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Solar and Grid-Based Wireless Charging of Static and Dynamic Electric Vehicles

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Abstract

The rapid adoption of Electric Vehicles (EVs) necessitates efficient and sustainable charging solutions. This paper presents an advanced solar and grid-based wireless charging system designed for both static and dynamic EVs. The proposed system integrates Plug-in Hybrid Electric Vehicles (PHEVs) and Plug-in Electric Vehicles (PEVs) with optimized charging scenarios and control strategies. A Raspberry Pi-based monitoring system ensures real-time control and efficiency. Utilizing solar energy reduces dependence on fossil-fuel-based power grids, lowering carbon emissions while addressing the challenges of charging costs. Wireless Power Transmission (WPT), based on inductive resonance enhances charging flexibility, particularly for dynamic charging scenarios. Simulation results demonstrate the impact of the proposed system on voltage stability, peak demand reduction, and cost-effectiveness in EV charging networks. Unlike conventional EV charging methods, which rely on traditional power infrastructures, this approach harnesses renewable energy for a cleaner and more sustainable future. The study validates the feasibility of wireless dynamic charging through MATLAB simulations, showcasing its effectiveness in enabling seamless energy transfer to moving EVs. This innovation paves the way for the widespread adoption of intelligent EV charging infrastructure.

Keywords: Electric Vehicle Charging, Plug-in Vehicle, Plug-in Hybrid Electrical Vehicle, Wireless Power Transmission.

I. INTRODUCTION

In today's world, electricity powers almost every aspect of our lives. From smartphones and laptops to essential household appliances, our dependence on electricity is undeniable. As the demand for electricity continues to grow, the transition to EVs presents a promising solution to combat environmental pollution [1]. With various renewable energy sources available for electricity generation, utilizing electricity for transportation is both feasible and sustainable [2]. EVs rely on rechargeable batteries, which act as energy storage units, requiring periodic recharging after a certain mileage. However, the need for a more efficient, faster, and convenient charging system has become increasingly evident. Consumers prefer seamless charging solutions without the hassle of carrying multiple chargers for different devices or enduring long wait times at charging stations [3], [4].

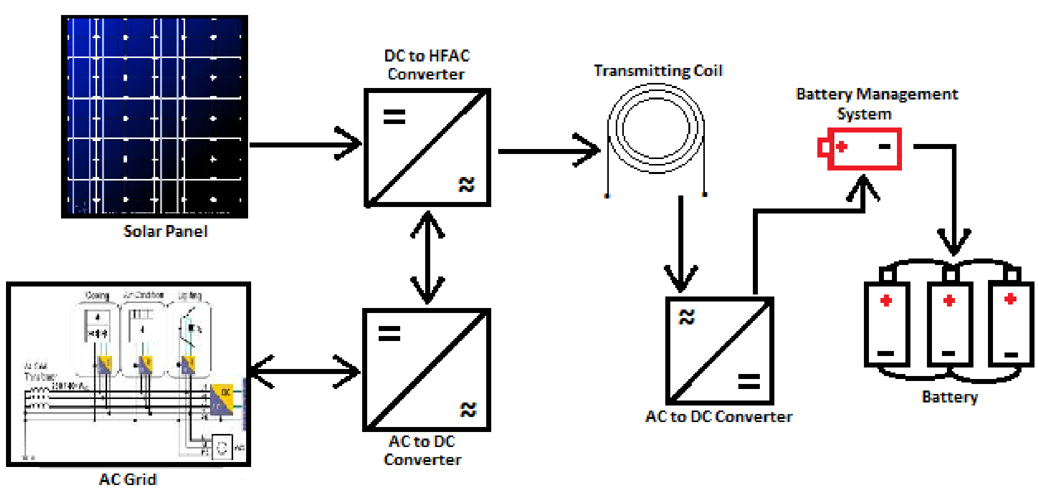

Figure 1. Block Diagram

To address these challenges, this paper proposes a wireless charging system for EVs, eliminating the need for physical connectors. The study explores the concept of WPT and enhances the efficiency of stationary wireless charging for electric cars, providing a more practical and user-friendly charging experience. With the continuous depletion of biofuels and rising fuel prices, owning and operating conventional vehicles has become increasingly challenging. To address this issue, EVs have been introduced, utilizing batteries as their primary power source.

Various charging technologies, such as DC and AC charging have been developed, primarily relying on wired plug-in connections. However, wired charging requires human intervention to initiate the process, leading to inefficiencies and inconvenience. To eliminate this dependency, wireless charging technology has been introduced [5]. This paper explores the concept of WPT using an inductive wireless charging system. The proposed system integrates a solar panel with a grid-connected setup as the primary energy source, facilitating wire-free power transmission to charge electric vehicles. Unlike conventional wired charging systems [6], which require different connectors based on vehicle manufacturer's specifications, the proposed wireless charging system enhances user convenience and reduces charging time. This setup is particularly beneficial for locations such as shopping malls, where vehicles can be charged while owners engage in other activities.

The system utilizes solar energy during daylight hours to power homes and industries while simultaneously supplying electricity to a High-Frequency AC (HFAC) inverter [7]. The energy from the solar panel is first converted to DC and then transmitted as HFAC as illustrated in Figure 1 [8]. The power is then processed through a resonator circuit to enhance transmission efficiency before being transferred via an inductive coil [9]. Through electromagnetic induction, current is induced in the secondary coil, which then passes through a resonator circuit, is converted back to DC and is finally regulated by a Battery Management System (BMS) to ensure optimal charging of the EV battery [10]. This wireless charging approach overcomes the limitations of traditional wired charging systems, offering a more efficient, standardized, and user-friendly solution for EV charging.

II. WIRELESS CHARGING METHODS

Various methods have been developed for wirelessly transmitting power to charge EVs. Some of the key approaches include:

- Capacitive Wireless Power Transfer
- Permanent Magnetic Wireless Power Transfer
- Inductive Wireless Power Transfer
- Resonant Inductive Wireless Power Transfer

2.1 Capacitive Wireless Charging System (CWCS)

Capacitive Wireless Power Transfer (CWPT) is primarily used for low-power applications such as portable electronics and mobile phone chargers. This method relies on coupling capacitors instead of coils or magnets to transfer energy from the transmitter to the receiver. The power transfer occurs through displacement current generated by an oscillating electric field [11]. A CWPT system typically consists of four metal plates forming a capacitive coupler. To optimize efficiency, maintain voltage levels, and minimize transmission losses, the AC voltage is first fed into a power factor adjustment circuit. It is then processed through an H-bridge network to generate high-frequency AC. To reduce impedance between the transmitter and receiver, inductors are placed in series with the coupling capacitor [12]. On the receiver side, AC power is rectified and filtered before being delivered to the battery via a BMS. The system operates at frequencies ranging from 100 kHz to 600 kHz. Key advantages of CWPT include minimal eddy current losses, lower cost, reduced weight, and improved tolerance to misalignment. However, its efficiency is affected by the size and positioning of the coupling capacitors. Due to the large air gap and high power consumption, CWPT is not widely used for EVs. One potential improvement involves integrating the car's bumper as a receiver to reduce the air gap and enhance efficiency [13].

2.2 Permanent Magnet Wireless Charging System (PMWCS)

PMWCS differs significantly from CWPT and IWPT, using synchronized permanent magnets as both the transmitter and receiver. When AC current is applied to the transmitter winding, it induces mechanical torque, rotating the transmitter magnet. This, in turn, causes a corresponding rotation in the receiver's permanent magnet, enabling power transfer. The mechanical energy at the receiver side is then converted into electrical energy [14]. Power converters rectify and filter the generated AC power before converting it into DC for battery charging. However, PMWCS faces challenges in both static and dynamic charging due to the inverse relationship between power transfer efficiency and the distance between the transmitter and receiver. While this method is suitable for stationary EV charging, its application in dynamic systems remains complex due to coupling limitations [15].

2.3 Inductive Wireless Charging System (IWCS)

Inductive Wireless Power Transfer (IWPT) is based on the principle of electromagnetic induction, first conceptualized by Nikola Tesla in 1914. This technique has been widely tested and implemented across various applications. IWPT enables wireless electricity transfer through mutual induction between transmitter and receiver coils. When AC power is supplied to the transmitter coil, it generates a magnetic field, inducing current in the receiver coil. This AC power is then converted into DC via power converters before being managed by the BMS for battery charging [16]. The efficiency of IWPT is influenced by factors such as operating frequency in the range of 19–50 kHz, mutual inductance, and the separation distance between coils. While IWPT is a well-established method for WPT, it has certain limitations. These include relatively slower charging speeds compared to wired connections and higher implementation costs due to the need for precise coil alignment and advanced power electronics [17].

2.4 Resonant Inductive Wireless Charging System (RIWCS)

RIWCS is an enhanced version of IWPT, designed to improve power transmission efficiency through resonant coupling [18]. This method employs high-quality resonators to achieve energy transfer at a higher rate while reducing magnetic field losses. Similar to IWPT, RIWCS relies on high-frequency AC supplied to the primary winding i.e. transmitter coil. The generated power is transferred to the receiver coil using electromagnetic fields. After rectification and filtering, the power is converted into DC to charge the EV battery [19]. Resonant coupling allows for power transmission over larger distances compared to IWPT. To optimize efficiency, compensation networks are integrated into both transmitter and receiver coils in either series or parallel configurations [20]. Due to the typical clearance requirements of 150–300 mm in EVs, the coupling coefficient in RIWCS ranges between 0.2 and 0.3. The system operates at frequencies from 10 kHz to 150 kHz, with compensation networks minimizing additional power losses [21].

2.5 Static Wireless Charging

Static wireless charging involves charging EVs while they are parked over a designated area equipped with embedded WPT coils. In this system, power converters and associated circuitry are installed underground, with the transmitter coil positioned beneath the vehicle. The transmitter coil generates high-frequency AC power, which is received by the receiver coil mounted on the underside of the vehicle. The received power is converted from AC to DC and regulated by the BMS before being stored in the battery. A wireless communication system ensures safety and optimizes charging efficiency. The efficiency of static wireless charging depends on factors such as coil alignment, power source strength, and air gap distance which is typically 150–300 mm [22]. This technology is particularly suited for parking lots, garages, office buildings, and shopping malls, enabling convenient and autonomous charging. To enhance user experience, an automated guidance system can be incorporated to assist drivers in precisely aligning their vehicles with the primary charging pad. Additionally, inductive communication or other short-range data exchange methods can be used between the vehicle's receiver coil and the charging station transmitter. This allows real-time adjustments to the charging process based on battery conditions and driver preferences. One of the main challenges in conventional EV charging is the need for specific charging plugs, which vary by manufacturer. This often forces consumers to carry dedicated chargers. Wireless charging eliminates this inconvenience while maintaining high efficiency of about 88–93%, comparable to plug-in charging systems that use isolation transformers [23]. The positioning of the coils plays a crucial role in optimizing energy transfer. Maximum power transfer occurs when the transmitting and receiving coils are vertically aligned, allowing maximum flux to pass between them [24].

III. SYSTEM OVERVIEW

3.1 Solar Model

The solar power output is influenced by several variables, including the dimensions of the solar panel, the intensity of solar radiation striking the panel, and the temperature increase in the solar modules. The power output is calculated using the following equation:

$$P(t) = BI(t)I_{sc}\left(1 + \frac{33}{1000}\cos\left(\frac{360d}{365}\right)\right) * \sin\alpha\sin\delta + \cos\alpha\cos\delta(\beta t) \quad (1)$$

$\beta = minutes\ before\ noon/4$

(2)

$\delta = 23.45 \left\{ sin \left[\frac{360(d+284)}{365}\right] \right\}$ `

(3)

Where:

- P(t) represents the solar-generated energy as a function of time t.
- BI(t) is the clearing index at time t.
- I_{sc} refers to the solar constant.
- α is the geographic latitude (user-dependent, calculated as 27° in this case).
- δ is the solar declination angle.

In this model, a photovoltaic generation system consisting of 20 solar panels is considered, with 2 series modules and 10 parallel strings. Each panel has a 300 Wp rating. The array's performance is evaluated under a module temperature of 25°C and a range of solar irradiance values from 100 W/m² to 1000 W/m².

3.2 Battery Charging and Discharging (Lithium-Ion Battery)

The charging and discharging characteristics of a lithium-ion battery can be modelled using the following mathematical equations:

Battery Charging Equation:

$$\left\{ B_{chg} = B_0 - K\frac{a}{a-it}j - k\frac{a}{a-it}it + A.e^{(-B.it)} \right\}$$

(4)

Battery Discharging Equation:

$$\left\{ B_{dchg} = B_0 - K\frac{a}{0.1\ a+it}j - k\frac{a}{a-it}it + A.e^{(-B.it)} \right\}$$

(5)

Where:

- B_{chg} represents the battery charging equation.
- B_{dchg} represents the battery discharging equation.
- j is the low-frequency dynamic current (A).
- it is the available battery capacity (Ah).
- K is the polarization constant.
- a is the battery capacity (Ah).
- A is the exponential zone amplitude (V).
- B is the exponential zone time constant inverse (Ah^{-1})
- B_0 is the standard voltage.
- k is the polarization resistance (Ω).

These equations represent the operations of the battery management system (BMS) in electric vehicles, ensuring optimized battery performance and efficiency.

3.3 WIRELESS POWER TRANSFER (WPT) OPERATION

WPT system operates through two primary modules: the transmitter and the receiver. A key characteristic of this system is the air gap between the primary transmitter coil and the secondary receiver coil, which impacts power transfer efficiency.

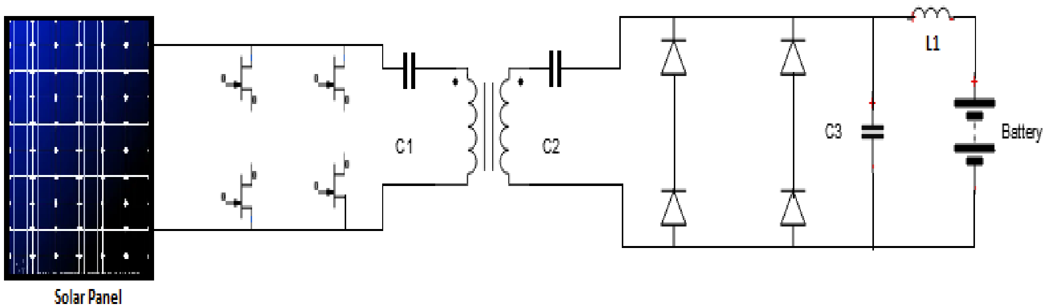

Figure 2. Basic Building Block

This gap leads to flux intensity loss, reducing overall efficiency; however, a resonator circuit with capacitors connected in series with both coils enhances inductive coupling, thereby improving energy transfer. The power supply for the primary coil consists of three main components: a grid connection providing the initial power input, a rectifier converting AC to DC, and an inverter that transforms DC back into high-frequency AC for efficient wireless transmission. The equivalent circuit model of the power supply includes a voltage source with an internal resistance, both of which significantly influence energy transfer efficiency [25]. A sinusoidal output generator is crucial for ensuring stable and effective WPT operation. The secondary coil's output voltage is processed through a DC-to-DC converter and a rectifier, converting the AC signal to DC before being supplied to the battery charging circuit as in Figure 2.

The rectifier, chopper circuit, and battery collectively regulate the voltage and current according to the battery's charging requirements, optimizing power flow. The air gap between the transmitter and receiver coils directly affects mutual inductance. A larger air gap results in greater leakage inductance and lower mutual inductance, necessitating higher current for power transfer, increasing energy losses, and reducing system efficiency. To mitigate these losses, a compensating capacitor is incorporated to enhance energy transfer efficiency. Both Static Wireless Power Transfer (SWPT) and Dynamic Wireless Power Transfer (DWPT) rely on charging pads as power transmitters. SWPT employs a single transmitting pad for stationary charging, whereas DWPT enables charging while the vehicle is in motion using multiple transmitting pads powered by a single source. Charging pads are designed in various configurations, including circular, rectangular, and double-D (DD) coil structures. Copper is commonly used due to its high conductivity, but High-Temperature Superconductors (HTS) are being explored for their superior efficiency and reduced resistive losses [26]. DWPT provides greater flexibility in system design, while SWPT remains constrained by single-pad configurations. EVs can be charged using either multiple transmission pads or a single long rail. A long transmission rail provides continuous power when an EV remains within its near-field range, offering benefits such as simplified control and a stable power supply. However, it also increases component costs, introduces a single point of failure, and suffers from inefficient coupling if there is a size disparity between the rail and the EV. In contrast, a multi-pad charging system enhances reliability by preventing complete system failure when a single pad malfunctions. It also allows selective activation of pads beneath the EV, reducing power wastage and electromagnetic radiation. However, this system is more complex, requiring additional power supplies, inverters, and control mechanisms, increasing overall costs. Optimizing coupling efficiency is essential, as power transfer efficiency decreases with increased air gaps. Matching the primary and secondary coil sizes also plays a vital role; a significant size difference reduces mutual inductance, diminishing performance. Similarly, improper spacing between pads can cause energy leakage when too close or power transmission gaps when too far apart, disrupting continuous charging [27]. To further improve efficiency, WPT systems incorporate resonant circuits to counteract high leakage inductance caused by loosely coupled coils. These systems employ capacitors and inductors arranged in series or parallel configurations. A series configuration enhances voltage gain and transmission range, whereas a parallel configuration improves current handling and minimizes losses, ensuring optimal energy transfer in wireless EV charging applications [28]. BMS plays a crucial role in blocking inrush power disturbances, filtering and smoothing power, and efficiently managing energy distribution between charging and driving [29-30].

IV. SIMULATION MODEL

This simulation focuses on solar-powered three-level inverter system capable of generating high-quality three-phase AC power. The integration of a boost converter, DC link capacitors, and an NPC inverter ensures efficient conversion, stability, and reduced harmonics, making it a viable solution for wireless EV charging in a parking area as in Figure 3.The system begins with a solar power source with a capacitor connected in parallel with the source, which helps in smoothing the voltage fluctuations and acting as an energy storage element. The circuit includes an inductor, a diode, and a switching device forming a boost converter. This boosts the DC voltage coming from the solar panel to a higher DC voltage required for the inverter operation. The switching pulses for the boost converter are controlled using a PWM signal, ensuring that the output DC voltage is regulated efficiently. The boosted DC voltage is stored across two capacitors C_1 & C_2. These capacitors help in stabilizing the DC bus voltage, which is crucial for maintaining a balanced output in the next stage. The Three-Level Converter converts DC voltage to three-phase AC output. It generates a more sinusoidal waveform compared to conventional two-level inverters, reducing harmonic distortions and improving efficiency. The inverter is triggered by PWM signals, which determine the switching sequence for generating the desired AC waveform. The inverter feeds its three-phase AC output (labelled A, B, and C) to a three-phase transmission line.

This output can be used for powering loads, integrating with the grid, or feeding an electric motor. The system includes pulse generation blocks that provide PWM signals for both the boost converter and the three-level inverter. A step function block is used to control switching instances, allowing dynamic changes in power levels. The boost converter maximizes power extraction from the solar panel. The three-level inverter reduces harmonics, leading to a cleaner AC output.

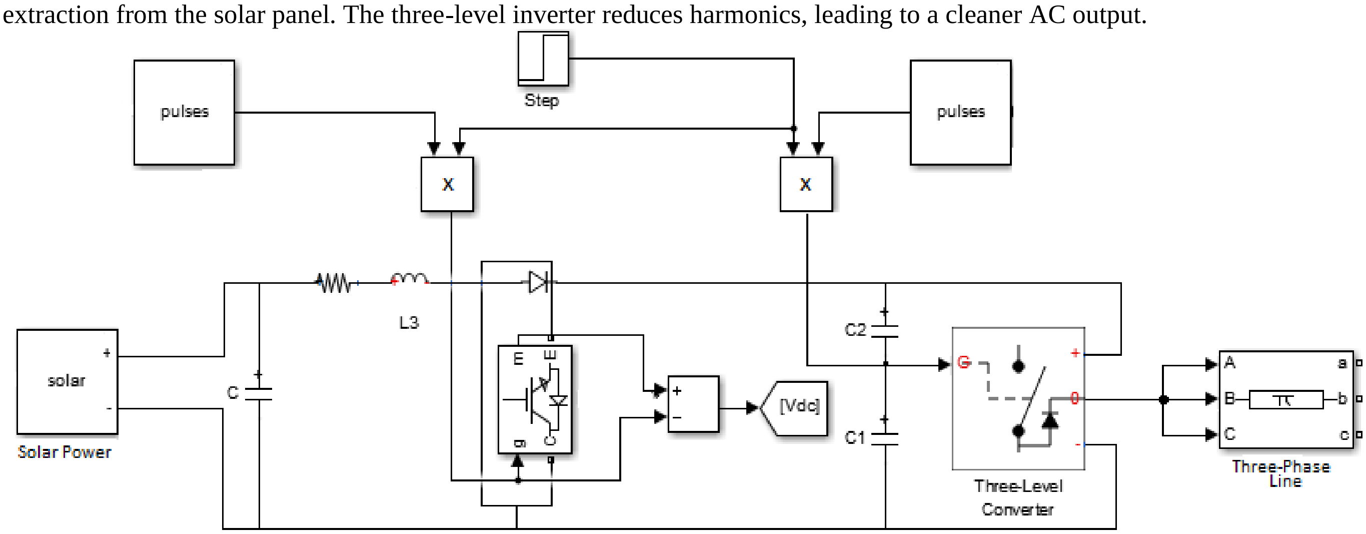

Figure 3. Simulation model for the charging of Electric Vehicle Wirelessly

The system's connection points, as depicted in Figure 4, serve as terminals for wireless charging. To simulate real-world conditions in India, irradiance levels are varied between 400–1000 W/m², and temperatures range from 25°C to 50°C. This MATLAB Simulink model effectively simulates a solar PV array's response to changes in irradiance and temperature, providing valuable insights for solar energy research and optimization. The ability to dynamically control input conditions makes it a powerful tool for performance evaluation, grid integration studies, and renewable energy system design. The inverted DC voltage and current, operating at 50 kHz, are smoothed using an IGBT bridge and resonator capacitor as in Figure 5. The incoming DC voltage (terminals 1 and 2) is modulated using pulse signals to generate a bipolar AC voltage at the output (terminals 3 and 4). The AC output from the secondary coil is rectified using a full-wave bridge rectifier for battery charging as in Figure 6. The system efficiently converts DC to high-frequency AC, transfers power wirelessly, and rectifies it back to DC for charging applications.

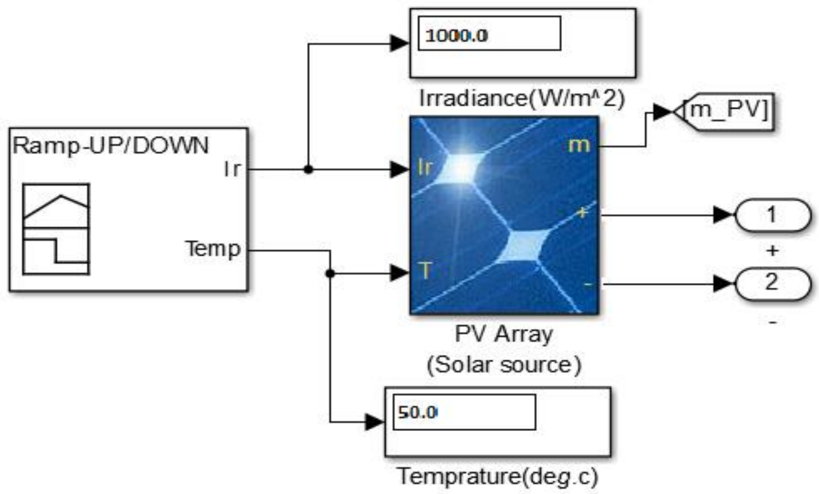

Figure 4. Solar source with day Temperature and irradiance variation

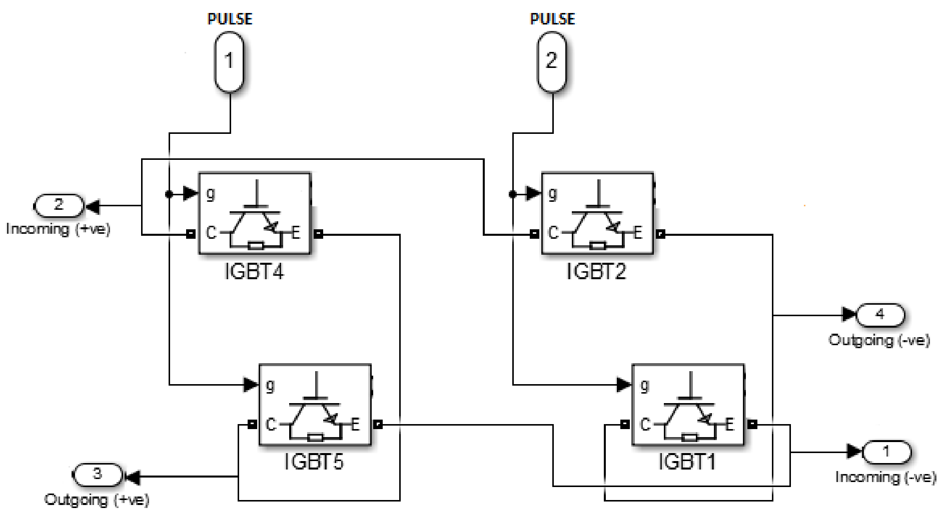

Figure 5. DC to HFAC conversion using IGBT

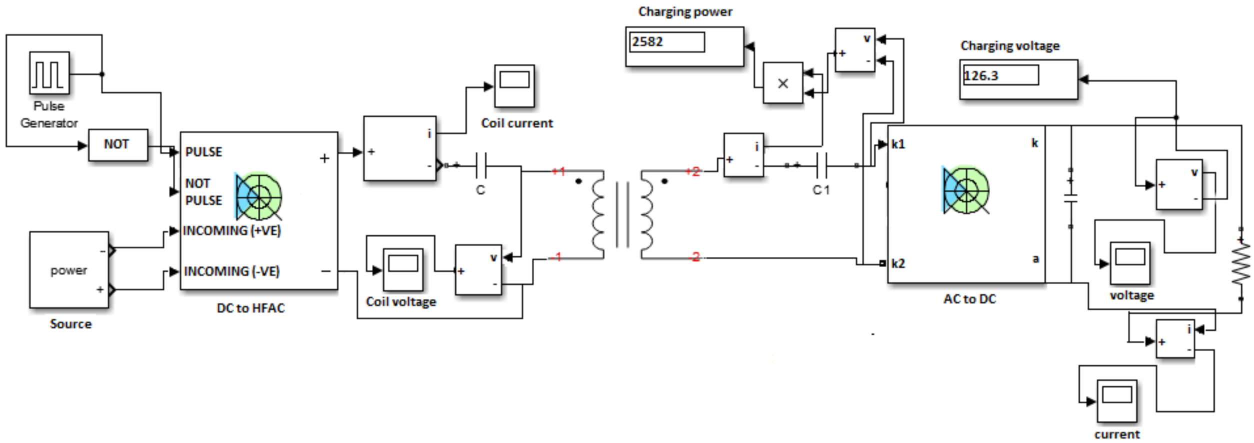

Figure 6. AC voltage across coil with frequency of 50 kHz

V. SIMULATION RESULT ANALYSIS

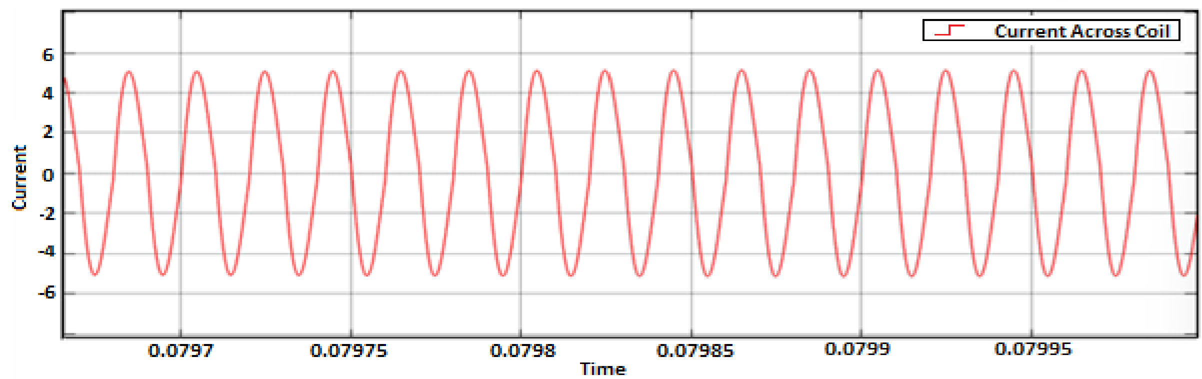

Figure 7. Resultant AC current output after HFAC conversion using IGBT Bridge (50 KHz)

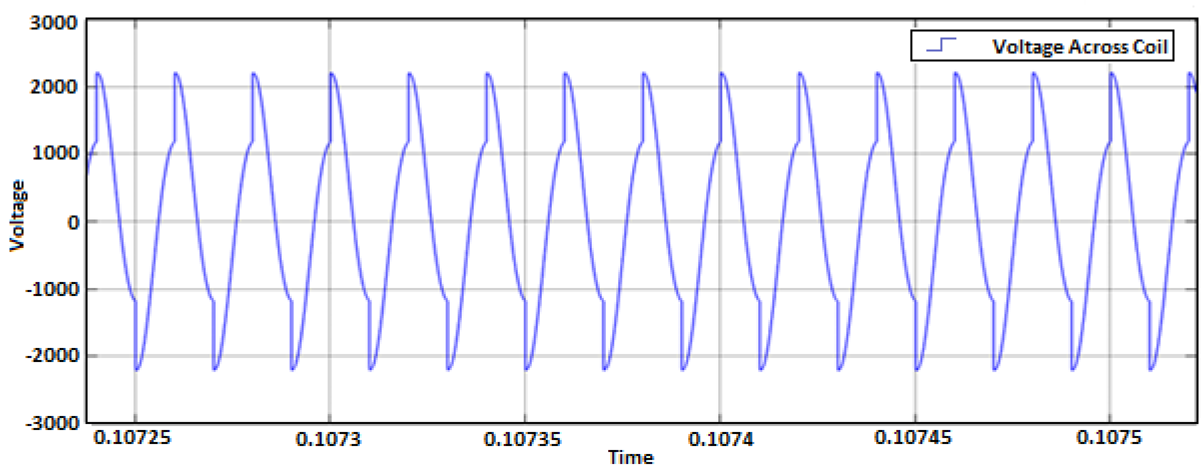

Figure 8. AC voltage across coil with frequency of 50 kHz

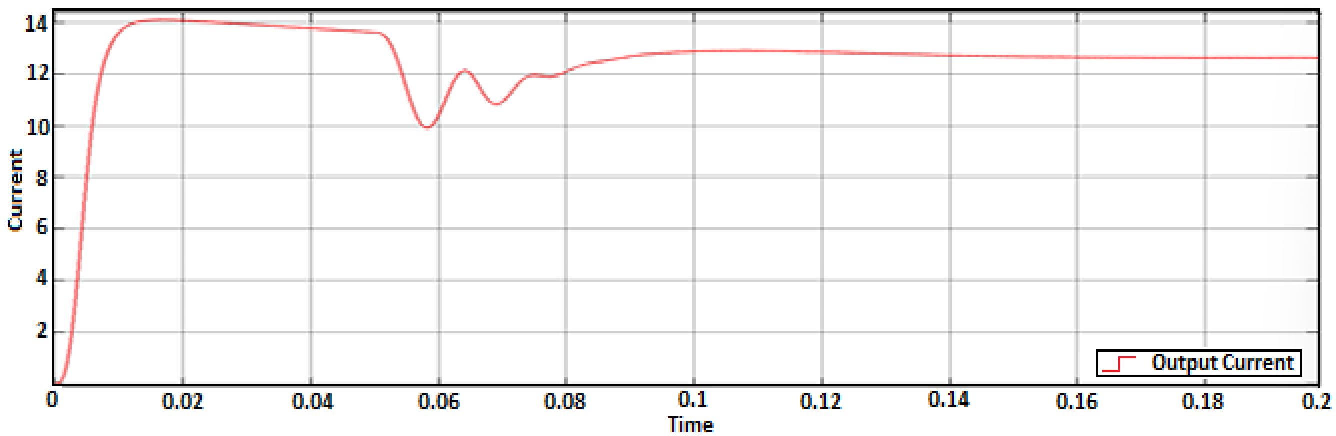

Figure 9. DC output current for charging

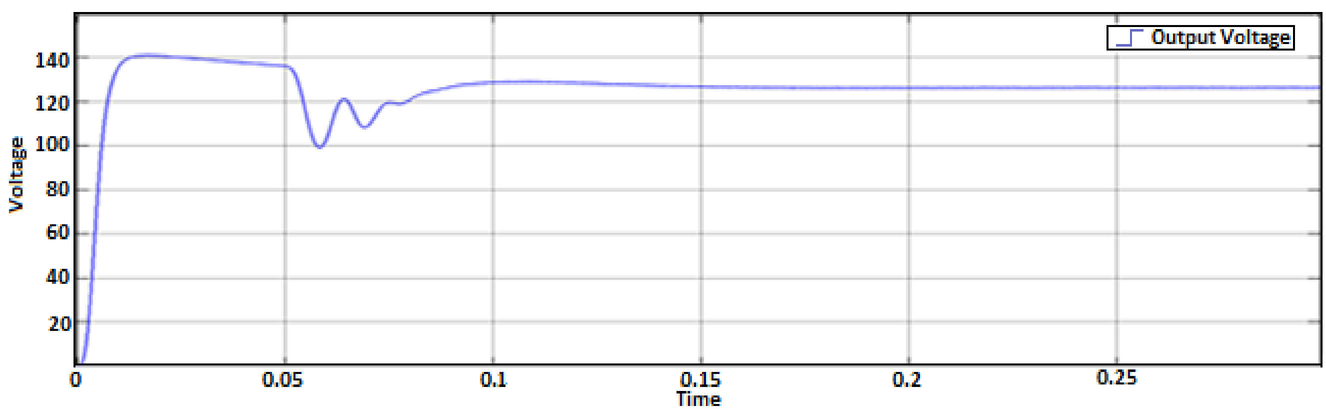

Figure 10. DC output voltage for charging

The simulation results demonstrate a high-frequency output where the current fluctuates between 5A and -5A as in Figure 7. The sinusoidal shape indicates that high-frequency AC (HFAC) is generated successfully in the primary coil. This waveform confirms that the switching circuit and coil resonance are working properly. The high-frequency current ensures efficient energy transmission across the inductive link. Any distortions or inconsistencies in this waveform could indicate power losses, impedance mismatches, or coil misalignment. The voltage varies from 2.6kV to -2.6kV as in Figure 8. Similar to the current waveform, it follows an alternating sinusoidal pattern, demonstrating high-frequency AC generation. This waveform validates that the system operates within the expected resonance conditions, ensuring maximum power transfer efficiency.

Figure 9 represents the output current response over time in WPT system used for EV charging. At t ≈ 0 s, the current rapidly rises from 0 A to approximately 14 A, indicating the initial inrush current when power is applied to the system. This surge is expected due to the sudden activation of inductive coupling. Around t ≈ 0.05 s, the current shows a dip followed by oscillations before stabilizing. These fluctuations are caused by the system's inductive nature, resonance effects, and transient interactions between the primary and secondary coils. After t ≈ 0.08 s, the current stabilizes at around 12 A, indicating that the system has reached its steady-state operating condition. The minor decline in current after stabilization suggests system losses or regulation mechanisms ensuring efficient power transfer.

Figure 10 illustrates the output voltage response of the WPT system. Similar to the current response, the voltage also experiences an initial rapid increase, peaking at around 140 V at $t \approx 0$ s. This surge is characteristic of an inductive power transfer system where energy is quickly transferred to the load. Around $t \approx 0.05$ s, the voltage exhibits a drop followed by multiple oscillations before stabilizing. These fluctuations correspond to the transient response of the system, influenced by factors such as coil impedance, resonant frequency, and control circuit response. After $t \approx 0.1$ s, the voltage stabilizes at approximately 120 V, indicating efficient energy transfer to the EV battery. The small reduction in voltage over time suggests that the system compensates for minor energy losses to maintain optimal charging conditions.

The system effectively transfers power with minimal energy loss, as seen from the stable voltage and current responses. The transient oscillations indicate the presence of a resonant coupling mechanism, which is common in WPT systems. Proper tuning of the resonant frequency can further enhance efficiency. The system settles into steady-state operation quickly, ensuring a consistent charging voltage and current, which is crucial for safe and efficient EV battery charging.

VI. CONCLUSION

WPT was successfully implemented to charge an EV battery efficiently. As EV batteries degrade over time, their charging process accelerates, requiring less time to reach their rated capacity. The simplicity of wireless charging, coupled with minimal driver involvement, significantly enhances user convenience and encourages wider adoption of electric mobility. Moreover, when combined with high power transfer efficiency, WPT emerges as a highly effective and scalable solution for EV charging. This technology not only reduces vehicle weight by eliminating bulky charging cables but also lowers manufacturing costs and extends the vehicle's driving range—one of the most critical challenges in EV adoption.

In addition to these advantages, WPT reduces wear and tear associated with traditional plug-in connectors, thereby increasing the durability and reliability of the charging system. It also enhances safety by eliminating the risk of electric shocks or short circuits caused by damaged charging cables, making it an ideal choice for urban environments and public charging stations. Furthermore, wireless charging can be seamlessly integrated into road infrastructure, enabling dynamic charging while vehicles are in motion, which has the potential to revolutionize long-distance EV travel.

Additionally, the project addresses a major concern among EV owners: the lack of standardization in charging plug designs. By eliminating the need for physical connectors, wireless charging ensures compatibility across various EV models, reducing dependency on multiple charging standards. The MATLAB simulation successfully demonstrates the transient and steady-state characteristics of a wireless power transfer system for EV charging. The results highlight the system’s ability to provide stable and efficient charging with minimal fluctuations after the initial transient phase. Future improvements, such as advanced control strategies and impedance matching techniques, can further optimize performance and reduce transient oscillations. As advancements in resonant inductive coupling and high-frequency power electronics continue, WPT is expected to become even more efficient and cost-effective. These developments reinforce the idea that wireless charging is not just an alternative but a crucial step toward the future of electric mobility, paving the way for a more sustainable and user-friendly transportation ecosystem.

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