A Solar-Integrated Wireless Charging System for Electric Vehicles

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ABSTRACT

This paper presents a well-integrated system combining photovoltaic (PV) energy harvesting and Wireless Power Transfer (WPT) technology to develop a Solar Wireless Electric Vehicle Charging System (SWEVCS). With the growing adoption of Electric Vehicles (EVs), the demand for efficient and sustainable charging infrastructure has become a critical issue. The proposed system utilizes photovoltaic panels as a clean renewable energy source to charge EVs, eliminating the need for physical cables. The system performance is evaluated using MATLAB simulations, considering key parameters, such as solar irradiance, power output, battery State of Charge (SOC), charging current, and voltage. The results indicate a peak power output of approximately 500 W during midday, and a high SOC of up to 100% by late afternoon. The charging current reaches almost 5 A, demonstrating the high system's efficiency in wireless energy transfer/WPT. The concerns of this study are the prospects of SWEVCS in minimizing reliance on the power grid while promoting Renewable Energy Solutions (RES) for EV charging. Future work will address scalability challenges and further improvement of WPT efficiency to advance this innovative charging technology.

Keywords-sustainable transportation; solar energy wireless charging; grid power; inductive coupling

I. INTRODUCTION

In recent years, the global need for sustainable transportation has driven the rapid adoption of EVs as a cleaner, more convenient, and eco-friendlier alternative to traditional internal combustion engine vehicles. Despite their advantages, conventional EV charging methods face significant challenges, including reliance on wired connections that require physical plugs and cables. These systems often lack flexibility, are less use-friendly, and contribute to environmental concerns due to their dependence on grid power, which may have a carbon footprint [1].

To address these limitations, the SWEVCS emerges as a cutting-edge solution that integrates solar energy harvesting with WPT technology. Photovoltaic panels are incorporated into the design of charging stations or canopies, to generate clean and renewable electricity from the sunlight. PV panels not only reduce the demand for grid power, but also align EV charging with sustainable energy practices, as illustrated in Figure 1, contributing to a more environmentally conscious transportation ecosystem [2]. In addition, WPT technology is another pivotal component of SWEVCS. By employing wireless charging technologies, such as resonant inductive coupling, the system enables the transmission of electrical energy, simplifying the charging process and reducing wear and tear on traditional charging cables [3].

Fig. 1. Schematic diagram of SWEVCS.

India is a prime example of a country where innovative EV charging solutions like SWEVCS could have a transformative impact. With transportation being a major contributor to air pollution in urban areas, transitioning to clean energy-based charging systems is critical. The ambitious goal of having achieved 30% electrification of vehicles by 2030, as outlined in the National Electric Mobility Mission Plan (NEMMP), sets a strong foundation for sustainable mobility in the country [4]. Figure 2 presents the annual demand scenario for electric EVs.

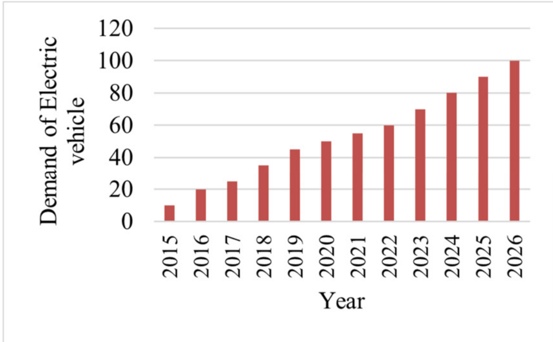

Fig. 2. Demand for EVs over the years.

II. LITERATURE REVIEW

Several studies have explored advancements in solar energy integration and wireless charging systems for EVs. Authors in [5] developed a grid-interfaced residential tool for providing PV energy to EVs. In [6], a wireless charging system was proposed that maintains high-power transfer efficiency when charging EVs with either 400 or 800 V nominal battery voltage at the same power level. Similarly, in [7], a comprehensive photovoltaic energy-based Electric Vehicle Charging Station (EVCS) was designed with efficient energy management strategies. Authors in [8] examined the optimization of the place and length of EVCSs and RES via the modified Teaching-Learning-Based Optimization (TLBO) technique, resulting in the reduction of the Voltage Stability, Reliability, Power Loss (VRP) index. Additionally, in [9], a roadside PV system was designed to charge the batteries of slow-moving EVs using a five-leg inverter, enhancing the probability of achieving the sustainability goal. Cost and user experience challenges have also been addressed. Authors in [10] proposed a Deep Q-Networks (DQN) based EV charging policy under a Time-of-Use tariff scheme, achieving over 20% of cost savings for users.

III. PROPOSED METHODOLOGY

A. *Design and Simulation of the Model*

The design and simulation of a solar wireless EV charging system was conducted using the MATLAB environment, incorporating several key steps to model and test its performance. The process begins with the detailed modeling of solar panels considering factors, such as efficiency, temperature coefficients, and shading effects, and continues with the simulation of the solar irradiance at a specified location to calculate the energy output. At the same time, the behavior of the energy storage system is modeled, including parameters like battery capacity, charging rates, and efficiency, while a charge controller model is implemented to regulate the energy flow. The inductive coupling mechanism for WPT is modeled within MATLAB, with simulations assessing power transfer efficiency as a function of the distance between the charging pad and the vehicle [11].

By integrating these individual components into a comprehensive system-level simulation, MATLAB serves as a powerful tool for designing and testing the solar wireless EV charging system. Smart control algorithms are developed to manage energy flow, monitor charging status, and optimize the overall charging process. Performance analysis is then conducted, encompassing efficiency, charging time, and system reliability. The software's optimization tools allow for the fine-tuning of system parameters, with the final results of the simulation being graphically presented providing a comprehensive understanding of energy production, storage levels, and charging activities over time. This process is repeated to ensure the optimal solution [12]. Figure 3 depicts a step-by-step diagram of the proposed methodology.

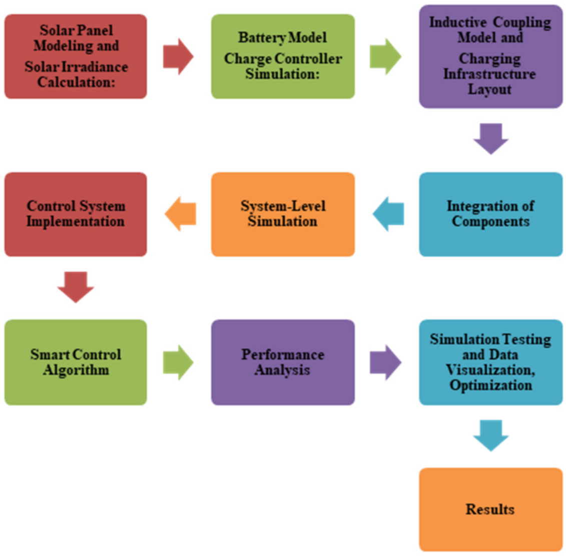

Fig. 3. Steps of the proposed methodology.

To simulate this system in MATLAB, several components are required to be calculated.

1) Solar Panel Model

The solar panel's output power as a function of sunlight:

$$P_{solar}(t) = \eta \cdot A \cdot G(t) \quad (1)$$

where $P_{solar}(t)$ is the solar panel power at time t, η is the efficiency of the solar panel, and $G(t)$ is the solar irradiance at time t.

The Simplified power transfer equation is expressed by:

$$P_{wireless}(t) = k \cdot \frac{V_{trans} \cdot V_{rec}}{[d(t)]^2} \quad (2)$$

where $P_{wireless}(t)$ is the WPT at time t, k is a constant, V_{trans} and V_{rec} are the transmitter and receiver voltages, respectively, and $d(t)$ is the distance between the transmitter and receiver at time t.

2) EV Model

The EV and its battery system are modeled, considering a simple battery model.

$$SOC\ (t + \Delta t) = SOC(t) + \frac{\eta_{charge} \cdot P_{wireless}(t)}{\text{Battery}_{\text{capacity}}} \quad (3)$$

where $SOC(t)$ is the state of charge/SOC of the battery at time t, η_{charge} is the charging efficiency, and $\text{Battery}_{\text{capacity}}$ is the battery capacity.

Equation 4 shows a typical battery charging model:

$$V_{battery}(t) = V_{initial} + \frac{I(t)}{C} . d(t) \quad (4)$$

The voltage $V_{battery}(t)$ is initialized correctly and is properly updated at each time step.

Table I presents the specifications of the components of a SWEVCS:

TABLE I. SPECIFICATIONS OF THE SWEVCS COMPONENTS

Apparatus required	Quantity
Solar panel	1
Transformer	1
LCD	1
Transmitter and receiver coil	1
Battery	1
PCB board	1
Voltage sensor	1
Resistor	1
Capacitor	2
Vehicle body	1
Transistors	2
Cables and Connectors	As per requirement
LED	4

The proposed SWEVCS consists of several key components, as shown in Figure 4 [15-17].

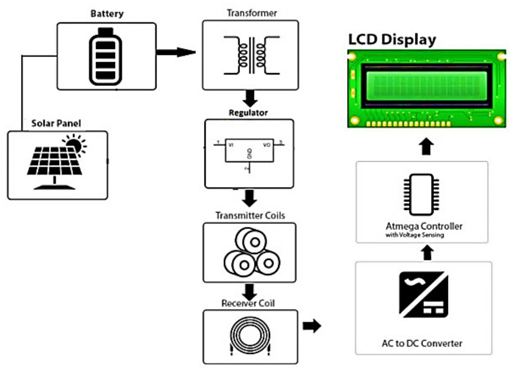

Fig. 4. The components of the proposed SWEVCS.

The process begins with the solar panel, which collects solar energy from the sun and stores it in a battery for later use (in case there is no sunlight) [13]. The stored energy is then transferred to a transformer, which converts the electrical energy into an appropriate voltage level for transmission, and it passes through the regulator to ensure stable output. The regulated power is fed to transmitter coils, which are embedded in the floor of the charging area generating an electromagnetic field for the WPT to the receiver coils located in the EV. The received energy is converted from AC to DC via an AC to DC converter to charge the vehicle's battery. The system is managed by an Atmega controller with voltage sensing, which monitors and controls the voltage for safe and efficient charging. The process is continuously displayed on an LCD screen, providing real-time charging status and battery information to the user [14].

IV. RESULTS AND DISCUSSIONS

A MATLAB simulation of the solar wireless EV charging demonstrates that effective charging depends on minimizing the transmitter-receiver distance and optimizing panel orientation. Strong sunshine enhances battery SOC, potentially reducing grid electricity use and boosting renewable energy. Challenges include weather effects, panel alignment, and the need for adaptive controls and improved energy storage [25, 26]. The simulation result graphs provide a detailed examination of the performance of the solar-powered EVCS over 24 hours. The irradiance curve of the sun exhibits the quantity of solar energy arriving per square meter per day in W/m², as portrayed in Figure 5. As a rule, this curve is bell-shaped, peaking at midday with the maximum possible intensity and up to 1000 W/m² in reach. It occurs when the sun is overhead, and energy capture is maximised. It is, therefore, gradually decreasing with proximity to the evening, and it will have been at its minimum level by night. It is critical to understand this profile to optimize the functioning of solar energy systems, which contributes to the design and improvement of the efficiency of solar panels and energy storage solutions.

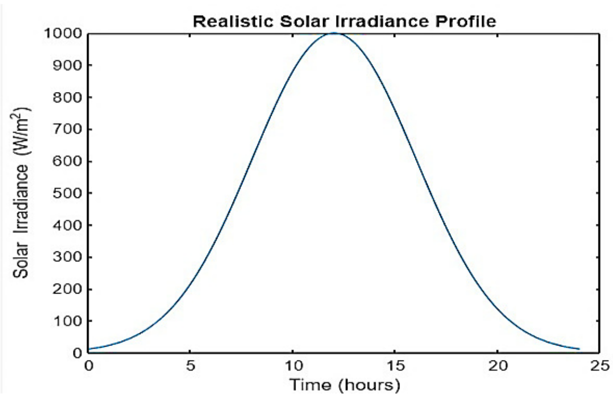

Fig. 5. The diurnal profile of solar irradiance.

Figure 6 illustrates the WPT efficiency, as a function of distance between transmitter and receiver coils. The efficiency decreases sharply with increasing distance, ranging from approximately 90% at 0 meters to nearly 0% at 1 meter. This exhibits the significance of proximity in minimizing energy loss, emphasizing the importance for maximizing efficiency in solar wireless charging systems.

The diurnal profile of power output from solar panels is shown in Figure 7, illustrating the variation in electricity generation throughout the day (measured in Watts). The output peaks at midday, coinciding with the maximum solar, can reach up to 2000 W. The curve decreases during the morning and late afternoon hours and drops to zero at night, highlighting the dependence of solar panels on sunlight for efficient operation.

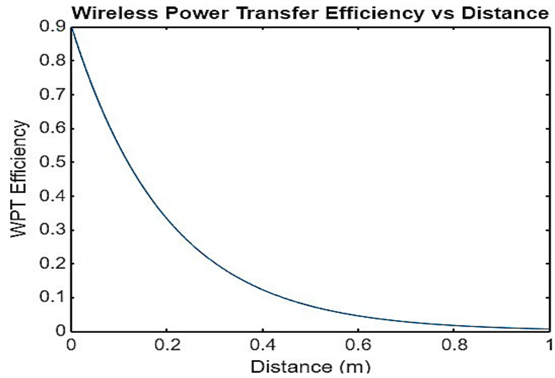

Fig. 6. WPT efficiency as a function of distance between transmitter-receiver coils.

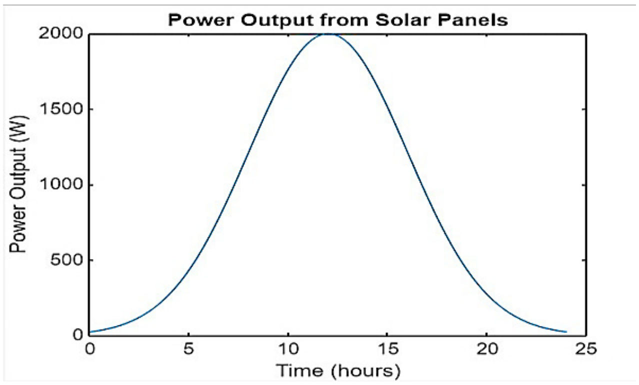

Fig. 7. The diurnal profile of solar panel power output.

Figure 8 presents the diurnal profiles of the simulated battery parameters including SOC, current, and voltage of the battery.

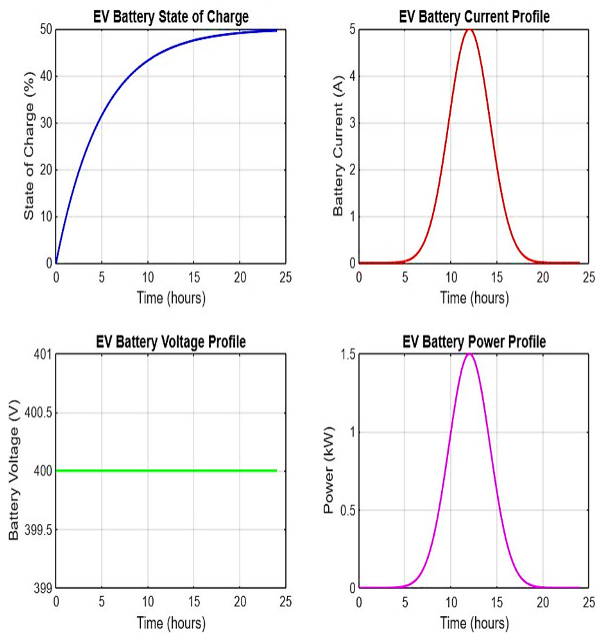

Fig. 8. Diurnal profiles of the simulated battery parameters.

Over time, the SOC percentage increases as energy is stored in the EV battery. It starts at 0% at dawn and gradually rises as the battery charges using sunlight. Typically, the SOC reaches its peak in the late afternoon, achieving 100% when solar power generation is optimized. For instance, SOC values around 80% can be observed at midday while the charging progress is ongoing, indicating adequate energy storage through e solar panels and the battery's ability to absorb available renewable energy. The battery's current profile illustrates the flow of current into the EV battery through the day. It peaks at around midday, reaching approximately 5 A due to maximal solar energy generation. This peak corresponds to the maximum power point of the solar panel. The voltage graph depicts the nominal voltage during the charging process, which remains stable at around 400 V. This stability ensures that electricity is transferred and managed effectively throughout the charging process.

V. CONCLUSIONS AND FUTURE WORK

The Solar Wireless Electric Vehicle Charging System (SWEVCS) is a valid and revolutionary approach to charging Electric Vehicles (EVs) more efficiently by harnessing solar energy and Wireless Power Transfer (WPT) technologies. The present study demonstrates that the system can achieve a peak power output of approximately 2 kW around midday, coinciding with optimal solar irradiance. This efficiency ensures that the captured solar energy is utilized effectively, allowing the battery's State of Charge (SOC) to have reached reach 100% by late afternoon, signifying excellent energy storage and management capabilities. The system ability to wireless transfer energy to the vehicle's battery, delivering a charging current of approximately 5 A under peak solar conditions, highlights its robust energy transfer capability. Furthermore, the stable nominal battery voltage of 400 V reinforces the system's reliability and operational stability. These features demonstrate not only the potential for reducing dependency on grid electricity, but also the role of solar wireless charging systems in promoting sustainable transportation solutions through the utilization of renewable energy sources.

Future work will focus on further optimizing the system's efficiency and exploring advanced battery management systems to enhance overall performance. Addressing challenges related to environmental factors and scaling the technology for real-world applications will also be essential to fully realize the potential of this innovative charging solution.

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