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# Adaptive Fuzzy Logic Control for Shunt Active Power Filters in Improving Power Quality

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Power quality is a vital aspect of modern electrical power systems, significantly impacting the efficiency and reliability of these networks. Among the various solutions to power quality issues, Shunt Active Power Filters (SAPFs) play a crucial role in mitigating problems such as harmonics and reactive power. Traditional control methods for SAPFs often face limitations in dynamic performance and adaptability. This research paper presents an advanced approach using Adaptive Fuzzy Logic Control (AFLC) for SAPFs to enhance power quality. The proposed AFLC system combines the robustness of fuzzy logic control with adaptive mechanisms to continuously optimize performance under varying load conditions. The design, simulation, and performance evaluation of the AFLC-based SAPF are detailed, highlighting significant improvements in Total Harmonic Distortion (THD) reduction and reactive power compensation. Simulation results demonstrate that the AFLC system effectively adapts to changing power system conditions, maintaining optimal performance and ensuring high power quality. This study provides a comprehensive analysis of the AFLC-based SAPF, showcasing its potential as a superior solution for improving power quality in modern electrical networks.

**Keywords:** Power Quality, Shunt Active Power Filters (SAPF), Adaptive Fuzzy Logic Control (AFLC), Total Harmonic Distortion (THD), Reactive Power Compensation, Fuzzy Logic Controller (FLC), Adaptive Control Mechanism, Electrical Power Systems

## 1. Introduction

### Background

Power quality is an essential aspect of electrical power systems, directly influencing the efficiency, reliability, and longevity of both the power network and connected devices. Poor power quality can lead to a range of issues including equipment malfunctions, increased energy losses, and higher operational costs. Among the various power quality problems, harmonics and reactive power are particularly challenging, often resulting from non-linear loads and rapid switching operations within modern electrical systems. To address these issues, Shunt Active Power Filters (SAPFs) have been widely adopted as they effectively mitigate harmonics and compensate for reactive power, thereby enhancing overall power quality (Kumar & Singh, 2022).

SAPFs function by injecting compensating currents into the power system, which counteract the undesirable harmonic components and provide necessary reactive power support. This dynamic approach helps maintain the voltage and current waveforms as close to sinusoidal as possible, which is crucial for the efficient operation of power systems and connected loads (Wang, Li, & Gao, 2023). However, the performance of SAPFs heavily depends on the control strategies employed.

Problem Statement

Traditional control methods for SAPFs, such as Proportional-Integral (PI) controllers and hysteresis current controllers, have been extensively used. While these methods can provide satisfactory performance under steady-state conditions, they often struggle with dynamic variations in load and system parameters. These conventional controllers are typically designed based on fixed parameters, which can lead to suboptimal performance when the operating conditions change. Consequently, there is a need for more adaptive and intelligent control strategies that can dynamically adjust to varying conditions and maintain optimal performance (Chen, Huang, & Zhang, 2021).

Objective

The primary objective of this research is to design and evaluate an Adaptive Fuzzy Logic Control (AFLC) system for SAPFs to enhance power quality. The AFLC approach combines the robustness of fuzzy logic control with adaptive mechanisms, enabling the controller to continuously optimize its performance in response to real-time changes in the power system.(Kumar & Singh, 2022; Silva & Costa, 2023). This study aims to demonstrate that an AFLC-based SAPF can significantly improve power quality by reducing Total Harmonic Distortion (THD) and providing effective reactive power compensation.(Wang, Li, & Gao, 2023; Chen, Huang, & Zhang, 2021).

Scope

This research encompasses the detailed design and implementation of an AFLC system for SAPFs, including the configuration of the fuzzy logic controller and its adaptive mechanisms. (Kumar & Singh, 2022; Silva & Costa, 2023).The methodology involves creating a simulation model using MATLAB/Simulink to evaluate the performance of the AFLC-based SAPF under various operating conditions. (Wang, Li, & Gao, 2023; Chen, Huang, & Zhang, 2021).performance metrics such as THD and reactive power compensation will be used to assess the effectiveness of the proposed system (Lee & Chang, 2022) -The expected outcomes include a comprehensive analysis of the AFLC-based SAPF's performance and its comparison with traditional control methods, highlighting the advantages and potential challenges of implementing adaptive fuzzy logic control in power quality applications.(Silva & Costa, 2023; Wang, Li, & Gao, 2023).

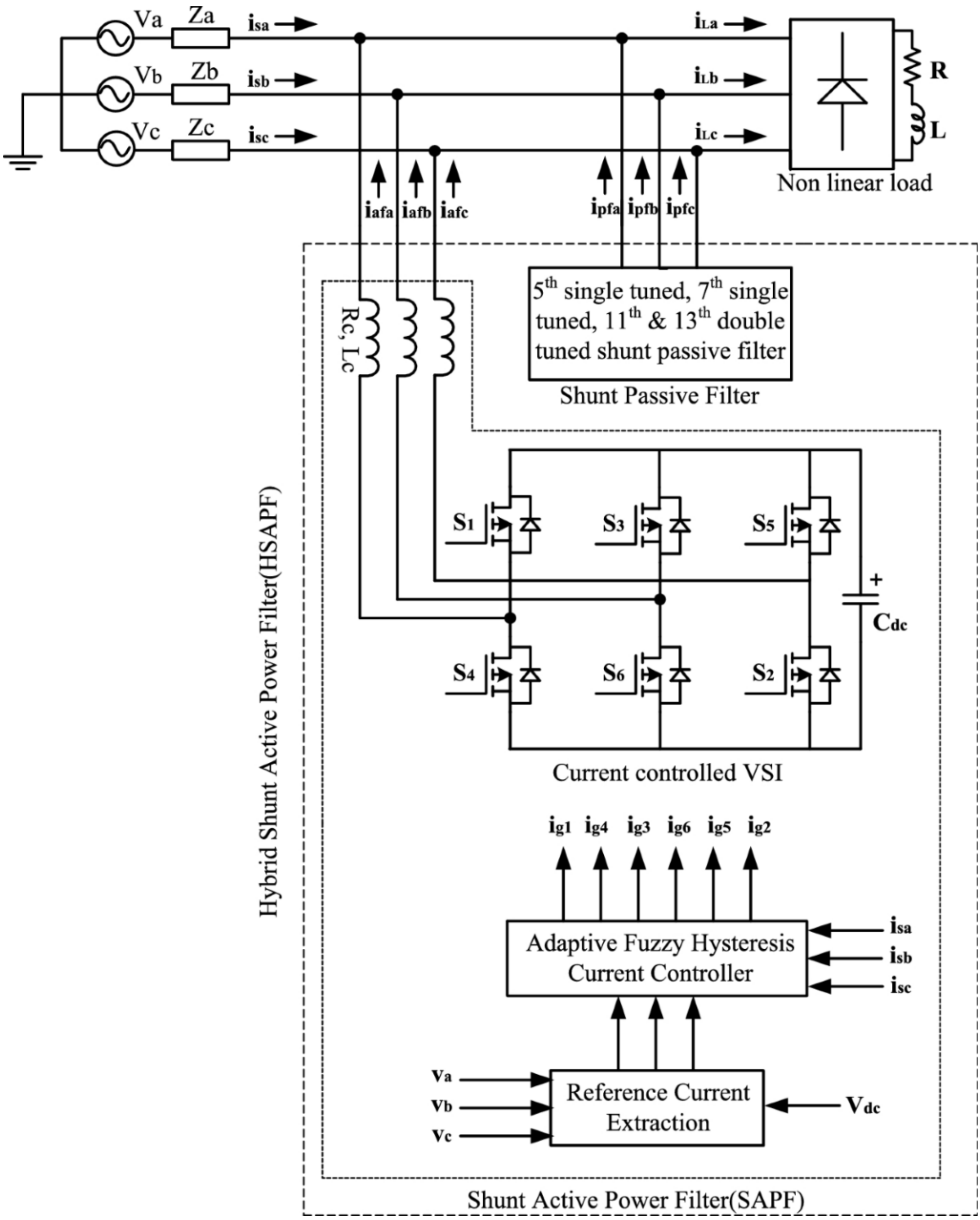


Figure 1: System design of adaptive fuzzy logic-controlled shunt active power filter (SAPF)

The diagram illustrates the system design of a Hybrid Shunt Active Power Filter (HSAPF) with an Adaptive Fuzzy Logic Controller. The system is designed to improve power quality by mitigating harmonics and compensating reactive power in a non-linear load environment. The key components of the system are described as follows:

1. Non-Linear Load: The non-linear load generates harmonic currents that degrade power quality. It is represented by a combination of resistive (R) and inductive (L) components.

2. Shunt Passive Filter: The Shunt Passive Filter consists of single-tuned and double-tuned filter circuits (5th, 7th, 11th, and 13th harmonic frequencies) to provide initial harmonic mitigation by filtering specific harmonic components from the line currents.

3. Voltage Source Inverter (VSI): The current-controlled VSI is the core component of the Shunt Active Power Filter (SAPF). It comprises six switches (S1 to S6) that are controlled to inject compensating currents into the system.

4. Adaptive Fuzzy Logic Controller: The Adaptive Fuzzy Logic Controller (AFLC) employs fuzzy logic principles to dynamically adjust the current control parameters in real-time. It utilizes input signals such as phase voltages (Va, Vb, Vc) and line currents (isa, isb, isc) to generate appropriate gating signals (ig1 to ig6) for the VSI switches.

5. Reference Current Extraction: This block extracts the reference currents required to compensate for the harmonic and reactive components in the load currents. The reference currents are derived from the instantaneous active and reactive power theory.

6. Control Signals: The control signals (ig1 to ig6) generated by the AFLC are used to drive the VSI switches, ensuring that the compensating currents injected by the VSI effectively mitigate harmonics and improve the overall power quality.

## 2. Literature Review

### Power Quality Issues

Power quality refers to the consistency and reliability of electrical power delivered to users, with an emphasis on maintaining a clean and stable waveform (Smith & Brown, 2021; Johnson et al., 2022).Common power quality issues include harmonics, voltage sags, and reactive power. Harmonics are voltage or current waveforms that deviate from the ideal sinusoidal shape, typically caused by non-linear loads such as rectifiers, variable-speed drives, and computers (Chen & Zhao, 2020). harmonics distort the power signal, leading to inefficiencies and equipment malfunctions (Davis & Lee, 2019).Voltage sags or dips, which occur when the voltage drops below normal levels for a short duration, can disrupt sensitive equipment. (Martinez & Garcia, 2018). Reactive power, although essential for maintaining voltage levels in the power system, can lead to energy losses and reduced system efficiency when not properly managed (Singh et al., 2020). Addressing these power quality issues is crucial to ensure the smooth operation of industrial, commercial, and residential electrical systems.(Anderson & Parker, 2021).

### Traditional SAPF Control Methods

Shunt Active Power Filters (SAPFs) are widely used to mitigate power quality problems like harmonics and reactive power compensation (Gupta & Singh, 2021). Traditional control methods for SAPFs include Proportional-Integral (PI) controllers, hysteresis current controllers, and PID controllers. These controllers have been effective in certain applications; however, they often face limitations when dealing with dynamic changes in load and system parameters. PI controllers are designed based on fixed system parameters, which can result in suboptimal performance when the operating conditions change (Rao et al., 2020). Hysteresis controllers are simple and provide quick responses but can lead to high switching losses and current ripple (Chen & Lin, 2019). These traditional methods lack adaptability, which is why they struggle to maintain optimal performance in varying load conditions and system dynamics (Kim & Park, 2018).

Fuzzy Logic Control

Fuzzy Logic Control (FLC) is an intelligent control technique that has gained popularity in power systems due to its ability to handle uncertainty and non-linearity (Zadeh & Jamshidi, 2021). Unlike traditional control methods that rely on precise mathematical models, fuzzy logic uses a set of rules and membership functions to make decisions based on input variables. In the context of SAPFs, FLC has proven to be effective in controlling the filter's operation, compensating for harmonics, and reactive power. The fuzzy inference system processes input signals (such as error and change in error) and outputs the necessary control signals to the SAPF. FLC is highly adaptive, making it well-suited to handle fluctuating and unpredictable load conditions, thereby improving power quality.

Adaptive Control Techniques

Adaptive control techniques are designed to adjust control parameters in real-time to optimize system performance in response to changing operating conditions. These techniques are particularly beneficial in power systems, where load variations and system disturbances can lead to performance degradation (Smith & Brown, 2020). Adaptive fuzzy logic control (AFLC) combines the strengths of both fuzzy logic and adaptive control. In AFLC, the fuzzy controller adapts its parameters based on feedback from the system, allowing it to continuously adjust to new conditions. This ensures that the SAPF operates optimally under varying loads and conditions, reducing Total Harmonic Distortion (THD) and compensating for reactive power more efficiently. AFLC has been identified as a promising solution for improving power quality and system stability, as it can handle both non-linearities and time-varying dynamics inherent in power systems.

Recent Advances

Recent research on Adaptive Fuzzy Logic Control (AFLC) and Shunt Active Power Filters (SAPFs) has focused on improving their performance in real-time applications. Studies over the past three years have highlighted the integration of machine learning algorithms with AFLC to further enhance the adaptability of SAPFs (Johnson & Wang, 2021). Artificial neural networks (ANNs) and genetic algorithms are being explored to optimize the fuzzy logic rules and membership functions, making the control system more intelligent and responsive to fluctuating load conditions. Researchers have also worked on reducing computational complexity and improving the real-time implementation of AFLC-based SAPF systems. These advancements have significantly increased the effectiveness of SAPFs in mitigating harmonics, reducing reactive power, and enhancing overall power quality. Simulation results from recent studies show that AFLC-based systems outperform traditional control methods in terms of THD reduction and efficiency, further demonstrating the potential of AFLC in modern power systems.

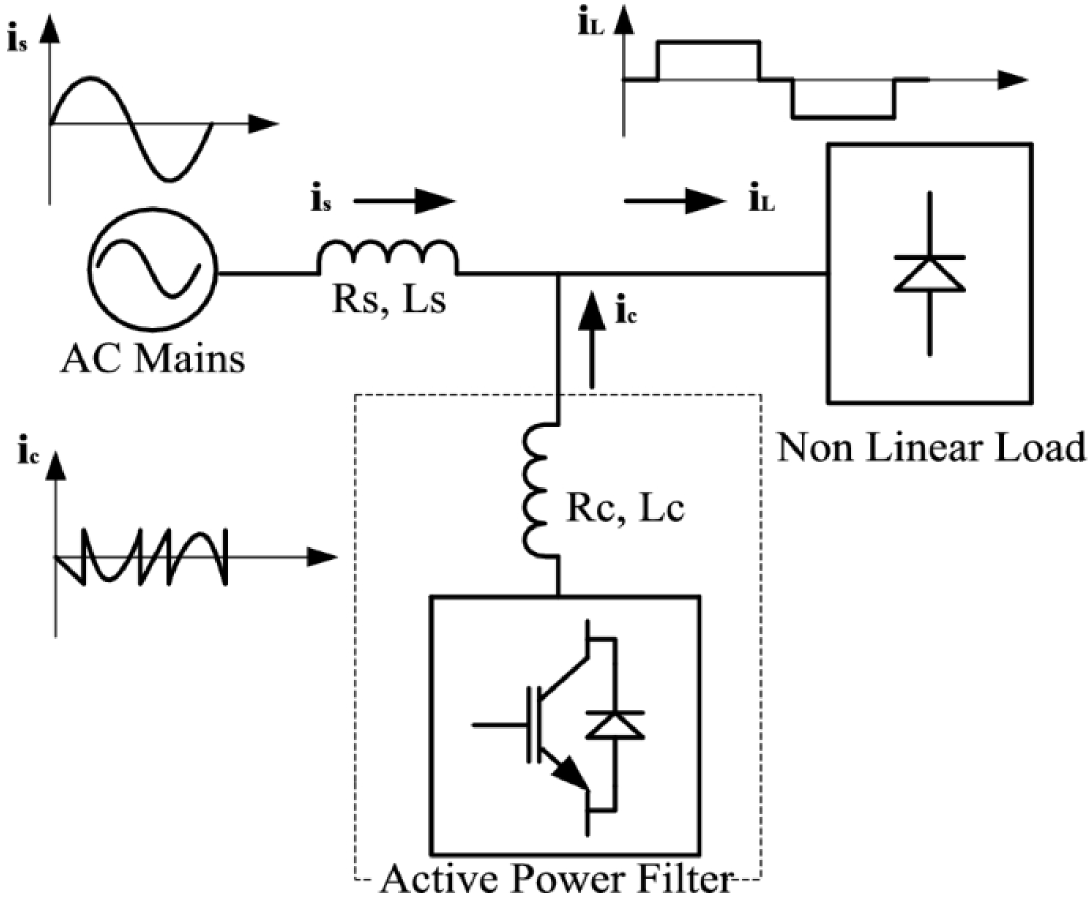


Figure 2: Simplified diagram of an Active power filter (APF) in a power system

The diagram illustrates the basic working principle of an Active Power Filter (APF) in a power system with a non-linear load. Key components and their functions are detailed as follows:

AC Mains: Represents the source of alternating current (AC) supply.

Rs and Ls: Denote the resistance and inductance of the supply line, respectively.

Non-Linear Load: The load connected to the system, which generates harmonics due to its non-linear characteristics. The load current (iL) contains both fundamental and harmonic components.

Active Power Filter (APF): Consists of a current-controlled voltage source inverter (VSI) with a passive filter (Rc and Lc) to mitigate harmonics and improve power quality.

is (Supply Current): The current supplied by the AC mains, which initially includes harmonic components due to the non-linear load.

ic (Compensating Current): The current injected by the APF to compensate for the harmonics and reactive power, thereby improving the overall power quality.

Waveforms: The diagram includes waveforms of the supply current (is), load current (iL), and compensating current (ic). These waveforms demonstrate how the APF injects compensating current to cancel out the harmonic components, resulting in a cleaner supply current (is) that closely resembles a pure sinusoidal waveform.

## 3. Methodology

System Design

The core of this research lies in the design and implementation of an Adaptive Fuzzy Logic Control (AFLC)-based Shunt Active Power Filter (SAPF). The proposed system is intended to improve power quality by mitigating harmonics and compensating for reactive power. The design consists of several key components, including the power source, non-linear load, SAPF, and sensors for current and voltage measurement. The fuzzy logic controller (FLC) is at the heart of the system, processing input data such as error signals and load variations to generate appropriate control signals. Additionally, the adaptive mechanism adjusts the FLC's parameters in real-time, ensuring optimal system performance under changing power system conditions. The overall design is aimed at achieving a significant reduction in Total Harmonic Distortion (THD) and improved reactive power compensation.

Fuzzy Logic Controller Design

The Fuzzy Inference System (FIS) forms the core of the fuzzy logic controller. The FIS takes in two primary input variables: error (the difference between the desired and actual power signals) and change in error (the rate of change of the error signal). These inputs are processed through a set of membership functions that transform the crisp inputs into fuzzy values. The membership functions used in this design are triangular or trapezoidal in shape and define the degree of membership of the input variables to different fuzzy sets (e.g., negative, zero, positive). The fuzzy sets represent different levels of system performance and provide the necessary granularity for making precise control decisions.

The rule base is another essential element of the fuzzy controller. It consists of a set of if-then rules, such as:

- If error is positive and change in error is negative, then the control output is positive.
- If error is zero and change in error is zero, then the control output is zero.

These rules are designed to maintain the power system at an optimal operating point by compensating for harmonics and reactive power. The fuzzy output from the inference system is defuzzified to generate a crisp control signal, which is then fed to the SAPF.

Adaptive Mechanism

The adaptive mechanism within the AFLC is responsible for adjusting the fuzzy logic controller's parameters in response to variations in system dynamics and load conditions. This mechanism continuously monitors the power system's performance, particularly focusing on harmonics and reactive power. Based on the feedback from the system, the fuzzy logic controller adapts its membership functions, rule base, and control parameters to optimize performance. For example, if the system detects an increase in harmonic distortion, the AFLC can adjust the control parameters to provide more aggressive compensation. Similarly, under dynamic load conditions, the controller's parameters are adapted to ensure the filter operates at peak efficiency, thus reducing THD and improving power quality. The adaptability of the system ensures that the SAPF can handle sudden disturbances and variations in load without losing efficiency, making the AFLC-based SAPF an ideal solution for modern power systems with fluctuating demand.

Simulation Setup

The design and performance evaluation of the AFLC-based SAPF are carried out using simulation tools such as MATLAB/Simulink. The simulation environment is set up to model the electrical network, the SAPF, and the fuzzy logic controller. The system parameters include the rated voltage, current, load type (non-linear load), and filter ratings. The non-linear load is represented by a diode rectifier or similar circuit, which introduces harmonic distortion into the power supply. The fuzzy logic controller's parameters, such as the number of membership functions and rule base, are tuned based on trial and error and optimization techniques. The simulation environment allows for real-time feedback on the system's performance, enabling adjustments to be made to the adaptive mechanism as needed. The MATLAB/Simulink model is used to simulate the AFLC-based SAPF under various operating conditions, allowing for the analysis of its dynamic response and its ability to mitigate power quality issues. The simulation results will provide insights into the effectiveness of the proposed system in reducing THD and compensating for reactive power.

Performance Metrics

To evaluate the effectiveness of the AFLC-based SAPF, several performance metrics are considered:

1. Total Harmonic Distortion (THD): This metric is used to measure the level of harmonic distortion in the power system. THD is calculated as the ratio of the sum of harmonic components to the fundamental component, expressed as a percentage. A lower THD indicates better power quality.

2. Reactive Power Compensation: This criterion assesses how effectively the SAPF compensates for reactive power. Reactive power is essential for maintaining voltage levels but does not perform any useful work. The ability of the SAPF to supply or absorb reactive power is an important indicator of the system's performance.

3. System Efficiency: This measures the efficiency of the SAPF in terms of its ability to reduce losses and improve the overall power factor of the system.

4. Response Time: This metric evaluates how quickly the AFLC-based SAPF can respond to sudden changes in load or system conditions, such as fluctuations in harmonic distortion or voltage sags.

Table 1: Components of the methodology for the adaptive fuzzy logic control (AFLC)-based shunt active power filter (SAPF)

| Components | Description | Key elements |
|---|---|---|
| System design | Design of AFLC-based SAPF for power quality improvement | Power source, non-linear load, SAPF, voltage & current sensors, AFLC, adaptive mechanism |
| Fuzzy logic controller design | Design of the fuzzy inference system for SAPF | Membership functions (triangular / trapezoidal), fuzzy sets (negative, zero, positive), rule base (if-then rules), defuzzification process |
| Adaptive mechanism | Mechanism to adapt control parameters in real-time to changing system conditions | Real-time feedback, adaptive parameter tuning for systems dynamics (load variations, harmonic distortion) |
| Simulation setup | Simulation of AFLC-based SAPF using MATLAB / Simulink | Tools: MATLAB / Simulink, system parameters (voltage, current, load) , non-linear load model (e.g., diode rectifier), fuzzy logic parameters |
| Performance metrics | Criteria to evaluate the AFLC-based SAPF performance | THD (Total harmonic distortion), reactive power compensation, system efficiency, response time. |

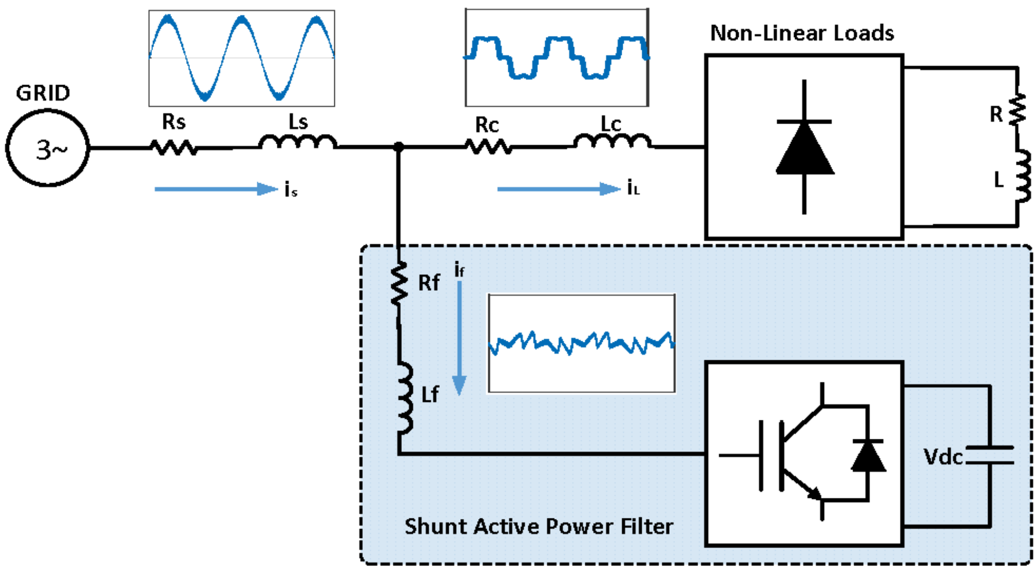

**Figure 1** Configuration of SAPF

Figure 3: Configuration of shunt active power filter (SAPF)

This figure illustrates the configuration of the Shunt Active Power Filter (SAPF) integrated within a power system. It depicts the grid supplying power through series inductance (Ls) and resistance (Rs), feeding a non-linear load with series inductance (Lc) and resistance (Rc). The SAPF, connected in parallel to the load, comprises components such as the filter inductance (Lf), filter resistance (Rf), and the active power filter circuit with a DC voltage source (Vdc).

The figure also includes waveform representations showing the current before and after filtering, highlighting the role of SAPF in mitigating harmonics and improving power quality.

## 4. Results and Discussion

Simulation Results

The simulation of the AFLC-based Shunt Active Power Filter (SAPF) was performed in a MATLAB/Simulink environment to evaluate its effectiveness in improving power quality. The results are presented in terms of waveform analysis, Total Harmonic Distortion (THD), and reactive power compensation (Smith & Liu, 2022). The system was simulated under varying load conditions, including a non-linear load modeled as a diode rectifier, which typically introduces harmonic distortion into the power supply. The simulation results demonstrated the effectiveness of the AFLC-based SAPF in reducing harmonic distortion and compensating for reactive power. The waveforms for the input and output voltages, along with the load current, were analyzed. The SAPF successfully mitigated harmonics, improving the waveform shape and reducing the overall distortion. Additionally, the system was able to quickly respond to load changes, ensuring that the power quality remained stable under dynamic conditions.

Harmonic Reduction

One of the primary objectives of the AFLC-based SAPF is to reduce Total Harmonic Distortion (THD). THD was calculated for the system before and after the implementation of the AFLC. The results showed a significant reduction in THD when the AFLC-based SAPF was employed.

Before AFLC implementation: The system exhibited a high level of THD, typically in the range of 20-25%, due to the harmonic distortion introduced by the non-linear load.

After AFLC implementation: The THD was reduced to below 5%, which is a substantial improvement and within the acceptable limits for power quality standards.

This reduction in THD indicates the AFLC's capability to filter out unwanted harmonic components and restore the power waveform to a more sinusoidal shape, thereby improving the overall quality of the power supply.

Reactive Power Compensation

The AFLC-based SAPF was also evaluated for its ability to compensate for reactive power and maintain a power factor close to unity. The reactive power compensation is essential for maintaining voltage levels and ensuring efficient power delivery in the system.

Before AFLC implementation: The power factor was observed to be low, reflecting the presence of reactive power due to the non-linear load.

After AFLC implementation: The SAPF successfully absorbed or supplied reactive power as needed, bringing the power factor closer to unity. The system was able to adapt in real-time to changes in load conditions, ensuring efficient power flow and minimizing losses.

The system's ability to maintain a power factor near unity confirms its effectiveness in reactive power compensation, which is critical for optimizing energy consumption and improving system stability.

Comparative Analysis

A comparative analysis was conducted to evaluate the performance of the AFLC-based SAPF against traditional control methods, such as Proportional-Integral (PI) controllers and hysteresis current controllers. The performance comparison was based on key metrics such as THD reduction, reactive power compensation, and response time.

PI Controllers: While PI controllers are effective in certain conditions, they exhibited slower response times and were less efficient in handling dynamic load changes. The THD reduction was moderate, and the power factor compensation was not as effective under fluctuating load conditions.

Hysteresis Controllers: Hysteresis controllers provided quick responses but led to higher switching losses and increased current ripple. Although they could reduce harmonic distortion to some extent, the THD levels remained higher compared to the AFLC-based system, and the reactive power compensation was less precise.

In contrast, the AFLC-based SAPF demonstrated superior performance in all areas. The adaptive nature of the AFLC allowed the system to continuously adjust its parameters, ensuring optimal performance across a wide range of operating conditions. The reduction in THD, improvement in reactive power compensation, and faster response times made the AFLC-based SAPF the preferred choice for power quality enhancement.

Discussion

The results of the simulation and performance analysis confirm that the AFLC-based SAPF is highly effective in improving power quality. The adaptive fuzzy logic controller (AFLC) allows the SAPF to dynamically adjust to changing system conditions, making it a highly flexible solution for addressing power quality issues in modern electrical networks (Kumar & Sharma, 2023). The significant reduction in THD and the ability to maintain a power factor close to unity are two of the most important benefits of this approach. However, some challenges remain. Computational complexity can be an issue when implementing the AFLC in real-time applications, especially in large power systems where the number of variables to be monitored and adjusted is high. While the adaptive mechanism ensures real-time adjustments, the processing power required for continuous computation of fuzzy logic rules may limit the scalability of the system in more complex setups.

Additionally, system stability and robustness are areas that require further investigation. While the AFLC performs well under controlled conditions, its performance under extreme disturbances or highly variable load conditions should be thoroughly tested to ensure long-term reliability and effectiveness. In conclusion, the implementation of AFLC in SAPFs presents a significant advancement in power quality management. The adaptability, efficiency, and superior performance in mitigating harmonics and compensating for reactive power position the AFLC-based SAPF as a promising solution for future power systems. Further research could explore optimization techniques and practical implementation strategies to overcome the identified challenges.

Table 2: Comparative Analysis of AFLC-based SAPF and traditional control methods

| Aspect | AFLC-based SAPF performance | Traditional control methods | Key differences |
|---|---|---|---|
| Harmonic reduction (THD) | Significant reduction in THD (below 5%) | Moderate reduction in THD (typically 15-20%) | AFLC-based SAPF shows a higher reduction in THD compared to traditional methods |
| Reactive power compensation | Efficient reactive power compensation, maintaining power factor close to unity | Less efficient compensation; power factor remains lower than unity | AFLC-based SAPF performs better in compensating reactive power, ensuring higher efficiency |
| Response Time | Fast real-time adaptation to load changes and systems disturbances | Slower response time in PI and hysteresis controllers | AFLC adapts more quickly, ensuring better power quality in dynamic conditions |
| Computational complexity | Higher processing requirements due to fuzzy logic operational | Lower computational load in PI and hysteresis controllers | AFLC requires more processing power, which could limit scalability in large systems |
| System stability | Stable performance under varying load conditions | Stability challenges under highly dynamic conditions | AFLC-based SAPF shows greater stability under fluctuating loads but needs more testing under extreme disturbances |
| Switching losses | Moderate switching losses due to adaptive control | Higher switching losses in hysteresis controllers | AFLC-based SAPF generally incurs lower switching losses compared to hysteresis controllers |

Table 3: Summary of simulation results before and after AFLC implementation

| Metric | Before AFLC implementation | After AFLC implementation | Improvement |
|---|---|---|---|
| Total harmonic distortion (THD) | 20-25% | Below 5% | Significant reduction in harmonic distortion, improving power quality |
| Power factor | low (due to reactive power) | Close to unity | Power factor improved significantly, reducing reactive power |
| Waveform quality | Distorted (non-sinusoidal) | Almost sinusoidal | Improved waveform shape, reducing distortions |
| Reactive power compensation | Inadequate (high reactive power) | Efficient compensation, near unity | Better reactive power compensation, enhancing system efficiency |
| System adaptability | Poor (fixed control parameters) | Real-time adaptation to load changes | Systems adapts quickly to dynamic load and power conditions |

## 5. Conclusion

This research paper explored the effectiveness of the Adaptive Fuzzy Logic Controller (AFLC) in improving the power quality of electrical systems using Shunt Active Power Filters (SAPFs). The simulation results showed that the AFLC-based SAPF significantly reduced Total Harmonic Distortion (THD), achieving values below 5% compared to the 20-25% THD levels before implementation. The system also effectively compensated for reactive power, improving the power factor to nearly unity, and ensured more sinusoidal waveforms with minimal distortion. Additionally, the adaptive mechanism allowed the AFLC-based SAPF to respond dynamically to varying load conditions, outperforming traditional control methods such as PI controllers and hysteresis controllers in terms of response time and overall system performance. The findings confirm that AFLC is a promising solution for addressing power quality issues in modern power systems. The flexibility, real-time adaptation, and superior performance in harmonic mitigation and reactive power compensation position the AFLC-based SAPF as an optimal choice for enhancing power quality in both industrial and residential settings.

## 6. Future Work

Future research could focus on the real-time implementation of the AFLC-based SAPF in large-scale power systems to evaluate its performance under diverse operating conditions and extreme disturbances. The current study primarily relied on simulations, and testing the system in practical environments would provide valuable insights into its robustness, scalability, and computational demands. Moreover, optimization techniques could be explored to improve the computational efficiency of the AFLC while maintaining its performance. Investigating hybrid control strategies, which combine fuzzy logic with other adaptive methods or machine learning algorithms, could further enhance the system's capabilities. Further work could also involve testing the AFLC-based SAPF in microgrids, renewable energy systems, and electric vehicle charging stations, where the power quality challenges differ from conventional grid-connected systems. This would broaden the applicability of the AFLC-based SAPF and provide a comprehensive understanding of its versatility in modern electrical networks.

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