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Optimized Charging Scheme Using Resonant Converter Technology for Electric Vehicles (EV) Battery Charging System

Sapna Bhagwandin Verma*, [1] and Ashok K. Pandey*

Abstract –*The rapid creation of electric vehicles (EVs) makes it necessary, that charging system must be efficient and reliable to support sustainable conveyance. This paper demonstrates an optimized charging scheme for EVs using a resonant converter technique. The system is proposed considering the significant challenges in EV battery charging, including efficiency, power density, and thermal management. Leveraging resonant converters that integrate full bridge, resonant tank, and High-Frequency Transformer (HFTF) with a proposed compensating element linked to the secondary side of the HFTF improves the safety and effectiveness of the EV charging system by adjusting the Duty Ratio of Constant Current and Constant Voltage modes. A model is developed to evaluate the resonant converter's behavior and its parameters are optimized for various charging scenarios. The experimental outcomes on MATLAB show the effect of the proposed scheme, demonstrating important improvements in the efficiency of the charger and stability of the overall system compared to charging methods that are traditionally used. The MATLAB results have been validated on the OPAL-RT real-time simulator. The optimized proposed model with a resonant converter-based charging scheme contributes a promising solution for the EV infrastructure, and future for quicker, more efficient, and reliable Electric Vehicle charging.*

Keywords – constant current (CC), constant voltage (CV), electric vehicle (EV), resonant converters.

1. INTRODUCTION

A pivotal component of global hard work is a transformation from normal petrol or diesel vehicles to electric vehicles (EVs) to decrease greenhouse gas production and achieve eco-friendly transportation. With the surge in EV adoption rate, the demand for dependable, efficient, and superior-performance charging systems becomes increasingly critical. When the traditional charger is used, they fight with issues related to efficiency, power density, and thermal management, obstructive their ability to meet the requirements of an increasing EV market [1-15].

Resonant converter technology is quickly replacing conventional charging methods, as it offers crucial advantages in efficiency and performance. Resonant converters use resonant circuits to transfer energy more effectively, thereby minimizing losses and electromagnetic interference (EMI). These features make the resonant converter more appropriate for applications requiring high frequency and high power, such as EV charging, where the main target is to minimize losses and improve system reliability is paramount.

Rigorous simulation validation is done to demonstrate the efficacy of an optimized resonant converter-based charging scheme. The results indicate considerable improvements in the charging efficiency and robustness of the system compared to traditional methods.

In the upcoming section the details of resonant converter technology, the developed system model, the optimization process, and the simulation and MATLAB experimental findings, highlighting the real-world benefits and potential of the proposed EV charging scheme are discussed.

The Resonant converters offer advantages like improved thermal management, and flexibility in voltage and current control, the nature of resonant converter is modular which allows scalability, the system in which the resonant converters are incorporated requires less maintenance as it reduces stress on switching components and thereby enhances the system stability [16-17].

Traditional chargers are compared with the charging systems with resonant converters having CC and CV modes in table 1 which shows the advantage of integrating a resonant Converter into traditionally used chargers.

2. MODEL CONFIGURATION

Figure 1 shows the proposed EV charging model integration for the Constant Current and Constant Voltage Mode through the Duty Ratio Controlled Optimized Charging Scheme for Electric Vehicles Using Resonant Converter Technology [27-29].

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Table 1. Comparison of traditional chargers and charging systems with resonant converters having CC and CV modes

Feature	Traditional Charger	Resonant Converter having CC and CV Mode
Efficiency	Efficiency is low due to higher power loss	Efficiency is high due to reduced power loss
Thermal Management	It generates more heat	It generates less heat, improving thermal management
Charging speed	Slow	Faster charging, especially up to 80-90% SOC
Electromagnetic Interference (EMI)	Hard-switching offers higher EMI	Soft-switching offers lower switching
Scalability	Limited scalability	Easily scalable to different battery capacities
Battery life	Potentially reduced due to heat and high current	Enhanced due to optimized charging profiles and reduced stress on battery
Operation modes	Typically operates in a single-mode	Supports dynamic switching between CC and CV modes
Control mechanism	It doesn't offer precise control	Precise control of duty ratio for stable current and voltage output
Heat generation	Higher heat generation	Lower heat generation
Voltage spikes	More prone to voltage spikes	Voltage spikes are significantly minimized
References	[18-20]	[18-26]

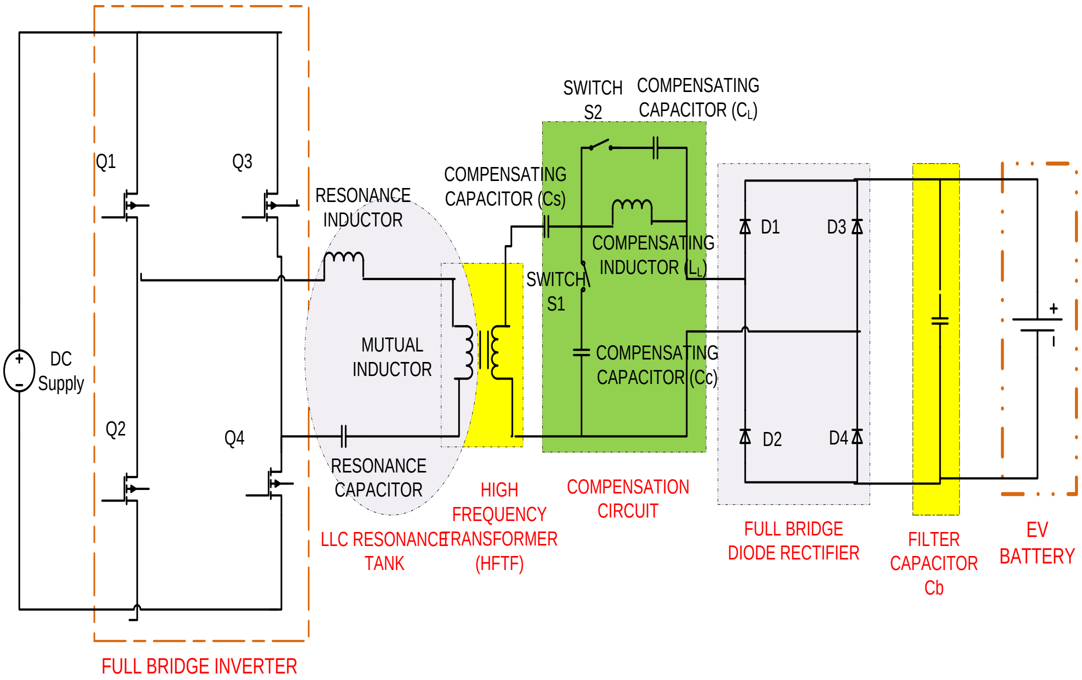

Fig. 1. Proposed EV charging model.

Resonant Converter Topology consists of Direct Current (DC) to Alternate Current (AC) Full-Bridge, LLC Resonant tank, and HFTF. The DC to AC Full-bridge consists of four Metal Oxide Field Effect Transistors (MOSFET) Q1, Q2, Q3, and Q4 followed by an LLC Resonant Tank consisting of a resonant inductor (Lr), a resonant capacitor (Cr), and a mutual inductance (Lm) on the primary side as shown in Fig. 1 and it has compensation circuit, Diode bridge Rectifier (DBR) and filter circuit on Secondary Side of high-frequency transformer (HFTF). This resonant tank minimizes switching losses, increasing system efficiency [30]. The values of resonance tank elements and the compensation elements are calculated using the following formulae

$$L_r = \frac{1}{(2\pi f_r)^2 C_r} \tag{1}$$

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$$C_r = \frac{1}{2\pi Q f_r R_{eq(AC)}} \tag{2}$$

$$C_L = \frac{I_{Bat}\pi^2}{4w_r V_{Bat}} \tag{3}$$

$$L_L = \frac{8V_{Bat}}{\pi^2 w_r I_{Bat}} \tag{4}$$

$$C_C = \frac{I_{Bat}\pi^2}{8w_r V_{Bat}} \tag{5}$$

$$C_S = \frac{C_C}{w_r^2 L_r C_C - 1} \tag{6}$$

$$\eta = \frac{\left|P_{Battery}\right|}{P_{input}} * 100 \tag{7}$$

In (1) L_r is the Resonant Inductor, f_r is the Resonant frequency and C_r is the Resonant Capacitor, in equation (2) Q is the Quality Factor and $R_{eq(AC)}$ is AC equivalent resistance. In equation (3) I_{Bat} is the Current in the Battery, C_L is the Compensating Capacitor for CV Mode, V_{Bat} is the Battery's voltage and w_r is the resonant angular frequency. In (4) L_L is the Compensating Inductor for CV Mode. In (5) C_C is the Compensating Capacitor for CC Mode. In (6) C_s is the Compensating Capacitor for CC and CV Mode. In (7) η is the efficiency of the proposed system, P_{input} is the input power and $P_{Battery}$ is the power in the battery.

Figure 2 explains the EV battery charging profile which shows the graph between battery voltage V_{bat} vs time plot to ensure the safety, reliability, and efficiency. Figure 3 shows the Flow chart for battery charging mode selection. When the battery charges from 0 to 80% state of charge (SOC), it is bound to keep in Constant current mode i.e. at 40A and increased voltage. This ensures fast charging up to 80% state of charge (SOC), after which the system switches to constant voltage mode, reducing the current to nearly 10A. This approach protects the battery from damage, as maintaining a high current until the end can cause severe damage [19-26]

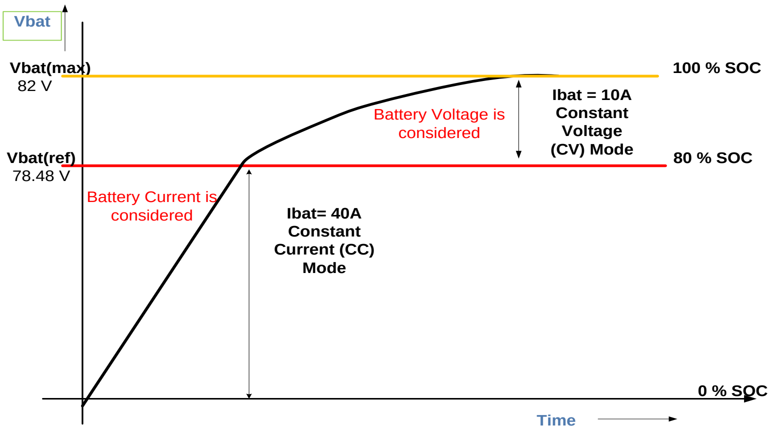

Fig. 2. EV battery charging profile.

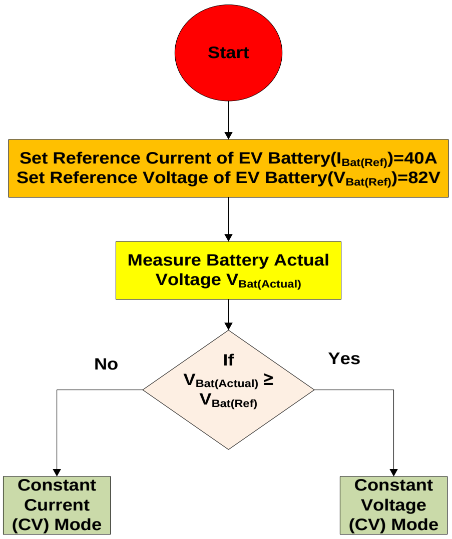

Fig. 3. Flow chart for battery charging mode selection.

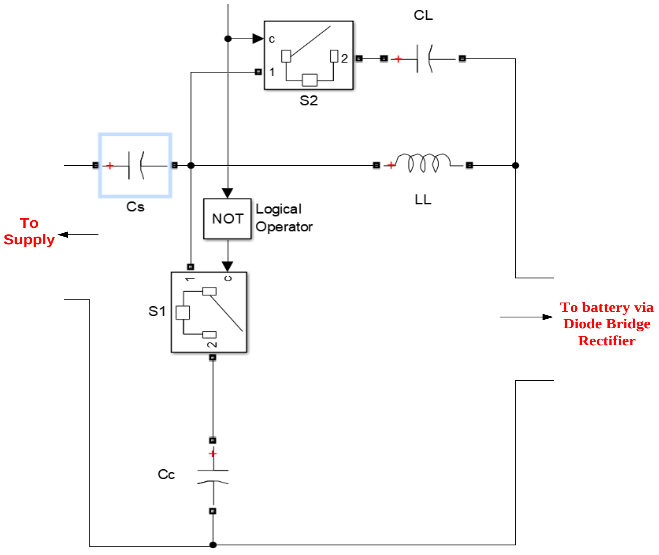

Fig. 3. Flow chart for battery charging mode selection.

Figure 4 shows the compensation system for Electric Vehicle batteries and Fig. 5 shows the selector switch position for CC and CV Mode. Based on the SOC level of the EV battery, the selector switch is adjusted with a threshold value. This threshold is set at the Vbat value corresponding to 80% SOC, meaning that once the battery exceeds this value, it will switch to CV Mode.

To reduce the current and voltage strain on the diodes of the DBR on the secondary side during CC & CV Mode a compensation system is integrated just before the diode bridge rectifier. Main selector Switch, 1 indicates CC Mode and 0 indicates CV Mode. Switch S2 ON, S1 OFF, compensating capacitor Cs & C_L and compensating Inductor L_L reduces the current stress on diodes during CC Mode, and Switch S1 ON, S2 OFF, compensating capacitor C_C and compensating Inductor L_L reduces the voltage stress during CV Mode. The compensation system is followed by an AC to DC full-bridge DBR connected to the capacitor filter.

The controlling strategy opted to control the output of I_{bat} and V_{bat} through Duty Ratio Control. Duty Ratio (D) is dynamically adjusted to ensure CC and CV mode for a specific State of Charge (SOC) range. Constant current during the initial charging phase is ensured using the Current Control Loop and constant voltage as the battery approaches full charge is ensured using the Voltage Control Loop.

The charging Profile has two Stages: In the first initial stage called Constant Current (CC) Mode which preserves a constant current till the voltage of the battery reaches a predefined threshold value, the duty ratio is adjusted to do so.

In Constant Voltage (CV) Mode to maintain a steady voltage while the current slowly reduces as the battery approaches full charge, the duty ratio is fine-tuned.

The Key Parameters of this system are the Input Voltage (V_{in}): 110 V DC and the Output Voltage Range (V_{out}): (72-82) V. The Switching Frequency is converted from 50Hz to 100MHz.

The proposed system possesses high-efficiency maintenance across a wide output voltage range owing to optimized duty ratio control. It possesses enhanced reliability as the system has reduced stress on resonant components and minimized electromagnetic interference (EMI) compared to traditional chargers. The system is versatile as it is capable of charging a large variety of EV batteries with diverse voltage requirements. With the addition of an advanced controller, more precise control of the proposed system is possible [30-31].

3. RESULT AND DISCUSSION

Figure 6 shows the HFTF Primary (Vp) and Secondary (Vs) voltages. Voltage can be stepped up/down using HFTF according to the demand of the connected battery.

The system parameters are compared in two ways in the first part the SOC is kept constant and the Duty ratio is changed and in the second part Duty ratio is kept constant and the SOC is changed.

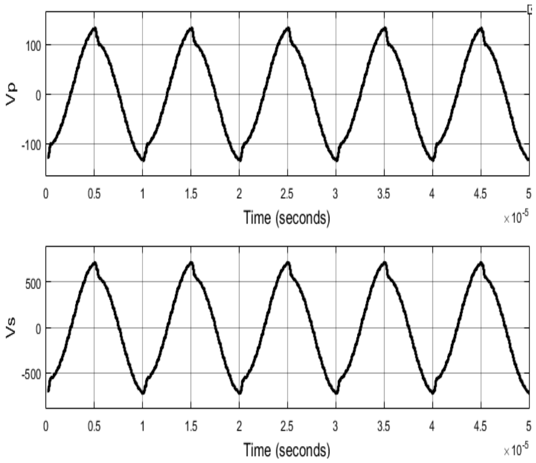

Fig. 6. HFTF primary (Vp) and secondary (Vs)voltage.

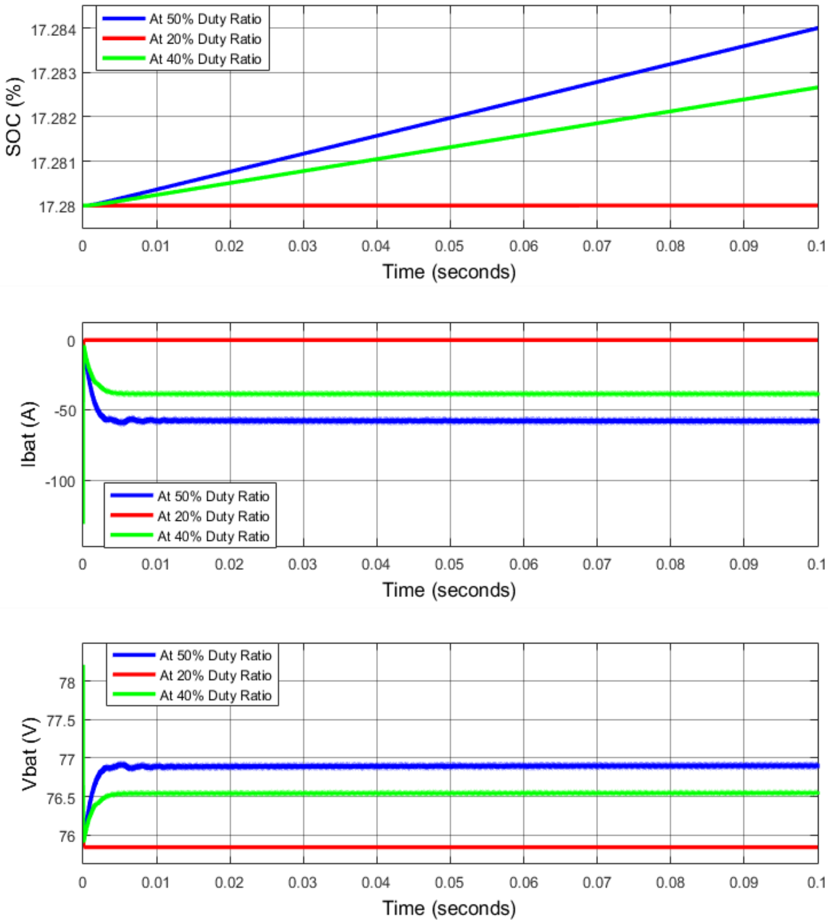

Fig. 1 Battery characteristics for various duty ratios at 20% SOC.

Figure 7 shows the battery characteristics for various Duty Ratios at 20% SOC. In this figure, SOC is maintained at 20% and the duty ratio is changed and it is observed that when the duty ratio is changed to 40%, desired value is obtained. The current is close to 40A as required.

Figure 8 demonstrates the battery characteristics for various Duty Ratios at 95% SOC. In this figure, SOC is maintained at 95% and the duty ratio is changed and it is observed that when the duty ratio is changed to 40%, desired value is obtained. The current is reduced to nearly 20A as required.

Figure 9 shows the Selector Switch condition at 20% SOC (CC MODE) & 95% SOC (CV MODE). It is observed that at 20% SOC, the model is designed to operate in Constant Current (CC) mode with the selector switch set to position 1, and at 95% SOC, the model is designed to operate in Constant Voltage mode with the selector switch set to position 0 as shown in Figure 5. The graph shown in Figure 9 confirms the proposed theory.

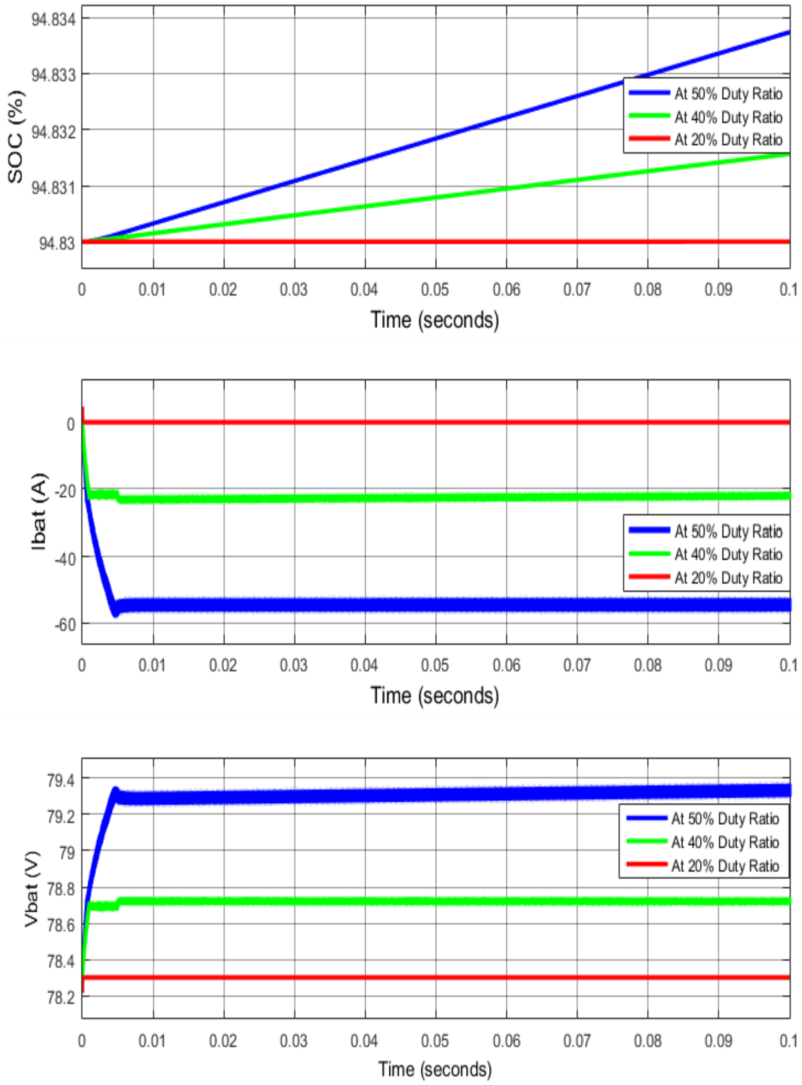

Fig. 2. Battery characteristics for various duty ratios at 95% SOC.

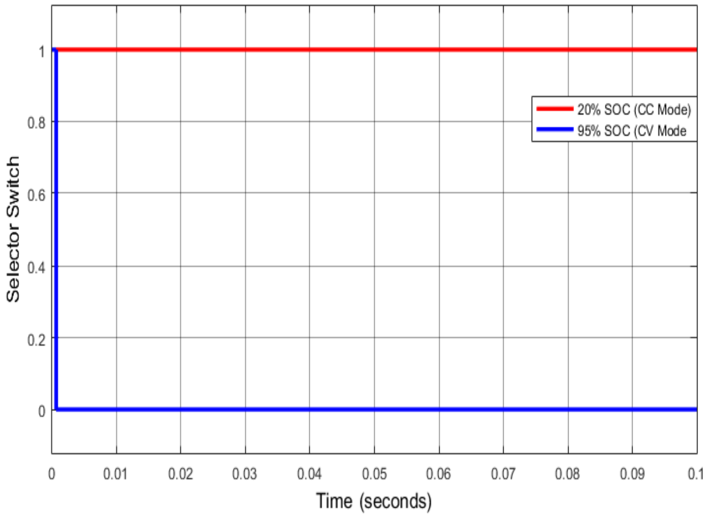

Fig. 3 Selector Switch condition at 20% SOC (CC MODE) & 95% SOC (CV MODE).

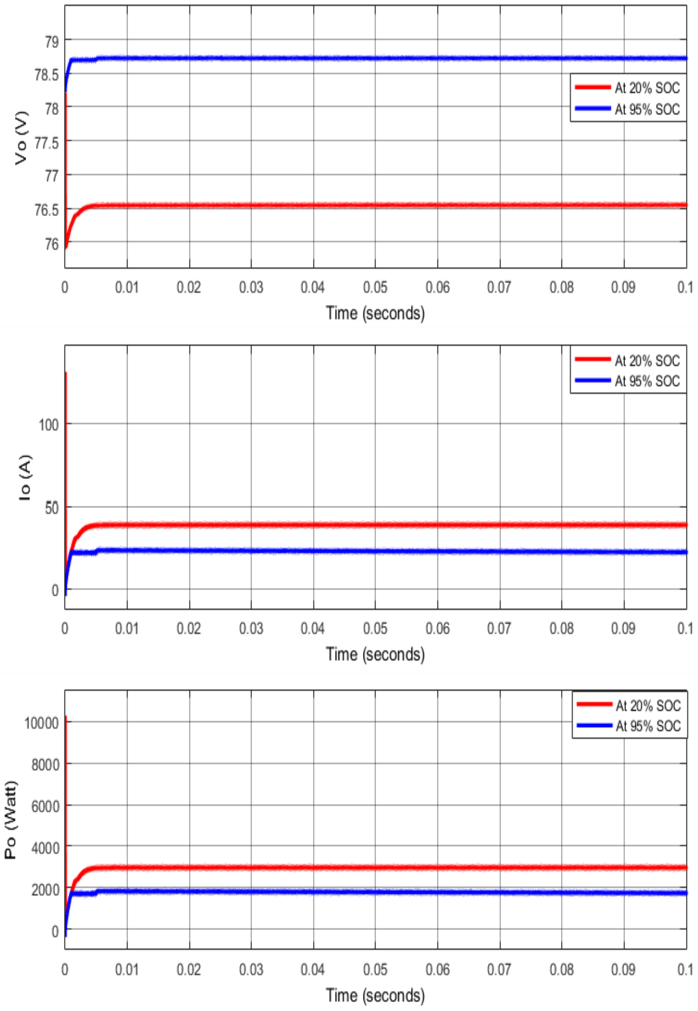

Fig. 4. Output characteristics of the proposed EV charging system at 20% & 95% SOC.

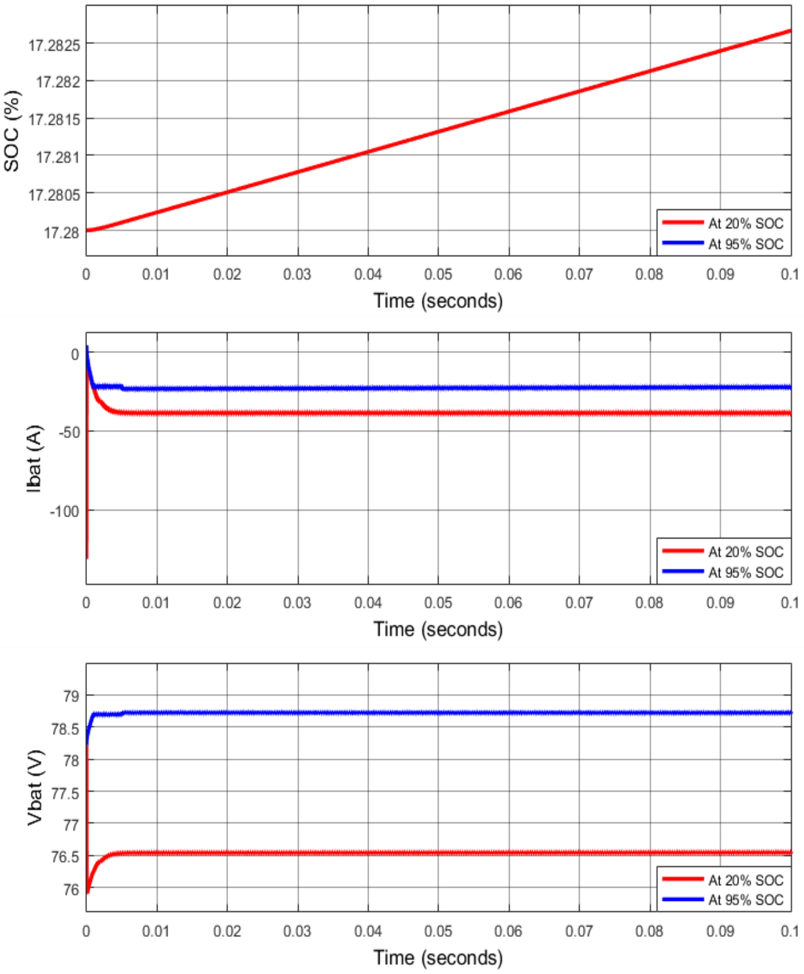

Fig. 5. Battery characteristics at 40% duty ratio for 20% and 95% SOC.

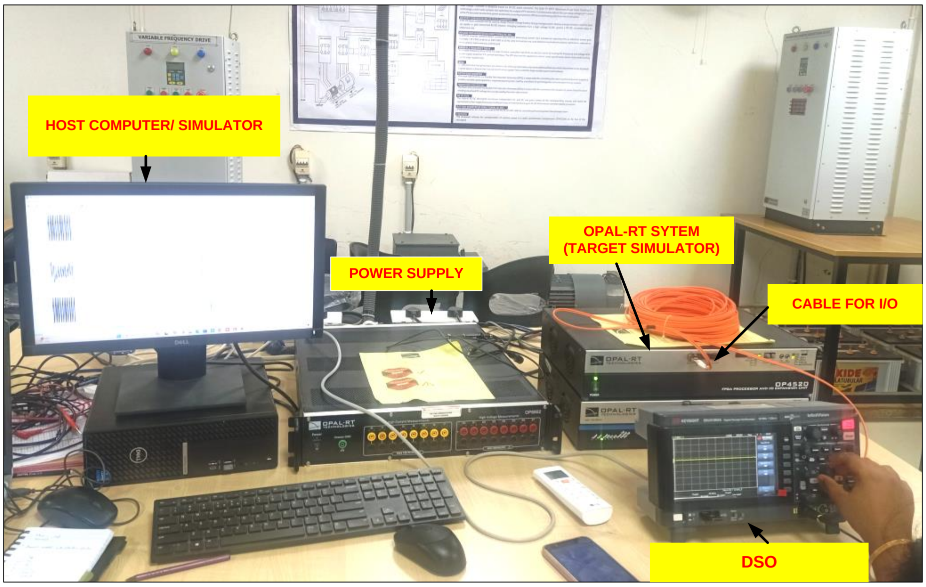

Fig. 6. OPAL RT experimental setup.

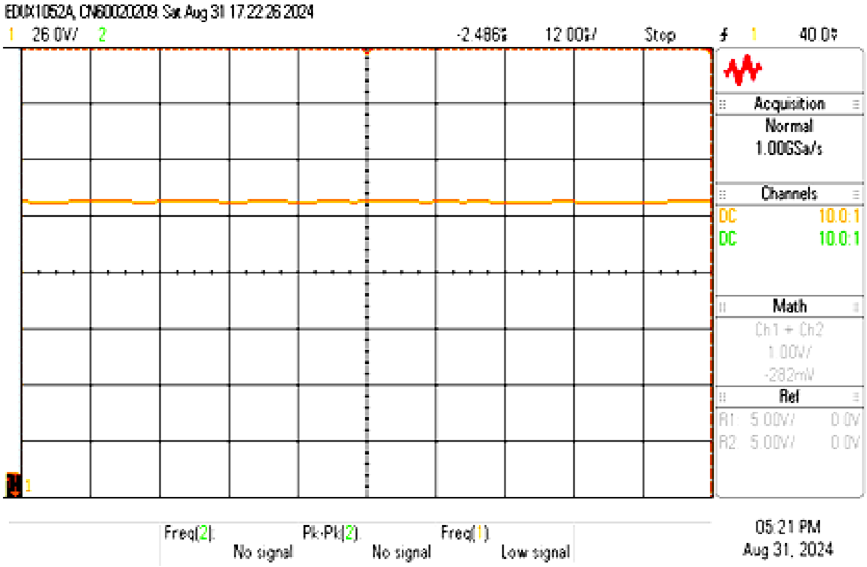

Fig. 7. OPAL-RT results for battery current (Ibat) at 20% SOC for the proposed system.

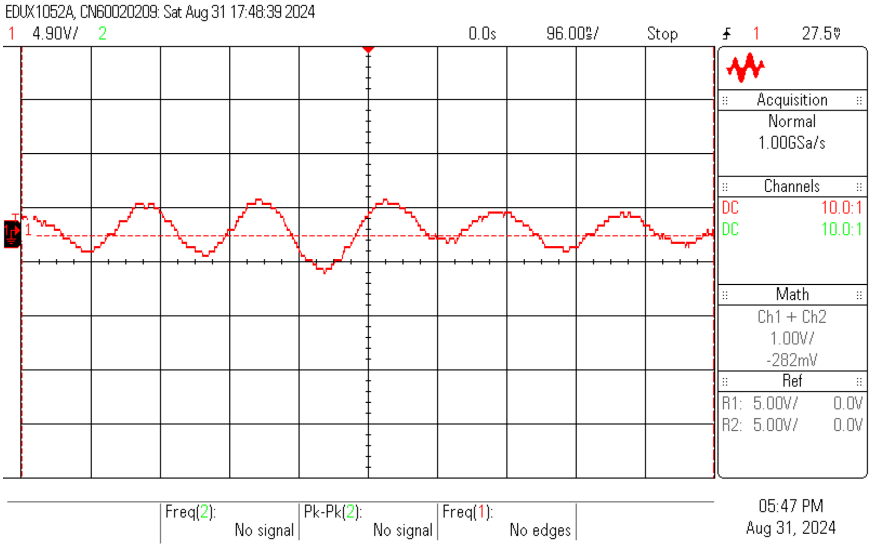

Fig. 14. OPAL-RT Results for battery current (Ibat) at 95% SOC for the proposed system.

Figure 10 demonstrates the output characteristics of the proposed Electric Vehicle charging system at 20% & 95% SOC. Fig. 11 shows the battery characteristics at 40% Duty Ratio for 20% and 95% SOC. Fig. 10 & 11 explain that using a resonant converter with CC and CV modes in EV battery charging and carefully setting and maintaining the duty ratio allows for achieving the desired and precise output. This precise control ensures the safety and longevity of the battery, which is challenging to achieve with traditional chargers. Using (7) the overall system efficiency is determined to be 96%. Figure 12 illustrates the experimental setup for OPAL-RT real-time validation of the proposed work which utilizes an OP4520 target simulator, host computer, Digital storage oscilloscope (DSO), and power supply. Figure 13 shows the OPAL-RT Results for battery current (Ibat) at 20% SOC for the proposed system and Fig. 14 shows the OPAL-RT Results for battery current (Ibat) at 95% SOC for the proposed system.

4. CONCLUSION

The duty ratio-controlled optimized charging scheme using resonant converter technology for EV charging has significantly improved constant current and voltage in MATLAB Simulink simulations. By dynamically managing the duty ratio, the system efficiently controls the charging process, enhancing overall charging efficiency and reducing power losses. The proposed scheme was validated through real-time simulation on the OPAL-RT OP4520 platform, with experimental results closely matching the simulations. This validation confirms the system's robustness and reliability, offering a promising solution for more efficient and sustainable EV charging infrastructure.

5. FUTURE SCOPE

Future research on this proposed system can explore integrating advanced controllers to have more precise output according to the system demand. It can be connected to Microgrid to utilize renewable sources of energy.

DECLARATION

Author contributions The first author conducted the simulation work, created the figures and tables included in the manuscript, and wrote the main text of the manuscript. The supervisor provided oversight, reviewed the simulation work, and examined the manuscript's main text. All authors contributed to the manuscript review.

Funding: Not applicable as no monetary support was received from any financial sources.

Data availability: Not Applicable

Conflict of interest: The authors declare no competing interests.

Ethical approval: No applicable

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