, and unified power quality conditioners (UPQC). Shunt APFs compensate for current harmonics by injecting equal but opposite harmonic currents, significantly improving the power factor. Series APFs are primarily used for voltage quality improvement by compensating supply voltage harmonics and mitigating issues such as sags, swells, and notches. UPQC combines both series and shunt APFs, ensuring simultaneous improvement in both voltage and current quality.

However, APFs face notable challenges, including high costs due to complex control algorithms and high-speed switching components. They also require additional power for operation, which impacts overall energy efficiency, and involve complexity in control, as advanced computation is needed for real-time harmonic detection and mitigation.

D. Hybrid Active Filters (HAFs) – The Optimal Solution

Hybrid Active Filters (HAFs) combine passive and active filtering techniques to enhance harmonic mitigation efficiency while reducing costs.

Hybrid active filters (HAFs) leverage both active and passive filtering techniques to enhance power quality. APFs are used for dynamically mitigating high-frequency harmonics, while passive filters (PFs) effectively suppress dominant low-frequency harmonics. This combination reduces system complexity, as HAFs require lower power ratings than standalone APFs, leading to reduced operational costs. Additionally, HAFs provide higher efficiency in variable load conditions, ensuring continuous harmonic suppression under dynamic load variations. Recent studies using MATLAB/Simulink simulations confirm the efficacy of HAFs in mitigating harmonics, reducing total harmonic distortion (THD), and maintaining overall power quality [1].

E. Advanced Control Strategies for Harmonic Mitigation

A recent study by A. Senthilkumar et al. (2011) [5] introduces a Neural Learning Algorithm (NLA) for controlling a Shunt Active Power Filter (SAPF), demonstrating its superior performance compared to conventional PI controllers.

The nonlinear algorithm (NLA)-based shunt active power filter (SAPF) offers significant improvements in power quality. It enhances harmonic mitigation by reducing source current total harmonic distortion (THD) from 36.02% to 2.50%. Additionally, it provides a faster response, reducing the settling time from 0.16 seconds (with a PI controller) to 0.06 seconds. The system also achieves lower power losses, with real power consumption decreasing by 18.5% and reactive power demand dropping by 84.47%. Furthermore, the NLA ensures real-time adaptability by dynamically adjusting compensation, optimizing power quality across varying load conditions.

These findings highlight the potential of AI-driven control strategies for optimizing hybrid active filter performance [4]. The integration of intelligent algorithms into HAFs presents an opportunity to enhance efficiency, adaptability, and cost-effectiveness, making them suitable for large-scale industrial applications [1]

III. PROBLEMS STATEMENT

Power quality refers to the stability and reliability of the electrical power supplied to devices. High-quality power ensures that voltage and frequency remain constant, allowing equipment to function efficiently without malfunctioning. In contrast, poor power quality can result in equipment failure, diminished performance, or even long-term damage. Several issues can affect power quality, including voltage sags, surges, harmonics, flicker, power factor inefficiency, and interruptions. Voltage sags are brief drops in voltage that can cause sensitive equipment to malfunction or reset, while surges are sudden increases in voltage, often leading to equipment damage. Harmonics, a key issue, involve waveform distortion, commonly caused by non-linear loads such as computers and LED lights. Flicker is characterized by rapid fluctuations in voltage, which can cause visible disturbances in lighting. Poor power factor, a measure of how efficiently electrical power is used, can result in higher electricity bills and increased strain on the grid. Finally, interruptions in power, whether temporary or sustained, disrupt operations and affect overall system reliability.

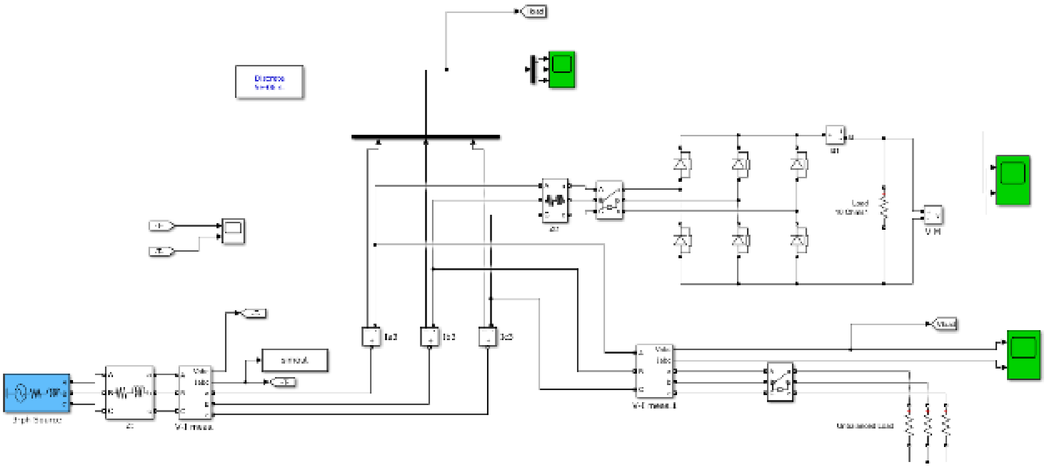


Fig. 1 Simulation design of power system without HAPF

A. Non-Linear Load

Non-linear loads are a major source of harmonics in modern power systems. These loads draw current in a manner that is not directly proportional to the applied voltage, distorting the electrical waveform. Examples of non-linear loads include refrigerators, air conditioners, induction heating equipment, arc furnaces, and rectifiers. The presence of these loads leads to several adverse effects. Harmonics distort both the voltage and current waveforms, causing power losses in distribution systems and transformers, which in turn reduce overall system efficiency. Furthermore, harmonics increase the root mean square (RMS) current, resulting in greater heating of electrical equipment such as transformers and motors. This increased heating can cause long-term damage to sensitive equipment and lead to voltage distortions that may affect other devices connected to the same power source.

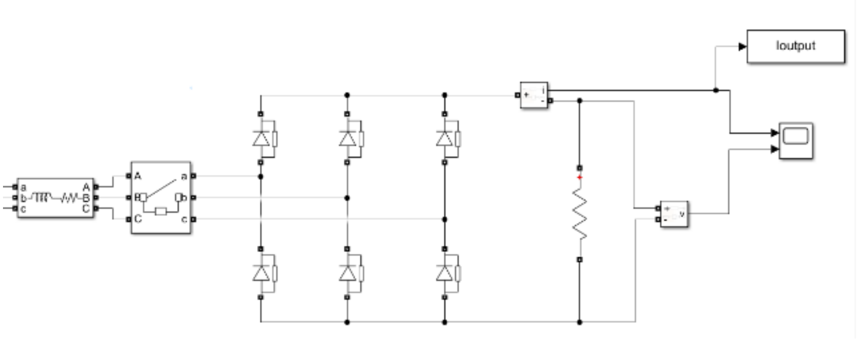


Fig. 2 Non-linear load (Balance Rectifier)

B. Harmonics

Harmonics in electrical systems refer to distortions in the waveform of electrical signals, primarily caused by non-linear loads. Ideally, alternating current (AC) systems should maintain a smooth sinusoidal waveform, but harmonics introduce deviations that distort this ideal form. Non-linear loads do not draw power continuously or smoothly, resulting in disturbances that superimpose harmonics onto the original waveform. These distortions can lead to inefficiencies and potential damage to equipment. Various sources of harmonics exist, including transformers, motors, and non-linear loads. In saturated transformers, the magnetic core becomes overwhelmed and behaves non-linearly, leading to distorted magnetization currents. Saturation can be caused by overloading, low supply voltage, inrush currents, or the presence of a direct current (DC) offset in the AC supply.

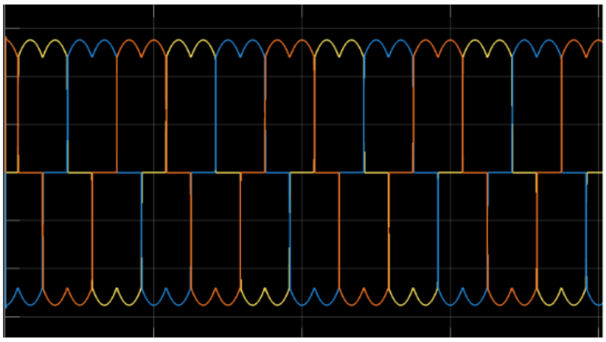
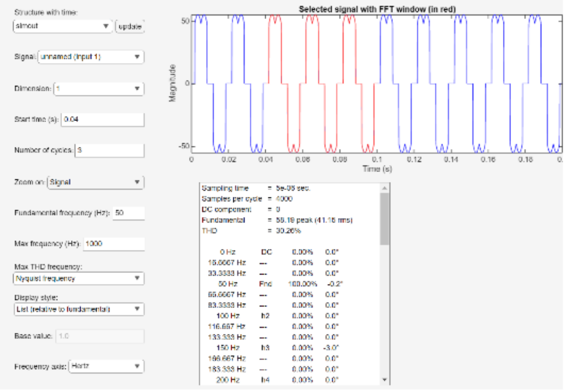


Fig. 3 Three phase harmonic graphs owned from simulation.

Preforming FFT analysis in our simulation we get following result.



Structure with time: simout
Signal: unnamed (input 1)
Dimension: 1
Start time (s): 0.04
Number of cycles: 3
Zoom on: Signal
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max THD frequency: Nyquist frequency
Display style: List (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

```
Sampling time       =  5e-06 sec.
Samples per cycle   =  4000
DC component        =  0
Fundamental         =  58.19 peak (41.15 rms)
THD                 =  30.26%

      0 Hz      DC      0.00%    0.0°
  16.6667 Hz    ---     0.00%    0.0°
  33.3333 Hz    ---     0.00%    0.0°
     50 Hz      Fnd   100.00%   -0.2°
  66.6667 Hz    ---     0.00%    0.0°
  83.3333 Hz    ---     0.00%    0.0°
    100 Hz      h2      0.00%    0.0°
  116.667 Hz    ---     0.00%    0.0°
  133.333 Hz    ---     0.00%    0.0°
    150 Hz      h3      0.00%   -3.0°
  166.667 Hz    ---     0.00%    0.0°
  183.333 Hz    ---     0.00%    0.0°
    200 Hz      h4      0.00%    0.0°
```

Fig. 4 FFT analysis at different frequency with 30.26% of THD

$$\text{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} V_{nrms}^{2}}}{V_f} \qquad (1)$$

According to the simulation results, the power system's Total Harmonic Distortion (THD) is 30.26% in the absence of the Shunt Active Power Filter (HAPF). The main cause of this high degree of distortion is the existence of non-linear loads—in this case, a rectifier—which cause the system to experience large harmonic currents. Excessive THD harms the longevity and dependability of electrical equipment in addition to reducing power system efficiency. This emphasises how urgently an efficient harmonic mitigation plan is needed. As will be discussed in the section on suggested approach, using an active power filter is therefore crucial to lowering THD and improving overall power quality.

IV. METHODOLOGY

We will address the issue of harmonics by utilizing a SAPF and HAPF. The SAPF operates by connecting in parallel with the electrical system to mitigate harmonic distortions caused by non-linear loads. These distortions, primarily in the form of harmonics, degrade power quality and reduce system efficiency. The SAPF continuously monitors the current drawn by the load, applying advanced control algorithms to detect harmonic content in real time. Its main function is to inject compensating currents into the system to neutralize these harmonics.

A. Shunt Active Power Filter (SAPF):

The process begins with the SAPF measuring the system's current using sensors. This current is analysed by the control unit to separate harmonic components from the fundamental frequency. Control methods such as the Instantaneous Reactive Power Theory (p-q theory) or Synchronous Reference Frame (d-q theory) are commonly used to identify the magnitude and phase of unwanted harmonics. After identifying the harmonic content, the SAPF generates compensating currents that are equal in magnitude but opposite in phase to the detected harmonics. These compensating currents are injected back into the system via power converters, typically through a Voltage Source Inverter (VSI). The VSI uses switching techniques such as Pulse Width Modulation (PWM) to synthesize the required waveform, effectively cancelling out the harmonics.

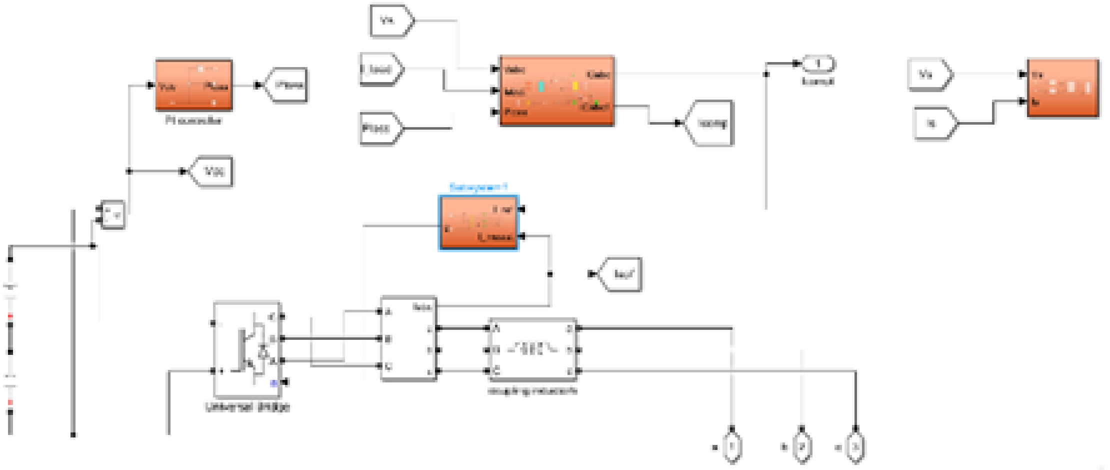


Fig. 5 Shunt Active Power Filter Obtained from the Simulation.

By neutralizing harmonics in real time, the SAPF ensures that the current drawn from the source remains clean and sinusoidal. This results in an improved power factor, reduced losses, and enhanced power quality, which prolongs the operational lifetime of electrical equipment. In our simulation, we connected the SAPF to the point of common coupling (PCC) in parallel with the load. This configuration actively regulates harmonic currents and reactive power in real time.

1) PQ Theory and I Compensation Current Calculation:

PQ theory focuses on regulating both real (active) and reactive power to enhance power quality. In our study, the PQ and $I_{\text{compcalculation}}$ block takes the source voltage (V_s), load current (I_{load}) and power loss (P_{loss}) as inputs. Using Clarke's transformation of voltage and current, the system calculates the compensating current (I_comp), which serves as input for the hysteresis controller.

MATLAB Simulink Formula for PQ Calculation is

P=(x1*y1) +(x2*y2); (2)

Q=(x2*y1) -(x1*y2); (3)

Valpha=x1; (4)

Vbeta=x2; (5)

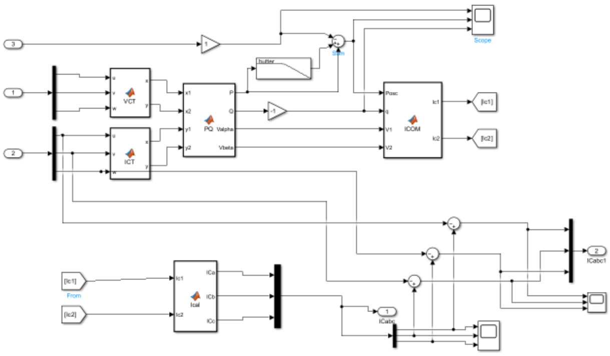


Fig. 6 PQ & I-compensation Calculation

2) Clarke Transformation:

The three-phase voltage (V_abc) is transformed into two-phase voltages (V_alpha,V_beta), which are easier to work with in the context of power calculations. Clarke Voltage Transformation is

x =sqrt (2/3) *(u-(0.5*v) -(0.5*w)) (6)

y =sqrt (2) *(0+(0.5*v) -(0.5*w)) (7)

3) Alpha Beta Current Block

The αβ current refers to the two-phase components of a three-phase current that have been transformed from the three-phase (abc) system to the αβ stationary reference frame using the Clarke transformation. This transformation is used in control systems, especially for electric motors and power electronics, to simplify the mathematical analysis and control of three-phase AC systems. The output currents Ic1 and Ic2 are then used by the Hysteresis Controller subsystem to generate the switching signals necessary for the SAPF's operation.

Ic1 = (-1/ (V1^2 + V2^2)) *((Posc*V1) +(q*V2)); (8)

Ic2 = (-1/ (V1^2 + V2^2)) *((Posc*V2) -(q*V1)); (9)

4) *Compensation Current Block*

Compensation current refers to the current injected into a power system to counteract undesirable effects like harmonics, unbalances, or reactive power that may arise from non-linear loads, unbalanced loads, or other disturbances. The goal of injecting compensation current is to improve power quality, achieve a near-ideal power factor, or maintain voltage stability.

[Ica]=sqrt (2/3) *(Ic1); (10)

[ICb]=sqrt (2/3) *((-0.5*Ic1) +((sqrt (3)/2) *Ic2)); (11)

[ICc]=sqrt (2/3) *((-0.5*Ic1) -((sqrt (3)/2) *Ic2)); (12)

B. *Hybrid Active Power Filter (HAPF)*

A Hybrid Active Power Filter (HAPF) is an advanced power quality solution that combines the benefits of both passive and active power filters to efficiently mitigate harmonics, improve power factor, and compensate for reactive power in electrical systems. Unlike a purely active power filter (APF), which relies entirely on power electronics to eliminate harmonics, the HAPF integrates passive filters (typically LC filters) with an active filtering system to enhance performance while reducing overall system cost and power losses.

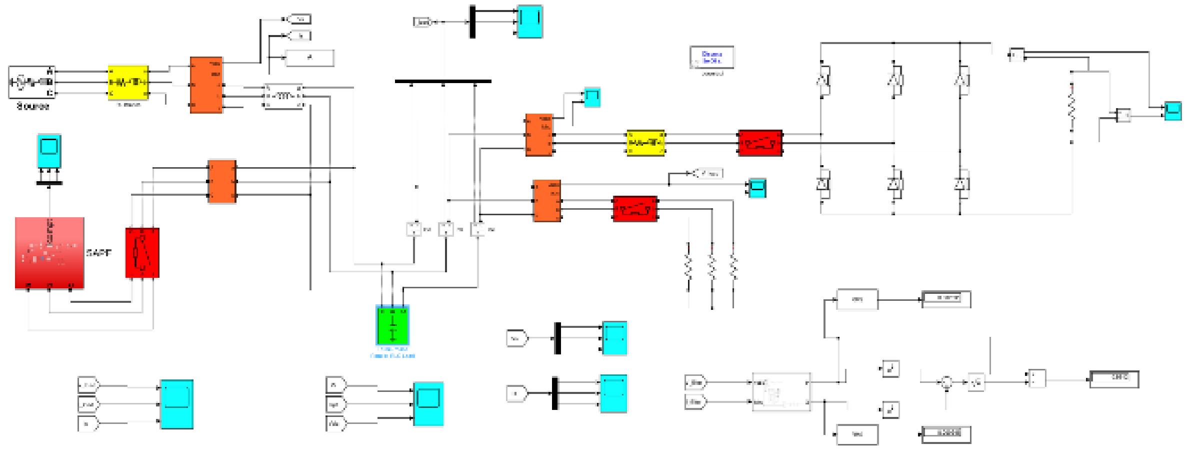
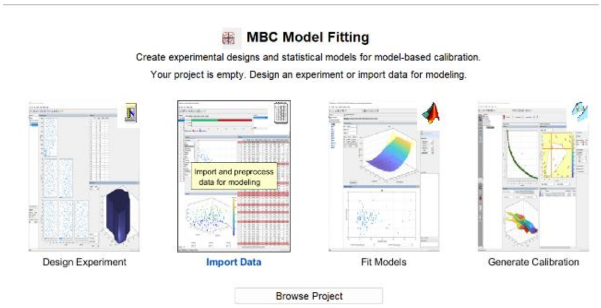


Fig. 7 Hybrid active power filter obtained from the simulation.

The passive filter is responsible for filtering lower-order harmonics and providing reactive power compensation, while the active filter dynamically compensates for higher-order harmonics and adapts to changing load conditions. This hybrid approach not only improves filtering efficiency but also minimizes the burden on the active power filter, leading to reduced energy consumption and improved system stability. Additionally, HAPFs effectively address resonance issues commonly associated with passive filters, making them a more reliable and practical solution for industrial applications, power distribution networks, and renewable energy systems where nonlinear loads introduce significant harmonic distortions.

C. *MBC Modelling*

Model-based calibration in MATLAB is used to optimize and refine system parameters by developing a mathematical representation of the system. This approach allows for simulating various scenarios, analyzing system behavior, and fine-tuning parameters to achieve optimal performance. By eliminating the need for physical prototypes, it significantly reduces both time and resource consumption.



Create experimental designs and statistical models for model-based calibration.

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Fig. 8 MBC model fitting page.

V. RESULT

The implementation of the SAPF in the power system resulted in a notable decrease in the THD of the source current. By injecting compensating currents, the SAPF effectively neutralized harmonic components, thereby enhancing overall power quality.

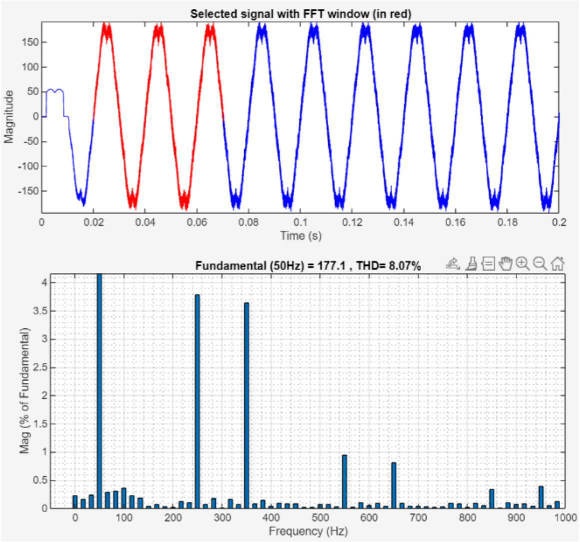

Fig. 9 FFT analysis after SAPF with 8.07% THD.

Decreased Total Harmonic Distortion (THD) in Isource: The THD in the source current (Isource) reduced to 8.07% once the SAPF was in operation. This significant decrease in THD shows how well the SAPF works to lower harmonics. The waveform below shows the source current's harmonic content after the SAPF was implemented.

After connecting the Hybrid Active Power Filter (HAPF) to the main line reduces electrical noise and distortion but power factor is reduced to 0.03147.

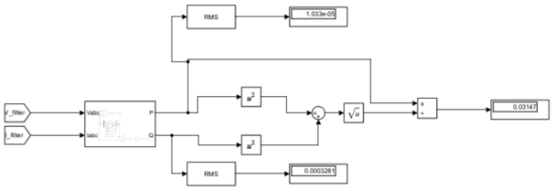

Fig. 10 Power factor without capacitor bank.

The major harmonics reduced after the implementation of the SAPF do not fall within the bounded region. With the integration of the HAPF into the power system, the THD in the source current was significantly minimized. The HAPF was engineered to inject the necessary currents, effectively eliminating the remaining harmonic components and enhancing overall power quality.

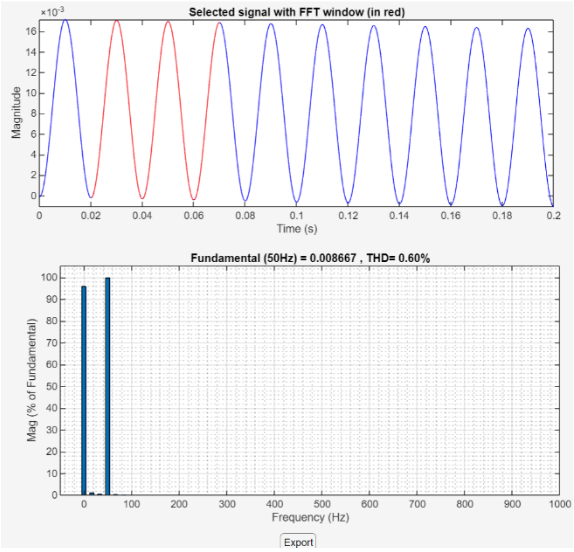

Fig. 11 FFT analysis after HAPF with 0.60% THD

The decrease in THD from 30.26% to 8.07% highlights the SAPF's effectiveness in significantly improving power quality by reducing harmonics, while the implementation of HAPF further lowers the THD to 0.60%. This outcome clearly demonstrates that the combined use of SAPF and HAPF has successfully fulfilled its intended objective.

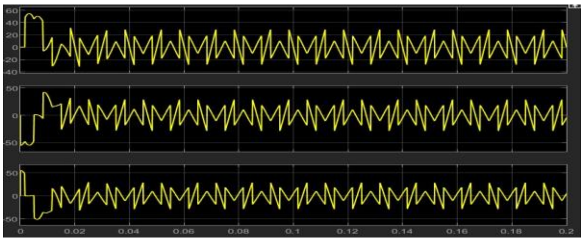

Fig. 12 Waveform of Compensation Currents

Impact of Compensation Currents on THD minimization nonlinear loads. By actively opposing and cancelling out the harmonics in the source current, compensation currents help restore a more sinusoidal waveform. THD reduce from 30.26% to 0.60%.

At 50 Hz, the Total Harmonic Distortion (THD) percentage reaches its highest level compared to other frequencies, indicating that the 3rd harmonic is the most dominant among the harmonic multiples. As the frequency increases, the influence of higher-order harmonics gradually decreases, aligning with the typical behaviour of harmonics in power systems.

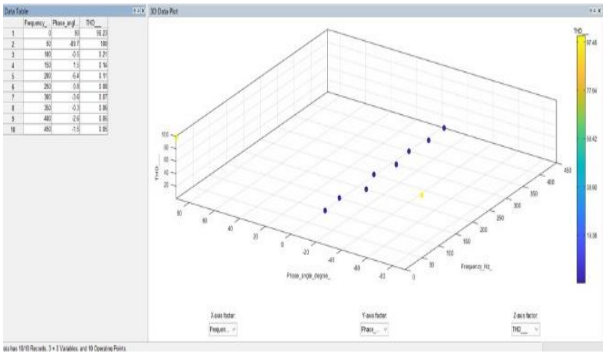

Fig. 13 3D analysis for 0.60% THD

VI. CONCLUSION

This research successfully demonstrates the design and implementation of Hybrid Active Power Filters (HAPFs) for mitigating harmonic distortion in power systems with nonlinear loads and correcting the power factor in linear loads. The HAPF significantly reduced Total Harmonic Distortion (THD) from 30.26% to 0.60% and improved the power factor from 0.03147 to 0.9912, resulting in a substantial enhancement of overall power quality. According to the IEEE 519 standard, THD in systems connected to the public grid must be below 6%, underscoring the effectiveness of the proposed solution. HAPFs are particularly advantageous in industrial and commercial applications, where maintaining power quality is critical. With advancements in control strategies and power electronics, modern HAPFs provide efficient and flexible real-time harmonic mitigation. As energy demands continue to rise, integrating HAPFs ensures high power quality and system reliability, benefiting both consumers and grid operators by reducing harmonics and optimizing performance

VI. REFERENCE

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