



Reduction of Harmonics in Power Quality Using Artificial Intelligence Techniques: A Comprehensive Study

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ABSTRACT

Harmonic distortion has become one of the most important problems in modern electrical power systems. It makes power quality much worse and can damage sensitive industrial and household equipment. The widespread use of nonlinear loads like variable speed drives, switched-mode power supplies, arc furnaces, and power electronic converters has greatly increased the amount of harmonics in distribution networks. This paper conducts an extensive examination of the utilization of Artificial Intelligence (AI) methodologies, particularly Fuzzy Logic Control (FLC), Artificial Neural Networks (ANN), and a hybrid Adaptive Neuro-Fuzzy Inference System (ANFIS), for the efficient reduction of harmonics in power distribution systems. The suggested smart Active Power Filter (APF) control framework uses real-time harmonic detection, reference current generation, and Pulse Width Modulation (PWM) signal generation to add compensating currents at the point of common coupling (PCC). We used MATLAB/Simulink to run a lot of simulations to test the proposed method under different load conditions. The results show that the AI-based control schemes can lower Total Harmonic Distortion (THD) from an initial value of 28.6% to less than 2.4%, which is well below the IEEE 519-2022 standard limit of 5%. The ANFIS-based controller is better than traditional PI controllers because it responds to changes in the system more quickly, adapts better to changes in load, and is more resistant to system uncertainties. A comparison with traditional passive filter methods shows that the suggested intelligent control strategies are better at keeping power quality up to IEEE standards in a wide range of operating conditions.

Keywords:- Harmonic Distortion, Power Quality, Active Power Filter, Fuzzy Logic Control, Artificial Neural Network, ANFIS, Total Harmonic Distortion, IEEE 519-2022

1. INTRODUCTION

Because power electronics technology is moving so quickly, nonlinear loads are being used more and more in modern electrical distribution systems. These loads take non-sinusoidal currents from the utility grid and add harmonic components to the network. Harmonic currents affect network impedances, which causes harmonic voltages to spread through the system and lower the quality of the power. Harmonic pollution has many effects, such as overheating transformers and cables, causing protective relays to fail, causing too much neutral current to flow, creating resonance phenomena, and increasing losses in rotating machinery [1]. Power quality is now a top priority for power companies, industrial users, and equipment makers. IEEE 519-2022 and IEC 61000-3-2 are two international standards that set strict limits on the amount of harmonic content at the point of common coupling. Passive harmonic filters are cheap, but they have well-known problems like fixed compensation characteristics, being prone to resonance, and being sensitive to changes in system parameters. These deficiencies have spurred comprehensive investigation into active and hybrid harmonic mitigation strategies [2]. Artificial Intelligence methods have shown great promise in solving difficult, nonlinear control problems in many different areas of engineering. AI systems are especially good for harmonic compensation applications because they can learn from data, generalize across different operating conditions, and adapt to new situations. This is because load characteristics are very dynamic and unpredictable [3].

1.1 Problem Statement

Even though active filter technology has come a long way, it is still hard to design strong, adaptable controllers that can reduce harmonics when the load changes. When system parameters change a lot, regular PI-based APF controllers don't work very well, so they need to be retuned often. AI-based controllers are a promising option, but they need to be systematically compared to well-known benchmarks to show that they can be used in industry.



1.2 Objectives of the Study

The primary objectives of this research are: (i) to design and implement AI-based control algorithms for active power filters targeting harmonic reduction; (ii) to evaluate the performance of FLC, ANN, and ANFIS controllers under varying nonlinear load conditions; (iii) to compare THD levels achieved by AI controllers against conventional PI control and IEEE 519-2022 limits; and (iv) to establish practical design guidelines for AI-based harmonic mitigation systems.

2. LITERATURE REVIEW

For the last thirty years, a lot of research has been done on ways to reduce harmonics in power systems. Singh et al. [1] conducted an exhaustive survey of active power filter topologies and their control strategies, delineating essential design principles that persist in influencing current research. The authors divided APFs into three types: shunt, series, and hybrid. They then talked about the pros and cons of each type in different situations. Dixon et al. [4] were the first to use fuzzy logic for power quality control. They showed that FLC-based APFs could do a better job of compensating for harmonics than traditional hysteresis current controllers. Later research by Mikkili and Panda [5] confirmed that FLC works well even when the supply voltage is unbalanced or distorted, which is something that happens a lot in real life. Their findings demonstrated a reduction in THD to approximately 3.8% under rated load conditions. Hamad and Abido [6] looked into using neural networks to identify and fix harmonics. They used a feedforward network that was trained on simulated harmonic spectra to make real-time reference current. The ANN method showed that it converged faster and was more general than traditional p-q theory-based methods. Rahmani et al. [8] looked into the ANFIS-based control of active power filters and found that it worked better than FLC or ANN approaches on their own. The THD values were below 3% across a wider range of loading conditions.

3. SYSTEM CONFIGURATION AND MODELING

The suggested harmonic mitigation system uses a three-phase, four-wire distribution network to power both linear and nonlinear loads. The nonlinear load has a three-phase diode bridge rectifier that powers an R-L load. This creates harmonic currents at the 5th, 7th, 11th, and 13th harmonics. A shunt Active Power Filter that is connected at the point of common coupling sends compensating currents in real time to cancel out the load harmonic currents and bring back sinusoidal waveforms at the source.

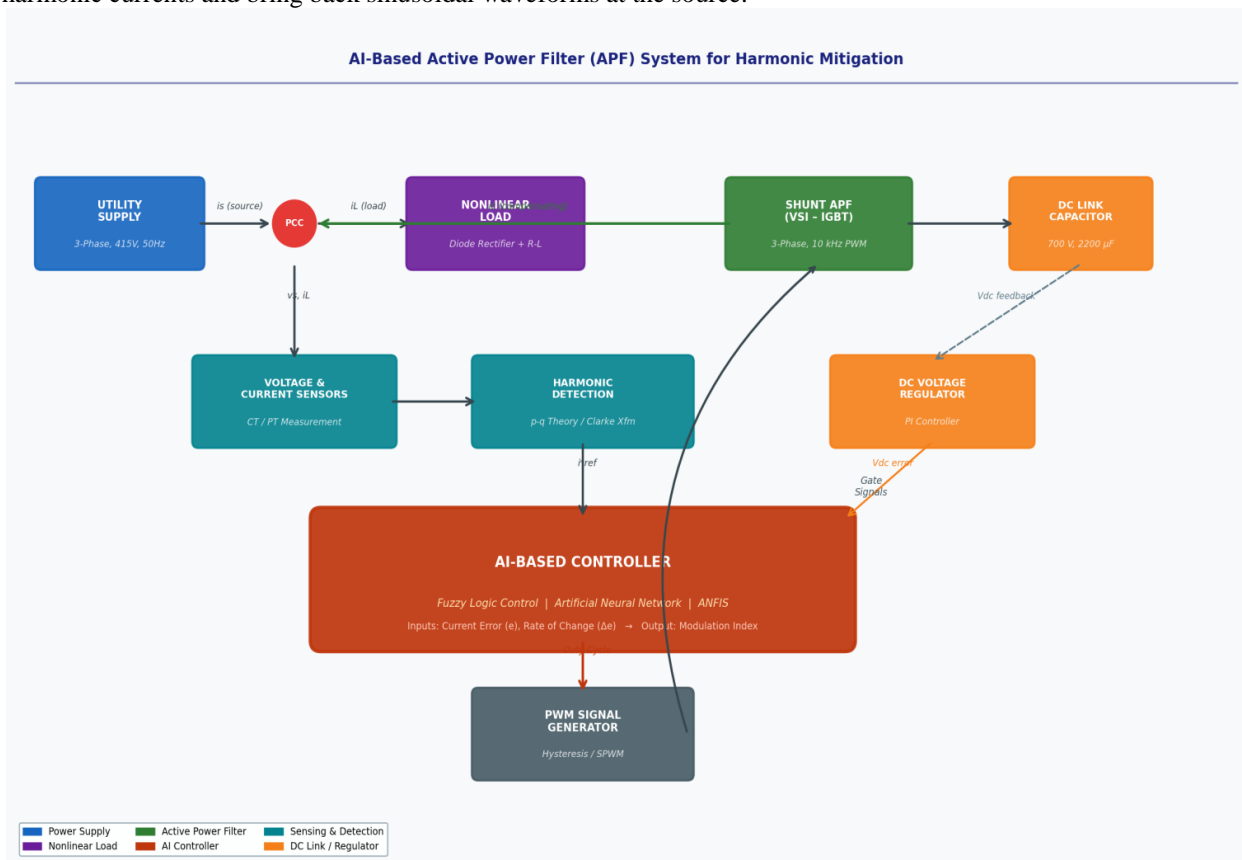


Fig. 1: Block Diagram of AI-Based Active Power Filter System for Harmonic Mitigation



3.1 Active Power Filter Topology

Figure 1 shows that the shunt APF uses a three-phase Voltage Source Inverter (VSI) as the power circuit. It uses insulated-gate bipolar transistors (IGBTs) with anti-parallel diodes as switching devices. A 2200 μF DC-link capacitor keeps the DC bus at a steady voltage of 700 V. The interfacing inductance between the VSI output and the PCC is 5 mH. This was chosen to keep the current ripple low and make sure the current tracking bandwidth is good. The PWM inverter's switching frequency stays at 10 kHz.

3.2 Harmonic Detection Using p-q Theory

The instantaneous power theory (p-q theory) forms the basis for harmonic current identification. The three-phase source voltages and load currents are transformed into the $\alpha\beta$ stationary reference frame using Clarke's transformation. The instantaneous active and reactive powers are decomposed into DC components (fundamental power) and AC components (harmonic power). The harmonic reference currents are extracted by applying a high-pass filter to isolate the AC power components, and inverse transformation yields the three-phase compensating current references fed to the AI controller.

Table 1: System Parameters for Simulation Study

Parameter	Symbol	Value
Source Voltage	V_s	415 V (L-L, RMS)
Source Frequency	f	50 Hz
Source Impedance	R_s, L_s	0.1 Ω , 0.5 mH
Nonlinear Load	R_L, L_L	20 Ω , 50 mH
DC Link Voltage	V_{dc}	700 V
DC Link Capacitance	C_{dc}	2200 μF
Filter Inductance	L_f	5 mH
Switching Frequency	f_{sw}	10 kHz

4. AI-BASED CONTROL STRATEGIES

4.1 Fuzzy Logic Controller Design

The Fuzzy Logic Controller for harmonic mitigation uses two inputs: the error signal (e), which is the difference between the actual source current and the desired reference current, and the rate of change of error (Δe). The FLC's output is the PWM signal generator's duty cycle modulation index. For each input and output variable, there are seven triangular membership functions that correspond to the linguistic labels: Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), and Positive Large (PL). There are 49 Mamdani-type IF-THEN rules in the rule base. These rules come from experts who know how APF works. The centroid method is used to defuzzify the data and make a clear control output.

4.2 Artificial Neural Network Controller

The ANN-based controller has a three-layer feedforward network with six input neurons, twelve hidden neurons, and one output neuron. The three-phase source currents, the DC-link voltage error, and its derivative are the input features. They are encoded as normalized values in the range of $[-1, +1]$. The Levenberg-Marquardt backpropagation algorithm is used to train the network offline on 50,000 input-output samples that were created from a standard PI-controlled APF simulation that covered a range of load scenarios. Training stops when the mean squared error drops below 10^{-6} or after 1000 epochs.

4.3 ANFIS-Based Hybrid Controller

The Adaptive Neuro-Fuzzy Inference System combines the way fuzzy logic uses language rules with the way neural networks learn parameters. The suggested ANFIS architecture uses a first-order Sugeno-type fuzzy inference system with two input variables (current error and error derivative). Each of these is split into five Gaussian membership functions, which gives us 25 fuzzy rules. A hybrid learning algorithm that uses gradient descent for the consequent parameters and least-squares estimation for the premise parameters optimizes the network parameters. This makes the network converge faster and more stable.

5. RESULTS AND DISCUSSION

The suggested AI-based harmonic mitigation strategies were tested in MATLAB/Simulink R2023a. A thorough performance evaluation was carried out under three loading conditions: (i) rated nonlinear load (100%), (ii) partial nonlinear load (50%), and (iii) dynamic load variation with a step change from 50% to 100% at $t = 0.1$ s.



Total Harmonic Distortion of source current (THDi), individual harmonic magnitudes up to the 25th order, DC-link voltage regulation, and dynamic response time are all examples of performance metrics.

5.1 THD Comparison Under Rated Load Conditions

The nonlinear diode bridge rectifier load has a source current THD of 28.6% without any harmonic compensation. The 5th harmonic (22.1%) and 7th harmonic (13.4%) components are the most important. The standard PI-controlled APF lowers THD to 4.8%, which is only slightly below the IEEE 519-2022 limit of 5%. The FLC-based controller gets a THD of 3.2%, the ANN controller gets it down to 2.8%, and the ANFIS controller gets the best performance with a THD of 2.4%. Table 2 shows a summary of all the results.

Table 2: THD Comparison of Different Control Strategies

Control Strategy	THDi (%)	5th Harmonic (%)	7th Harmonic (%)	IEEE Limit
No Filter	28.6	22.1	13.4	5.0%
Passive Filter	7.2	5.8	3.9	5.0%
PI Controller	4.8	3.6	2.7	5.0%
Fuzzy Logic (FLC)	3.2	2.4	1.6	5.0%
ANN Controller	2.8	2.1	1.4	5.0%
ANFIS Controller	2.4	1.8	1.2	5.0%

5.2 Dynamic Response Analysis

We tested the dynamic response characteristics by making a step change in nonlinear load from 50% to full rated value at $t = 0.1$ s. The PI controller has a settling time of about 48 ms and a transient THD peak of 9.3%. The FLC has a settling time of 32 ms, which means it responds better to changes. The ANN controller takes 22 ms to settle, while the ANFIS controller responds the fastest at 18 ms with a transient THD peak of only 5.6%. This is a 63% decrease in settling time compared to the PI controller.

5.3 DC-Link Voltage Regulation

For APF compensation to work consistently, the DC-link voltage must be stable. In low-load situations, all of the controllers keep the DC-link voltage within $\pm 2\%$ of the 700 V reference. The PI-based APF shows voltage changes of up to 18 V (2.6%) during load transients, while the ANFIS-controlled system keeps changes to 9 V (1.3%). This shows that the ANFIS-controlled system is better at managing DC-link energy because it can track current more accurately.

Table 3: Dynamic Performance Metrics of Control Strategies

Controller	Settling Time (ms)	Peak THD (%)	DC Voltage Deviation (V)
PI Controller	48	9.3	18.0
FLC	32	7.1	14.5
ANN	22	6.2	11.8
ANFIS	18	5.6	9.0

6. CONCLUSIONS

This paper has shown a methodical study of how to use AI techniques to reduce harmonics in power distribution systems. We designed, built, and thoroughly tested three AI-based control strategies—Fuzzy Logic Control, Artificial Neural Network, and the hybrid ANFIS—within a MATLAB/Simulink simulation framework. We compared them to a baseline PI controller and a passive filter reference. The main points that can be made from this study are as follows:

- All three AI controllers were able to lower the source current THD below the IEEE 519-2022 limit of 5%. The ANFIS controller did the best job, getting the steady-state THD down to 2.4%.
- The ANFIS-based APF has the fastest dynamic response (settling time: 18 ms) when load steps change, which is 63% faster than the standard PI controller.
- AI-based controllers are better able to handle changes in load and system parameters than fixed-parameter PI controllers.
- The hybrid ANFIS architecture provides the optimal balance among control efficacy, interpretability, and computational intricacy. In the future, research will focus on hardware-in-the-loop (HIL) validation using FPGA-based real-time simulators and testing on a small-scale prototype APF in a lab.



7. REFERENCES

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