International Journal of Trend in Scientific Research and Development (IJTSRD)
Volume 10 Issue 5, Sep-Oct 2026 Available Online: www.ijtsrd.com e-ISSN: 2456 – 6470

ANFIS-Based Intelligent PWM Control for Harmonic Mitigation and Power Quality Enhancement in Multilevel Inverter-Based Active Power Filters

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ABSTRACT

The growing use of non-linear loads such as rectifiers, variable-frequency drives and power electronic converters injects harmonic currents into distribution networks, which raise losses, overheat equipment and degrade power quality. Shunt active power filters (APFs) built on multilevel inverters can cancel these harmonics, but their performance depends heavily on the pulse width modulation (PWM) controller that decides the switching instants. Conventional PI, hysteresis and artificial neural network (ANN) based controllers either need careful tuning, switch at variable frequency, or require long training and still lose accuracy under changing load conditions. This paper proposes an adaptive neuro-fuzzy inference system (ANFIS) based intelligent PWM controller for a cascaded H-bridge (CHB) multilevel inverter based shunt APF. The ANFIS block combines the reasoning of fuzzy logic with the learning ability of neural networks to adapt the modulation index and the switching instants of the H-bridge cells to the measured harmonic content of the load current. The filter is modelled in MATLAB/Simulink (R2018a) in five-level and seven-level configurations. The proposed controller reduces the total harmonic distortion (THD) to 0.15%, compared with 3.59% for an ANN-based PWM controller, while delivering 300 V / 6 A at five levels and 500 V / 10 A at seven levels. The results confirm that ANFIS-based PWM control is an effective route to harmonic mitigation and power quality enhancement in multilevel inverter-based APFs.

KEYWORDS: *Active power filter (APF), adaptive neuro-fuzzy inference system (ANFIS), cascaded H-bridge, harmonic mitigation, multilevel inverter, power quality, pulse width modulation (PWM), total harmonic distortion (THD).*

How to cite this paper: Dipak Pandit Kawar | Pramod Kumar Rathore "ANFIS-Based Intelligent PWM Control for Harmonic Mitigation and Power Quality Enhancement in Multilevel Inverter-Based Active Power Filters" Published in International Journal of Trend in Scientific Research and Development (ijtsrd), ISSN: 2456-6470, Volume-10 | Issue-5, October 2026, pp.1729-1735, URL: www.ijtsrd.com/papers/ijtsrd142288.pdf

IJTSRD142288

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I. INTRODUCTION

Reliable, distortion-free electrical power is essential for modern industry, yet the wide use of non-linear loads makes it hard to guarantee. Rectifiers, uninterruptible power supplies, variable-speed drives and renewable energy interfaces draw non-sinusoidal currents. These currents cause harmonic distortion, reactive power demand, voltage imbalance, extra heating and premature failure of equipment. Passive LC filters are simple but bulky, fixed-tuned and prone to resonance with the grid. Active power filters (APFs) overcome these limits by measuring the distortion in real time and injecting an equal and opposite compensating current through a power electronic inverter.

Recent work has focused on improving APF control and integrating APFs with renewable sources. Mishra et al. [1] combined a hybrid renewable energy system with a shunt APF and placed the renewable source on the dc side of the filter. This stabilised the dc-link voltage and reduced THD for balanced and unbalanced non-linear loads under ideal and distorted grid conditions. Multilevel inverters (MLIs) are attractive for APFs at medium and high power because they produce stepped waveforms with lower

dv/dt and lower harmonic content. Chamarthi et al. [2] proposed enhanced level-shifted and phase-shifted PWM schemes for cascaded five-level NPC H-bridge inverters, which balanced switch utilisation and junction temperature and reached about 2.3% THD and 97.8% efficiency on a 1 kVA prototype. Buccella et al. [3] introduced pulse active width modulation for l-level cascaded H-bridge (CHB) inverters to suppress low-order harmonics in line with EN 50160 and CIGRE limits.

Selective harmonic mitigation has also been studied for asymmetric structures. Zhang et al. [4] developed a power-matching selected harmonic mitigation PWM (SHM-PWM) for asymmetric CHB inverters and solved for the switching angles with improved particle swarm optimisation. Zhang et al. [5] addressed zero-sequence circulating current in parallel three-level four-leg converters that perform APF duties, using space vector modulation with non-adjacent redundant vectors and PI plus feedforward control. The choice of modulation strongly affects losses and THD. Biswas et al. [6] proposed a modified reference saturated third-harmonic injected equal-loading PWM that reduced THD and conversion losses in voltage source converter (VSC) based renewable systems. Zhang et al. [7] designed a three-layer discontinuous PWM for the Vienna rectifier with an LCL filter, which balanced the neutral point and reduced resonant current and zero-crossing distortion.

Photovoltaic (PV) systems are a major driver of these studies. Mishra et al. [8] built a PV-fed shunt active harmonic filter in which the reference current was generated with a PI controller and hysteresis current control. Shen and Chung [9] used hybrid PWM with soft voltage transition and a nonlinear output inductor to reduce ground leakage current and ripple in a transformerless PV inverter. Sarker et al. [10] implemented high-definition sinusoidal PWM on an FPGA to lower inverter output harmonics with real-time adjustment of the modulation index. Intelligent methods have also appeared: Moeini et al. [11] applied Q-learning to selective harmonic current mitigation PWM for grid-connected converters, trading switching losses against filter size. Raj and Bhattacharjee [12] showed that an LCL filter is still needed to remove voltage and current harmonics in double-stage grid-connected PV plants. Dalai et al. [13] used sinusoidal PWM with phase-shift modulation to cut current distortion in single-phase grid-connected PV systems. Mebrahtu et al. [14] combined a shunt APF with space vector PWM to keep industrial THD within IEEE limits. Moeini and Wang [15] proposed asymmetric selective harmonic current and voltage modulation PWM for CHB converters in electric vehicle charging stations to meet power quality standards.

These studies show three persistent gaps. First, most controllers rely on fixed-gain PI or hysteresis loops whose performance degrades when the load changes. Second, offline-optimised SHE or SHM patterns [3], [4], [15] require heavy computation and cannot easily track dynamic harmonic profiles. Third, ANN-based controllers adapt better but need large training sets, many iterations and careful selection of layers and neurons, and they act as black boxes. An adaptive neuro-fuzzy inference system (ANFIS) addresses these gaps. It learns from input–output data like a neural network but keeps an interpretable fuzzy rule base, and it trains quickly with a hybrid least-squares and back-propagation algorithm.

The main contributions of this paper are as follows:

1. A shunt APF based on a cascaded H-bridge multilevel inverter is modelled in five-level and seven-level configurations.
2. An ANFIS-based intelligent PWM controller is developed that adapts the modulation index and the switching instants of the H-bridge cells to the measured harmonic content of the load current.
3. The proposed controller is evaluated through FFT analysis in MATLAB/Simulink and compared with an ANN-based PWM controller in terms of THD, output voltage and output current.

The rest of the paper is organised as follows. Section II describes the system configuration. Section III presents reference current generation and conventional PWM control. Section IV details the proposed ANFIS-based PWM controller. Section V discusses the simulation results, and Section VI concludes the paper.

II. System Configuration

The proposed shunt APF is connected in parallel with a non-linear load at the point of common coupling (PCC), as in the shunt topologies of [1], [8] and [14]. The filter injects a compensating current so that the source supplies only the fundamental, in-phase component of the load current. By Kirchhoff's current law at the PCC:

$$i_s(t) - i_L(t) - i_c(t) \qquad (1)$$

where i_s is the source current, i_L the load current and i_c the current injected by the APF. The load current contains a fundamental active part, a fundamental reactive part and a harmonic part:

$$i_L(t) = I_1 \sin(\omega t \quad \phi_1) + \sum_{h=3}^{\infty} I_h \sin(h\omega t \quad \phi_h) \qquad (2)$$

For ideal compensation, the APF must supply the reactive and harmonic parts so that i_s becomes sinusoidal and in phase with the supply voltage.

A. Cascaded H-Bridge Multilevel Inverter

The power stage is a cascaded H-bridge (CHB) inverter, chosen for its modularity and its fine control of the compensating voltage [2], [3], [15]. Each H-bridge cell has four IGBTs (Q1–Q4) and an isolated dc capacitor of voltage V_{dc}. Turning on Q1 and Q4 gives $+V_{dc}$, turning on Q2 and Q3 gives $-V_{dc}$, and turning on Q1–Q3 or Q2–Q4 gives 0. With N identical cells in series per phase, the inverter output voltage and the number of levels are:

$$v_o(t) = \sum_{k=1}^{N} v_{H,k}(t), \qquad m = 2N + 1 \qquad (3)$$

Two cells (N = 2) give a five-level waveform and three cells (N = 3) give a seven-level waveform; both are studied in this paper. More levels make the stepped output closer to a sine wave, which lowers harmonic content and reduces the size of the coupling filter.

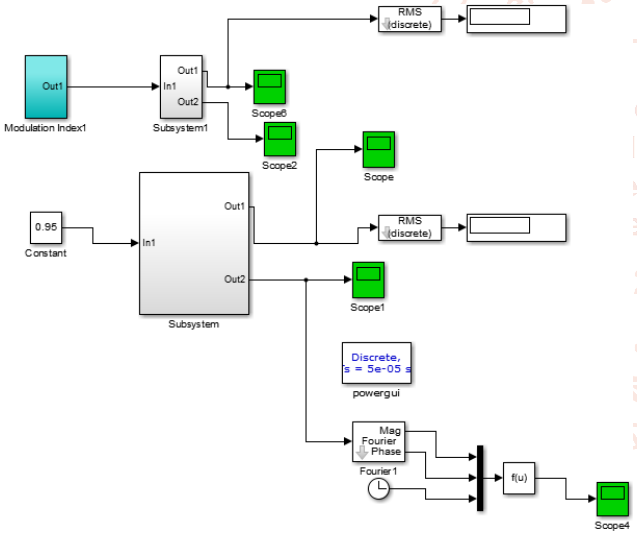


Fig. 1. Simulink model of the proposed CHB multilevel inverter based shunt APF.

B. Coupling Filter and DC Link

The inverter is connected to the PCC through a series RLC branch that smooths the switching ripple of the injected current. The dc-link capacitor of each cell must hold a steady voltage, since fluctuations disturb compensation and raise switching losses [1]. The dc-link voltage is regulated by a PI loop whose output sets the small active current the APF draws to cover its own losses:

$$I^*_{loss} = K_p\, e_{dc}(t) + K_i \int e_{dc}(t)\, dt \qquad (4)$$

where $e_{dc} = V_{dc}^* - V_{dc}$ is the dc-link voltage error.

III. Reference Current Generation and Conventional PWM Control

A. Reference Compensating Current

The controller first extracts the fundamental active component of the load current, I_{1p}, and adds the loss current from the dc-link loop. The desired source current is a sinusoid in phase with the unit template $u(t) = v_s(t)/V_{sm}$ of the supply voltage:

$$i_s^*(t) = \left(I_{1p} + I^*_{loss}\right) u(t) \qquad (5)$$

The reference compensating current is then the difference between the measured load current and this desired source current:

$$i_c^*(t) - i_L(t) - i_s^*(t) \qquad (6)$$

The current error $e(t) = i_c^*(t) - i_c(t)$ drives the modulator. How quickly and accurately this error is driven to zero decides the harmonic performance of the APF.

B. Level-Shifted Sinusoidal PWM

For multilevel inverters, carrier-based sinusoidal PWM (SPWM) is the most common method because it is simple and switches at a fixed frequency [2], [10], [13]. In level-shifted (phase-disposition) SPWM, $m - 1$ triangular carriers of equal frequency f_c and peak-to-peak amplitude A_c are stacked vertically and compared with one modulating signal of amplitude A_m. The amplitude modulation index and frequency ratio are:

$$m_a = \frac{2A_m}{(m-1)A_c}, \qquad m_f = \frac{f_c}{f_m} \qquad (7)$$

A switch in a cell turns on when the modulating signal exceeds the carrier assigned to that cell. When $m_a = 0$ there is no output, at $m_a = 0.5$ the fundamental output is half of the reference, and at m_a = 1 the output fundamental equals the reference. Above 1 the inverter enters over-modulation and low-order harmonics rise.

C. Limitations of Conventional Controllers

Hysteresis current control keeps the injected current inside a fixed band around its reference. It responds fast but its switching frequency varies with load, which spreads the harmonic spectrum and complicates filter design [8]. PI-based PWM operates at a fixed frequency, but fixed gains are tuned for one operating point and lose accuracy when the harmonic profile changes. Offline SHE/SHM patterns [3], [4], [15] eliminate selected harmonics precisely but need heavy computation and stored angle tables. ANN-based PWM adapts to changing loads but requires large training data, many iterations and trial-and-error selection of the network structure. These limits motivate a controller that adapts online, trains quickly and stays interpretable.

IV. Proposed ANFIS-Based Intelligent PWM Controller

The proposed controller replaces the fixed-gain PWM stage with an ANFIS block that sets the modulation index and the switching instants of the H-bridge cells in real time. Its overall flow is: sense the load current, extract the reference compensating current, compute the current error and its rate of change, let ANFIS adjust the modulating signal, generate level-shifted PWM pulses for the CHB cells, and verify the result by FFT analysis.

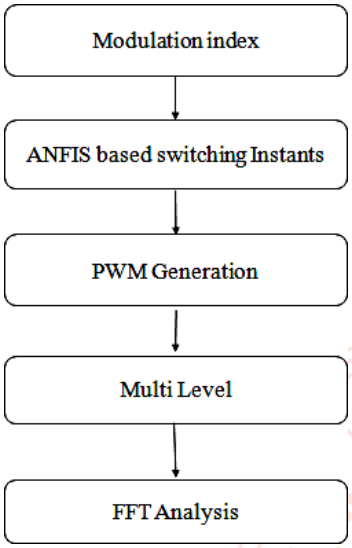


Fig. 2. Flow diagram of the proposed ANFIS-based PWM APF.

A. ANFIS Structure

ANFIS is a first-order Takagi–Sugeno fuzzy system whose parameters are tuned by neural network learning. It uses two inputs: the current error $e(k)$ and its change $\Delta e(k) = e(k) - e(k-1)$. For two inputs x and y, a typical rule i reads:

$$\text{IF } x \text{ is } A_i \text{ AND } y \text{ is } B_i \text{ THEN } f_i = p_i x + q_i y + r_i \qquad (8)$$

The network has five layers.

Layer 1 (fuzzification): Each node computes a membership grade using a generalised bell function with premise parameters a_i, b_i and c_i:

$$\mu_{A_i}(x) = \frac{1}{1 + \left|\frac{x - c_i}{a_i}\right|^{2b_i}} \qquad (9)$$

Layer 2 (rule firing): Each node multiplies incoming grades to give the firing strength of a rule:

$$w_i = \mu_{A_i}(x)\,\mu_{B_i}(y) \qquad (10)$$

Layer 3 (normalisation): Each firing strength is divided by the sum of all strengths:

$$\bar{w}_i = \frac{w_i}{\sum_j w_j} \qquad (11)$$

Layer 4 (consequent): Each node weights its linear rule output with consequent parameters p_i, q_i and r_i:

$$O_{4,i} = \bar{w}_i f_i = \bar{w}_i (p_i x + q_i y + r_i) \qquad (12)$$

Layer 5 (output): A single node sums all rule outputs to give the correction to the modulation signal:

$$\Delta m(k) = \sum_i \bar{w}_i f_i \qquad (13)$$

B. Hybrid Learning

ANFIS is trained with a hybrid algorithm. In the forward pass the premise parameters are held fixed and the consequent parameters are found by least-squares estimation. In the backward pass the error is propagated back and the premise parameters are updated by gradient descent. The training error minimised is:

$$E = \frac{1}{2}\sum_{k=1}^{P}\left(i_c^*(k) - i_c(k)\right)^2 \qquad (14)$$

where P is the number of training pairs. Training data are taken from the APF model under a range of load conditions. Because the consequent parameters are solved in one step, ANFIS converges in far fewer epochs than a back-propagation ANN of similar accuracy.

C. ANFIS-Based Modulation Index and Switching Instants

The ANFIS output updates the modulating signal before it is compared with the stacked carriers:

$$v_m(k) = [m_a + \Delta m(k)]\,\frac{i_c^*(k)}{I_{c,max}} \qquad (15)$$

The adapted signal is limited to the linear range ($0 \le m_a + \Delta m \le 1$) to avoid over-modulation. Three effects follow. First, the modulation index tracks the harmonic content of the load current, so the injected voltage is just large enough to cancel the distortion. Second, the crossing points of v_m with the carriers, which are the switching instants of each IGBT, shift adaptively with the operating condition. Third, the cascaded structure lets each H-bridge cell take a share of the compensating voltage, which gives fine control of amplitude and phase. The PWM generator then applies the resulting gate pulses to Q1–Q4 of every cell.

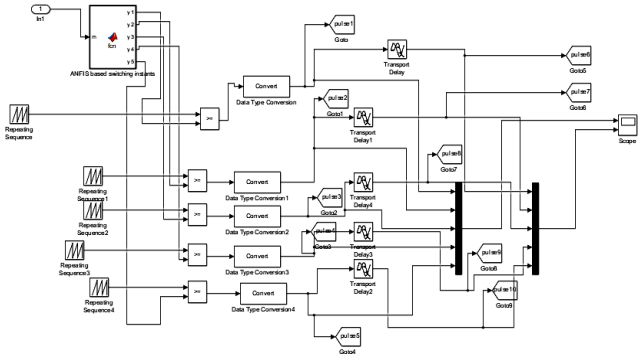


Fig. 3. ANFIS-based switching instants and PWM generation model.

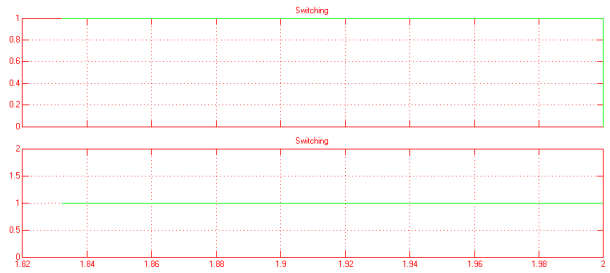


Fig. 4. Switching sequence of the H-bridge.

V. Simulation Results and Discussion

The proposed ANFIS-based PWM APF cuts the THD to 0.15%, against 3.59% for the ANN-based controller, a reduction of about 95.8%. The system was modelled in MATLAB/Simulink (MATLAB 9.4, R2018a) using SimPowerSystems blocks for the IGBT H-bridges, the RLC coupling branch, the measurement units and the FFT analysis tool. Each H-bridge, its gate logic and its measurements were built as a subsystem so that the five-level and seven-level models share the same structure. The main simulation settings are listed in Table I.

TABLE I. Simulation Parameters of the Proposed APF

Parameter	Five-level APF	Seven-level APF
Controller	ANFIS-based PWM	ANFIS-based PWM
H-bridge cells per phase (N)	2	3
Switching devices	IGBT	IGBT
Output voltage (V)	300	500
Output current (A)	6	10
Fundamental frequency (Hz)	60	60
Simulation platform	MATLAB / Simulink R2018a	MATLAB / Simulink R2018a

A. Modulation Index and Switching Behaviour

The modulation index generation subsystem (Fig. 5) supplies the reference signals that the ANFIS block adapts before comparison with the carriers. In the switching-instant model (Fig. 3), four repeating-sequence carriers are compared with the adapted modulating signal to produce the gate pulses of the five-level inverter, which matches the m − 1 carriers required by level-shifted PWM. The H-bridge switching sequence follows the expected pattern: Q1 and Q4 for positive output, Q2 and Q3 for negative output, and Q1–Q3 or Q2–Q4 for the zero state.

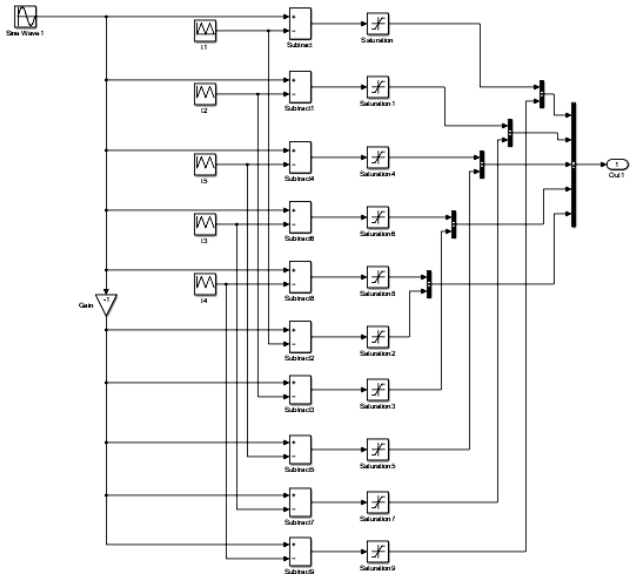


Fig. 5. Modulation index generation subsystem.

B. Five-Level Operation

In the five-level configuration the APF produces a clean five-step output voltage of 300 V and an output current of 6 A. Both waveforms show five distinct levels between their positive and negative peaks, which confirms correct level generation by the two cascaded cells.

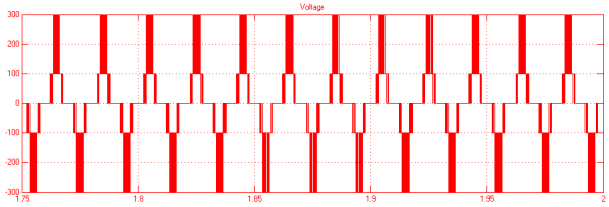


Fig. 6. Five-level output voltage.

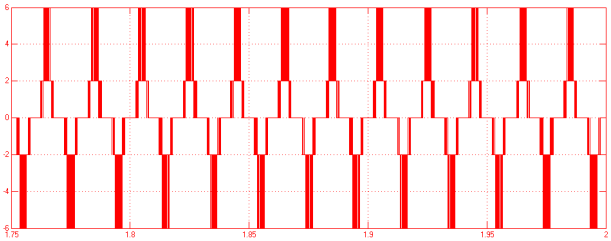


Fig. 7. Five-level output current.

C. Seven-Level Operation

Adding a third cell raises the output to seven levels, 500 V and 10 A. Both waveforms show seven distinct levels, and the finer voltage steps bring the output closer to a sine wave than the five-level case. The APF continually adjusts this current to the measured harmonic content of the load, which keeps the source current nearly sinusoidal.

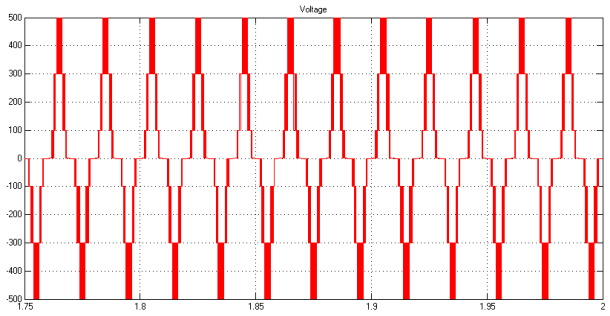


Fig. 8. Seven-level output voltage.

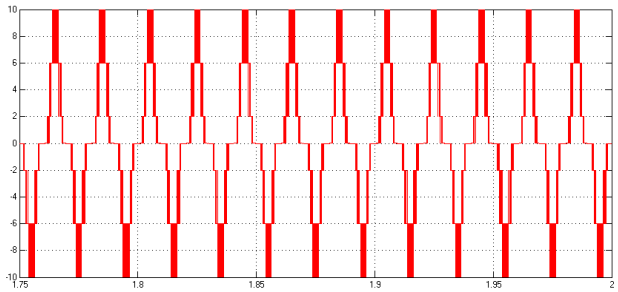


Fig. 9. Seven-level output current.

D. Harmonic Analysis

THD measures the harmonic content of a waveform relative to its fundamental:

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \times 100\% \qquad (16)$$

FFT analysis of the grid current over five cycles gives a fundamental (60 Hz) component of 9.468 A and a THD of 0.15% (Fig. 10). This is far below the 5% current distortion limit commonly applied under IEEE Std 519 and well below the values reported for PWM-based harmonic mitigation schemes such as [2] and [14].

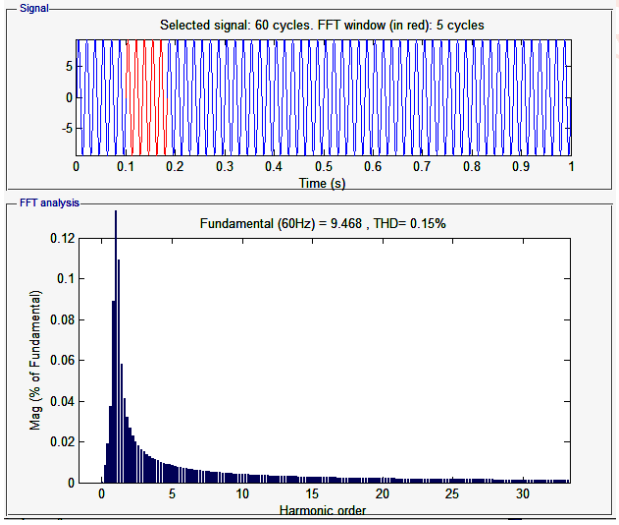


Fig. 10. FFT spectrum of the grid current with the proposed ANFIS-based APF (THD = 0.15%).

E. Comparison with the ANN-Based Controller

Table II compares the proposed controller with an ANN-based PWM controller for the same APF application.

TABLE II. Performance Comparison

Parameter	ANN-based PWM (previous work)	ANFIS-based PWM (proposed)
Output voltage	200 V	300 V (5-level), 500 V (7-level)
Output current	Not reported	6 A (5-level), 10 A (7-level)
THD	3.59%	0.15%

The proposed controller performs better for three reasons. The fuzzy rule base captures the non-linear link between current error and required modulation, which the hysteresis and fixed-gain controllers cannot represent. Hybrid learning tunes the rule parameters in few epochs, unlike the long iterative training of the ANN. The multilevel CHB stage lets these finer control decisions turn into finer voltage steps, which directly lowers THD.

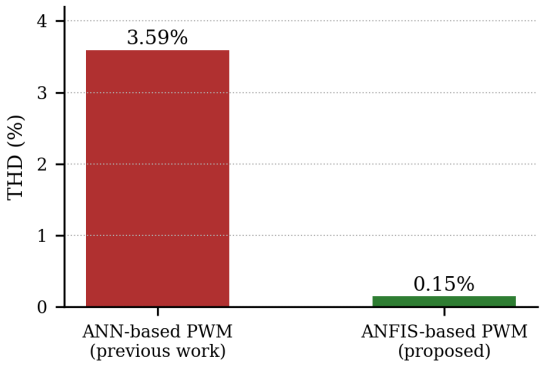


Fig. 11. THD comparison of previous and proposed work.

VI. Conclusion

This paper presented an ANFIS-based intelligent PWM controller for a cascaded H-bridge multilevel inverter based shunt active power filter. The ANFIS block adapts the modulation index and the switching instants of the H-bridge cells to the measured harmonic content of the load current, combining the interpretability of fuzzy logic with the learning ability of neural networks. MATLAB/Simulink results show that the proposed APF delivers 300 V / 6 A in five-level operation and 500 V / 10 A in seven-level operation, and reduces THD to 0.15% compared with 3.59% for an ANN-based PWM controller. The controller trains faster than an ANN, needs no stored switching-angle tables and keeps distortion well within IEEE Std 519 limits.

Future work will cover hardware validation on a DSP or FPGA platform, reduction of the ANFIS computational load for real-time use, testing under unbalanced and distorted grid voltages, and integration of the APF with renewable sources and energy storage in smart grid settings.

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