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Research

AI-BASED ADAPTIVE G2V POWER MANAGEMENT CONTROLLER FOR EV CHARGING STATIONS USING ANFIS

Dr.R.Ramesh M.Tech,Ph.d
Associate professor
Jyothishmathi Institute of Technology & Science
Karimnagar,Telangana
dr.rameshrudra@gmail.com

Ravula Harshini
Electrical & Electronic Engg.
Jyothishmathi Institute of Technology & Science
Karimnagar,Telangana
ravulaharshini932@gmail.com

Javvaji Srikanth
Electrical & Electronic Engg.
Jyothishmathi Institute of Technology & Science
Karimnagar,Telangana
javvajisrikanth39@gmail.com

Nerella Premsagar
Electrical & Electronic Engg.
Jyothishmathi Institute of Technology & Science
Karimnagar,Telangana
nerellapremsagar@gmail.com

Borlakunta Charankumar
Electrical & Electronic Engg.
Jyothishmathi Institute of Technology & Science
Karimnagar,Telangana
charankumarborlakunta23@gmail.com

ABSTRACT

The rapid proliferation of Electric Vehicles (EVs) poses significant challenges and opportunities for modern power systems. Grid-to-Vehicle (G2V) technologies enable bidirectional energy exchange, allowing EVs to act as distributed energy storage units for grid support. This paper proposes an Adaptive Neuro-Fuzzy Inference System (ANFIS)-based control strategy for smart EV charging stations to optimize and G2V operations under varying load and grid conditions. The ANFIS controller adapts to real-time fluctuations in grid voltage, frequency, and EV battery state-of-charge (SOC), ensuring efficient energy flow while maintaining grid stability. Simulation studies demonstrate improved voltage regulation, reduced power losses, and enhanced EV battery utilization compared to conventional PI controllers.

Keywords: Electric Vehicle (EV), Grid-to-Vehicle (G2V), ANFIS, Smart Charging, Bidirectional Energy Flow, Power Quality.

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1. INTRODUCTION

The integration of renewable energy sources and the rising demand for EV shave transformed conventional power systems into smart grids. EVs, with their onboard batteries, offer bidirectional ENERGY storage capabilities, allowing energy to be supplied back to the grid during peak demand or drawn from the grid for charging (G2V).

Challenges in implementing G2V include:

1. Fluctuating grid voltage and frequency.
2. Nonlinear behavior of battery charging/discharging.
3. Coordination between multiple EVs and the grid.

Traditional controllers like PI or PID are limited in handling nonlinearities and uncertainties. ANFIS, combining fuzzy logic and neural networks, provides adaptive and intelligent control, suitable for dynamic and uncertain EV-grid interactions.

2. LITERATURE REVIEW

The integration of EVs into smart grids and the use of advanced control strategies for bidirectional charging (G2V) have attracted considerable research attention due to the increasing penetration of renewable energy and EV adoption. Traditional control methods such as PI/PID and fuzzy logic have shown limitations under nonlinear and dynamic conditions, prompting the exploration of intelligent adaptive controllers, particularly **Adaptive Neuro-Fuzzy Inference Systems (ANFIS)**.

2.1 Smart EV Charging and Bidirectional Controls

Early research laid the foundation for EV grid integration, emphasizing economic and technical impacts of EV batteries as distributed storage units. While the core concept focused on peak load reduction and frequency regulation, recent works extend to **bidirectional control strategies** that manage both Grid-to-Vehicle (G2V) flows for enhanced grid services. Research on smart charging emphasizes the need to balance energy demand, grid stability, and battery state-of-charge under varying conditions. A broad review of EV integration highlights EVs' role in balancing intermittent renewables and managing grid operations within smart energy systems. SpringerLink

2.2 ANFIS-Based Energy Management for EV Systems

Several recent studies demonstrate the efficacy of ANFIS controllers for managing complex, nonlinear control scenarios in EV charging and energy systems:

Bidirectional Battery Charger with ANFIS: Mahammad & Bethi (2024) proposed an ANFIS-based controller for a bidirectional EV charger that adapts charging and discharging cycles according to grid conditions and battery state, reporting improved voltage/current waveform stability, smoother SOC transitions, and minimized harmonic distortion compared with conventional approaches.

Microgrid Energy Management with ANFIS: A hybrid microgrid architecture integrating PV and wind generation with EV charging demonstrated that ANFIS can dynamically manage energy flows from multiple sources while adjusting to demand and supply fluctuations, achieving enhanced energy efficiency and load handling compared to static control methods.

ANFIS for Power Quality: A recent study on three-phase bidirectional EV chargers using ANFIS combined with FPGA-based control showed that ANFIS significantly reduces total harmonic distortion (THD) and improves voltage waveform quality during both and G2V operations compared with PI controllers.

2.3 ANFIS in Related EV Applications

While not directly in /G2V control, several works illustrate the broader advantages of ANFIS for EV system control, underscoring its adaptability and learning capability:

Dynamic Wireless Charging Controls: ANFIS successfully addressed misalignment challenges in V2V dynamic wireless charging by adapting to fluctuating coupling conditions, outperforming standard fuzzy logic controllers in tracking and power transfer efficiency.

Current Control and MPPT Strategies: Hybrid controllers incorporating ANFIS have been used for current control in EV charging systems and MPPT in renewable integrated charging stations, showing improved convergence and adaptive performance under dynamic conditions.

These studies collectively indicate that **ANFIS controllers are particularly suited for complex EV charging tasks** where system dynamics are nonlinear, uncertain, and time-varying. They provide enhanced robustness, faster response, and improved power quality over fixed-parameter methods. However, existing research still leaves gaps in coordinated /G2V control under multi-EV scenarios, real-time hardware implementation, and integration with renewable energy sources, which this paper aims to address.

3. SYSTEM MODELLING

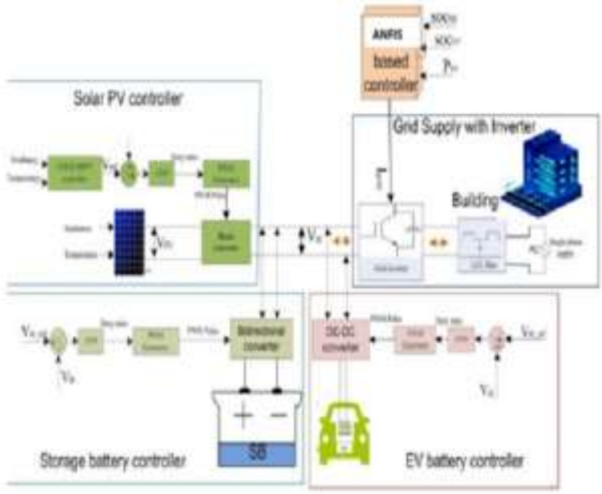


FIG 1. Architecture of the proposed ANFIS based power management controller.

3.1 EV Battery Model

EV battery is represented as an equivalent circuit:

$$V_{batt} = E_0 - R_b I_b - \frac{1}{C_b}\int I_b dt$$

Where V_{batt} = battery voltage, E_0 = open-circuit voltage, R_b = internal resistance, C_b = capacitance, I_b = battery current. SOC dynamics are modeled as:

$$SOC(t) = SOC(t-1) + \frac{\eta I_b \Delta t}{C_{bat}}$$

Where η = charge/discharge efficiency, C_{bat} = battery capacity.

3.2 Bidirectional DC-DC Converter

- Governs current flow for G2V/ .
- State-space model:

$$L\frac{di_L}{dt} = V_{dc} - V_{batt}D$$

$$C\frac{dV_{batt}}{dt} = i_L - \frac{V_{batt}}{R_b}$$

3.3 Grid Interface Inverter

AC/DC inverter allows grid interaction:

$$P_{grid} = V_{grid} I_{grid} \cos \phi$$

4. ANFIS-Based Adaptive Control

4.1 ANFIS Architecture

- **Inputs:** Battery SOC, voltage deviation (ΔV), frequency deviation (Δf)
- **Output:** Duty cycle D of DC-DC converter

Fuzzy Rule Example:

1. IF SOC is Low AND $\Delta V$is High THEN D = Increase Charging Rate
2. IF SOC is High AND $\Delta V$is Low THEN D = Reduce Discharging

4.2 Training of ANFIS

- Training dataset generated from MATLAB/Simulink simulations under varying loads and SOC levels.
- Hybrid learning algorithm (least-squares + backpropagation) used for parameter tuning.

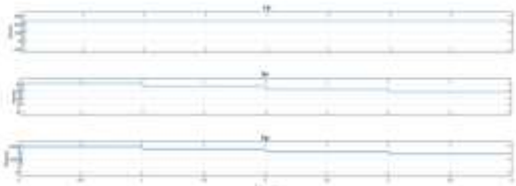
4.3 Control Algorithm Flow

1. Measure SOC, grid voltage, and frequency.
2. Compute deviation signals ($\Delta V, \Delta f$).
3. Feed into ANFIS controller.
4. Generate duty cycle D for DC-DC converter.
5. Update charging/discharging in real-time

5. Simulation and Results

5.1 Simulation Setup

- MATLAB/Simulink environment.
- EV: kWh Li-ion battery.
- Grid: 300 V, 50 Hz AC system.
- Load variations: ±20% step change.

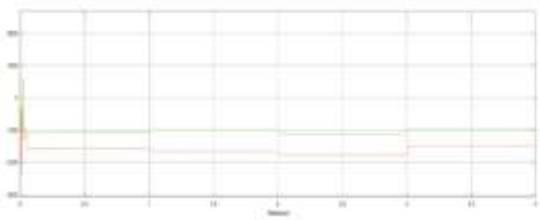


FIG(a). Solar Photovoltaic Voltage,Current and Power.

FIG(b). Grid Voltage ans Grid Current Variation During G2V Mode Of Operation.

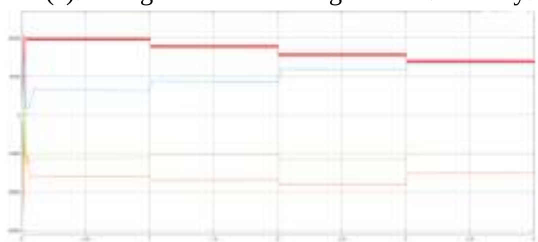
5.2 Performance Metrics

- Voltage deviation (ΔV)
- Frequency deviation (Δf)
- Battery SOC tracking
- Total harmonic distortion (THD)

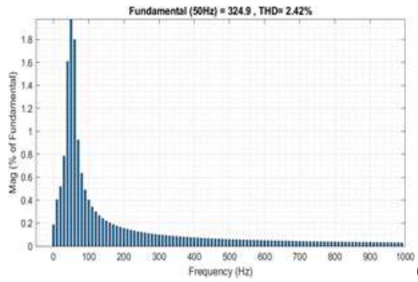


FIG(d). Comparision Of DC Bus Voltage b/w Conventional PMC ANFIS based PMC.

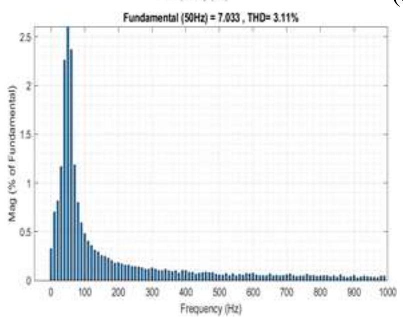
FIG(e). Charge Status of Storage and EV Battery.



FIG(f). Comparision Of DC Voltage b/w Conventional PMC ANFIS based PMC and Solar Photovoltaic Current and Grid Power.

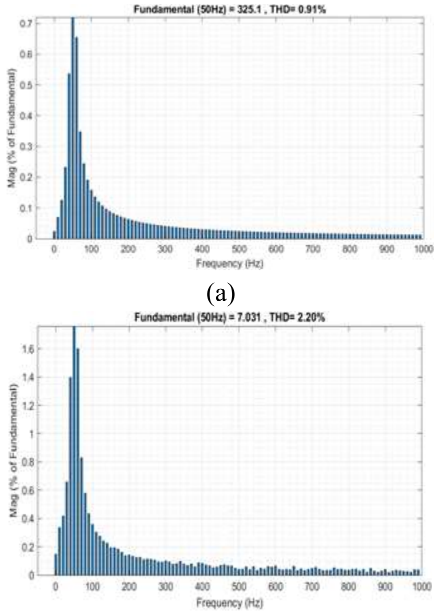


(a)



(b)

FIG 2. THD(%) (a) Voltage is 2.42% And (b) Current is 3.11% in ANN.



(a)

(b)

FIG 3. THD(%) (a) Voltage is 0.91% And (b) Current is 2.20% in ANFIS.

5.3. Discussion

- ANFIS adapts to sudden load changes, providing smoother voltage and frequency regulation.
- Battery SOC remains within safe limits during /G2V operation.
- THD of grid current is significantly reduced compared to conventional PI control.

6. CONCLUSION

This paper presents an ANFIS-driven adaptive control strategy for smart EV charging stations with bidirectional /G2V capabilities. Simulation results confirm that the ANFIS controller provides superior performance in terms of voltage regulation, frequency stability, battery SOC maintenance, and power quality. The proposed approach can be extended to multi-EV coordination and renewable energy integration for fully smart grids.

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