Advanced Control Strategies for Enhanced Harmonic Mitigation with Series Active Filters

D.K. Nishad*, [1], A.N. Tiwari*, and Saifullah Khalid^

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Abstract – *This review examines Series Active Filters (SAFs), which is a significant answer to the harmonic distortions caused by non-linear load integration in power systems and the control approaches used for them. Controllers that are linear, nonlinear, adaptive, and intelligent are discussed, along with their advantages, disadvantages, and applications. In addition to this, the review investigates how hybrid and AI-based methodologies might be utilized to enhance SAFs. Within the time, frequency, and hybrid time-frequency domains, we investigate different techniques for harmonic detection and evaluate the extent to which they are applicable depending on the system's parameters. In the final part of this evaluation, we will examine the ways in which artificial intelligence and machine learning might enhance the performance of SAF control systems. Power quality can be improved by modern power electronics, artificial intelligence, and machine learning, making the future more energy efficient and ecologically friendly.*

Keywords – Series active filter, Power quality, Control methodology, Linear control, Nonlinear control, Adaptive control, Intelligent control, Artificial intelligence.

1. INTRODUCTION

Increasing non-linear demands in modern power systems pose electricity quality concerns [1]. Power systems get harmonic currents from power supplies, variable-speed motors, and arc furnaces [2]. Harmonics can cause equipment overheating, efficiency, power factor loss, and power system resonance [2]. Conventional passive filters are effective but large having a fixed frequency tuning, and it may resonate with the system's impedance [3]. Due to their ability to overcome these challenges and offer flexible solutions, series active filters (SAFs) have gained popularity as reliable power quality improvers [4]. SAFs inject compensating currents equal to and opposite to harmonic components in load current to reduce their effects [1]. SAF's performance is affected by its control strategy. SRF and Instantaneous Power Theory (p-q) control theories have proved successful [5, 6]. Advanced methods are needed to handle complex load characteristics and ensure system resilience.

Recent advancements in adaptive control, artificial intelligence-based techniques, and robust control methodologies open new avenues for significantly enhancing harmonic mitigation with SAFs [7]. Adaptive algorithms continuously adjust control parameters to address changing system conditions, while AI-based methods can handle complex nonlinearities [8]. Robust control techniques offer stability and performance guarantees, even under uncertainties and disturbances [9]. Fig.1 illustrates the SAPF and Fig.2 represents the illustration of complete survey.

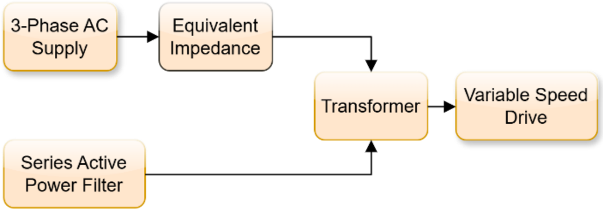

Fig. 1. Illustration of series active power filter.

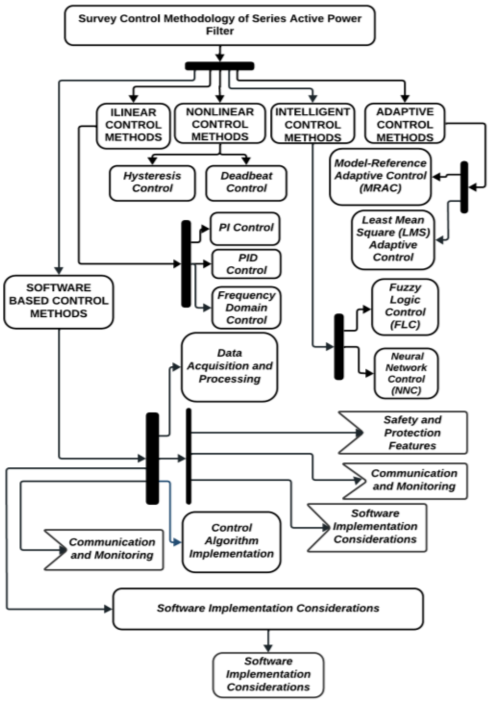

Fig. 2. Illustration of survey.

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2. CLASSIFICATION OF HARMONIC DETECTION METHODS

2.1 Time-Domain Methods

Synchronous detection is based on a synchronous reference frame aligned with the fundamental frequency. Provides good accuracy and simplicity, especially in balanced systems [10], [11]. Instantaneous Power Theory (p-q theory) calculates active and reactive power components in instantaneous values. Well-suited for three-phase systems and handles unbalanced conditions but can be sensitive to noise [12], [13]. Sine Multiplication Techniques involve multiplying the load current with in-phase and quadrature-phase sine waves. Simple, but accuracy depends on synchronization and can be affected by DC offsets [14].

2.2 Frequency-Domain Methods

The signal is broken down into its frequency components using the traditional Fourier Transform (FT) method. Although it is accurate and provides the complete harmonic spectrum, it requires a significant amount of computer power for real-time applications [15]. The Fast Fourier Transform, sometimes known as FFT, is an optimized implementation of the Fourier Transform. Although it is computationally efficient, it is still most suitable for steady-state and offline analysis [16], [17].

2.3 Hybrid Time-Frequency Domain Methods

Wavelet Transform provides a multi-resolution analysis of signals in both time and frequency domains. It helps detect transient events and change harmonic content but can be computationally demanding [17]. Adaptive Notch Filters Adjust real-time parameters to track specific harmonic frequencies. It can offer fast tracking but could be unstable in particular scenarios [18].

2.4 Adaptive Algorithms

The Least Mean Squares (LMS) algorithm is an iterative algorithm based on gradients used for parameter optimization. The sluggish convergence speed can be a problem, even though it is simple and sturdy [19]. In particular, when dealing with non-stationary signals, the Recursive Least Squares (RLS) algorithm provides faster convergence than the LMS algorithm. The possibility of stability problems and an increase in the complexity of the computation [19], [20].

2.5 Artificial Intelligence-Based Methods

Neural Networks (TNs) can acquire knowledge and adjust to intricate nonlinear interactions between load patterns and harmonics. These systems' 'black-box' nature may necessitate substantial training [21]. Using fuzzy logic is an excellent way to deal with uncertainties and inaccurate data. It is appropriate for use when formulating accurate mathematical models is difficult [22]. Some of the more frequent approaches are listed here; however, there are several other techniques and variations used.

Table 1. Classification by Domain.

Domain	Harmonic Detection Method	References
Frequency Domain	Fourier Transform (DFT, FFT)	[23], [24]
Time Domain	Synchronous Detection	[25], [26]
Time Domain	Synchronous Reference-Frame (SRF)	[25], [27]
Time Domain	Instantaneous Power (p-q Theory)	[26], [28]
Time Domain	Sine-Multiplication	[29]

Table 1 illustrates the classification by domain. The Table 2 shows the best methods based on system characteristics (balanced vs. unbalanced), transient handling needs, and computational constraints and Table 3 shows The best Method Characteristics and Considerations based on a balanced-unbalanced system.

Table 2. Characteristics and Considerations.

Method	Advantages	Disadvantages	Suitability	References
Fourier Transform	Accurate for steady-state	Computationally intensive, slow response	Offline analysis, steady-state loads	[23], [24]
Synchronous Detection	Simple, good transient response	Requires balanced conditions	Systems with balanced loads	[25], [26]
SRF Theory	Handles unbalanced conditions, fast response	Requires coordinate transformations	General purpose, unbalanced loads	[25], [27]
p-q Theory	Handles unbalanced conditions	Requires 3-phase system, balanced conditions	3-phase systems	[26], [28]
Sine-Multiplication	Simple implementation	Sensitive to noise and DC offsets	Single-phase systems	[29]

Table 3. The best Method Characteristics and Considerations based on a balanced-unbalanced system.

Factor	Advantageous Detection Method	Disadvantageous Detection Method
System Characteristics		
Balanced System	Synchronous Detection (Simple implementation) [25], [26]	Fourier Transform (Computationally expensive for real-time applications) [23], [24]
Unbalanced System	SRF Theory (Handles unbalanced conditions) [25], [26]	p-q Theory (Limited to 3-phase systems and may not be suitable for unbalanced conditions) [26], [28]
Transient Handling Needs		
Fast Transient Response Required	SRF Theory [25], [27]	Fourier Transform (Slow response for real-time transient detection) [23], [24]
Slower Transient Response Acceptable	Synchronous Detection (Simple and efficient for steady-state) [25,26]	It may not be suitable for systems with frequent transients [27]
Computational Constraints		
Limited Computational Resources	Synchronous Detection (Simple to implement) [25], [26]	Fourier Transform (Computationally demanding) [23], [24]
High Computational Resources Available	SRF Theory (Offers flexibility and good performance) [25], [27]	It may not be necessary for simpler systems with limited computational power [24]

3. CONTROL METHODOLOGIES

3.1 Linear Control Methods

3.1.1 Proportional-Integral (PI) Control

PI control is a widely used method for SAPFs due to its simplicity and ease of implementation. It works by adjusting the injected compensating current based on the difference between the measured line current and a desired reference current. The proportional term reacts to the current error in real time, injecting more compensating current when the error is significant and vice versa. However, it cannot eliminate steady-state errors [30].

The integral term accumulates the error over time, gradually adjusting the compensating current to eliminate the steady-state error. This ensures the injected current converges to the reference, even with constant disturbances [31].

While PI control performs well for basic applications, it may struggle with highly dynamic loads or significant system uncertainties. In such cases, more advanced control methods, like Deadbeat control or Model-Reference Adaptive Control (MRAC), might be needed [32].

3.1.2 Proportional-Integral-Derivative (PID) Control

The PID control method is widely used for series active power filters (SAFs) because of its ease of use and efficiency in fundamental applications. PID controllers are straightforward and easy to build, and they require a minimal amount of computing power. The optimization process begins with Ziegler-Nichols tuning. Identifier control is resistant to oscillations in both the system and the load. There is the potential for both the reduction of sound steady-state harmonics and the improvement of power quality [33-35]. Limitations in adaptability It is possible for PID controllers to become unstable or require regular retuning when they are subjected to extremely dynamic loads or huge system uncertainties. Compared to advanced methods like Deadbeat control, PID may exhibit slower response and potential tracking errors. Achieving optimal performance through manual tuning can be time-consuming and require expertise. Combining PID with other methods, like fuzzy logic, offers improved adaptability. Research on automated tuning algorithms promises simpler and more efficient PID optimization.

3.1.3 Frequency Domain Control

This method utilizes frequency-domain analysis to design controllers specifically targeting undesired harmonic components. However, it may become complex for handling multiple harmonics and varying load scenarios.

3.2 Nonlinear Control Methods

3.2.1 Hysteresis Control

This fast and robust method exhibits rapid response to current errors but can lead to high switching frequency and potential instability. Fig.3 illustrates the Hysteresis current control block diagram.

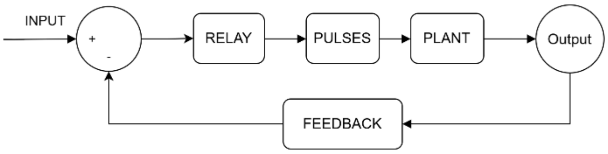

Fig. 3. Hysteresis current control representation.

Stability and switching frequency are improved by dynamic band shaping via adaptive hysteresis or dead-zone control [36], [37]. Mixing hysteresis with other control approaches like PI control can enhance benefits and minimize problems [38]. Predictive switching Current algorithms can identify problems and switch beforehand, lowering switching frequency and harmonics [39].

Deadbeat Control provides fast transient response and exact harmonic compensation but requires appropriate system parameters and may be noise-resistant. As shown in [40], predictive deadbeat control predicts errors and improves tracking. In [41], robust deadbeat control uses disturbance observers and robust design to handle uncertainty. Combining deadbeat control with other methods like PI control can improve performance and robustness (42).

3.3 *Adaptive Control Methods*

3.3.1 *MRAC control*

This method adjusts controller parameters based on a reference model, improving tracking performance under dynamic conditions but requiring complex design and computational resources. Model-Reference Adaptive Control (MRAC) keeps evolving for complex systems, offering dynamic performance in various applications, including power electronics [43], [44]. Fig. 4 illustrates the MRAC Control diagram.

Improved Tracking Performance Direct Model Reference Adaptive Control (DMRAC) simplifies design by directly using errors between plant and reference model, achieving fast tracking in studies. ulti-Model Adaptive Control (MMAC) adapts to diverse operating conditions by switching between pre-trained models. Robust Adaptive Control (RAC) integrates disturbance observers and robust adaptation mechanisms, offering uncertainty resilience. H-infinity Adaptive Control (H∞AC) Utilizes H-infinity theory for guaranteed performance bounds under external disturbances. Machine Learning Integration Neuro-Adaptive Control Combines MRAC with neural networks for data-driven adaptation and improved performance under unknown dynamics. Reinforcement Learning-based MRAC leverages reinforcement learning for self-tuning and online learning capabilities. Least Mean Square (LMS).

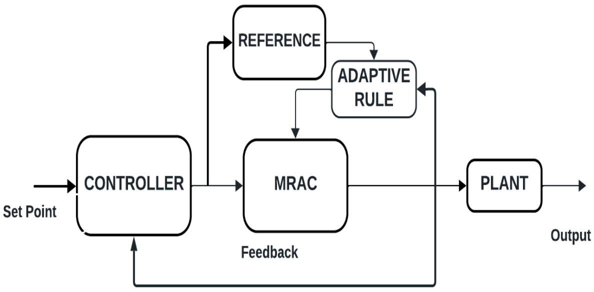

Fig. 4 Model-Reference Adaptive Control

Adaptive Control used algorithm automatically tunes filter coefficients based on error signals, offering flexibility and robustness but potentially slow convergence. While Least Mean Square (LMS) remains a popular choice for its simplicity and robustness, recent advancements are pushing [45], [46]. Variable Step-Size LMS Algorithms like Normalized LMS adjust step size based on error signals, improving convergence speed and stability. *Leaky LMS i*ntroduces a "forgetting factor" to prioritise recent data, enhancing tracking ability in dynamic environments. Affine Projection LMS Combines LMS with projection techniques, offering faster convergence and improved noise tolerance. Integration with Machine Learning combining LMS with AI techniques like neural networks enables data-driven adaptation and fault detection. In Table 4 Comparison of Adaptive Control Methods are given.

Table 4. Comparison of Adaptive Control Methods.

Method	Principle	Advantages	Disadvantages	Applications
(LMS	Gradient descent optimization, error minimization	Simple, robust, computationally efficient	Sensitivity to noise, slow convergence in specific scenarios	Control of fundamental power quality issues [47],[48]
RLS	Faster convergence handles non-stationary signals	Higher complexity, potential stability issues	Systems with fast-changing parameters	[48], [49]
ANN-based	Emulates learning, adaptive to complex patterns	Handles complex distortions, potential for good performance	Requires training data, black-box nature (challenging to interpret)	Systems with complex non-linear loads [50]

3.4 *Intelligent Control Methods*

3.4.1 *Fuzzy Logic Control (FLC)*

This approach leverages expert knowledge to handle nonlinearity and uncertainties, but rule design and tuning can be challenging. Fig. 5 represent of the FLC.

Adaptive FLC utilises online tuning algorithms to adjust fuzzy rules automatically, improving performance under varying conditions. Neuro-fuzzy control combines FLC with neural networks for data-driven adaptation and enhanced learning capabilities. Hybrid approaches integrating FLC with other control methods, like PI control, balance expert knowledge and robust performance. Fig. 6 shows ANFIS architecture.

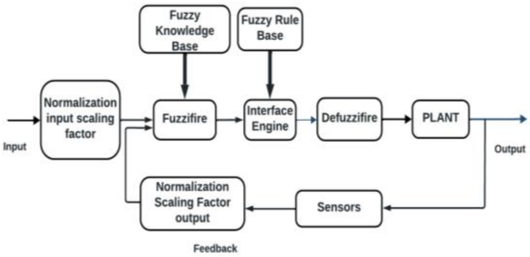

Fig. 5. Schematic diagram of FLC.

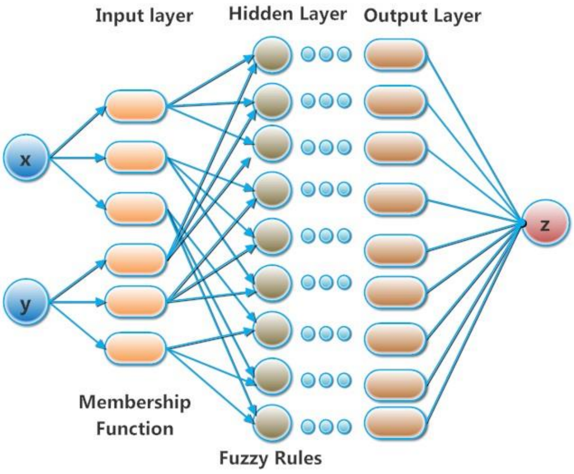

Fig. 6. ANFIS architecture.

3.5 Neural Network Control (NNC)

This method learns from data to adapt to changing conditions, offering excellent flexibility but requiring large datasets and training time. Edge Computing and On-device Learning deploying NNCs directly on SAF controllers reduces reliance on cloud infrastructure and enables faster decision-making at the edge . Explainable AI (XAI) and Interpretable ML research efforts are developing transparent and explainable NNC frameworks, fostering trust and facilitating troubleshooting . *Hybrid Approaches* combining NNC with other methods, like PID control, leverage their combined strengths for enhanced performance and robustness. Fig.7 illustrate Block Diagram of NNC.

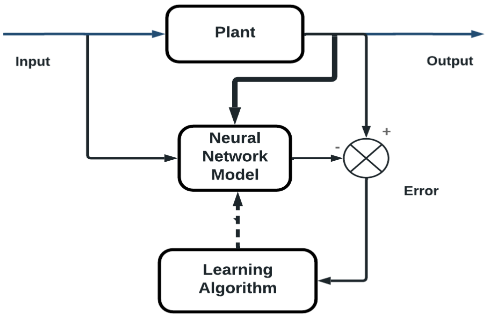

Fig. 7. Block Diagram of NNC.

3.6 Software-Based Control Methods

The software control methodology of an SAF plays a crucial role in its effectiveness and performance. Here's a breakdown of the key elements:

3.6.1 Data Acquisition and Processing

Current and voltage sensing continuously measure the line current and voltage using high-precision sensors like Hall Effect or voltage transformers. Fig.8 represent the block of diagram of DAQ and processing.

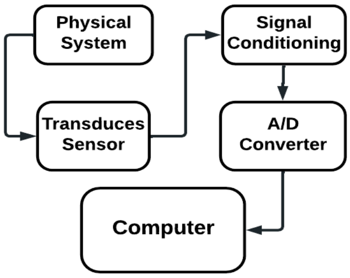

Fig. 8. Block diagram of data acquisition and processing.

Signal Conditioning amplifies and filters raw sensor signals to remove noise and ensure accurate data representation. ADC converts the analogue signals from sensors into digital data for further processing.

3.6.2 Control Algorithm Implementation

Choosing a control strategy based on specific requirements, select the appropriate control algorithm, such as PI, Deadbeat, or Model-Reference Adaptive Control (MRAC). Based on the chosen strategy, harmonic extraction extracts fundamental and harmonic components from the measured data using techniques like the Fourier Transform or Park transformation. Reference current generation calculates the desired compensating current waveform to counteract undesired harmonics and improve power quality. Pulse Width Modulation (PWM) generation converts the reference current into switching signals for the inverter that injects the compensating current into the line.

3.6.3 Safety and Protection Features

Overcurrent and Overvoltage Protection implement hardware and software safeguards to limit currents and voltages within safe operating ranges. DC Link Voltage Regulation maintains the inverter's DC link voltage stable for proper operation. Ground Fault Protection includes detecting and isolating ground faults to prevent equipment damage.

3.6.4 Communication and Monitoring

MODBUS or CAN Interface enables communication between the control software and external devices for monitoring and control purposes. Real-Time Data Visualization Display key system parameters like line currents, voltages, and harmonic content for operator observation and analysis. Fault Logging and Diagnostics Record and store operational data for troubleshooting and performance analysis.

3.7 Software Implementation Considerations

Choose a programming language and platform that can efficiently handle real-time data acquisition and control calculations for real-time processing. Computational Efficiency optimize algorithms and code structure to minimize processing time and ensure timely control decisions. Reliability and Robustness implement error handling and exception management to ensure stable operation even under unexpected conditions.

Table 5 focuses on software-based control methods for enhanced harmonic mitigation with a series of active filters:

Table 5. Software-Based Control Methods.

Control Method	Description	Advantages	Disadvantages	Programming considerations
Synchronous Reference Frame (SRF) Theory	Transforms AC signals to rotating d-q reference frame	Handles unbalanced loads, fast transient response, good filtering	Coordinate transformations increase the complexity	Real-time calculation requires efficient DSP or microcontroller [26],[28]
p-q Theory (Instantaneous Power Theory)	Calculates instantaneous active & reactive power	Handles unbalanced loads, suitable for 3-phase systems	Susceptible to noise, requires good synchronisation	Computationally intensive; benefits from the powerful processor [47],[48]
Adaptive Algorithms (LMS, RLS, etc.)	Adjust filter parameters iteratively based on error minimization	Potential for self-tuning, robust to changing conditions	It can be computationally complex, and susceptibility to stability issues	Requires careful tuning may need a dedicated processor for complex algorithms
Neural Network-based Methods	Emulate biological learning to map complex load patterns	Handles non-linear loads, good filtering potential with training	Requires extensive training data, can be computationally intensive, black-box nature	May need specialized hardware for real-time execution (GPUs, AI accelerators) [50]

4. RECENT ADVANCEMENTS AND FUTURE DIRECTIONS

4.1 Hybrid Control Techniques

Significant advancements have been made in hybrid control techniques for series active power filters (SAFs), which enhance harmonic mitigation performance and system robustness. Model-predictive control (MPC) employs real-time system models to predict future behaviour and optimize control actions, achieving faster response and improved dynamic performance. ANFIS combine neural networks and fuzzy logic to adapt to system uncertainties and load variations in real time, enhancing robustness and harmonic mitigation across diverse operating conditions. Multi-Objective Optimization optimizes multiple objectives simultaneously, such as harmonic mitigation, DC link voltage regulation, and power loss minimization, for improved overall system efficiency and performance. HIL Simulation Integrates real-time hardware components with simulated models, enabling efficient testing and refinement of advanced control algorithms before deployment. These advancements will lead to smarter, more adaptable, and more efficient SAFs, which will contribute to cleaner and more reliable power distribution systems.

4.2 Artificial Intelligence (AI) and Machine Learning (ML)

For control, these techniques offer the potential for self-learning and optimization, promising robust and adaptable SAF control. The ever-increasing prevalence of power electronics-based loads generates various power quality concerns, including harmonic distortion, voltage fluctuations, and imbalanced reactive power. SEAPFs actively inject compensating waveforms to counter these issues, but their performance highly relies on efficient control strategies. While conventional methods often struggle with system uncertainties and dynamic variations, AI and ML offer promising alternatives for intelligent and adaptable control. Advantages of AI and ML-based Control Adaptability These methods can learn from operational data and adjust their control strategies in real time, handling system uncertainties and dynamic changes effectively . Harmonic Detection and Compensation AI and ML algorithms excel at identifying and mitigating diverse harmonic components, significantly improving power quality . Fault Detection and Diagnosis techniques analyse data to detect potential faults in the SEAPF or the power system, enabling proactive maintenance and preventing downtime .

After finalising this survey, we have found some research gap and these are as:

In a real-world implementation, no research addresses data quality and hardware limits when transitioning AI models from simulation to large-scale power distribution. Uncertainty modelling reviews could underline the necessity for AI methods that explicitly handle renewable energy sources' uncertainty and variability. Hybrid AI approaches combining AI methods like fuzzy logic and neural networks may improve accuracy and robustness. Cybersecurity AI-controlled systems' cybersecurity threats are neglected, making dispersed power supply vulnerable. Series Active Filters (SAFs) with advanced control strategies could improve global power quality management. Global power systems are complex, so AI and ML integration for adaptive and intelligent control is essential. Problems and gaps in research this review emphasizes international collaboration and innovation in AI model transition from simulation to large-scale grids. Cybersecurity, AI-controlled system cybersecurity threats are understudied, suggesting international research to secure distributed power grids.

Here, a Table 6 given below for comparative table for research direction, their challenges, and benefits:

Table 6. Research Directions and Challenges.

Research Direction	Potential Benefits	Challenges
Control Strategies Leveraging AI/Machine Learning	Enhanced prediction of harmonics, adaptive tuning in complex scenarios, proactive filtering	Data requirements, real-time computational constraints, potential interpretability issues
Robust Control Techniques for non-ideal Conditions	Improved performance under grid voltage distortions, system parameter variations	Algorithm design complexity, trade-off with efficiency
Optimization methods for multi-objective control	Simultaneously improve harmonic mitigation, energy efficiency, and overall power quality optimization	Formulation of comprehensive optimization problems, computationally demanding
Control with Wide-Bandgap (WBG) Semiconductors	Faster switching speeds, reduced losses, enabling higher filter frequencies for handling broader harmonic ranges	Cost of WBG devices, control complexity at ultrafast switching speeds
Decentralized and Multi-Agent Control	Improved scalability, reliability, and flexibility for large-scale or microgrid scenarios	Consensus algorithms, communication requirements, potential stability issues
Advanced Modulation Techniques	Enhanced filter performance with reduced switching losses and ripple	Complex implementation, impact on control loop dynamics
Holistic Power Quality Management	Control algorithms targeting not just harmonic mitigation, but also voltage regulation, reactive power compensation, and grid interaction	Multi-objective optimization challenges, overall system-level control complexity

5. SIMULATION RESULTS AND DISCUSSION

Table 7 represents Typical parameter values used for simulating the performance of series active power filters in Matlab/Simulink.Fig. 8 illustrates Matlab/Simulink model setup for simulating the performance of a series active power filter with SRF control.

Table 7. Parameters used for simulating series active power filters.

Parameter	Typical Value	Description
Supply Voltage (V)	400 V (phase-to-phase RMS)	Three-phase AC supply voltage
Supply Frequency (Hz)	50 Hz	Frequency of the AC supply
Supply Resistance (R_s)	0.1 Ω	Resistance of the supply side
Supply Inductance (Ls)	0.5 mH	Inductance of the supply side
Load Resistance (R_L)	10 Ω	Resistance of the load
Load Inductance (LL)	15 mH	Inductance of the load
Filter Inductance (L_f)	1 mH	Inductance of the series filter
Filter Resistance (R_f)	0.1 Ω	Resistance of the series filter
DC-Link Voltage (V_{dc})	700 V	DC-link voltage of the inverter
DC-Link Capacitance (C_{dc})	100 μF	Capacitance of the DC-link
Switching Frequency (f_{sw})	10 kHz	Switching frequency of the inverter
Sampling Time (T_s)	0.2 μs	Sampling time for control

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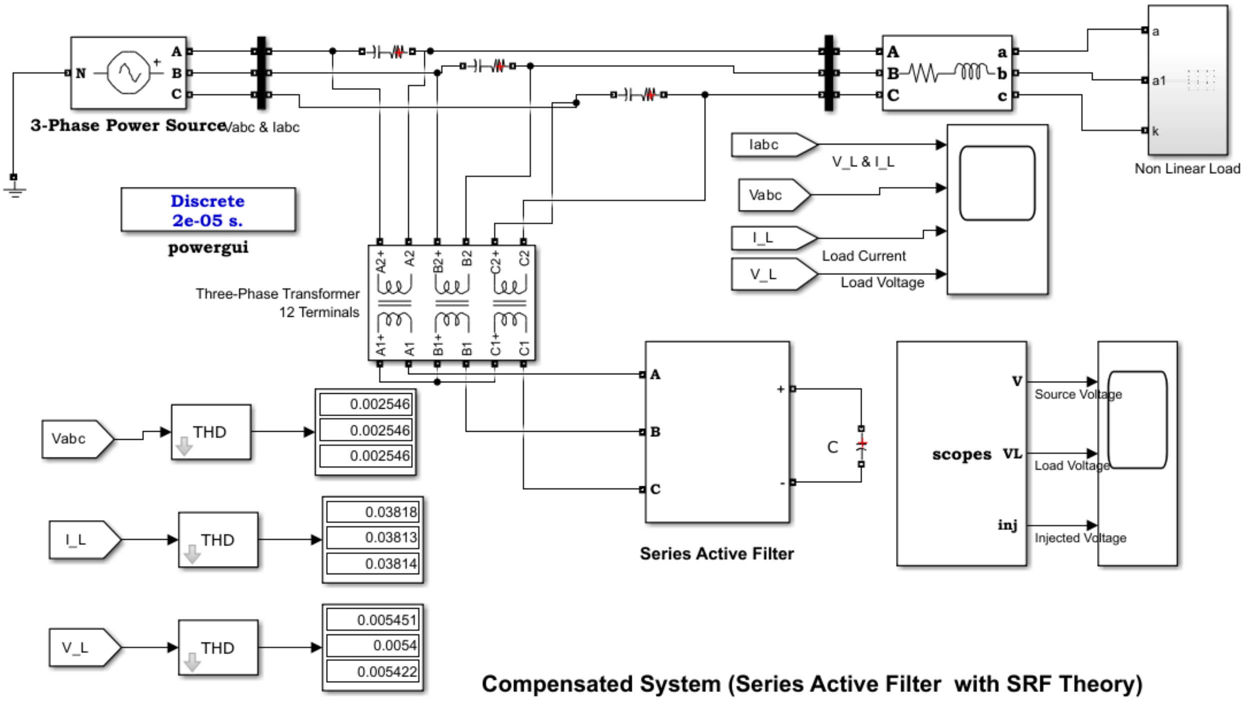

Fig. 8. Matlab/Simulink Model Setup.

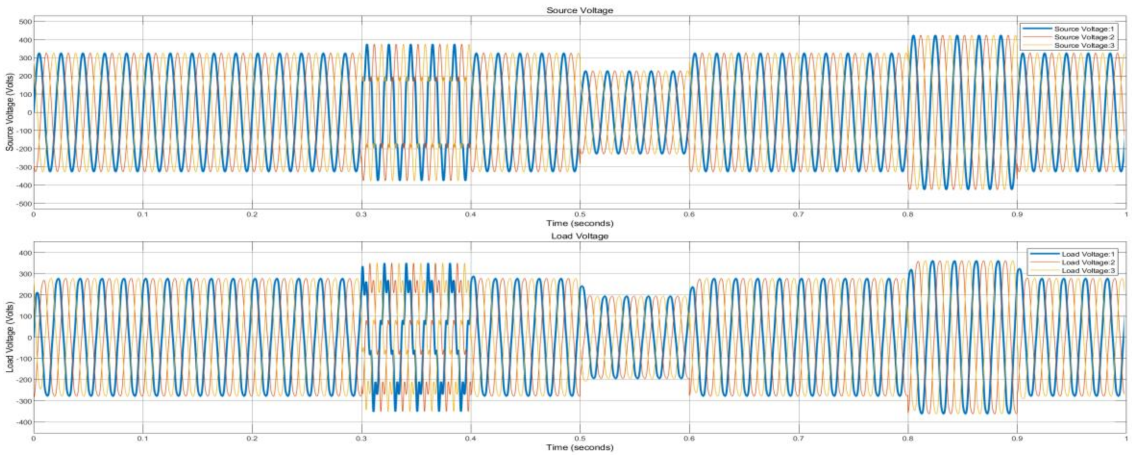

Fig. 9. Source Voltage and Load Voltage Waveform of Uncompensated System.

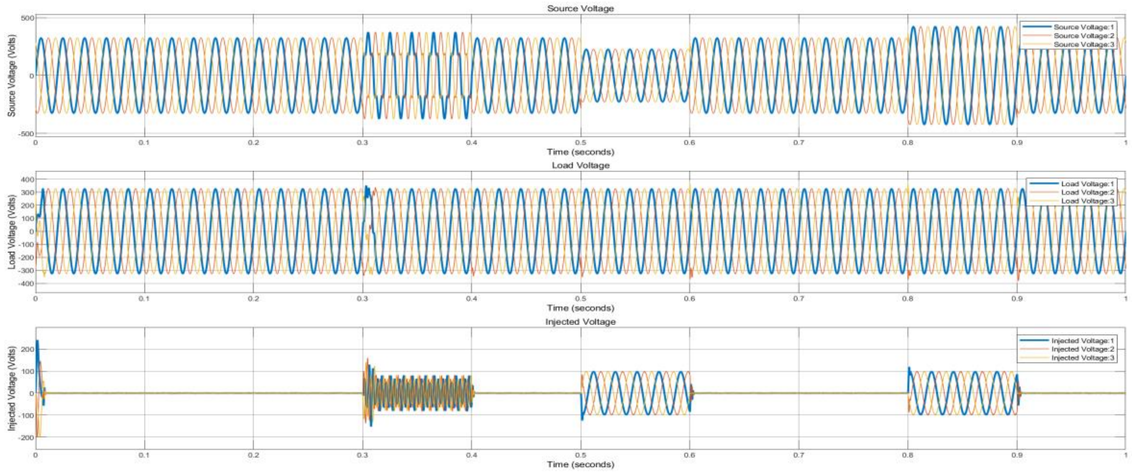

Fig. 10. Source Voltage, Load Voltage Waveform and Injected Voltage waveform of Compensated System.

Fig. 9 is simulated Waveforms of source voltage and load voltage for an uncompensated system with harmonic distortion. Fig. 10 is also simulated Waveforms of source voltage, load voltage, and injected voltage for a compensated system using a series APF.

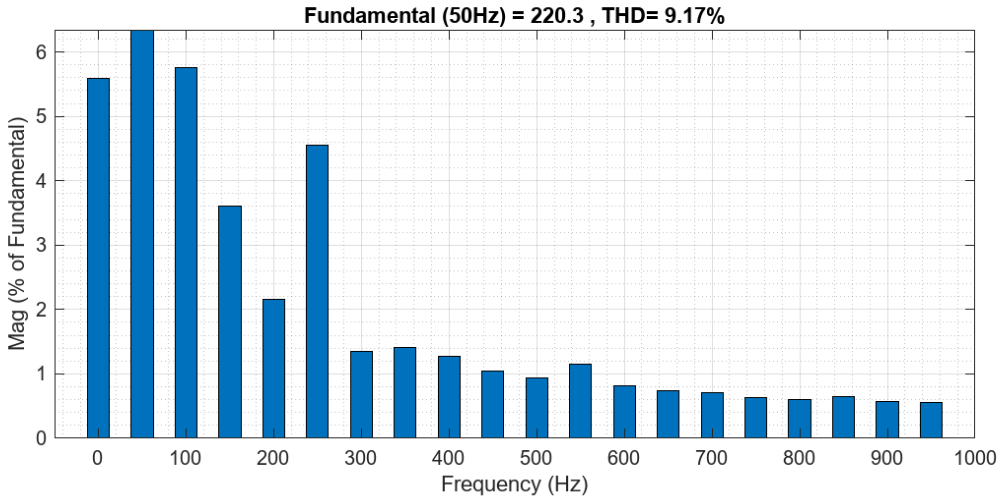

Fig. 11. THD of Load Voltage Waveform of Uncompensated System at t=0.5 Second.

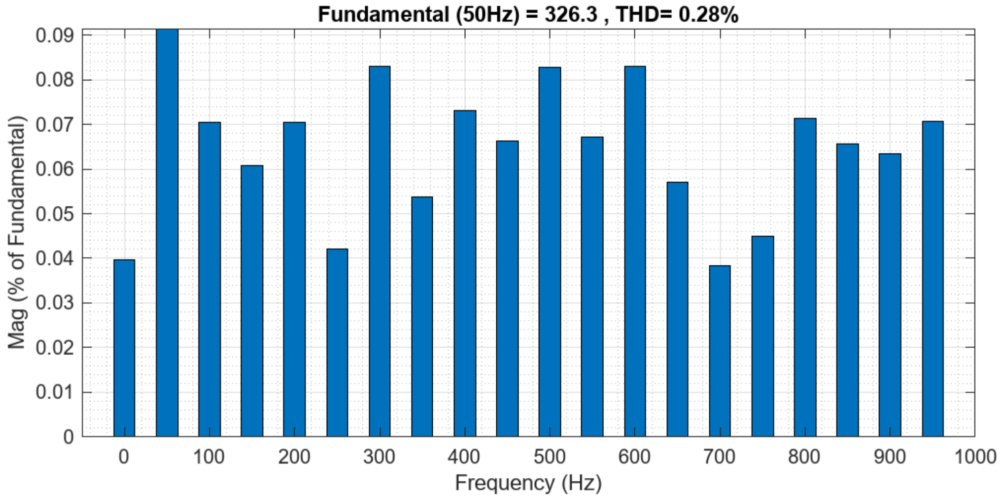

Fig. 12. THD of Load Voltage Waveform of Compensated System at t=0.5 Second.

Fig. 11 represents THD of the load voltage waveform for an uncompensated system at t=0.5 seconds.Fig. 12 represents THD of the load voltage waveform for a compensated system at t=0.5 seconds The simulation results demonstrate the effectiveness of the proposed series APF in mitigating voltage harmonics and improving the load voltage quality. The results are summarized below:

1. *Load Voltage THD Reduction*

Without APF: Load voltage THD = 9.17%
With series APF using SRF theory: Load voltage THD reduced to 0.28%

2. *Harmonic Voltage Compensation*

The series APF injects a compensating voltage in opposite phase with the harmonic voltage at the point of common coupling (PCC). This injected voltage effectively cancels out the harmonic voltage components, resulting in a nearly sinusoidal load voltage waveform.

3. *Source Voltage Quality*

The source voltage THD was around 12.3% due to the presence of 5th and 7th harmonic components at 20% of the nominal voltage.

After compensation by the series APF, the load voltage THD is reduced to 0.28%, well within the IEEE-519 standard limits of 5% for THD.

4. *DC Link Voltage Control*

The sliding mode controller (SMC) employed for the DC link voltage control shows better performance with lower oscillations and faster response compared to a conventional PI controller.

The SMC maintains a constant DC link voltage of around 700V, ensuring proper operation of the voltage source inverter in the APF.

5. *Discussion*

The series active power filter, when controlled using the synchronous reference frame (SRF) theory, proves to be an effective solution for mitigating voltage harmonics and improving the overall power quality at the load terminals. The SRF theory accurately extracts the harmonic components from the distorted supply voltage, enabling the APF to generate the required compensating voltage references.The injected voltage by the series APF cancels out the harmonic voltage components at the PCC, resulting in a nearly sinusoidal load voltage waveform with a significantly reduced THD of 0.28%. This meets the stringent power quality standards set by IEEE-519 and IEC 61000-3-6 for voltage THD limits.The sliding mode controller used for DC link voltage regulation exhibits superior performance compared to traditional PI controllers. Its fast response and robustness against parameter variations and load disturbances ensure a constant DC link voltage, which is crucial for the proper operation of the voltage source inverter in the APF system.Overall, the combination of the SRF theory for harmonic extraction, the series APF topology for voltage compensation, and the sliding mode control for DC link voltage regulation provides an effective solution for improving the power quality at the load terminals, even in the presence of significant voltage distortions and harmonics in the supply side.

6. CONCLUSION

Series active filters (SAFs) are an effective solution for the mitigation of harmonic distortion due to non-linear loads in power systems. The efficiency of SAF largely depends on the control strategy used. This paper reviews the various methodologies in control such as linear (PI, PID), nonlinear (hysteresis, deadbeat), adaptive (MRAC, LMS), intelligent (fuzzy logic, neural network), and software-based control by considering their potential advantages and drawbacks in control design.

Various harmonic detection methods are broken down to five broad categories, which include time-domain methods, frequency-domain methods, hybrid time-frequency domain, adaptive methods, and AI-based methods. Other than transient handling needs and computational constraints, method selection can be done depending upon various factors, in which the most important one is whether the system is balanced or unbalanced.

Recent advances in this field include hybrid techniques that capitalize on the strengths of the approaches, such as model predictive control combined with fuzzy logic. AI and machine learning are enabling SAF control to become more adaptive and intelligent.

Future research in this direction is now focused on the porting of AI models from simulation to large-scale grids, such as cybersecurity of AI-controlled systems and global power quality management using SAFs with advanced control.

Advanced control strategies, particularly hybrid and AI-based approaches, are going to increasingly play the determining role in enhancing the performance of series active filters for harmonic mitigation in modern power.

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