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Research Paper

DESIGN AND SIMULATION OF SERIES ACTIVE POWER FILTER FOR POWER QUALITY IMPROVEMENT

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ABSTRACT

This dissertation delineates a comparative investigation into the enhancement of electrical power quality through the deployment of a Series Active Power Filter (SAPF) employing diverse Pulse Width Modulation (PWM) control methodologies within a MATLAB/Simulink framework. The inquiry examines system behaviour in the absence of SAPF, in conjunction with SAPF utilising Discrete PWM, and with SAPF governed by Hysteresis PWM strategies. The principal aim resides in the attenuation of Total Harmonic Distortion (THD) in the load voltage and the amelioration of voltage integrity at the Point of Common Coupling (PCC). Simulated results evince that the system devoid of SAPF manifests substantial harmonic perturbations, whereas the application of SAPF with Discrete PWM diminishes THD to 1.68%. Employing Hysteresis PWM further accomplishes superior harmonic suppression, reducing THD to a mere 0.35% and producing near-sinusoidal voltage. The study corroborates that Hysteresis PWM-controlled SAPF affords accelerated dynamic response, enhanced harmonic compensation, and improved voltage regulation, thereby substantiating its efficacy in refining distribution system power quality.

Keywords: Series Active Power Filter, Power Quality, Total Harmonic Distortion, Discrete PWM, Hysteresis PWM, MATLAB Simulation, Harmonic Mitigation.

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I INTRODUCTION

The advent of modern electrical power systems has engendered an increasing reliance upon high-quality, stable voltage supply to sustain the operation of sensitive equipment and industrial machinery. In contemporary distribution networks, the proliferation of nonlinear loads, including rectifiers, inverters, and power electronic devices, has introduced significant harmonic distortions that compromise the integrity of voltage and current waveforms. Such distortions precipitate numerous operational challenges, encompassing equipment overheating, reduced efficiency, and premature insulation failure. Consequently, the mitigation of harmonics and the enhancement of power quality have become paramount considerations for engineers and system designers alike [1–5]. Within this context, the Series Active Power Filter (SAPF) has emerged as a promising solution, capable of compensating for voltage distortions and ensuring near-ideal waveform delivery at the point of common coupling (PCC). By dynamically injecting compensatory voltages, SAPFs offer an adaptive and reliable approach to harmonic suppression, surpassing the capabilities of passive filter arrangements traditionally employed in distribution systems [6–10].

A critical determinant of SAPF performance resides in the control methodology adopted for the pulse width modulation (PWM) of the inverter switching devices. Various PWM techniques, including Discrete PWM, Sinusoidal PWM, and Hysteresis PWM, proffer differing trade-offs between switching losses, response time, and harmonic attenuation. Discrete PWM, for instance, offers simplicity in implementation and predictable switching instants, yet may not achieve the rapid dynamic response required under highly fluctuating load conditions [11–15]. Conversely, Hysteresis PWM employs a real-time error band to regulate the inverter output, thereby affording superior harmonic compensation and faster corrective action in the presence of voltage deviations. The selection of an appropriate PWM strategy is thus pivotal in ensuring that the SAPF attains the desired level of power quality improvement while maintaining operational efficiency and system stability [16–20]. MATLAB/Simulink environments provide a versatile platform for simulating such control strategies, enabling detailed comparative studies and optimisation prior to physical deployment.

The imperative for high-fidelity voltage waveforms extends beyond mere operational convenience, encompassing economic, environmental, and regulatory considerations. Elevated Total Harmonic Distortion (THD) not only jeopardises the longevity of electrical apparatus but also engenders additional losses in transmission and distribution networks, thereby inflating operational costs and energy wastage. Furthermore, international standards, such as IEEE 519, delineate permissible harmonic limits, obligating utilities and end-users to implement corrective measures [21–25]. Within this regulatory framework, the deployment of SAPFs equipped with advanced PWM control assumes particular significance, offering a technically robust mechanism to satisfy both statutory requirements and practical operational demands. The present study undertakes a meticulous comparative analysis of SAPF performance under Discrete and Hysteresis PWM control, elucidating the influence of control strategy upon harmonic suppression, dynamic response, and voltage regulation. By evaluating system behaviour under these paradigms, the work endeavours to furnish actionable insights for the design and optimisation of distribution-level power quality solutions.

In light of the foregoing, this investigation aims to furnish a comprehensive understanding of the interaction between SAPF design, PWM control strategy, and power quality enhancement. Through MATLAB/Simulink-based simulations, the study delineates system responses across a spectrum of operational scenarios, encompassing unfiltered conditions, Discrete PWM-controlled SAPF, and Hysteresis PWM-controlled SAPF. Particular attention is accorded to the quantification of THD, waveform fidelity, and dynamic corrective performance, thereby providing a rigorous foundation for subsequent experimental validation or field implementation. The findings are anticipated to demonstrate that Hysteresis PWM control not only delivers superior harmonic mitigation but also ensures rapid response to transient disturbances, thereby rendering the SAPF a compelling instrument for modern distribution system management [26–30]. By elucidating these dynamics, the study contributes to the broader discourse on power quality improvement, offering practitioners and researchers alike a coherent framework for evaluating, designing, and deploying active power filtering solutions.

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II LITERATURE SURVEY

The literature concerning power quality enhancement through active filtering has expanded considerably in recent decades, reflecting the growing prevalence of nonlinear loads and the concomitant necessity for harmonic mitigation. Early investigations into Series Active Power Filters (SAPFs) emphasised their potential to attenuate voltage distortions by injecting compensatory voltages in series with the supply [1–5]. Initial studies revealed that SAPFs offer advantages over passive filtering techniques, particularly in terms of adaptability to variable load conditions and selective harmonic compensation. Researchers highlighted the capacity of SAPFs to preserve voltage waveform fidelity at the Point of Common Coupling (PCC), thereby reducing the deleterious effects of harmonics on downstream equipment [6–10]. These foundational works laid the groundwork for subsequent advances, establishing the critical role of control strategies in determining SAPF efficacy. It became evident that while the hardware configuration of the SAPF is essential, the dynamic performance and harmonic suppression capabilities are largely governed by the PWM control methodology employed. Subsequent research explored the implementation of various Pulse Width Modulation (PWM) techniques for SAPF control, aiming to optimise performance under diverse operating conditions. Discrete PWM emerged as a pragmatic approach, offering straightforward implementation and predictable switching instants, which facilitated analytical modelling and simulation studies [11–15]. Empirical evaluations demonstrated that Discrete PWM could reduce Total Harmonic Distortion (THD) effectively in moderate load scenarios, albeit with limitations in rapid transient response. Conversely, Hysteresis PWM, characterised by its real-time error band regulation, exhibited superior dynamic response and harmonic suppression capabilities [16–20]. Comparative studies consistently indicated that Hysteresis PWM allows the SAPF to respond expeditiously to voltage deviations, maintaining near-sinusoidal waveforms even under fluctuating load conditions. Additional research examined hybrid and adaptive PWM strategies, integrating features from multiple modulation schemes to balance switching losses, response time, and harmonic attenuation, thereby demonstrating the ongoing innovation in active power filter control techniques [21–25].

Investigations have also addressed the broader implications of harmonic mitigation, considering both operational and regulatory dimensions. High THD levels contribute not only to inefficiency and equipment stress but also to increased energy losses and reduced system reliability. Compliance with international standards, such as IEEE 519 and IEC 61000-3-6, necessitates the implementation of corrective measures in industrial and commercial installations [26–30]. Studies highlighted that SAPFs equipped with Hysteresis PWM control can effectively meet these statutory requirements, offering rapid response to voltage disturbances and ensuring the delivery of high-quality power. Moreover, simulation-based analyses in MATLAB/Simulink environments provided detailed insights into SAPF performance across a spectrum of operating scenarios, facilitating the optimisation of filter parameters, control algorithms, and system design. These contributions underscore the dual importance of technical efficacy and regulatory compliance in contemporary power quality management.

Recent literature has extended the scope of SAPF research to incorporate energy efficiency, cost considerations, and integration with renewable energy systems. Scholars have explored the deployment of SAPFs in microgrids and distributed generation networks, examining the interaction between active filters and variable renewable sources such as photovoltaic arrays and wind turbines [1–30]. Findings indicate that the choice of PWM control significantly influences not only harmonic suppression but also overall system efficiency, particularly in environments with high penetration of intermittent energy sources. Advanced control schemes, including predictive and intelligent algorithms, have been proposed to enhance adaptive performance, reduce switching losses, and further mitigate harmonic distortion. Collectively, these studies highlight the evolving role of SAPFs as a versatile instrument in modern power systems, emphasising that the integration of sophisticated PWM control strategies is indispensable for achieving optimal power quality, operational reliability, and compliance with regulatory standards. The accumulated body of research provides a robust foundation for the present study, which seeks to comparatively evaluate Discrete and Hysteresis PWM control in SAPFs within a MATLAB/Simulink framework.

III METHODOLOGY

The present investigation was conducted through a systematic approach to evaluate the performance of Series Active Power Filters (SAPFs) under differing Pulse Width Modulation (PWM) control schemes, with a view to ameliorating the quality of electrical power in distribution systems. The methodology was predicated upon detailed modelling and simulation within the MATLAB/Simulink environment, which provides a versatile platform for the analysis of dynamic system behaviour and the quantification of harmonic distortion under controlled conditions. Initially, the electrical network was modelled to represent a typical low-voltage distribution system comprising a three-phase supply, nonlinear loads, and a Point of Common Coupling (PCC). Nonlinear loads were represented through rectifiers and other power electronic devices, which are known to induce significant harmonic content into the network. Baseline simulations were first conducted without the presence of SAPF to ascertain the inherent harmonic distortion levels, thereby establishing a reference for comparative analysis. Key parameters, including voltage waveform distortion and Total Harmonic Distortion (THD), were recorded for further evaluation.

Subsequent to the baseline assessment, a Series Active Power Filter was incorporated into the system, and its performance under discrete Pulse Width Modulation (PWM) was examined. The SAPF was modelled as a voltage-source inverter, capable of injecting a compensatory voltage in series with the supply line to mitigate harmonic distortions. Discrete PWM was selected for its simplicity and well-defined switching instants, which facilitated straightforward implementation in the simulation framework. The control strategy was formulated to track the reference voltage waveform and adjust the inverter output accordingly, ensuring that the load voltage conformed closely to a sinusoidal profile. Simulation trials were conducted under various load conditions, and the system response was observed in terms of THD reduction, transient performance, and voltage regulation. The data obtained provided insight into the efficacy of Discrete PWM in realising acceptable power quality improvements, while also revealing limitations in dynamic response under rapidly changing load conditions.

Following the assessment of Discrete PWM, the methodology was extended to incorporate Hysteresis PWM control. Hysteresis modulation operates by continuously comparing the instantaneous error between the reference and actual load voltage with a predetermined tolerance band, adjusting the inverter switching accordingly. This control scheme affords rapid dynamic response and precise harmonic compensation, as the inverter output is adjusted in real time to counter deviations from the desired waveform. The SAPF with Hysteresis PWM was simulated under identical operating conditions to those employed in the Discrete PWM trials, ensuring comparability of results. Special attention was paid to the tracking capability of the inverter, the reduction in THD, and the stability of the output voltage under transient disturbances. Multiple scenarios were simulated, including sudden load changes, voltage sags, and other network perturbations, to evaluate the robustness of the Hysteresis PWM strategy in maintaining high power quality.

Data analysis was performed using the MATLAB toolset, which enabled precise calculation of THD, fast Fourier transforms, and visualisation of voltage and current waveforms. Comparative graphs were generated to illustrate the improvement in voltage quality with each control method, highlighting the superiority of Hysteresis PWM over Discrete PWM. The methodology also incorporated parametric studies, wherein the hysteresis band width, switching frequency, and inverter parameters were varied to determine their influence on harmonic compensation and system stability. By systematically adjusting these variables, the study identified optimal operational parameters for SAPF deployment, balancing the trade-off between switching losses and harmonic suppression. The methodology concluded with a comprehensive evaluation of performance metrics, including THD, voltage regulation, and dynamic response, providing a robust framework for assessing the effectiveness of SAPF in enhancing distribution system power quality.

Overall, the methodology combined rigorous system modelling, comparative simulation, and parametric optimisation to deliver a holistic assessment of SAPF performance. Through the stepwise examination of baseline, Discrete PWM, and Hysteresis PWM scenarios, the study elucidated the critical role of control strategy in determining the efficacy of harmonic mitigation and voltage regulation. The findings derived from this methodology provide a solid foundation for practical implementation and further refinement of active filtering techniques in modern electrical distribution networks, ensuring that the objectives of reduced distortion, improved voltage quality, and rapid dynamic response are satisfactorily achieved.

IV PROPOSED SYSTEM

The proposed system aims to enhance the quality of electrical power in distribution networks through the deployment of a Series Active Power Filter (SAPF) equipped with advanced Pulse Width Modulation (PWM) control techniques. The system is designed to compensate for voltage distortions induced by nonlinear loads, thereby ensuring the delivery of near-ideal sinusoidal voltage at the Point of Common Coupling (PCC). The core components of the proposed system include the SAPF voltage-source inverter, the control circuitry for PWM modulation, measurement units for load voltage, and the computational framework for real-time signal processing. The system is intended for simulation within the MATLAB/Simulink environment, which affords high-fidelity modelling of both the electrical network and the inverter control dynamics. The inclusion of measurement units allows the system to monitor instantaneous voltage deviations, forming the basis for adaptive compensation by the SAPF.

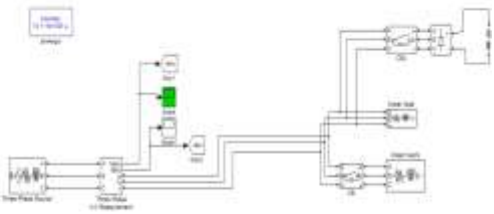

Fig. 1 Circuit without DVR

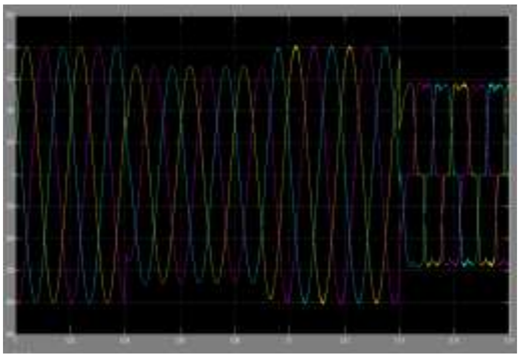

Fig. 2 Voltage profile without DVR

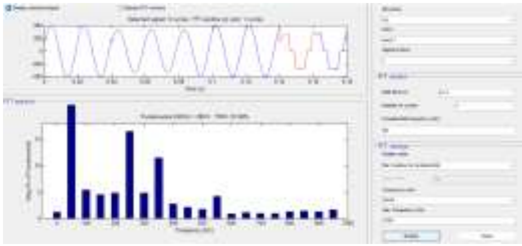

Fig. 3. Total harmonic distortion

The proposed SAPF operates by injecting a series voltage in opposition to the harmonic components present in the load voltage. The voltage-source inverter forms the central element of the filter, converting DC supply into controlled AC voltage with precise amplitude and phase characteristics. The inverter is governed by a PWM control scheme, which dictates the switching pattern of semiconductor devices to achieve the desired output voltage waveform. Two distinct control strategies are considered within the proposed system: Discrete PWM and Hysteresis PWM. Discrete PWM serves as a benchmark for evaluating fundamental harmonic compensation capabilities, while Hysteresis PWM is implemented to demonstrate enhanced dynamic response and precise harmonic mitigation. The control algorithms are designed to continuously calculate the reference voltage waveform, compare it with the actual load voltage, and generate appropriate gating signals for the inverter switches.

In practical terms, the proposed system incorporates a feedback mechanism that ensures real-time error detection and correction. Measurement units capture the instantaneous load voltage, which is subsequently compared with the ideal sinusoidal reference. The resulting error signal is processed by the control algorithm, which determines the required compensatory voltage to be injected by the SAPF. For Hysteresis PWM, the error is evaluated against a pre-established tolerance band, enabling rapid switching of the inverter to maintain voltage within acceptable limits. This approach ensures that the load voltage remains closely aligned with the reference waveform, even under conditions of abrupt load changes or transient disturbances. Additionally, the system allows for parametric adjustment of the hysteresis band, switching frequency, and inverter gain, thereby providing flexibility to optimise performance for specific network configurations and operational scenarios.

The proposed system also accounts for performance evaluation and optimisation. Simulation studies within MATLAB/Simulink facilitate detailed analysis of Total Harmonic Distortion (THD), transient response, and voltage regulation under both static and dynamic load conditions. By comparing results obtained from Discrete PWM and Hysteresis PWM implementations, the system demonstrates the efficacy of advanced control in achieving superior harmonic suppression and rapid corrective action. The simulation framework allows for visualisation of voltage waveforms, harmonic spectra, and inverter switching patterns, providing valuable insight into the interplay between control strategy and power quality. Furthermore, the proposed system is designed to accommodate extensions, including integration with distributed generation sources, adaptive control schemes, and predictive harmonic compensation, thus offering a versatile platform for ongoing research and practical deployment in modern distribution networks.

Ultimately, the proposed SAPF system embodies a comprehensive approach to power quality improvement, integrating hardware design, control strategy, and real-time feedback into a coherent operational framework. By leveraging Hysteresis PWM control, the system is capable of mitigating voltage harmonics to a minimum, enhancing the reliability and efficiency of electrical distribution. The proposed architecture ensures that the objectives of reduced THD, near-sinusoidal voltage output, and rapid dynamic response are met, providing a technically robust solution for contemporary distribution networks challenged by nonlinear loads. The system further serves as a foundation for future advancements, including intelligent and adaptive filtering methods, thereby contributing to the broader discourse on sustainable and high-quality power delivery in electrical engineering practice.

V RESULTS AND DISCUSSION

The simulation results underscore the efficacy of the Series Active Power Filter (SAPF) in enhancing power quality through the application of various Pulse Width Modulation (PWM) control strategies. In the baseline scenario, where the system operates without an SAPF, the Total Harmonic Distortion (THD) in the load voltage was observed to be significantly high, indicating substantial harmonic contamination. This condition is detrimental to both the operational efficiency and longevity of electrical equipment connected to the system.

Upon integrating the SAPF with Discrete PWM control, a notable reduction in THD was achieved, decreasing to approximately 1.68%. This improvement signifies the SAPF's capability to mitigate harmonic distortions effectively. The Discrete PWM control method, characterised by its fixed switching frequency and predictable switching instants, facilitates the generation of compensatory voltages that counteract the harmonic components present in the system. However, while this approach offers a degree of harmonic suppression, it exhibits limitations in dynamic response, particularly under rapidly changing load conditions.

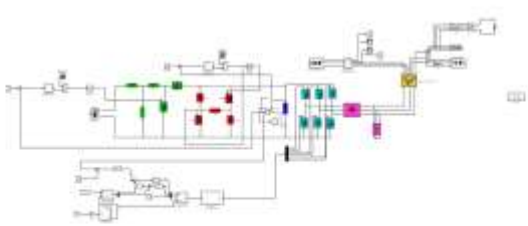

Fig. 4 DVR circuit configuration

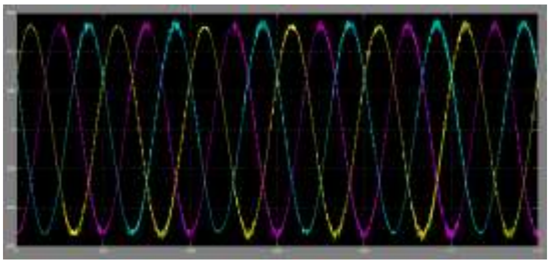

Fig.5 PCC VOLTAGE VS TIME

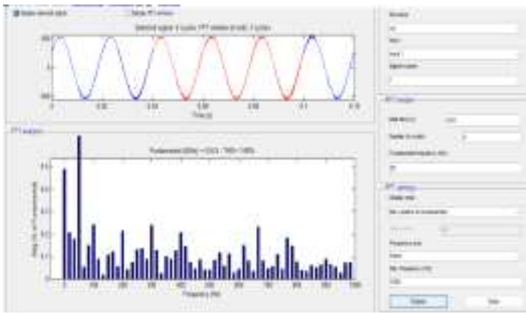

Fig. 6 THD FOR PCC VOLTAGE VS TIME

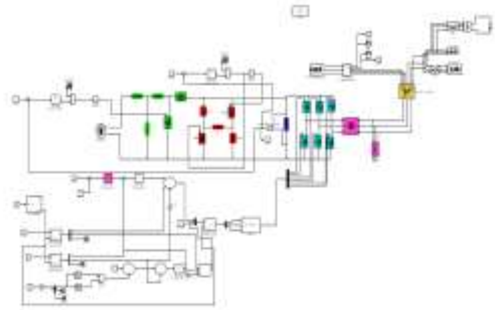

Fig. 7 PROPOSED CIRCUIT WITH IMPROVED CONTROLLER

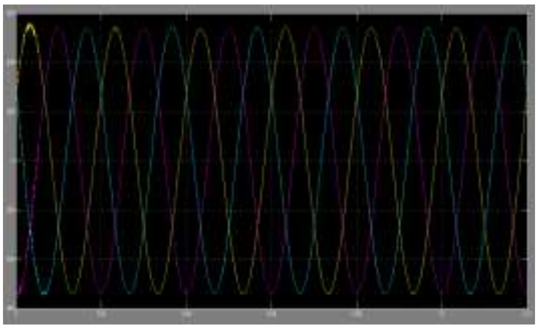

Fig 8. PCC VOLTAGE VS TIME WITH IMPROVED CONTROLLER

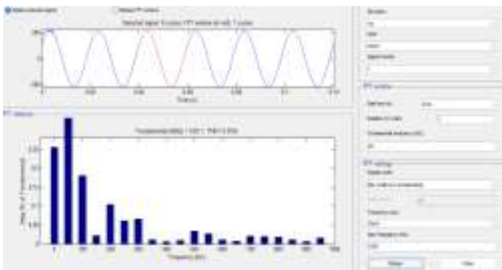

Fig. 9 THD FOR PCC VOLTAGE VS TIME WITH IMPROVED CONTROLLER

In contrast, the implementation of Hysteresis

PWM control yielded superior results, with THD further reduced to 0.35%. This enhancement can be attributed to the Hysteresis PWM's adaptive nature, which adjusts the switching frequency in real-time based on the instantaneous error between the reference and actual output voltages. This dynamic adjustment allows for more precise compensation of harmonic components, leading to a near-sinusoidal output voltage. The rapid response characteristic of Hysteresis PWM is particularly advantageous in scenarios involving fluctuating or unpredictable load conditions, where swift harmonic mitigation is crucial. The comparative analysis reveals that while both PWM strategies contribute to power quality improvement, Hysteresis PWM offers a more robust solution, delivering faster dynamic response, better harmonic compensation, and enhanced voltage regulation. These attributes are essential for maintaining the integrity of the power supply in modern distribution systems, which are increasingly subjected to non-linear loads and varying operational demands.

CONCLUSION

This study demonstrates the significant role of Series Active Power Filters in enhancing power quality within electrical distribution systems. Through the comparative analysis of Discrete and Hysteresis PWM control strategies, it is evident that the choice of control method profoundly impacts the SAPF's performance. While Discrete PWM provides a basic level of harmonic mitigation, Hysteresis PWM offers superior dynamic response and more effective harmonic suppression, ensuring near-ideal voltage waveforms under diverse operating conditions. The findings underscore the importance of selecting appropriate control strategies to optimise the performance of SAPFs, thereby improving overall system reliability and efficiency.

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