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Design and Analysis of Single-Tuned Passive Filters for Total Harmonic Distortion (THD) Mitigation and Power Quality Enhancement

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Abstract

Harmonic distortion caused by nonlinear loads is a significant challenge in power systems, often resulting in reduced efficiency, overheating, and equipment malfunction. Despite the availability of various mitigation techniques, many fail to offer a cost-effective and practical solution for distribution networks. This research addresses that gap by designing and analyzing a five-stage single-tuned passive filter (STPF) system to mitigate harmonics in a 400V, 50Hz distribution network. The main objective is to reduce Total Harmonic Distortion (THD) in voltage and current to meet IEEE 519-2022 standards. The proposed filter system targets the 5th, 7th, 9th, 11th, and 13th harmonic orders using a simulation model developed in MATLAB/Simulink. The system initially showed high THD levels of 16.06% in voltage and 17.57% in current. After applying the filters, the voltage THD was reduced to 3.89%, and the current THD dropped to 2.52%. These results confirm the effectiveness of STPFs in improving power quality under nonlinear loading conditions.

Keywords: Harmonic Mitigation; Passive Filters; Power Quality; Resonant Frequency; Total Harmonic Distortion

1. Introduction

In today's electrical systems, more and more devices—like power electronics, variable speed drives, and switching equipment—are being used. While these technologies improve efficiency and control, they also create harmonic distortion. Harmonics are unwanted signals that are multiples of the main frequency, and they can cause serious issues, such as overheating of equipment, unexpected malfunctions, and increased energy consumption (Gupta et al., 2020). If Total Harmonic Distortion (THD) levels are too high, electrical equipment may wear out faster, leading to higher maintenance costs and lower overall efficiency. That is why it is important to find effective ways to reduce harmonics and keep power systems running smoothly (Suryanarayana & Ravindranath, 2018).

THD is a key factor in measuring power quality, and the IEEE 519 standard sets clear guidelines on how much harmonic distortion is acceptable (IEEE, 2022). These guidelines are essential for protecting electrical devices and ensuring the stability of power systems. Following these standards helps industries and utilities maintain reliable operations, avoid damage to equipment, and improve overall system performance. Companies need to take the proper steps to control harmonic distortion to meet these requirements.

Various filtering techniques have been proposed to mitigate harmonic distortion. Among them, single-tuned passive filters (STPFs) are widely utilized for their simplicity, cost-effectiveness, and reliability in fixed-frequency applications. Gupta, Kumar, and Singh (2020) conducted a comprehensive review of passive and active filters, highlighting that although active filters provide superior dynamic compensation, their implementation is often constrained in low-voltage systems due to high costs and complex control requirements. In contrast, STPFs offer selective harmonic attenuation with simpler design and lower maintenance demands. However, Math and Jones (2019) noted that precise tuning and quality factor optimization are essential in STPF design to avoid issues like parallel resonance and ineffective filtering.

Several studies have further explored passive filter design through simulation-based methods. Suryanarayana and Ravindranath (2018) investigated the causes and mitigation of harmonics in industrial systems and recommended passive filters as a practical solution, though their work lacked a comprehensive simulation framework. Al-Yousif, Wanik, and Mohamed (2004) demonstrated various passive filter configurations for harmonic suppression but did not conduct a performance analysis based on stepwise filter deployment. Similarly, Nelson (2004) discussed the relevance of frequency-specific filter tuning in petrochemical industries but focused more on theoretical perspectives than implementation or simulation. Acharya and Bista (2021) recently implemented multiple tuned passive filters in commercial buildings and reported substantial THD reduction. However, their study did not assess the incremental impact of sequential filter activation, nor did it provide an evaluation of power quality metrics such as reactive power compensation. Bui and Vo (2020) proposed hybrid filter approaches for harmonic mitigation in microgrid systems. Still, they acknowledged that passive filters remain more economically viable in many practical scenarios due to their low cost and ease of deployment.

Despite the breadth of existing work, there remains a gap in the literature regarding detailed simulation-based analysis of multiple STPFs implemented in sequence and their combined effect on THD reduction and power quality enhancement. In particular, few studies quantify the performance improvements in terms of active and reactive power or provide a framework for evaluating each filter's contribution within a larger filter bank.

This research aims to fill that gap by designing and simulating a five-stage STPF system targeting the 5th, 7th, 9th, 11th, and 13th harmonic orders in a 400 V, 50 Hz three-phase distribution network subjected to nonlinear loads. The main objective is to evaluate the effectiveness of these filters in reducing voltage and current THD to levels within IEEE 519-2022 standards, while also analyzing their effect on active and reactive power flows. By adopting a sequential filter activation approach and evaluating performance at each stage using MATLAB/Simulink, this study provides a detailed insight into the cumulative and individual impact of each filter.

The key contributions of this work are: (i) the development of a systematic design methodology for STPFs with component sizing based on target harmonic frequencies, (ii) a simulation-based evaluation model using MATLAB/Simulink to observe the progressive improvement in power quality, and (iii) quantitative analysis of harmonics. This study establishes STPFs as an effective and affordable solution for harmonic mitigation in distribution systems with nonlinear loads.

2. Methodology

2.1 System Overview

The proposed system configuration is illustrated in Figure 1. The system under study is a three-phase, 400V, 50Hz distribution network with nonlinear loads introducing significant harmonic distortion. These loads primarily consist of power electronic converters, such as a three-phase diode bridge rectifier, which generate dominant odd-order harmonics. To mitigate these harmonic distortions, a passive filter bank is connected in parallel to the load side of the system.

It includes a 250 kVA Yg-Yg distribution transformer and a combination of five single-tuned passive filters, each rated at 20 kVAr, targeting harmonics of the 5th, 7th, 9th, 11th, and 13th orders. Before implementing filters, voltage and current THD were measured at 15.97% and 17.25%, respectively. The harmonic mitigation performance is evaluated based on IEEE 519-2022 standards to ensure compliance with permissible harmonic levels.

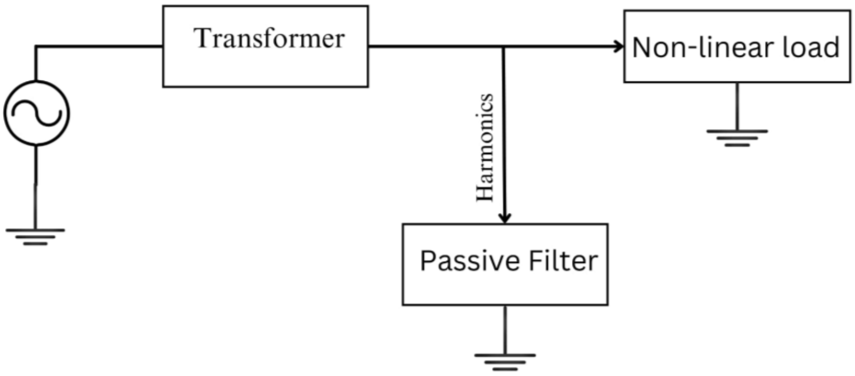


Figure 1:Block Diagram of Proposed Model

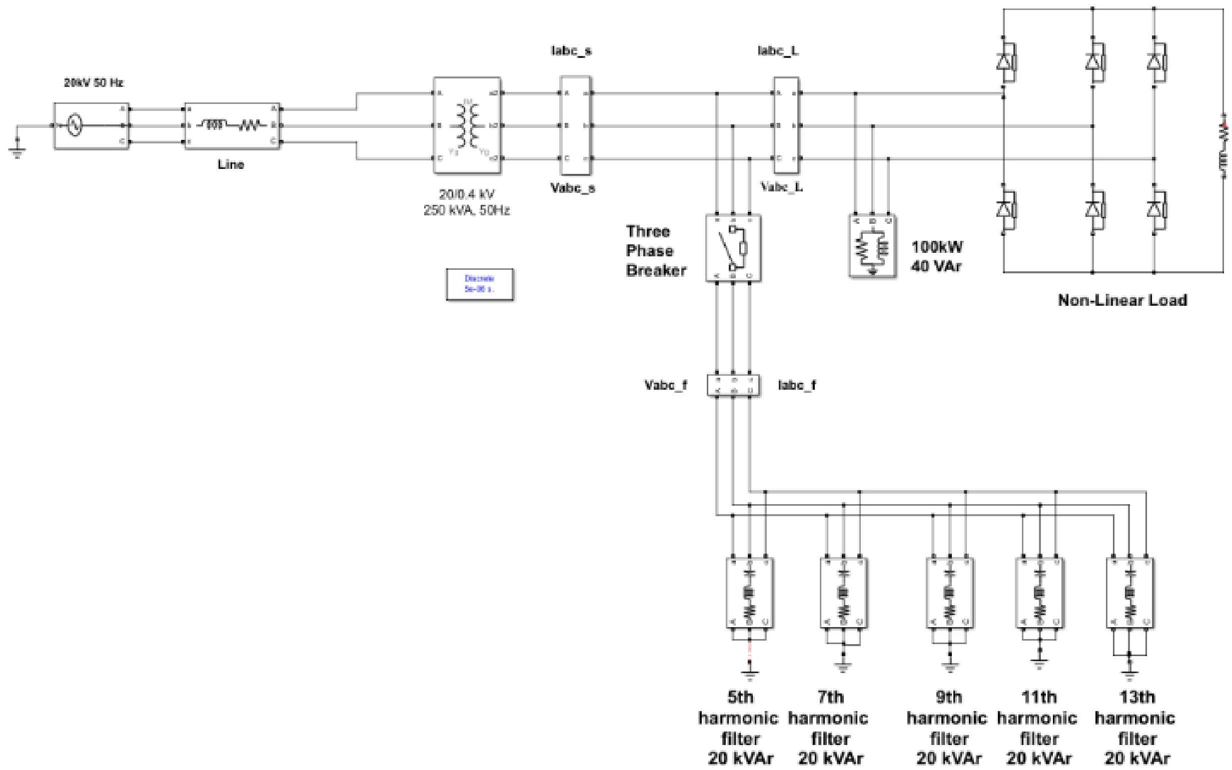


Figure 2: MATLAB Implementation of Proposed Model

2.2 Methodological Framework

The step-by-step algorithmic approach adopted in this study is presented in Figure 3. It outlines the complete process from initial harmonic analysis to the design, simulation, and validation of single-tuned passive filters (STPFs). The flow ensures a systematic implementation, starting from assessing harmonic distortion in the system and progressing through filter design, MATLAB/Simulink modeling, simulation execution, and performance evaluation.

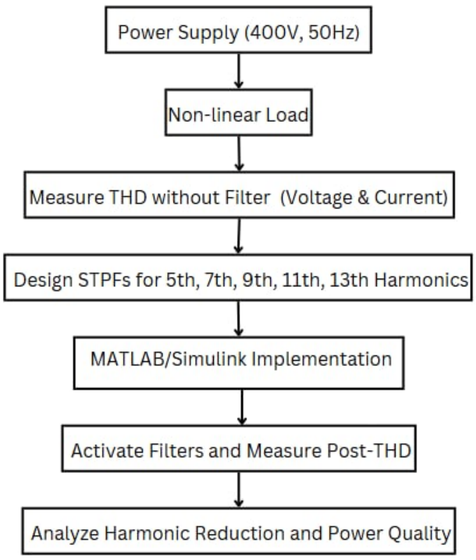


Figure 3: Methodological Block Diagram of STPF Implementation

2.3 Single-Tuned Passive Filter Design

A single-tuned passive filter is designed to resonate at a specific harmonic frequency, effectively mitigating targeted harmonic components. It consists of a series of connections of a resistor (*R*), inductor (*L*), and capacitor (*C*), which are selected to achieve resonance at the desired harmonic frequency. In this study, filters were designed to address the 5th, 7th, 9th, 11th, and 13th harmonics, common in systems with nonlinear loads. Each filter has a reactive power rating of 20 kVAr and a quality factor (*Q*) of 100 to ensure sharp tuning. The resonance frequency for each filter is determined by multiplying the system's base frequency (50 Hz) by the corresponding harmonic order. For example, the 5th harmonic filter is tuned to 250 Hz (5 × 50 Hz).

Once installed, the single-tuned passive filter provides a low-impedance path at its tuned frequency, allowing the corresponding harmonic current to bypass the network and flow through the filter. For instance, the 5th harmonic filter offers minimal impedance at 250 Hz, effectively shunting the 5th harmonic current away from the power supply. This reduces the harmonic content in the voltage and current waveforms, improving overall power quality.

The key criterion in designing this type of filter is selecting appropriate values for capacitors, inductors, and resistors to ensure an acceptable power factor at the line frequency.

The Capacitive reactance is related to reactive power as (Al-Yousif et al., 2004),

$$X_c = \frac{V_{rc}^2}{Q_c} \quad (1)$$

where V_{rc} is the nominal voltage of the condenser and Q_c is the reactive power supplied by the condenser. The filter capacitance value is then obtained through,

$$C_{STF} = \frac{1}{2\pi f_S X_c} \quad (2)$$

where f_s is the frequency of the supply mains. The inductance value of the filter is then calculated by,

$$L_{SRF} = \frac{1}{(2\pi f_S)^2 h_O^2 C_{STF}} \quad (3)$$

Where, h_o is the order of the harmonic to which the filter is designed to tune.

The value of filter resistor R is related to the quality factor (Q factor), which shows the sharpness of the resonance. Then the Q-factor is described as,

$$Q = \frac{X_n}{R} = \frac{\sqrt{\frac{L_{STF}}{C_{STF}}}}{R} \quad (4)$$

where X_n is the characteristic reactance. This resistance value can be decided by choosing a suitable quality factor value between 30 and 100 (Nelson, 2004).
The design parameter of the system is tabulated in Table 1.

Table 1: Design Parameter of System

Harmonic Order	Resistance (R) [Ω]	Inductance (L) [H]	Capacitance (C) [F]
5th	0.016	1.01e-3	3.97e-4
7th	0.0114	5.197e-4	3.97e-4
9th	0.0089	3.14e-4	3.97e-4
11th	0.0073	2.1e-4	3.97e-4
13th	0.0062	1.5e-4	3.97e-4

3. Simulation Result and Discussion

3.1 THD of Voltage and Current

The passive filter model was designed and simulated using the MATLAB® platform, integrating Simulink® and the SimPowerSystems™ library, to evaluate its effectiveness in mitigating harmonics in a three-phase, three-wire electrical distribution network. The system under analysis featured a three-phase rectifier-based non-linear load, which is known for introducing significant harmonic distortions due to its non-linear behavior. The supply provided to the system was 400V at 50Hz, a standard low-voltage supply in many distribution networks.
Single-tuned passive filters are designed to target specific harmonic frequencies by creating a low-impedance path for those frequencies, thereby diverting harmonic currents away from the primary electrical system. These filters are particularly effective in reducing specific harmonics, such as the 5th, 7th, 9th, 11th, and 13th, which are commonly found in power systems due to the presence of non-linear loads. In this study, the passive filters were activated at 0.25 seconds, immediately beginning to mitigate the dominant harmonic components. As the filters engaged, the current and voltage waveforms gradually shifted towards more sinusoidal shapes, indicating a substantial reduction in harmonic distortion. Before activating the filters, the system exhibited Total Harmonic Distortion (THD) values of 16.06% for voltage and 17.57% for current. However, the system's harmonic performance improved markedly once the passive filters were applied. The voltage THD decreased to 3.89%, and the current THD dropped to 2.52%, as detailed in Table 2.

Table 2: THD of Voltage and Current Before and After Passive Filter Activation

Parameter	Before filtering	After filtering (at 0.25 sec)
Voltage THD (%)	16.06	3.89
Current THD (%)	17.57	2.52

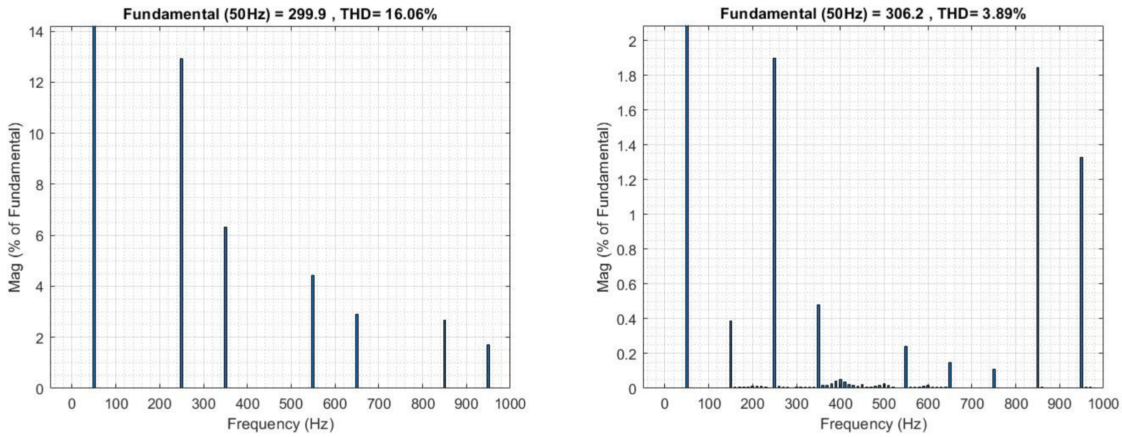


Figure 4: FFT Analysis of Voltage THD Before and After Passive Filter Activation, respectively.

A Fast Fourier Transform (FFT) analysis was performed to identify the harmonic frequencies present in the system's current and voltage waveforms. This analysis revealed the specific harmonic components, such as the 5th, 7th, 9th, 11th, and 13th harmonics, contributing to the high Total Harmonic Distortion (THD). The FFT results helped quantify the distortion levels and confirmed that the single-tuned passive filters effectively reduced these dominant harmonics, improving the overall waveform quality and power performance. The FFT analysis of Current and Voltage THD before and after filter activation is shown in Figures 4 and 5. This dramatic reduction demonstrates the high efficiency of single-tuned passive filters in selectively attenuating harmful harmonic frequencies.

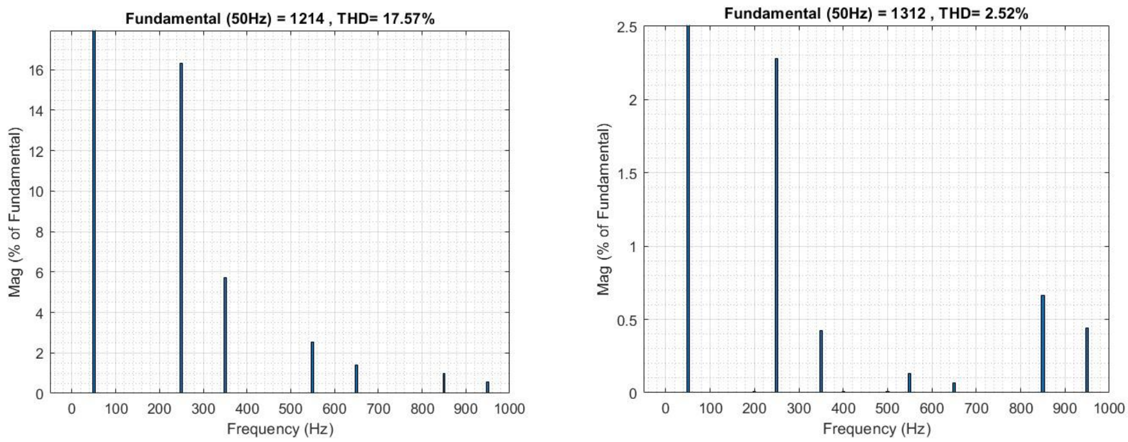
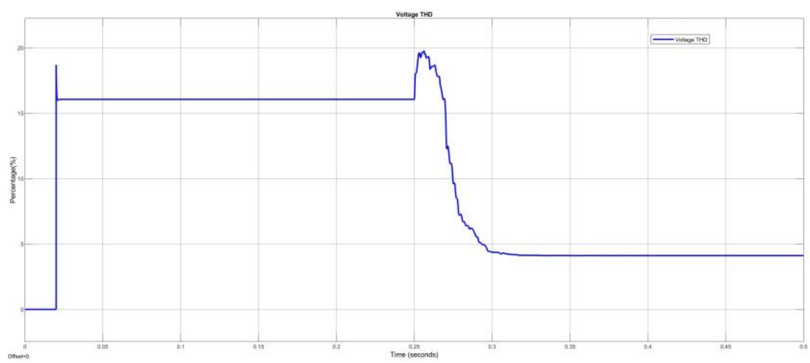


Figure 5: FFT Analysis of Current THD Before and After Passive Filter Activation, Respectively



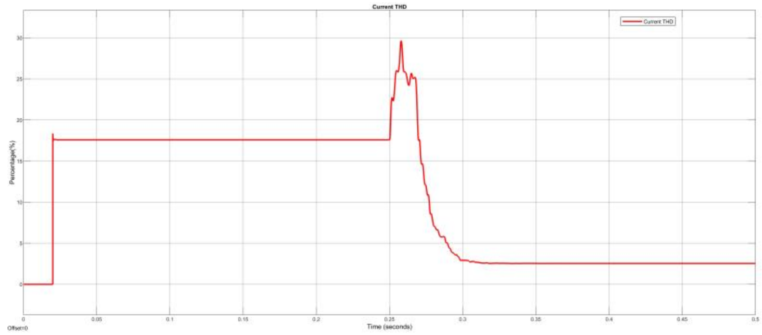


Figure 6: Voltage and Current THD change

By reducing the THD to these lower levels, the system's voltage and current waveforms became much closer to ideal sinusoidal shapes, as shown in Figure 7. This is crucial for maintaining power quality and ensuring the reliable operation of electrical equipment. The results clearly illustrate that single-tuned passive filters are an effective and practical solution for mitigating harmonics, thus improving the overall performance and stability of electrical power systems.

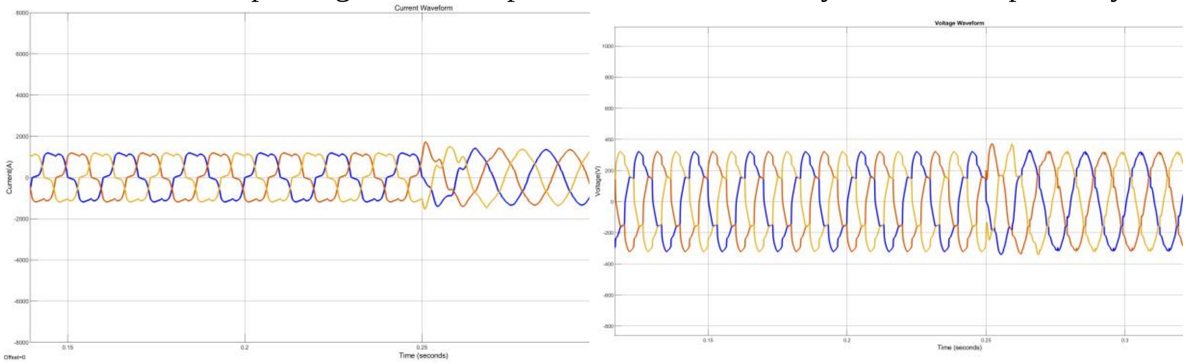


Figure 7: Current and Voltage Waveforms Showing Improved Sinusoidal Shape After Harmonic Mitigation

Figure 8 illustrates the dynamic interaction between the filter current, source current, and source voltage after activating the single-tuned passive filters. It shows that the filter current absorbs harmonic components, allowing the source current to align more closely with the sinusoidal source voltage. This behavior confirms effective harmonic mitigation and improved waveform quality.

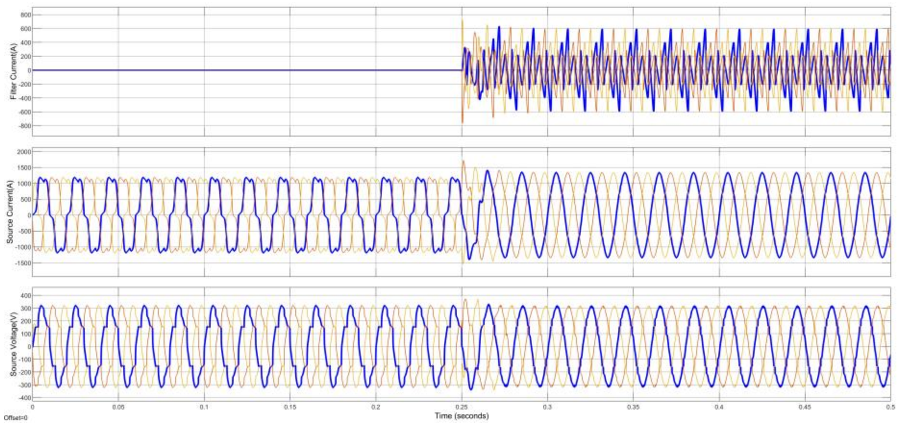


Figure 8: Filter Current, Source Current, and Source Voltage Waveform

3.2 Harmonic Reduction Analysis with Sequential Activation of Single-Tuned Passive Filters

The results in Table 3 demonstrate a significant reduction in both voltage and current Total Harmonic Distortion (THD) as additional harmonic filters are progressively activated. When only the 5th harmonic filter is engaged, the voltage THD and current THD are 9.13% and 6.38%, respectively. As more filters are switched on to target higher-order harmonics, there is a consistent decrease in both voltage and current THD.

Table 3: Harmonic Reduction Analysis with Sequential Activation of Single-Tuned Passive Filters

Filter Configuration	**Voltage THD (%)**	**Current THD (%)**
5th Harmonic Filter	9.13	6.38
5th + 7th Harmonic Filters	8.06	4.37
5th + 7th + 9th Harmonic Filters	6.57	3.60
5th + 7th + 9th + 11th Harmonic Filters	4.80	2.73
All Harmonic Filters (5th, 7th, 9th, 11th, and 13th)	3.89	2.52

With all harmonic filters (5th, 7th, 9th, 11th, and 13th) active, the voltage THD drops to 3.89% and the current THD to 2.52%, showing substantial harmonic suppression improvement. This progression illustrates the effectiveness of employing multiple single-tuned passive filters to mitigate harmonic distortion in the system and improve power quality.

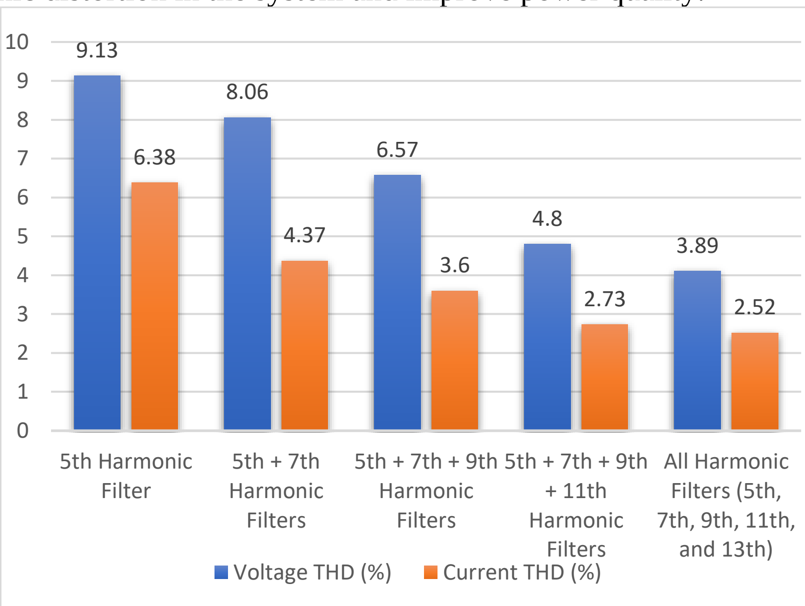


Figure 9: Harmonic Reduction Analysis with Sequential Activation of Single-Tuned Passive Filters

3.3 Power Quality Enhancement

Implementing single-tuned passive filters in the system reduced harmonic distortion and significantly improved power quality, as evident from the active and reactive power measurements. Following the activation of the filters, the simulation results show that the active power (P) stabilized at 607.9 kW, indicating a steady delivery of real power to the load with minimal fluctuations. This stability in active power is crucial for maintaining efficient operation of electrical systems, as it ensures that the energy being consumed is effectively utilized for performing useful work.

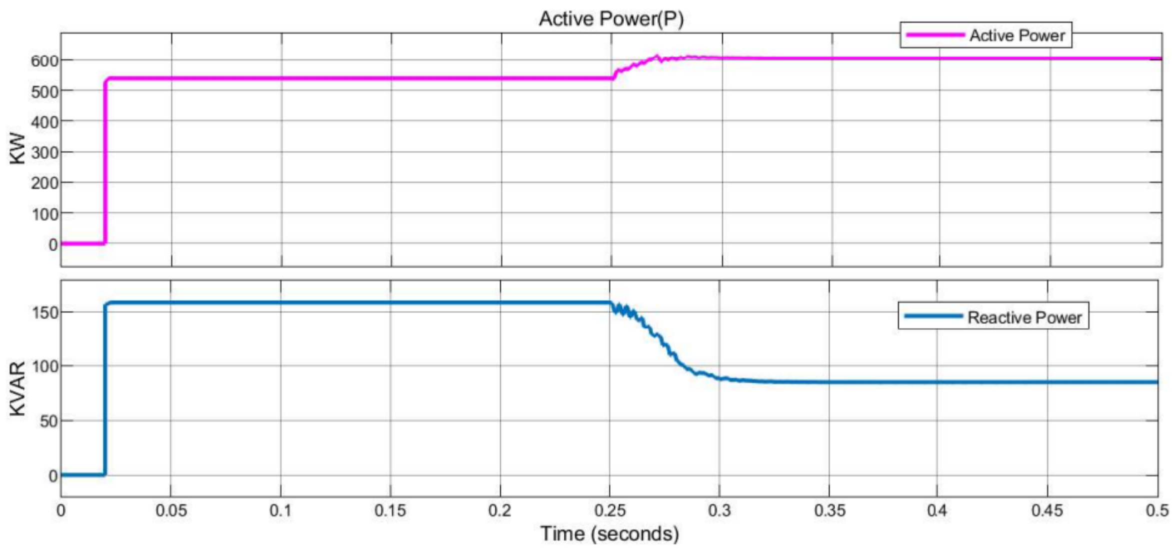


Figure 10: Active and Reactive Power Improvement

The reactive power (Q) also decreased to 84.68 kVAr, a key indicator of enhanced power factor and reduced energy losses. Reactive power is typically associated with the non-productive energy in the system, which arises from the presence of inductive and capacitive elements and contributes to inefficiencies. By reducing the reactive power, the system's power factor improves, signifying that less power is being wasted in the form of reactive energy. This indicates that the filters successfully mitigated the harmonic components that previously contributed to the elevated reactive power levels.

3.4 Impedance Characteristics of the Filters

Figure 8 shows the impedance-frequency response of the single-tuned passive filters. As expected, the impedance drops to nearly zero ohms at the resonance frequencies corresponding to the targeted harmonic orders (250 Hz, 350 Hz, 450 Hz, 550 Hz, and 650 Hz). This behavior confirms the filters' effective tuning, providing a low-impedance path for the respective harmonic currents.

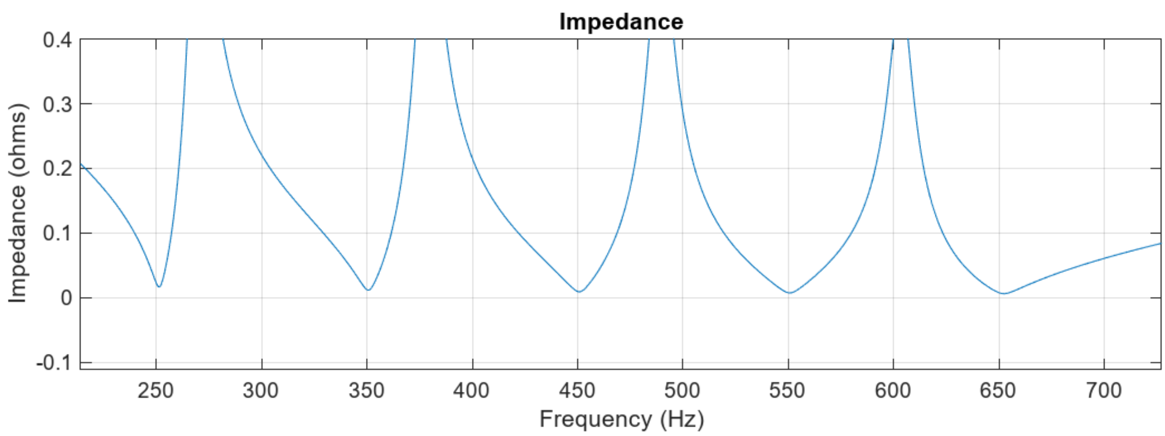


Figure 11: Impedance Characteristics of Single-Tuned Passive Filters at Target Harmonic Frequencies

By minimizing the impedance at these frequencies, the filters successfully shunt the harmonic currents away from the supply network, reducing their impact on voltage and current waveforms. This aligns with the intended design objective of mitigating harmonics and improving overall power quality in the system.

4. Conclusion

This study successfully demonstrates the design and effectiveness of a five-stage single-tuned passive filter (STPF) system for mitigating harmonic distortion in a 400 V, 50 Hz three-phase distribution network with nonlinear loads. The system initially exhibited high distortion levels, with voltage THD at 16.06% and current THD at 17.57%, exceeding IEEE 519-2022 limits. Through the sequential activation of filters tuned to the 5th, 7th, 9th, 11th, and 13th harmonic orders, voltage THD was reduced to 3.89%, and current THD dropped to 2.52%, achieving compliance with the standard. The filter system's progressive deployment also showed incremental improvement at each stage, confirming the value of targeting multiple harmonic orders for comprehensive distortion mitigation.

In addition to harmonic suppression, the STPFs improved overall power quality. The active power stabilized at 607.9 kW, and reactive power was reduced to 84.68 kVAr, indicating better power factor and reduced energy losses. FFT and impedance-frequency analysis validated the filters' ability to provide low-impedance paths at their tuned frequencies, effectively diverting harmonic currents. These findings establish STPFs as a cost-effective, reliable solution for harmonic mitigation in low-voltage distribution systems. The results provide a strong foundation for future research on adaptive and hybrid filters to enhance performance under dynamic loading conditions.

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