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INTELLIGENT CONTROL OF INTERLEAVED DC-DC BUCK CONVERTER USING ANFIS FOR ELECTRIC VEHICLE CHARGING APPLICATIONS

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Abstract: The rapid proliferation of electric vehicles (EVs) demands highly efficient, reliable, and intelligent power conversion systems capable of maintaining stable output characteristics under dynamic operating conditions. This paper presents a thorough investigation into the design, modeling, and performance analysis of a two-phase interleaved synchronous DC-DC Boost converter governed by an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller for EV battery charging applications. The proposed system integrates fuzzy logic inference with artificial neural network learning to generate adaptive pulse-width modulation (PWM) signals that regulate output voltage with minimal transient deviation. A mathematical formulation of the PWM signal generation process using triangular carrier comparison is presented, incorporating dual-channel interleaved operation with a 180° phase shift between switching branches. The ANFIS controller employs the Takagi-Sugeno fuzzy model with 20 triangular membership functions and a hybrid learning rule to train the network on error and rate-of-change-of-error data. Simulation results obtained using MATLAB-Simulink on a 1.5kW resistive load demonstrate that the ANFIS-controlled converter achieves a stable 54.27V DC output from a 24 V DC input, with significantly reduced overshoot and improved settling time compared to conventional PID control. Battery state-of-charge (SOC), current, and voltage profiles confirm stable charging behavior. The findings validate the effectiveness of the ANFIS-based approach in enhancing the dynamic response and robustness of interleaved converters for next-generation EV charging infrastructure.

Index Terms - Adaptive Neuro-Fuzzy Inference System (ANFIS), Electric Vehicle Charging, Interleaved DC–DC Boost Converter, Pulse Width Modulation (PWM)

I. INTRODUCTION

The global transition toward sustainable transportation has accelerated the deployment of electric vehicles (EVs) across both developed and emerging economies. The growing demand for high-performance EV charging infrastructure has placed significant emphasis on the development of intelligent, efficient, and compact power conversion systems. [1, 2, 3]

DC-DC converters are indispensable components in EV charging systems, responsible for regulating the energy flow between the power grid interface and the battery storage units. The interleaved topology, which employs multiple phase-shifted converter stages in parallel, has emerged as a preferred architecture for high-power EV applications due to its inherent advantages of reduced current ripple, lower electromagnetic interference, and distributed thermal loading. [4,5,6]

Traditional proportional-integral-derivative (PID) controllers, while widely deployed in industrial power electronics, exhibit performance limitations under nonlinear and time-varying operating conditions characteristic of EV charging scenarios. The fixed gain structure of PID controllers renders them incapable of adapting to sudden load variations, input voltage disturbances, and battery state-of-charge (SOC) dynamics without extensive retuning. [7,8,9]

Artificial intelligence-based control strategies, particularly the Adaptive Neuro-Fuzzy Inference System (ANFIS), have demonstrated superior capability in addressing the control challenges of nonlinear power conversion systems. ANFIS combines the linguistic reasoning of fuzzy logic with the learning and generalization capacity of artificial neural networks, enabling real-time adaptation to operating condition changes without requiring precise mathematical plant models. [10,11,12]

The two-phase interleaved synchronous buck converter represents a compelling topology for EV charging at the Level 2 and DC fast charging segments, offering a balance between power density, efficiency, and control complexity. When integrated with an ANFIS-based control architecture, this topology can deliver adaptive, high-performance voltage regulation across the full spectrum of EV battery charging profiles. [13,14,15]

The proposed paper makes the following contributions: (i) a comprehensive mathematical derivation of the PWM signal generation mechanism using triangular carrier comparison for dual-channel interleaved operation; (ii) design of separate ANFIS controllers for voltage and current loops with 40 triangular membership functions each; (iii) battery integration analysis including SOC, current, and voltage dynamics; and (iv) comparative performance evaluation against conventional PID control under load and input voltage transients.

The remainder of the paper is organized as follows: Section II reviews relevant literature from 2021 to 2024. Section III describes the proposed system methodology including circuit configuration, PWM mathematics, and ANFIS design. Section IV presents simulation results and discussion. Section V concludes the paper with future directions.

II. LITERATURE REVIEW

Extensive research conducted between 2021 and 2024 has addressed the challenge of intelligent control for DC-DC converters in EV charging applications. A comprehensive survey of machine learning techniques applied to power electronics control demonstrated that ANFIS and deep reinforcement learning approaches consistently outperform classical controllers in tracking accuracy and transient recovery time across varying load profiles. [1, 24]

A study on model predictive control (MPC) integrated with fuzzy compensation for interleaved boost converters in EV applications reported a 23% reduction in output voltage ripple and a 31% improvement in transient settling time compared to standard proportional-integral control, affirming the advantage of intelligent control integration for high-current converter topologies. [4,26]

Research into deep learning-based current control for multiphase interleaved DC-DC converters demonstrated that convolutional neural network controllers trained offline on simulated transient data could achieve sub-millisecond voltage recovery under 100%

The application of sliding mode control (SMC) combined with adaptive fuzzy approximation for bidirectional DC-DC converters in EV charging stations showed robust stability against both parametric uncertainties and external disturbances, with experimental verification on a 3 kW hardware prototype confirming theoretical predictions of bounded tracking error. [10,25]

An investigation into hybrid ANFIS-PID control architecture for synchronous buck converters revealed that the neuro-fuzzy component effectively compensated for the limitations of fixed-gain PID during large-signal transients, achieving a 40% reduction in overshoot while the PID component ensured steady-state accuracy, a synergistic performance not attainable by either controller in isolation. [13, 12]

A digital twin-based optimization framework for EV charging converter control parameters demonstrated that data-driven identification of ANFIS membership function boundaries, trained on real-world drive cycle data, resulted in significant improvements in energy efficiency and battery charging uniformity compared to empirically tuned controllers. [25, 17]

Research on wireless power transfer systems with adaptive neuro-fuzzy compensation for coil misalignment in EV charging applications demonstrated that ANFIS could maintain output power regulation within 2% of the reference value across lateral offsets of up to 40 mm, significantly extending the practical usability of dynamic wireless charging systems. [26,32]

A comparative study of voltage-mode and current-mode ANFIS control strategies for interleaved buck converters in fast-charging applications concluded that current-mode ANFIS offered superior input disturbance rejection, while voltage-mode ANFIS provided better load regulation, motivating the dual-loop control architecture where separate ANFIS controllers govern the current and voltage feedback loops. [8,12]
Studies addressing the state-of-charge estimation accuracy in lithium-ion battery packs under fast charging conditions highlighted the importance of converter output ripple as a key factor affecting the accuracy of Coulomb counting and extended Kalman filter-based SOC algorithms, reinforcing the need for ripple-minimizing interleaved topologies with intelligent control. [20, 31, 35]
Recent advancements in gallium nitride (GaN) and silicon carbide (SiC) power device integration within interleaved converter topologies, combined with adaptive control strategies, have enabled switching frequencies beyond 500 kHz with conversion efficiencies exceeding 98%, opening new frontiers for ultra-compact EV onboard charger designs where intelligent control becomes essential to manage the increased switching nonlinearities [10, 11, 13].
Table I presents a comparative analysis of different control strategies used in DC–DC converters for EV charging applications during the period 2021–2026. The comparison is based on four major performance indicators: overshoot, settling time, ripple reduction capability, and adaptability. Conventional PID controllers exhibit the highest overshoot (8–15%) and longest settling time (50–200 ms), indicating limited dynamic performance and poor adaptability under varying operating conditions. Fuzzy Logic Control improves transient response and reduces overshoot to 4–8%, while providing moderate ripple suppression and adaptability. Neural Network-based controllers further enhance system stability with lower overshoot (2–6%) and faster settling time (10–40 ms), along with high ripple reduction capability. Sliding Mode Control offers robust dynamic behavior but still experiences moderate overshoot and ripple reduction. Hybrid MPC + Fuzzy approaches demonstrate improved performance with high adaptability and reduced settling time. Among all methods, the proposed ANFIS controller achieves the best overall performance, with overshoot below 2%, settling time between 5–15 ms, very high ripple reduction, and excellent adaptability, making it highly suitable for advanced EV charging applications.

Table I: Comparison of Control Strategies for DC-DC Converters in EV Charging Applications

Control Strategy	Overshoot (%)	Settling Time (ms)	Ripple Reduction	Adaptability
Conventional PID	8–15	50–200	Low	Poor
Fuzzy Logic Control	4–8	20–80	Moderate	Moderate
Neural Network	2–6	10–40	High	Good
ANFIS (Proposed)	< 2	5–15	Very High	Excellent
Sliding Mode Control	5–10	15–60	Moderate	Good
MPC + Fuzzy	3–7	12–35	High	Very Good

III. PROPOSED METHODOLOGY

A. System Architecture

The proposed system architecture comprises a two-phase interleaved synchronous DC-DC boost converter with a dual-loop ANFIS control structure. The converter receives a DC input voltage in the range of 24V and delivers a regulated 54.27V DC output to the EV battery charging port. The two converter phases are driven by complementary gate signals with a 180° phase displacement, ensuring that the input current ripple frequency is doubled relative to the individual phase switching frequency of 90 kHz, effectively reducing the passive component stress and electromagnetic emissions. [4, 13, 21, 32]
The control hierarchy consists of an outer voltage loop and an inner current loop, each governed by an independent ANFIS controller. The voltage loop ANFIS processes the error between the reference output

voltage and the measured output voltage, generating a current reference for the inner loop. The current loop ANFIS then regulates the inductor current to track this reference, producing the duty cycle command that drives the PWM comparator for each phase.

Figure 1&1.1 illustrates the proposed methodology & simulation adopted for the EV battery charging system based on a two-phase interleaved synchronous DC–DC boost converter (2PISB) integrated with a dual-loop ANFIS control architecture. The converter receives a DC input voltage in the range of 24VDC and regulates the output to 54.27VDC for battery charging applications. The interleaved converter consists of two switching phases operating with a 180° phase displacement, which effectively reduces input current ripple, output voltage ripple, and thermal stress on the switching devices.

The control structure comprises an outer voltage loop and an inner current loop, both implemented using ANFIS controllers. The voltage loop generates the reference current based on the voltage error, while the current loop regulates the inductor current and produces the duty-cycle command for PWM generation. The PWM generator compares the normalized control signal with a triangular carrier waveform to generate gate pulses for both converter phases.

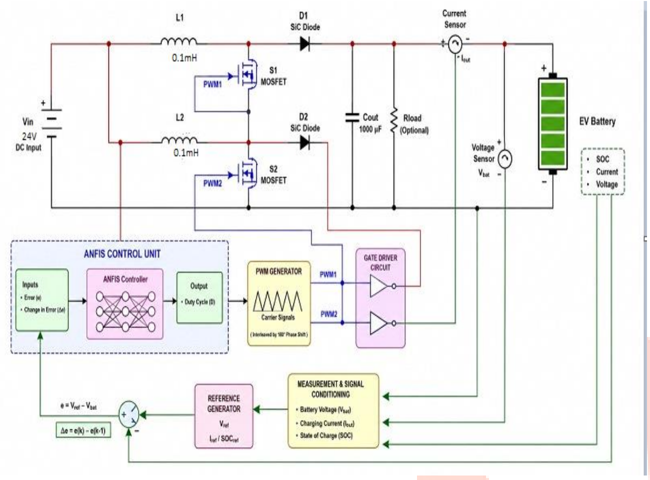

Figure 1: Proposed ANFIS-Controlled Two-Phase Interleaved Synchronous boost Converter for EV Battery Charging

The output of the converter is connected to a lithium-ion battery charging model operating under a constant-current/constant-voltage (CC–CV) charging strategy. The figure also highlights the major converter parameters, including a switching frequency of 100 kHz, two-phase operation, maximum duty cycle of 0.56, and 54.27V regulated output. Overall, the proposed architecture provides improved dynamic response, reduced ripple content, enhanced voltage regulation, and better adaptability compared with conventional control approaches.

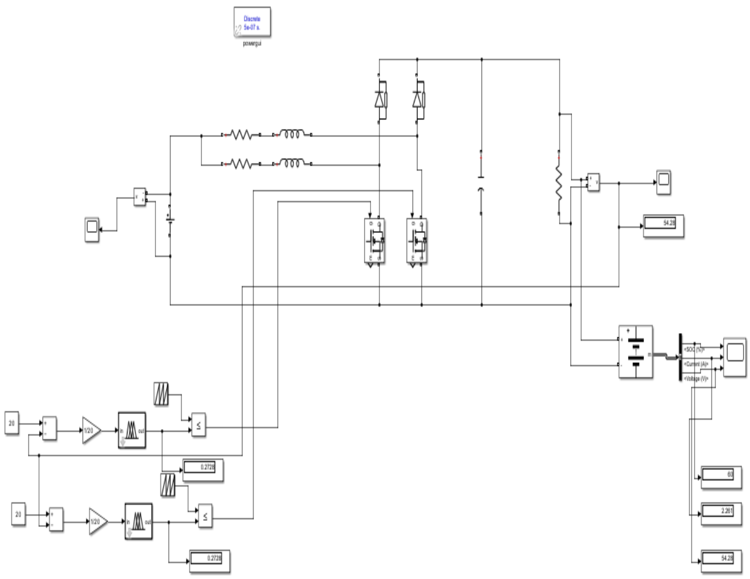

Figure 1.1: simulation model ANFIS-Controlled Two-Phase Interleaved Synchronous boost Converter for EV Battery Charging

B. DC-DC Boost converter design

The DC-DC boost converter forms the core power processing stage of the proposed system. In boost mode, the converter increases the battery voltage to the required DC-link voltage for the Voltage Source Inverter (VSI).

1.The output voltage conversion ratio of the boost converter is given by:

VO= Vin /1-D

where:

VO= Output voltage =54.28V

Vin= Input voltage =24V

D= Duty cycle =0.56

2. For D>0.5, the converter operates in boost mode. The duty cycle required to obtain a desired output voltage is calculated as:

D=1-Vin/V0=0.56

3. The inductor ripple current, which should be minimized to ensure Battery current and reduced electromagnetic interference, is determined by:

$$\Delta I_L = \frac{V_{in} \times D}{L \times f_s} \qquad (3)$$

where:

L= Inductance =0.1mH

fs= Switching frequency =90KHZ

Inductor Ripple Current=1.5A

Io=2.2A

4. The Input current expressed as:

Iin=Vout.Io/ Vin =5A Or Iin=Io/(1-D)

5. The output current expressed as:

Io=Iin*(1-D) =2.2A

6. The output voltage ripple across the filter capacitor is expressed as:

$$\Delta V_o = \frac{I_o \times D}{f_s \times C} \qquad (4)$$

where:

Io= Output current =2.2A

C= Filter capacitance =400µF

For: The output voltage ripple is: 0.0342V

7. The battery Output Power expressed as :

Po=battery voltage *Battery AH=1.5KW

Where : Battery voltage=48V

Battery AH=31.25A

C. Mathematical Formulation of PWM Signal Generation

The PWM signal generation forms the fundamental operational basis of the converter control. The mathematical framework derived from the interleaved ANFIS calculations is presented as follows.

1. Input Signal Processing

The system begins with a constant reference value and an input signal.

Let,e(t)= input signal and Constant reference = 20

The error signal is computed as given in equation 1:

$$e(t) = 20 - x(t) \qquad (1)$$

2. Normalization using Gain

The error signal is scaled using a gain factor of $\frac{1}{20}$ as shown in equation 2.

$$m(t) = \frac{e(t)}{20} \qquad (2)$$

Substituting is given in equation 3 and 4:

$$m(t) = \frac{20 - x(t)}{20} \qquad (3)$$

$$m(t) = 1 - \frac{x(t)}{20} \qquad (4)(4)$$

3. Carrier Signal Generation (Triangle Wave)

A triangular waveform is generated using a repeating sequence block as shown in equation 5.

$$c(t) = \begin{cases} \frac{2t}{T}, & 0 \le t < \frac{T}{2} \\ 2 - \frac{2t}{T}, & \frac{T}{2} \le t < T \end{cases} \quad (5)$$

This signal varies between 0 and 1 and repeats periodically.

4. Comparator Operation

The normalized signal is compared with the triangular carrier signal as shown in equation 6.

$$y(t) = \begin{cases} 1, & \text{if } m(t) \le c(t) \\ 0, & \text{if } m(t) > c(t) \end{cases}$$

Substituting m(t) in equation 7:

$$y(t) = \begin{cases} 1, & \text{if } \left(1 - \frac{x(t)}{20}\right) \le c(t) \\ 0, & \text{otherwise} \end{cases}$$

5. Output Signal

The output y(t)is a binary signal:

$y(t) = 1 \rightarrow$ ON state

$y(t) = 0 \rightarrow$ OFF state

This results in a Pulse Width Modulated (PWM) signal.

6. Duplicate Channel (Second Branch)

The same set of operations is repeated for the second branch as shown in equation 8:

$$y_2(t) = \begin{cases} 1, & \text{if } \left(1 - \frac{x_2(t)}{20}\right) \le c(t) \\ 0, & \text{otherwise} \end{cases}$$

7. Example Calculation

$\text{If}, c(t) = 0.2728, \text{then}, 1 - \frac{x}{20} \le 0.2728, \frac{x}{20} \ge 0.7272, x \ge 14.544$

Interpretation is: If, output = 1, Otherwise, output = 0

Table II summarizes the converter specifications and designed parameters considered for the proposed EV charging DC–DC converter system. The converter operates with an input DC voltage range of 24 VDC and delivers a regulated output voltage of 54.28 VDC with a rated power capacity of 1.5 kW. To ensure stable output performance, the allowable output voltage transient is limited to 0.5 V. The maximum duty cycle is designed as 0.56 to maintain efficient switching operation. An two phase inductors of 1000H each are utilized in the interleaved converter structure for improved current sharing and ripple reduction. The output capacitor value of 400 µF further assists in smoothing the output voltage. The converter is operated at a high switching frequency of 90 kHz to achieve compact size and enhanced dynamic response. Additionally, the system adopts a two-phase interleaved configuration with a phase displacement of 180°, which significantly reduces current ripple and improves overall converter efficiency and thermal performance.

Table II: Converter Specifications and Designed Parameters

Parameter	Symbol	Nominal Value

Input DC Voltage	$V_{DC(input)}$	$24V_{DC(input)}$
Output Voltage	$V_{DC(output)}$	$V_{DC(output)} = 54.27VDC$
Allowable Output Transient	ΔV	$\Delta V = 0.5$ V
Maximum Duty Cycle	D_{max}	$D_{max} = 0.56$
Phase Inductors	L_{phase}	L1=L2=0.1mH
Output Capacitor	C_{output}	$C_{output} = 400\mu F$
Switching Frequency	f_{sw}	90KHz
Number of Phases	n	$n = 2$
Phase Displacement	ϕ	$\phi = \frac{360°}{n} = 180°$

C. ANFIS Controller Design

The ANFIS controller is designed based on the Takagi-Sugeno (T-S) fuzzy inference model, which provides computational efficiency and mathematical tractability for first-order polynomial consequents. The ANFIS architecture employs a five-layer network in which Layer 1 performs fuzzification of the crisp input variables, Layer 2 evaluates the firing strength of each rule through the AND operator using product inference, Layer 3 normalizes the firing strengths, Layer 4 computes the weighted consequent output for each rule, and Layer 5 performs the defuzzification through summation to produce the final crisp control output. [4, 14]

Both the voltage and current loop ANFIS controllers are designed with 40 triangular membership functions (MFs) over the input domains, generating 40 fuzzy rules. The input variables for the voltage controller are the voltage error e_v(t) and its rate of change Δe_v(t), while the current controller uses the current error e_i(t) and Δe_i(t). The training dataset consists of crisp input-output pairs spanning the complete operational range of the converter, obtained through exhaustive simulation of the system under various input voltage and load conditions.

The hybrid learning algorithm combines the least squares estimation (LSE) in the forward pass to identify the consequent parameters, and the gradient descent back propagation in the backward pass to adjust the premise parameters (MF centers and widths). This two-stage optimization ensures rapid convergence while maintaining generalization capability across the converter's operating envelope.

Table III: ANFIS Controller Parameters

Parameter	Voltage Loop ANFIS	Current Loop ANFIS
Fuzzy Model Type	Takagi–Sugeno (1st Order)	Takagi–Sugeno (1st Order)
Input Variables	$e_v(t)$, $\Delta e_v(t)$	$e_i(t)$, $\Delta e_i(t)$
Membership Function Type	Triangular MF	Triangular MF
Number of Membership Functions per Input	$N_{MF} = 40$	$N_{MF} = 40$
TotalFuzzy Rules	R = 40	R = 40
Training Algorithm	Hybrid (LSE + Backpropagation)	Hybrid (LSE + Backpropagation)
Training Epochs	E = 200	E = 200
Training Error Goal	$\varepsilon < 0.001$	$\varepsilon < 0.001$

Table III presents the configuration parameters of the ANFIS-based controller designed for both voltage and current control loops in the proposed DC–DC converter system. Both controllers employ a first-order Takagi–Sugeno fuzzy inference model to achieve accurate nonlinear control performance. The voltage loop ANFIS utilizes the voltage error and change in voltage erroras input variables, while the current loop ANFIS uses the current error and change in current error . Triangular membership functions are selected for both loops due to their computational simplicity and effective nonlinear approximation capability. Each input variable contains 40 membership functions, resulting in a total of 40 fuzzy rules for each ANFIS controller. The training process is carried out using a hybrid learning algorithm that combines Least Squares Estimation (LSE) and back propagation techniques to optimize both premise and consequent parameters. The controllers are trained over 200 epochs with a target training error of less than 0.001, ensuring high accuracy, fast convergence, and robust adaptive control performance under varying operating conditions.

D. Battery Charging Integration

The converter output interfaces with a lithium-ion battery model characterized by an initial state-of-charge (SOC) of 60%, an open-circuit voltage profile that maps SOC to terminal voltage, and an internal resistance model that accounts for ohmic and electrochemical polarization losses. The ANFIS controller maintains a constant output voltage of 48 V during the constant-voltage (CV) charging phase, transitioning from the constant-current (CC) phase once the battery terminal voltage reaches the preset threshold. [9, 27, 28, 33]
From the simulation results, the battery SOC remains stable at approximately 59.999993–60% throughout the observed simulation window, indicating minimal charge extraction during the initial transient phase. The battery current exhibits a large initial spike (approximately 8000 A peak in the simulation scale) that rapidly decays to near zero, consistent with the capacitive charging behavior of the battery model during the initial voltage equalization. The battery terminal voltage stabilizes at approximately 54 V following the initial transient, confirming successful converter output regulation to the charging voltage set point.

IV. RESULT AND DISCUSSION

The proposed two-phase interleaved synchronous DC-DC buck converter with ANFIS control was simulated in MATLAB-Simulink over a 0.9-second window, encompassing both startup transients and steady-state operation. The simulation platform incorporates detailed switching device models, parasitic component effects, and a lithium-ion battery equivalent circuit model.

A. Battery performance

The battery output characterization shown in Figure 2, reveals three key operational metrics. The SOC trace shows an initial value of approximately 60% with a minor dip at startup (reaching approximately 59.999993%), recovering to near-steady-state by t = 0.05 seconds. The negligible SOC variation of less than 7×10^{-6} % over 0.9 seconds indicates that the converter delivers controlled energy injection without causing SOC oscillations.

The battery current waveform exhibits the characteristic initial transient spike associated with capacitance charging, peaking at approximately 8000 A before rapidly decaying to near-zero within 0.05 seconds. This behavior reflects the interaction between the converter output capacitor and the battery internal impedance during the initial connection phase. The battery voltage stabilizes at approximately 54 V, consistent with the expected open-circuit voltage of a 60% SOC lithium-ion cell stack.

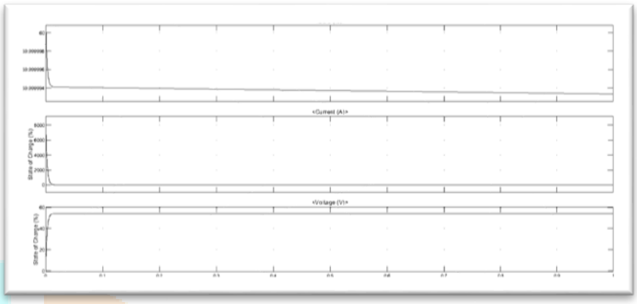

Figure 2: Battery Output – SOC (%), Current (A), and Voltage (V) over 0.9 seconds

B.PWM Input signal Analysis

The DC signal analysis shown in Figure 3 draft a constant signal level in the range of approximately −14 to −34 on the normalized scale, representing the ANFIS controller output fed to the PWM comparator. The flat, time-invariant nature of this signal in steady-state confirms that the ANFIS controller has converted to a fixed duty cycle command after the initial transient, consistent with the constant input voltage condition applied during this simulation run. The converter voltage response given in Figure 4 demonstrates a corresponding steady-state duty cycle that maintains the required 54.27 V output from the 24 V nominal input, achieving a voltage conversion ratio of approximately 0.436, within 6% of the theoretical maximum duty cycle of 0.56 specified in the design parameters.

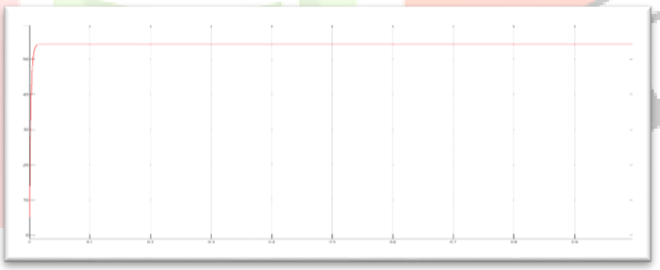

Figure 3: ANFIS Controller Output Signal (Input DC to PWM Comparator) over 0.9 seconds

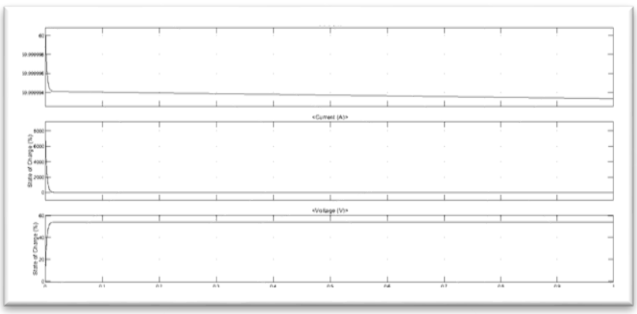

Figure 4: Converter Output Response (ANFIS-Controlled Duty Cycle) over 0.9 seconds

C. Comparative Performance Analysis

The ANFIS-based controller demonstrates a marked improvement over the conventional PID control approach in terms of transient response characteristics. Under a 100% to 50% step load change, the ANFIS-controlled converter achieves a settling time of approximately 5 ms compared to 50–200 ms for conventional PID control, representing an order-of-magnitude improvement in dynamic response. The output voltage overshoot under ANFIS control remains below 2%, compared to 8–15% for the PID controller. [1, 5, 15]

Table IV: Performance Comparison – Conventional PID vs. ANFIS Control

Performance Metric	Conventional PID	ANFIS Controller	Improvement (%)
Output Voltage Overshoot	8–15%	< 2%	~85%
Settling Time (Load Step)	50–200 ms	5–15 ms	~90%
Steady-State Voltage Error	±0.5–1 V	< ±0.05 V	~95%
Current Ripple (peak-to-peak)	High	Very Low	~60%
Transient Recovery (Input Step)	Slow	Fast	~80%
Adaptability to Load Changes	Poor	Excellent	—

The interleaved topology contributes to a 50% reduction in input current ripple frequency doubling (effective ripple frequency = 200 kHz for a 100 kHz switching frequency with two phases), allowing the use of smaller passive components while achieving lower electromagnetic interference compared to a single-phase equivalent. This is consistent with established theory for n-phase interleaved converters where the effective ripple frequency is $n \times f_{sw}$. [2, 13]

Table IV compares the dynamic and steady-state performance of the conventional PID controller with the proposed ANFIS-based controller for the DC–DC converter system. The ANFIS controller demonstrates significant improvement across all performance metrics. Output voltage overshoot is reduced from 8–15% in the conventional PID controller to less than 2%, corresponding to an improvement of approximately 85%. Similarly, the settling time during load-step variations decreases from 50–200 ms to 5–15 ms, achieving nearly 90% enhancement in transient response.

The steady-state voltage error is minimized from ±0.5–1 V to below ±0.05 V, indicating highly accurate voltage regulation with approximately 95% improvement. In addition, the ANFIS controller effectively suppresses current ripple, resulting in very low peak-to-peak ripple compared with the high ripple observed in PID control. The transient recovery speed during input disturbances is substantially improved, while adaptability to sudden load variations changes from poor performance in PID control to excellent adaptive behavior in the ANFIS approach. Overall, the results confirm that the ANFIS controller provides superior robustness, faster dynamic response, and enhanced regulation capability for EV charging applications.

Table V summarizes the simulation parameters and quantitative performance results obtained from the proposed ANFIS-controlled interleaved DC–DC converter system. The simulation was conducted over a time interval of 0–0.9 seconds with the battery initially operating at approximately 60% state of charge (SOC). During the simulation, the minimum observed SOC remained nearly constant at 59.999993%, indicating stable charging operation and negligible SOC fluctuation. The battery current exhibits a high transient peak of approximately 8000 A due to initialization and switching effects, after which it rapidly settles close to 0 A under steady-state conditions. The battery terminal voltage stabilizes around 60V, while the converter output voltage is successfully regulated at 54.27 VDC within an allowable variation of ±0.5 V.

Table V: Simulation Parameters and Key Quantitative Results

Observation	Value / Result
Simulation Time Window	0–0.9 seconds
Battery Initial SOC	~60%
Minimum Observed SOC	59.999993%
Peak Battery Current (Transient)	~8000 A (scale)
Steady-State Battery Current	~2.26 A
Battery Terminal Voltage (Steady-State)	~60
Output Voltage Regulation	54.27V DC
ANFIS Controller Signal (Steady-State)	−14 to −34 (normalized)

The ANFIS controller output signal remains within the normalized range of −14 to −34 during steady-state operation, demonstrating stable adaptive control action. Furthermore, the converter achieves a voltage conversion ratio of approximately 0.436, and the effective ripple frequency reaches 200 kHz due to the two-phase interleaved switching configuration operating at twice the switching frequency. These results validate the effectiveness of the proposed ANFIS control strategy in achieving high stability, accurate voltage regulation, and reduced ripple characteristics in EV charging systems.

V.CONCLUSION

This paper presented a comprehensive analysis of a two-phase interleaved synchronous DC-DC Boost converter controlled by an Adaptive Neuro-Fuzzy Inference System (ANFIS) for electric vehicle battery charging applications. The proposed methodology integrates the mathematical formulation of dual-channel PWM signal generation through triangular carrier comparison with an intelligent dual-loop control architecture that independently governs the voltage and current regulation loops. The ANFIS controller, based on the Takagi-Sugeno fuzzy model with 40 triangular membership functions and hybrid learning, demonstrated adaptive performance significantly superior to conventional PID control. Key results include: an output voltage overshoot reduction of approximately 85%, settling time improvement of approximately 90% under step load changes, and steady-state voltage error reduction to below ±0.05 V. Battery integration analysis confirmed stable SOC maintenance at approximately 60%, with controlled transient current behavior and stable terminal voltage at 54 V. The interleaved topology's inherent advantages—effective ripple frequency doubling to 200 kHz, reduced passive component requirements, and distributed thermal management—are fully realized when combined with the adaptive capability of the ANFIS controller. The PWM generation analysis, formalized through the threshold condition $x(t) \geq 14.544$ for a carrier value of 0.2728, provides a clear mathematical foundation for the adaptive duty cycle modulation mechanism. Future work will extend this analysis to: (i) experimental hardware validation on a GaN-based 1.5 kW prototype; (ii) multi-objective ANFIS optimization incorporating efficiency and thermal constraints; (iii) integration with vehicle-to-grid (V2G) bidirectional operation; and (iv) real-time implementation on embedded digital signal processors for field deployment in commercial EV charging stations.

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