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Critical Analysis of Active Filter for Harmonic Reduction under Varying Load

Abstract: - In this paper, we give the main focus on the proliferation of non-linear loads in power systems, the mitigation of harmonics has become a critical concern to ensure stable and efficient operation. This study presents an analysis of an advanced control active filter (ACAF) designed for harmonic reduction under varying load conditions. The ACAF is a sophisticated solution that employs advanced control algorithms to effectively suppress harmonics and maintain power quality. The research investigates the performance of the ACAF under varying load conditions, which represent real-world scenarios where power consumption fluctuates. A comprehensive analysis is conducted to evaluate the filter's ability to adapt and maintain harmonic suppression efficiency across different load profiles. The study considers various load scenarios, including steady-state operation, transient load changes, and dynamic load fluctuations. The findings of this research contribute to the understanding of advanced control active filters in practical power systems with non-linear loads and varying operating conditions. The analysis provides valuable insights into the design, optimization, and implementation of ACAFs for harmonic mitigation, ultimately improving power quality and system reliability in modern electrical networks. A classified list of 38 publications on this topic is also given for the quick reference.

Keywords: Advanced Control Active Filter: ACAF, Harmonic Reduction: HR, Varying Load: VL, Voltage Regulation: VR, Transient Response: TR, Adaptive Control: AC, Predictive Control: PC.

1. INTRODUCTION

In contemporary power systems, the proliferation of non-linear loads, such as variable speed drives, switched-mode power supplies, and electronic equipment, has led to an increase in harmonic distortion and power quality issues. Harmonic distortion not only affects the performance of electrical equipment but also poses challenges for grid stability and reliability. To address these challenges, advanced control active filters (ACAFs) have emerged as promising solutions for harmonic reduction under varying load conditions [1]. The analysis of ACAFs is crucial for understanding their effectiveness in mitigating harmonics while accommodating fluctuations in load demand. This introduction outlines the significance of analysing ACAFs in the context of modern power systems and highlights the objectives and scope of the research.

Background: The presence of non-linear loads in power systems results in distorted current and voltage waveforms, leading to harmonic distortion. Harmonics can cause overheating, voltage fluctuations, and equipment malfunctions, thereby compromising system performance and efficiency. Traditional passive filters have limitations in addressing dynamic load changes and may not provide sufficient harmonic suppression [2].

Role of ACAFs: ACAFs represent an advanced approach to harmonic mitigation, employing active control techniques to dynamically adjust filter parameters and respond to varying load conditions. By actively injecting compensating currents, ACAFs can effectively cancel out harmonic currents and maintain power quality within acceptable limits.

Objective of Analysis: The primary objective of this study is to analyze the performance of ACAFs for harmonic reduction under varying load conditions. The analysis aims to evaluate the ability of ACAFs to adapt to changes in load demand while maintaining efficient harmonic suppression. Key performance metrics such as

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total harmonic distortion (THD), voltage regulation, and transient response will be investigated to assess the efficacy of ACAFs compared to traditional filtering methods [3].

Scope of Research: The analysis will consider a range of load scenarios, including steady-state operation, transient load changes, and dynamic load fluctuations. Mathematical modelling and simulation techniques will be employed to study the behaviour of ACAFs under different operating conditions. Furthermore, advanced control strategies such as adaptive control, predictive control, and fuzzy logic will be explored to enhance the adaptability and robustness of ACAFs.

Significance of Study: The findings of this research will contribute to the advancement of power quality enhancement techniques and provide valuable insights into the design and optimization of ACAFs for real-world applications. Understanding the performance characteristics of ACAFs under varying load conditions is essential for ensuring reliable and efficient operation of modern power systems [4].

The analysis of ACAFs for harmonic reduction under varying load conditions is critical for addressing power quality challenges and improving the stability and reliability of electrical networks. This research aims to provide a comprehensive understanding of ACAFs and their role in mitigating harmonics in dynamic operating environments.

2. VARYING LOAD

In the context of electrical systems, a "varying load" refers to the dynamic changes in power consumption or demand experienced by the system over time. This variation can occur due to several factors, including changes in user behaviour, the operation of different equipment, and external influences such as weather conditions.

Varying loads are common in many electrical systems, including residential, commercial, and industrial settings. For instance, in a residential area, the load may vary throughout the day as occupants use different appliances, turn lights on and off, or operate heating and cooling systems based on comfort requirements. In industrial environments, production processes may result in fluctuating power demands as machinery and equipment are activated or deactivated [5]. In the context of analysis and control of electrical systems, addressing varying loads involves developing strategies to accommodate changes in demand while maintaining stable operation and optimal performance. This may include implementing advanced control techniques, such as load forecasting, demand-side management, and adaptive control algorithms, to anticipate and respond to load variations in real-time. The analysis aims to evaluate how well the active filter can adapt to changes in load demand and dynamically adjust its operation to ensure efficient harmonic suppression across different operating scenarios [6].

3. ACTIVE FILTER (AF):

An active filter is an electronic device used in electrical systems to suppress unwanted harmonic distortion and improve power quality. Unlike passive filters, which consist of passive components such as resistors (R), capacitors (C), and inductors (L), active filters incorporate active components like operational amplifiers, transistors, and integrated circuits to actively manipulate the electrical signal [7].

Here are some key aspects and features of active filters:

- Harmonic Suppression
- Dynamic Control
- Flexibility and Tenability
- Integration with Power Systems
- Efficiency and Effectiveness
- Cost Considerations

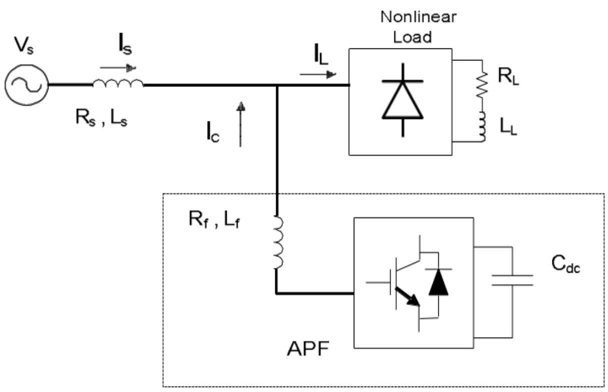

Fig. 1 Active Filter

Parallel connected load with AFC is shown in figure number-1. By this process harmonics in the line current (i_c) are reduced. Hence the current in phase with voltage will flow in the circuit.

Equation of current is given below.

$$i_c(t) = i_L(t) + i_c(t) \qquad \text{....(1)}$$

Equation of the source current after compensation is given below.

$$i_c(t) = I_{cn}\ \text{Sin}\ (\omega t) \qquad \text{....(2)}$$

Power losses are meet out by the following equation, total peak current supplied by the source is given below [8].

$$I_{cp} = I_{cn} + I'_c \qquad \text{....(3)}$$

Error value (difference between the actual capacitor voltage and its reference value) is fed to the controller to obtained desired output.

4. ADVANCED CONTROL ACTIVE FILTER (ACAF):

An Advanced Control Active Filter (ACAF) is a sophisticated electronic device used in power systems to mitigate harmonic distortion and improve power quality. Unlike passive filters, which are fixed and offer limited flexibility, ACAFs employ advanced control algorithms and active components to dynamically adjust and compensate for harmonic currents and voltages in real-time [9].

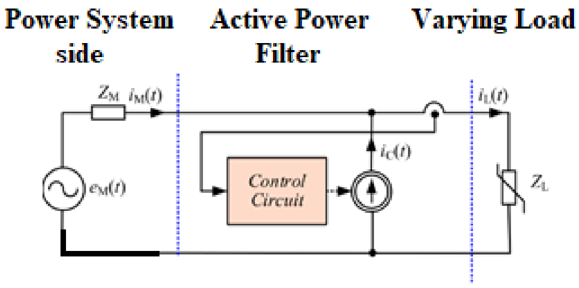

Fig. 2 Advanced Control Active Filter

Here are key features and components of an ACAF:

- ➢ Advanced Control Algorithms
- ➢ Active Components

- Sensing and Monitoring
- Filtering and Compensation
- Adaptability and Flexibility
- Integration with Power Systems
- Performance Monitoring and Optimization

Overall, Advanced Control Active Filters play a crucial role in improving power quality and reducing harmonic distortion in electrical systems [10].

5. FUZZY LOGIC CONTROLLED ADVANCED CONTROL FILTER:

Fuzzy logic is a mathematical framework used for modelling and controlling systems with uncertain or imprecise input data.

FLC employs linguistic variables and fuzzy rules to make decisions based on vague or subjective information.

In the context of an active filter, fuzzy logic is utilized to adaptively adjust the filter parameters in response to varying system conditions and load profiles. Fuzzy logic controllers are particularly effective in handling nonlinear and time-varying systems, making them suitable for dynamic power systems with fluctuating loads [11].

Advanced Control Filtering (ACF):

- Advanced control filtering techniques involve the use of active components and control algorithms to suppress harmonics and improve power quality.
- Active filters generate compensating currents that cancel out harmonic distortions in real-time, ensuring smooth and efficient power delivery.
- ACFs are capable of dynamically adjusting their operation to maintain optimal performance under changing load conditions and harmonic profiles.

Benefits and Applications:

- FLCACFs are well-suited for applications where power quality requirements are stringent and load conditions are variable.
- They can effectively mitigate harmonics caused by nonlinear loads, improve voltage regulation, and enhance overall system stability [12].
- FLCACFs find applications in industrial power systems, renewable energy integration, data centers, and other environments where harmonic distortion and power quality issues are prevalent.

Fuzzy logic controllers for SAPF is designed successfully and implemented to improve the quality of electrical power. It is achieved by maintaining voltage regulation. The error between V_{dcr} and V_{dc} is processed through fuzzy logic controller as shown in Fig. 3.

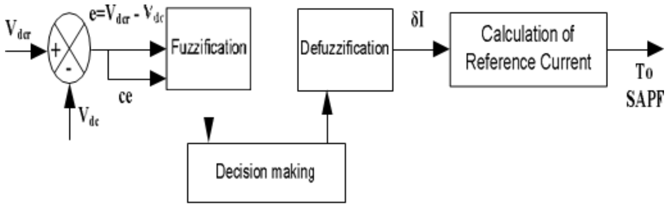

Fig. 3 Fuzzy logic controlled SAPF.

6. SHUNT ACTIVE FILTERS (SAPF)

SAPFs are devices used to compensate for reactive power, harmonics, and other power quality issues in electrical networks. They are connected in parallel (shunt) with the load and inject compensating currents to cancel out harmonic currents and correct power factor [13].

Proportional-Integral (PI) Controller:

- A PI controller is a common type of feedback control mechanism used in systems where precise control of a process variable is required.
- The PI controller calculates an output signal based on the error between the desired setpoint and the actual measured value of the process variable.
- The proportional term responds to the current error, while the integral term accounts for past errors over time, providing steady-state control.

Fuzzy Logic Control (FLC):

- Fuzzy logic is a mathematical framework that deals with uncertainty and imprecision by using linguistic variables and fuzzy rules.
- FLC allows for the creation of rules based on expert knowledge and fuzzy logic principles to make decisions in a complex and uncertain environment [14, 15].

Integration of Fuzzy Control with PI Controller:

- In a Fuzzy Controlled PI Controller for SAPF, fuzzy logic is used to adjust the parameters of the PI controller based on the system's operating conditions.
- Fuzzy rules are defined to map the input variables (e.g., load current, harmonic content, system voltage) to the output control signals of the PI controller.
- The fuzzy system evaluates the current state of the system and determines the appropriate adjustments to the proportional and integral gains of the PI controller.
- This adaptive control approach allows the SAPF to effectively respond to changes in the load profile, harmonic content, and system dynamics, ensuring optimal performance under varying operating conditions [16, 17].

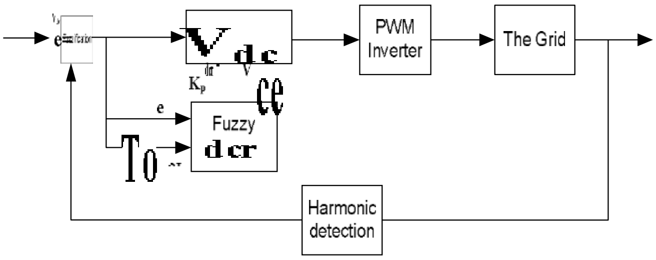

Fig. 4 Fuzzy controlled PI controller for SAPF.

7. FUZZY LOGIC CONTROLLER WITH PLL SYNCHRONIZATION FOR SAPF:

A Fuzzy Logic Controller (FLC) with Phase-Locked Loop (PLL) synchronization for a Shunt Active Power Filter (SAPF) represents a sophisticated control system designed to mitigate harmonics and improve power quality in electrical networks [18]. Here's an overview of how this combined system works:

Shunt Active Power Filter (SAPF):

- SAPF is a power electronics-based device used to compensate for reactive power, harmonic currents, and other power quality issues in electrical systems.
- It is typically connected in parallel (shunt) with the load and injects compensating currents to mitigate harmonic distortion and correct power factor.

Fuzzy Logic Controller (FLC):

- Fuzzy logic control is a control strategy that uses linguistic variables and fuzzy rules to make decisions based on uncertain or imprecise input data.
- FLC allows for the creation of rules based on expert knowledge and system dynamics to adjust the control parameters of the SAPF in real-time [19, 20].

Phase-Locked Loop (PLL):

- PLL is a control system used to synchronize the phase and frequency of a signal with a reference signal.
- In the context of SAPF, PLL is used to detect the fundamental frequency and phase angle of the grid voltage, which is essential for generating the compensating currents accurately [21].

Integration of Fuzzy Logic Controller with PLL Synchronization:

- In a Fuzzy Logic Controller with PLL Synchronization for SAPF, the PLL is used to extract the fundamental components of the grid voltage and current.
- The FLC then analyzes the harmonic content and other system parameters to determine the appropriate compensating currents to inject into the system.
- Fuzzy rules are defined to map the input variables (such as harmonic content, phase angle error, and voltage amplitude) to the output control signals of the SAPF.

The combined system ensures accurate synchronization with the grid and effective harmonic compensation under varying operating conditions [22, 23].

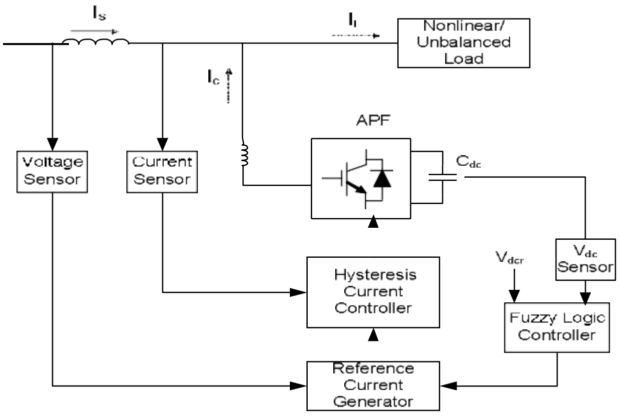

Fig. 5 Fuzzy logic controller with PLL synchronization for SAPF

8. ANN BASED CONTROLLING OF SAPF

An Artificial Neural Network (ANN)-based controlled Shunt Active Power Filter (SAPF) is a sophisticated control system that utilizes neural network algorithms to manage and optimize the operation of the SAPF in electrical networks. Here's an overview of how this system works:

Shunt Active Power Filter (SAPF):

SAPF is a power electronic device used to improve power quality by compensating for reactive power, mitigating harmonics, and correcting power factor in electrical systems. It is typically connected in parallel (shunt) with the load and generates compensating currents to mitigate harmonic distortions and other power quality issues [24, 25].

Artificial Neural Network (ANN):

ANN is a computational model inspired by the structure and function of the human brain. It consists of interconnected nodes (neurons) organized in layers, including input, hidden, and output layers.

ANN can learn from data patterns and adapt its internal parameters to perform various tasks, including pattern recognition, classification, and control [26].

Integration of ANN with SAPF:

In an ANN-based controlled SAPF, the ANN serves as the intelligent controller for adjusting the operation of the SAPF based on system conditions and performance requirements.

The ANN receives inputs such as grid voltage, grid current, harmonic content, and system parameters.

Through a process of training, the ANN learns to map the input variables to the desired output control signals of the SAPF.

During operation, the ANN processes the input data in real-time and generates the appropriate control signals to regulate the compensating currents injected by the SAPF [27, 28].

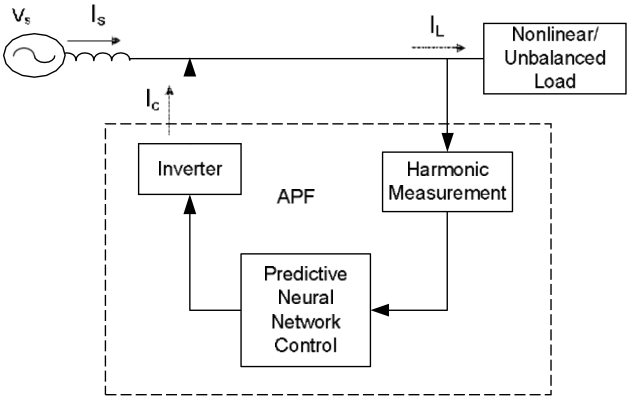

Fig. 6 ANN Based Controlling of SAPF

9. GA BASED ANN BASED CONTROLLING OF SAPF:

Genetic Algorithm (GA) to optimize the parameters of an Artificial Neural Network (ANN) that controls a Shunt Active Power Filter (SAPF). Let's break down the components:

- Shunt Active Power Filter (SAPF): A SAPF is a power electronics-based device used to mitigate harmonics, improve power factor, and regulate voltage in electrical systems. It dynamically injects current into the system to counteract unwanted effects. Artificial Neural Network (ANN): An ANN is a computational model inspired by the structure and function of the biological brain. It consists of interconnected nodes (neurons) organized in layers. ANNs can learn patterns and relationships from data and make predictions or decisions based on that learning. Genetic Algorithm (GA): A GA is a metaheuristic optimization algorithm inspired by the process of natural selection. It is used to evolve solutions to optimization and search problems. GA operates on a population of potential solutions applying genetic operators such as mutation, crossover, and selection to evolve towards better solutions [31, 32].

Here's how the process typically works:

- **Model Design:** Design the architecture of the ANN that will control the SAPF. This includes determining the number of layers, the number of neurons in each layer, and the activation functions.
- **Parameter Optimization:** Define the parameters of the ANN (weights and biases) that need to be optimized to achieve the desired control behaviour of the SAPF [29, 30].
- **Fitness Function:** Define a fitness function that evaluates how well the ANN performs in controlling the SAPF. This could be based on metrics such as Total Harmonic Distortion (THD) reduction, power factor correction, voltage regulation, etc [34].

GA to optimize the parameters of the ANN

- Genetic Algorithm Optimization
- Evolutionary Process
- Validation and Testing

This approach leverages the ability of ANNs to learn complex relationships from data and the optimization capabilities of GAs to efficiently search the solution space for optimal control parameters. It's a powerful technique for tuning the control of complex systems like SAPFs [35, 36].

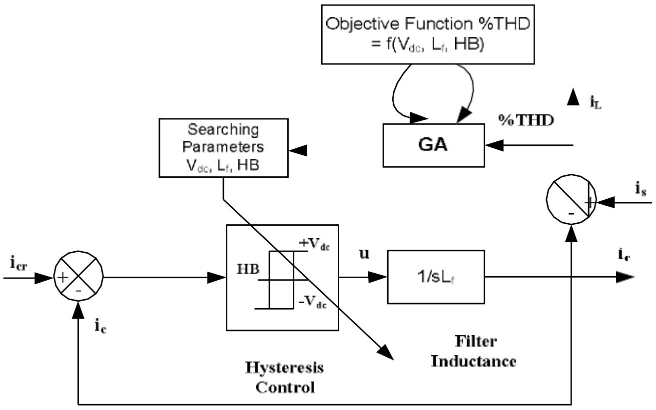

Fig. 7 GA based controlling of SAPF [33].

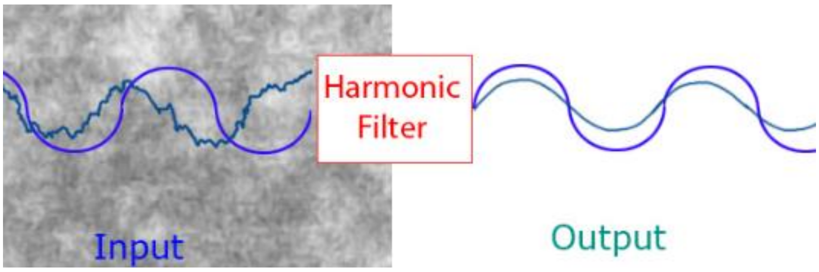

Fig. 8 Wave form of Harmonic filter.

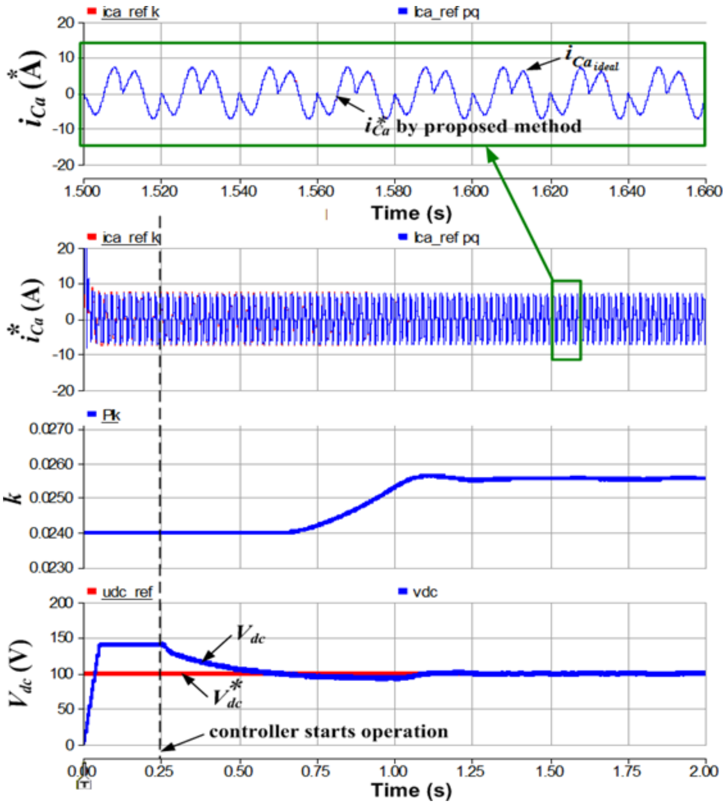

Fig. 9 I, V, k & V_{dc} parameters & plot of Advanced Control Active Filter.

Uncompensated source current, Compensated source current and DC link voltage with PI controller [37, 38].

The clear improvement can be observed in performance of SAPF as given in table.

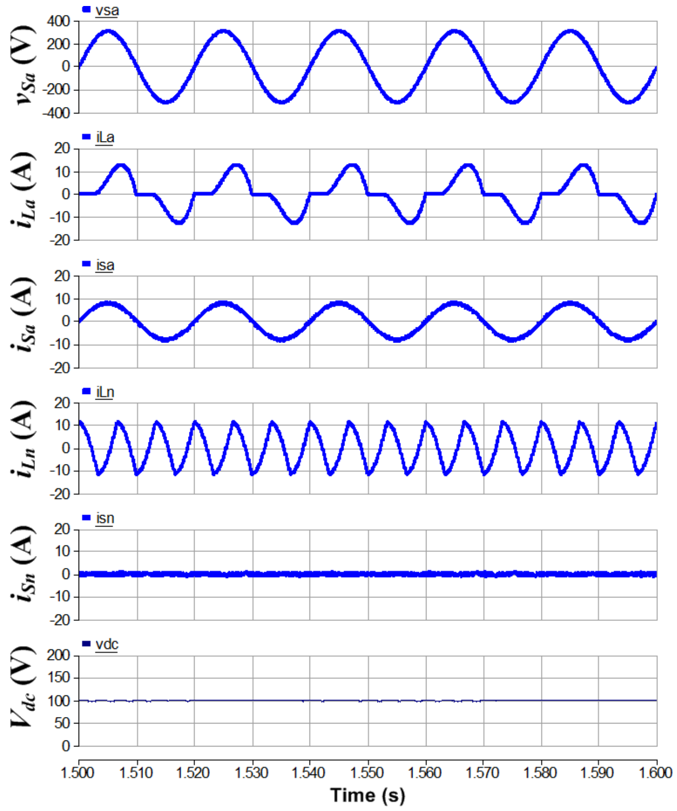

Fig. 10 Compensating performance of Advanced Control Active Filter over conventional method.

Table 1: Comparison between Conventional and Adaptive Controller for SAPF.

Particular	**SAPF with Conventional Controller**	**SAPF with Adaptive Controller**	**Load**
Control Strategy	Fixed control strategy	Adaptive control strategy	NA
Harmonic Reduction Ability	Limited	Enhanced	NA
Performance under Varying Load	May degrade due to fixed control strategy	Maintains performance due to adaptive control strategy	NA
Complexity	Low	High	NA
Cost	Lower	Higher	NA
Response Time	Fixed	Adaptive	NA
Robustness	Limited	Higher	NA
Percentage THD	1.63 %	3.34 %	Load-1
	13.78 %	3.66 %	Load-2
Percentage Drop in V_{dc}	16.8 %	4.07 %	

This table provides a simplified overview. In reality, the comparison would be more nuanced and could depend on specific implementations, load conditions, and system requirements.

10. CONCLUSION

In this paper analysis has been done in between Advanced Control and Conventional Control Technique Applied in Active Filter for Harmonic Reduction under Varying Load. All cases have their own pros and cons. SAPF with Conventional Controller percentage THD is 13.78% which is reduced as 3.66% in case of SAPF with Adaptive Controller and SAPF with Conventional Controller percentage drop in V_{dc} is 16.8% which is reduced as 4.07% in case of SAPF with Adaptive Controller. Above data will helpful for researchers in this field.

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