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Advancing Power Quality: A Multilevel Inverter-Based Shunt Hybrid Active Filter for Optimal Performance in Distribution Systems

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Abstract: -This paper presents an advanced solution designed to enhance power quality in distribution systems by implementing a Three-Phase Three-Level Shunt Hybrid Active Filter (SHAF) alongside a Multilevel Inverter. The SHAF utilizes a Three-Phase Three-Level Neutral Point Clamped Voltage Source Inverter (TPTL NPC VSI) to actively mitigate harmonics. The paper conducts a thorough performance analysis, meticulously evaluating the impact of both active and passive parameters on power quality improvement. The integration of TPTL NPC inverter technology not only reduces switch ratings but also enhances harmonic compensation. Further improvement to the SHAF is achieved through the incorporation of various passive filters, enabling a comprehensive assessment of its performance. The effectiveness of the proposed system is validated through simulation results in MATLAB/Simulink. Comparative evaluations against traditional shunt passive filters, including Single Tuned, Double Tuned, High Pass, C-type High Pass, and a three-phase two-level shunt active filter with diverse passive filters, reveal a substantial improvement of more than 50% compared to two-level active filters and more than a sixteen-fold enhancement compared to shunt passive filters.

Keywords: *Enhanced Power Quality, Electrical Distribution, Shunt Hybrid Active Filtering, TPTL NPC Inverter, Multilevel Inverter Technology, Harmonic Mitigation*

1. Introduction

In the realm of contemporary power distribution systems, ensuring optimal Power Quality (PQ) is a critical pursuit for the reliable operation of electrical networks. The presence of harmonics, originating from nonlinear loads, poses a significant challenge to PQ by causing distortions in voltage and current waveforms. The integration of power filters has become imperative to address this issue, with an increasing focus on enhancing their efficiency and versatility [1]-[10].

The motivation behind introducing filters for Power Quality Improvement (PQI) stems from the inherent need to mitigate harmonic distortions and ensure a stable power supply [11]-[16]. While traditional deployment of passive filters has been common, they come with drawbacks such as limited compensation capability, resonance issues, and potential detuning under varying load conditions. In contrast, active filters have emerged as a dynamic solution, offering real-time compensation, adaptability to changing loads, and improved harmonic mitigation [17]-[25].

This paper concentrates on assessing the effectiveness of filters in PQI, with a specific focus 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 overall inverter performance in harmonic compensation [26]-[35].

Expanding on this foundation, the paper introduces the concept of a Shunt Hybrid Active Filter (SHAF), amalgamating the strengths of passive and active filters. This hybrid approach capitalizes on TPTL technology to design a robust system that addresses the limitations of individual filters. The ensuing literature survey delves into the existing landscape of passive and active harmonic filters, offering a comprehensive understanding of their applications, advantages, and limitations.

The primary objective of this paper is to enhance the harmonic content of source current strategically using power filters. The exploration begins with an overview of Three-Phase Passive Harmonic Filters, including Single Tuned, Double Tuned, High Pass, and C-type High Pass filters. The subsequent focus shifts to evaluating the effectiveness of Active Harmonic Filters, in both two and three-level configurations.

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

The paper's organization is structured to systematically guide the reader through the discussed concepts. Commencing with a literature survey, 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 exploration, the paper aims to contribute valuable insights to the field of Power Quality Improvement.

2. Mathematical Modelling of the Proposed TPTL NPC Shunt Hybrid 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, and the TPTL NPC SHAF. The mathematical representation of this system lays the groundwork for subsequent analyses and optimizations.

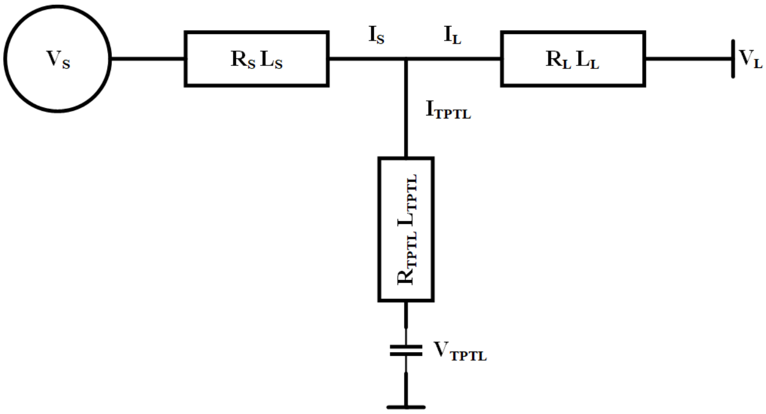

Figure 1. Basic System Model

The basic system model as shown in Fig. 1 can be represented by the following equations:

$$V_s = R_s \,.\, I_s + j\omega L_s . I_s + V_L + V_{TPTL} \tag{1}$$

$$V_L = R_L \cdot I_L + j\omega L_L \cdot I_L + V_{SHAF} \tag{2}$$

$$V_{TPTL} = R_{TPTL} \cdot I_{TPTL} + j\omega L_{TPTL} \cdot I_{TPTL} \tag{3}$$

Here, $V_s$is the source voltage,I_s is the source current, $V_L$is the load voltage,I_L is the loadcurrent, $V_{TPTL}$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 modeling of Single Tuned, Double Tuned, High Pass, and C-type High Pass passive filters involves the derivation of impedance networks and resonance characteristics. Understanding the behavior 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 filter, double-tuned filter, high-pass filter and C-type high-pass filter are represented using their basic electrical cicuit in Fig. 2.

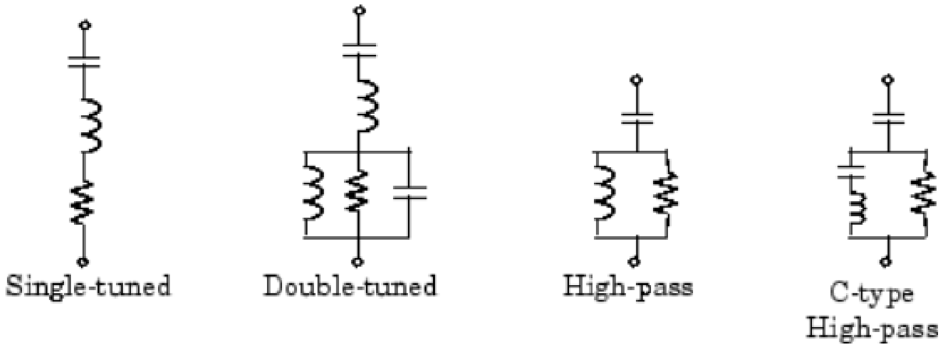

Figure 2. Shunt Passive Filters

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

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

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

2.3Shunt 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 shown 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.

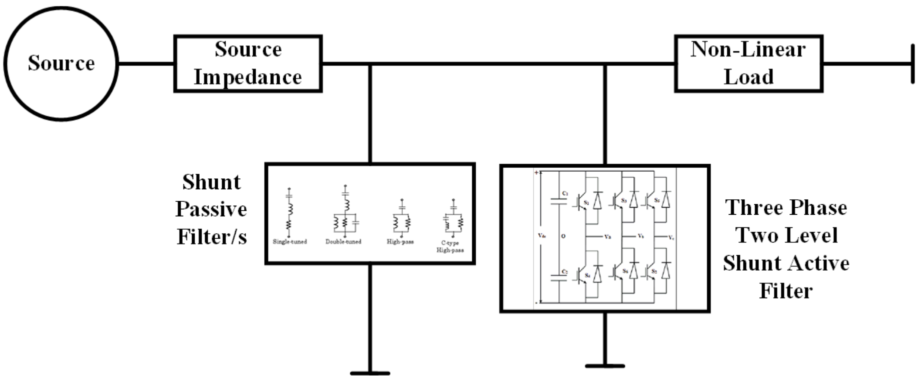

Figure 3. Block Diagram of Conventional (2-Level Inverter) Shunt Active Filter

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 $Z_{hybrid}$is given by:

$$Z_{hybrid} = Z_{passive} + Z_{active} \quad (5)$$

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

2.4Shunt 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 modeling 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**.**

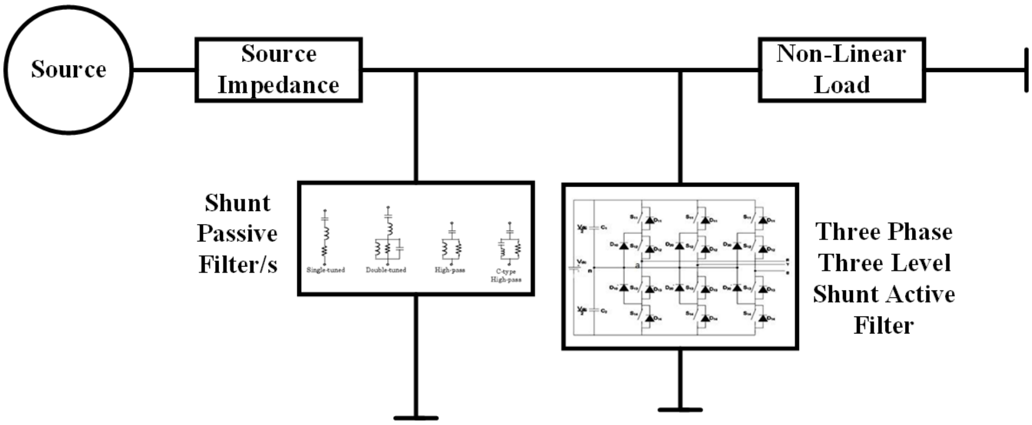

Figure 4. Block Diagram of Proposed (3-Level Inverter) Shunt Hybrid Active Filter

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

$$Z_{hybrid,\ 3L} = Z_{passive} + Z_{active,\ 3L} \quad (6)$$

The impedance of the three-level active filter $Z_{active,\ 3L}$ 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.

3. Modeling and Analysis Using MATLAB/Simulink

The MATLAB/Simulink simulation model depicted in Fig. 7 represents a three-phase three-level shunt hybrid active filter (SHAF) employing a multilevel inverter approach for power quality enhancement in a distribution system. The SHAF is strategically connected to the load bus within the distribution network. The simulation model comprises the following key components:

- Three-Phase Voltage Source: Symbolizing the voltage source at the Point of Common Coupling (PCC) in the distribution system.
- Three-Phase Load: Representing the load attached to the distribution system, which can exhibit both linear and nonlinear characteristics.
- Three-Phase Shunt Hybrid Active Filter (SHAF): Comprising a capacitor bank and a multilevel inverter, the SHAF aims to provide reactive power compensation. The multilevel inverter, utilizing the diode-clamped topology, injects active power to mitigate harmonics and other disturbances present in the load current. The values for passive filter are referred from [29].
- Multilevel Inverter: Employed to synthesize a sinusoidal waveform by combining multiple DC voltage sources.

- Control System: The SHAF's control system encompasses both a current controller and a voltage controller. The current controller generates switching signals for the multilevel inverter, strategically eliminating harmonics and disturbances in the load current. Simultaneously, the voltage controller ensures the maintenance of a constant DC voltage level across the capacitor bank. This comprehensive MATLAB/Simulink model serves as a valuable tool for analyzing and optimizing the performance of the proposed SHAF in the distribution system. The working of system is referred from [17].

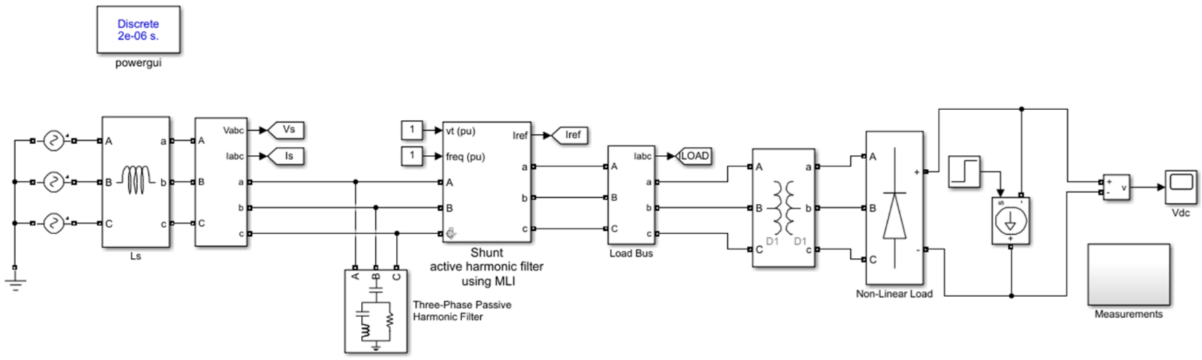

Figure 5.MATLAB/Simulink Schematic of the Proposed Three-Phase Three-Level Inverter-Based Shunt Hybrid Active Filter

This illustration (Fig. 5) showcases the MATLAB/Simulink diagram encapsulating the conceptualization and simulation of the proposed power quality improvement system. The model integrates a three-phase three-level inverter within a shunt hybrid active filter (SHAF) configuration. Key components such as the three-phase voltage source, load, SHAF with a capacitor bank and multilevel inverter, multilevel inverter block employing a diode-clamped topology, and the intricate control system are visually represented. The interaction and dynamic response of these elements in the simulated environment provide valuable insights into the performance and efficacy of the proposed system in enhancing power quality within the distribution network.The MATLAB/Simulink model parameters are listed in Table 1.

Table 1. Parameters of the system

Sr. No.	Parameter	Value
1	Fundamental Frequency (f)	60 Hz
2	System Voltage (Three Phase)	440V
3	Control Method	Hysteresis Control
4	Inverter Devices Type	IGBT
5	Load Type	Current Controlled Load
6	DC Link Capacitor	4700uF, 5000V x 2
7	Passive Filter Power Compensation Max Level	500KvA
8	Active Filter Inductance	1mH
9	MATLAB Version	2020a

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The FFT analysis of the source current without any filter in Fig. 6 shows that the current is highly distorted, with a total harmonic distortion (THD) of 20.82%. Fig. 7 shows FFT analysis of source current usingproposed TPTL inverter-based Hybrid Active Shunt filter with Double tuned shunt passive filter which is 1.23% for fundamental frequency of 60 Hz.

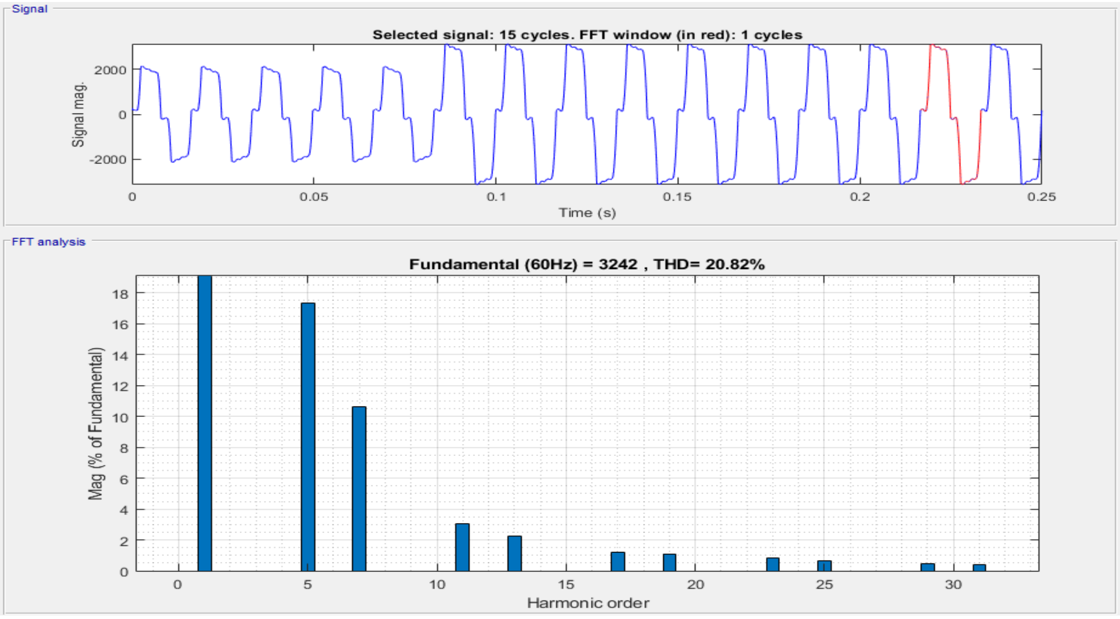

Figure 6.FFT Analysis of the Source Current without any filter

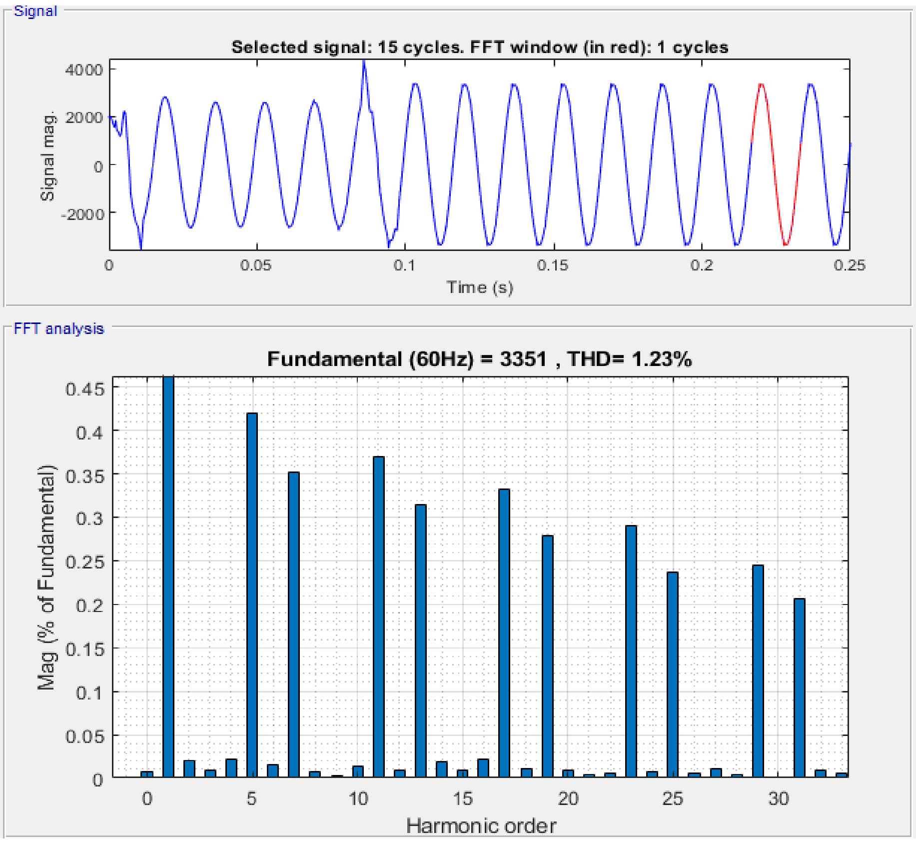

Figure 7. FFT Analysis of the Source Current with proposed TPTL inverter-based Hybrid Active Shunt filter with Double tuned shunt passive filter

Likewise, utilizing the developed MATLAB/Simulink model, FFT values for the source current were observed across various combinations, and these results have been systematically tabulated in Table 2 for convenient reference.

Table 2.Comparison of FFT values of Source Currents using different combinations

Sr. No.	Type	FFT Value
1	Without Any Filtering	20.41%
2	For STF	20.69%
3	For DTF	20.82%
4	ForHPF	20.27%
5	ForCTF	20.33%
6	Using conventional active filter (Two Level Inverter Based)	4.12%
7	Using conventional active filter (Two Level Inverter Based) along with STF	3.12%
8	Using conventional active filter (Two Level Inverter Based) along with DTF	3.00%
9	Using conventional active filter (Two Level Inverter Based) along with HPF	2.86%
10	Using conventional active filter (Two Level Inverter Based) along with CTF	2.74%
11	Using proposed Shunt Active Power Filter (TPTL Inverter Based)	2.11%
12	Using proposed Shunt Active Power Filter (TPTL Inverter Based) along with STF	1.68%
13	Using proposed Shunt Active Power Filter (TPTL Inverter Based) along with DTF	1.23%
14	Using proposed Shunt Active Power Filter (TPTL Inverter Based) along with HPF	1.45%
15	Using proposed Shunt Active Power Filter (TPTL Inverter Based) along with CTF	1.27%

Table 2 provides a detailed comparison of Fast Fourier Transform (FFT) values representing source currents under various filtering configurations, as simulated in the MATLAB/Simulink model. The baseline scenario without any filtering (Sr. No. 1) exhibits an FFT value of 20.41%, serving as a reference for subsequent evaluations. Introducing Single Tuned (STF) and Double Tuned Filters (DTF) (Sr. Nos. 2 and 3) incrementally reduces the FFT values to 20.69% and 20.82%, respectively. High Pass Filter (HPF) and C-Type High Pass Filter (CTF) (Sr. Nos. 4 and 5) effectively attenuate low-frequency components, achieving FFT values of 20.27% and 20.33%, respectively.

The application of a conventional active filter (Two Level Inverter Based) significantly enhances harmonic mitigation, yielding an FFT value of 4.12% (Sr. No. 6). Combining the conventional filter with STF, DTF, HPF, and CTF (Sr. Nos. 7 to 10) further reduces the FFT values, emphasizing the synergistic effects of these filtering techniques. Notably, the proposed Shunt Active Power Filter with TPTL Inverter (Sr. No. 11) outperforms conventional methods, achieving a remarkable FFT value of 2.11%. Combining the proposed filter with different passive filters (STF, DTF, HPF, and CTF) consistently demonstrates superior harmonic reduction, with FFT values ranging from 1.27% to 1.68%.

In conclusion, the simulation results underscore the efficacy of the proposed Shunt Active Power Filter with TPTL Inverter in significantly improving power quality by minimizing harmonic content. The hybrid approach, integrating TPTL technology with diverse passive filters, demonstrates a remarkable reduction in FFT values, emphasizing its potential for practical implementation in distribution systems to achieve enhanced power quality.

4. Conclusion

In conclusion, this paper presents a comprehensive exploration and analysis of power quality improvement in distribution systems through the innovative integration of a Three-Phase Three-Level Shunt Hybrid Active Filter (SHAF) employing a Multilevel Inverter. The research emphasizes the imperative need for optimal power quality in contemporary electrical networks, where harmonic distortions, stemming from nonlinear loads, pose a significant challenge to stable and efficient operations.

The introduction of power filters, a crucial element in addressing these challenges, has witnessed a shift from traditional passive filters to dynamic active filters. While passive filters exhibit certain limitations, active filters offer real-time compensation, adaptability to varying loads, and improved harmonic mitigation. The focus of this study centers on the Three-Phase Three-Level (TPTL) Neutral Point Clamped (NPC) Voltage Source Inverter, capitalizing on its capacity to reduce switch ratings and enhance inverter performance for harmonics compensation.

A groundbreaking contribution of this paper is the introduction and analysis of the Shunt Hybrid Active Filter (SHAF), particularly the TPTL-based SHAF, which combines the strengths of both passive and active filters. The hybrid approach, leveraging the advantages of TPTL technology, aims to overcome the limitations of individual filters, thereby achieving a substantial improvement in power quality.The primary objective of the study is to enhance the harmonic content of source current through strategic filter implementation.

The presented MATLAB/Simulink model showcases the SHAF with a Multilevel Inverter approach, and the results affirm the effectiveness of the proposed system. Comparative analysis against various conventional shunt passive filters and active filters underscores the superior performance of the proposed TPTL-based SHAF, demonstrating a remarkable improvement of over 50% compared to two-level active filters and more than sixteen times compared to shunt passive filters.

In summary, this research offers valuable insights into the realm of Power Quality Improvement, providing a robust foundation for future advancements in distribution systems. The proposed SHAF, with its innovative integration of TPTL technology and diverse passive filters, presents a promising solution for practical implementation, paving the way for enhanced power quality in contemporary electrical networks.

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