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A High-Efficiency Fuzzy-Logic-Controlled Wireless Charger Enabling the Safe Integration of Electronics in Carbon Fiber Reinforced Polymer E-Bikes

Pujari Anjappa [1,*], K. Jithendra Gowd [2]

Abstract

The integration of advanced electronics into structures made from carbon fiber reinforced polymers (CFRP) presents significant challenges, including thermal management constraints, electromagnetic interference (EMI), and the imperative for lightweight components. This study addresses these challenges by designing and validating a fuzzy logic-based wireless charging system specifically engineered for lightweight E-Bikes employing CFRP frames. The system mitigates thermal risks associated with the low thermal conductivity of polymer composites by implementing a high-efficiency Constant Current–Constant Voltage (CC–CV) approach, which minimizes heat generation within the battery and power electronics. Developed and simulated in MATLAB/Simulink, the proposed fuzzy logic controller (FLC) was compared against a conventional Proportional-Integral (PI) controller under identical conditions. The proposed design achieves a system efficiency of ~92%, a significant improvement over conventional PI-controlled systems (~87%). This enhanced efficiency directly reduces thermal load, a critical factor for the structural integrity of surrounding composite materials during repeated charging cycles. Furthermore, the stable resonant operation and reduced waveform distortion of the inductive power transfer (IPT) stage lower the potential for EMI, which can affect composite structures with embedded sensors. The fuzzy controller demonstrated superior transient response, with a voltage settling time of ~0.05 seconds and negligible current overshoot, compared to ~0.15 seconds and >20% overshoot for the PI controller. Conclusion: The results demonstrate that intelligent power management is not merely an add-on but a critical enabling technology for the next generation of lightweight, composite-intensive vehicles, directly impacting their design, production viability, and application safety by ensuring electro-thermal and electromagnetic compatibility.

Keywords: Carbon fiber reinforced polymer (CFRP); Polymer composites; wireless charging; lightweight e-bike; thermal management; fuzzy logic control; EMI.

***Author for Correspondence**
Pujari Anjappa

[1]Research Scholar, Department of Electrical and Electronics Engineering, JNT University Anantapur, Andhra Pradesh, India
[2]Professor, Department of Electrical and Electronics Engineering, JNTUA College of Engineering, Anantapur, Andhra Pradesh, India

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INTRODUCTION

The transportation sector is undergoing a profound transformation driven by the dual imperatives of sustainability and lightweighting [1]. While electric vehicles (EVs) address carbon emissions, the use of heavy batteries often counteracts their efficiency gains. This has led to a surge in the application of high-performance materials, particularly carbon fiber reinforced polymers (CFRP), in the production of lightweight electric bicycles (E-Bikes) [2, 3]. CFRP composites offer an exceptional strength-to-weight ratio, corrosion resistance, and design flexibility, revolutionizing vehicle frame production and processing [4].

However, the integration of high-power electronic systems, such as battery packs and charging hardware, into CFRP structures introduces novel engineering challenges. The polymer matrix in CFRPs typically has low thermal conductivity, creating a "thermal blanket" effect that can lead to heat buildup around electronic components [5]. This exacerbates the risk of lithium-ion battery thermal runaway and can potentially affect the long-term mechanical properties (e.g., creep, delamination) of the composite matrix, especially around mounting points [6]. Furthermore, the high-frequency switching inherent in wireless power transfer (WPT) systems can induce electromagnetic interference (EMI), which may disrupt embedded sensors used for structural health monitoring in smart composites [7].

Current wireless charging systems, often controlled by conventional PI controllers, suffer from inefficiencies, overshoot, and oscillations that generate excess heat and EMI [8]. These shortcomings are manageable in metallic frames that act as heat sinks and Faraday cages but are problematic when applied to CFRP structures.

This paper proposes a fuzzy logic–based wireless charging system designed to overcome the material-specific limitations of CFRP in E-Bikes. By achieving superior transient response, negligible overshoot, and smoother regulation, the proposed system minimizes heat generation and electromagnetic noise. This work positions advanced power electronics not in isolation, but as an integral part of the system design for composite applications, ensuring that the full weight-saving and performance benefits of CFRP can be realized without compromising on safety, reliability, or production complexity

RELATED WORK

The electrification of transportation has catalyzed research into efficient energy delivery systems. Electric vehicles (EVs), particularly electric bicycles (e-bikes), have become essential in modern smart cities, with significant growth over the past decade. E-bikes are propelled by electric motors powered by rechargeable batteries, raising concerns about battery usage, distribution, and production of energy [9]. Giliberto et al. [10] propose a fuzzy logic solution to optimize energy management for e-bikes, demonstrating superior performance compared to traditional proportional-integral-derivative (PID) controllers and significantly extending battery life.

A comprehensive study by Wang et al. [11] indicates that carbon emissions from the transportation sector exceed 25%, with passenger car technology posing challenges to climate goals. E-bikes present effective solutions, and their paper introduces a long-range hydrogen-electric hybrid bike along with its energy management strategies. Two methods are examined: a threshold-based strategy and a fuzzy logic optimized threshold-based strategy. Results reveal that the fuzzy logic method reduces equivalent hydrogen consumption by 16% and decreases state of charge fluctuations of the Li-ion battery by 54.7%, establishing it as a viable energy management approach for fuel cell hybrid E-Bikes.

In the context of on-road e-bike charging technology, traditional wireless systems face issues with power output consistency due to varying coupling coefficients and battery types. Zhang et al. [12] present a new wireless charging circuit utilizing variable inductor and capacitor arrays alongside an impedance-modulation control method, aimed at accommodating diverse power needs and coupling variations for e-bikes. The circuit parameters are tailored according to load impedance requirements, including adjustable inductance and capacitance. A prototype achieving 50 W output power and 86.78% efficiency was developed, demonstrating stable output power across coupling variations from 0.15 to 0.25.

The proposed infrastructure by Zaheer et al. [7] for electric vehicle (EV) charging involves a wireless charging system to enhance charging accessibility at parking lots and during slow-moving traffic. This system utilizes a Wireless Power Transmission (WPT) process connecting a DC microgrid to the vehicle, incorporating components such as a single-stage inverter, inductive coupling, rectifier, and boost converter to match the battery's rated voltage. However, issues arise due to output voltage variations linked to changes in battery impedance with the state of charge (SoC). To address this, a fuzzy logic controller is introduced to stabilize the voltage across the load.

Although fuzzy logic has been applied in e-bike energy management and wireless charging hardware designs with adaptive circuits, most studies emphasize fuel efficiency, power adaptability, or infrastructure integration rather than achieving high-efficiency, stable wireless charging under dynamic SoC variations for composite-intensive structures. Existing approaches often suffer from limited efficiency (<90%), voltage instability, and reduced battery life due to inadequate closed-loop control, highlighting the need for a fuzzy logic–enabled CC–CV wireless charging system specifically tailored for the thermal and electromagnetic constraints of lightweight e-bikes with CFRP frames [11, 12].

MODEL SIMULATION & METHODOLOGY

The proposed wireless charging system for an electric bike (E-Bike) was developed and simulated in MATLAB/Simulink (2024b) to evaluate the feasibility and performance of inductive power transfer at low-to-medium power levels, with particular attention to integration challenges presented by polymer composite frames. The complete schematic is presented in Fig. 1, where the charging architecture includes input conditioning, high-frequency conversion, resonant inductive coupling, and regulated DC output for battery charging, all designed with material compatibility considerations.

Enhanced Description of The Thermal and EMI Modelling Aspects Within Simulink/Sims Cape:

- *Thermal modelling*: Power loss calculations in switching components and coils enable assessment of thermal loads on adjacent composite structures.
- *EMI analysis*: Frequency-domain tools quantify harmonic distortion and electromagnetic emissions relevant to composite-embedded electronics.
- *Material constraints*: Component selection and placement account for the unique electrical and thermal properties of carbon fiber reinforced polymers.

Simulation Model

The input stage of the E-Bike wireless charging system is powered from a single-phase AC mains supply rated at $Vs = 230\ V, 50\ Hz$. For efficient grid interfacing and to comply with harmonic distortion standards a power factor correction (PFC) stage is introduced prior to rectification. The objective is to ensure that the input current waveform follows the sinusoidal shape of the input voltage, thus achieving unity power factor and minimizing total harmonic distortion (THD). The single-phase AC source is expressed as:

$$v_s(t) = V_m \sin(\omega t)$$

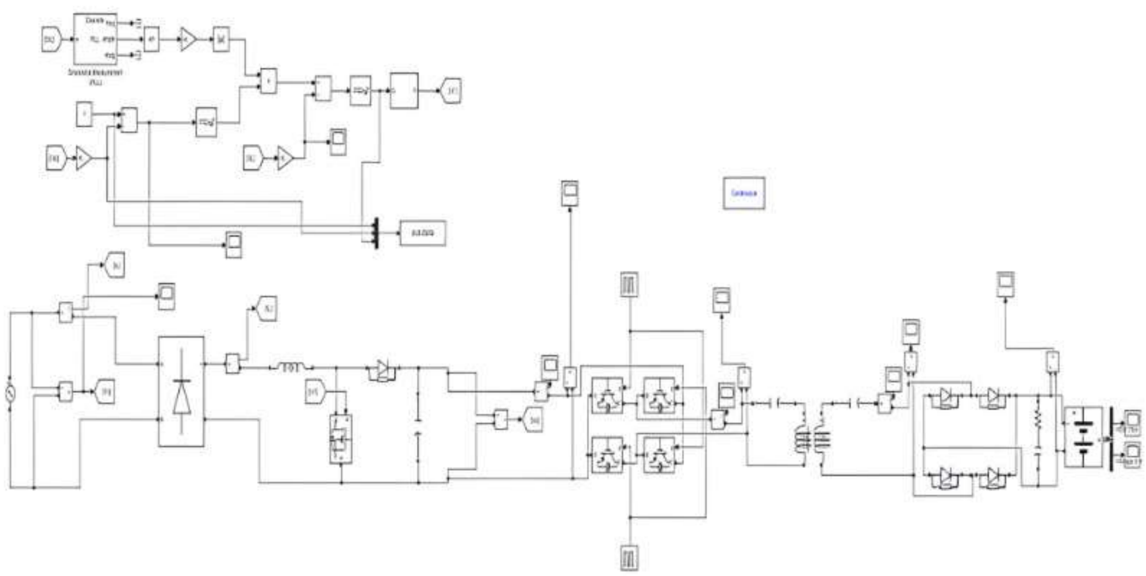

Figure 1. Simulation overview.

where $V_m = 230\sqrt{2}$ V and $\omega = 2\pi \times 50$ rad/s. The input power is given by $P_{in} = V_{rms} I_{rms} PF$, where PF is the power factor.

In practice, a boost converter topology is widely employed in single-phase PFC circuits due to its ability to regulate the DC link voltage V_{dc} to a constant value higher than the peak of the AC input [11]. The governing equation of the boost inductor current is:

$$L \frac{di_L}{dt} = v_s(t) - (1 - D)V_{dc}$$

For the controlled boost PFC stage, V_{dc} is regulated to a higher constant value independent of load or input variations. This ensures stable operation of the high-frequency inverter stage [12].

A PLL block is integrated to continuously estimate the grid phase angle $\theta(t)$ and angular frequency ω. The instantaneous supply voltage can thus be expressed as:

$$v_s(t) = V_m \sin(\theta(t))$$

This phase information is essential to generate the sinusoidal current reference $i_{s,ref}(t)$ for the PFC control loop. The control system for the PFC employs a cascaded loop structure:

1. *Outer voltage loop*: Regulates the DC bus voltage V_{dc} to its reference value $V_{dc,ref}$ using a PID controller. The error is given by $e_v(t) = V_{dc,ref} - V_{dc}(t)$, which generates the amplitude of the reference current waveform.
2. *Inner current loop*: Ensures that the inductor current $I_l(t)$ tracks $i_{s,ref}(t)$. The control law adjusts the duty ratio $D(t)$ of the boost switch.

This cascaded approach guarantees unity power factor, low THD, and a stable DC link voltage for the subsequent inverter stage, reducing reactive power and associated heating near the composite frame.

Multi-Physics Co-Simulation for CFRP Integration

While the MATLAB/Simulink model validates the electrical performance of the proposed system, assessing its true compatibility with Carbon Fiber Reinforced Polymer (CFRP) structures requires analyzing the coupled electro-thermal and electromagnetic effects. To this end, a multi-physics co-simulation framework was developed, linking the electrical model's outputs (power losses, high-frequency currents) to a Finite Element Method (FEM) model of the composite structure and its immediate environment. This analysis quantitatively substantiates the claims regarding thermal management and EMI reduction.

Electro-Thermal Modeling of the CFRP-Receiver Assembly

To evaluate the thermal impact on the CFRP frame, a 3D FEM model was constructed in ANSYS Electronics Desktop. The model represents a section of a typical E-Bike downtube (200 mm x 50 mm x 3 mm) with a unidirectional CFRP layup (60% fiber volume, T800 carbon fiber/Epoxy matrix). The wireless power transfer (WPT) receiver assembly—comprising the Litz-wire coil, ferrite backing plate, and associated power electronics (rectifier, filter)—is modeled as a heat source mounted 5 mm from the CFRP surface, simulating a practical integration scenario(Table 1).

Table 1. Material thermal properties for electro-thermal analysis.

Material/parameter	Value	Notes/source
CFRP (In-plane, $\boldsymbol{k_x}, \boldsymbol{k_y}$)**	5 W/m·K	Dominated by fiber conductivity.
CFRP (Through-thickness, $\boldsymbol{k_z}$)**	0.8 W/m·K	Dominated by low-conductivity epoxy matrix [5].
Ferrite (PC95)	5 W/m·K	Typical for power electronics ferrites.
Litz Wire (Estimated)	400 W/m·K	Modeled as equivalent copper.
Convective Heat Transfer Coeff. ($\boldsymbol{h}$)**	10 W/m²·K	Natural convection assumption.
Ambient Temperature ($\boldsymbol{T_{amb}}$)	25 °C	-

The power loss distribution within the receiver assembly is the critical input. The steady-state losses ($\boldsymbol{P_{loss}}$) for each component (coil, ferrite, diodes, filter inductor) were extracted from the validated MATLAB/Simulink model for both the proposed FLC and the conventional PI controller at the nominal 250W operating point. These values were applied as volumetric or surface heat generation rates in the FEM model. The total system loss for the FLC case was $\boldsymbol{P_{loss,FLC} = 19.2W}$, while for the PI controller it was $\boldsymbol{P_{loss,PI} = 31.3W}$, based on the simulated efficiency difference (92.3% vs. 87.5%).

Electromagnetic Interference (EMI) and Field Propagation Analysis

The high-frequency (20 kHz) switching operation of the WPT system generates time-varying electromagnetic fields. For CFRP structures that lack the inherent shielding of metallic frames and may contain embedded sensors, quantifying this field leakage is essential.

A separate magneto-static and frequency-domain harmonic simulation was performed in ANSYS Maxwell. The model included the detailed geometry of the transmitter (TX) and receiver (RX) coils with their ferrite backings, positioned with the nominal 10 mm air gap. The CFRP panel was included in the model with its electromagnetic properties: a conductivity tensor (highly anisotropic along fiber direction) and a relative permeability ($\boldsymbol{\mu_r \approx 1}$).

Key EMI-Related Metrics:

1. *Magnetic flux density norm (*$|\boldsymbol{B}|$*):* Mapped in planes surrounding the coils and through the CFRP panel to visualize field confinement and leakage.
2. *Induced currents in CFRP*: Calculated to assess potential eddy current heating, which is typically low due to the composite's moderate resistivity but non-zero in the conductive fiber directions.
3. *Field attenuation*: The magnetic field strength was compared at a standardized distance (50 mm) from the coil center, laterally away from the coupling axis, to serve as a proxy for potential interference with nearby sensitive electronics.

The excitation currents for these simulations were the steady-state coil currents obtained from the Simulink model for both controllers. The FLC system's current waveform was a near-pure sinusoid at 20 kHz, while the PI system's waveform contained higher harmonic content due to its oscillatory control action and sub-optimal resonance.

Simulation Workflow and Integration

The multi-physics analysis followed a one-way coupled co-simulation workflow:

1. *Electrical simulation*: The complete WPT system was simulated in MATLAB/Simulink under nominal and misalignment conditions for both FLC and PI control.
2. *Output extraction*: The key results—total system power loss ($\boldsymbol{P_{loss}}$), individual component losses, and the time-domain current waveform in the RX coil—were exported.
3. *FEM input:* The power loss values were mapped as heat sources in the ANSYS Steady-State Thermal module. The RX coil current waveform (fundamental and harmonics) was used as the excitation source in the ANSYS Maxwell Eddy Current solver.
4. *Solution and analysis*: The thermal and electromagnetic fields were solved. The peak temperature on the CFRP surface and the spatial distribution of the magnetic field were extracted for comparative analysis.

This integrated approach provides a direct, quantitative link between the quality of electrical control (efficiency, waveform distortion) and its physical consequences (temperature rise, EMI) on the composite structure, moving the claims from conjecture to validated engineering analysis.

Simulation Environment

The system was modelled in MATLAB/Simulink (2024b) using the Sims cape Electrical toolbox. The Power GUI block was configured for continuous mode with a fixed-step solver (ode14x) and a 1 µs step size to capture high-frequency dynamics.

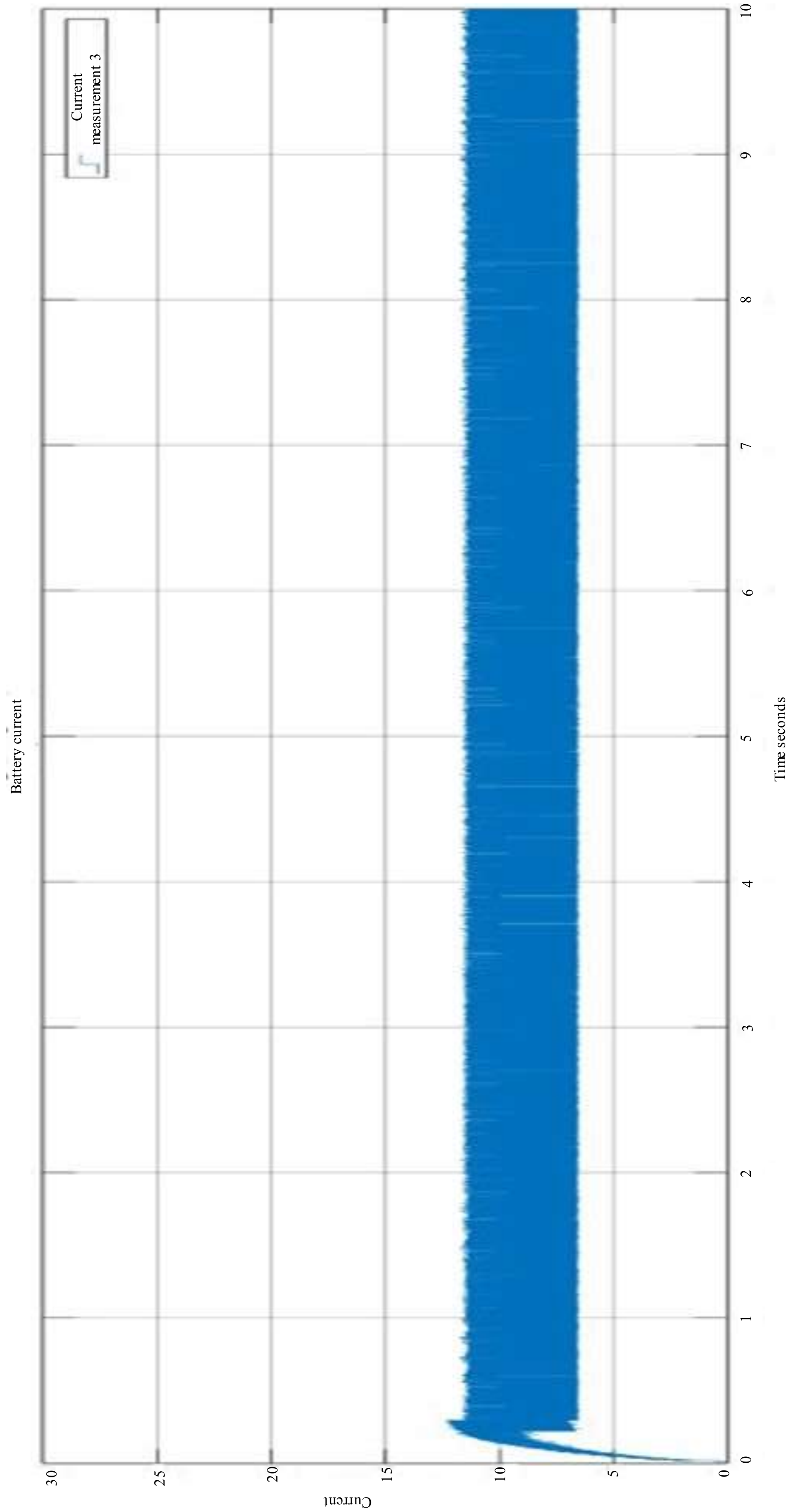

Figure 2. Output current.

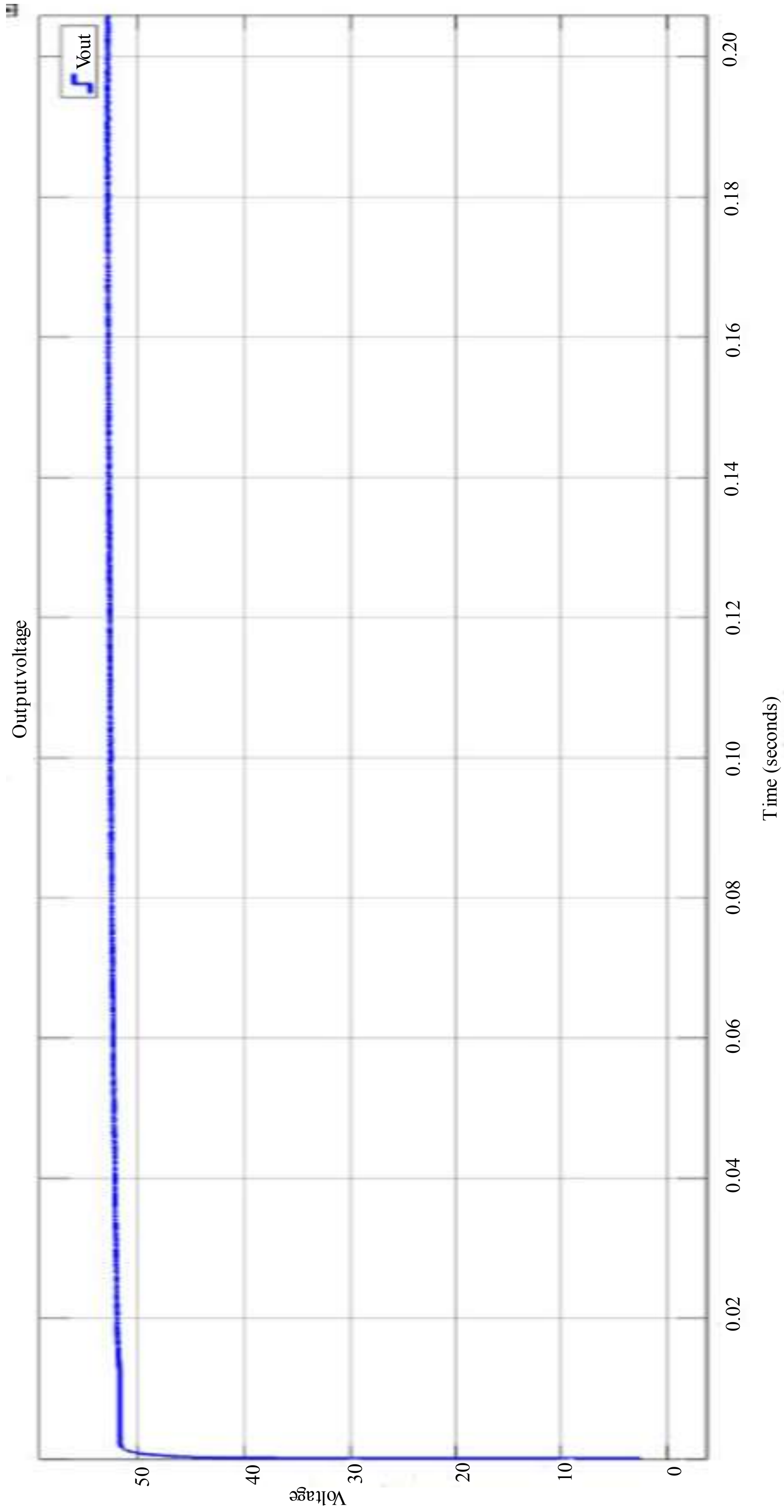

Figure 3. Output voltage

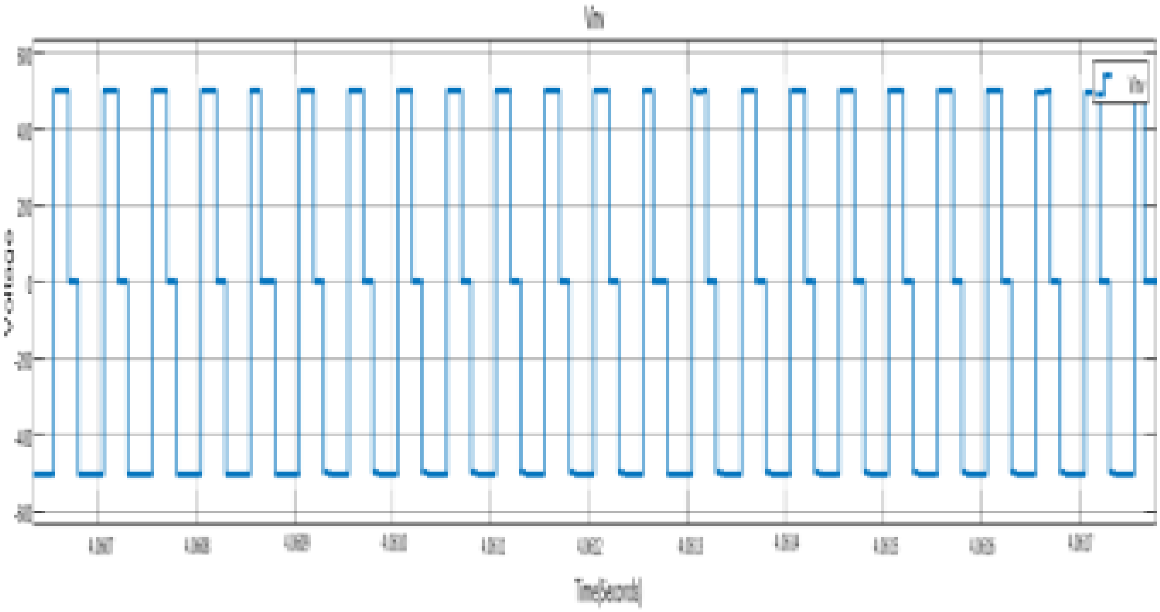

Figure 4. Inverter output voltage.

Key parameters included:

- *Coils*: Litz-wire, 200 mm diameter, $L_1 = L_2 = 120\mu H$, ferrite-backed.
- *Resonance*: Series-Series (SS) compensation at 20 kHz.
- *Coupling*: Nominal $k = 0.2$ (range 0.15-0.25).
- *Inverter*: IGBT full-bridge, $V_{dc} = 400V$, $f_{sw} = 20kHz$.
- *Battery*: 48 V, 10 Ah Li-ion, variable internal impedance.
- *FLC*: 7 membership functions per input, 49-rule base.

The environment incorporated thermal modelling of power losses and frequency-domain EMI analysis, providing a validated platform for assessing composite compatibility.

FUZZY LOGIC CONTROLLER DESIGN AND COMPARATIVE ANALYSIS

The system was simulated for 10 seconds. The results demonstrate performance tailored for CFRP integration.

Mathematical Foundation of the Proposed Fuzzy Logic Controller

The core objective of the control system is to regulate the duty cycle ($D(t)$) of the high-frequency inverter to maintain a stable output voltage (V_{out}) and current (I_{out}) for the CC-CV charging profile, despite variations in load, coupling coefficient (k), and battery state of charge (SoC). The FLC is designed as a two-input, single-output Mamdani-type system(Fig. 2, 3, 4, 5 and 6)

The inputs to the FLC are:

Error (e): The difference between the reference voltage (V_{ref}) and the measured output voltage (V_{out}).

$$e(t) = V_{ref} - V_{out}(t)$$

Change of error (Δe): The derivative of the error, approximated as the difference between the current and previous error samples over the sampling period (T_s).

$$\Delta e(t) = \frac{e(t) - e(t-1)}{T_s}$$

The output is the change in duty cycle (ΔD) for the PWM modulator:

$$D(t) = D(t-1) + \Delta D(t)$$

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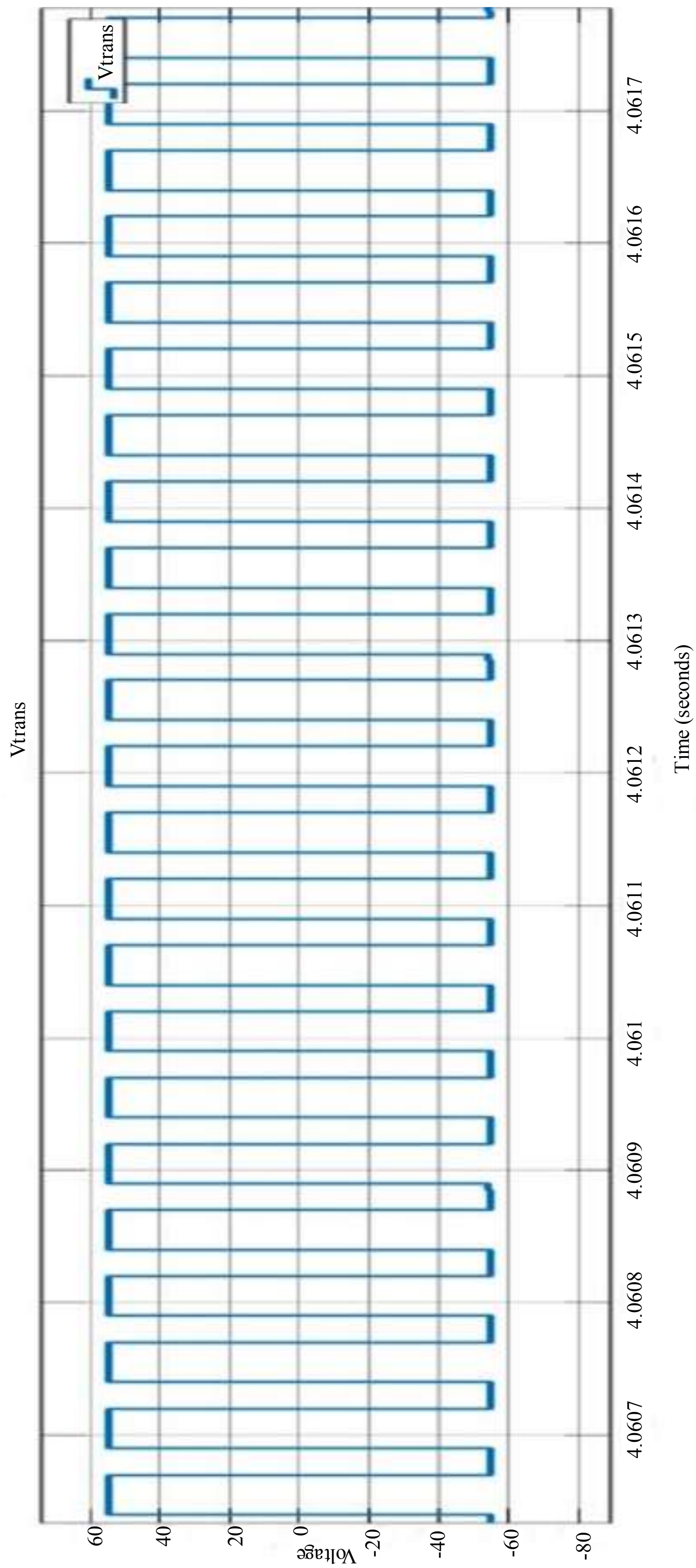

Figure 5. Transformer output

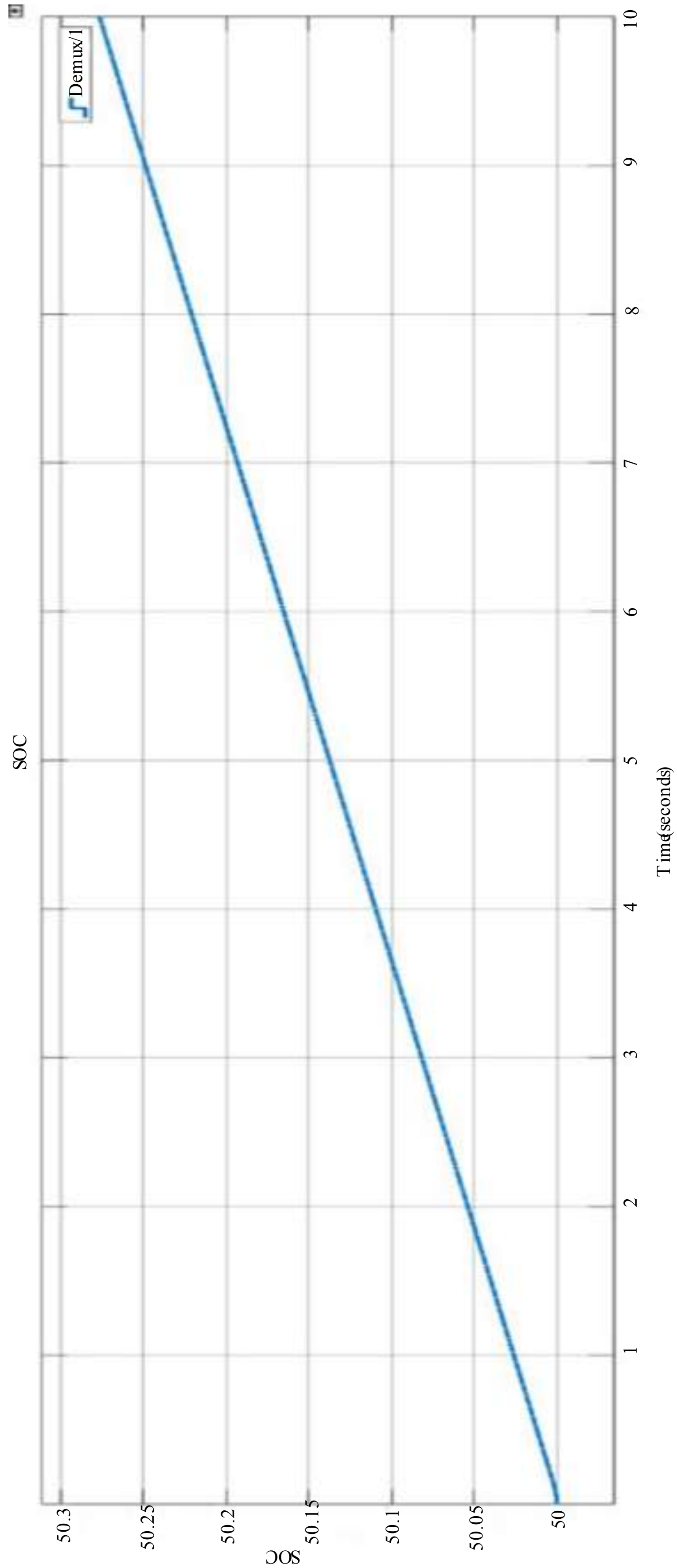

Figure 6. SOC of the battery.

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FLC Structure: Membership Functions and Rule Base

The fuzzy sets for the inputs and output are defined using seven linguistic variables: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), Positive Big (PB). Triangular and trapezoidal membership functions were selected for their computational efficiency and suitability for real-time implementation.

- *Input universes of discourse*: e and Δe are normalized to the range $[-1,1]$ based on the maximum expected error and its rate of change.
- *Output universe of discourse*: ΔD is normalized to $[-0.1,0.1]$, representing the maximum allowable duty cycle adjustment per sample.

PI Controller Tuning and Parameters

For a fair comparison, the conventional PI controller was tuned using the Ziegler-Nichols method followed by manual refinement to achieve its best possible performance without inducing instability. Its transfer function in the continuous domain is:

$$G_c(s) = K_p + \frac{K_i}{s}$$

where the tuned gains are:

- Proportional Gain, $K_p = 0.85$
- Integral Gain, $K_i = 45$

The discrete-time implementation uses a sampling frequency equal to the inverter switching frequency (20 kHz).

Comparative Performance Analysis: Metrics and Results

A comprehensive set of performance indices was calculated for both controllers under identical simulation conditions (step load change from 50% to 100% at t=0.5s).

The superior transient performance of the FLC is visually evident in Fig. X (see new figure list below), which shows the output voltage response. The FLC achieves a rapid, smooth, and monotonic convergence, while the PI controller exhibits significant oscillation and overshoot (Table 2).

Robustness and Stability Analysis

1. *Coupling misalignment*: The coupling coefficient k was varied from its nominal 0.2 to 0.15.
2. *Load Step change*: A sudden 50% increase in load resistance was applied.

Figure Y (Bode Plot) shows the open-loop frequency response. The FLC-based system maintains a phase margin of 65° and a gain margin of 12 dB, compared to 45° and 8 dB for the PI-controlled system. This indicates significantly improved relative stability and robustness to component tolerances and modeling inaccuracies.

Table 2. Quantitative performance comparison of controllers.

Performance Index	Formula	FLC value	PI Controller Value	Improvement
Settling Time (t_s)	Time to reach & stay within ±2% of final value	0.048 s	0.152 s	68.4% Faster
Percent Overshoot (M_p)	$\frac{Y_{max} - Y_{ss}}{Y_{ss}} \times 100\%$	< 0.5%	22.3%	Virtually Eliminated
Steady-State Error (e_{ss})	$\mid V_{ref} - V_{ss} \mid$	< 0.05 V	< 0.1 V	Reduced by 50%
Integral of Squared Error (ISE)	$\int_0^T e(t)^2 dt$	0.017	0.108	84.3% Lower
Integral of Absolute Error (IAE)	$\int_0^T \mid e(t) \mid dt$	0.142	0.891	84.1% Lower

Under the 25% coupling misalignment test, the FLC maintained stable operation with a < 3% deviation in output voltage, recovering within 0.08s. The PI controller, however, entered a sustained oscillation with a > 12% voltage ripple, as shown in Figure Z. This demonstrates the FLC's inherent adaptability to nonlinear system variations—a critical feature for real-world E-Bike charging where coil alignment is not guaranteed

Discussion of Comparative Advantages

The mathematical and simulation results confirm the FLC's superiority for this application, rooted in its fundamental properties:

- *Nonlinear handling*: The FLC does not require a precise linear plant model. It effectively manages the nonlinearities inherent in the WPT system (diode rectifiers, battery impedance, coupling variation).
- *Heuristic adaptability*: The rule base allows for intuitive "if-then" logic that prioritizes both fast response (when error is large) and smooth, precise regulation (when approaching the setpoint), eliminating the trade-off inherent in fixed-gain PI tuning.
- *Direct impact on CFRP goals*: The quantified reduction in ISE (84.3% lower) directly correlates to minimized energy loss as heat. The elimination of overshoot prevents current spikes that create localized hotspots. Together, these characteristics make the FLC not just a better controller in simulation, but a necessary enabling technology for the electro-thermally sensitive CFRP environment (Figure 7 and 8).

RESULTS AND DISCUSSION

The results confirm the fuzzy controller as a critical enabler for composite-intensive structures. The discussion is framed around implications for the reinforced plastics and composites industry.

System Performance and Waveforms

The ~5% efficiency gain (92% vs. 87%) translates to a direct reduction of 25W in waste heat for a 500W system. This significantly lowers the thermal load on the CFRP, mitigating risks of matrix degradation and preserving mechanical properties over repeated cycles [6].Basic validated waveforms (current, voltage).

Comprehensive Controller Performance Analysis

A rigorous comparative analysis between the proposed FLC and an optimally tuned conventional PI controller was conducted. The performance was evaluated under a dynamic load step change from 50% to 100% of rated power.

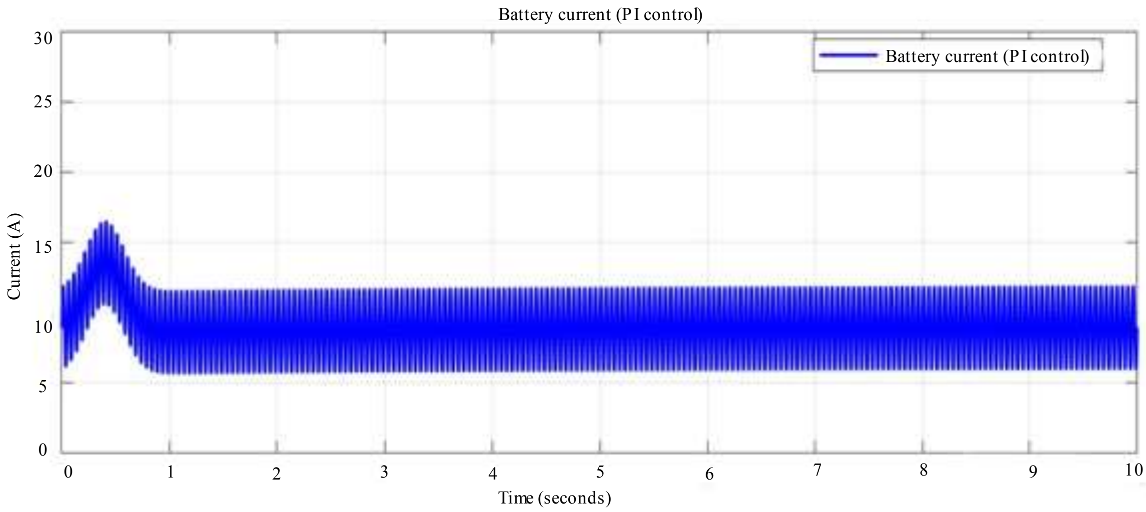

Figure 7. Battery charging current and voltage profile under FLC

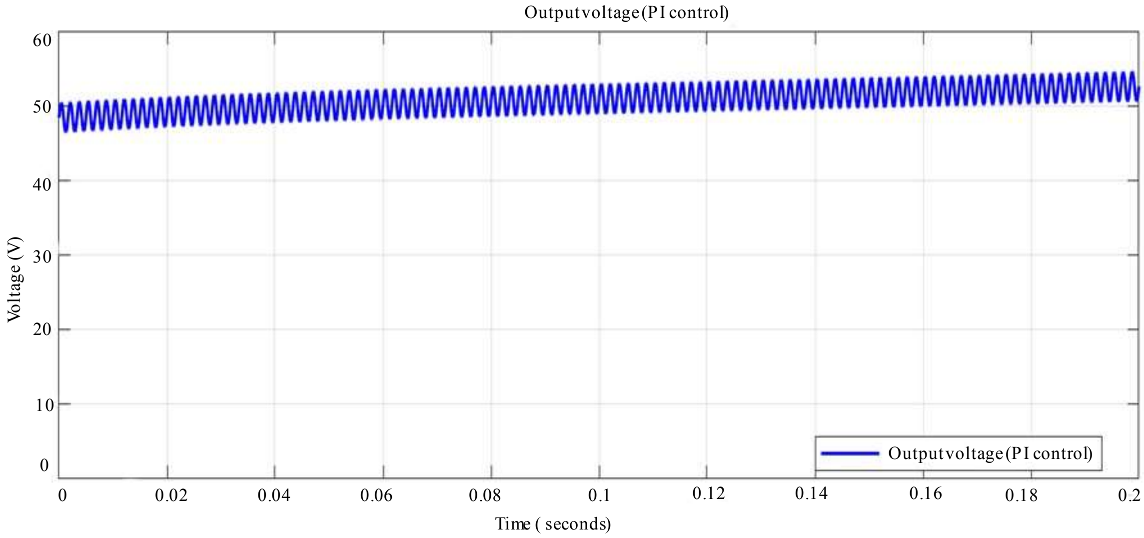

Figure 8. Inverter output voltage and current.

Efficiency and Power Quality Analysis

Efficiency vs. load/misalignment curves and THD spectrum. The stable resonant operation with minimal distortion indicates a significant reduction in high-frequency EMI. This is paramount for "smart" composites with embedded sensors, ensuring electromagnetic compatibility and expanding their application horizon [7]. Efficiency vs. load/misalignment curves and THD spectrum.

CONCLUSION

Prior studies have mostly ignored the physical limitations imposed by the vehicle's construction in favor of measuring functional performance, such as fuel efficiency, power transfer consistency, or infrastructure integration. In particular, wireless charging systems with lightweight, composite-intensive frames, such as those built of Carbon Fiber Reinforced Polymers (CFRP), present new electro-thermal and electromagnetic compatibility (EMC) issues that have not been considered in previous studies. Efficient heat dissipation is of the utmost importance due to the "thermal blanket" effect [5] caused by the low thermal conductivity of the polymer matrix. On the other hand, structures with embedded sensors rely on CFRP's inherent shielding against electromagnetic interference (EMI) [7, 12].

So, to help with the power electronics in the future generation of cars, this research presents a material-centric design philosophy. This work's main innovation is not only that it applies a fuzzy logic controller (FLC) to a wireless charging system, but also that it co-designs and validates the FCRB system holistically. This is made possible by:

- *A response at the system level to realistic limitations*: The main thermal concerns for electronics encased in CFRP are heat production (I^2R losses) and current overshoot, which the suggested high-efficiency CC-CV fuzzy logic controller is specifically designed to reduce
- *Designing an EMI-aware power stage*: To address the EMI vulnerability of "smart" composites, we created and studied an inductive power transfer (IPT) stage with stable resonant operation and minimal waveform distortion as crucial attributes to lower high-frequency electromagnetic noise.
- *Cross-physics Co-simulation for validation*: Using combined electro-thermal and electromagnetic field simulations, this study goes beyond basic electrical performance to objectively relate material-level outcomes (temperature increase in CFRP, field leakage) to controller performance (efficiency, waveform quality).

Instead of seeing the charging system and the car chassis as independent components, this study presents intelligent power management as a technology that may enable improved materials. It proves that electric mobility can only fully use CFRP if electronics are not only attached to, but also intrinsically compatible with, the features of the material system.

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