INTERNATIONAL JOURNAL OF NOVEL RESEARCH AND DEVELOPMENT (IJNRD)
© 2026 IJNRD | Volume 11, Issue 4, April 2026 | ISSN: 2456-4184 | IJNRD.ORG

HYBRID PSO-ANFIS CONTROL FOR HARMONIC MITIGATION IN A REDUCED-SWITCH SEVEN-LEVEL INVERTER FOR GRID-CONNECTED DERS

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Abstract : As global utility frameworks transition toward the widespread integration of Distributed Energy Resources (DERs), such as solar photovoltaics and wind energy, the role of power electronic inverters has become critical to grid stability. In grid-connected architectures, the Point of Common Coupling (PCC) serves as the critical interface between the Distributed Energy Resource (DER) and the utility network. Consequently, maintaining superior voltage quality at the PCC is of greater regulatory significance than the raw inverter output, as it directly impacts the power quality delivered to other interconnected loads. This paper presents an optimized Selective Harmonic Elimination (SHE) strategy for a 7-level reduced switch inverter topology aimed at improving power quality in Distributed Energy Resource (DER) systems. Multilevel inverters are essential for DC-to-AC conversion, traditional Cascaded H-Bridge [1] (CHB) topologies for 7-level outputs require 12 power switches, leading to increased hardware costs, switching losses, and system complexity. To address this, a Reduced Switch Topology is employed, utilizing only 7 switches [3] to achieve a 7-level waveform.

This paper presents first the harmonic mitigation by using NR method was presented, after that a hybrid Particle Swarm Optimization (PSO) and Adaptive Neuro-Fuzzy Inference System (ANFIS) controller is proposed to minimize the THD and the harmonic contents of the inverter output voltage. The PSO algorithm is utilized to perform an offline global search for optimal switching angles $(\alpha 1, \alpha 2, \alpha 3)$ which are subsequently used to train the ANFIS network for real-time, adaptive control. The switching angles are to be employed for a seven-level reduced switch [2] multilevel inverter connected to an ac power grid. The NR method and PSO-ANFSI method for calculating switching angles were implemented in the MATLAB/Simulink environment. The results show the effectiveness of the PSO-ANFSI optimization method.

Keywords: Multilevel Inverter, switching angles, Reduced Switch Topology, Selective Harmonic Elimination (SHE), PSO-ANFIS, Newton-Raphson, Total Harmonic Distortion (THD).

I. INTRODUCTION

In the contemporary industrial landscape, high-power and medium-voltage applications—such as industrial motor drives and utility-scale grid interfaces—demand robust power electronic solutions. Since single power semiconductor switches cannot be directly connected to medium-voltage grids due to voltage rating limitations, multilevel inverters (MLIs) have emerged as the standard alternative. Beyond achieving high power ratings, MLIs are ideally suited for interfacing renewable energy sources like photovoltaics, wind, and fuel cells into the grid. The primary advantages of MLIs include enhanced medium-voltage capability, reduced switching losses, lower dv/dt stress, and significantly improved electromagnetic compatibility. Among the various architectures—including Neutral Point Clamped (NPC) and Flying Capacitor (FC) types, the Cascaded H-Bridge (CHB) and its derivatives, such as the reduced switch topology used in this research, are preferred for their modularity and efficiency.

A critical factor in MLI performance is the determination of optimal switching angles. To maximize efficiency and minimize switching losses, strategies operating at the fundamental switching frequency are employed, where devices commute only once per cycle to generate a staircase output waveform. Specifically, the Selective Harmonic Elimination Pulse Width Modulation (SHE-PWM) technique is utilized to target the elimination of lower-order harmonics. As the number of inverter levels increases, the harmonic content naturally decreases; however, the mathematical complexity of the system also rises. For grid-connected systems, the voltage quality at the Point of Common Coupling (PCC) [9] is of greater concern than the inverter output itself. Achieving high-quality power at the PCC requires solving complex, non-linear transcendental equations to determine the precise switching angles. Traditionally, iterative numerical methods like the Newton-Raphson [6] (NR) approach have been used. However, these methods suffer from a heavy reliance on accurate initial guesses and often fail to converge across a wide range of modulation indices.

To address these limitations, this paper proposes an intelligent hybrid control strategy combining Particle Swarm Optimization (PSO) and an Adaptive Neuro-Fuzzy Inference System (ANFIS). By utilizing PSO for global optimization and ANFIS for real-time estimation, this research aims to provide a robust solution for minimizing Total Harmonic Distortion (THD) at the PCC, ensuring compliance with stringent grid standards.

1.1. CHB vs Reduced Switch Inverter Topology

The hardware configuration utilized in this study is a Reduced Switch Multilevel Inverter (RS-MLI). Unlike the traditional Cascaded H-Bridge (CHB) which requires 12 switches for a 7-level output, this topology significantly reduces the component count to minimize switching losses and overall system cost. The circuit consists of a DC sources integrated with a specific arrangement of power MOSFETs/IGBTs. By controlling the switching states, the inverter generates a stepped output voltage waveform with seven distinct levels: +3Vdc, +2Vdc, +Vdc, 0, -Vdc, -2Vdc, -3Vdc.

a single-phase H-bridge as shown in fig1. the four switches are controlled to generate the output Vo with the levels of Vdc. When the switches S1 and s4are turned on according to the switching angle then the output voltage is +Vdc, if the switches S2 and S3 are ON then obtained voltage are –Vdc, the output voltage is 0 either of the switches S1andS2 or S3 and S4 is turned ON. In this manner for the cascaded h-bridge multi levels the switching pattern is given to the series structure of the bridges. The cascaded h-bridge structure and the stepped waveform related with their switching angles are shown in fig 4. For the seven-level inverter three DC sources are required. The switching devices are to be turned ON at different instants based on the switching angles. The number of levels in the cascaded h-bridge structure is given by N=2S+1.Here S is the number of sources.

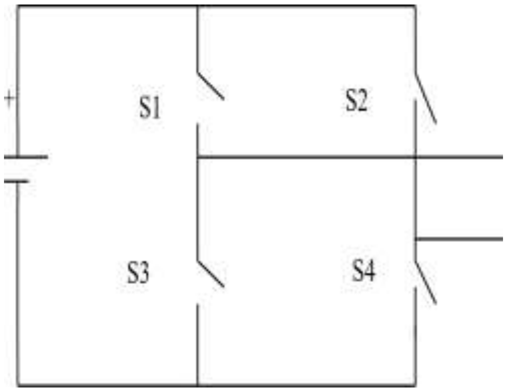

Fig 1. Single phase H-bridge with DC source

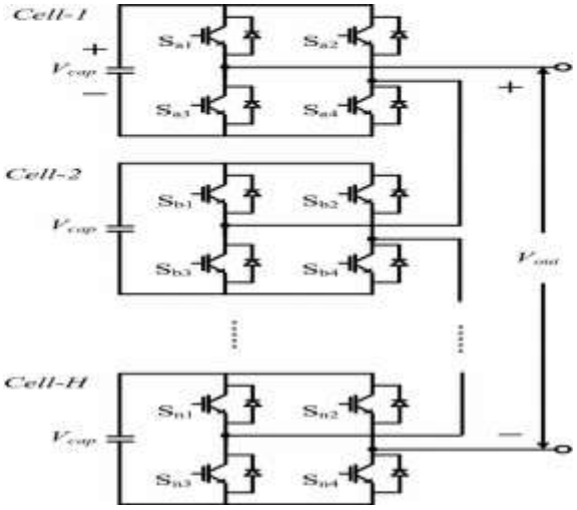

Fig 2. Cascaded H-bridge 7-Level inverter

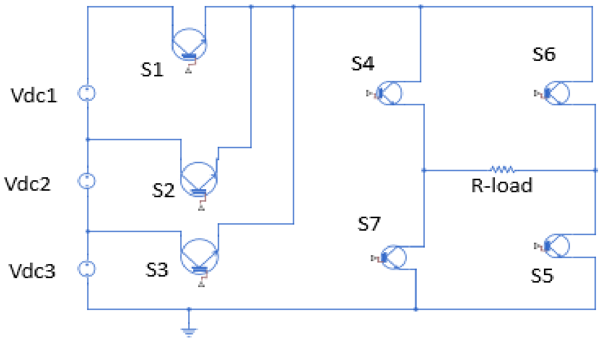

Fig 3. Reduced switch topology

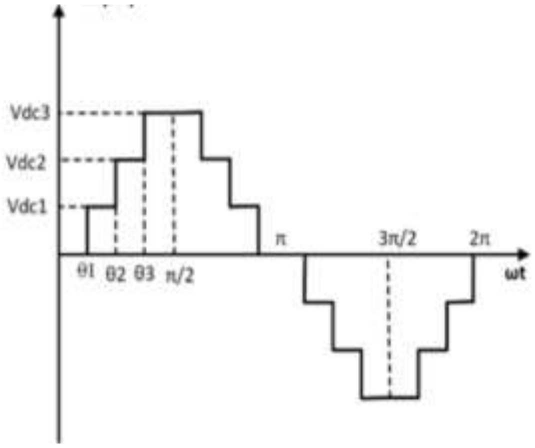

Fig 4. Seven level output voltage

The power circuit configuration of the proposed single-phase 7-level reduced-switch inverter is presented in Figure 3. The topology utilizes three isolated symmetrical DC voltage sources (Vdc1=Vdc2=Vdc3=Vdc) and only seven power semiconductor switches (S1 to S7). This arrangement is significantly more efficient than a conventional Cascaded H-Bridge (CHB) inverter, which requires 12 switches to achieve the same 7-level output. The reduced component count lowers the total cost, complexity, and cumulative switching losses of the system.

Target Voltage	S1	S2	S3	S4	S5	S6	S7	Active DC Sources
+3Vdc	ON	ON	ON	OFF	OFF	OFF	OFF	Vdc1,Vdc2,Vdc3
+2Vdc	ON	ON	OFF	OFF	OFF	OFF	ON	Vdc1,Vdc2
+Vdc	ON	OFF	OFF	OFF	OFF	ON	ON	Vdc1
0	OFF	OFF	OFF	OFF	ON	ON	ON	None
−Vdc	OFF	ON	OFF	OFF	ON	ON	OFF	Vdc1 (reversed)
−2Vdc	OFF	ON	ON	OFF	ON	OFF	OFF	Vdc1,Vdc2 (reversed)
−3Vdc	OFF	OFF	OFF	ON	OFF	OFF	OFF	Vdc1,Vdc2,Vdc3 (reversed)

Table 1. switching pattern for reduced seven level inverter

Advantages of this Topology:

Reduced Complexity: Lower gate driver requirements.
Cost-Effectiveness: Fewer semiconductor devices compared to NPC or CHB topologies.
Higher Efficiency: Reduced total conduction and switching losses.

1.2 Modulation Strategies for Multilevel Inverters

Modulation techniques for multilevel inverters (MLIs) are generally categorized by their switching frequency. High-frequency methods involve numerous commutations per cycle, whereas low-frequency methods focus on fundamental switching. Among the most prominent strategies are Carrier-Based Sinusoidal PWM (SPWM), Space Vector PWM (SVPWM), and Selective Harmonic Elimination (SHE).

Recent computational advances have spurred the development of Evolutionary Algorithms (EA) stochastic techniques that simulate biological evolutionary processes to solve complex optimization problems. Unlike traditional methods, EAs are highly effective in navigating non-continuous and non-convex solution spaces to find global or near-global optima. In this research, a Particle Swarm Optimization (PSO) based method is proposed to solve the transcendental equations of the SHE-PWM problem. While the conventional Newton-Raphson (NR) method is a dominant numerical technique, it is restricted by its heavy reliance on a precise initial guess and its tendency to converge toward local optima. By transitioning to a PSO-based fitness function, the requirement for an "intelligent initial guess" is eliminated, allowing for the identification of absolute optimum switching angles across the entire modulation range.

To validate this approach, switching angles obtained from both the NR and PSO methods were implemented on a seven-level cascaded H-bridge inverter. Using Fast Fourier Transform (FFT) analysis, the Total Harmonic Distortion (THD) was calculated at the inverter output. A comparative study of these results demonstrates the superior harmonic suppression capabilities of the proposed PSO-based strategy.

2 Selective Harmonic Elimination (SHE)

Originally developed by Patel and Hoft (1973), the SHE [9] method is designed to synthesize a quarter-wave symmetric staircase voltage waveform. By strategically calculating switching angles (α), this technique can eliminate up to k-1 specific low-order harmonics while simultaneously controlling the fundamental voltage amplitude. Any remaining high-frequency harmonics are typically mitigated using relatively small filter circuits.

To maintain the required harmonic cancellation and ensure a valid staircase waveform, the switching angles must strictly satisfy the following monotonicity constraint:$0 < \alpha 1 < \alpha 2 < \alpha 3 < 90$

significant challenges of the SHE strategy is the restricted operational range; if the calculated angles violate the above condition, the solution becomes invalid. For a typical seven-level inverter, this limitation often restricts the feasible Modulation Index (M) to a narrow range, typically between 0.2 and 1.15.

2.1 Selective Harmonic Elimination (SHE) Equations

The goal of SHE is to identify the switching angles $(\alpha 1, \alpha 2, \alpha 3)$ that produce the desired fundamental voltage while eliminating specific low-order harmonics (typically the 5th and 7th).

Voltages of the inverter dc sources are Vdc and all are to be constant, then the Fourier series expansion of the inverter output voltage is given by:

$$V(\omega t)=\sum_{n=1,3,5}^{\infty}\left(\frac{4Vdc}{n\pi}[\cos(n\alpha 1)+\cos(n\alpha 2)+\cos(n\alpha 3)]\sin(\omega t)\right) \qquad (1)$$

To eliminate the 5^{th} and 7^{th} harmonics while maintaining the desired fundamental magnitude (V1), we must solve the following system of non-linear transcendental equations:

$$\cos(\alpha 1)+\cos(\alpha 2)+\cos(\alpha 3)=3M \qquad (2)$$

$$\cos(5\alpha 1)+\cos(5\alpha 2)+\cos(5\alpha 3)=0 \qquad (3)$$

$$\cos(7\alpha 1)+\cos(7\alpha 2)+\cos(7\alpha 3)=0 \qquad (4)$$

Constraints: To ensure a valid 7-level staircase waveform, the angles must satisfy the following condition:

$$0 < \alpha 1 < \alpha 2 < \alpha 3 < 90$$

3 Newton-Raphson (NR) Algorithm for SHE

The NR [5] method is a well-established iterative numerical technique utilized for solving the systems of non-linear transcendental equations derived from the Selective Harmonic Elimination (SHE) technique. To solve equations (2), (3), and (4) for the required switching angles, the following algorithmic steps were implemented:

Step 1: Initialize the process with a random guess for the switching angles (α).
Step 2: Set the modulation index M starting from 0.1.
Step 3: Evaluate the system of equations F(α), the target vector B(m), and the Jacobian matrix J(α).
Step 4: Compute the error correction vector: d(α) = J($\alpha)^{-1}$) [B(m) - F(α)].
Step 5: Update the switching angles: α_{n+1} = α_n+ d α_n.
Step 6: Iterate Steps 3 through 5 until the error converges within the specified tolerance for the optimum angles.
Step 7: Increment the modulation index (m)stepwise.
Step 8: Repeat the entire process (Steps 2–7) to cover the full range of modulation indices.

This algorithm was developed in MATLAB to generate a comprehensive dataset of switching angles relative to the modulation index constraints.

3.1 The Static Lookup Table (LUT) Approach

To provide a fair comparison against the intelligent PSO-ANFIS hybrid, the NR-generated angles were implemented using a 1-D Lookup Table (LUT) block in Simulink.
Input: The Modulation Index (M).
Output: Three distinct paths for the switching angles ($\alpha 1, \alpha 2, \alpha 3$)
Limitation: Unlike the ANFIS controller, which performs intelligent nonlinear mapping, the LUT relies on simple linear interpolation between fixed data points, which can introduce errors during transitions.

3.2 Pulse Generation Logic

To translate these mathematical angles into physical gate signals for the 7-level reduced switch topology, a dedicated MATLAB Function Block was utilized.
Logic Conversion: The function compares the instantaneous phase of the fundamental frequency (ωt) against the generated angles. A signal is generated when the phase exceeds the specific switching angle.
Pulse Mapping: These signals are mapped to the L_pulses (Left-leg) and R_pulses (Right-leg) specifically for the reduced switch configuration.
Result: The pulses trigger the IGBTs to synthesize the staircase output voltage waveform.

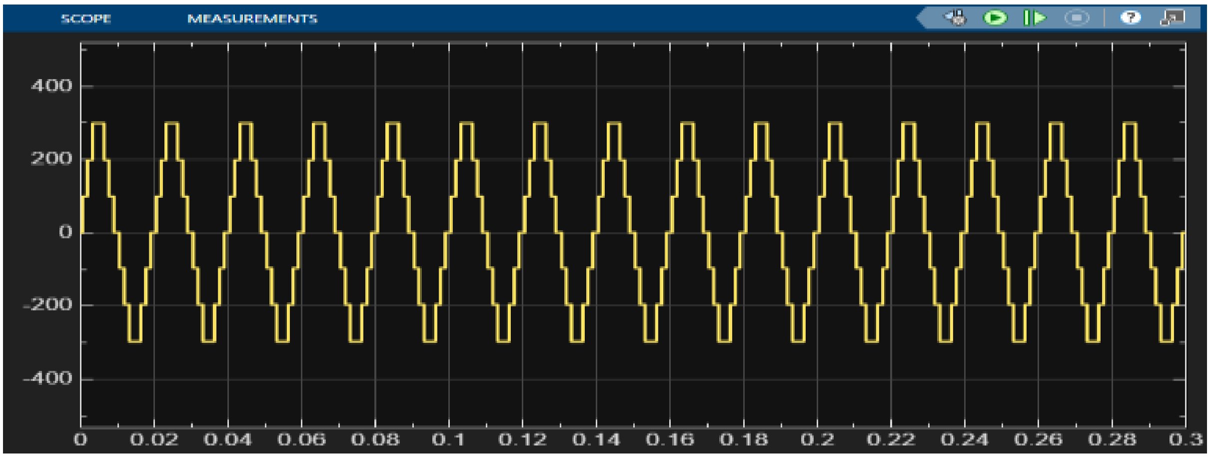

Fig 5. Inverter Output voltage without LC filter

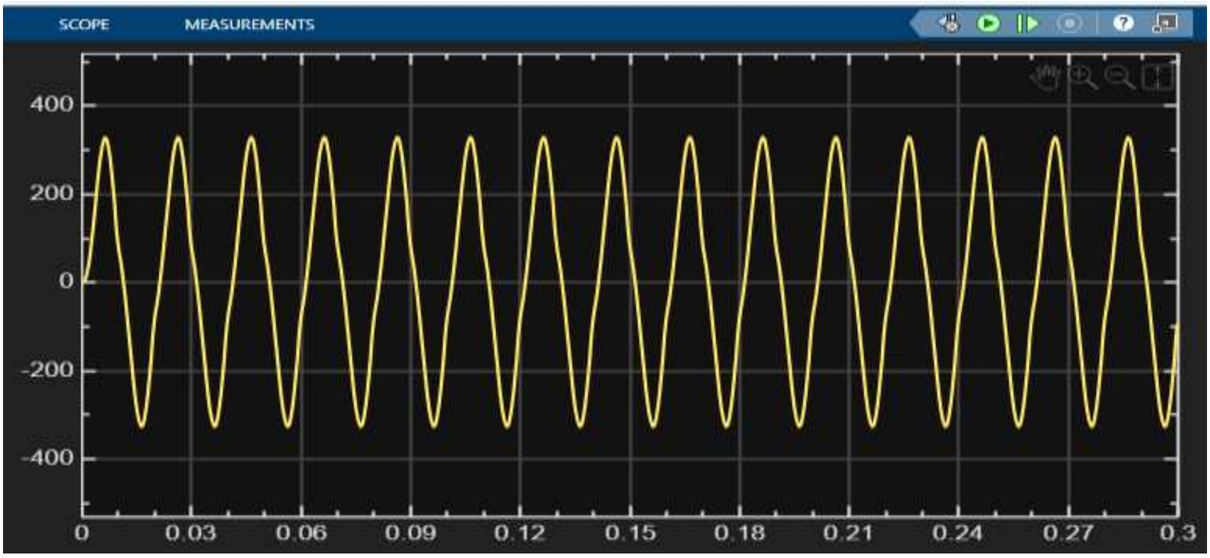

Fig 6. Inverter Output voltage with LC filter

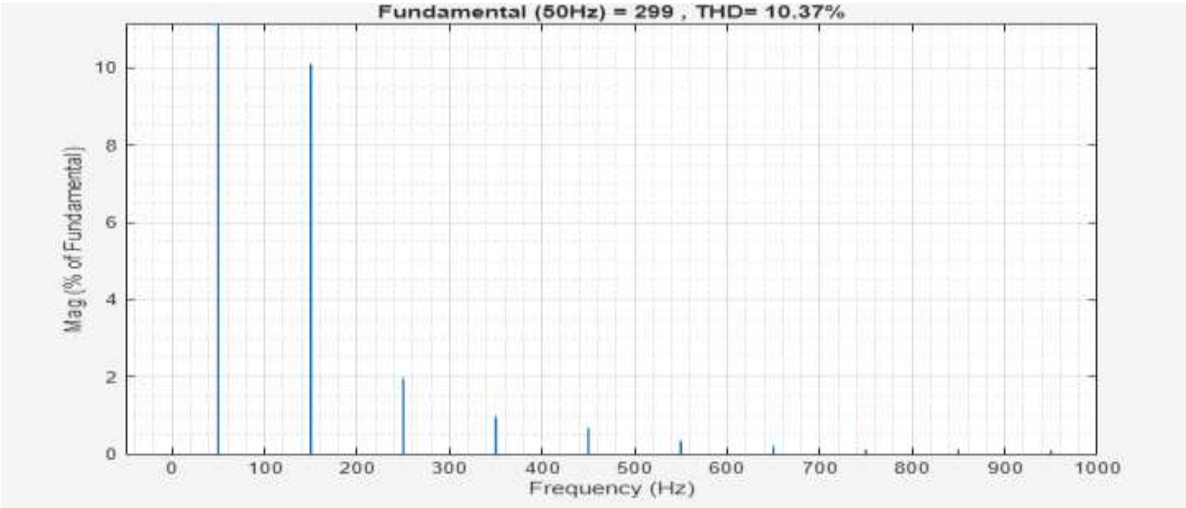

Fig 7. Harmonic Spectrum

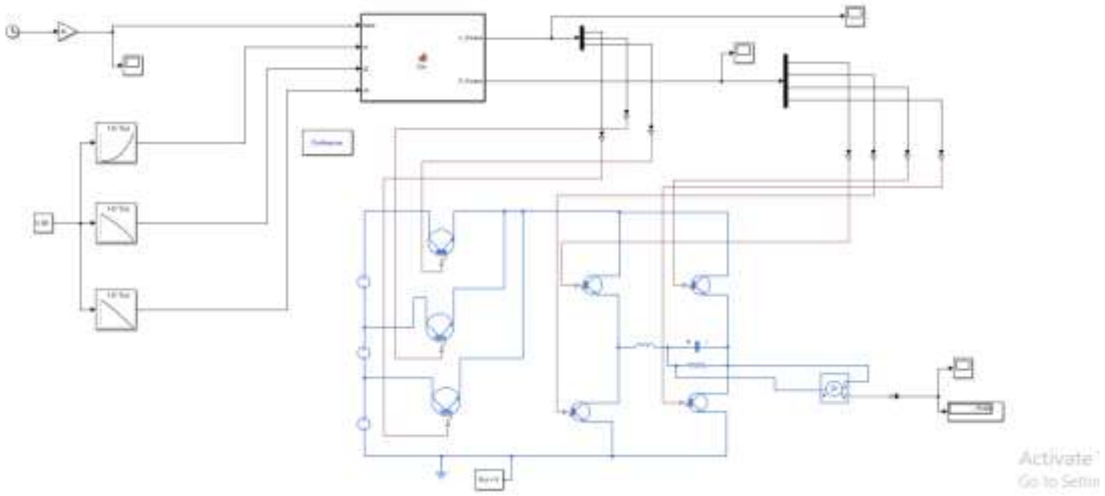

Fig 8. Reduced switch inverter Simulation Diagram with LC filter (NR-method)

Inverter parameters	
DC Source voltage	100v

Switch type	IGBT
Internal resistance	0.001ohm
L value in filter	25mH
C value in filter	50uF

Table 2. Inverter parameters

4 Proposed PSO-ANFIS Hybrid Control Strategy

The proposed controller integrates the global search capabilities of Particle Swarm Optimization (PSO) with the real-time adaptive nature of the Adaptive Neuro-Fuzzy Inference System (ANFIS). This hybrid strategy overcomes the computational lag of pure optimization while maintaining superior accuracy over traditional methods like Newton-Raphson.

4.1 Global Optimization via PSO

The first phase involves using PSO [13] to solve the non-linear Selective Harmonic Elimination (SHE) equations. Unlike the Newton-Raphson (NR) method, which requires a precise initial guess and often fails to converge for certain ranges of the Modulation Index (M), PSO initializes a "population" of random switching angles and iteratively moves them toward the global minimum.

4.2 Problem Formulation

The Modulation Index (M) is defined as the ratio of the fundamental output voltage to the maximum possible voltage (Vdc). To identify the best switching angles (α), we define an Objective Function (f) to be minimized by the PSO algorithm:

$$Minimize\ f(\alpha) = \left|M - \frac{V1}{Vdc}\right| + \frac{\sqrt{{V_5}^2 + {V_7}^2}}{V1} \qquad (5)$$

Where:

M: The target Modulation Index.

V1: The fundamental voltage component.

$\boldsymbol{V_5}, \boldsymbol{V_7}$**:** The magnitudes of the 5th and 7th harmonic components.

4.1 The Constraints:

The optimization is subject to the following transcendental equations derived from the Fourier series:

Fundamental: $\cos(\alpha 1) + \cos(\alpha 2) + \cos(\alpha 3) = \frac{3\pi M}{4}$

Harmonic Cancellation: $\sum_{i=1}^{3} \cos(n\alpha_i) = 0$ for n = 5,7

Furthermore, to ensure a valid 7-level staircase waveform, the switching angles must satisfy the monotonicity constraint: $0 < \alpha 1 < \alpha 2 < \alpha 3 < 90$.

By minimizing this function, the PSO ensures the fundamental voltage requirement is met while the 5th and 7th harmonics are forced toward zero, resulting in the lowest possible Total Harmonic Distortion (THD).

4.2 Dataset Preparation and ANFIS Training

While PSO is highly accurate, its high computational demand makes it unsuitable for direct real-time hardware execution. To solve this, a Sugeno-type ANFIS network is trained using an offline PSO-generated dataset.

Data Generation: The PSO algorithm was executed for M ranging from 0.4 to 1.0. For every M value, 50 particles searched for the absolute minimum THD, creating a comprehensive training matrix.

Training Process: This matrix was loaded into the MATLAB Neuro-Fuzzy Designer. The network utilized a hybrid learning algorithm combining least-squares and backpropagation to minimize the error between the PSO target and the ANFIS output until the target tolerance was reached.

4.3 Real-Time Estimation and Pulse Generation

The trained ANFIS structure is exported to a Simulink block to act as the "Intelligence Layer" of the inverter. The ANFIS architecture consists of three primary layers:

1. **Input Layer:** Receives the instantaneous Modulation Index (M) based on DC link voltage monitoring.
2. **Fuzzification Layer:** Converts the crisp input (M) into fuzzy sets using Bell-shaped Membership Functions (MFs) for smooth transitions.
3. **Defuzzification Layer:** Instantly outputs the optimized switching angles ($\alpha 1, \alpha 2, \alpha 3$).

4.4 Control Logic Flow

The final control sequence is executed in the Simulink environment as follows:

Sensing: The system monitors the DC link voltage to calculate the current M.

Estimation: The ANFIS block predicts the optimal α values for that specific M in real-time.

Firing Logic: A MATLAB Function Block compares the system's phase angle (ωt) against the predicted α values.

Result: The logic generates L_pulses and R_pulses to trigger the IGBTs in the 7-level reduced switch topology, producing a clean, staircase sinusoidal wave.

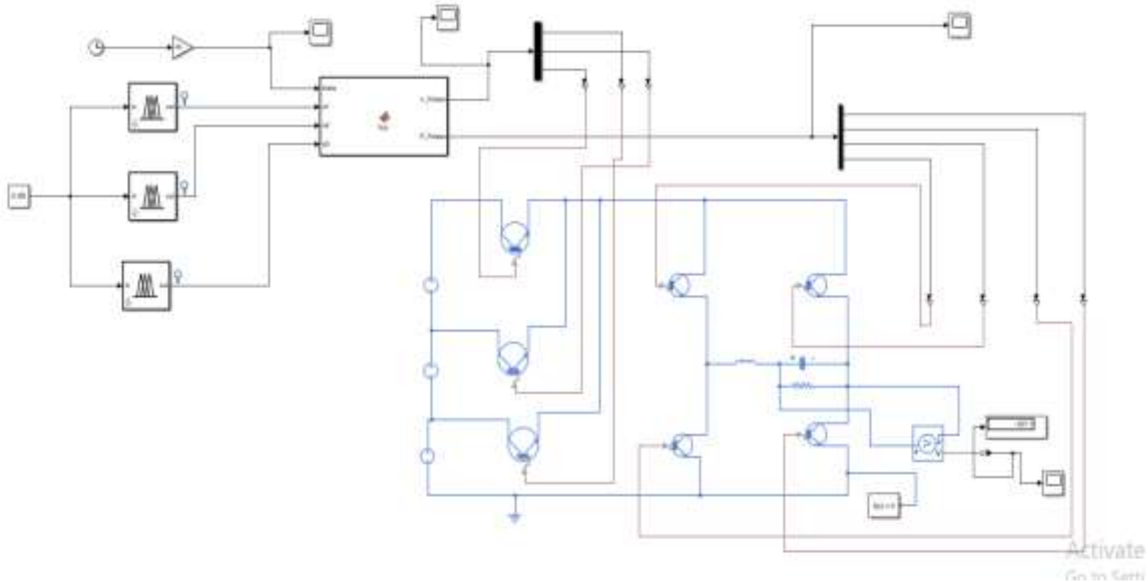

Fig 9. Reduced switch inverter simulation with LC filter (PSO-ANFIS method)

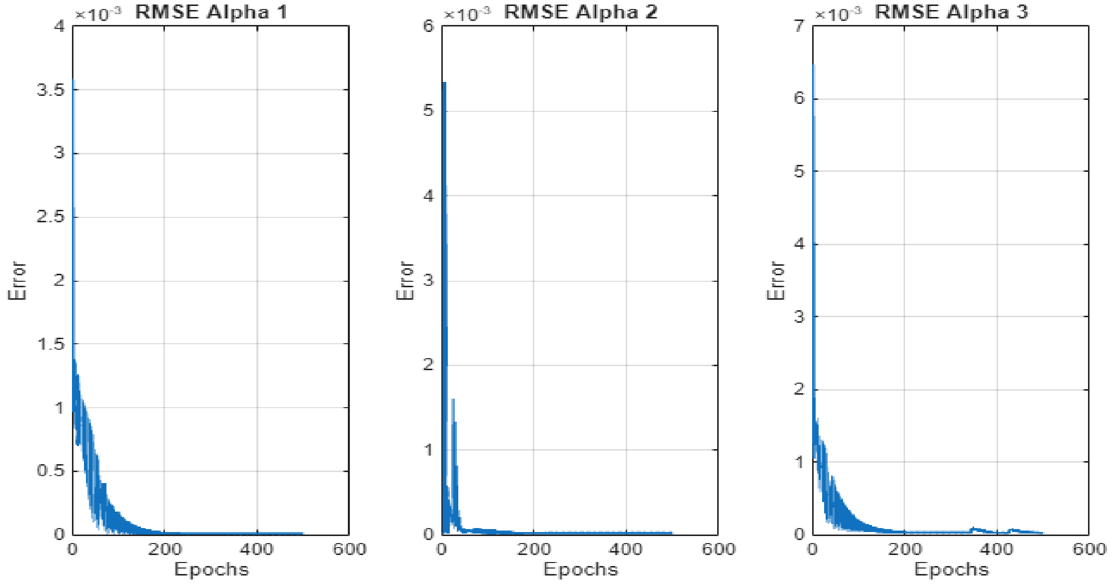

Fig 10. ANFIS Training Error Plot

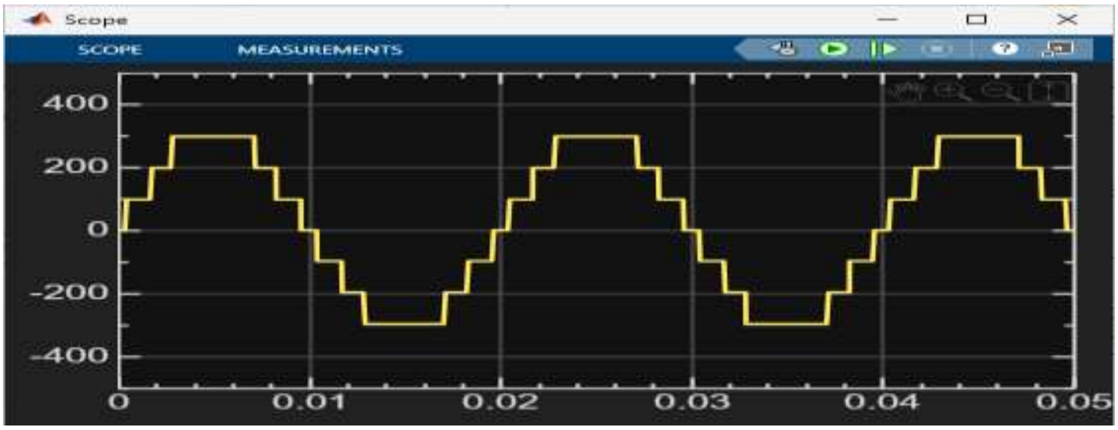

Fig 11. Inverter output voltage without LC filter

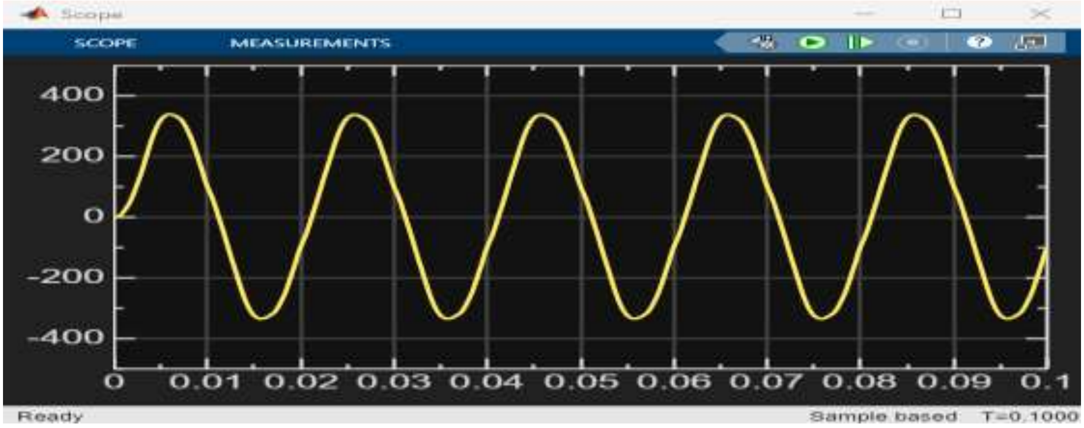

Fig 12. Inverter output voltage with LC filter

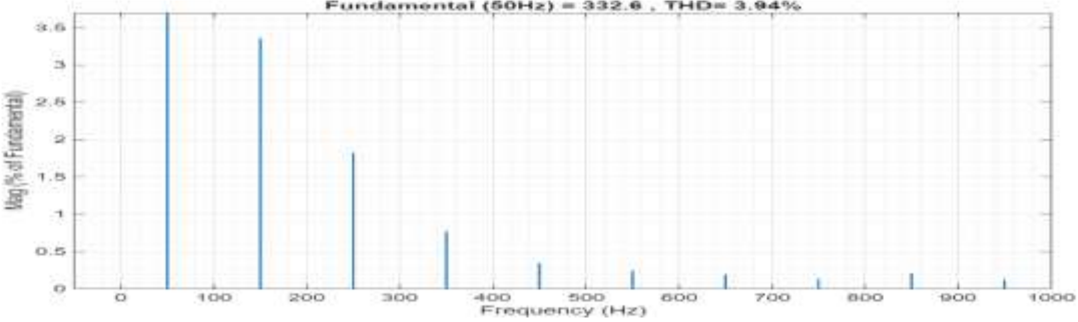

Fig 13. Harmonic Spectrum

Parameter	NR-method		PSO-ANFIS method	
	Without filter	**With filter**	**Without filter**	**With filter**
RMS output voltage(Vrms)	280.6	299	311.8	332.6
THD (%)	15.93	10.37	13.52	3.94

Table 3. Comparison of THD values in NR and PSO-ANFIS methods

By using the PSO-ANFIS optimization method the harmonic contents in the inverter output voltage (PCC) are minimized compared with the conventional method (NR-method). The PSO-ANFIS method can give the best results than the NR-method. The comparison table for the THD values in the NR-method and the PSO-ANFIS optimization method are given in the table 3. From that the amount of the THD in the PSO-ANFIS optimization method should be less. The results show the strength of the PSO-ANFIS over the NR-method.

5. CONCLUSION:

This paper evaluated a grid-connected seven-level inverter utilizing a reduced switch topology to improve power quality at the output of the inverter. By comparing the conventional Newton-Raphson (NR) method with the proposed PSO-ANFIS hybrid controller, the following conclusions were drawn:

Hardware Efficiency: The use of a reduced switch configuration successfully decreased the total component count, leading to lower switching losses and higher overall system efficiency compared to traditional Cascaded H-Bridge structures.

Superior Harmonic Mitigation: The PSO-ANFIS controller outperformed the NR method by reducing the THD at the PCC to 3.94%, compared to 10.37% with the conventional approach.

Voltage Performance: The proposed method achieved a higher RMS output voltage of 332.6 V, ensuring better utilization of the DC link.

Standard Compliance: Most significantly, the hybrid intelligent strategy brought the system within the IEEE 519 standard limits (<5%), whereas the NR method remained non-compliant.

In summary, the integration of a reduced switch hardware design with a PSO-ANFIS provides a highly effective, low-cost, and robust solution for modern grid-integrated renewable energy systems.

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