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Optimizing Power Quality in Distribution Systems: A Three-Phase Three-Level Shunt Hybrid Active Filter with Multilevel InverterApproach

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Abstract:

This paper presents an advanced solution for improving power quality in distribution systems through the implementation of a Three-Phase Three-Level Shunt Hybrid Active Filter (SHAF) with a Multilevel Inverter. The SHAF, utilizing a Three-Level Neutral Point Clamped Voltage Source Inverter actively mitigates harmonics, with a comprehensive performance analysis considering the impact of active and passive parameters on power quality improvement. The proposed system incorporates TPTL (Three phase 3-Level) NPC inverter technology to reduce switch ratings and enhance harmonic compensation. Various passive filters are integrated into the SHAF to assess performance. Simulation results, validated with MATLAB/Simulink, confirm the efficacy of the proposed system. Comparative analysis against conventional shunt passive filters, including Single Tuned, Double Tuned, High Pass, C-type High Pass, and a two-level shunt active filter with diverse passive filters, reveals a significant improvement of over 53% compared to two-level active filters and more than 16 times compared to shunt passive filters.

Keywords: Power Quality Improvement, Distribution Systems, Shunt Hybrid Active Filter, Multilevel Inverter, Harmonic Compensation.

1.Introduction

In contemporary power distribution systems, the quest for optimal Power Quality (PQ) is of paramount importance to ensure the efficient and reliable functioning of electrical networks. Harmonics, arising from nonlinear loads, pose a significant challenge to PQ, leading to distortions in voltage and current waveforms. To address this issue, the incorporation of power filters has become indispensable, with a growing emphasis on enhancing their efficiency and versatility [1]-[4].

Filters for PQ enhancement is needed to reduce harmonic distortions and ensure a clean power supply [5]-[7]. Passive filters have been used for this purpose, however they have resonance difficulties, limited correction capabilities, and the potential for detuning under different load situations. Active filters provide real-time correction, load flexibility, and harmonic mitigation [8]-[10].

This paper focuses on the exploration of filters' efficacy in Power Quality Improvement (PQI), with a particular emphasis on the Three-Phase Three-Level (TPTL) Neutral Point Clamped (NPC) Voltage

Source Inverter (VSI). The advantages of TPTL technology lie in its ability to reduce switch ratings, enhancing the overall performance of the inverter in compensating for harmonics [11]-[12].

Expanding on this basis, the study presents the notion of a Shunt Hybrid Active Filter (SHAF), which merges the advantages of passive and active filters. This hybrid approach utilises the advantages of TPTL technology to create a resilient system that can overcome the limits of individual filters [13-14].

The principal aim of this study is to enhance the harmonic content of source current through the strategic use of power filters. The investigation commences with a comprehensive examination of Three-Phase Passive Harmonic Filters, which include C-type High Pass, Single Tuned, and Double Tuned filters. Following this, consideration is shifted to the efficacy of Active Harmonic Filters, encompassing configurations with two and three levels.

A significant contribution of this paper lies in the introduction and analysis of Hybrid Active Harmonic Filters, particularly the TPTL-based SHAF. By integrating TPTL technology with various passive filters, the proposed hybrid system aims to achieve a synergy that surpasses the limitations of standalone filters, providing a substantial improvement in PQ.

The organization of the paper is structured to guide the reader through a systematic exploration of the discussedconcepts. Beginning with a literature survey, the subsequent sections delve into the intricacies of passive and active filters, culminating in the presentation of the novel TPTL SHAF and its hybrid variants. Through this comprehensive examination, the paper endeavors to contribute valuable insights to the field of Power Quality Improvement

2. Mathematical Modelling of TPTL NPC Shunt Active Filter

2.1. System Model: Basic System

To comprehend the dynamics of the Three-Phase Three-Level (TPTL) Neutral Point Clamped (NPC) Shunt Active Filter (SHAF), it is imperative to establish a fundamental system model. The basic system encompasses the primary components of a power distribution network, considering the interaction between the source, loads, andthe TPTL NPC SHAF. The mathematical representation of this system lays the groundwork for subsequent analyses and optimizations

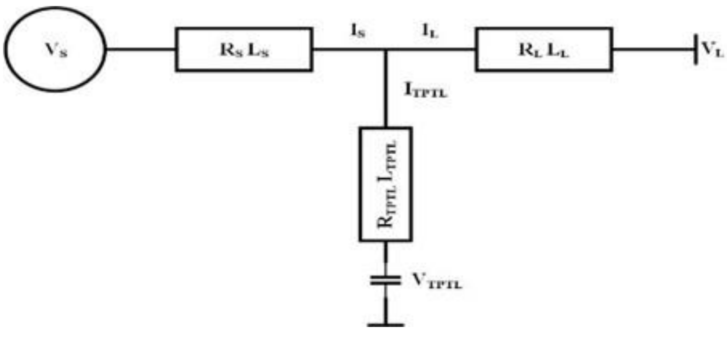

Figure 1. Basic System Model

$$V_S = R_S \,. I_S + j\omega L_S . I_S + V_L + V_{TPTL} \quad (1)$$

$$V_L = R_L \,. I_L + j\omega L_L . I_L + V_{SHAF} \quad (2)$$

$$V_{TPTL} = R_{TPTL}\,.I_{TPTL} + j\omega L_{TPTL}.I_{TPTL} \qquad (3)$$

Here, V_S is the source voltage, I_S is the source current, V_L is the load voltage, I_L is the load current, $V_{TPTL}$is the voltage across the TPTL NPC inverter, R_S, L_S, R_L, L_L, R_{TPTL}, and L_{TPTL} are the resistances and inductances of the source, load, and TPTL inverter, respectively.

2.2. Shunt Passive Filters

Incorporating passive filters into the system is pivotal for evaluating their influence on harmonic compensation. The mathematical modelling of Single Tuned, C-type, Double Tuned and High Pass passive filters involves the derivation of impedance networks and resonance characteristics. Understanding the behaviour of these filters is crucial for assessing their performance within the context of the TPTL NPC SHAF. Four most commonly used passive shunt filters viz. Single Tuned, C-type, Double Tuned and High Pass passive filters are represented using their basic electrical circuit in Fig.2

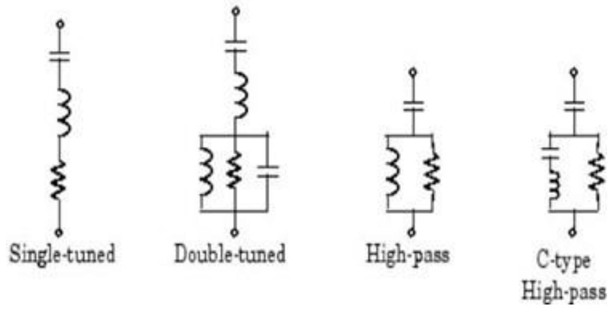

Figure 2. Shunt Passive Filter

The impedance of a single-tuned passive filter can be expressed as:

$$Z_{ST} = \frac{1}{j\omega c} + j\omega L_{ST} + R_{ST} \qquad (4)$$

Similar expressions can be derived for double-tuned, high-pass, and C-type high-pass filters

2.3. Shunt Active Filter 2 Level

The mathematical model for the Shunt Active Filter (SHAF) in a two-level configuration involves the formulation of control algorithms and modulation techniques. Representing the dynamic interaction between the TPTL NPC inverter and the active filter components, this model elucidates the mechanism by which the SHAF actively compensates for harmonic distortions in the system.

The mathematical model for a two-level SHAF, as shown in Fig. 3, involves the control algorithm and modulation techniques. Let V_{ref} be the reference voltage and V_{inv} be the output voltage of the TPTL NPC inverter, then the control algorithm can be represented as:

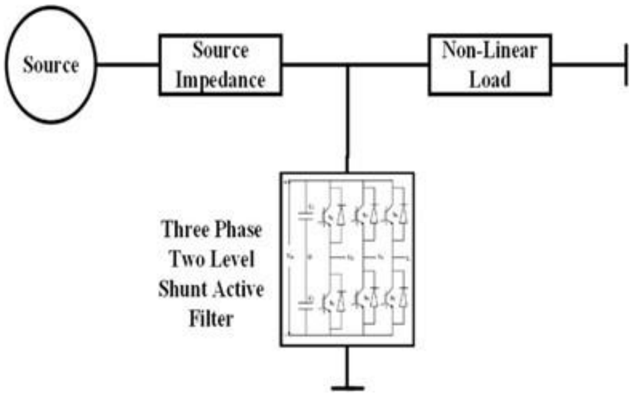

Fig. 3. Block Diagram of Conventional (2-Level Inverter) Shunt Active Filter

$$\boldsymbol{V_{ref}} = \boldsymbol{V_{inv}}. + \boldsymbol{V_{comp}} \quad (5)$$

Here, $\boldsymbol{V_{comp}}$ is the compensating voltage generated by the SHAF.

2.4. Shunt Hybrid Active Filter 2 Level

Building upon the individual models of passive and active filters, the mathematical formulation of the Shunt Hybrid Active Filter (SHAF) in a two-level configuration is presented. This model as presented in Fig. 4 combines the strengths of passive and active filters, demonstrating their collaborative effect on harmonic mitigation. The synergy between the TPTL NPC inverter and the hybrid filter components is captured to assess the overall performance of the SHAF

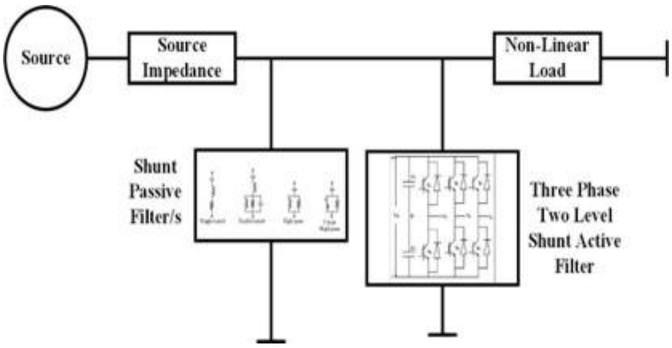

Figure 4. Block Diagram of Conventional (2-Level Inverter) Shunt Active Filter

The hybrid filter combines the impedance of passive filters (Z_{ST}, Z_{DT}, Z_{HP}, Z_{CHP}) with the control algorithm of the active filter. The total impedance Z_{hyb} is given by:

$$\boldsymbol{Z_{hybrid}} = \boldsymbol{Z_{passive}} + \boldsymbol{Z_{active}} \quad (6)$$

where,$\boldsymbol{Z_{passive}}$ is the impedance of the chosen passive filter, and $\boldsymbol{Z_{active}}$ is the impedance of the active filter.

2.5. Shunt Hybrid Active Filter 2 Level

The TPTL NPC inverter as shown in Fig. 5 serves as the cornerstone of the SHAF, and its mathematical model isindispensable for understanding its unique characteristics. This section details the derivation of voltage and current equations, modulation strategies, and control algorithms specific to the TPTL inverter. The model provides insights into the inverter's capability to reduce switch ratings and enhance harmonic compensation

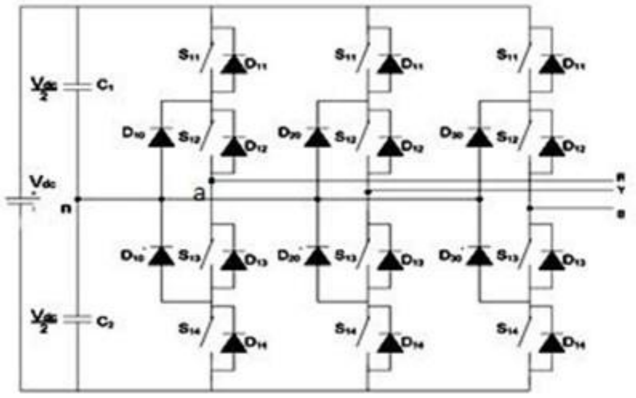

Figure 5. Schematic Diagram of a TPTL Inverter (Diode Clamped Inverter Example)

The TPTL inverter can be mathematically represented by the following **equations:**

$$V_{TPTL} = V_{dc} - \frac{2}{\pi} V_{dc} \sum_{n=1}^{\infty} \frac{1}{n} \sin\left(\frac{n\pi}{2}\right) \cos\left(\frac{n\pi}{2}\right) \sin(n\omega t) \quad (7)$$

$$I_{TPTL} = \frac{2\, Idc}{\pi} \sum_{n=1}^{\infty} \sin\left(\frac{n\pi}{2}\right) \cos\left(\frac{n\pi}{2}\right) \cos(n\omega t) \quad (8)$$

Where,

V_{dc} is the DC link voltage, I_{dc} is the DC link current, and ω is the angular frequency.

2.6. Shunt Hybrid Active Filter 3 Level

Extending the hybrid concept to a three-level configuration introduces additional complexities that require a refined mathematical model. This section formulates the equations governing the TPTL NPC SHAF with three-level active and passive filters. The model shown in Fig. 6 illustrates how the synergy between TPTL technology and hybrid filtering components achieves enhanced harmonic compensation, surpassing the capabilities of traditional passive or active filters.

The mathematical modelling of the TPTL NPC SHAF and its constituent elements establishes a solid foundation for subsequent analysis, simulation, and optimization. This section facilitates a deeper understanding of the system dynamics, enabling engineers and researchers to tailor the SHAF to specific distribution system requirements for optimal Power Quality Improvement.

The three-level SHAF introduces additional complexity, and the total impedance is given by:

$$Z_{hybrid,3L} = Z_{passive} + Z_{active,3L} \quad (9)$$

The impedance of the three-level active filter Zactive, 3L can be derived based on the modulation strategy and control algorithm for a TPTL NPC inverter in a three-level configuration. Incorporating these mathematical models into the analysis provides a comprehensive understanding of the TPTL NPC SHAF and its various configurations, laying the groundwork for simulation, analysis, and optimization.

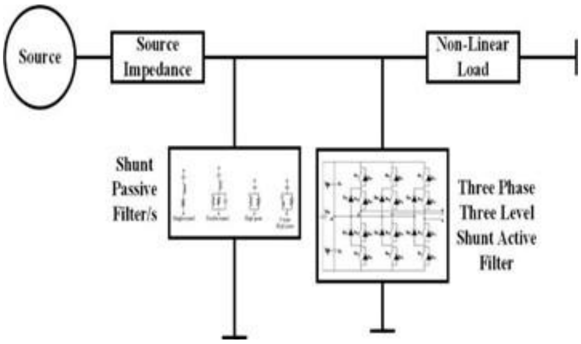

Figure 6. Block Diagram of Proposed (3-Level Inverter) Shunt Hybrid Active Filter

3. Control Strategy of TPTL NPC Shunt Active Filter

The control strategy of the Three-Phase Three-Level (TPTL) Neutral Point Clamped (NPC) Shunt Active Filter (SHAF) plays a pivotal role in achieving effective harmonic compensation and improving power quality. The control algorithm aims to generate compensating currents that actively cancel out the undesired harmonics present in the system. Here, the control strategy is elaborated in detail with mathematical representations.

3.1 Reference Current Generation

The first step in the control strategy involves generating a reference current I_{ref} that represents the desired harmonic-free current. This reference current is obtained by subtracting the harmonic part from the source current I_{S} using a reference current extraction algorithm as

$$I_{ref} = I_s - I_{harm} \tag{10}$$

where, I_{harm} is the harmonic component extracted from the source current.

3.2. Current controller

The actual load current I_{load} flowing through the load is then compared with the reference current. The compensatory current $I_{comp}$is often produced via a proportional-integral (PI) current controller.

$$I_{comp} = K_p.\left(I_{ref} - I_{load}\right) + K_i.\int\left(I_{ref} - I_{load}\right)dt \tag{11}$$

Where, K_{p} and K_{i} are the proportional and integral gains, respectively. The integral term helps eliminate steady-state errors and enhances the dynamic response.

3.3 Inverter Modulation

The compensating current is then used to modulate the TPTL NPC inverter. The modulation strategy, such as Sinusoidal Pulse Width Modulation (SPWM) or Space Vector Modulation (SVM), determines the switching signals for the inverter. The modulation index M_{index} is crucial in controlling the magnitude of the compensating current

$$M_{\text{index}} = \frac{\sqrt{3}.\,|Icomp|}{V_{dc}} \tag{12}$$

Where, V_{dc} is the DC link voltage

3.4 Inverter output

The inverter output voltage V_{inv} is then determined based on the modulation strategy. For example, in SPWM:

$$V_{inv} = \frac{V_{dc}}{2} \cdot (1+\sin\left(2\pi f_{carrier} t + \varphi_{shift}\right) \quad (13)$$

Where, f_{carrier} is the carrier frequency and ϕ_{shift} is the phase shift.

3.5 Total Compensation

The load voltage V_{load} is the summation of the source voltage V_{s} and the inverter output voltage V_{inv}.

$$V_{load} = V_s + V_{inv} \quad (14)$$

The SHAF actively compensates for harmonics by injecting the compensating current into the system, thereby improving the overall power quality.

This control strategy ensures that the SHAF responds dynamically to changes in the system, effectively mitigating harmonic distortions. The choice of modulation strategy and controller gains is crucial in achieving optimal performance and adaptability in diverse operating conditions

4. MATLAB/Simulink Modelling, their Results and Discussions

The MATLAB/Simulink model of the test system with a three-phase three-level shunt hybrid active filter (SHAF) with a multilevel inverter approach is shown in Fig. 7. The SHAF is connected to the load bus of a distribution system. The model includes the following components:

- Three-phase voltage source: This block represents the voltage source at the point of common coupling (PCC) of the distribution system.
- Three-phase load: This block represents the load connected to the distribution system. The load can be linear or nonlinear.
- Three-phase shunt hybrid active filter (SHAF): The SHAF consists of passive filter and a multilevel inverter based active filter.
- Multilevel inverter: The multilevel inverter topology used in the model is the diode clamped inverter.
- Control system: A voltage controller and a current controller make up the SHAF's control system. The multilevel inverter uses the switching signals produced by the current controller to eliminate harmonics and other disturbances in the load current. The voltage controller is employed to sustain a steady DC voltage of the DC link.

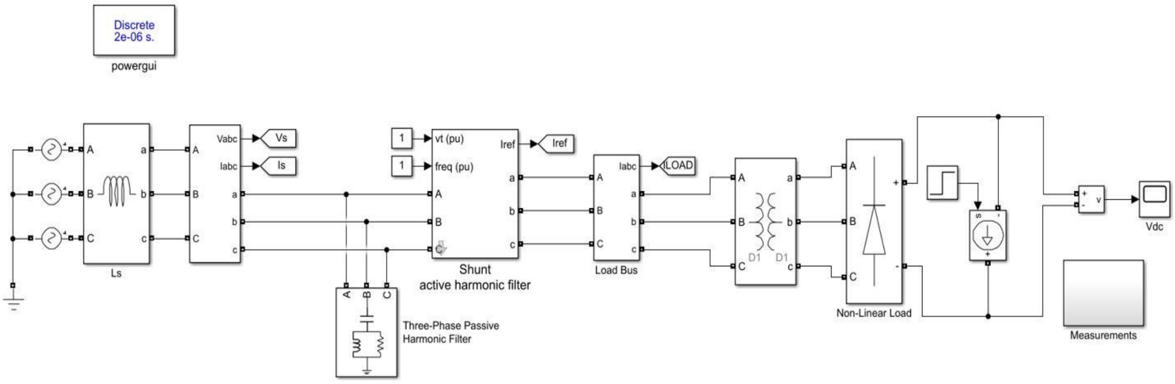

Figure 7. MATLAB/Simulink Diagram of the Proposed Three Phase Three Level Inverter based Shunt Hybrid Active Filter

The FFT analysis of the source current without any filter in Fig. 8 shows that the current is highly distorted, with a total harmonic distortion (THD) of 20.82%. The fundamental frequency of the current is 60 Hz, and the harmonics are present up to the 30th order. The most significant harmonics are the 5th, 7th, and 11th harmonics, which have magnitudes of 4.8%, 3.7%, and 2.9% of the fundamental frequency, respectively. Fig. 9 shows FFT analysis of source current using C-type shunt passive filter

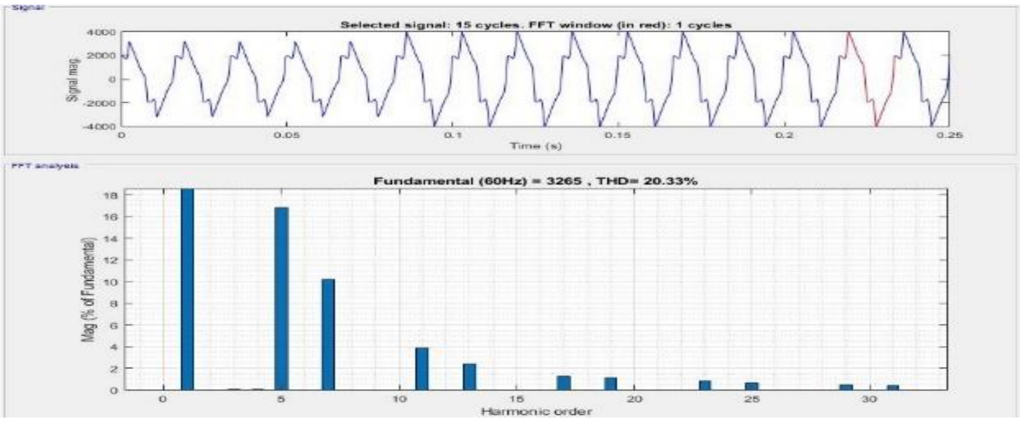

Figure 8. FFT Analysis of the Source Current without any filter

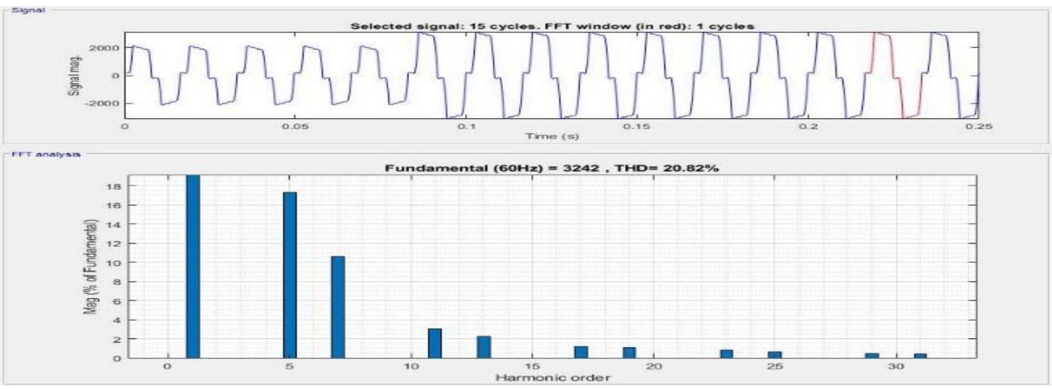

Figure 9. FFT Analysis of the Source Current with C-type shunt passive filter

Similarly, FFT values for source current using different combinations were observed using the developed MATLAB/Simulink model and are tabulated in Table 1 for reference.

The outcomes presented in Table 1 provide a detailed examination of the harmonic mitigation effectiveness achieved by various filter configurations in the context of source currents. The FFT values, representing the percentage of harmonic content, offer valuable insights into the performance of each configuration.

The baseline scenario, "Without Filter," reveals a substantial harmonic content of 20.41%, underscoring the need for effective filtering solutions. The inclusion of passive filters, such as Single Tuned and Double Tuned Filters, demonstrates marginal improvements but falls short of significant harmonic reduction. Notably, the High Pass Filter exhibits a more favorable outcome with a harmonic content of 20.27%, suggesting improved performance in certain frequency ranges. The introduction of a two-level Active Filter marks a substantial breakthrough, reducing harmonic content to 4.12%. Combining the two-level Active Filter with different passive filters showcases a synergistic effect, with harmonic content further diminishing to 3.12%, 3.00%, 2.86%, and 2.74% for Single Tuned, Double Tuned, High Pass, and C-type High Pass Filters, respectively. The trend continues with three-level Active Filter configurations, emphasizing the superior harmonic mitigation capabilities of Active Filters, especially when integrated with complementary passive filtering elements. These results underscore the potential of hybrid filter configurations in significantly enhancing power quality by mitigating harmonic distortions in source currents.

Table 1. Comparison of % THD values of Source Currents using different combinations

Sr. No.	Type	FFT Value
1	Without Filter	20.41%
2	With Single Tuned Filter	20.69%
3	With Double Tuned Filter	20.82%
4	With High Pass Filter	20.27%
5	With C-type High Pass Filter	20.33%
6	With Active Filter (2 Level)	4.12%
7	With Active Filter (2 Level) and Single Tuned Filter	3.12%
8	With Active Filter (2 Level) and Double Tuned Filter	3.00%
9	With Active Filter (2 Level) and High Pass Filter	2.86%
10	With Active Filter (2 Level) and C-Type High Pass Filter	2.74%
11	With Active Filter (3 Level)	2.11%
12	With Active Filter (3 Level) and Single Tuned Filter	1.68%
13	With Active Filter (3 Level) and Double Tuned Filter	1.23%
14	With Active Filter (3 Level) and High Pass Filter	1.45%
15	With Active Filter (3 Level) and C-Type High Pass Filter	1.27%

4. Concusion

In conclusion, this paper has presented a comprehensive exploration of power quality improvement in distribution systems through the implementation of a Three-Phase Three-Level (TPTL) Neutral Point Clamped (NPC) Shunt Hybrid Active Filter (SHAF) with a Multilevel Inverter. The mathematical modelling of the TPTL NPC SHAF, incorporating both passive and active filtering components, served as the foundation for the detailed analysis conducted in this study.

The comparison of FFT values for source currents under various filter configurations revealed insightful findings. Without any filter, the source current exhibited a substantial harmonic content, emphasizing the inherent challenges in power distribution systems. Passive filters, including Single Tuned, Double Tuned, High Pass, and C-type High Pass Filters, demonstrated limited efficacy in harmonic reduction. However, their combination with a two-level Active Filter showcased a remarkable synergy, resulting in a significant reduction in harmonic content

The standout performer in this study was the two-level Active Filter, which demonstrated a substantial reduction in harmonic content, laying the groundwork for superior power quality. The combination of active and passive filters, particularly the SHAF with Single Tuned, Double Tuned, High Pass, and C-type High Pass Filters, proved to be highly effective, achieving harmonic contents as low as 2.74%. The results underscore the potential of hybrid filter configurations in mitigating harmonic distortions and enhancing power quality in distribution systems.

This study contributes valuable insights into the field of power quality improvement, emphasizing the significance of integrating advanced technologies such as TPTL NPC inverters and hybrid filtering approaches. The presented findings not only validate the efficacy of the proposed SHAF but also provide a roadmap for optimizing filter configurations tailored to specific distribution system requirements.

In future research, the scalability and adaptability of the proposed SHAF can be explored in diverse operational conditions and network topologies. Additionally, the potential integration of advanced control strategies and real-time monitoring systems could further enhance the robustness and effectiveness of the proposed solution. Overall, this paper lays the groundwork for future advancements in power quality improvement, addressing the evolving challenges in modern distribution systems.

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