Wireless Power Transfer System by Using Optical Technology for Electric Vehicles

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***Abstract*— This research introduces a dynamic Optical Wireless Power Transfer (OWPT) system for charging both aerial and ground electric vehicles (EVs). Laser transmitters installed on an overhead facility track and charge vehicles continuously using tracking cameras. Analytical formulas are developed to analyze power and energy transmission, demonstrating the existence of maximum points inversely dependent on environmental conditions. Numerical simulations validate the theoretical findings. The study suggests design implications for ground EVs, highlighting the superiority of the dynamic OWPT system over other wireless transfer technologies. This innovation promises efficient, weather-resilient charging solutions for EVs, enhancing sustainability in transportation.**

Keywords*— Dynamic OWPT, Wireless Charging, Laser Transmitters, Renewable Energy, Tracking Cameras, Analytical Formulas, Maximum Power, Environmental Attenuation, Numerical Simulations, Ground EV Design, Comparative Analysis

INTRODUCTION

The imperative to address global warming has become a key driver for promoting the widespread adoption of Electric Vehicles . As per the Organisation for Economic Cooperation and Development , the transportation sector, responsible for over 50% of global oil consumption, contributes to approximately 20% of worldwide carbon dioxide emissions. Consequently, the transportation sector emerges as a primary focus for countries' climate change mitigation policies. In response to mounting environmental apprehensions regarding CO2-induced global warming, policymakers are actively advocating for the adoption of electrified vehicles (EVs) as a strategic measure to curtail these emissions.

The EV Volumes database site records a notable surge in global Electric Vehicle (EV) and Plug-In Hybrid Electric Vehicle (PHEV) sales, reaching 2.1 million units in 2018, reflecting a substantial 64% year-over-year increase and accounting for a 2.2% market share for the year. This rapid adoption is attributed to pivotal factors such as advancements in battery technology, including enhanced energy density, lifespan, and safety, along with significant cost reductions in batteries and power electronics. Additionally, the emergence of Wireless Power Transfer (WPT) in recent years has opened new possibilities.

This report will delve into the discussion of candidate Wireless Power Transfer (WPT) techniques suitable for high-power, near-field wireless Electric Vehicle (EV) applications. A more detailed exploration of these techniques will be presented in a subsequent section of the report.

Power electronics technology is integral to various aspects of Electric Vehicles (EVs) and their chargers, demanding bidirectional capability and grid-forming control for the battery charger, thereby contributing to increased design costs. This functionality enables the battery and charger to collaboratively establish a local microgrid. Nevertheless, a promising alternative solution to address plug-in concerns for charging EVs is the implementation of wireless electric vehicle charging systems (WEVCS).

Therefore, the discussion of Wireless Electric Vehicle Charging Systems (WEVCS) begins by placing initial emphasis on Wireless Power Transfer (WPT). In the operational context of Electric Vehicles (EVs), the BMS becomes indispensable for monitoring battery parameters, including current, voltage, and temperature. Moreover, simultaneous charging of a large number of EVs can lead to utility supply issues, such as deviations in line voltage and frequency, an increase in total harmonic distortion in the line current, and a surge in peak load on the utility.

I.WIRELESS POWER TRANSFER (WPT)

The transmission of electrical energy from a power source to an electrical load across an air gap, eliminating the need for wires or connectors, characterizes Wireless Power Transfer technology. The essential components of a WPT system encompass the transmitter and receiver coils. Recently, WPT has regained prominence as a viable technology and has undergone extensive investigation and development. Various methods for electrical power transfer, such as capacitive-based WPTs and inductively coupled WPTs, exist. Notably, among these methods, inductively coupled WPTs have emerged as the most widely applied and utilized by researchers.

A.WPT Concept

Figure 2 shows the block diagram of a basic structure of the typical WPT system which consists of several stages to

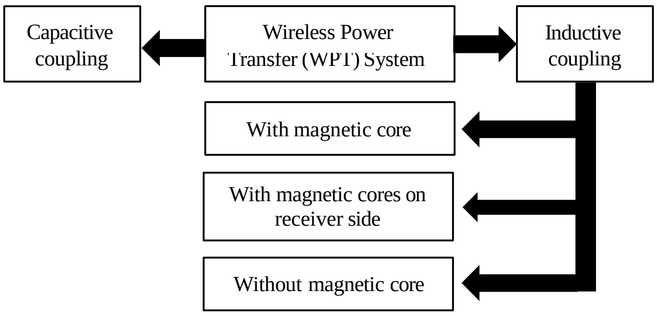

Fig. 1. Classification of WPT system.

wirelessly transfer power from the supply to the load. The key components of the Wireless Power Transfer (WPT) system can be summarized as follows:

- The loosely coupled transmitting and receiving coils.
- The compensation networks.
- The power electronics converters and control electronics.

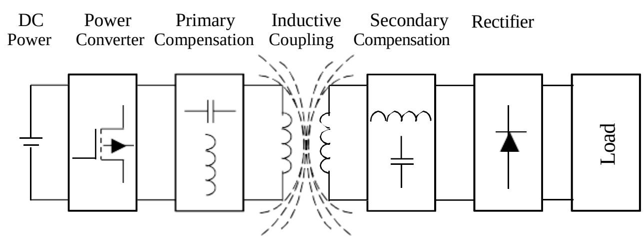

Fig. 2. Basic structure of typical WPT system

A typical Wireless Power Transfer (WPT) system typically employs input DC voltage derived from a DC supply or a battery. The DC input voltage is subsequently converted into a high-frequency AC voltage form. In this process, the current flowing through the transmitting coil produces an alternating magnetic field, inducing an AC voltage in the receiving coil. The resonating interaction with the secondary compensation network significantly enhances the transferred power and efficiency. Ultimately, the AC voltage is rectified to provide power for DC loads.

Considering the implementation of Wireless Power Transfer (WPT), power transfer efficiency emerges as a crucial practical consideration. Due to the loose coupling between the transmitter and receiver coils, in contrast to tightly coupled systems with a transformer core, capturing the transmitted electrical power.

Several researchers have tackled this issue and have published techniques to enhance the range of power transfer efficiency. These include impedance matching and notably the incorporation of passive, resonant relay coils to amplify the oscillating magnetic flux at the receiving antenna. In essence, when the transmitter and reception coils resonate at the same frequency, the energy transfer can occur over the greatest possible distance.

Demonstrations of end-to-end efficiencies exceeding 90% have been showcased for high-power applications, such as charging plug-in hybrid vehicles. Each

To attain such high levels of effectiveness, each stage of the system had to function at a 97-98% efficiency level or higher. Achieving this performance required meticulous design to minimize losses at each stage. Nevertheless, in lower power applications, feasibilities of over 80% efficiency and coil-to-coil efficiencies (power transfer efficiency between the transmitter and reception coils) of 90% or more were attainable. [5].

Wireless Power Transfer (WPT) technology holds the promise of eliminating traditional cable connectors or physical connections, ushering in new levels of convenience for the charging of millions of everyday electronic devices. [6], [9]. WPT brings an additional advantage of reducing costs related to the maintenance of direct connectors. It ensures safe power transfer to applications requiring sterility or hermetic sealing while providing robust and consistent power delivery to rotating, highly mobile industrial equipment [4], [5].

B.Highly Resonants WPT Systems

a) Resonant: In general, resonance involves the oscillation of energy between two modes, as seen in a mechanical pendulum where energy oscillates between potential and kinetic forms. It's possible for a system to be at resonance while still accumulating a significant store of energy.

If the system's rate of energy loss was higher than its rate of energy loss surpasses the rate of energy injection, a buildup occurs. The behavior of an isolated resonator can be defined by two fundamental factors: the resonant frequency ωo and the intrinsic loss rate, Γ. The resonator's quality factor, denoted as Q, which gauges its energy storage efficiency ($Q = \omega o/2\Gamma$), is determined by the ratio of these two factors. [5]. Figure 3 is an example of an electromagnetic resonator circuit with an inductor, capacitor and resistor.

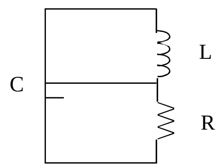

Fig. 3. Basic of resonator.

The energy in this circuit is stored in the magnetic field by the inductor and the electric field by the capacitor, and it oscillates at a resonant frequency between both before dissipating in the resistor. This resonator's resonant frequency and quality factor are expressed as:

$$\omega_o = \frac{1}{\sqrt{LC}} \quad (1)$$

$$Q = \frac{\omega_0}{2\Gamma} = \sqrt{\frac{L}{C}}\,\frac{1}{R} \quad (2)$$

According to the expression for Q in Equation 2, the quality factor of the system will increase if the circuit's loss, or R, is reduced.

shortened by an additional closed-loop CT-CV charging technique.

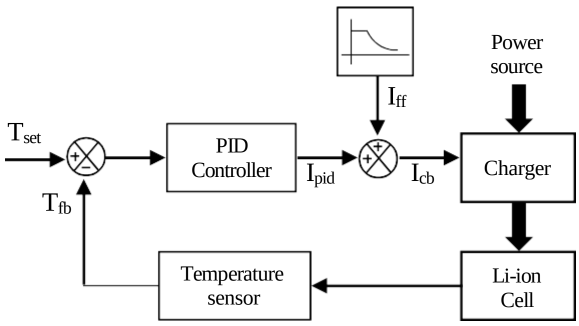

Fig. 4 Control loop block diagram for CT-CV scheme [19].

A.Charging Technologies

The system depicted in Figure 6 enables charging a car through a single-phase connection, a three-phase connection, or inductive energy transfer. Cars are categorized into level 1, level 2, and level 3 based on their power ratings, as outlined in Table 1. The technology employed in this system allows for both grid assistance and power recovery, supporting bidirectional energy flow and delivery of reactive power. This multifunctional converter facilitates grid connections across wired and wireless networks.

Wired charging: As per [20], wired charging technologies necessitate a direct connection between the electric vehicle (EV) and the charging system through cables. These technologies are categorized into AC charging technologies and DC charging technologies. AC charging technologies involve charging the battery indirectly in electric vehicles (BEVs) by using the onboard charger (OBC) to feed the battery. In these systems, the conversion unit, responsible for converting AC to DC, is situated inside the vehicle, contributing to an increase in the overall system weight. AC charging technologies are typically employed in single-phase on-board (OB) slow charging systems or three-phase OB fast charging systems. In contrast, DC charging technologies have the capability to directly charge the battery, enabling fast-charging capabilities. Two subgroups of DC charging technologies are off-board fast charging and off-board rapid charging systems.

Wireless charging: Meanwhile, wireless charging technologies are categorized into three types: near-field charging technologies, medium-field charging technologies, and far-field charging technologies. The first two are the most prevalent and widely used for Battery Electric Vehicles today. The demand for wireless charging technologies is increasing daily. These technologies are more cost-effective compared to wired charging and eliminate the need for a direct connection to EV batteries. Instead, they utilize high-frequency AC to wirelessly charge batteries by converting the grid-frequency AC . The high-frequency AC is transmitted via a transmitter pad and received by a receiver pad attached to the BEV being charged.

problems of wireless charging technologies is that they can quickly spiral out of control.

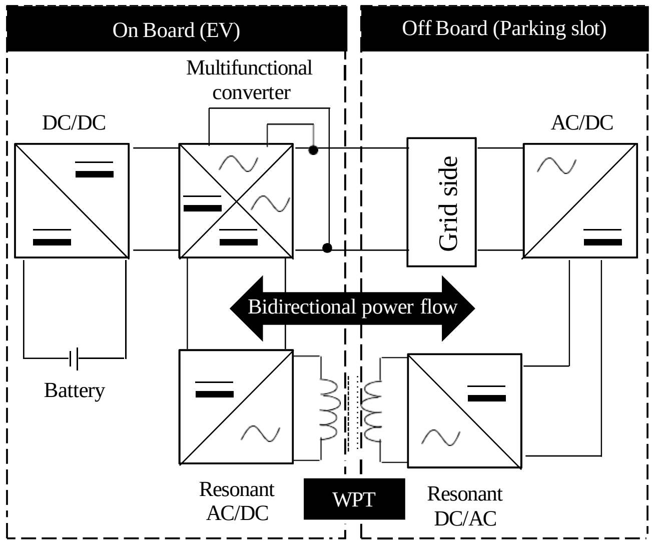

Fig. 5. On-board and Off-board charging using bidirectional charger.

EVs CHARGING POWER LEVEL

Level	Charger	Usage	Power range (kW)	Charging time (hour)
1	On-board	Home	~1.44~1.92	~17
2	On-board	Public	~3.10~19.20	~8
3	Off-board	DC station	From 120-240	~0.5

TABLE 1 EVS CHARGING POWER LEVEL

BATTERY MANAGEMENT SYSTEM

Energy storage systems (ESSs) are experiencing rapid growth in the electrical power system products, driven by the evolving global landscape for electrical distribution and consumption. Among the technologies identified, batteries and capacitors are particularly susceptible to dangers and safety issues [21]. To ensure the operational safety of the system's battery pack, a system control unit, known as a battery management system (BMS), is modeled and implemented [22].

The primary function of a BMS is to safeguard the battery, ensuring the supervision of each cell for safety, cell balancing, and aging purposes. Additionally, the BMS ensures that any abnormal state in the system infrastructure triggers predetermined corrective procedures. The BMS market provides three different implementation topologies: centralized, distributed, and modular.In a centralized topology, a single control unit and a group of battery cells are connected via numerous wires. In a distributed architecture, each control unit is connected to a specific battery cell through a single communication connection. Finally, in a modular design, a single battery cell is managed by several control units, with interconnections among the control units [23]. The most economical but least expandable BMS is the centralized one. Figure 7 illustrates the structure for implementing the BMS.

BMS manages battery packs, whether connected internally or externally, and utilizes common data such as cell voltages, pack current, pack voltage, and pack temperature to determine battery values. It estimates the state of charge (SOC), state of health (SOH), depth of discharge (DOD), and operational critical parameters of the cells/battery packs using these measurements. Figure 8 illustrates how BMS employs these data points to investigate various significant capabilities and functions. It helps to increase battery life and keep pace with the demand requirements of the original power network.

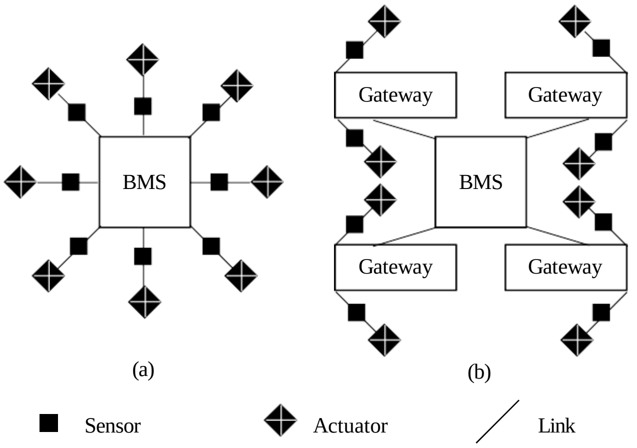

Fig. 6. BMS structure implementation: (a) centralized (b) distributed.

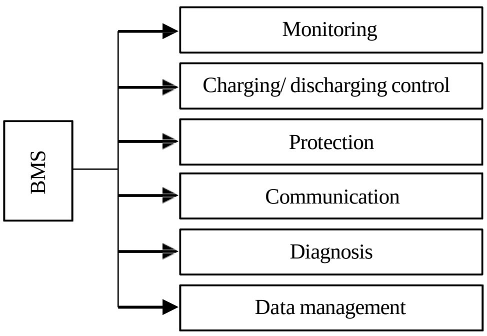

Fig. 7. Functionality of BMS.

I. IMPACTS OF EVCHARGING STATIONS ON ELECTRIC POWER GRID

The proliferation of electric charging stations has a significant impact on the stability of electric power systems, leading to various potential effects outlined in key points in Figure 9. However, this review focuses solely on the discussion of power quality.

A. Harmonics

Earlier works clearly demonstrate the significant generation of harmonic currents and voltages during Electric Vehicle (EV) charging. The detrimental effects of harmonic currents on a distribution network are attributed to the integration of large-scale EV systems [24]. Studies indicate that a penetration rate of 10% or more of EVs into distribution networks can lead to adverse effects on consumers and utility equipment. At low Plug-in EV (PEV) penetration, harmonic distortions in the case of PEV charging on a smart grid distribution system are within tolerable limits [25]. However, substantial PEV penetration reveals a considerable Total Harmonic Distortion (THD) voltage. Rapid charging results in high THD currents ranging between 12 and 14 percent, significantly impacting low-voltage residential distribution networks [26]. Another research piece compared the harmonics produced by a single EV charge with the charging of multiple EVs [27]. As the number of EVs connected to a distribution network increased comparison study proved that the summing of THD is not alinear multiplication.

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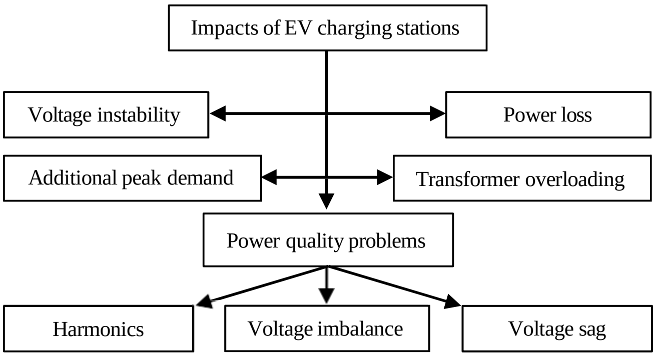

Fig. 8. Impacts of EV charging stations.

A. Voltage imbalance

In a three-phase system, when there is voltage variation, the changes in voltage magnitude or phase angle are not equal. Initially, at the beginning of the low-voltage feeder, EV charging stations were found to have a negligible impact. However, a significant impact was observed at the feeder's end [28]. Another scenario occurs when the unevenly distributed demand in the three-phase system makes AC single-phase EV charging highly phase-imbalanced. To alleviate voltage imbalance, a smart charging strategy was proposed. This method can significantly reduce security issues, even with widespread EV adoption.

B. Voltage sag

Voltage sag refers to a reduction in the Root Mean Square (RMS) voltage at the power frequency for a duration ranging from 0.5 cycles to 1 minute. This phenomenon in distribution network voltage often occurs due to factors such as short circuits, overload, or the starting of electric motors. It has been observed that at 20% Electric Vehicle (EV) penetration, the voltage sag may exceed acceptable limits [29].However, voltage droop charging presents a solution by significantly reducing voltage sag, with minimal impact on the overall EV charging time. Furthermore, the implementation of a smart grid with a load management technique offers excellent opportunities to enhance voltage sag and overall power quality in distribution networks [30].

III.RESULT

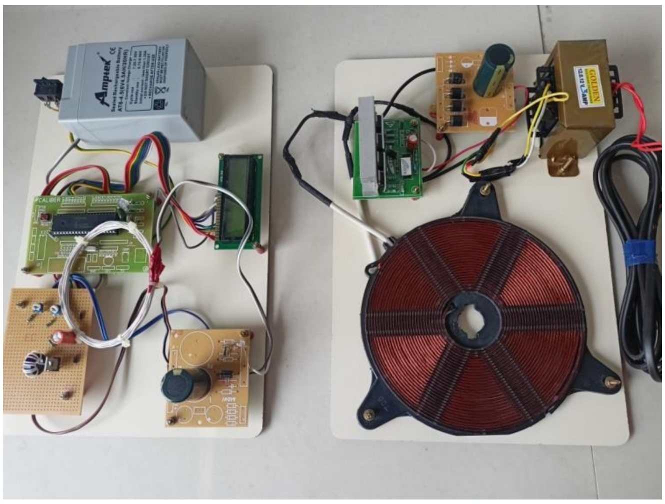

Fig 9. Snapshot of Proposed Hardware Kit

LCD DISPLAY SNAPSHOT

Fig 9.1 Status of Charging Power

Fig 9.2 30% Battery in Approximately 30 Min

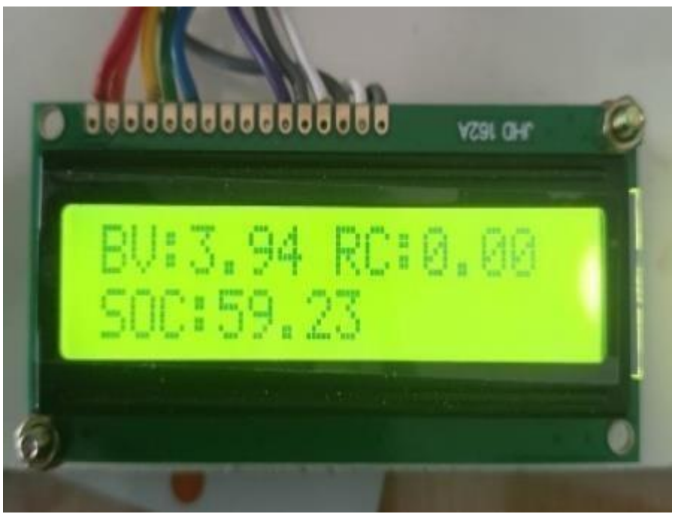

Fig 9.3 60% Battery in Approximately 60 Min

Fig 9.4 90% Battery in Approximately 130 Min

IV CONCLUSION

This paper provides an overview of the wireless electric vehicle charging system (WEVCS). The Wireless Power Transfer (WPT) concept is discussed, offering a foundational understanding of WEVCS. A simple circuit structure is presented to illustrate the operation of WPT, along with suggestions for enhancing the WPT system. The review also explores the connection of Electric Vehicles (EVs) to the power grid, examining how the battery charging system operates. The discussion delves into charging system knowledge, comparing control topologies. It proceeds to analyze the available charging technologies in current markets and highlights ongoing developments toward grid health. Simultaneously, the paper includes insights into the battery management system, emphasizing its role in efficient power flow management for cost-effective battery maintenance and EV operation. The discussion concludes by examining the impacts of WEVCS on the power grid, emphasizing the importance of taking precautions in the future to enhance power quality improvements for consumers.

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