



Analysis of Passive Power Filter Placement in an Electrical Distribution System

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ABSTRACT

The widespread use of variable-frequency drives (VFDs), converter-based loads, and distributed generation can produce significant harmonic distortion in industrial distribution systems. This study evaluates a selected passive-filter placement strategy using ETAP for a multi-voltage electrical distribution system containing utility supply, diesel generation, photovoltaic generation, a VFD-fed industrial motor, and a low-voltage nonlinear load. Harmonic load-flow simulations were used to compare bus-voltage total harmonic distortion (THD_V) before and after installing a combined Single-Tuned Passive Filter (STPF) and High-Pass Filter (HPF) configuration. Before filtering, the highest documented bus-voltage distortions were 16.03% at SS-05C, 11.69% at SS-PV-B, and 11.24% at SS-05A. The 28.23% value shown in the ETAP output is treated as current distortion (THD_I) and is therefore not directly compared with the bus-voltage THD_V values. After filtering, THD_V decreased to 0.73% at SS-05C, 4.81% at SS-PV-B, and 3.26% at SS-05A. The study is presented as a practical selected-placement case study rather than a formal optimization method, and full IEEE 519 compliance is not claimed because the contractual Point of Common Coupling (PCC) is not explicitly documented.

Keywords: Harmonic distortion; passive power filter; single-tuned passive filter; high-pass filter; ETAP; power quality.

1. Introduction

The increasing adoption of industrial automation and power electronic technologies has significantly transformed modern electrical power systems. In industrial facilities, commercial buildings, and utility networks, various power electronic devices such as Variable Frequency Drives (VFDs), Uninterruptible Power Supplies (UPS), rectifiers, inverters, switched-mode power supplies (SMPS), and adjustable speed drives are widely utilized to improve energy efficiency, process control, and operational flexibility. These technologies enable precise control of electrical equipment and contribute to energy conservation; however, their extensive utilization has introduced new challenges related to power quality, particularly harmonic distortion [1].

Harmonics are sinusoidal voltage or current components whose frequencies are integer multiples of the fundamental frequency of the power system. In a 50 Hz electrical network, harmonic frequencies commonly occur at the 3rd, 5th, 7th, 11th, and 13th orders, corresponding to frequencies of 150 Hz, 250 Hz, 350 Hz, 550 Hz, and 650 Hz, respectively. These harmonic components are generated primarily by non-linear loads that draw current in a non-sinusoidal manner despite being supplied by a sinusoidal voltage source. As a result, the interaction between the source impedance and harmonic currents produces distorted voltage waveforms throughout

the electrical system, leading to deviations from ideal operating conditions [2].

The rapid growth of non-linear electrical loads has made harmonic distortion one of the most important power quality issues in modern power systems. Unlike traditional linear loads, which draw current proportional to the applied voltage, non-linear devices employ semiconductor switching techniques that generate harmonic currents over a wide frequency spectrum. The cumulative effect of these harmonics can significantly deteriorate the performance of electrical equipment and reduce the overall efficiency of the power system. Consequently, utilities and industrial operators are increasingly concerned about the impact of harmonics on system reliability, operational costs, and equipment lifespan [3].

The presence of harmonics in electrical networks can produce numerous adverse effects. Harmonic currents increase power losses in transformers, cables, generators, and rotating machines due to additional heating effects. Excessive heating accelerates insulation degradation and shortens equipment service life. Harmonics can also cause voltage distortion that affects sensitive electronic equipment, leading to malfunction, measurement errors, and process interruptions. Furthermore, capacitor banks used for power factor correction are particularly vulnerable to harmonic resonance, which may result in excessive currents,

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overvoltage, and premature capacitor failure. In severe cases, harmonics can interfere with communication systems, create nuisance tripping of protective relays, and compromise the coordination of protection schemes [4].

In industrial power systems, harmonic-related problems are particularly significant because large concentrations of VFDs and rectifier-based equipment are commonly employed in manufacturing processes, mining operations, power plants, and process industries. Facilities utilizing conveyor systems, pumps, compressors, and motor drives often experience elevated harmonic levels due to the widespread application of variable-speed technologies. Without proper harmonic mitigation measures, these installations may experience increased maintenance costs, reduced system efficiency, and unexpected equipment outages. Therefore, comprehensive harmonic assessment has become an essential component of modern power system planning and operation [5].

To ensure acceptable power quality levels, international standards and guidelines have been developed to regulate harmonic distortion. Among these standards, IEEE Std 519-2014 is one of the most widely recognized references for harmonic control in electrical power systems. The standard establishes recommended limits for voltage and current harmonic distortion at the Point of Common Coupling (PCC), where the utility system interfaces with customer facilities. Harmonic performance is typically evaluated using indices such as Total Harmonic Distortion (THD), Individual Harmonic Distortion (IHD), and Total Demand Distortion (TDD). Compliance with IEEE 519 limits helps prevent adverse impacts on electrical equipment and promotes reliable system operation [6, 7].

Accurate harmonic analysis is essential for identifying the sources of harmonic distortion and evaluating mitigation strategies. Advances in computer-based power system simulation have enabled engineers to model harmonic-producing devices and assess their impact under various operating conditions. Electrical Transient Analyzer Program (ETAP) is one of the most widely used software platforms for power system analysis. ETAP provides comprehensive harmonic assessment capabilities, including Harmonic Load Flow Analysis, Frequency Scan Analysis, Harmonic Spectrum Evaluation, and Filter Design Tools. These features enable engineers to identify critical harmonic sources, determine dominant harmonic orders, and evaluate compliance with harmonic standards efficiently [8].

Various harmonic mitigation techniques have been proposed to reduce the negative effects of harmonics. Among these techniques, passive filters remain one of the most commonly implemented solutions due to their simplicity, reliability, and cost-effectiveness. Passive filters consist of combinations of capacitors, inductors, and resistors tuned to specific harmonic frequencies. By providing a low-impedance path for harmonic currents, passive filters effectively reduce harmonic distortion and improve power factor simultaneously. Single-tuned filters are typically designed to suppress dominant harmonic orders such as the 5th or 7th harmonics, while high-pass filters are utilized for mitigating higher-order harmonics [9].

Although passive filters offer several advantages, they may experience limitations under varying operating conditions. Changes in system impedance and load characteristics can affect filter performance and potentially introduce resonance phenomena. To overcome these limitations, active power filters (APFs) have been developed as an advanced harmonic mitigation solution. Active filters utilize power electronic converters and digital control algorithms to inject compensating currents that cancel harmonic components generated by non-linear loads. Unlike passive filters, active filters can dynamically adapt to changing load conditions and simultaneously mitigate multiple harmonic orders, making them highly effective in complex power systems [10, 11].

The selection between passive and active filtering techniques depends on several factors, including the harmonic spectrum, system configuration, load variability, performance requirements, and economic constraints. Therefore, comparative analysis of these filtering methods is necessary to determine the most suitable harmonic mitigation strategy for a particular electrical network. Evaluating the effectiveness of passive and active filters through simulation studies can provide valuable insights into their performance and practical implementation.

Accordingly, this study evaluates a practical source-oriented placement of passive filters using ETAP. The contribution is a transparent before-and-after assessment of harmonic-voltage distortion in a multi-source industrial distribution system. The study does not claim a new placement-optimization algorithm; instead, it evaluates a selected filter arrangement and explicitly identifies the additional data required for resonance, sensitivity, and field-validation studies.

2. Literature Review

2.1 Harmonics in Power Systems

The increasing implementation of power electronic equipment in modern electrical distribution systems has significantly improved the efficiency, controllability, and flexibility of industrial processes. Equipment such as Variable Frequency Drives (VFDs), rectifiers, inverters, soft starters, Uninterruptible Power Supplies (UPS), and other converter-based devices are widely utilized in industrial plants, commercial facilities, and utility applications. Although these technologies provide substantial operational advantages, they also introduce power quality problems due to their non-linear operating characteristics. One of the most significant power quality concerns associated with these devices is harmonic distortion [12].

Harmonics are sinusoidal voltage or current components whose frequencies are integer multiples of the fundamental system frequency. In electrical systems operating at 50 Hz, harmonic frequencies occur at 150 Hz, 250 Hz, 350 Hz, 450 Hz, and higher multiples corresponding to the third, fifth, seventh, ninth, and subsequent harmonic orders. These harmonic components combine with the fundamental waveform and cause deviations from the ideal sinusoidal shape. Consequently, electrical quantities such as voltage and current become distorted, leading to reduced power quality and decreased system performance [2].

The generation of harmonics is primarily associated with non-linear loads. Unlike linear loads, which draw current proportional to the applied voltage, non-linear loads draw current in discontinuous pulses. This non-sinusoidal current contains harmonic frequency components that flow through the system impedance and create harmonic voltage distortion. As the number of non-linear loads increases within a distribution network, the cumulative harmonic effect becomes more significant, resulting in increased distortion levels throughout the system [3].

In industrial distribution systems, harmonics are commonly generated by motor drive systems, welding equipment, arc furnaces, battery charging systems, and various power electronic converters. These devices often operate continuously and contribute substantial harmonic currents to the network. Since distribution systems serve as the interface between electrical sources and end-user loads, harmonic currents generated at one location may propagate throughout the network and affect other connected equipment. Therefore, harmonic propagation is a critical issue that must be carefully analyzed in distribution system studies [5].

The effects of harmonic distortion on distribution system performance are extensive. One of the most common impacts is the increase in power losses within conductors and transformers. Harmonic currents increase the root mean square (RMS) current flowing through electrical equipment, resulting in additional copper losses. Furthermore, higher-frequency harmonic components contribute to increased eddy-current and stray-flux losses within transformer cores. These additional losses lead to excessive temperature rise, accelerated insulation aging, and reduced equipment lifespan [3].

Electrical machines operating under distorted voltage conditions may also experience adverse effects. Harmonic voltages can produce pulsating torques, mechanical vibration, acoustic noise, and reduced efficiency. Prolonged operation under such conditions may increase maintenance requirements and decrease machine reliability. Similarly, protective devices such as relays and circuit breakers may operate inaccurately due to waveform distortion, potentially compromising system protection and coordination [4].

Capacitor banks used for power factor correction are particularly sensitive to harmonic distortion. The interaction between capacitor banks and system inductance may create resonance conditions that amplify harmonic currents and voltages. Resonance can result in excessive capacitor currents, overheating, dielectric stress, and premature equipment failure. Therefore, harmonic studies are essential whenever capacitor banks or harmonic mitigation devices are introduced into the distribution system [13].

Another important consequence of harmonic distortion is voltage quality degradation. Excessive harmonic voltages may interfere with sensitive electronic equipment, causing malfunctions, data errors, and operational interruptions. In industrial facilities where process continuity is critical, poor power quality can lead to production losses and increased operational costs. Therefore, maintaining harmonic levels within acceptable limits is necessary to ensure reliable and efficient system operation.

To address these issues, harmonic evaluation has become a standard practice in modern power system engineering. Harmonic studies enable engineers to identify dominant harmonic sources, assess harmonic propagation, evaluate compliance with applicable standards, and determine appropriate mitigation measures. Among various harmonic mitigation techniques, Passive Power Filters are widely employed due to their simplicity, reliability, and cost-effectiveness. However, the effectiveness of a Passive Power Filter depends heavily on its installation location within the distribution system. Consequently, detailed harmonic analysis is required to determine the most suitable filter placement strategy.

The IEEE Std 519-2014 standard provides guidelines for assessing harmonic distortion and establishing acceptable harmonic limits. According to this standard, voltage Total Harmonic Distortion (THD_v) at the Point of Common Coupling (PCC) should generally not exceed 5% for systems below 69 kV. Compliance with these limits is essential for ensuring adequate power quality and minimizing the negative impacts of harmonic distortion on electrical equipment and system performance [6, 14, 15].

As harmonic distortion levels vary among different buses within a distribution system, identifying the locations with the highest harmonic concentrations becomes an important aspect of harmonic studies. Buses experiencing elevated harmonic levels are often considered critical locations for harmonic mitigation. Therefore, harmonic analysis serves as the foundation for determining the optimal placement of Passive Power Filters in electrical distribution networks.

2.2 Harmonic Assessment for Passive Power Filter Placement

The successful implementation of Passive Power Filters requires a comprehensive understanding of harmonic behaviour within the electrical distribution system. Filter effectiveness is influenced not only by its electrical parameters but also by its installation location. Therefore, harmonic assessment plays a crucial role in identifying the most appropriate bus for filter placement and ensuring maximum harmonic reduction performance [16].

Harmonic assessment generally begins with the identification of harmonic sources within the system. Non-linear loads such as Variable Frequency Drives, rectifiers, and inverter-based equipment are analysed to determine their harmonic emission characteristics. The harmonic current spectrum generated by these devices serves as the basis for evaluating harmonic propagation and identifying dominant harmonic frequencies. Since different types of equipment generate different harmonic spectra, understanding source characteristics is essential for filter design and placement [17].

One of the most widely used methods for harmonic assessment is Harmonic Load Flow Analysis. This analysis evaluates the distribution of harmonic voltages and currents throughout the electrical network under steady-state operating conditions. Harmonic load flow studies provide detailed information regarding harmonic distortion levels at each bus, enabling engineers to identify locations where harmonic problems are most severe. These locations are

often selected as candidate buses for Passive Power Filter installation.

The primary parameter used in harmonic assessment is Total Harmonic Distortion (THD). THD provides a quantitative measure of waveform distortion and is widely used as an indicator of power quality. High THD values indicate significant harmonic contamination and may signal the need for corrective actions.

The voltage THD can be calculated using:

$$THD_V = \frac{\sqrt{V_2^2 + V_3^2 + \dots + V_n^2}}{V_1} \times 100\% \quad (1)$$

Where:

V_1 is the fundamental voltage component

V_2 to V_n represent harmonic voltage components.

Similarly, current THD is expressed as:

$$THD_I = \frac{\sqrt{I_2^2 + I_3^2 + \dots + I_n^2}}{I_1} \times 100\% \quad (2)$$

Where:

I_1 is the fundamental current component

I_2 to I_n are harmonic current components

In addition to THD, harmonic spectrum analysis is an essential component of filter placement studies. Harmonic spectrum analysis provides information regarding the magnitude and frequency of individual harmonic orders. This information is used to identify dominant harmonics and determine the tuning frequency of the Passive Power Filter. For instance, if the fifth harmonic exhibits the highest magnitude among all harmonic components, a single-tuned filter designed for the fifth harmonic frequency may be selected as the most appropriate mitigation solution [9].

The selection of filter placement locations is typically based on several technical criteria. First, buses with the highest THD values are prioritized because they experience the greatest harmonic distortion. Second, buses located near major harmonic-producing loads are considered strategic locations because filtering harmonics at their source prevents harmonic propagation throughout the network. Third, system configuration and power flow characteristics are evaluated to ensure that filter installation does not create adverse interactions with other system components [18].

Another important aspect of harmonic assessment is resonance analysis. The installation of capacitive components within Passive Power Filters may alter the system impedance characteristics and potentially create resonance conditions. Frequency scan analysis is commonly performed to identify resonance frequencies and ensure that they do not coincide with dominant harmonic orders present in the system. This analysis is essential for preventing harmonic amplification and ensuring stable filter operation.

Modern harmonic studies are commonly conducted using simulation software such as ETAP. ETAP provides comprehensive tools for harmonic load flow analysis, harmonic spectrum evaluation, frequency scan studies, and filter design optimization. Through simulation, engineers

can compare harmonic levels before and after filter installation and evaluate the effectiveness of different placement alternatives. This approach reduces implementation risks and allows filter performance to be optimized prior to actual installation.

The results of harmonic assessment provide the technical basis for Passive Power Filter placement decisions. By identifying buses with high harmonic distortion levels, determining dominant harmonic orders, and evaluating system resonance characteristics, engineers can select the most effective filter location and configuration. Consequently, harmonic assessment serves as a critical step in improving power quality, reducing harmonic-related losses, and ensuring compliance with IEEE Std 519-2014 requirements within electrical distribution systems.

2.3 Passive Power Filter Placement in Distribution Systems

Passive Power Filters (PPFs) are among the most widely implemented solutions for mitigating harmonic distortion in electrical distribution systems. Compared to other harmonic mitigation technologies, passive filters offer several advantages, including simple construction, high reliability, low maintenance requirements, and relatively low installation costs. These characteristics make passive filters particularly suitable for industrial facilities where harmonic distortion is primarily generated by non-linear loads such as Variable Frequency Drives (VFDs), rectifiers, inverters, and other power electronic equipment [9].

A Passive Power Filter consists of combinations of inductors, capacitors, and, in some configurations, resistors connected in series or parallel arrangements. The primary function of the filter is to provide a low-impedance path for harmonic currents at specific frequencies. As a result, harmonic currents are diverted through the filter branch rather than flowing through the electrical distribution network. This mechanism effectively reduces harmonic current propagation and improves voltage quality throughout the system [3].

The operating principle of a passive filter is based on resonance phenomena. By selecting appropriate values of inductance and capacitance, the filter can be tuned to a specific harmonic frequency. At the tuning frequency, the filter impedance becomes significantly lower than the system impedance, attracting harmonic currents corresponding to that harmonic order. Consequently, the magnitude of harmonic distortion within the distribution system is reduced. The tuning frequency of a passive filter is generally determined according to the dominant harmonic order identified during harmonic spectrum analysis [13].

Several passive filter configurations are commonly used in electrical power systems. Among these configurations, the Single-Tuned Filter is the most widely applied due to its effectiveness in mitigating dominant harmonic frequencies. A single-tuned filter is designed to suppress a specific harmonic order, typically the 5th or 7th harmonic, which are frequently generated by six-pulse converter systems and variable speed drives. Because these harmonic components usually contribute the largest percentage of total harmonic distortion, reducing their magnitude can significantly improve overall power quality [9].

In addition to single-tuned filters, Double-Tuned Filters may be employed when two dominant harmonic frequencies are present simultaneously. These filters are capable of mitigating two harmonic orders using a single filter structure. High-Pass Filters are also utilized for suppressing higher-order harmonic components that cannot be effectively eliminated using conventional tuned filters. However, for most industrial applications, single-tuned filters remain the preferred solution because of their simplicity and economic feasibility [9].

The effectiveness of a Passive Power Filter depends greatly on its placement within the electrical distribution system. Even a properly designed filter may fail to achieve satisfactory harmonic reduction if installed at an inappropriate location. Therefore, determining the optimal filter placement is one of the most critical aspects of harmonic mitigation studies.

Generally, Passive Power Filters are installed according to one of three placement strategies. The first strategy involves installing the filter directly at the harmonic source. In this configuration, the filter is connected near non-linear loads such as VFDs or rectifiers. This approach prevents harmonic currents from propagating throughout the distribution system and is often considered the most effective placement method. By filtering harmonics at their source, the harmonic burden on transformers, feeders, and other system components can be significantly reduced [16,17].

The second strategy involves installing the filter at a distribution bus where harmonic distortion is concentrated. Harmonic Load Flow Analysis often reveals that certain buses exhibit higher THD values than others due to the accumulation of harmonic currents from multiple sources. Installing a filter at these critical buses can provide substantial harmonic reduction and improve power quality for a larger portion of the distribution network. This approach is commonly applied when multiple harmonic-producing loads are connected to the same bus [18].

The third strategy involves placing the filter near sensitive equipment or at the Point of Common Coupling (PCC). This configuration is intended to maintain compliance with harmonic standards and protect critical equipment from excessive harmonic distortion. Although this approach can improve local power quality, it may not be as effective in preventing harmonic propagation throughout the entire system compared to source-based filtering [19].

To determine the most appropriate filter location, harmonic assessment results obtained from Harmonic Load Flow Analysis are evaluated. Buses exhibiting the highest Total Harmonic Distortion (THD) values are generally considered primary candidates for filter installation. The dominant harmonic order at these buses is then identified using harmonic spectrum analysis. Based on this information, the filter tuning frequency and electrical parameters can be determined to maximize harmonic reduction performance [20].

Another important consideration in Passive Power Filter placement is the interaction between the filter and system impedance. The addition of capacitive and inductive elements alters the system frequency response and may introduce resonance conditions. If resonance occurs near a

dominant harmonic frequency, harmonic distortion can be amplified instead of reduced. Therefore, frequency scan analysis is typically performed before filter installation to evaluate system resonance characteristics and ensure safe filter operation [21].

Simulation software such as ETAP plays a crucial role in filter placement studies. ETAP enables engineers to perform harmonic load flow analysis, harmonic spectrum analysis, and frequency scan studies within a single simulation environment. Through comparative simulations conducted before and after filter installation, the effectiveness of different placement alternatives can be evaluated quantitatively. Parameters such as THDv, THDi, harmonic spectrum distribution, and compliance with IEEE Std 519-2014 limits can be assessed to determine the most effective filter placement strategy [22].

In this study, Passive Power Filter placement is determined based on the results of harmonic load flow analysis conducted using ETAP software. The bus exhibiting the highest harmonic distortion level is selected as the filter installation location. Subsequently, the dominant harmonic frequency identified through harmonic spectrum analysis is used as the basis for filter tuning. The performance of the proposed filter is evaluated by comparing harmonic distortion levels before and after filter implementation. The results provide insight into the effectiveness of Passive Power Filter placement in improving power quality and reducing harmonic distortion within the electrical distribution system.

The proper placement of Passive Power Filters not only reduces Total Harmonic Distortion but also contributes to improved system efficiency, reduced equipment losses, enhanced operational reliability, and compliance with international power quality standards. Therefore, filter placement analysis represents a fundamental step in the design and implementation of harmonic mitigation solutions in modern electrical distribution systems.

2.4 ETAP-Based Harmonic Analysis

To evaluate harmonic distortion and determine the optimal placement of Passive Power Filters (PPFs), a harmonic analysis was conducted using Electrical Transient Analyzer Program (ETAP) software. The simulation model was developed based on the actual configuration of the electrical distribution system, consisting of utility grid supply, diesel power generation units, transformers, distribution buses, industrial loads, and harmonic mitigation devices. ETAP was selected because it provides comprehensive tools for harmonic load flow analysis, harmonic spectrum evaluation, and filter performance assessment within a single simulation platform [23].

The studied distribution system consists of two primary power sources, namely a utility grid represented by a short-circuit capacity of 5000 MVA_{sc} and a diesel power plant rated at 10 MW. Both sources are connected to the main 20 kV distribution bus through 15 MVA power transformers. The medium-voltage distribution network supplies several downstream buses operating at voltage levels of 3.3 kV and 0.4 kV through step-down transformers with capacities ranging from 1.5 MVA to 2.5 MVA.

The system includes both linear and non-linear loads. The major harmonic-producing load is a Variable Frequency Drive (VFD) connected to a 500 kW industrial motor at the 3.3 kV industrial motor bus. In addition, a 700 kVA non-linear load is connected to the 0.4 kV distribution bus. These loads utilize power electronic switching devices that generate harmonic currents during operation. Consequently, harmonic currents are injected into the distribution system and propagate through transformers, feeders, and buses, potentially affecting the overall power quality of the network [2].

The first stage of the analysis involved performing a conventional load flow study to verify the operating condition of the electrical system under normal loading conditions. The load flow analysis provided information regarding bus voltages, power flows, transformer loading, and equipment operating conditions. These results served as the basis for subsequent harmonic studies by ensuring that all network components operated within their acceptable limits. After completing the load flow analysis, Harmonic Load Flow Analysis was performed to evaluate harmonic distortion throughout the distribution system. In ETAP, harmonic sources were modelled based on the harmonic spectrum associated with the Variable Frequency Drive and the non-linear load. The harmonic load flow calculation determined harmonic voltage and current magnitudes at each bus and identified the locations experiencing the highest harmonic distortion levels [8].

The harmonic load flow results provide valuable information regarding the distribution of Total Harmonic Distortion of Voltage (THDv) and Total Harmonic Distortion of Current (THDi) throughout the network. Buses exhibiting elevated THD values are considered critical locations because excessive harmonic distortion may lead to increased power losses, transformer overheating, capacitor stress, and reduced equipment lifespan. Furthermore, comparison of measured THD values with IEEE Std 519-2014 limits allows assessment of power quality compliance within the distribution system [15].

In addition to THD evaluation, harmonic spectrum analysis was conducted to identify dominant harmonic orders generated by the non-linear loads. The harmonic spectrum illustrates the contribution of each harmonic component to the overall distortion level. Since the Variable Frequency Drive represents the primary harmonic source in the system, lower-order harmonics such as the 5th and 7th harmonics are expected to contribute significantly to the total harmonic distortion. Identification of dominant harmonic frequencies is essential because the tuning frequency of the Passive Power Filter must correspond to the harmonic orders requiring mitigation [24].

Based on the harmonic assessment results, three passive filter units were incorporated into the ETAP model. Two Single-Tuned Filters, designated as HF1 and HF2, were installed at the industrial motor bus near the Variable Frequency Drive. These filters were designed to suppress dominant low-order harmonics generated by the VFD, thereby preventing harmonic currents from propagating to upstream distribution buses. Installing the filters close to the harmonic source improves mitigation effectiveness because

harmonic currents are absorbed before spreading throughout the network [16].

A High-Pass Filter, designated as HF3, was installed at the 0.4 kV bus supplying the 700 kVA non-linear load. Unlike single-tuned filters, the high-pass filter is intended to suppress higher-order harmonic components that may remain after the dominant harmonics have been mitigated. The combination of single-tuned and high-pass filters provides broader harmonic suppression capability and improves overall system power quality [25].

To evaluate the effectiveness of the proposed filter placement strategy, harmonic simulations were conducted before and after filter installation. The comparison focused on changes in THDv, THDi, and harmonic spectrum characteristics at critical buses throughout the distribution system. A successful filter implementation is indicated by a substantial reduction in harmonic distortion levels and compliance with IEEE Std 519-2014 requirements [15].

The selected filter locations were based on the principle of source-oriented harmonic mitigation. Since the Variable Frequency Drive and non-linear load represent the primary harmonic-producing equipment in the system, placing the filters close to these sources minimizes harmonic propagation and reduces the harmonic burden on transformers, feeders, and upstream buses. This placement strategy also improves system efficiency by reducing harmonic-related losses and enhancing voltage quality throughout the distribution network.

Through ETAP simulation, the effectiveness of Passive Power Filter placement can be quantitatively assessed. The analysis provides technical justification for filter installation, identifies optimal mitigation locations, and demonstrates the capability of passive filtering techniques to improve power quality in industrial distribution systems. Therefore, ETAP-based harmonic analysis serves as an essential tool for supporting filter placement decisions and ensuring reliable operation of modern electrical distribution networks.

2.5 Research Gap and Novelty

The increasing use of non-linear loads in industrial power systems has encouraged extensive research on harmonic analysis and harmonic mitigation techniques. Various studies have investigated the impact of harmonic distortion on electrical equipment, power quality performance, and system reliability. In addition, numerous harmonic mitigation methods have been developed, including passive filters, active filters, and hybrid filtering systems. Among these approaches, Passive Power Filters (PPFs) remain widely applied due to their simple design, low maintenance requirements, and cost-effective implementation [26].

Several previous studies have focused on evaluating harmonic distortion levels in electrical distribution systems using simulation software. These studies generally emphasize the identification of dominant harmonic sources, measurement of Total Harmonic Distortion (THD), and assessment of compliance with harmonic standards such as IEEE Std 519-2014. The results demonstrate that harmonic distortion can significantly affect transformer performance, increase system losses, reduce equipment lifetime, and degrade overall power quality [27]. However, most of these

studies primarily focus on harmonic assessment without providing detailed analysis regarding the optimal placement of harmonic mitigation devices.

Other researchers have investigated the application of Passive Power Filters for reducing harmonic distortion generated by non-linear loads. These studies have shown that properly designed Single-Tuned Filters are capable of effectively suppressing dominant harmonic frequencies, particularly the 5th and 7th harmonic orders commonly produced by Variable Frequency Drives (VFDs) and power electronic converters. Furthermore, High-Pass Filters have been applied to reduce higher-order harmonic components that remain after the dominant harmonics have been mitigated. Although the effectiveness of these filters has been widely demonstrated, the majority of previous investigations focus primarily on filter design and parameter selection rather than filter placement strategy [25].

In ETAP-based harmonic studies, researchers commonly evaluate harmonic performance before and after filter installation to determine the effectiveness of harmonic mitigation. Most of these studies assume predetermined filter installation locations and concentrate on comparing THD_v and THD_i values after filter implementation [28]. Consequently, limited attention has been given to the process of determining the most suitable filter location based on harmonic propagation characteristics, harmonic source distribution, and bus harmonic distortion levels.

Another limitation identified in previous research is that many studies consider only a single harmonic source or a single filter installation point. In practical industrial distribution systems, harmonic distortion often originates from multiple sources operating at different voltage levels. The interaction between these harmonic sources can create complex harmonic propagation patterns that require comprehensive analysis to determine the most effective mitigation strategy [29, 30]. Therefore, a systematic approach for selecting filter locations based on actual harmonic behaviour within the network remains an important research topic.

The electrical distribution system investigated in this study consists of multiple voltage levels, including a 20 kV medium-voltage network, a 3.3 kV industrial motor bus, and a 0.4 kV low-voltage distribution bus. The system is supplied by both a utility grid and a diesel power plant and contains harmonic-producing loads in the form of a Variable Frequency Drive (VFD) connected to a 500-kW industrial motor and a 700 kVA non-linear load. The presence of these loads creates harmonic distortion that propagates throughout the distribution network and affects system power quality [23].

Unlike previous studies that mainly emphasize filter design, this research focuses on the analysis of Passive Power Filter placement within the electrical distribution system. Harmonic Load Flow Analysis and Harmonic Spectrum Analysis are utilized to identify buses experiencing the highest harmonic distortion levels and to determine the dominant harmonic frequencies present in the system. Based on these results, Single-Tuned Filters and a High-Pass Filter are strategically installed near harmonic-

producing loads to minimize harmonic propagation and improve overall system performance [18].

The novelty of this study is intentionally framed as a practical case-study contribution rather than a new optimization method. The work combines harmonic assessment, source-oriented filter placement, and consistent before-and-after THD_V evaluation in a multi-voltage ETAP model containing utility supply, diesel generation, photovoltaic generation, a VFD-fed motor, and a separate low-voltage nonlinear load. Because no mathematical objective function or automated location-search algorithm is implemented, the manuscript uses the terms selected placement and proposed configuration rather than optimal placement.

Through this approach, the research contributes to the development of a systematic methodology for determining the optimal placement of Passive Power Filters in electrical distribution systems. The findings are expected to provide useful references for power system engineers in improving power quality, reducing harmonic-related losses, enhancing equipment reliability, and ensuring compliance with IEEE Std 519-2014 harmonic standards [19].

Table 1

Research Gap.

Component	Parameter	Value	Ref.
Harmonic distortion analysis	Analysis objective	Identification of harmonic distortion only	[1, 2]
Passive filter design	Design consideration	Filter sizing and tuning frequency	[3, 4]
ETAP harmonic simulation	Evaluation method	Comparison of harmonic levels before and after filter installation	[5, 6]
Single-Tuned Passive Filter	Harmonic mitigation	Mitigation of specific harmonic orders	[7, 8]
Harmonic mitigation studies	Filter placement strategy	Fixed or predetermined filter locations	[9, 10]
Proposed research	Novelty	Optimization of STPF and HPF placement using ETAP to achieve maximum harmonic reduction and compliance with IEEE Std. 519-2014.	This study

3. Research Methodology

3.1 Research Method

This study employs a quantitative simulation-based case-study approach using ETAP to evaluate harmonic distortion before and after a selected passive-filter configuration. The

main comparison is based on bus-voltage total harmonic distortion (THD_V), while current distortion (THD_I) is identified separately where it appears in the ETAP output.

The primary objective of this research is to evaluate the harmonic conditions of the electrical system before and after the installation of a passive power filter. The analysis focuses on Total Harmonic Distortion Voltage (THDv), Total Harmonic Distortion Current (THDi), harmonic spectrum characteristics, and compliance with IEEE 519-2014 standards.

The model is verified through fundamental-frequency load-flow convergence and by maintaining the same network topology and bus list for the documented before-and-after harmonic simulations. Field measurements or independent-software validation were not available in the source dataset and are therefore identified as limitations.

3.2 Research Procedure

The research procedure consists of several stages, beginning with literature review and ending with the evaluation of harmonic mitigation performance. Initially, relevant references regarding power quality, harmonics, passive power filters, IEEE 519-2014 standards, and ETAP harmonic analysis are collected and reviewed to establish the theoretical foundation of the study.

Subsequently, the electrical distribution system is modeled in ETAP according to the actual system configuration. After all electrical parameters are entered into the software database, a harmonic load flow simulation is performed to obtain the initial harmonic condition of the system.

The dominant harmonic orders are then identified based on the harmonic spectrum obtained from the simulation results. A passive power filter is designed according to the dominant harmonic frequency and reactive power compensation requirements. After the filter parameters are determined, the passive power filter is installed in the ETAP model. Harmonic analysis is repeated to evaluate the effectiveness of the proposed filter. Finally, the results before and after filter installation are compared to determine the harmonic reduction achieved by the proposed mitigation method.

The electrical distribution system is represented using the ETAP single-line diagram and includes a utility source, a 10-MW PLTD/diesel generation source, photovoltaic generation, transformers, medium- and low-voltage buses, a 500-kW VFD-fed motor, a 700-kVA nonlinear load, and passive-filter branches.

The electrical distribution system is represented using a Single Line Diagram (SLD) developed in ETAP. The model consists of the main components of the power system, including utility sources, transformers, buses, cables, feeders, and electrical loads.

All equipment parameters are entered according to their technical specifications. Transformer data include rated power, voltage level, impedance, and connection type. Load data include active power, reactive power, and harmonic characteristics of nonlinear loads.

The nonlinear loads are modelled using harmonic current spectra to represent actual operating conditions. These harmonic-producing loads serve as the primary sources of harmonic distortion within the system.

The purpose of system modelling is to create a realistic representation of the electrical network so that the simulation results accurately reflect actual operating conditions. Prior to filter implementation, the model is verified through load flow and harmonic analysis to ensure that all components operate correctly.

3.4 Passive Power Filter Simulation

The passive-filter simulation evaluates the combined filter configuration documented in the ETAP model. The study does not claim global optimality because the available dataset does not include an objective function, automated placement algorithm, or complete candidate-bus comparison.

The passive power filter is designed as a single-tuned filter targeting the dominant harmonic order identified during the initial harmonic analysis. The filter consists of capacitor and inductor components connected in a shunt configuration at the selected bus location.

3.5 Harmonic Analysis

Harmonic analysis is conducted to evaluate the level of harmonic distortion within the electrical distribution system and to identify the impact of nonlinear loads on power quality. The analysis begins by identifying harmonic-producing loads and performing harmonic load flow simulations in ETAP. The simulation results provide information regarding voltage distortion, current distortion, harmonic spectrum distribution, and dominant harmonic orders present in the system. These parameters are essential for understanding the harmonic characteristics and identifying buses that experience significant distortion levels.

Harmonic load flow is used to calculate distortion throughout the modeled network. Bus values are reported as THD_V, while branch-current distortion is identified as THD_I. IEEE Std 519 limits are formally assessed at the PCC; because the contractual PCC is not explicitly documented here, the 5% value is used only as an internal screening reference for buses below 69 kV.

3.6 Data Analysis

The data analysis stage is conducted to evaluate the effectiveness of the Passive Power Filter (PPF) in reducing harmonic distortion within the electrical distribution system. The analysis is based on the comparison of simulation results obtained before and after filter installation. The main parameters evaluated include Total Harmonic Distortion Voltage (THDv), Total Harmonic Distortion Current (THDi), and harmonic spectrum distribution at the observed buses.

The primary quantitative comparison is the change in THD_V between the no-filter and combined-filter cases. Percentage reduction is used to describe the observed improvement. Sensitivity analysis, frequency scan, individual STPF-only and HPF-only cases, and field validation were not available in the source dataset and are identified as priorities for future work.

3.7. Stage of The Research

The research stages describe the systematic procedure followed in this study, beginning with a literature review and concluding with the evaluation of Passive Power Filter performance. Each stage is structured to ensure that the analysis is carried out comprehensively and that the obtained results accurately represent the harmonic conditions of the electrical distribution system.

A comprehensive literature review is conducted to examine power quality issues, harmonic distortion phenomena, Passive Power Filter technology, and the harmonic limits established by IEEE 519-2014. Various scientific journals, conference proceedings, technical reports, and relevant textbooks are reviewed to establish a strong theoretical foundation for the study. This stage also facilitates the selection of an appropriate harmonic mitigation method and analytical approach for the investigated system.

The required electrical system data are subsequently collected to support the simulation process. These data include the single-line diagram of the distribution system, transformer specifications, cable parameters, bus ratings, load characteristics, and operating conditions of nonlinear loads. Accurate data collection is essential for developing a representative system model and ensuring reliable simulation results.

System modelling is carried out using ETAP software by representing all electrical components in the form of a Single Line Diagram (SLD). The modeled components include utility sources, transformers, buses, feeders, and loads. Each component is assigned the corresponding electrical parameters obtained during the data collection stage. Special consideration is given to nonlinear loads due to their significant contribution to harmonic generation. Verification of the developed model is performed through load flow analysis to confirm proper system operation before harmonic studies are conducted.

Validation of the system model is followed by harmonic load flow analysis to determine the existing harmonic conditions within the electrical network. The simulation provides information regarding voltage distortion, current distortion, harmonic spectrum distribution, and dominant harmonic orders. The resulting Total Harmonic Distortion Voltage (THDv) and Total Harmonic Distortion Current (THDi) values are assessed against the limits specified in IEEE 519-2014 to identify potential power quality concerns.

Evaluation of the harmonic analysis results enables the identification of dominant harmonic frequencies contributing to system distortion. These frequencies form the basis for the design of the Passive Power Filter (PPF). The filter design process includes selecting the target harmonic order, determining the required reactive power compensation, specifying the tuning frequency, and calculating the capacitor and inductor parameters required for the filter configuration. The designed filter is intended to provide a low-impedance path for harmonic currents, thereby minimizing harmonic propagation throughout the system.

Implementation of the Passive Power Filter is performed within the ETAP model at the selected bus location. The installation point is determined according to the harmonic analysis results and the location of the dominant harmonic sources. Harmonic load flow simulations are subsequently conducted under identical operating conditions to assess the influence of the filter on system performance.

A comparative evaluation is carried out using the simulation results obtained before and after filter implementation. The comparison focuses on THDv values, THDi values, harmonic spectrum characteristics, and compliance with IEEE 519-2014 requirements. The percentage reduction in harmonic distortion is also examined to quantify the effectiveness of the proposed mitigation technique. This assessment provides a clear indication of the capability of the Passive Power Filter to enhance power quality.

Comprehensive analysis and discussion of the obtained results are conducted to evaluate the overall performance of the proposed filter. The effectiveness of the Passive Power Filter is determined based on its ability to reduce harmonic distortion, suppress dominant harmonic components, and improve system operating conditions. Conclusions are formulated based on the findings, while recommendations are provided to support future studies related to harmonic mitigation and power quality enhancement in electrical distribution systems.

To determine the most effective harmonic mitigation strategy, several filter placement scenarios are evaluated during the simulation process. The Single-Tuned Passive Filter (STPF) and High-Pass Filter (HPF) are installed at different candidate buses that exhibit significant harmonic distortion or are located near major nonlinear loads. Each placement scenario is analysed under identical operating conditions to identify the configuration that provides the greatest reduction in harmonic distortion while maintaining acceptable voltage profiles and stable system operation. This optimization process ensures that the selected filter location delivers the highest performance with efficient utilization of the filter components.

Following the optimization process, the electrical performance of the selected filter configuration is further verified by examining the harmonic spectrum at critical buses throughout the distribution network. Particular attention is given to the reduction of dominant harmonic orders, changes in voltage profiles, and the interaction between the installed filters and the existing electrical system. This verification confirms that the proposed filter configuration effectively suppresses harmonic propagation without introducing resonance or adversely affecting the normal operating characteristics of the power distribution system.

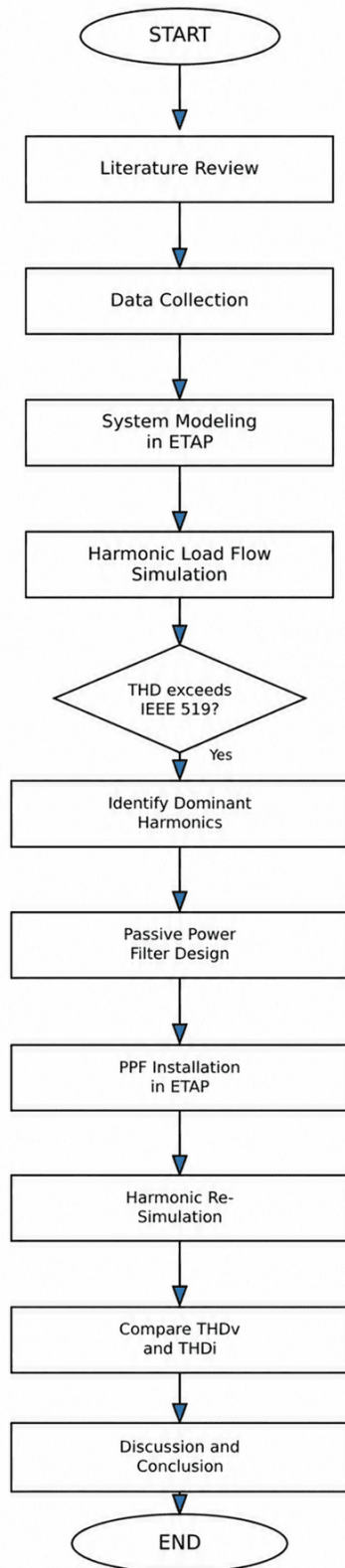
Flowchart Research Stages:

Fig.1. Research Flowchart of Harmonic Mitigation Using Passive Power Filter (PPF) Based on ETAP Simulation.

Figure 1 summarizes the simulation workflow adopted in this study. The decision stage is interpreted as an internal harmonic screening step rather than a formal IEEE 519 compliance determination at every bus. After the baseline harmonic analysis, the selected passive-filter configuration is implemented and the same network is re-simulated for direct before-and-after comparison.

The study continues with the collection of electrical system data, including the single-line diagram, transformer specifications, bus ratings, cable parameters, and load characteristics. These data are used to develop a representative electrical distribution system model in ETAP. The developed model is verified through load flow analysis to ensure that the operating conditions accurately represent the actual system before harmonic studies are conducted.

Harmonic Load Flow simulation is performed to determine the existing harmonic conditions within the distribution network. The calculated Total Harmonic Distortion of Voltage (THDv) and Total Harmonic Distortion of Current (THDi) at each bus are compared with the limits specified in IEEE Std. 519-2014. The decision stage shown in the flowchart evaluates whether the measured harmonic distortion exceeds the permissible limits. If the harmonic levels remain within the standard, the system is considered acceptable. Conversely, excessive harmonic distortion requires further harmonic mitigation analysis.

The identification of dominant harmonic orders provides the basis for designing the Passive Power Filter. The filter design includes determining the target harmonic frequencies, reactive power compensation, tuning frequency, and electrical parameters of the capacitor and inductor. In this study, the proposed mitigation scheme combines a Single-Tuned Passive Filter (STPF) and a High-Pass Filter (HPF) to suppress dominant harmonic components while minimizing higher-order harmonics.

The designed filters are implemented in the ETAP model at the selected installation bus. The installation location is determined based on the harmonic analysis results to maximize harmonic reduction while maintaining stable system operation. Harmonic re-simulation is subsequently performed under identical operating conditions to evaluate the influence of the installed filters on the electrical distribution system.

The final stage compares the harmonic performance before and after filter installation by evaluating THDv, THDi, and the harmonic spectrum at all observed buses. The discussion and conclusion summarize the effectiveness of the proposed filtering scheme in reducing harmonic distortion, improving power quality, and achieving compliance with IEEE Std. 519-2014. This systematic workflow ensures that every stage of the research contributes to obtaining reliable simulation results and validating the proposed harmonic mitigation method.

4. Results and Discussion

4.1 Single Line Diagram of The Simulated System

The electrical system used in this study was modelled in ETAP using a single line diagram (SLD) to represent the configuration of the power distribution network and the location of harmonic-producing loads. The simulated system consists of a utility grid source connected to a main distribution bus through a transformer and protection devices. Several electrical loads are connected to the main bus, including linear loads and non-linear loads that contribute to harmonic distortion within the system.

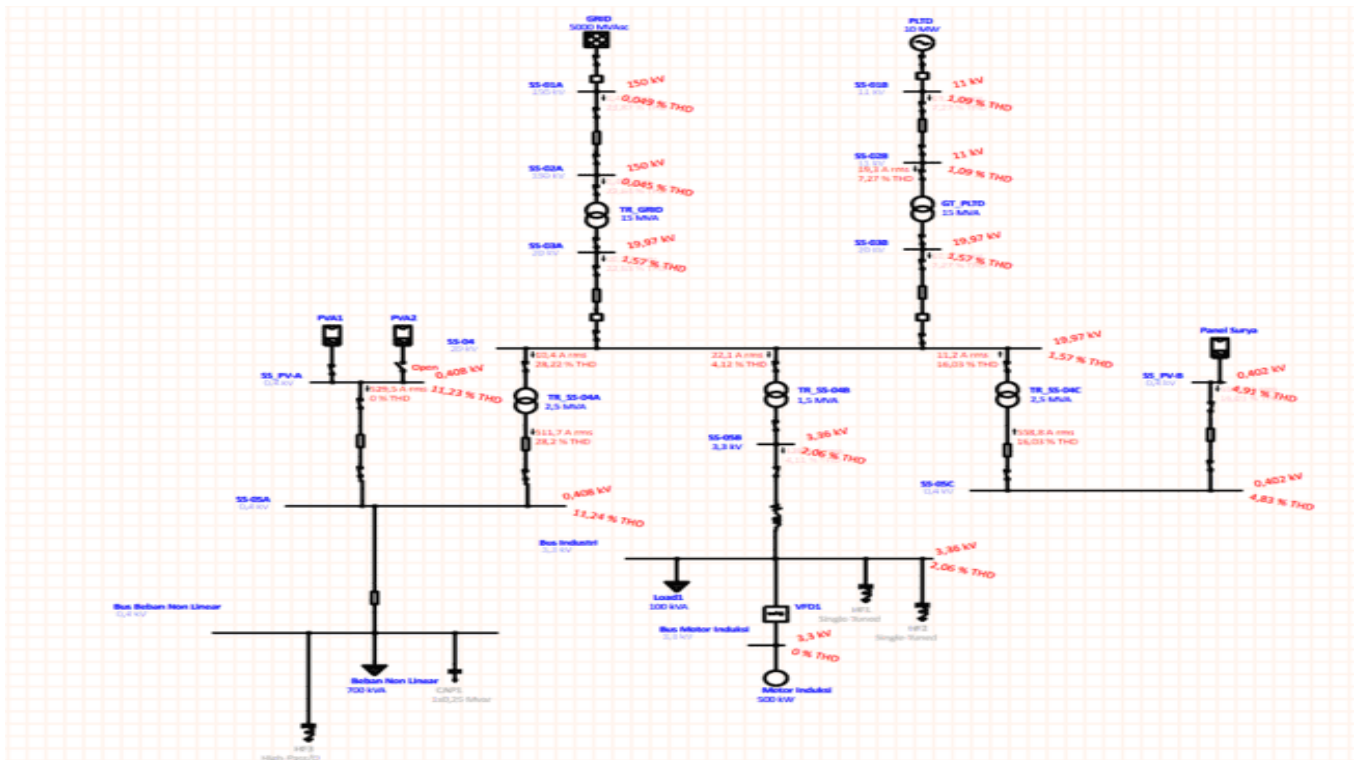


Fig.2. Single Line Diagram of the Simulated System in ETAP

As shown in Fig. 2, the ETAP model contains a utility source, a 10-MW PLTD/diesel generation source, photovoltaic generation, transformers, distribution buses, a 500-kW VFD-fed industrial motor, a 700-kVA nonlinear load, and passive-filter branches. This system description is used consistently throughout the revised manuscript.

The main distribution bus functions as the central point for power distribution to various electrical loads. Several load buses are connected to the main bus, including induction motor loads, motor control devices, and other industrial electrical equipment. The system also includes a Variable Speed Drive (VSD), which is a significant source of harmonic currents due to its power electronic switching operation. The presence of the VSD introduces non-linear characteristics into the network and causes distortion in both current and voltage waveforms.

The selected filtering arrangement is source-oriented: the passive-filter branches are placed near the principal nonlinear-load sections. This placement is an engineering selection based on the modeled harmonic behavior rather than the result of a mathematical optimization algorithm.

In addition, capacitor banks are incorporated into the system to provide reactive power compensation and support voltage regulation. However, because capacitor banks may interact with system inductance and potentially create resonance conditions, harmonic analysis is required to ensure that the filter design effectively mitigates harmonic distortion without introducing additional power quality issues.

The developed ETAP model serves as the basis for conducting harmonic load flow analysis and evaluating the effectiveness of the Single-Tuned Passive Filter. The simulation compares system performance before and after

filter installation by observing harmonic voltage distortion, harmonic current distortion, and Total Harmonic Distortion (THD) levels at critical buses. The results obtained from these analyses are used to assess compliance with the harmonic limits specified in IEEE Std 519-2014 and to determine the effectiveness of the proposed harmonic mitigation method.

4.2 Harmonic Simulation Result

4.2.1 Harmonic Load Flow Simulation Results Before Filter Installation

Harmonic analysis was first conducted on the electrical distribution system before the installation of the harmonic filter to evaluate the existing power quality condition and identify buses experiencing excessive harmonic distortion. The simulation was performed using the Harmonic Load Flow module in ETAP, where the system included several non-linear loads, particularly the Variable Frequency Drive (VFD) connected to the industrial motor load. These non-linear devices generate harmonic currents that propagate throughout the network and affect voltage quality at different buses.

generated within the network can influence distributed

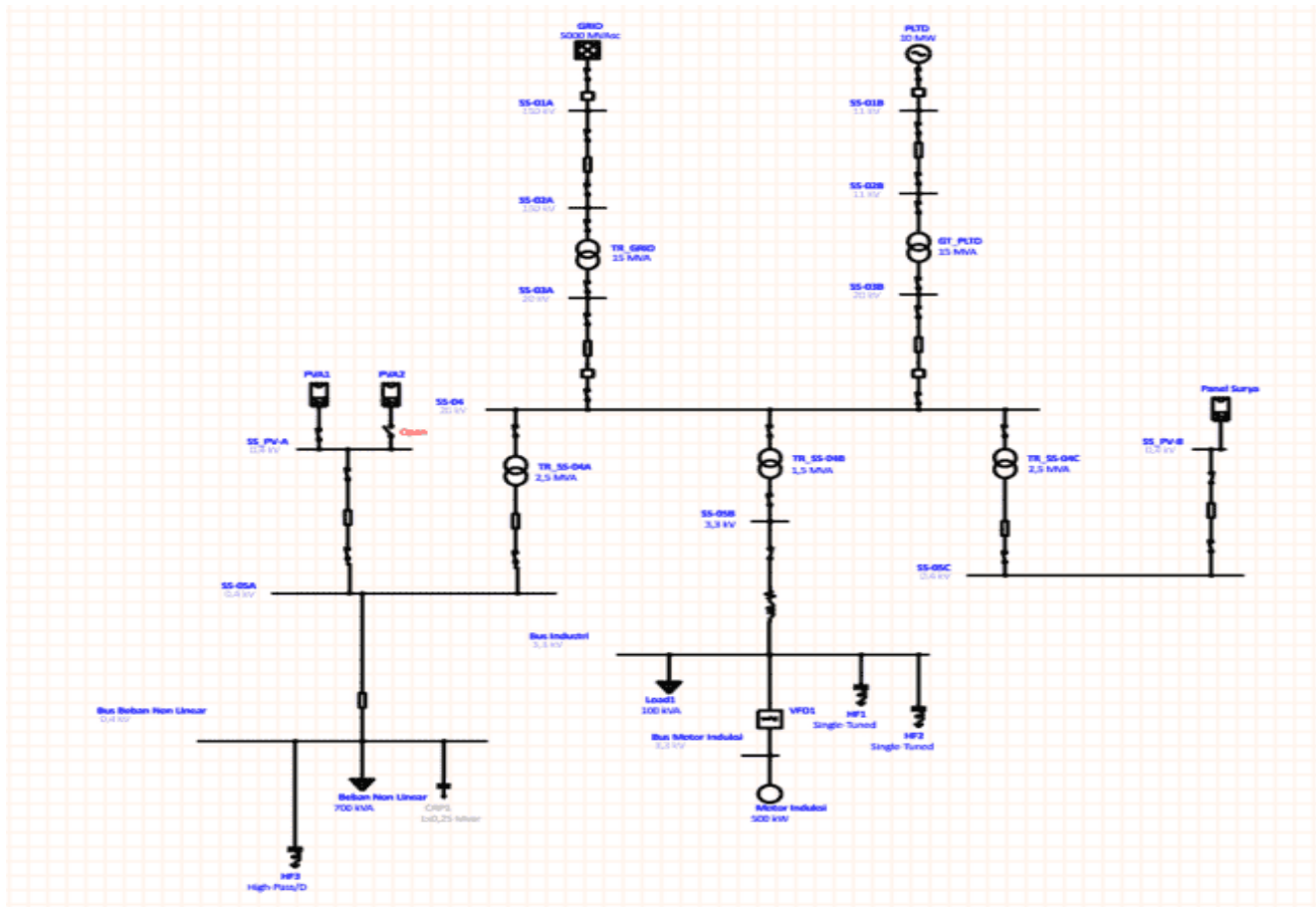


Fig.3. Harmonic Load Flow Simulation Results Before Filter Installation.

Figure 3 presents the baseline harmonic-load-flow result. Bus-level values in Table 2 are interpreted as voltage total harmonic distortion (THD_V). Distortion is nonuniform across the network because harmonic-current injection and system impedance differ by location.

The industrial bus SS-05A records THD_V = 11.24%, while SS-05C reaches 16.03%. These values identify the downstream industrial and low-voltage sections as critical locations in the documented baseline.

The 28.23% value shown near the transformer branch in the ETAP output is treated as current distortion (THD_I), not bus-voltage THD_V. It is therefore reported separately and is not used to identify the highest pre-filter bus-voltage distortion.

At the main distribution bus, harmonic distortion is lower but still exceeds acceptable limits. The simulation indicates THD values ranging from approximately 4.12% to 7.27% at several intermediate buses. These values demonstrate that harmonic currents generated by the VFD propagate through the transformer and distribution network, affecting adjacent buses and electrical equipment connected to the same system.

The photovoltaic (PV) integration point also experiences harmonic distortion. The bus connected to the solar generation system records a THD value of approximately 4.83%, while another PV-side bus reaches approximately 11.69% THD. Although these values are lower than those measured near the VFD, they indicate that harmonics

generation interfaces and potentially affect inverter performance.

Meanwhile, buses connected directly to the utility grid show very low distortion levels. The harmonic voltage distortion at the 150 kV grid side is approximately 0.04–0.05% THD, which is well below the recommended limit. This result indicates that the utility source provides a relatively clean voltage waveform and that the majority of harmonics originate from the internal industrial loads rather than the external power system.

IEEE Std 519 applies harmonic limits at the Point of Common Coupling. Because the contractual PCC is not explicitly identified in the available dataset, the 5% voltage-THD value is used only as an internal screening reference for buses below 69 kV rather than as a formal facility-wide compliance determination.

The results confirm that the existing system condition before filter installation is characterized by excessive harmonic distortion, particularly around the VFD load. Therefore, a Single-Tuned Passive Filter (STPF) or High Passed Dumped Passive Filter is proposed and installed near the harmonic source to reduce harmonic current injection and improve the overall harmonic performance of the electrical distribution system.

Table 2
Harmonic Distortion Before Filter Installation

Bus/Location	Voltage Level	THD (%)
Grid Side SS-01A	150 kV	0.04
Grid Side SS-02A	150 kV	0.05
PLTD Side SS-01B	11 kV	2.09
PLTD Side SS-02B	11 kV	7.27
Main Bus SS-04	20 kV	4.12
Transformer SS-04A	0.4 kV	28.23
Bus Industri SS-05A	3.3 kV	11.24
Bus Industri SS-05B	3.3 kV	4.11
Bus Industri SS-05C	0.4 kV	16.03
PV Bus SS-PV-B	0.4 kV	11.69
Solar Panel Bus	0.4 kV	4.83

4.2.2 Harmonic Simulation Results After Filter Installation

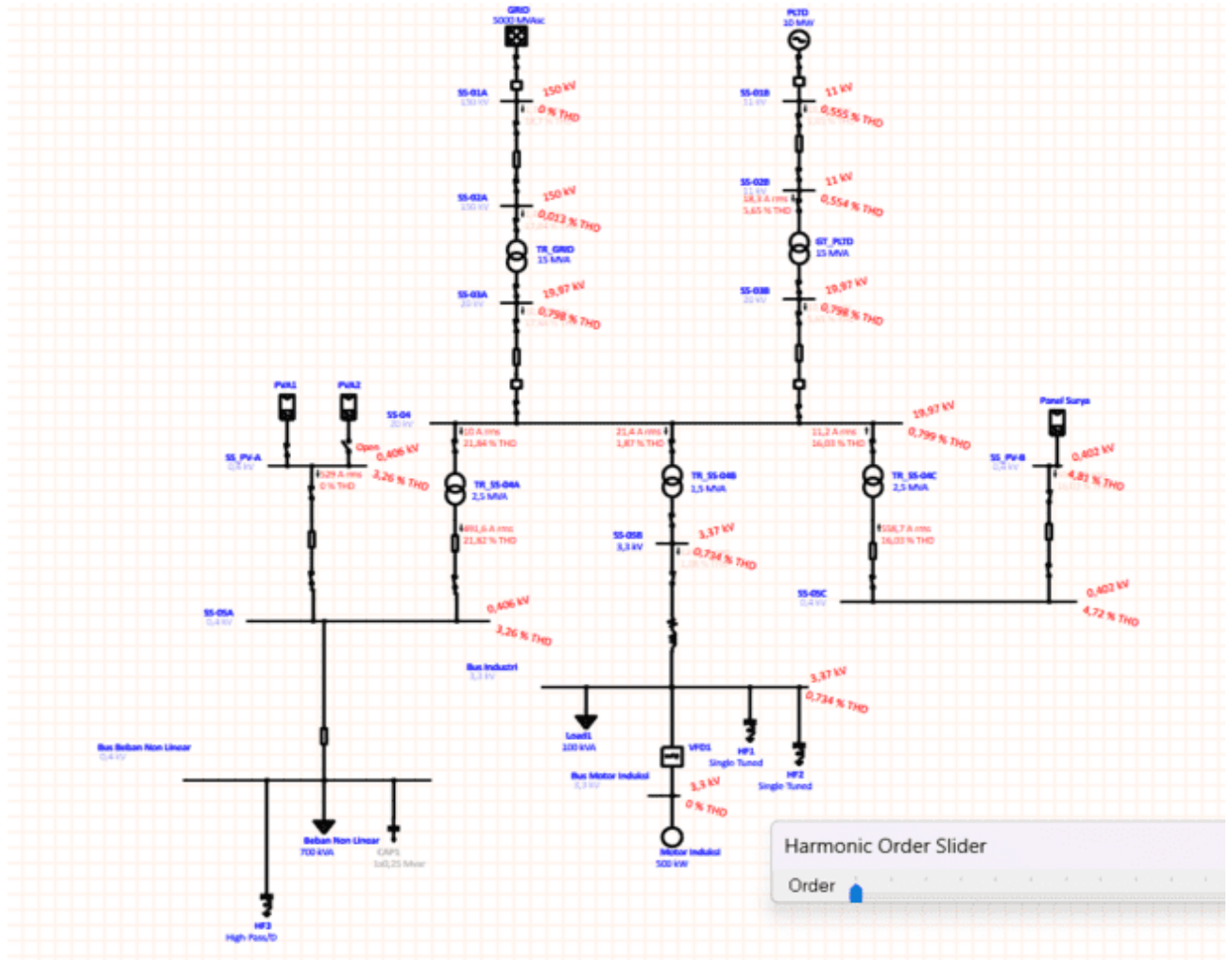


Fig.4. Harmonic Load Flow Simulation Results with Single-Tuned Passive Filter and High-Pass Filter

The harmonic mitigation performance was evaluated by conducting a harmonic load flow analysis on the electrical distribution system equipped with passive filters. The filtering scheme consists of a Single-Tuned Passive Filter (STPF) installed near the Variable Frequency Drive (VFD) and a High-Pass Filter (HPF) connected to the non-linear

load bus. This hybrid passive filtering configuration was designed to suppress both dominant harmonic components and higher-order harmonics generated by non-linear loads.

Figure 4 presents the harmonic-load-flow result after applying the combined passive-filter configuration. The available results represent the net effect of the combined filtering scheme; separate STPF-only and HPF-only simulations were not available.

The combined configuration substantially reduces bus-voltage THD_V. The strongest documented improvement occurs at SS-05C, where THD_V decreases from 16.03% to 0.73%. At SS-05A, THD_V decreases from 11.24% to 3.26%, while SS-PV-B decreases from 11.69% to 4.81%.

The bus associated with the industrial motor records a THD value approaching 0%, indicating that harmonic distortion at the motor terminal has been effectively eliminated. This condition contributes to improved equipment performance, lower thermal stress, and enhanced operational reliability. In addition, the PV-connected bus

exhibits a reduction in THD from 11.69% to 4.81%, while the solar panel bus records a THD value of 4.72%. These values satisfy the maximum harmonic distortion limit recommended by IEEE Std 519-2014.

The High-Pass Filter installed at the non-linear load bus plays an important role in attenuating higher-order harmonics that cannot be fully absorbed by the Single-Tuned Passive Filter. While the STPF is designed to target the

dominant harmonic frequency produced by the VFD, the HPF provides additional harmonic suppression over a broader frequency range. The combination of both filters results in a more comprehensive harmonic mitigation strategy and improves the overall effectiveness of the harmonic reduction process.

The utility grid side and generator side maintain very low harmonic distortion levels, with THD values remaining below 1%. This condition indicates that the harmonic currents generated by non-linear loads are effectively confined within the filtered section of the system and do not significantly affect the upstream power supply network.

Overall, the simulation results confirm that the combined application of the Single-Tuned Passive Filter and High-Pass Filter effectively improves power quality by reducing harmonic distortion throughout the electrical distribution system. Most buses operate within the harmonic limits specified in IEEE Std 519-2014, demonstrating that the proposed filtering configuration is capable of mitigating harmonics generated by VFDs and other non-linear loads while maintaining stable system operation.

The results demonstrate effective harmonic-voltage attenuation for the documented operating condition. However, the numerical contribution of the STPF and HPF cannot be separated without individual filter-only simulations, and no claim is made regarding resonance avoidance, system-loss reduction, reliability improvement, or equipment lifetime because those quantities were not directly evaluated.

The simulation results also indicate that the coordinated operation of the STPF and HPF enhances the overall harmonic performance of the distribution network by reducing harmonic propagation across interconnected buses. This improvement contributes to more stable voltage conditions, decreases the risk of excessive equipment heating, and minimizes additional power losses caused by harmonic currents. Furthermore, the achieved THD values demonstrate that the proposed filter configuration provides an effective and practical solution for industrial power systems with significant nonlinear loads, supporting reliable system operation and long-term compliance with IEEE Std. 519-2014.

Based on Table 3, the largest documented THD_V reduction is 95.45% at SS-05C. Significant reductions are also observed at SS-03A, SS-03B, and SS-02B. The results quantify the net performance of the combined filter configuration but do not establish global placement optimality.

The industrial bus (SS-05A), which is directly affected by the VFD operation, experiences a reduction in THD from 11.24% to 3.26%, satisfying the IEEE Std 519-2014 limit of 5%. Likewise, the PV-connected bus (SS-PV-B) records a reduction from 11.69% to 4.81%, indicating that the harmonic impact on the photovoltaic subsystem has been successfully mitigated.

Overall, the filtering configuration effectively improves system power quality and enables most buses to operate within the recommended harmonic distortion limits specified by IEEE Std 519-2014.

Table 3

Comparison of THD Values Before and After Filter Installation

Bus Location	Voltage Level	THD Before (%)	THD After (%)	Reduction (%)
SS-01A (Grid Side)	150 kV	0.04	0.00	100.00
SS-02A (Grid Side)	150 kV	0.05	0.01	80.00
SS-03A	20 kV	11.57	0.79	93.17
SS-01B (PLTD Side)	11 kV	2.09	0.56	73.21
SS-02B (PLTD Side)	11 kV	7.27	0.55	92.43
SS-03B	20 kV	11.57	0.79	93.17
SS-04 (Main Bus)	20 kV	4.12	1.87	54.61
SS-PV-A	0.4 kV	11.23	3.26	70.97
SS-05A (Industrial Bus)	3.3 kV	11.24	3.26	70.99
SS-05B (Industrial Bus)	3.3 kV	4.11	0.73	82.24
SS-05C	0.4 kV	16.03	0.73	95.45
SS-PV-B	0.4 kV	11.69	4.81	58.85
Panel Surya Bus	0.4 kV	4.83	4.72	2.28

4.3 Harmonic-Voltage Screening Relative to IEEE Std 519

IEEE Std 519 specifies harmonic limits at the Point of Common Coupling (PCC). Because the contractual PCC is not explicitly documented in the available system dataset, this section uses the 5% voltage-THD value only as an internal screening reference for assessed buses below 69 kV.

The simulation results obtained before filter installation indicate that several buses exceeded the recommended IEEE limit. High THD levels were primarily observed at buses located near the non-linear loads and VFD system. The highest distortion was recorded at bus SS-05C with a THD value of 16.03%, followed by SS-PV-B with 11.69% and SS-05A with 11.24%. These values demonstrate the significant impact of harmonic-producing loads on the electrical distribution system.

The implementation of the Single-Tuned Passive Filter (STPF) and High-Pass Filter (HPF) significantly improved the harmonic performance of the system. Most buses experienced substantial reductions in THD and successfully complied with the IEEE Std 519-2014 requirements. The industrial bus SS-05A, for example, recorded a reduction from 11.24% to 3.26%, while bus SS-05C decreased from 16.03% to 0.73%. Similar improvements were observed at the main distribution bus and the generator-side buses.

Table 4 summarizes the internal harmonic-voltage screening before and after filter installation. The 150-kV grid-side values are retained for reference and should not be classified using the same 5% threshold applied to buses below 69 kV.

Table 4
Compliance Assessment Based on IEEE Std 519-2014

Bus	THD Before (%)	THD After (%)	IEEE Limit (%)	Before Filter	After Filter
SS-01A	0.04	0.00	5.0	Comply	Comply
SS-02A	0.05	0.01	5.0	Comply	Comply
SS-03A	11.57	0.79	5.0	Not Comply	Comply
SS-01B	2.09	0.56	5.0	Comply	Comply
SS-02B	7.27	0.55	5.0	Not Comply	Comply
SS-03B	11.57	0.79	5.0	Not Comply	Comply
SS-04	4.12	1.87	5.0	Comply	Comply
SS-PV-A	11.23	3.26	5.0	Not Comply	Comply
SS-05A	11.24	3.26	5.0	Not Comply	Comply
SS-05B	4.11	0.73	5.0	Comply	Comply
SS-05C	16.03	0.73	5.0	Not Comply	Comply
SS-PV-B	11.69	4.81	5.0	Not Comply	Comply
Panel Surya Bus	4.83	4.72	5.0	Comply	Comply

Based on Table 4, six buses exceeded the IEEE Std 519-2014 limit before the installation of harmonic filters, namely SS-03A, SS-02B, SS-03B, SS-PV-A, SS-05A, SS-05C, and SS-PV-B. These buses were directly influenced by harmonic currents generated by the VFD and other non-linear loads. Excessive harmonic distortion at these locations may lead to increased power losses, transformer overheating, reduced equipment lifespan, and voltage waveform distortion.

The installation of the STPF and HPF successfully reduced harmonic distortion to acceptable levels at all buses. Following the implementation of the filtering system, all buses recorded THD values below the maximum limit of 5%, indicating full compliance with IEEE Std 519-2014. The results confirm that the proposed filter configuration effectively mitigates harmonics and significantly improves the power quality of the electrical distribution system.

The compliance assessment demonstrates that the combined use of Single-Tuned Passive Filters and High-Pass Filters provides an effective and reliable solution for harmonic reduction in distribution systems containing VFDs and other non-linear loads. Consequently, the proposed filtering scheme can be considered suitable for maintaining harmonic levels within acceptable standards while enhancing the overall operational performance and reliability of the electrical network.

4.4 Combined Filter Performance Evaluation

The performance of the proposed harmonic mitigation system was evaluated by analyzing the reduction of Total Harmonic Distortion (THD) throughout the electrical distribution network. The filtering configuration consists of a Single-Tuned Passive Filter (STPF) and a High-Pass Filter (HPF), which operate together to suppress harmonic currents generated by the Variable Frequency Drive (VFD) and other non-linear loads.

The Single-Tuned Passive Filter was designed to target the dominant harmonic frequency generated by the VFD. By providing a low-impedance path at the tuned harmonic frequency, the STPF absorbs a significant portion of the harmonic current before it propagates through the distribution network. This mechanism effectively reduces harmonic distortion at buses located near the harmonic source.

The High-Pass Filter complements the operation of the STPF by attenuating higher-order harmonics that are not effectively eliminated by the tuned filter. Unlike the STPF, which focuses on a specific harmonic order, the HPF provides harmonic suppression over a wider frequency range. Consequently, the combined filtering scheme is capable of mitigating both low-order and high-order harmonics, resulting in a more comprehensive improvement in power quality.

The strongest reduction at SS-05C indicates that the selected filter configuration is particularly effective for the low-voltage section associated with the nonlinear load. The different reduction levels among buses reflect the combined influence of filter location, harmonic current injection, and network impedance.

The effectiveness of the filtering system can also be observed from the overall compliance with IEEE Std 519-2014. Prior to filter installation, several buses exceeded the allowable THD limit of 5%. Following the implementation of the STPF and HPF, all buses achieved THD values below the recommended limit, indicating that the proposed filtering scheme successfully improves power quality and system reliability. In addition, the reduction of harmonic distortion minimizes the adverse effects of nonlinear loads, such as transformer overheating, excessive power losses, and premature equipment aging. These results demonstrate that the combined application of STPF and HPF provides an effective and practical solution for harmonic mitigation in industrial power distribution systems while ensuring stable and reliable network operation.

Table 5
Filter Performance Evaluation

Bus	THD Before (%)	THD After (%)	THD Reduction (%)
SS-03A	11.57	0.79	93.17
SS-02B	7.27	0.55	92.43
SS-04	4.12	1.87	54.61
SS-05A	11.24	3.26	70.99
SS-05B	4.11	0.73	82.24
SS-05C	16.03	0.73	95.45
SS-PV-B	11.69	4.81	58.85

Based on Table 5, the highest harmonic reduction is achieved at bus SS-05C with a reduction of 95.45%, followed by buses SS-03A and SS-02B with reductions exceeding 92%. The industrial bus SS-05A, which is directly

connected to the VFD, records a reduction of approximately 71%, demonstrating the effectiveness of the filtering system in mitigating harmonics at the primary harmonic source.

Overall, the results demonstrate that the combined application of the Single-Tuned Passive Filter and High-Pass Filter provides effective harmonic mitigation throughout the electrical distribution system. The significant reduction in THD values and full compliance with IEEE Std 519-2014 confirm the suitability of the proposed filtering configuration for improving power quality in systems containing non-linear loads and power electronic converters.

4.5 Discussion

The reduction pattern can be explained by the interaction between filter location, harmonic-current injection, and network impedance. Buses electrically close to the filtered nonlinear-load sections experience larger reductions because a greater portion of harmonic current is diverted through the filter branches before propagating upstream. The smaller reduction at the solar-panel bus shows that the same filter configuration does not affect all network locations equally.

The results are qualitatively consistent with previous passive-filter planning studies, which show that mitigation effectiveness depends on both filter tuning and electrical location. Direct numerical comparison is limited because published studies use different networks, harmonic spectra, filter ratings, and optimization objectives. Future work should therefore include complete filter R-L-C data, individual harmonic spectra, frequency-scan analysis, separate STPF-only and HPF-only cases, multiple operating conditions, and field or independent-model validation.

5. Conclusion

This study evaluated a selected combined passive-filter configuration in an ETAP model of a multi-voltage electrical distribution system. The analysis is intentionally framed as a practical case study rather than a new optimization method.

In the baseline case, the highest documented bus-voltage distortions were $\text{THD}_V = 16.03\%$ at SS-05C, 11.69% at SS-PV-B, and 11.24% at SS-05A. The 28.23% value shown near the transformer branch was treated separately as current distortion (THD_I).

With the combined filter configuration, THD_V decreased to 0.73% at SS-05C, 3.26% at SS-05A, and 4.81% at SS-PV-B. These results demonstrate effective harmonic-voltage mitigation for the documented operating condition.

Formal IEEE 519 compliance cannot be claimed without explicit PCC identification and the applicable current-distortion criteria. Likewise, global optimality, resonance avoidance, loss reduction, reliability improvement, and robustness under changing operating conditions are not established by the available dataset.

The specific contribution is therefore a transparent ETAP case assessment with consistent before-and-after harmonic-voltage reporting. Future work should report complete filter parameters, harmonic spectra, frequency scans, individual filter-only cases, multiple operating conditions, optimization-based placement, and field or independent-software validation.

CRedit Authorship Contribution Statement

Gina Aprilia: Conceptualization, Methodology, Software, Investigation, Data Curation, Formal Analysis, Writing – Original Draft. **Ardini Gita Cahyani:** Validation, Visualization, Data Analysis, Writing – Review & Editing. **Aidil Iqraman Sewang:** Supervision, Project Administration, Methodology Review, Writing – Review & Editing.

Declaration of Competing Interest

The authors state no conflict of interest.

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Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request. The ETAP simulation model, harmonic load flow results, and filter design parameters used in this research can be provided for academic and research purposes.

References

- [1] R. C. Dugan, M. F. McGranaghan, S. Santoso, and H. W. Beaty, *Electrical Power Systems Quality*, 3rd ed. New York, NY, USA: McGraw-Hill Education, 2012.
- [2] J. Arrillaga and N. R. Watson, *Power System Harmonics*, 2nd ed. Chichester, United Kingdom: John Wiley & Sons, 2003.
- [3] J. C. Das, *Power System Harmonics and Passive Filter Designs*. Hoboken, NJ, USA: John Wiley & Sons, 2015.
- [4] F. C. De La Rosa, *Harmonics and Power Systems*. Boca Raton, FL, USA: CRC Press, 2006.
- [5] A. Kusko and M. T. Thompson, *Power Quality in Electrical Systems*. New York, NY, USA: McGraw-Hill, 2007.
- [6] Institute of Electrical and Electronics Engineers, "IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems," New York, NY, USA, 2014.
- [7] A. E. Emanuel, *Power Definitions and the Physical Mechanism of Power Flow*. Hoboken, NJ, USA: John Wiley & Sons, 2010.
- [8] J. Arrillaga, B. C. Smith, N. R. Watson, and A. R. Wood, *Power System Harmonic Analysis*. Chichester, United Kingdom: John Wiley & Sons, 1997.
- [9] J. G. C. Costa, C. H. G. Treviso, and M. L. Heldwein, "Passive harmonic filters: Design and practical considerations," *IEEE Ind. Appl. Mag.*, vol. 24, no. 5, pp. 58–67, 2018, doi: 10.1109/MIAS.2017.2770645.
- [10] B. Singh, K. Al-Haddad, and A. Chandra, "A review of active filters for power quality improvement," *IEEE Trans. Ind. Electron.*, vol. 46, no. 5, pp. 960–971, 1999, doi: 10.1109/41.793345.
- [11] S. George and V. Agarwal, "A DSP-based optimal algorithm for shunt active filter under non-sinusoidal supply voltage conditions," *IEEE Trans. Power Electron.*, vol. 22, no. 2, pp. 593–601, 2007, doi: 10.1109/TIE.2006.881997.
- [12] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics: Converters, Applications, and Design*, 3rd ed. Hoboken, NJ, USA: John Wiley & Sons, 2003.
- [13] W. Xu, T. Ding, X. Li, and H. Liang, "Resonance-free shunt

- capacitors---Configurations, design methods and comparative analysis," *IEEE Trans. Power Deliv.*, vol. 31, no. 5, pp. 2287–2295, 2016.
- [14] T. M. Blooming and D. J. Carnovale, "Application of IEEE Std 519-1992 Harmonic Limits," in *IEEE Petroleum and Chemical Industry Conference*, Philadelphia, PA, USA, 2006, pp. 1–9. doi: 10.1109/PCICON.2006.359698.
- [15] Institute of Electrical and Electronics Engineers, "IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems," New York, NY, USA, 1993.
- [16] T. H. Ortmeier and T. Hiyama, "Distribution system harmonic filter planning," *IEEE Trans. Power Deliv.*, vol. 11, no. 4, pp. 2005–2012, 1996.
- [17] B. Singh and V. Verma, "Selective compensation of power-quality problems through active power filter by current decomposition," *IEEE Trans. Power Deliv.*, vol. 23, no. 2, pp. 792–799, 2008, doi: 10.1109/TPWRD.2007.911126.
- [18] M. T. Au and J. V. Milanović, "Planning approaches for the strategic placement of passive harmonic filters in radial distribution networks," *IEEE Trans. Power Deliv.*, vol. 22, no. 1, pp. 347–353, 2007.
- [19] C. J. Chou, C.-W. Liu, J.-Y. Lee, and K.-D. Lee, "Optimal planning of large passive harmonic filters set at high voltage level," *IEEE Trans. Power Syst.*, vol. 15, no. 1, pp. 433–441, 2000.
- [20] M. R. Jannesar, A. Sedighi, M. Savaghebi, A. Anvari-Moghaddam, and J. M. Guerrero, "Optimal passive filter planning in distribution networks with nonlinear loads and photovoltaic systems," in *Proceedings of the 20th European Conference on Power Electronics and Applications (EPE'18 ECCE Europe)*, Riga, Latvia, 2018, pp. 1–9.
- [21] W. Xu, Z. Huang, Y. Cui, and H. Wang, "Harmonic resonance mode analysis," *IEEE Trans. Power Deliv.*, vol. 20, no. 2, pp. 1182–1190, 2005.
- [22] J. Cabral Leite, I. Pérez Abril, and M. S. Santos Azevedo, "Capacitor and passive filter placement in distribution systems by nondominated sorting genetic algorithm-II," *Electr. Power Syst. Res.*, vol. 143, pp. 482–489, 2017.
- [23] M. E. El-Hawary, *Electrical Power Systems: Design and Analysis*. Boca Raton, FL, USA: CRC Press, 2018.
- [24] H. Akagi, "Active harmonic filters," *Proc. IEEE*, vol. 93, no. 12, pp. 2128–2141, 2005, doi: 10.1109/JPROC.2005.859603.
- [25] H. Akagi, E. H. Watanabe, and M. Aredes, *Instantaneous Power Theory and Applications to Power Conditioning*. Hoboken, NJ, USA: John Wiley & Sons, 2007.
- [26] S. C. Bhattacharya and D. M. Divan, "Design and implementation of a hybrid series active filter system," *IEEE Trans. Ind. Appl.*, vol. 35, no. 6, pp. 1324–1330, 1999, doi: 10.1109/28.806052.
- [27] M. H. J. Bollen and I. Y. H. Gu, *Signal Processing of Power Quality Disturbances*. Hoboken, NJ, USA: John Wiley & Sons, 2006.
- [28] Z. Huang, Y. Cui, and W. Xu, "Application of modal sensitivity for power system harmonic resonance analysis," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 222–231, 2007.
- [29] R. Langella, A. Testa, and S. A. Papathanassiou, "Power quality issues in distributed generation systems," *Electr. Power Syst. Res.*, vol. 81, no. 1, pp. 1–7, 2011, doi: 10.1016/j.epsr.2010.08.008.
- [30] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1398–1409, 2006, doi: 10.1109/TIE.2006.881997.