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"A Comparative Analysis of Shunt Active Power Filter and Hybrid Active Power Filter"

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ABSTRACT

This research paper presents a comparative analysis of Shunt Active Power Filters (SAPF) and Hybrid Active Power Filters (HAPF) in mitigating harmonic distortion in power systems caused by non-linear loads such as rectifiers, and unbalanced loads. Harmonics not only reduces system efficiency but can also lead to equipment damage. The SAPF generates compensating currents to reduce Total Harmonic Distortion (THD). For a system with rectifiers and an unbalanced load, the SAPF reduced THD from 30.26% to 5.72%, showcasing its effectiveness. On the other hand, the HAPF combines active and passive filtering techniques to reduce harmonics by 5.72% to 0.60% suppression across a broader frequency range. This paper analyzes the design, control strategies, and performance of both filters, focusing on subsystems like the PI Controller, PQ and I Compensation subsystem, Hysteresis Controller, and PQ Measurement subsystem. The study highlights the relative advantages, limitations, and applications of SAPFs and HAPFs, providing a comprehensive understanding of their roles in improving power system performance and stability.

Keywords:- APF, SAPF, HAPF, THD, PI, PQ

INTRODUCTION

In modern power systems, ensuring high-quality and reliable electrical power is essential due to the growing use of sensitive electronic devices and the common integration of renewable energy sources. Non-linear loads such as variable frequency drives and rectifiers introduce harmonic distortions, which lead to problems like voltage fluctuations, equipment overheating, and increased energy losses. To address these issues, various harmonic mitigation techniques have been developed over time. Initially, passive filters were employed; however, they come with limitations such as fixed compensation capability, resonance problems, and reduced efficiency in dynamic environments.

Shunt active power filters (SAPFs) emerged as a significant advancement, offering dynamic and precise harmonic compensation. Despite their effectiveness, the complexity and evolving demands of modern power systems necessitate more versatile solutions. Hybrid active power filters (HAPFs) represent an innovative approach by combining the strengths of both active and passive filters, delivering superior performance in mitigating harmonics and enhancing power quality. This paper presents a comparative analysis of shunt active power filters and hybrid active power filters, focusing on their design, operational principles, and effectiveness in addressing power quality challenges in modern electrical systems.

LITERATURE REVIEW

1. Harmonics

In a separate study, S. Parthasarathy et al. (2012)[5] identified harmonics as a leading issue related to power quality. Non-linear loads, such as converters, inverters, and choppers, lead to this problem. These types of loads create harmonic currents. These currents are then injected into the supply system, which ultimately decreases overall efficiency.

Since the 1980s, industries have increasingly used power electronic devices for various tasks. These include applications like uninterrupted power supplies (UPS), variable frequency drives (VFD), and switch-mode power supplies (SMPS). Unfortunately, these semiconductor devices can distort sinusoidal currents. This distortion results in harmonic currents flowing through system impedance and generating voltage harmonics.

The idea of harmonics pertains to steady states, whereby the waveform under analysis is presumed to repeatindefinitely [7]. Basically, harmonics are current or voltage waveforms whose frequencies are integer multipleof fundamental frequency (2x, 3x, 4x, etc.). These harmonics are created by a variety of sources, including non-linear loads and devices. These days, by use of modern devices, up to 63rd harmonics are measurable. But themost regularly found harmonics are between 3rd to 25th [4].

2. **Filters**

A filter is an electronic device that filters a particular frequency and blocks or attenuates others with the help of a resistor, capacitor, inductor, and other electronic components. Filters are used to remove noise, harmonics, and to produce clean and steady signals.

Zainal Salam et al, (2006)[8]In their paper on harmonic distortion in power distribution systems, state that there are two general approaches to limiting harmonic distortion. The first is passive filtering, and the second is active powering. The simplest and conventional way of limiting the harmonic distortion takes the passive filtering method. Ordinary inactive channels consist of inductance, capacitance, and resistance components arranged and tuned to control sounds.

2. Passive filters

S.Parthasarathy et al.(2012)[5] , mentioned passive filters are widely used for harmonic mitigation and have been a traditional solution in power systems. Mainly passive filters contain passive elements like resistor, capacitor, and inductor and these work without the need of an external power source. Their function is either to divert harmonic currents away from the line or to prevent their flow between different sections of the system by tuning specific frequencies.

Tomá Hruby et al. (2014) [2] provide measured results of two different types of broadband passive power filters
powered by the Pacific 3120ASX programmable three-phase power source and compare them to those of a simulation model created using the EMTP-ATP program. This demonstrates that, provided the supply voltagequality is good, the tested filters are quite effective. The filter's performance is also impacted by the voltage quality at the coupling.

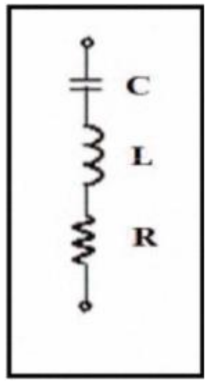


Fig. 1 Single tuned passive filter. [5]

3. Active Power Filter

S.Parthasarathy (2012)[5] et al, in their paper, APF overcomes the drawbacks of passive filters by using a power converter to perform harmonic current rejection.Shunt Active Power Filter (SAPF) is developed to suppress harmonic currents and simultaneously compensate reactive power. SAPF acts as a current source in parallel with the nonlinear load.The APF power converter is controlled to produce a compensation current equal to but opposite to the harmonic current generated by the nonlinear load. Active filters use an active component like an operational amplifier along with a passive component such as resistor capacitor and inductor.

Lukas Motta et al. (2016) [3] employed a PQSine Active power filter to compare active and passive power filters. The Active Power Filter is tested with a variety of electrical loads and applications. The study concluded that active filters outperformed passive filters for a variety of reasons, including flexibility, accuracy, and enhanced
power factor.

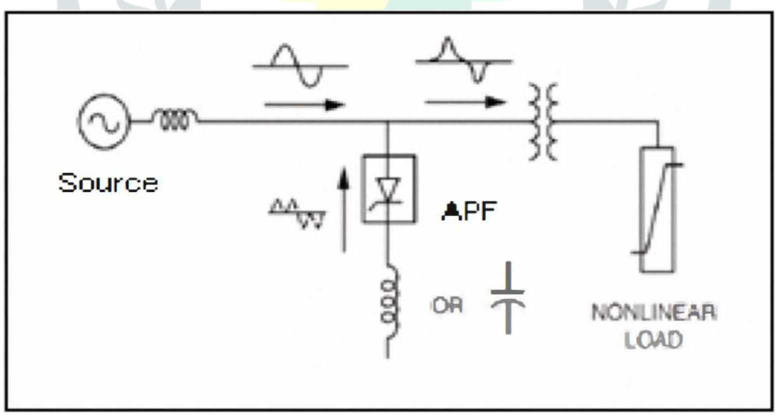


Fig. 2 Block diagram of APF.[5]

4. Shunt Active Power Filter

Zainal Salam et al., (2006)[8] It consists of a DC bus capacitor (□□), a power electronic switch and an interface inductor (□□). The APF shunt acts as a current source, compensating for harmonic currents due to nonlinear loads. The operation of the APF shunt is based on injecting a compensation current equal to the distorted current, thereby eliminating the original distorted current. The purpose of the APF shunt is to obtain a sinusoidal current (is) using the relationship: □□ =□□-□□

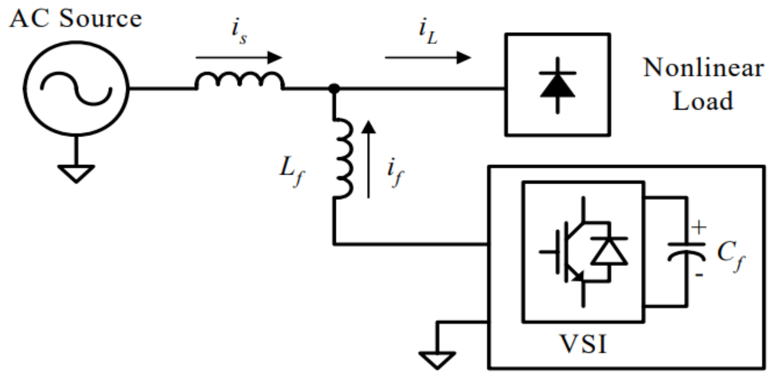


Fig. 3 Principle configuration of a VSI based shunt APF. [8]

Shunt active power filters can be categorized according to their architecture, number of phases, and kind of converter. A voltage source converter or a current source converter may be utilized in the SAPF. Various VSC circuits can be used to achieve different SAPF topologies. Three-phase, four-wire, and single-phase APF systems make up the third category, which is based on the number of phases [1].

5. Power Factor

Power Factor is a term referring to how conveniently electrical power is being used in electrical appliances . It is the ratio of real power used to do work to the apparent power .

$$\textbf{Power Factor (PF)} = \frac{\square\square\square\square\ \square\square\square\square\square\ (\square)}{\square\square\square\square\square\square\square\square\square\ \square\square\square\square\square\ (\square)}$$

6. Total Harmonic Distortion(THD)

Total Harmonic Distortion(THD) is a measure of harmonic distortion in a signal , representing the ratio of the sum of the power of all harmonic components to the power of the fundamental frequency.

THD for Current

$$\textbf{THD} = \sqrt[\square]{\frac{\square_{\square}^{\square}+\square_{\square}^{\square}+\square_{\square}^{\square}+\ldots\ldots\ldots\ldots\ldots\ldots+\square_{\square}^{\square}}{\square_{\square}^{\square}}}$$

Where:

- $\square_1$ =RMSvalueofthefundamental current (1st harmonic)
- $\square_2, \square_3, \square_{\square}$=RMSvaluesofthe2nd,3rd,and nth harmonics
- □□□ =Total Harmonic Distortion for current

PROBLEM IDENTIFICATION

Inherent harmonic issues caused by non-linear loads were historically limited to heavy industrial applications and managed by specialists. However, the prevalence of non-linear loads has increased significantly, extending to a wide range of sectors, including domestic settings. Non-linear loads introduce distorted current waveforms by drawing current disproportionately to the applied voltage, degrading power quality. This degradation can manifest as device malfunctions, flickering lights, and system inefficiencies. Common examples include computers, variable frequency motors, and devices with switched mode power supplies (SMPS), which often produce pulse waveforms with high crest factors

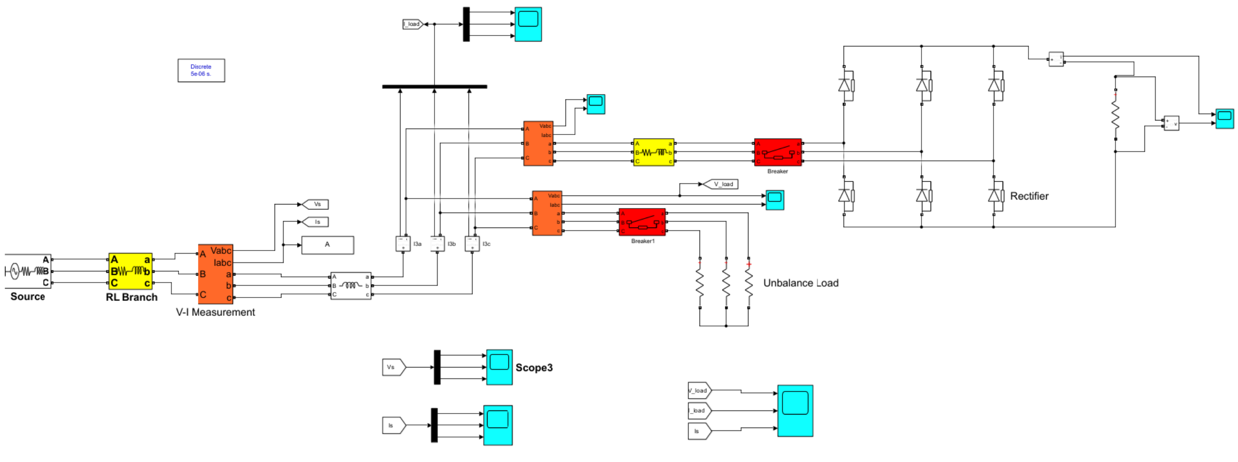


Fig. 4 Simulink diagram of a transmission line with non-linear load and unbalanced load.

Maintaining power quality is essential to ensure reliable operation of electrical systems and devices. To investigate the impact of non-linear loads on power quality, MATLAB simulations were performed. The study involved a three-phase transmission line with a three-phase full-wave AC to DC uncontrolled converter and an unbalanced three-phase resistive load. These simulations demonstrated how non-linear loads distort current and voltage waveforms, adversely affecting the overall power quality of the system.

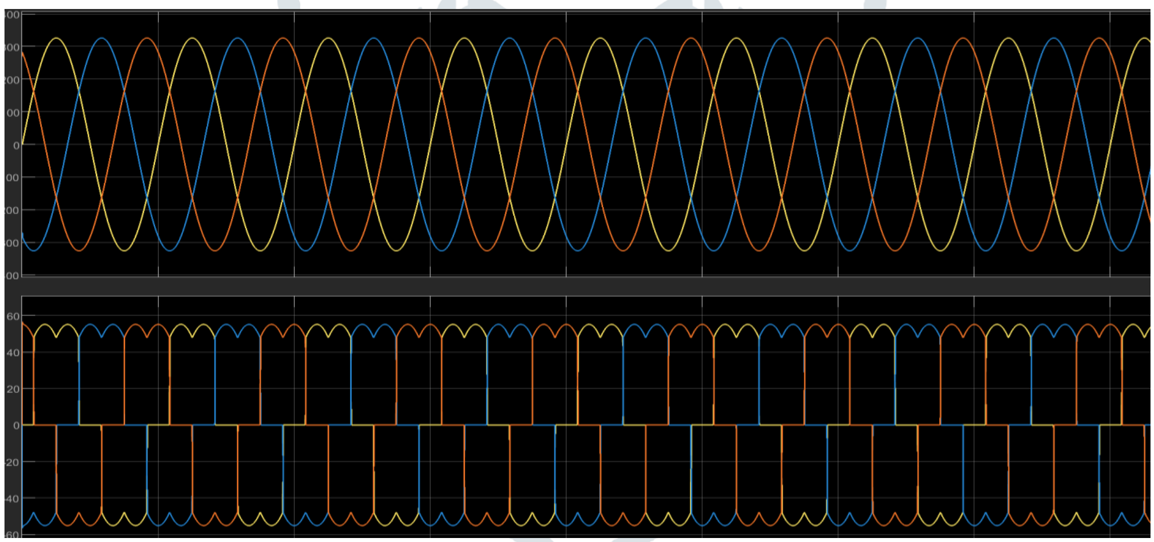


Fig. 5 Harmonic Graph between Voltage and Current.

This study aims to address these power quality challenges by comparing the performance of two mitigation techniques: the shunt active power filter (SAPF) and the hybrid power filter (HPF).

PROPOSED METHODOLOGY

This study compares Shunt Active Power Filters (SAPF) and Hybrid Active Power Filters (HAPF) for mitigating harmonic currents and improving power quality. The SAPF includes four key subsystems: a PI Controller to regulate DC bus voltage, a PQ and I Compensation unit to calculate reference currents, a Hysteresis Controller for switching signal generation, and a PQ Measurement module for performance monitoring. The HAPF combines a passive filter to suppress low-order harmonics with an active filter to address high-order harmonics, using advanced controllers for dynamic adaptation. Both filters are validated through simulations, comparing their effectiveness, cost, and scalability.

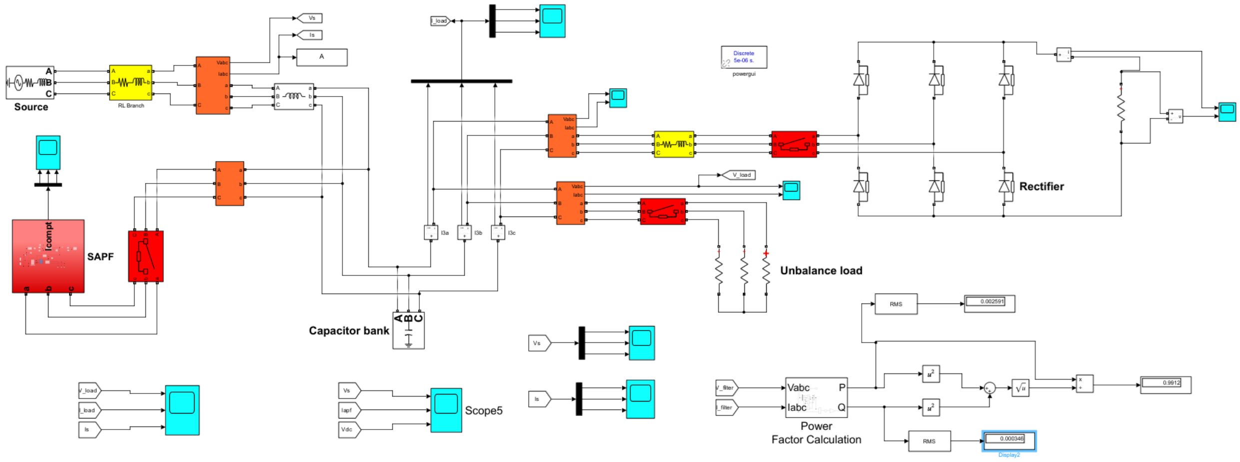


Fig. 6 Complete simulation.

The design and implementation of a Shunt Active Power Filter (SAPF) for mitigating harmonic currents generated by non-linear loads, thereby improving overall power system quality. The SAPF framework is structured into four essential subsystems:

1. PI Controller Subsystem

The PI (Proportional-Integral) Controller subsystem plays a critical role in the operation of the Shunt Active Power Filter (SAPF) by regulating the DC bus voltage, which is essential for the stable and efficient functioning of the SAPF. This subsystem ensures that the SAPF maintains the required voltage level, enabling it to generate the compensating currents necessary for harmonic mitigation. In this section, we will explore the design and operation of the PI Controller subsystem, detailing its components and their interactions

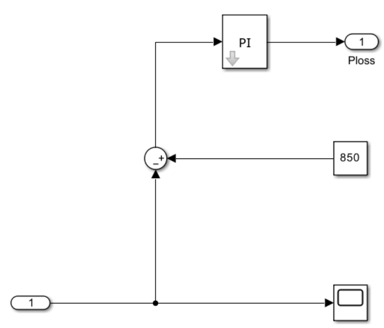


Fig. 7 PI controller.

2. PQ and I Compensation Calculation Subsystem

The PQ and I Compensation Calculation subsystem is a critical component within the Shunt Active Power Filter (SAPF) that determines the reference compensating currents necessary to mitigate harmonic currents in the power system. This subsystem utilizes the PQ theory, which involves the real-time calculation of active (P) and reactive (Q) power, to generate the compensating currents that the SAPF injects into the system. The following sections detail the design and operation of this subsystem, highlighting the process of calculating the compensating currents.

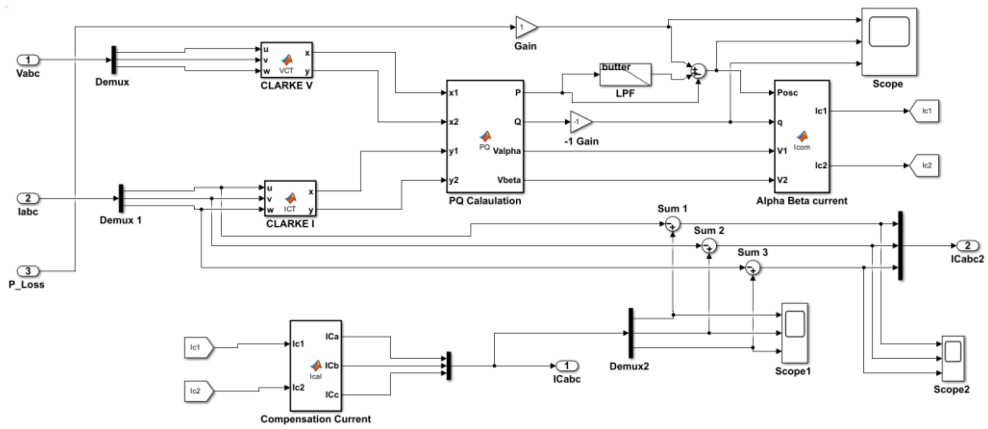


Fig. 8 PQ and I compensation Calculation sub-system.

3. Clarke Transformation

After the muxes organize the three-phase signals, the Vabc and Iabc outputs are fed into MATLAB function blocks designed to perform Clarke's transformation. Clarke transformation is a mathematical technique that converts three-phase (abc) quantities into two-phase (αβ) quantities, which simplifies the analysis and calculation of power components in the system.

● **Clarke Current Transformation:-** Similarly, the three-phase current (Iabc) is transformed into two-phase currents (Ialpha, Ibeta), representing the load currents in the transformed reference frame.

x =sqrt(2/3)*(a-(0.5*b)- (0.5*c));

y =sqrt(2)*(0+(0.5*b)- (0.5*c));

These transformed voltages and currents are crucial for the subsequent steps in the PQ and I Compensation Calculation process.

4. 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.

MATLAB Simulink Formula for Alpha Beta Current Calculation is

Ic1 = (-1/(v1^2 + v2^2))*((Posc*v1)+(q*v2));

Ic2 = (-1/(v1^2 + v2^2))*((Posc*v2)-(q*v1));

5. 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.

MATLAB Simulink Formula for Compensation Current Calculation is

Ica = sqrt(2/3)*(Ic1);

Icb = sqrt(2/3)*((-0.5*Ic1)+((sqrt(3)/2)*Ic2));

Icc = sqrt(2/3)*((-0.5*Ic1)-((sqrt(3)/2)*Ic2));

6. MBC(Model Based Calibration) Modeling

The comparative analysis is conducted by examining the network's performance in terms of frequency, Total Harmonic Distortion (THD), and phase angles under two scenarios: with and without the connection of the Shunt Active Power Filter (SAPF). The data for both scenarios is pre-collected and stored in separate files one containing the frequency, THD, and phase angle values for the network without the SAPF, and another for the network with the SAPF.

These datasets are imported and analyzed to visualize the relationship between frequency, THD, and phase angle. The visualization involves generating both 2D and 3D plots, which serve to illustrate the comparative behavior of the network under the influence of the SAPF. Through these plots, an optimized model is developed that captures the interaction among the frequency, THD, and phase angle, thereby facilitating the derivation of insights into the network's performance improvement when using the SAPF.

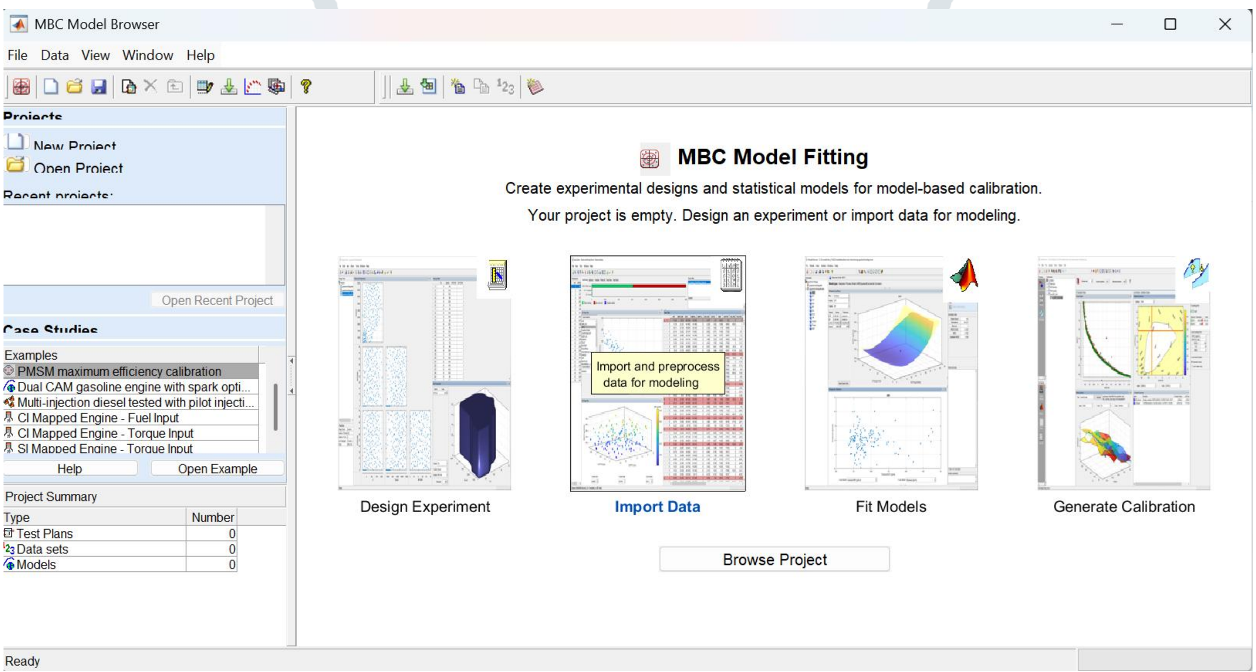


Fig. 9 MBC Model fitting.

RESULT

1. THD Without Connecting SAPF

Before connecting the SAPF, the power system experienced significant harmonic distortion due to the influence of non-linear loads. These included a three-phase unbalanced load and a three-phase rectifier. These non-linear components introduced multiple harmonics into the system, severely affecting power quality.

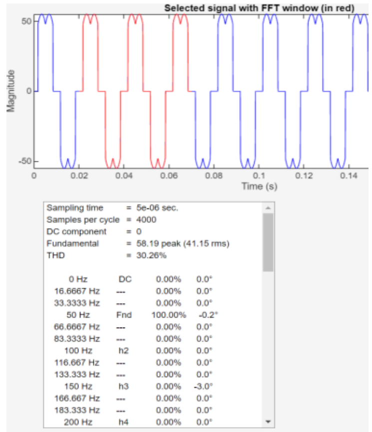


Fig. 10 FFT Analysis of Without Shunt Active Power Filter.

- **Measured THD in Source Current (Isource)**: The Total Harmonic Distortion (THD) in the source current was observed to be **30.26%**, indicating a substantial level of distortion. This high THD resulted in adverse effects such as equipment overheating, increased power losses, and reduced operational efficiency of connected electrical devices.

2. THD After Connecting SAPF

After implementing the SAPF in the power system, the THD in the source current was significantly reduced. The SAPF was designed to inject compensating currents that effectively neutralize the harmonic components present in the system, But there is some amount of THD present in the system which exceeds the safe region.

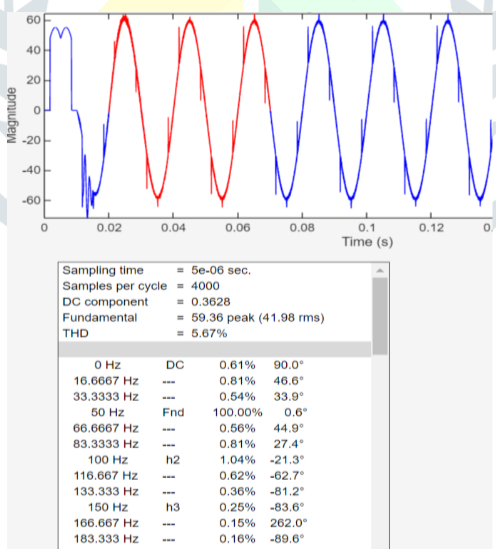


Fig. 11 FFT Analysis of ShuntActive Power Filter.

● **Reduced THD in Isource** : With the SAPF active, the THD in the source current (Isource) was reduced to 5.72%. This significant reduction in THD indicates the effectiveness of the SAPF in mitigating harmonics and ensuring that the power system operates within acceptable limits

3. THD After Connecting HAPF

After connecting the HAPF in the power system, the remaining THD in the source current was drastically reduced. The HAPF was designed to inject required currents that effectively neutralize the remaining harmonic components present in the system, thereby improving the overall power quality.

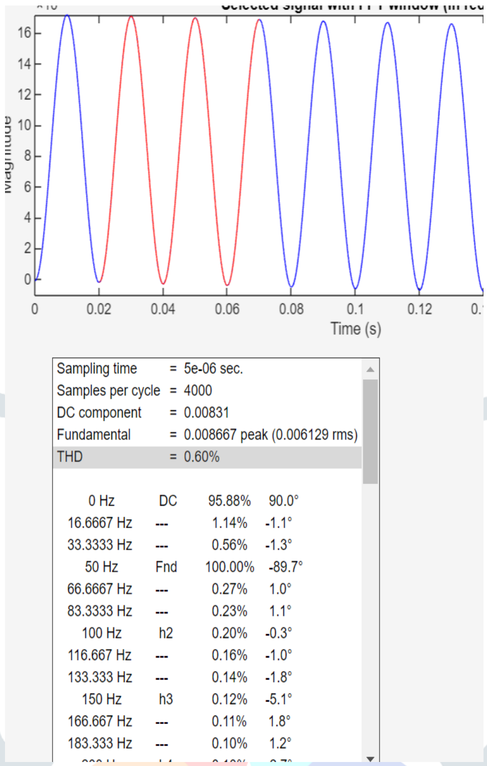


Fig. 12 FFT Analysis of Hybrid Active Power Filter.

4. Comparing FFT Analysis between Without SAPF, With SAPF and HAPF in List format

The reduction in THD from 30.26% to 5.72% demonstrates the SAPF's capability to significantly enhance power quality by mitigating harmonics and implementation of HAPF reduce the THD to 0.60%. This result is a clear indication that the SAPF with HAPF has successfully achieved its intended purpose.

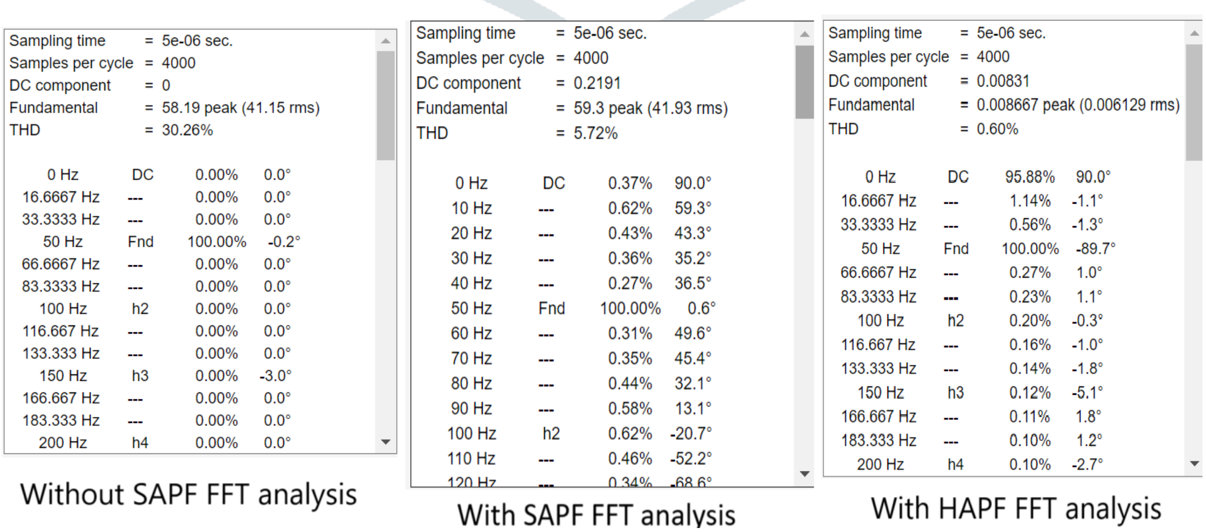


Fig. 13 FFT Analysis between without SAPF, with SAPF and HAPF

Parameter	Without SAPF	With SAPF	With HAPF
THD in Current Source (%)	30.26%	5.72%	0.60%

Table 11 THD without SAPF, with SAPF, & with HAPF

This table highlights the efficiency of the SAPF and HAPF in mitigating harmonic distortion and enhancing the system's overall power quality. The findings validate that the integration of the SAPF and HAPF effectively compensates for harmonic currents produced by non-linear loads, ensuring a cleaner, more stable, and reliable power supply.

5. Comparing FFT Analysis between Without SAPF, With SAPF and HAPF in Bar Format

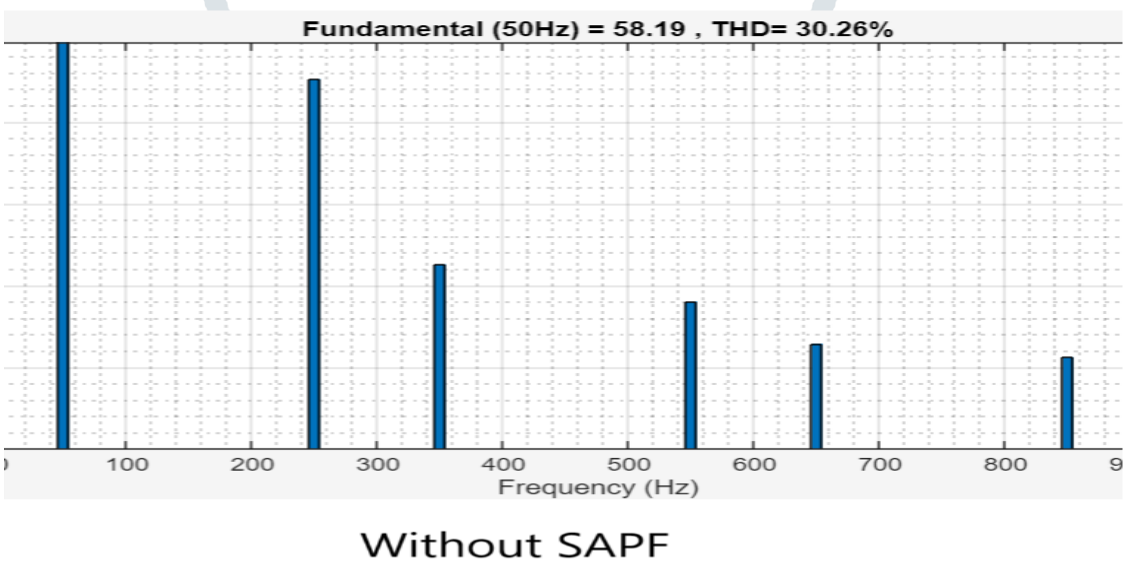
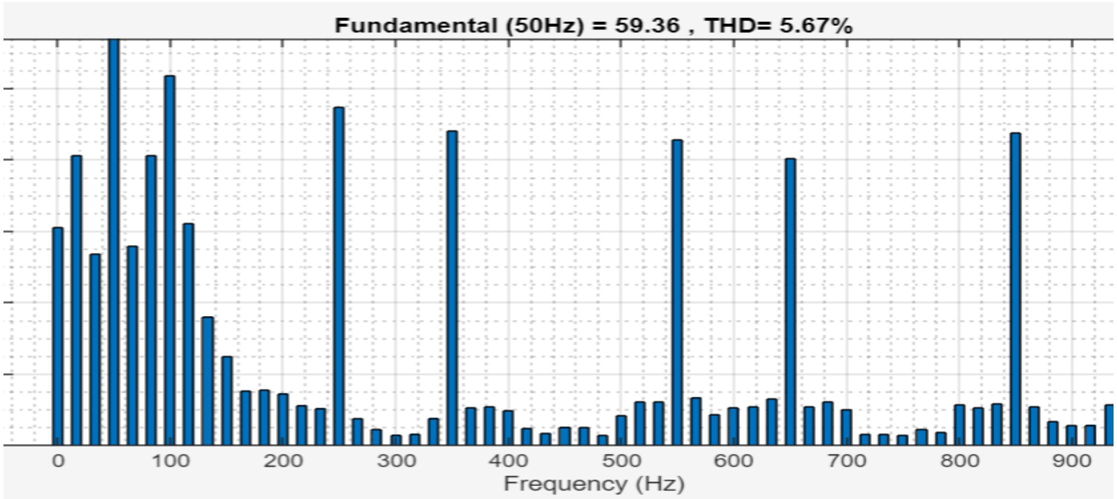
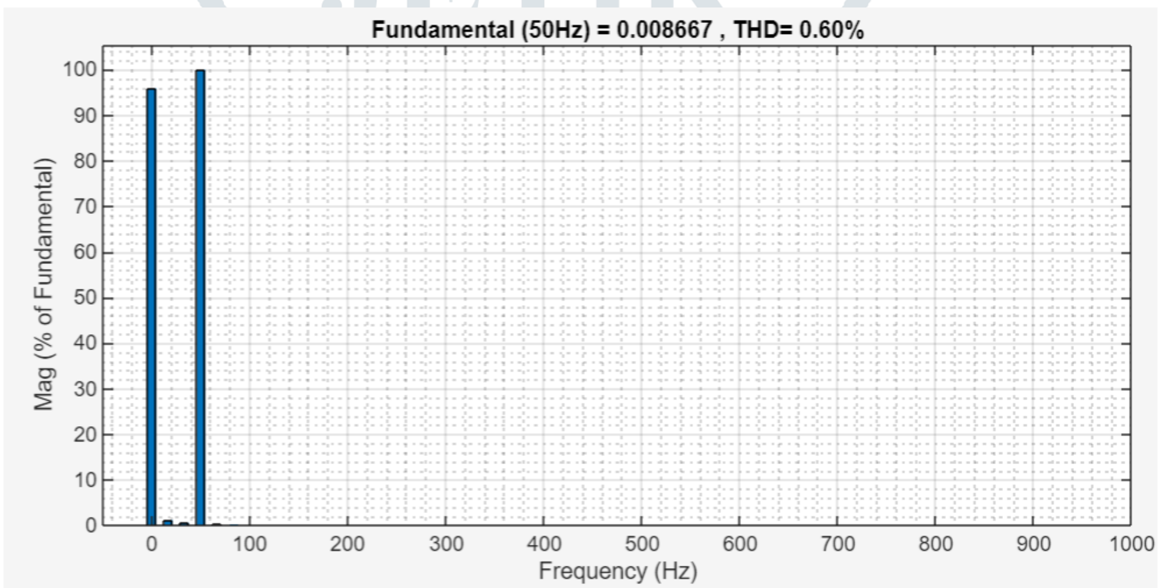


Fig. 14 FFT Analysis in bar format without SAPF



With SAPF

Fig. 15 FFT Analysis in bar format with SAPF



With HAPF

Fig. 16 FFT Analysis in bar format with HAPF

6. MBC (Model Based Calibration)

1. MBC Modeling Comparison between Without SAPF and With SAPF

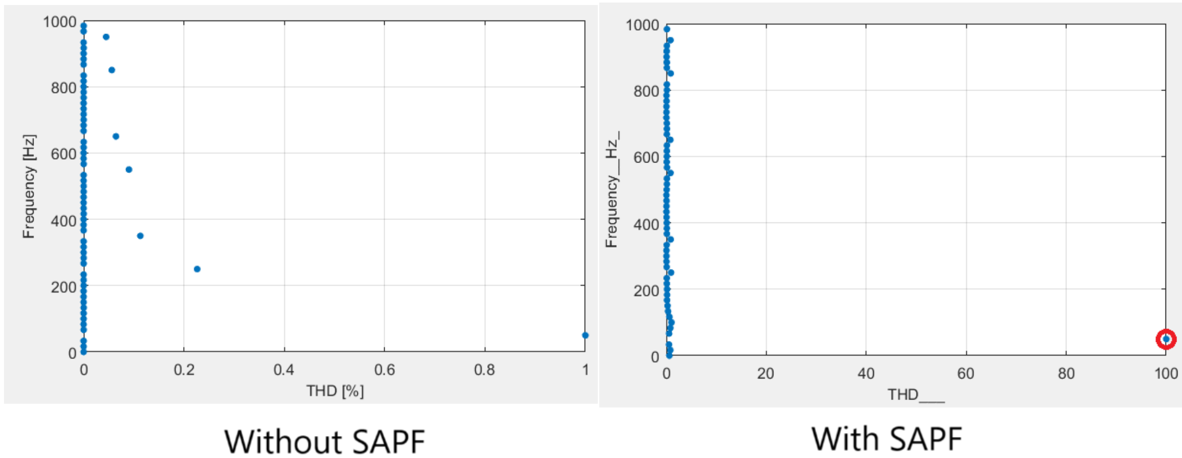


Fig. 17 Comparison between With and Without SAPF.

The graph "Without SAPF" shows a clear presence of multiple harmonic components across a range of frequencies, as evidenced by the scattered points along the x-axis (THD [%]). These points indicate higher Total Harmonic Distortion (THD), with noticeable contributions from different harmonic orders. This demonstrates that the system without the Shunt Active Power Filter (SAPF) experiences significant harmonic distortion, which can negatively affect power quality and system performance.

On the other hand, the graph "With SAPF" shows a marked improvement in harmonic mitigation. Most of the points are concentrated along the y-axis (frequency [Hz]), indicating that the THD has been substantially reduced. Only one distinct outlier remains at higher THD values, corresponding to the third harmonic component, but overall, the harmonic content is significantly minimized. This illustrates the effectiveness of the SAPF in injecting compensating currents to neutralize harmonic components, thereby improving the overall power system quality and reducing distortion.

2. MBC Modeling Comparison between With SAPF and With HAPF

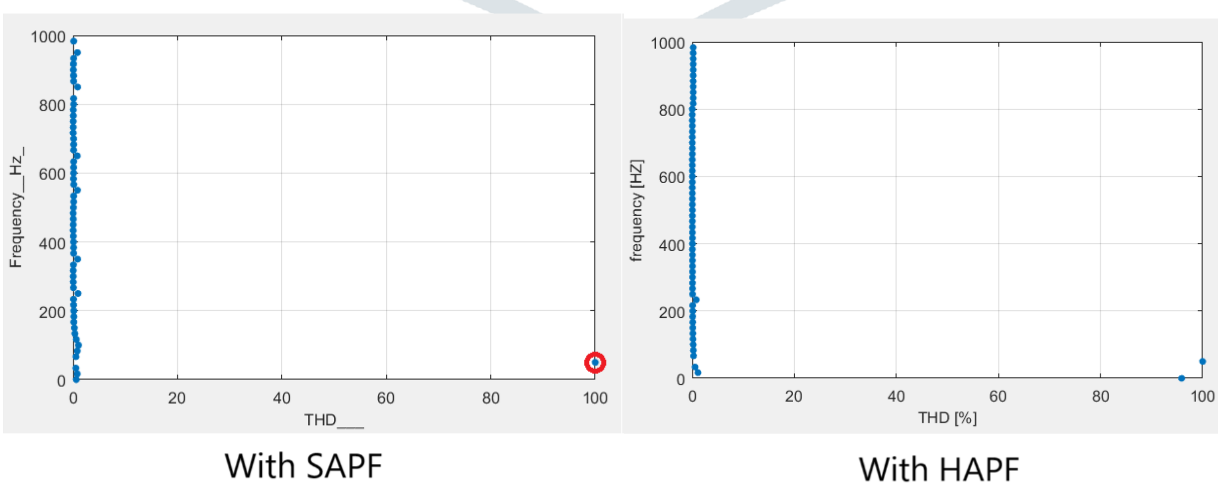


Fig. 18 Comparison between SAPF and HAPF.

The left graph (with SAPF) shows a more prominent harmonic component at the third harmonic, indicated by the data point farther from the y-axis. In contrast, the right graph (with HAPF) demonstrates a more effective reduction in Total Harmonic Distortion (THD), with fewer points away from the x-axis, signifying minimized harmonics. This highlights the superior harmonic mitigation capability of the HAPF compared to the SAPF.

Comparison from Data Inspector Result

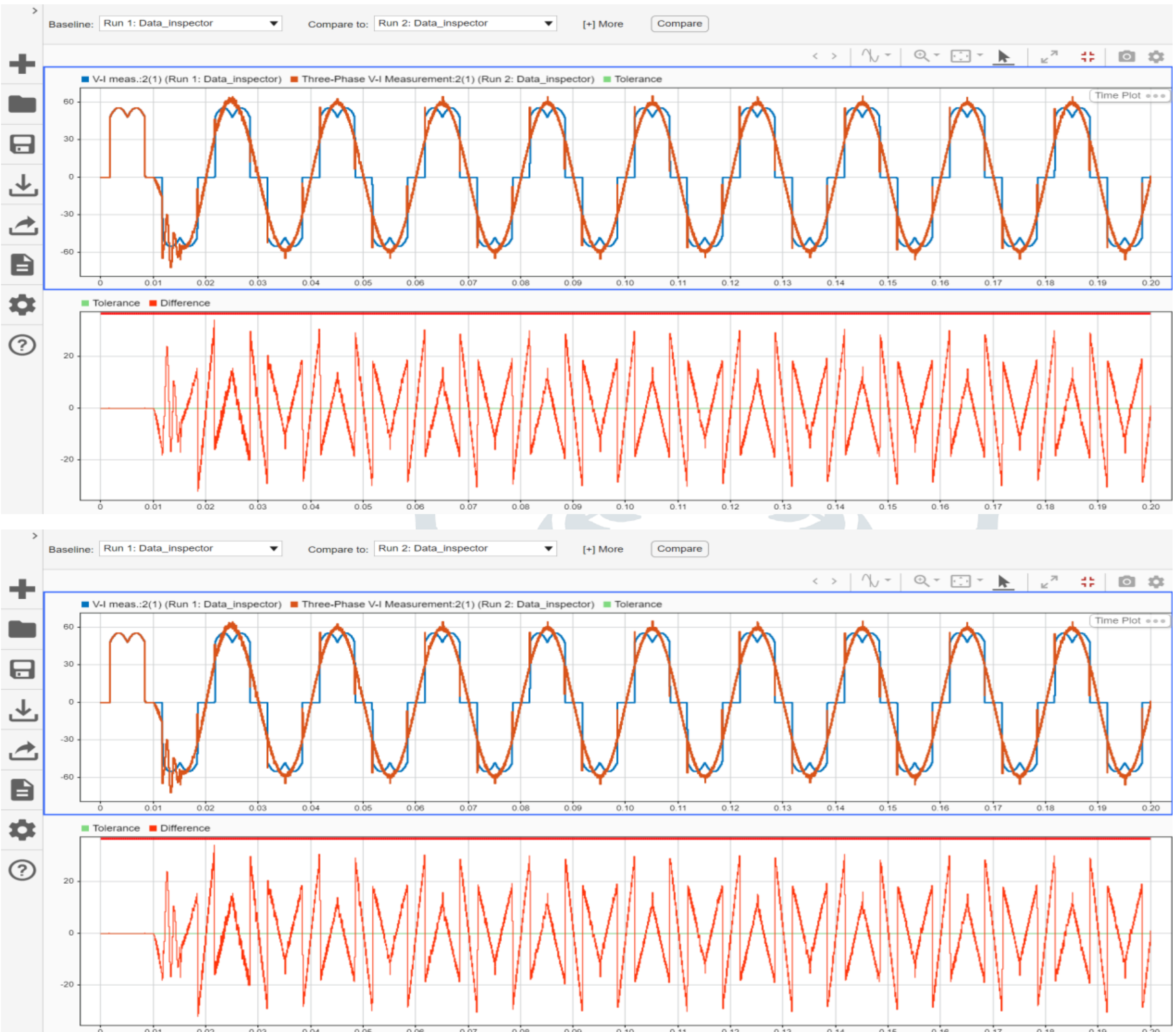


Fig.19 Data Inspector Comparison between Without SAPF and With SAPF

The SAPF improves signal quality by reducing harmonic distortion, as seen in the smoother blue waveform. The difference plot shows that the SAPF reduces harmonics effectively and stays within acceptable limits. This proves that the SAPF is good at improving power quality.

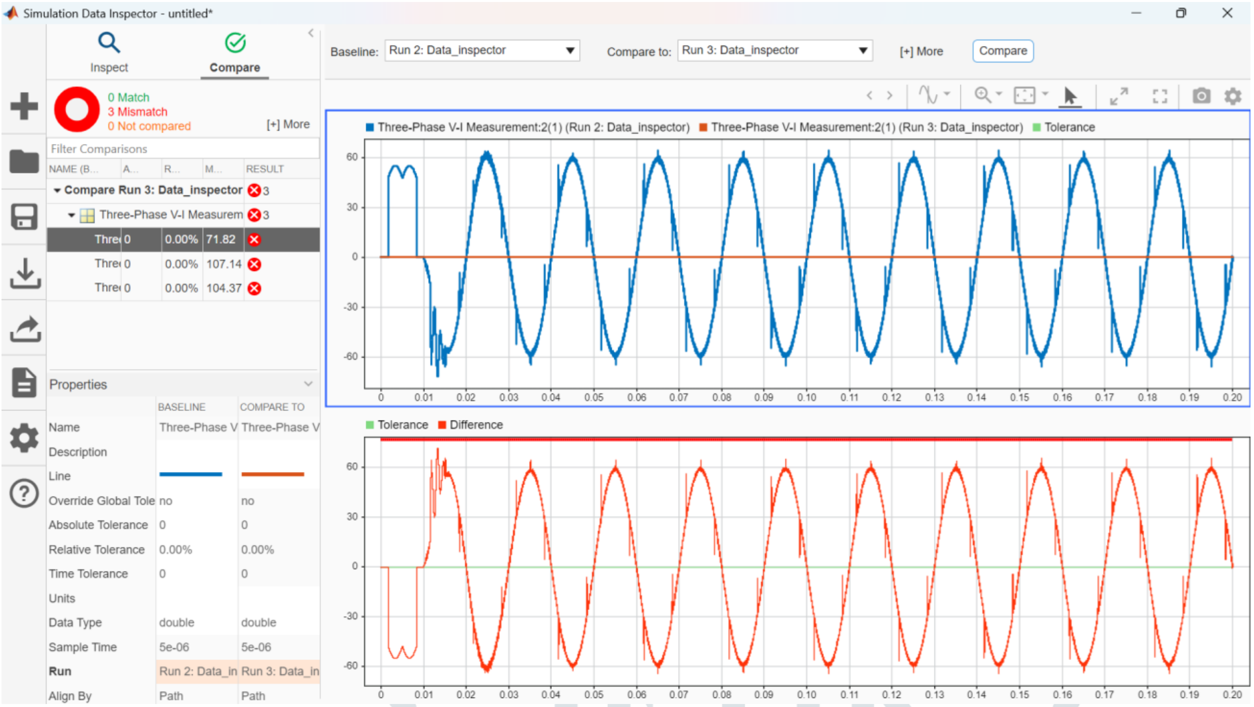


Fig.20 Data Inspector Comparison between With SAPF and With HAPF

The results show that the Hybrid Active Power Filter (HAPF) effectively improves the quality of the signal by reducing harmonic distortion. In the top graph, the blue waveform, which represents the compensated signal, is smooth and closely resembles a sinusoidal shape, indicating successful harmonic mitigation. The orange line serves as the reference and remains flat for comparison. In the bottom graph, the red line shows the difference between the compensated signal and the reference. Although there are some fluctuations initially, the difference stabilizes and stays within the acceptable tolerance limits (green line). This demonstrates that the HAPF performs well in reducing harmonics and improving overall power quality.

CONCLUSION

The results clearly indicate that the system's harmonic content was approximately 30.26%, a level significantly higher than acceptable for the reliable operation of equipment. With the implementation of the Shunt Active Power Filter (SAPF), the Total Harmonic Distortion (THD) in the source current was effectively reduced to 5.72%. However, the SAPF has limitations; it can only compensate for harmonics up to a certain extent. To achieve further harmonic reduction, a Hybrid Active Power Filter (HAPF) was employed, successfully bringing the THD down to an impressive 0.60%.

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