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Enhancing Single-Phase Transformer Performance with A Pass-Tune Filter Under Various Load Conditions

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ABSTRACT

Although single-phase transformers are crucial parts of contemporary electrical power networks, reactive power demands and harmonic distortions can severely impair their performance under non-linear. In order to improve transformer performance by reducing harmonic distortions and enhancing power quality, this study suggests integrating a pass-tune filter. The study shows how the suggested filter affects transformer efficiency and voltage control under a range of load conditions, such as linear, non-linear, and fluctuating loads. A single-phase transformer (3 KVA, 220 volts, and 50 Hz) is simulated in this work. Different topologies of filters have been used in this work. The results demonstrate the pass-tune filter's potential as an affordable remedy for power quality problems, guaranteeing dependable transformer operation in practical applications. Different loads (linear load and non-linear load) before and after adding the filters were examined. THD due to higher distortion in the R-L load reaches 22% and 49% for the voltage and current, respectively. Fast Fourier Transform (FFT) analysis after applying the filters to both voltage and current shows acceptable total harmonic distortion values within standards (less than 5%). Simulation findings show that the pass-tune filter effectively reduces losses, improves overall operating stability, and lowers total harmonic distortion (THD).

Keywords: *Single Phase Transformer; Harmonic, Reduction losses, Filters, Non-linear load, THD*

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1. INTRODUCTION

One of the most crucial parts of the network that generates and distributes energy is the electrical transformer; any malfunction in these parts will lower the power system's reliability and cause the power supply to cut off [1]. Transformers are essential components of power grids and power systems because they guarantee the dependable and safe operation of the electrical system. Transformers are static devices that induce mutual coupling between circuits using one winding, or two or more coupled windings, with or without a magnetic core[2]. When connecting electrical grids across greater distances, power transformers play a crucial role in power networks. For safe operating conditions, power transformers must be regularly inspected[3]. Using big data and intelligent terminal communication equipment, the distribution transformer operation status is being tracked. IoT systems can guarantee the power supply system's stability [4].

To avoid unanticipated failures and to incorporate distributed renewable energy sources into the distribution grid, distribution transformers must be regularly monitored [5]. Electrical networks that contain current and voltage harmonics may experience excessive losses and elevated temperatures in distribution transformers, shortening their operating life [6], [7]. Transformer short-circuit problems have the potential to seriously impair the power supply and result in large financial losses[8].

The effects of voltage harmonics on transformer aging and losses have received less attention than those of current harmonics [9], [10]. Recent research, however, indicates that in oil-filled distribution transformers, distorted voltage excitation can dramatically raise temperature and losses. Tests have been performed both open-circuit and short-circuit to assess how harmonics affect transformer performance. To measure power loss and assess eddy-current-related resistance, equations have been developed. Overall, distribution transformer losses and temperature rise can be negatively impacted by the presence of current and voltage harmonics, emphasizing the significance of tackling harmonic pollution in power [11], [12].

Examining the shift in losses under harmonic situations is one way to lessen the impact of harmonics on transformer losses [13]. One method is to calculate harmonic winding losses using the AC resistance factor model, which is more accurate than the traditional model [14]. An alternative approach is to reduce harmonic levels by designing an inverter with a diode-clamped topology and connecting it to a transformer to measure the losses caused by harmonics [15]. Furthermore, the sub-harmonic content and losses of a transformer can be examined under various circumstances using a mathematical model based on the Finite Element Method[16]. Lastly, a dual-active-bridge converter's phase current harmonic content can be decreased by the use of a control technique, which will essentially lower low-order harmonics. The analysis and assessment of a harmonic-filtering distribution transformer (HFDT) for harmonic reduction in low-voltage distribution networks are covered in the article supplied. It doesn't address in detail how to reduce the impact of harmonics on transformer losses [17].

This paper's main goal is to improve single-phase transformer performance by addressing reactive power and harmonic distortion issues across varied load scenarios. A 3 kV, 220-volt, 50 Hz single-phase transformer's performance has been examined in this work through a simulation model test in MATLAB Simulation about linear and non-sinusoidal loads. Under linear and nonlinear conditions, the study aims to assess the filter's effects on transformer operation. By achieving these objectives, the study aims to offer a workable, affordable way to increase transformer longevity and reliability, ultimately aiding the creation of stronger, more effective electrical power systems. Additionally, a pass-tune filter was built to mitigate the effects of harmonic distortion on the transformer's performance.

2. SIGNIFICANCE OF THIS STUDY

The research gap is that most previous studies have focused on designing passive filters tailored to a single topology or limited operating conditions. The literature lacks studies proposing a unified design that can be applied to multiple configurations and operating conditions. The contribution of this research is the design and validation of a single passive filter that can be used with both back-to-back and H-bridge configurations, maintaining effective performance across multiple operating conditions and firing angles. The importance of this contribution lies in its greater flexibility, reduced design complexity, and practicality compared to traditional ad hoc designs. The effectiveness of this design is demonstrated through the results presented in the research.

3. THE PROPOSED METHODOLOGYAND TOOLS

This study's approach combines theoretical analysis, modeling, and result evaluation to determine how effectively a pass-tune filter can improve single-phase transformer performance across different load scenarios. The first step in the procedure is creating a simulation model of the transformer that includes its fundamental characteristics, including resistance, inductance, and analogous circuit elements. To mimic other load conditions, such as linear and non-linear loads that present reactive power issues and harmonic distortions, this model is expanded. In order to increase power quality, a pass-tune filter is especially designed to target harmonics, such as the third, fifth, and seventh orders, utilizing mathematical concepts.

Specifically, a C-type filter (a third-order high-pass filter with low losses and reduced risk of ringing) has been used in parallel with a double-tuned double-suppressor filter. This configuration offers better high-harmonic suppression while targeting two fundamental harmonics (e.g., the 5th and 7th) via a single unit, rather than using separate single filters for each harmonic.

In comparison, recent literature shows that practical applications tend to use single-tuned filters or single high-pass filters. In contrast, more recent studies indicate the effectiveness of double/suppressor filters and improved performance when combined with configurations such as the C-type.

We now include a discussion and comparison section with recent work (see citations below) and illustrate the parameter design, tuning procedures, and simulation/measurement results that demonstrate the practical advantages of this configuration in the context of our study.

Table 1 shows the Comparison of passive harmonic filter types.

Table 1: Comparison of passive harmonic filter types [18]–[21]

Type of Filter	Strengths	Weaknesses	Justification in the context of the study
Single-tuned	Very effective at a specific harmonic frequency (such as 5th or 7th), simple design and low cost	Requires separate filter for each harmonic; risk of resonance if not properly tuned	Traditional solutions are often limited to this, but it is not sufficient to comprehensively reduce THD.
Double-tuned	Targets two main compatibilities in one unit, better efficiency than using separate filters.	More complex design and tuning; may require additional damping elements.	Provides suppression of two fundamental harmonics (such as 5th and 7th) with only one filter.
C-type	Better performance at high harmonics; lower losses; greater stability against resonance	Higher size and complexity than simple filters	Allows reduction of high harmonics with comfortable damping at wide frequencies
High-pass	Suppresses a wide range of high harmonics; direct design	Does not handle important low harmonics (5th, 7th)	Usually used with single/double tuned, but alone is not sufficient
Suggested configuration (C-type + Double-tuned)	Combines the advantages of both types: reduction of low harmonics (5th, 7th) + suppression of high band, with reduced possibility of resonance	Relatively more complex than discrete filters, but offers better performance with fewer elements than a multi-filter array.	Most suitable for the scenario of high distortion single-phase transformers as in our study.

The transformer model and the pass-tune filter architecture are implemented and simulated using the MATLAB/Simulink platform. The power factor, total harmonic distortion (THD), and harmonic content under each load scenario are examined using MATLAB's Signal Processing and Power Systems toolboxes, both with and without the filter. A 3 KVA single-phase transformer, 220 volts, and a frequency of 50 Hz were used in this work. Table 2 shows the transformed notations used in this paper.

Table 2. Parameters of Single-Phase Transformer

	Value	Unit
Rated Power	3	KVA
Voltage	220/110	Volt
Current	13.663/27.272	A
Frequency	50	Hz
Turn ration	1/2	-----
R load	15	ohm
L load	0.0056127	H

To monitor its performance metrics, the transformer model is put through a range of load circumstances in the simulation environment. To assess the pass-tune filter's effect on reducing harmonics and raising power factor, it is integrated into the circuit model. Frequency-domain analysis, waveform visualization, and the calculation of crucial performance parameters are enabled by MATLAB's features. To measure the filter's improvements, outcomes are compared across situations. Before the pass-tune filter is physically implemented, its performance can be thoroughly understood using this simulation-based method, which provides a quick, accurate, and economical way to validate the proposed improvement plan.

4. DESIGN OF PASSIVE HARMONIC FILTER AND PARAMETER EFFECT

Passive harmonic filters consist of passive electrical components, including resistors, inductors, and capacitors (RLCs). The inductor and capacitor values are selected to achieve resonance at the harmonic frequency to be filtered. These filters are generally classified into two basic types: series filters and bypass filters. Bypass filters are primarily used in AC systems, where they are connected in parallel with the system or with a non-linear load that generates harmonics. When tuned to the appropriate frequency, these filters create a series resonance condition that lowers the impedance at the target frequency, allowing harmonics to pass through the filter rather than into the electrical system. Bypass filters are less expensive than series filters because they are designed to achieve graded isolation levels. These filters are also known as "tap filters" for their ability to target specific harmonic frequencies. They can be classified into several types, the most prominent of which are single-tuned filters, double-tuned filters, and high-pass filters, as shown in Figure 1.[22], [23].

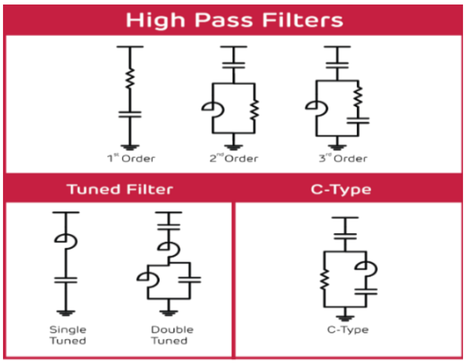


Fig 1. Passive Filters Types

A-DESIGN OF A DOUBLE-TUNED FILTER DESIGN

The conventional double-tuned filter is composed of the series resonance circuit and the parallel resonance circuit. The structure of this type of filter is shown in Figure 1. The series resonance circuit (L1, C1) and parallel resonance circuit (L2, C2) have resonance frequencies ωs and ωp respectively[23], [24]. They can be formulated as:

$$\begin{bmatrix}\omega_s \\ \omega_p\end{bmatrix} = \begin{bmatrix}\frac{1}{\sqrt{L_1 C_1}} \\ \frac{1}{\sqrt{L_2 C_2}}\end{bmatrix} \tag{1}$$

$$Ca=Cb=Q/V2 \times 2\pi f \tag{2}$$

The two parallel single-tuned filters are converted to one double-tuned filter, as shown

$$\begin{bmatrix}\omega_a \\ \omega_b\end{bmatrix} = \begin{bmatrix}\frac{1}{\sqrt{L_a C_a}} \\ \frac{1}{\sqrt{L_b C_b}}\end{bmatrix} \tag{3}$$

Both configurations are equivalent, which means they have equal impedance Z=Zab. That's Leeds to

$$\omega_a \omega_b = \omega_s \omega_p \tag{4}$$

$$C_1 = C_a + C_b \tag{5}$$

$$C_b \frac{1}{\omega_a^2} + C_a \frac{1}{\omega_b^2} = C_1 \frac{1}{\omega_p^2} \tag{6}$$

$$L_1 = \frac{1}{C_a \omega_a^2 + C_b \omega_b^2} \tag{7}$$

$$L_2 = \frac{\left(1 - \frac{\omega_a^2}{\omega_s^2}\right)\left(1 - \frac{\omega_a^2}{\omega_p^2}\right)}{\omega_a^2 C_1} \tag{8}$$

$$C_2 = \frac{1}{L_2 \omega_p^2} \tag{9}$$

Double-tuned filters are very effective at reducing harmonic distortion in power systems because they provide a passive filtering network that targets two distinct harmonic frequencies simultaneously. Usually, this filter is made up of a mix of resistors, capacitors, and inductors arranged to create two tuned branches, each of which reverberates at a specific harmonic frequency, like the fifth and seventh or other troublesome harmonics. The design procedure requires accurate component value computations based on the source impedance, load parameters, and the system's harmonic spectrum. Compared to employing separate single-tuned filters, double-tuned filters minimize filter size and cost while reducing overall total harmonic distortion (THD), which is especially useful in applications with numerous dominant harmonics. They also promote voltage regulation and power factor, thereby boosting the stability and performance of electrical networks.

B-DESIGN OF C-TYPE FILTER

It consists of main capacitor C1 connected in series with parallel combination of C2+L & resistance R. Hence four designs equations are presented [24]. The value of the main capacitor & inductor can be calculated in the same way as in a single-tuned filter. A C-Type filter's design aims to reduce power losses, improve resonance damping in power systems, and provide effective harmonic mitigation. This filter creates a unique "C" shape by combining a parallel resistor with a series-tuned LC branch. To achieve low impedance at that frequency and efficiently filter it out, the series LC branch is tuned to the target harmonic, such as the fifth or seventh harmonic. The second capacitor is tuned to the inductor at power frequency to reduce power frequency loss & is calculated as below,

$$C1 = \frac{Q}{V^2 \times 2 \times \pi \times f} \tag{10}$$

$$L = \frac{1}{C1 \times (2 \times \pi \times f \times r)^2} \tag{11}$$

$$R = QHf \times (2 \times \pi \times f \times r) \times L \tag{12}$$

$$C2 = \frac{1}{(V \times 2 \times \pi \times f)2 \times L} \qquad (13)$$

Where,
Q = reactive power produced by the filter at power frequency
V = voltage at which the filter is to be installed
f = power frequency
fr = tuning frequency
QHf = quality factor of the filter (0-5)

In order to enhance filter stability and reduce possible resonance circumstances, a parallel resistor is used. Based on the system's harmonic analysis and the required attenuation level, the design procedure determines the inductance, capacitance, and resistance values. Because C-Type filters are more efficient than traditional single-tuned filters, they are especially well-suited for applications that demand high-performance filtering with low losses, such as in high-voltage AC transmission systems or industrial facilities with significant non-linear loads.

5. MODELING AND SIMULATION OF TRANSFORMER, PASSIVE FILTERS, LINEAR LOAD, AND NON-LINEAR LOAD

An effective way to analyze and understand a transformer's behavior across varied operating conditions is to model and simulate it in MATLAB. Core losses, magnetizing reactance, main and secondary winding resistances and reactance, and other similar circuit parameters are commonly used to model the transformer. A dynamic transformer model that captures both its steady-state and transient responses can be created using MATLAB/Simulink.

Without requiring real prototypes, this simulation environment enables testing of the transformer under various load types, voltage levels, and fault scenarios. Furthermore, transformer simulation tools such as Simulink's Power Systems Toolbox include built-in components that facilitate waveform visualization, efficiency analysis, and harmonic performance analysis.

The constant impedance of a linear load means that, in steady-state conditions, the waveforms of voltage and current remain sinusoidal and in phase. Induction motors running at constant speeds, resistive heaters, and incandescent lights are a few examples of linear loads. Linear loads are commonly used in transformer applications as a starting point for assessing performance parameters such as efficiency, voltage control, and thermal behavior. By modeling and simulating linear loads in MATLAB, one may compare non-linear load scenarios and get insight into the optimal operation of transformers. This guarantees that design enhancements, such as passive filters, are successfully verified in harmonic-distortion-free environments. The transformer's performance was tested under several loading conditions, starting with a normal linear load, which was modeled as an RL combination, as shown in Figure 2.

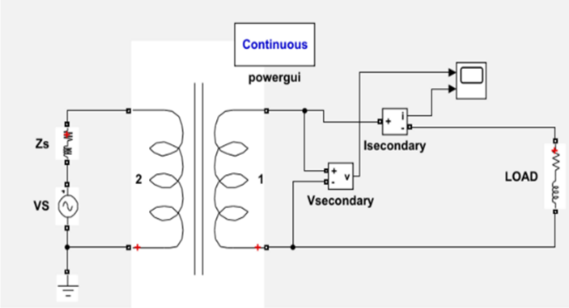


Fig 2: single-phase transformer with RL load

While the case on nonlinear loads was tested using two configurations commonly used in industrial applications, a back-to-back controlled Thyristor with RL and a single-phase full-controlled H-bridge rectifier with RL, the two configurations were simulated in MATLAB/SIMULINK and presented in Figures 3 and 4.

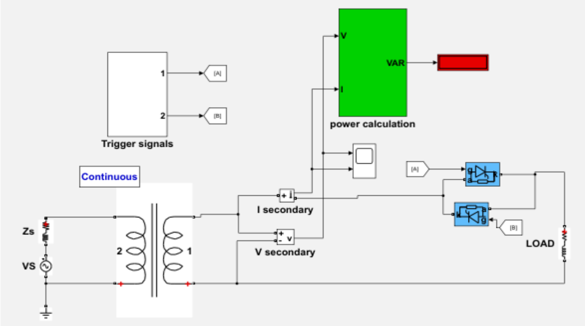


Fig 3: single-phase transformer with back-to-back controlled Thyristor

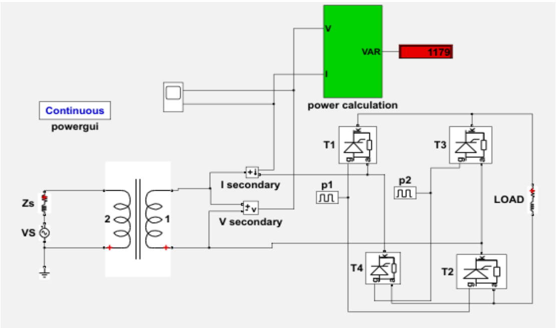


Fig 4: single-phase transformer with full-controlled H-bridge rectifier

Because non-linear loads draw current in non-sinusoidal waveforms, causing harmonic distortion that impairs voltage quality and system stability, they pose serious problems for electrical systems. Variable-frequency drives (VFDs), which are becoming increasingly common in contemporary power systems, are typical examples. Nonlinear loads on transformers result in higher losses, increased heating, and decreased efficiency. In MATLAB, modeling and simulating nonlinear loads entails integrating the system model with the loads' harmonic-producing properties. This enables examination of how they affect transformer performance and assessment of mitigating strategies such as passive filters. Designing robust and effective power systems requires an understanding of how non-linear loads and transformers interact.

In electrical systems, passive filters are crucial parts for reducing harmonic distortions and enhancing power quality. Passive components, such as resistors, inductors, and capacitors, arranged to suppress specific harmonic frequencies, make up these filters. The most popular varieties are C-type, double-tuned, and single-tuned filters; each is intended to eliminate a certain harmonic. Because of their affordability, reliability, and ease of use, passive filters are widely used. They are incorporated into transformer applications to mitigate the negative effects of harmonics produced by non-linear loads, including noise, overheating, and increased losses. Passive filters can be precisely tuned and optimized using MATLAB simulation, ensuring performance across a range of operating conditions while preserving system stability and effectiveness.

6. RESULTS AND DISCUSSION

In this section, the results of the three configurations related to linear and nonlinear loads are tested in the following points:

Simulation results for different loads (linear and non-linear) before adding the filter. In this case, consider the transformer load to be linear, and, referring to the circuit in Figure 2, the results are as shown in Figure 5.

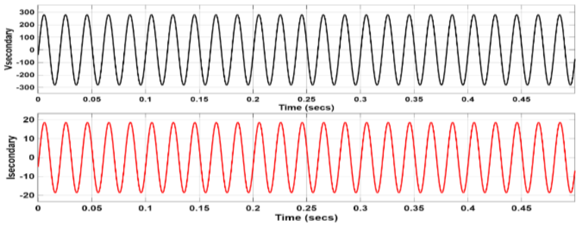


Fig 5: voltage and current for a single-phase transformer with RL load

The results of this case, shown in Figure 5, present the voltage and current on the secondary side of the transformer as pure sinusoidal waveforms with no distortion due to the load's linearity. For the case of nonlinear loads and the circuits in Figures 3 and 4, the results are shown in Figures 6 and 7. It is worth noting that both models operate as full-signal rectifiers; therefore, due to their widespread use in industrial fields, they were chosen for this study and to demonstrate the feasibility of a single filter design applicable to both models. Figure 6 represents the time waves of the voltage (top) and current (bottom) in the reversed state of a single-phase transformer with an RL load.

The voltage waveform is almost sinusoidal, with pronounced distortions due to the imperfect nature of the reversed state, while the current waveform is more distorted, with sharp peaks. This is due to the inductive component in the load, which shifts the current phase relative to the voltage, along with the appearance of high-frequency harmonic components. This phenomenon affects power quality, increasing total harmonic distortion (THD), and necessitates the use of appropriate filters to improve the waveform and minimize negative effects on system efficiency.

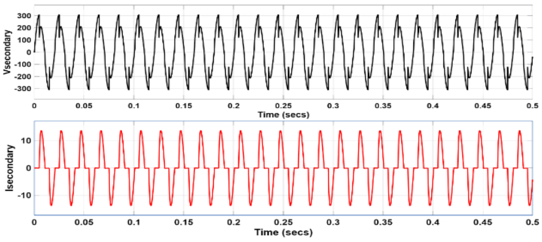


Fig 6: voltage and current for Back-to-back with RL load

The results shown in Figure 6 for the back-to-back configuration indicate that both voltage and current are distorted. The results for the H-bridge configuration are shown in Figure 7.

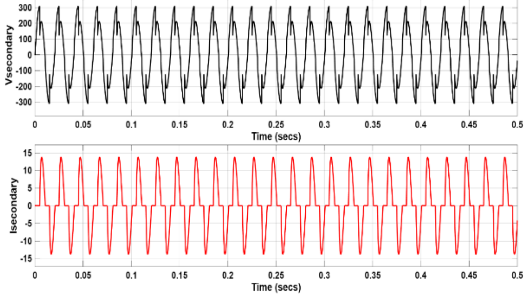
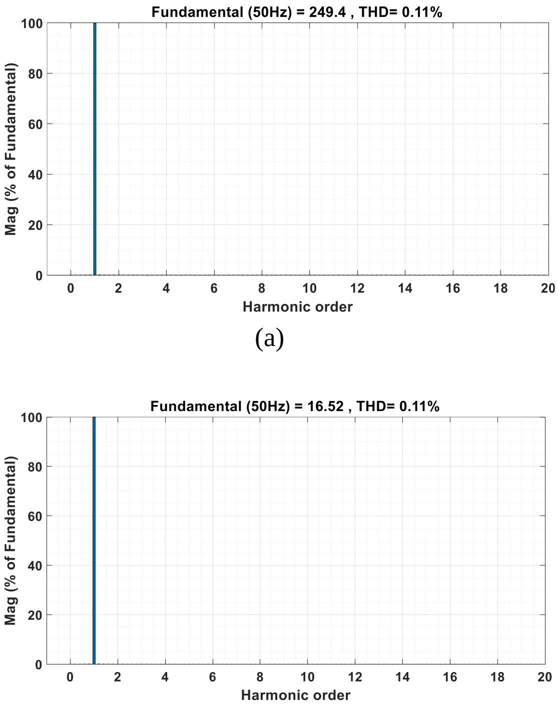


Fig 7: voltage and current for a fully controlled H-bridge rectifier with RL load

It can be notice from the results shown in Figures 5,6 and 7 that the shape of the voltage and current in the case of RL loads is sinusoidal while in the case of nonlinear loads are distorted and by applying Fast Fourier transformation on both voltage and current to evaluate the total harmonic distortion the result of FFT analysis in first case (linear load) is presented in Figure 8. A Fourier Transform (FFT) analysis of the voltage harmonics reveals the fundamental component at 50 Hz, approximately 249,4 V. The total harmonic distortion (THD) is only 0.11%, a low value indicating that the voltage waveform is very close to sinusoidal filtering. We note that the harmonic values for higher orders (2, 3, 4, …) decrease significantly, indicating the system's effectiveness in reducing non-wireless harmonics, thereby improving power quality beyond its preferred range.



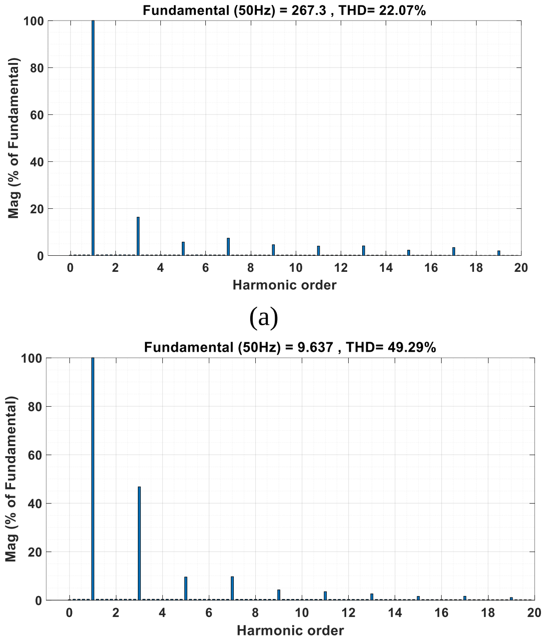
(a)

(b)

Fig 8: Total Harmonic distortion (a) voltage (b) current for RL load

The figure represents the harmonic analysis of the current in an RL-type load using a fast Fourier transform (FFT). The fundamental component at 50 Hz is approximately 16.52 A, with a relatively low total harmonic distortion (THD) of 0.11%. It is evident that the higher-order harmonic components gradually decrease with increasing harmonic order, indicating that the current maintains a close sine wave shape with limited distortion. This result reflects good system performance and the effectiveness of the filters used to reduce harmonics, which contribute to improved operating efficiency and reduced negative impacts on associated electrical equipment. It's clear from Figures (8a, 8b) that the FFT analysis of both voltage and current shows acceptable total harmonic distortion values according to the standards (less than 5%).

On the other hand, the FFT analysis for the first nonlinear load configuration (back-to-back) is shown in Figure 9. Figure (a) shows a fast Fourier transform (FFT) analysis of the voltage in the series configuration with an RL load. The fundamental component of the voltage at 50 Hz is 267.3 V, with pronounced odd-harmonic components, such as the 3rd, 5th, and 7th. These harmonics are caused by the load's nonlinearity, distorting the voltage waveform from a perfect sinusoid. The total harmonic distortion (THD) value was approximately 22.07%, which is moderate, indicating that the voltage is still relatively close to a sinusoidal shape but with noticeable distortions that could affect power quality if they increase.

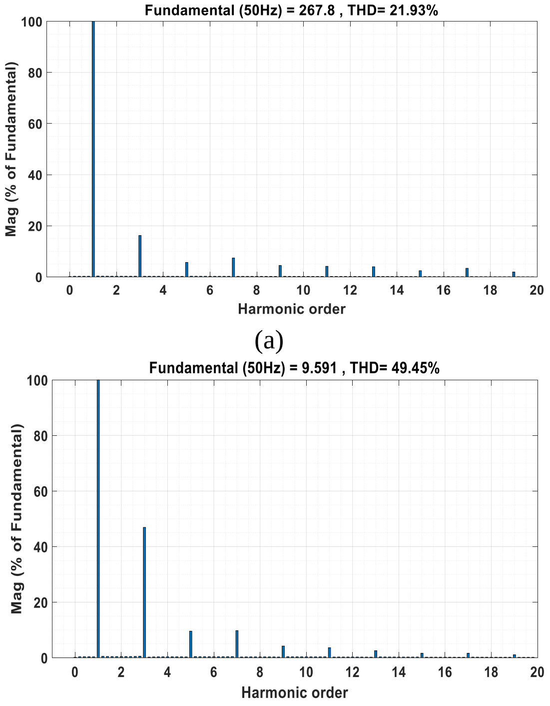


(a)

(b)

Fig 9: Total Harmonic distortion (a) voltage (b) current for back-to-back with RL load

Figure (b) shows a fast Fourier transform (FFT) analysis of the current in the same configuration. The fundamental component of the current at 50 Hz is 9.637 A, but the harmonic components, particularly the third and fifth, reach high levels relative to the fundamental, with some peaks approaching half their value. This indicates that the current is more affected by the load's nonlinear nature, as nonlinear loads draw a pulsed current with a high proportion of harmonics. The total harmonic distortion (THD) was approximately 49.29%, which is very high and indicates that the current is far from sinusoidal, potentially leading to increased conductor and equipment losses, higher temperatures, and reduced system efficiency. Figures (9a, 9b) show unacceptable THD values due to higher distortion in the waveforms. The second nonlinear load (H-bridge) FFT analysis is shown in Figure 10. The figure shows a fast Fourier transform (FFT) analysis of the voltage at the fundamental frequency of 50 Hz with a value of 267.8 V. Prominent individual harmonic components, such as the 3rd, 5th, and 7th, are present, as well as higher harmonics up to the 19th order, but to a lesser extent. The total harmonic distortion (THD) value is approximately 21.93%, indicating moderate distortion of the voltage waveform compared to a perfect sine wave. This distortion is caused by the nonlinear load effect, which generates non-sinusoidal currents that affect the voltage through the system impedance. This distortion can lead to reduced power quality, increased equipment losses, and potentially interference with sensitive equipment if left unaddressed.



(a)

(b)

Fig 10: Total Harmonic distortion (a) voltage (b) current for a full-controlled H-bridge rectifier with RL load

The figure shows the harmonic spectrum of an electrical signal, with the relative amplitudes of the various harmonics expressed as a percentage of the fundamental component at 50 Hz. The fundamental component has a value of approximately 9.591, while strong second- and third-order harmonic components are approximately 50% of the fundamental, indicating significant signal distortion. The total harmonic distortion (THD) is 49.45%, a high level that means a significant deviation from the ideal sinusoidal waveform and can negatively affect the efficiency of electrical systems and associated devices.

Figure (10a,10b) shows higher distortion in the wave forms with unacceptable values for THD. In the case of RL load and as clearly shown in figure 5 the Total harmonic distortion is within the limits which is less than 5%, unlike in the cases nonlinear loads presented in Figures 6 and 7 the value of THD is 22.07% and 49.3% in back-to-back and 21.93% and 49.45% in H-bridge configuration which is in both cases are too high from the standard values, simulation Results for Non-Linear Load After Adding a Filter. To reduce THD in cases of nonlinear loads, a hybrid passive filter (double-tuned filter + C-type) is used. For this purpose, the total reactive power in the circuit and the harmonic orders are needed. Referring to the circuits shown in Figures 3 and 4, the variations in reactive power and THD with changes in triggering angle are shown in Tables 3 and 4, respectively.

Table 3. firing angle effect on back-to-back circuit

Firing angle (alpha)	Q(VAR)	THDv	THDi
0	239	1.29	2.25
30	472	10.37	8.05
60	993.9	19.81	26.63
90	1183	22.07	49.3

Table 4. firing angle effect on full controlled H-bridge rectifier

Firing angle (alpha)	Q(VAR)	THDv	THDi
0	224.1	2.24	2.29
30	459.4	10.16	7.9
60	991.3	19.74	26.81
90	1179	21.93	49.45

By choosing the worst case at alpha=90, the total reactive power Q=1183 for both configurations and using the equations (10-13) with QFL=75 and QFH=2, and the dominant harmonics are the odd harmonics as shown in Figures 6 and 7, the elements of the proposed hybrid passive filters are as shown in Table 5.

Table 5. DTPF with HTC-type parameters

Harmonic order	Type of filter	C1(μF)	C2(μF)	L1 (mH)	L2 (mH)
3&5	Double	155.6	702.65	3.8	1.1

7&9	Tuned Filter	155.6	2500	1	0.064614
Harmonic order	Type of Filter	C1(μF	C2(μF)	L(mH)	R (ohm)
11-∞	High Tuned C-Type	77.82	0.1945	1.1	7.4387

After matching the calculated filter parameters and the duo based on the dominant harmonics and reactive power, this suggests using the same parameters for both back-to-back and H-bridge configurations, as shown in Figures 11 and 12.

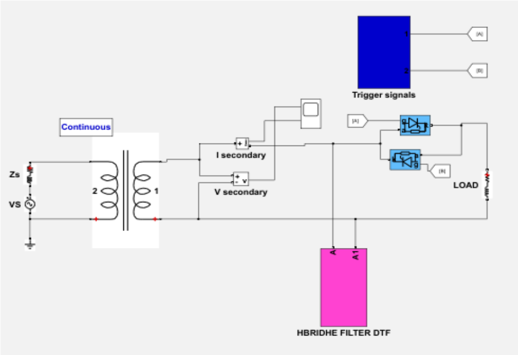


Fig 11: back-to-back controlled Thyristor with filter

Figure 11 presents the complete circuit of a back-to-back configuration with a tuned filter designed. While Figure 12 relates to the h-bridge configuration.

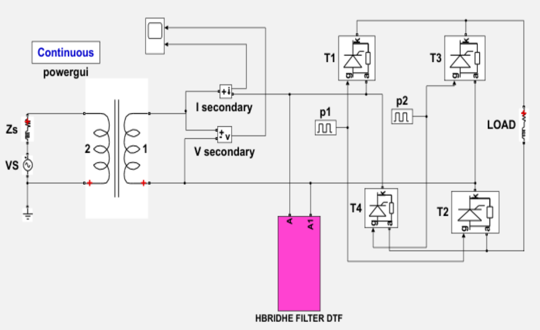


Fig 12. fully controlled H-bridge rectifier with filter

The final results, showing the voltage and current after the proposed hybrid passive filter is connected, are shown in Figures 13 and 14.

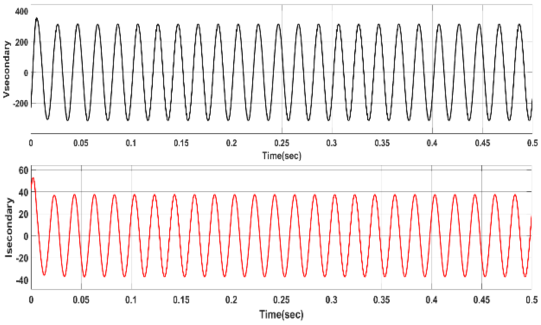


Fig 13. voltage and current for Back-to-back with filter

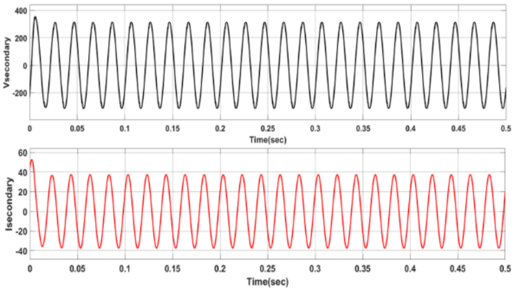


Fig 14. voltage and current for the H-bridge with filter

The THD Variations for the voltage and current in both circuits are summarized in Tables 6 and 7. Table 6 shows how the firing angle alpha affects the Total Harmonic Distortion (THD) for voltage (THD v) and current (THD i) in a back-to-back circuit. Low harmonic distortion is indicated by the THD v and THD i being negligible at alpha = 0. But both THD v and THD i gradually increase as the firing angle rises, with THD v increasing most noticeably. Significant harmonic distortion in the circuit is indicated by the THDv peaking at 0.98 and the THDi rising to 0.26 at alpha = 90. This pattern demonstrates how sensitive harmonic distortion is to changes in firing angle in these circuits.

Table 6. THD variation on back-to-back circuit

Firing angle (alpha)	THDv	THDi
0	0.12	0.09
30	0.11	0.08
60	0.52	0.13
90	0.98	0.26

Table 7. THD variation on H-bridge circuit

Firing angle (alpha)	THDv	THDi
0	0.51	0.5
30	0.54	0.1
60	0.51	0.16
90	0.96	0.26

The relationship between firing angle (alpha) and total harmonic distortion (THD) in a back-to-back circuit is shown in the table. Both the voltage (THDv) and current (THDi) harmonics noticeably rise with increasing firing angle. This pattern implies that greater firing angles lead to greater harmonic distortion, which may affect system efficiency and power quality. These harmonic effects must be carefully accounted for, particularly when working at higher firing angles.

In practice, applying the results to single-phase transformers is not complicated or expensive, unlike three-phase transformers. However, the main obstacle in this research was the unavailability of a single-phase transformer with the required specifications. A practical connection was implemented using an H-bridge circuit for a single-phase rectifier with a variable RL load, within the capabilities available in the laboratory, as shown in Fig. 15. In addition, back-to-back control has been examined.

Actual measurements revealed total harmonic distortion (THD) in both the current and voltage waves, confirming the validity of the theoretical results.

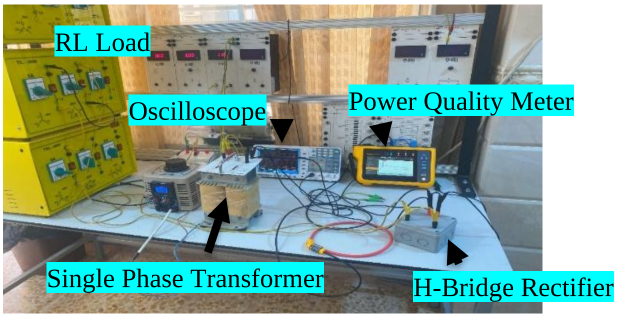


Fig 15. The experimental setup in the lab

Figure 16 shows a sine waveform captured using an oscilloscope. It represents an AC voltage or current signal with a frequency of approximately 50 Hz and a period of 20 ms, which corresponds to the standard electrical network frequency. The maximum signal value is approximately ±60.4 V, indicating a true RMS value of approximately 42.7 V. The waveform is regular and smooth, with no obvious distortions or deviations, indicating high signal quality and no harmonic components or nonlinear load-induced distortions. These results confirm that the electrical system or circuit being measured is operating in a steady state and that the voltage or current source provides a balanced, symmetrical output about the zero axis.

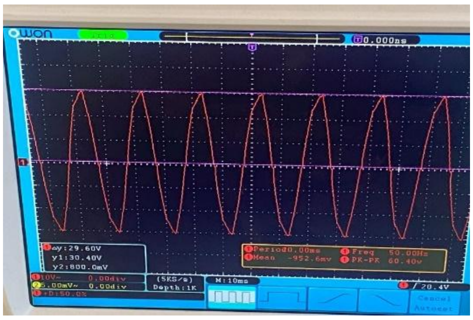


Fig 16. The Voltage waveform

While Fig. 17 shows the harmonic analysis of a current signal measured with a PQ Meter. The horizontal axis shows the harmonic orders (3rd, 5th, 7th, etc.), while the vertical axis shows the percentage of each harmonic relative to the fundamental component. The total harmonic distortion (THD) is 26.5%, a high value indicating the presence of significant harmonic components in the signal, particularly the 3rd and 5th harmonics, which represent the highest values after the fundamental component. This result indicates that the connected load is nonlinear (such as electronic loads or rectifiers), distorting the fundamental sine waveform and increasing losses and electromagnetic interference in the electrical system. This situation requires the application of filtering or compensation techniques to improve the quality of the electrical power.

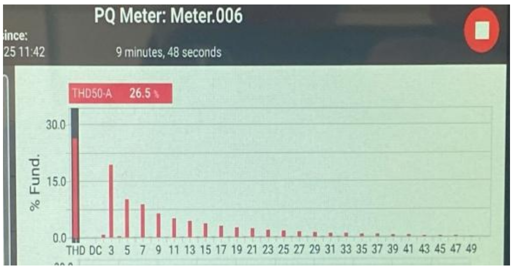


Fig 17. The THD for the current

Fig. 18 shows the harmonic analysis of the voltage using a power quality meter (PQ meter). The horizontal axis shows the harmonic orders (3rd, 5th, 7th, …), while the vertical axis represents the corresponding voltage values for each harmonic component in volts. The reading indicates a total harmonic component (THC) of approximately 9.743 volts, suggesting some distortion in the sine-wave voltage. It is noted that low-order harmonics, such as the 3rd, 5th, and 7th, are the most prominent components, indicating that the distortion originates from nonlinear loads, such as saturated transformers, rectifiers, or power electronic devices. The presence of these harmonics leads to poor voltage quality and increased losses in electrical components, necessitating the use of harmonic filters or compensation techniques to improve the stability and performance of the electrical system.

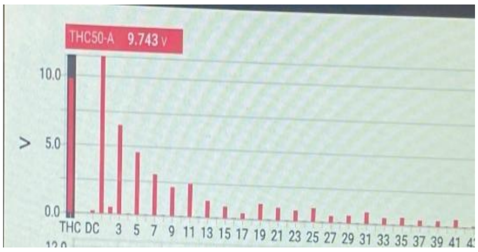


Fig 18. The THD for the Voltage

Figure 19 represents a reading of an electrical signal displayed on a UNI-T UTD2072CL oscilloscope. It shows a nearly sine wave with a peak value of approximately ±24.4 volts and a cycle time of approximately 200 microseconds, corresponding to a frequency of approximately 5 kHz. These measurements are used academically to analyze electrical signals, whether they are generated by an alternating current (AC) source or the output of an electronic circuit (such as an inverter or power converter). This image illustrates the importance of studying the waveform, frequency, and amplitude to evaluate the performance of the electrical or electronic system under test. A regular sine wave is an indicator of stable operation and low harmonic distortions, while any deviation from the sine wave indicates the presence of distortions or disturbances in the circuit.

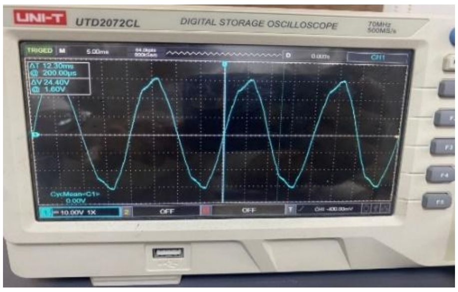


Fig 19. The THD for the Voltage

Figure 20 shows an electrical signal measured by an oscilloscope. It represents a non-sinusoidal, quasi-square, or distorted waveform with an amplitude of approximately ±400 mV and a frequency of approximately 5 kHz (a cycle time of approximately 200 microseconds). From an academic perspective in electrical engineering, this signal is a practical example of harmonic distortion caused by the presence of nonlinear components in a circuit, such as power electronic switches, diodes, or rectifier circuits. This image is important in analyzing signal quality and the system's ability to maintain the desired waveform. Examining it helps evaluate the performance of filters, modulation techniques, and inverter or converter control, making it an essential tool in diagnosing and optimizing modern electrical and electronic systems.

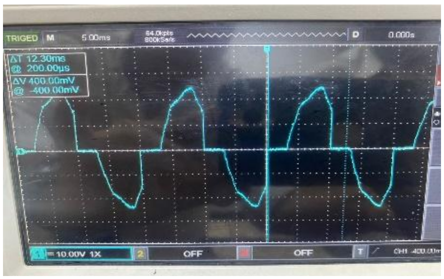


Fig 20. The THD for the Voltage

Fig. 21 shows the current harmonic spectrum for phase A analyzed using a power quality analyzer. The fundamental value is 57.2 mA, with pronounced third-, fifth-, ninth-, and other harmonic components gradually decreasing in amplitude. This image is of great academic importance in electrical engineering because it represents the frequency analysis of the electrical signal, which serves as the basis for evaluating power quality. It helps determine the extent to which non-linear loads, such as inverters and electronically controlled motors, affect the electrical system. Understanding these harmonics is essential for reducing total current distortion (THD), improving power transmission efficiency, and protecting sensitive equipment from thermal surges or electromagnetic vibrations caused by high harmonics.

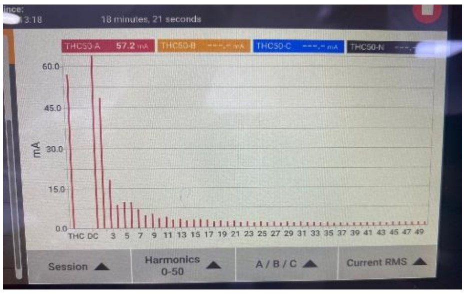


Fig.21. The THD for the current

7. CONCLUSION

This study shows that, by successfully reducing harmonic distortion and enhancing power quality, the addition of a pass-tune filter greatly improves the performance of single-phase transformers across a range of load conditions. Verified by MATLAB simulations, the results show significant reductions in total harmonic distortion (THD) under both linear and nonlinear load conditions. The THD at firing angle =90, which is considered the worst case, is reduced from 22.07 % for voltage and 49.3% for current in back-to-back configuration to 0.98% and 0.26%, respectively, and from 21.93% for voltage and 49.45% for current in H-bridge configuration to 0.96% and 0.26 %. In addition to reducing transformer losses and thermal stress, the pass-tune filter ensures stable, dependable performance even under extreme conditions. These results highlight the pass-tune filter as an affordable and useful technique for addressing reactive power and harmonic distortion issues in contemporary power systems, opening the door to its wider use in residential, commercial, and industrial electrical networks.

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