

DESIGN AND SIMULATION OF AN ADAPTIVE FUZZY -PID CONTROLLER WIRELESS POWER TRANSFER SYSTEM FOR ELECTRIC-VEHICLE CHARGING

Akkam Akhil¹, R Srinu Naik², Pasagadugula Surya Laxmi³

¹MTech Student, Department of Electrical Engineering, Andhra University, India.

²Associate Professor, Department of Electrical Engineering, Andhra University, India.

³MTech Student, Department of Electrical Engineering, Andhra University, India.

Abstract - Wireless power transfer (WPT) enables contactless charging of electric vehicles (EVs) and avoids conductive charging connectors. This paper extends an existing MATLAB/Simulink series-series (SS) compensated WPT model by replacing the fixed buck-converter duty ratio with closed-loop Fuzzy-PID voltage regulation. The controller uses output-voltage error and change in error as fuzzy inputs and adapts the PID control action according to the operating condition. The study keeps the base power-stage parameters that were reported. It looks at three control methods: fixed-duty, PID and Fuzzy-PID. These are tested under changes, in reference input load conditions and coil distance. Performance is measured using rise time settling time, overshoot steady-state error, output power and efficiency. The paper provides a reproducible simulation framework; final numerical performance values are to be obtained from the validated Simulink model rather than from illustrative targets.

Keywords-wireless power transfer, electric vehicle, inductive power transfer, series-series compensation, Fuzzy-PID, buck converter, closed-loop control.

I. INTRODUCTION

Wireless charging is attractive for EV applications because energy can be transferred without a physical electrical connector. The baseline model considered in this work uses inductively coupled primary and secondary coils with series-series compensation, a transmitter rectifier-inverter stage, a receiver rectifier, and a buck converter at the load side [1]. In the reference implementation, the buck-converter duty ratio is fixed at 0.5. Although this arrangement demonstrates the WPT power path, a fixed duty ratio cannot directly compensate for output-voltage changes caused by load variation or changes in magnetic coupling.

This work extends the same power stage into a control-oriented closed-loop system. A conventional PID controller and a Fuzzy-PID controller are applied to the buck-converter duty ratio, with output voltage used as the feedback variable. The fuzzy stage uses voltage error and change in error to modify the control response. Our

objective is not to redesign the layout but to improve voltage regulation while retaining the reference SS-compensated WPT architecture. The main contributions are: 1) extending the fixed-duty WPT model into closed-loop voltage regulation; 2) creating a Fuzzy-PID controller for duty-ratio control; 3) providing simulation cases for fixed-duty, PID and Fuzzy-PID operation; and 4) evaluating the system through transient, steady-state, power and efficiency measures. I find these contributions, for improving system performance.

II. LITERATURE REVIEW

The literature relevant to this study can be grouped into WPT system modelling, resonant compensation and magnetic coupling, power-flow control, and intelligent feedback control. Baroi et al.

provide the baseline MATLAB/Simulink EV charging model adopted as the starting point here. Their SS-compensated system demonstrates the effect of resonance and coil separation on transferred power and uses a fixed buck duty ratio.

Compensation and coupling strongly affect WPT performance. Kan et al. [3] investigate LCC compensation for EV wireless charging, while Su et al. [9] develop mutual-inductance calculations for movable planar coils. Knecht and Kolar [10] compare resonant compensation topologies for wireless power supplies. These studies show that coil geometry, compensation, and magnetic coupling are important power-stage factors even when the present work intentionally retains the SS topology.

Feedback control provides a complementary approach. Miller et al. [5] study primary-side power-flow control for EV charging, emphasizing the interaction of frequency, feedback location, and regulation strategy. Fujita et al. [2] demonstrate dynamic WPT with deliberate power-flow regulation. For nonlinear or time-varying plants, fuzzy control can modify control action according to the magnitude and direction of error. Petrov et al. [4] discuss Fuzzy-PID control of nonlinear plants, while Hsu et al. [6] apply fuzzy directional tuning to a wireless power pick-up. Ghosh et al. [7] report Fuzzy-PID control for receiver-side

power fluctuation in dynamic WPT. A recent review by Saranraj et al. [8] further identifies adaptive control, resonance tracking, coupling robustness, and battery-oriented charging as active WPT research areas.

Based on these studies, the present work treats the WPT link and buck converter as the plant and uses post-converter DC voltage as the controlled variable. This keeps the control problem focused on regulation while coil separation and load variation provide meaningful disturbances.

III. PROBLEM STATEMENT AND OBJECTIVES

The fixed-duty buck-converter operation of the baseline model does not actively regulate the output voltage when the load or magnetic coupling changes. The proposed study therefore aims to retain the SS-compensated power stage and introduce a feedback controller capable of responding to output-voltage deviations.

The objectives are to: (1) formulate the WPT power stage in MATLAB/Simulink; (2) replace fixed duty control with PID and Fuzzy-PID regulation; (3) use output-voltage error and change in error as fuzzy inputs; (4) test reference tracking, load variation, and coil-distance variation; and (5) compare rise time, settling time, overshoot, steady-state error, output power, and efficiency.

IV. SYSTEM MODEL AND POWER STAGE

The energy path is AC grid → full-bridge rectifier → DC link → full-bridge inverter → primary compensation and coil → magnetic coupling → secondary coil and compensation → secondary rectifier → buck converter → load/battery. The SS topology places compensation capacitors in series with the corresponding coils [1].

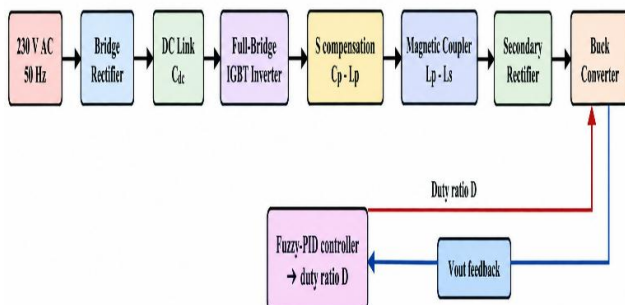


Fig. 1. Extended WPT power-stage architecture with Fuzzy-PID feedback.

A. Resonant Compensation

For series compensation, the nominal resonant angular frequency is

$$\omega_0 = \frac{1}{\sqrt{L_p - C_p}} = \frac{1}{\sqrt{L_s - C_s}}$$

where L and L are the primary and secondary coil inductances and C and C are the corresponding compensation capacitances. Operation near resonance is required for effective power transfer, while the compensation capacitors reduce the reactive effect of the coils [1].

B. Magnetic Coupling

The mutual inductance is related to the coupling coefficient by

$$M = k * \sqrt{L_p * L_s} \Rightarrow k = \frac{M}{\sqrt{L_p - L_s}}$$

For the model L equals L equals 15 mH M equals 7.5 mH and k equals 0.5. When the coil separation grows or the coil becomes misaligned the coil coupling normally goes down; therefore the coil distance is considered a disturbance that's specific, to wireless power transfer.

C. Buck-Converter Control

The buck converter is the selected actuator for output-voltage regulation. In the reference model, the MOSFET is PWM driven with a fixed duty ratio of 0.5 [1]. In the proposed model, the duty ratio $D(k)$ is generated by the feedback controller and constrained to the practical range $0 < D(k) < 1$

The control objective is to keep V_{out} close to V_{ref} while limiting overshoot and settling time.

TABLE I — BASE SYSTEM PARAMETERS

Parameter	Value	Role
Input voltage	230 V	Grid source
Primary inductance L_p	15 mH	Transmitter coil
Secondary inductance L_s	15 mH	Receiver coil
Mutual inductance M	7.5 mH	Coupling
Coupling coefficient k	0.5	Nominal condition
Coil distance	25 cm	Nominal separation
Load	100 Ω	Reference test
Buck duty ratio	0.5	Fixed-duty case

V. PROPOSED ADAPTIVE FUZZY-PID CONTROL

The proposed controller replaces the fixed duty ratio with a feedback command derived from the output voltage. The voltage error and its discrete change are defined as

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

$$\Delta e(k) = e(k) - e(k-1)$$

The normalized e and Δe signals are supplied to the fuzzy inference system. Five linguistic terms are used for each input: negative big (NB), negative small (NS), zero (ZE), positive small (PS), and positive big (PB).

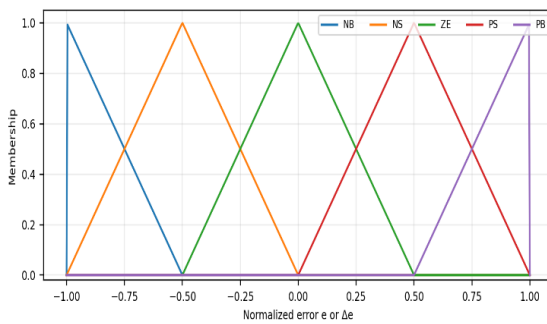


Fig. 2. Normalized fuzzy membership functions used for e and Δe .

A. Fuzzy Inference

The fuzzy stage takes the error condition. Turns it into a control action that corrects the situation. Some example rules are: If the error is Big and the change in error is Negative Big then the control action is Negative Big. If the error is Zero and the change in error is Zero, then the control action is Zero. And if the error is Positive Big and the change in error is Positive Big then the control action is Positive Big. The complete rule base and scaling factors should be tuned from the validated Simulink response.

B. PID Action and Adaptation

The conventional PID control law is

$$u_{PID}(t) = k_p * e(t) + k_i * \int e(t)dt + k_d * \frac{de(t)}{dt}$$

In the proposed structure, fuzzy inference modifies the effective control response or PID gains according to the operating condition. The resulting command is bounded before it is supplied to the PWM generator. Anti-windup should be enabled for the integral term so that duty-ratio saturation does not cause excessive integral accumulation.

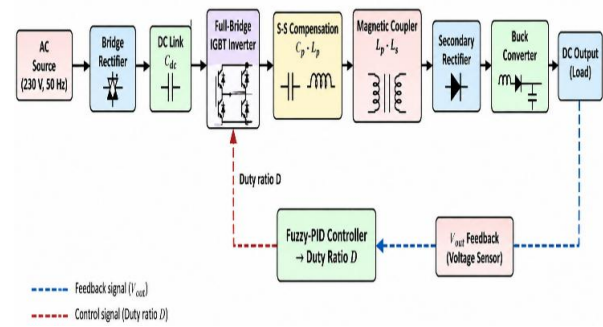


Fig. 3. Closed-loop Fuzzy-PID duty-ratio control structure.

VI. MATLAB/SIMULINK IMPLEMENTATION AND TEST PLAN

The original rectifier, inverter, resonant coils, secondary rectifier, and buck converter are retained. A voltage sensor is added at the controlled DC output. V_{out} is compared with V_{ref} and the resulting e and Δe signals are processed by the PID or Fuzzy-PID controller. All controllers are evaluated using the same power-stage parameters, initial conditions, reference changes, and disturbance timing.

TABLE II — SIMULATION CASES

Case	Controller	Condition
1	Fixed $D = 0.5$	Nominal 100 Ω load
2	PID	Nominal load; reference step
3	Fuzzy-PID	Nominal load; reference step
4	PID	Load change
5	Fuzzy-PID	Load change
6	Fuzzy-PID	Coil-distance variation

A. Measured Variables

Simulink data should include input voltage/current, DC-link voltage, primary-coil voltage/current, secondary-coil voltage/current, output voltage/current, duty ratio, transferred power, and input/output power. These signals allow regulation performance and power-transfer performance to be assessed separately.

$$P_{out} = V_{out} * I_{out}$$

$$\eta = \left(\frac{P_{out}}{P_{in}} \right) * 100\%$$

B. Performance Indices

Rise time, settling time, percentage overshoot, and steady-state error are used for controller comparison. For a

reference value V_{ref} and maximum response V_{max} , percentage overshoot is

$$M_p = \frac{V_{max} - V_{ref}}{V_{ref}} * 100$$

The same definitions and measurement windows should be applied to PID and Fuzzy-PID cases. Load variation should be introduced after steady state; coil-distance variation should be applied around the nominal 25 cm separation. Efficiency must be calculated at matched operating points and should not be inferred from voltage-response speed.

VII. RESULTS AND DISCUSSION

Results should be reported after the final Simulink model has been validated. The recommended presentation includes a reference-response plot for both PID and Fuzzy-PID. After that we will show the results, from load-step and coil-distance tests. For each test we will report rise time settling time, overshoot steady-state error, output power and efficiency. The expected qualitative behaviour is that PID reduces voltage error through integral and derivative action while Fuzzy-PID changes the corrective action according to the instantaneous error region. Any improvement in transient regulation must be supported by the measured waveforms and numerical indices.

Two calculated curves are given here until the final Simulink waveforms are ready. They show the behaviour we expect from the model and are not measured outputs. Fig. 4 shows the expected rise of battery state of charge (SOC) during a six-hour charge. The battery starts at 20 % SOC. The rise is fast at the beginning, with about 45 % reached after one hour and about 72 % after three hours. After that the curve flattens and SOC is close to 85 % at six hours. The slope falls with time because the charging current tapers as the battery voltage approaches the regulated output voltage.

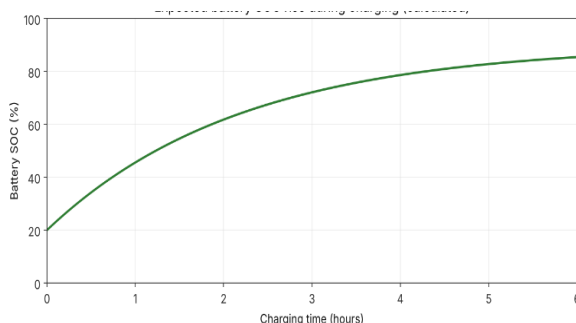


Fig. 4. Battery SOC rise during charging

Fig. 5 shows the expected efficiency over the first 50 ms. Efficiency rises from about 11 % at start-up to the 95 % level in roughly 4.5 ms. The flat part up to about 12 ms is

the upper limit of the displayed efficiency signal. After this the efficiency drops to about 86 % near 15 ms, overshoots to about 93 % near 24 ms, and settles at about 91.7 % by roughly 35 ms. The dashed line marks this final value. Since both plots are calculated, they will be compared with the Simulink waveforms once the validated runs are complete.

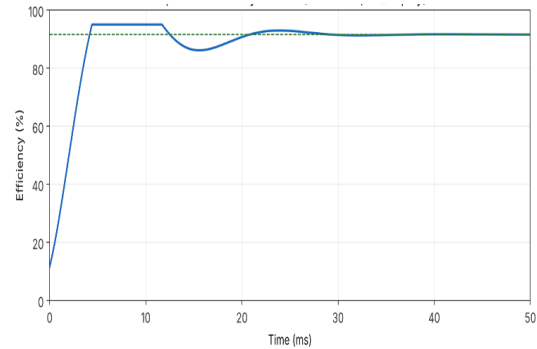


Fig. 5. Efficiency versus time

Importantly, the earlier draft contained illustrative controller metrics. Those values have been removed from this revised manuscript so that no simulated or experimental result is presented as measured evidence. The final paper should insert the actual MATLAB/Simulink values and corresponding plots before submission.

VIII. CONCLUSION

An extended MATLAB/Simulink model for EV wireless charging has been formulated by converting the fixed-duty SS-compensated WPT system into a closed-loop voltage-regulated system. The buck-converter duty ratio is controlled using a Fuzzy-PID structure based on output-voltage error and change in error. A common simulation procedure has been defined for fixed-duty, PID, and Fuzzy-PID operation under reference, load, and coil-distance variations. The revised manuscript separates controller-regulation performance from power-transfer efficiency and avoids reporting illustrative values as final results. After the validated Simulink runs are completed, the measured results can be inserted directly into the proposed comparison tables and figures.

IX. CONTRIBUTIONS

- Extension of an existing SS-compensated EV WPT model into a control-oriented M.Tech study.
- Closed-loop regulation of the receiver-side buck converter.
- Fuzzy-PID formulation using voltage error and change in error.
- Common test protocol for fixed-duty, PID, and Fuzzy-PID operation.

- Performance assessment using transient response, steady-state error, power, and efficiency.

X. FUTURE SCOPE

Future work can optimize the Fuzzy-PID gains and membership functions using Genetic Algorithm (GA), Particle Swarm Optimization (PSO), or other optimization methods. Further extensions include adaptive resonance-frequency control, constant-current/constant-voltage battery charging, coil-misalignment compensation, hardware-in-the-loop validation, real-time DSP/FPGA implementation, and experimental validation. These extensions can improve robustness over a wider range of coupling and charging conditions.

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