

Design and Calculation of Single Tuned Passive Filter for Harmonic Mitigation in a 1250 kVA Distribution Transformer at PT. INKA (Persero) Madiun

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Informasi Artikel

Diajukan, 31 Desember 2024

Diterima, 30 Mei 2025

Diterbitkan, 10 Juni 2025

Keyword :

Passive Filter, Harmonics, Single-Tuned, Power Quality

ABSTRACT

In an effort to enhance quality and customer satisfaction, PT. INKA continues to innovate and improve its products, evidenced by increasingly advanced railway facilities. This study provides reference data for PT. INKA (Industri Kereta Api) Madiun in designing a filter to enhance power quality in transformers, prevent equipment damage caused by harmonics, and ensure the reliability of the protection system. The research, conducted at PT. INKA (Persero) Madiun, specifically focused on Trafo Station B, using a quantitative method with a descriptive approach to systematically and accurately describe variables. Measurements before filter installation showed current THD values of 28,50%, 4,0%, and 2,4% in phases R, S, and T, and voltage THD values of 1,51%, 1,55%, and 1,57%. After the filter was installed, current THD decreased to 11,07%, 1,37%, and 1,09%, and voltage THD to 0,87%, 0,85%, and 0,81%. Based on simulations using ETAP software, the passive single-tuned filter design successfully reduced harmonic distortion with specifications of a 2285 μ F capacitor, a 0,00308732 H inductor, and a 0,011-ohm resistor. The findings demonstrate the filter's effectiveness in improving power quality and ensuring system reliability.

1. INTRODUCTION

In electrical power system distribution, train production facilities represent one of the largest energy consumers, primarily due to the extensive use of electrical equipment in their operations, including office areas. According to researchers [1], nearly all electrical devices incorporate electronic components. These include common appliances such as air conditioners, fans, water pumps, computers, and others. Researchers [2] highlight that while electronic devices contribute to increased efficiency and ease of use, they also introduce challenges to power quality. This is because such devices are classified as electronic loads, which are known sources of harmonics. Harmonics are defined as periodic waveforms whose frequencies are integer multiples of the fundamental system frequency. As noted by researchers [3], the presence of harmonics can distort the main sinusoidal waveform. Similarly, researchers [4] point out that harmonics alter the ideal waveform, transforming it into a distorted, non-sinusoidal form. Researchers [5] further stress the significance of managing harmonic distortion, especially in environments with high energy consumption such as office buildings and industrial sectors, where losses can be substantial. These findings underscore the critical importance of analyzing harmonic phenomena, especially considering that modern power systems still predominantly operate using alternating current (AC), where ideally sinusoidal waveforms are expected.

The issue of power quality, influenced by consumer loads, is partly due to the use of nonlinear loads. A nonlinear load is characterized by a situation in which the output waveform does not align with the input voltage in each half-cycle, resulting in current and voltage waveforms that deviate from their ideal sinusoidal forms, often leading to distortion [6]. While the electrical energy supplied to the load typically has a sinusoidal waveform, the use of nonlinear loads causes the waveform shape to change. These loads cause the current flowing through the system to differ from the sinusoidal voltage waveform. Nonlinear loads refer to electronic equipment that uses semiconductor components as switches, which contributes to current distortion. The presence of nonlinear loads leads to the generation of harmonics in the electrical power system. Harmonics are high-frequency waves that are integer multiples of the system's fundamental frequency. These harmonics cause deviations in the frequency of both current and voltage, which significantly impact power quality. As a result, the current and voltage waveforms become non-sinusoidal, with the harmonic frequencies overlapping with the fundamental frequency, leading to further distortion.

One of the consequences of harmonics is the generation of heat in electrical equipment [7]. Distribution transformers, which are key components in power systems, are particularly affected by harmonics. A distribution transformer is designed to step down the voltage from 20 kV to 380/220 V for use by various loads. These transformers are directly connected to the loads, particularly nonlinear loads used by consumers, making them susceptible to harmonic distortion. The presence of harmonics in distribution transformers results in a factor-k value, which represents the influence of harmonic load currents at different frequencies. This factor leads to derating of the transformer and an increase in power losses [8]. To mitigate these effects, two types of filters are commonly used to reduce harmonic distortion: active filters and passive filters. Active filters utilize active components such as operational amplifiers (Op-Amps) and transistors, while passive filters rely on passive components like resistors, capacitors, and inductors. Passive filters offer advantages such as lower equipment costs compared to active filters, as well as the ability to improve power quality by compensating for reactive power. One example of a passive filter is the single-tuned passive filter, which is designed to reduce harmonics at a specific order or operating frequency [9].

Previous research has focused on the design of a single-tuned passive filter to reduce harmonics in nonlinear loads. The objective is to mitigate harmonics by placing the designed filter between the power source and five types of nonlinear loads: energy-saving lamps, fluorescent lamps, refrigerators, televisions, and pump motors. The study's results demonstrate a reduction in the Total Harmonic Distortion (THD) of the current from 17.8% before installation to 10.2% after the filter was applied. The THD value of the voltage also decreased from 3.8% to 2.5% [10]. This study analyzes the design of a passive filter to suppress harmonics in nonlinear load installations. The research involves designing a passive filter to mitigate harmonics, with simulations conducted using MATLAB. The measurements indicate that the initial voltage THD was 9.41%, and the current THD was 15.05%. After the filter was installed, the voltage THD decreased to 6.61%, and the current THD dropped to 10.40%. Additionally, the power factor improved from 0.971 to 0.992 [11]. For this study, the author chose a 1250 kVA transformer due to its large load capacity. The single-tuned passive filter was selected to minimize harmonics, as harmonic measurements of the transformer showed that the only values exceeding the standard were at the third harmonic order. The effectiveness of the single-tuned passive filter in reducing harmonics serves as a reference for assessing the impact of its installation.

2. RESEARCH METHODS

In this study, the methodology used to design and calculate a single tuned passive filter for harmonic mitigation in a 1250 kVA distribution transformer at PT. INKA (Persero) Madiun involves several key steps. The process begins with an analysis of the existing electrical system, including measurements of harmonic distortion at the load and distribution network. Next, an appropriate filter type, namely the single tuned passive filter type, is selected and designed to attenuate the dominant harmonic frequencies. The filter's dimensions and specifications are calculated based on the measured harmonic data, utilizing calculation methods in accordance with international standards. Simulation analysis and field testing are also conducted to ensure that the designed filter effectively reduces harmonic distortion and improves the power quality at the facility.

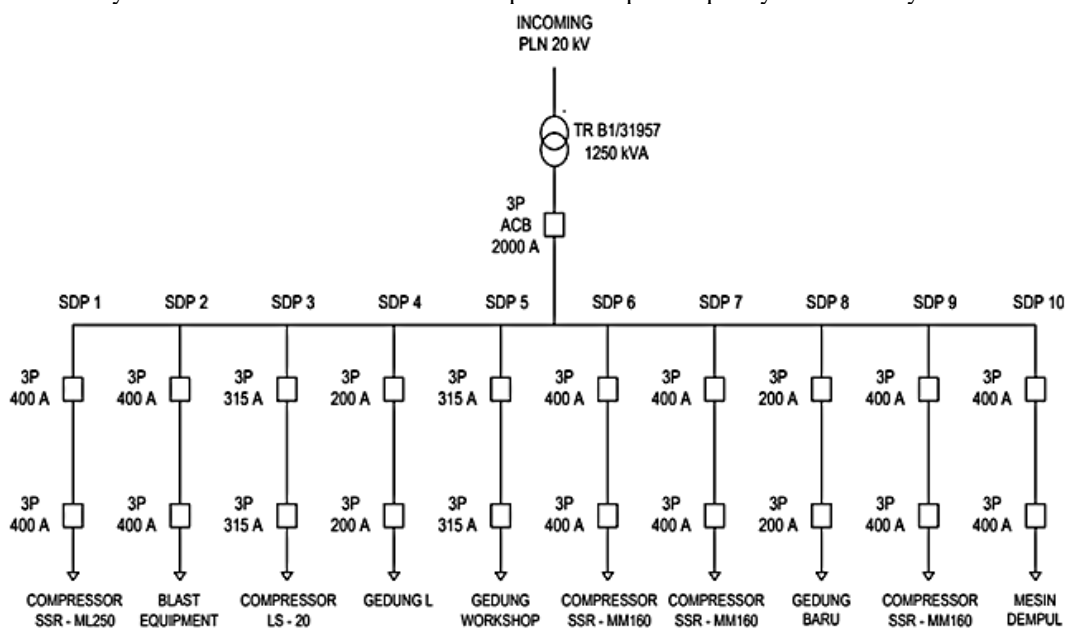


Figure 1. Single Line Diagram of 1250 kVA Distribution Transformer PT. INKA (PERSERO) Madiun

2.1. Harmonis Analysis

In this section, a harmonic analysis is performed to identify the level of harmonic distortion in the existing electrical system at PT. INKA (Persero) Madiun. Measurements are taken at various points within the distribution network and at the 1250 kVA distribution transformer, which is the focus of this study. The obtained harmonic data is then analyzed to determine the dominant frequencies and the total harmonic distortion (THD) present, using appropriate harmonic analysis tools. The results of this analysis provide insights into the impact of harmonics on power quality and serve as the foundation for designing the single tuned passive filter aimed at mitigating harmonics in the system. The initial calculations required are data from THD (Total Harmonic Distortion) and TDD with the following equations [12]:

$$THD_I = \sqrt{\frac{\sum_{h=2}^{h_{max}} I_h^2}{I_1^2}} \tag{1}$$

Where THDI represents the Total Harmonic Distortion (THD) of the current component in percentage, I_h represents the harmonic current value at order h in amperes, I_1 represents the fundamental current value in amperes, and h is the harmonic order. Both I and I_h are obtained using a power quality analyzer HIOKI 3169-20 set to a 3P4W (three-phase-four-wire) cable configuration. After obtaining the highest THDI value during the measurement period, the TDD value at that time can be determined using the following equation [12]:

$$TDD_I = \sqrt{\frac{\sum_{h>1}^{h_{max}} I_h^2}{I_L^2}} \tag{2}$$

Where TDD represents the THDI value of the maximum current component in percentage, I_h represents the harmonic current value at order h in amperes, I_L represents the fundamental current value at peak load in amperes, and h is the harmonic order (3, 5, 7, etc.). The TDD value is essential in assessing the overall harmonic distortion in the electrical system, as it helps to quantify the impact of harmonics on system performance. Higher TDD values indicate a greater presence of harmonic currents, which can lead to equipment malfunctions and inefficiencies.

Table 1. Voltage Harmonics Standard Based on IEEE 519-2014 [13]

<i>Bus Voltage V at PCC</i>	<i>Individual Harmonics</i>	<i>Total Harmonic Distortion (%)</i>
$V \leq 1.0 \text{ kV}$	5.0	8.0
$1 \text{ kV} < V \leq 69 \text{ kV}$	3.0	5.0
$69 \text{ kV} < V \leq 161 \text{ kV}$	1.5	2.5
$161 < V$	1.0	1.5*

Table 2. Current Distortion Limits For 120V to 69 kV Systems [14]

<i>Maximum harmonic current distortion in percent of I_L</i>						
<i>Individual harmonic order (odd harmonic)^{a, b}</i>						
<i>I_{sc}/I_L</i>	<i>3 < h < 11</i>	<i>11 < h < 17</i>	<i>17 < h < 23</i>	<i>23 < h < 35</i>	<i>35 < h < 50</i>	<i>TDD</i>
$< 20^c$	4,0	2,0	1,5	0,6	0,3	5,0
$20 < 50$	7,0	3,5	2,5	1,0	0,5	8,0
$50 < 100$	10	4,5	4,0	1,5	0,7	12,0
$100 < 1000$	12	5,5	5,0	2,0	1,0	15,0
> 1000	15	7	6,0	2,5	1,4	20,0

After obtaining the TDD value that indicates the maximum harmonic content present in the system, the next required data is the IHDI value at the time when the THD value is highest, using the following equation [12]:

$$IHD_I = \sqrt{\frac{I_h^2}{I_1^2}} \tag{3}$$

Where IHDI represents the harmonic current distortion (IHD) value at harmonic order h in percentage, I_h represents the harmonic current value at order h in amperes, and I_1 represents the fundamental current value in amperes. This IHDI parameter will later be needed for designing a passive filter at a specific harmonic order.

2.2. Single Tuned Type Passive Filter Design

The Single Tuned Type Passive Filter is a widely utilized passive filter design that focuses on attenuating specific frequencies within electrical or electronic systems. This type of filter is characterized by a single resonant frequency, which can be tuned to effectively eliminate unwanted frequency components from an input signal. Typically, the design consists of passive components such as resistors (R), inductors (L), and

capacitors (C), which are strategically arranged to achieve the desired frequency response. Single Tuned Filters are commonly applied in power systems to mitigate harmonic distortions and high-frequency noise, ensuring improved signal quality and system stability. The design and performance of such filters are critical in applications requiring precise frequency control and minimal interference. Previously, the IHDI value, in addition to being used for designing filters, can also be used to calculate the performance degradation of transformers (Derating Factor). To calculate the Derating Factor, the following equation [15] can be used:

$$\text{Derating Factor} = \frac{1}{k} \times 100\% \quad (4)$$

Where the value of the Derating Factor indicates the maximum load that a transformer can handle due to the presence of harmonics. To calculate the value of factor K, the following equation can be used [15]:

$$K = \left[1 + \frac{e}{1+e} \left(\frac{I_1}{I} \right)^2 \sum_{n=2}^N n^q \left(\frac{I_n}{I_1} \right)^2 \right]^{\frac{1}{2}} \quad (5)$$

Where e represents the eddy current losses caused by the sinusoidal current at the fundamental frequency divided by the losses due to DC current at the reference temperature, q is the exponential constant (the value used is 1,7), I_1 represents the fundamental current (A), and I_n represents the harmonic current at order n (A).

After obtaining the Derating Factor value, the next step is to design the passive filter. This filter serves to minimize the disturbances caused by harmonics. At this stage, the required data is the IHD_I values to determine at which harmonic order the harmonics do not meet the standard [16]. After identifying the harmonic order that does not comply with the standard, a passive filter is designed to reduce the harmonics at that order. Some parameters for designing the filter include the capacitor (C), inductor (L), and resistor (R) for each order, using the following formula [16]:

$$X_C = \frac{kV^2}{Q_{comp}} \quad (6)$$

Where,

X_C = Capacitor reactance (Ω)

kV = Voltage

Q_{comp} = Reactive power compensation (kVAR)

After the capacitive reactance (X_C) value is determined, the next step is to calculate the required capacitance (C) for the capacitor, with the calculation as follows [16]:

$$C = \frac{1}{2\pi f X_C} \quad (7)$$

Where,

C = Capacitor value (Farad)

f_0 = Frequency system (Hz)

X_C = Capacitor reactance (Ω)

To determine the inductor value in a single tuned passive filter, the inductive reactance (X_L) value must be calculated. After calculating the inductive reactance (X_L), the inductance (L) value for the inductor component can be determined [16].

$$X_L = \frac{X_C}{h_n^2} \quad (8)$$

Where,

X_L = Inductor reactance (Ω)

X_C = Capacitor reactance (Ω)

h_n = n^{th} harmonic order

From the calculation results of the inductive reactance value (X_L) above, it can be seen that the harmonics to be filtered are harmonics of the 3th order. So, the characteristic reactance value of the filter can be determined.

$$X_n = h_n X_L \quad (9)$$

Where,

X_n = Filter characteristic reactance (Ω)

h_n = n^{th} harmonic order

X_L = Inductor reactance (Ω)

From the results of the calculation of the inductive reactance value (X_L), the inductance value (L) required for the inductor can be determined so that the calculation is as follows [16].

$$L = \frac{X_L}{2\pi f_0} \quad (10)$$

Where,

L = Inductance value of passive filter (H)

X_L = Inductor reactance (Ω)

f_0 = Frequency system (Hz)

In this simulation, the filter quality factor value (Q) selected is 100. To determine the value of resistance (R) on the single tuned passive filter resistor, it can be calculated using the following equation [16].

$$R = \frac{X_n}{Q} \quad (11)$$

Where,

R = Resistance value of passive filter (Ω)

X_n = Filter characteristic reactance (Ω)

Q = Quality Factor

3. RESULT AND ANALYSIS

This section presents the results and analysis of the design and calculation of a single tuned passive filter for harmonic mitigation in a 1250 kVA distribution transformer at PT. INKA (Persero) Madiun. The calculations include the selection of filter component values, frequency response analysis, and the estimation of harmonic reduction achieved after the filter installation. Additionally, the discussion will evaluate the performance of the filter in reducing harmonic distortion in the power distribution system and its impact on the operational efficiency of the transformer. The obtained results will be compared to relevant standards and guidelines to ensure the effectiveness of the filter design in improving power quality.

3.1. Determining the R, L, and C values in Passive Filters

When determining the filter value to reduce harmonics, the correct capacitor value must be ensured. If the harmonic current is small while the capacitor capacity is larger, a new issue, such as over-capacitance, may arise. This condition can lead to an increase in temperature on other equipment, one of which is the conductor, due to the rise in current and voltage. After the identification process, the next step is to determine the power factor (pf) value. Then, calculate the required capacitance and inductance values for the passive filter. To obtain the capacitance value (C) in a single tuned passive filter, the reactive power of the capacitor (Q_{Comp}) and the capacitive reactance (X_C) values must be determined. It is assumed that the power factor improvement is 0,95, so the calculation is as follows:

$$\begin{aligned} Q_{comp} &= \sqrt{\left(\frac{P_1}{PF_1}\right)^2 - P_1^2} - \sqrt{\left(\frac{P_1}{PF_2}\right)^2 - P_1^2} \\ &= \sqrt{\left(\frac{229}{0,77}\right)^2 - 229^2} - \sqrt{\left(\frac{229}{0,95}\right)^2 - 229^2} = 114,9 \text{ kVAR} = 0,0115 \text{ MVAR} \end{aligned}$$

After determining the Q_{Comp} value required to meet the reactive power of the harmonic source, the next step is to calculate the capacitive reactance (X_C) using the following equation:

$$X_C = \frac{kV^2}{Q_{Comp}} = \frac{0,4^2}{0,115} = 1,39 \text{ k}\Omega = 1390 \Omega$$

After determining the capacitive reactance (X_C) value, the next step is to calculate the required capacitance (C) for the capacitor, with the calculation as follows:

$$C = \frac{1}{2\pi f_0 X_C} = \frac{1}{2 \times 3,14 \times 50 \times 1390} = 0,00229116 \text{ F} = 2285 \mu\text{F}$$

The focus of the filter design is a single tuned filter at the 3rd order. Therefore, after the frequency is set to $3 \times 50 \text{ Hz} = 150 \text{ Hz}$, the attenuation of the harmonic frequency must meet the requirements for the use of capacitor and inductor components.

$$L = \frac{1}{(\omega_n)^2 C} = \frac{1}{(2 \cdot \pi \cdot 150)^2 \times 0,00229116} = 0,00308732 \text{ H}$$

$$X_L = \omega_L = 2 \cdot \pi \cdot 50 \cdot (0,00308732) \text{ H} = 0,9694 \Omega$$

A resistor component with a very small value is also needed to conduct the harmonic current. The filter quality factor (Q) for the single tuned filter is chosen between 30 and 60. In this filter design, the value of Q is chosen to be 30. Therefore, the resistor value can be calculated as follows:

$$R = \frac{X_n}{Q} = \frac{0,00308732}{30} = 0,011 \Omega$$

Table 3. Passive Filter Specifications Based on Calculations

Parameter	Value
Q_{Comp}	114,9 kVAR
XC	1390 Ω
XL	0,969 Ω
C	2285 μ F
L	0,00308732 H
R	0,011 Ω

3.2. Simulation Result

The field measurement results are compared and the measured values are shown in Table 4. The current THD values obtained using the harmonics analyzer for phases R, S, and T are 28.5%, 4.0%, and 2.4%, respectively. In contrast, according to the ETAP software modeling, the current THD before filter implementation is 28.50%, 4.0%, and 2.4% for phases R, S, and T, respectively.

Table 4. Comparison of Total Harmonic Distortion Values

THD Value	Measurement Result		
	Harmonics Analyzer	ETAP 19 Simulation	
Current (%)	Real Time	Without Filter	Using Filter
R	28,5%	28,50%	11,07%
S	4,0%	4,0%	1,37%
T	2,4%	2,4%	1,09%
Voltage (%)	Realtime	Without Filter	Using Filter
R	1,51%	1,51%	0,87 %
S	1,55%	1,55%	0,85 %
T	1,54 %	1,54 %	0,81 %

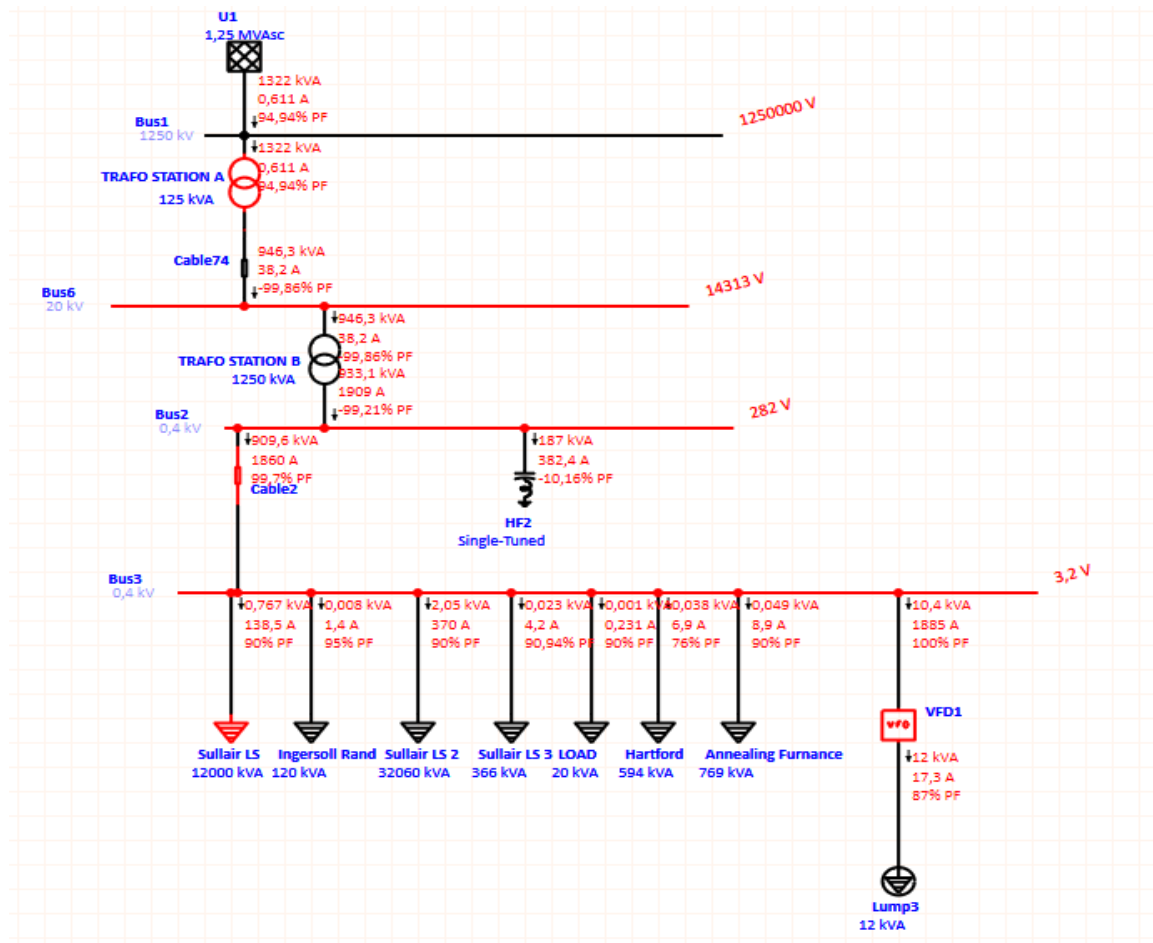


Figure 2. Harmonic Analysis Before Implementing Passive Filters

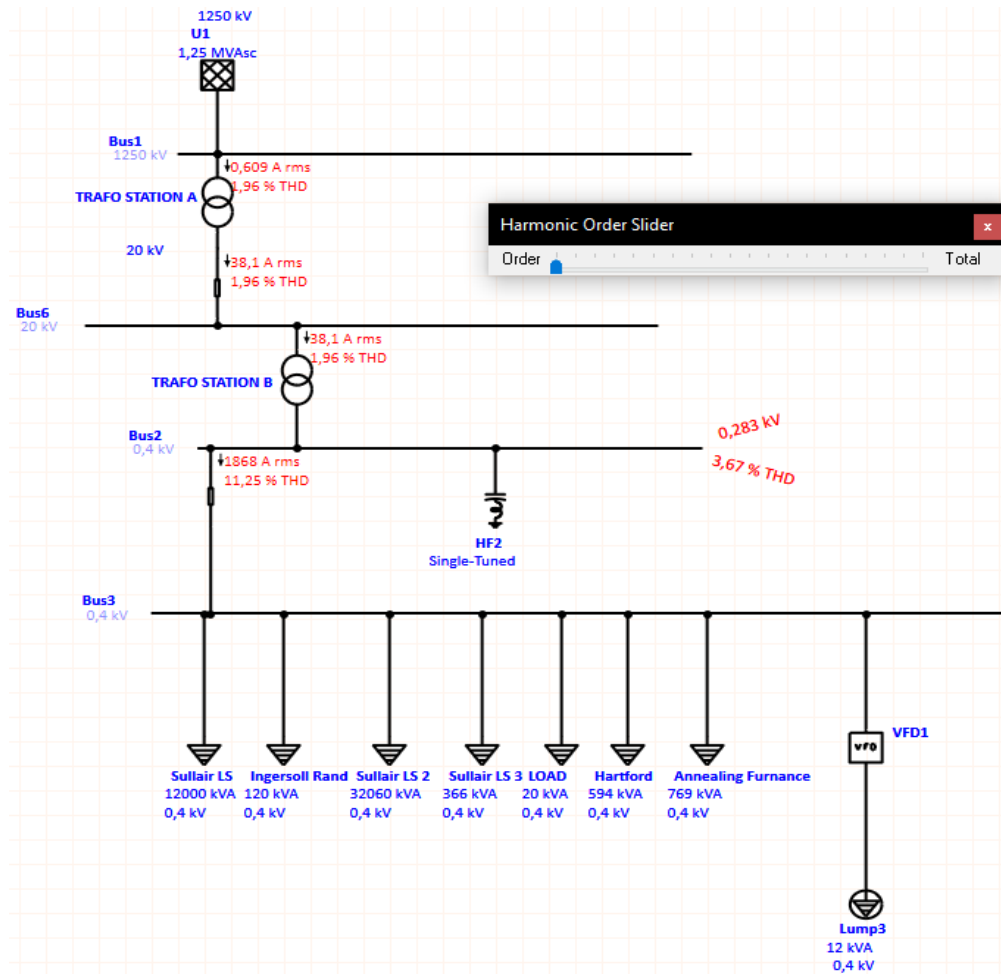
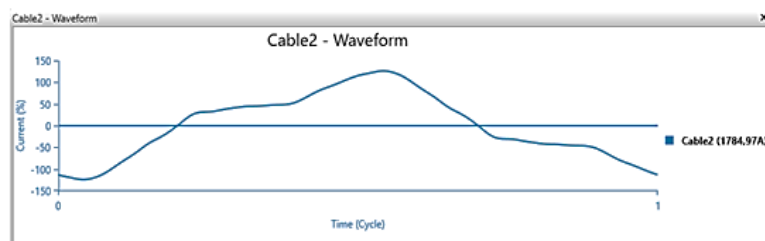
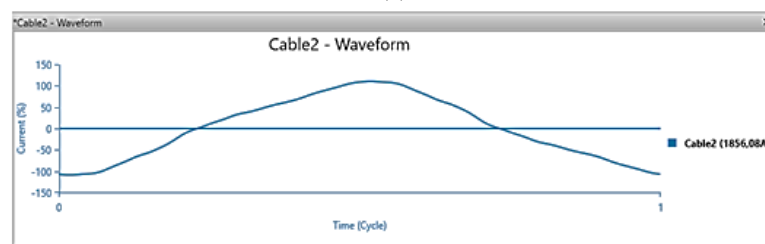


Figure 3. Harmonic Analysis After Implementing Passive Filters

Based on Figure 2 and Figure 3, THD values for phases R, S, and T decreased to 11.07%, 1.37%, and 1.09%, respectively, while THDv for the same phases also reduced from 1.51%, 1.55%, and 1.57%. Active power at bus 1 dropped from 909.6 kVA with 1860 A and a 99.7% power factor to 820.5 kVA with 1736 A and a 99.4% power factor after the filter was installed at bus 2. The simulation shows the single-tuned passive filter effectively reduces power losses.

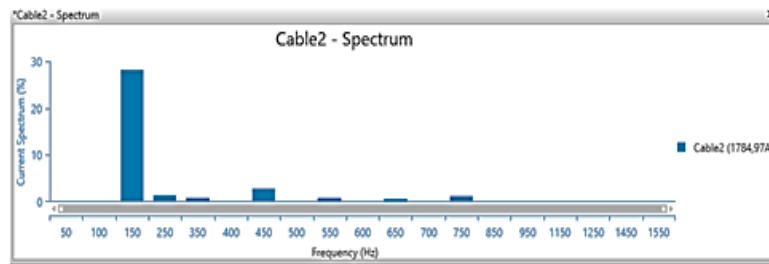


(a)

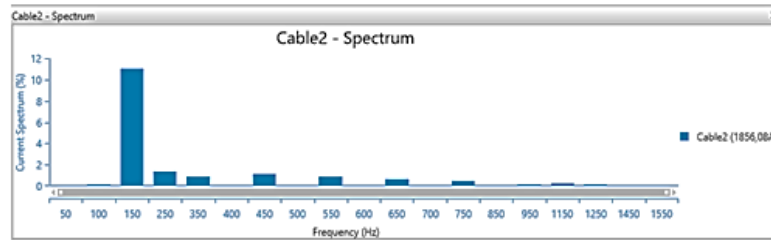


(b)

Figure 4. Waveform Distortion Due to Harmonics: Before (a) and After (b) Passive Filter Installation



(a)



(b)

Figure 5. Spectrum Harmonics: Before (a) and After (b) Passive Filter Installation

The analysis of harmonic distortion before and after the installation of a passive filter can be summarized as follows. In the waveform before the passive filter installation (Figure 4a), the current signal shows significant distortion, deviating from the ideal sinusoidal shape. The peak current amplitude is 1784,97 A, indicating the presence of harmonics typically caused by non-linear loads such as inverters, rectifiers, or electronic devices. These harmonics reduce system efficiency and can generate excessive heat in electrical equipment. After the installation of the passive filter (Figure 4b), the current waveform becomes smoother and closer to an ideal sinusoidal shape, reflecting a reduction in harmonic distortion. The peak current amplitude increases to 1856,08 A, showing that the passive filter not only mitigates harmonic components but also optimizes current flow. This improvement highlights the effectiveness of the passive filter in enhancing power quality and protecting electrical systems from the adverse effects of harmonics.

The harmonic spectrum analysis reveals significant improvements after the installation of a passive filter. Before the filter installation (Figure 5a), the spectrum shows considerable harmonic components, especially at lower harmonic orders such as the 3rd harmonic (150 Hz), which reaches approximately 30% of the fundamental. Higher-order harmonics, including those at 250 Hz, 350 Hz, and beyond, are also present, contributing to overall harmonic distortion. After the filter installation (Figure 5b), the dominant 3rd harmonic is significantly reduced to around 12%, and higher-order harmonics are minimized to negligible levels. This reduction in harmonic content indicates a substantial improvement in power quality, with the passive filter effectively mitigating harmonic distortion and enhancing system reliability and efficiency.

The findings of this study demonstrate that the application of a passive filter significantly reduces harmonic distortion in electrical systems, both in the time and frequency domains. Prior to the installation of the filter, the current waveform exhibited severe distortion, with a peak current of 1784,97 A, indicating the presence of substantial harmonic components commonly introduced by nonlinear loads such as inverters and rectifiers. After the filter installation, the waveform became smoother and more sinusoidal, and the peak current increased to 1856,08 A, suggesting improved current flow efficiency and a reduction in reactive power circulation. These results are consistent with previous research that also reported enhanced power quality through harmonic mitigation using passive filters [17]. However, the present study provides additional insight through a more detailed quantitative harmonic spectrum analysis. Specifically, the third-order harmonic, which initially reached 30% of the fundamental component, was reduced to approximately 12%, and higher-order harmonics were effectively suppressed to negligible levels. This contrasts with earlier studies that primarily reported reductions in THD without discussing the behavior of individual harmonic orders or changes in peak current values [18]. Therefore, this research contributes further evidence that passive filters not only attenuate harmonic distortion but also enhance the overall efficiency and reliability of power systems.

3.3. Discussion

The use of a Single Tuned Passive Filter for harmonic mitigation in a 1250 kVA distribution transformer system presents several limitations. Primarily, Single Tuned Passive Filter are effective only for a specific harmonic frequency typically the dominant one and are not suitable for mitigating multiple harmonic orders. This limits their performance in systems with varying or complex harmonic spectra. Additionally, Single Tuned

Passive Filter are sensitive to changes in load conditions. Variations in load can shift harmonic frequencies, reducing the filter's effectiveness or causing detuning [19]. The risk of resonance, particularly if the filter is not properly coordinated with system impedance, may also result in voltage or current amplification at certain frequencies, potentially harming equipment. Single Tuned Passive Filter have a fixed filtering capacity and are not adaptive to real-time harmonic variations, unlike active filters. Furthermore, they contribute reactive power to the system, which may negatively impact power factor and require additional compensation. Therefore, while Single Tuned Passive Filter are cost-effective and suitable for stable harmonic conditions, their application in dynamic or high-distortion environments should be carefully evaluated [20].

The implementation of a single tuned passive filter presents several practical benefits for industrial power systems. The filter effectively reduces specific harmonic orders, thereby improving power quality and decreasing Total Harmonic Distortion (THD). This enhancement leads to more stable voltage and current waveforms, which are critical for the reliable operation of sensitive equipment. Furthermore, by mitigating harmonic currents, the filter helps protect electrical components from overheating and premature failure, while also reducing energy losses in the distribution network. These improvements contribute to greater system efficiency and lower operational costs. From a regulatory perspective, the use of passive filters supports compliance with harmonic standards such as IEEE 519, helping industries avoid penalties and ensuring system compatibility. In addition, compared to active solutions, passive filters offer a more economical and low-maintenance approach, making them suitable for small to medium-scale applications. In conclusion, the study demonstrates that single tuned passive filters provide a practical, cost-effective, and efficient solution for harmonic mitigation in various industrial settings.

4. CONSLUSION

Based on the results of the calculations and simulations, it can be concluded that the measurement and analysis of Total Harmonic Distortion (THD) at the transformer station B, before the filter installation, showed the following THD values for the current: 28,50% for phase R, 4,0% for phase S, and 2,4% for phase T. For voltage, the THD values were 1,51% for phase R, 1,55% for phase S, and 1,57% for phase T. After the filter was installed, the THDi values decreased significantly to 11,07% for phase R, 1,37% for phase S, and 1,09% for phase T. Meanwhile, the THDv values dropped to 0,87% for phase R, 0,85% for phase S, and 0,81% for phase T. The simulation and analysis results using ETAP software showed that the single-tuned passive filter designed to reduce the total harmonic distortion in the SDP Transformer used a capacitor of 2285 μF , an inductor of 0,00308732 H, and a resistor of 0,011 ohms.

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