AN EVALUATION OF WIRELESS POWER TRANSMISSION TECHNIQUE FOR E-ROAD VEHICLE PROTOTYPE

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***Abstract* — The emergence of multiple additional technologies marks a vital advance in the field of communication. Wireless technology enables the transfer of electrical energy without taking physical connections, therefore reducing the losses generally linked to power transmission via traditional wiring. This paper presents a thorough review and detailed examination of the different ways employed in wireless power transmission. It features a relative analysis of colorful wireless power transmission(WPT) styles, outlining their separate benefits and downsides, while also probing into common comprehensions and the introductory understanding of WPT. In addition, it investigates both short- range and long- range power transmission technologies, taking into account the influence of colorful parameters. This review underscores the most recent developments in wireless energy conversion designs, including their operations in electric vehicles.**

***Keywords* — Wireless power transfer, Inductive power transfer, Near- Far field power transfer, Electrical vehicle dynamic charging, Resonance power transfer**

I. INTRODUCTION

The advancement of power transmission to different electronic loads has been an ongoing trip since the arrival of electricity in the 18th century. Specially, Michael Faraday innovated a system of wireless power transfer (WPT) in 1831 with his discovery of electromagnetic induction. This principle continues to serve as the foundation of ultramodern WPT ways and dominated the discipline for nearly seventy times after its original disclosure [1]. The WPT system signifies a groundbreaking system of power transmission, exercising electromagnetic fields to transmit electricity through networks without the need for physical lines or direct contact. The roots of this technology can traced back to the 19th century, stressed by the preface of Maxwell's equations in 1864 [2], and Henry Poynting's analysis of electric swells as energy overflows, which established the base for his theorem in 1884 [3]. Nikola Tesla further developed this idea towards the end of the same century [4]. Despite multitudinous unprofitable trials during Tesla's time, his vision has ultimately come to consummation with the emergence of advanced semiconductor technology. At present, WPT technology extensively espoused due to its practicality. A variety of styles, including ray, radio surge, microwave oven, capacitive coupling, and inductive coupling, have been developed to support this technology [5]. Among these ways, resonance- grounded inductive coupling stands out for its effective power transmission capabilities. These styles are particularly salutary in colorful surroundings where the lack of wiring and exposed connections is profitable, similar as in sparkling manufactories, mining operations, and aquatic settings. Likewise, as vessels and electric vehicles decreasingly calculate on wireless battery charging to promote global transportation electrification, WPT is poised to play a vital part. As a result, it is an anticipated that technologically advanced societies will borrow this technology on a global scale in the future [5]. This paper presents the significance of WPT and compares different theoretical ways used across colorful WPT operations, with a particular emphasis on the Dynamic E-Road Electrical Vehicle (DEREV), which signifies a major unborn operation of WPT. Wide marketable relinquishment requires addressing several challenges. A crucial design challenge is to ameliorate power transmission distance without immolating performance. In addition, enhancing misalignment forbearance and cargo characteristics are essential factors to consider [6]. The structure of this paper is as follows Section II reviews the literature, while Section III examines colorful WPT ways and technologies. Section IV provides theoretical perceptivity into coil design within WPT systems. The advantages and disadvantages of wireless charging are bandied in Section V, and Section VI showcases different WPT systems enforced for Dynamic E-Road Electrical Vehicle(DEREV) operations.

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II. LITERATURE REVIEW

Nikola Tesla, a Serbian innovator, was a trailblazer in the sphere of electricity transmission via electromagnetic flux viscosity, particularly with his creation of the Tesla coil in 1891 and the establishment of the Wardenclyffe Tower, which reached a height of about 57 measures. This innovative device operated on a 300- kW signal at a frequency of 150 kHz, enabling it to transmit energy over distances of over to three kilometers without counting on conventional connections

[7]. Despite his ambition to develop a extensively embraced wireless power transmission system that encompassed both transmitters and entering halls, Tesla eventually could not achieve this vision due to fiscal limitations. By 1906, advancements in his exploration had effectively halted, performing in the sealing of critical accoutrements by authorities, which led to the palace's obliteration in 1916. Originally, John Schuder proposed the idea of wireless power transfer technology in 1961[8], followed by William Brown in 1964, and Peter Glaser in 1968 [9]. still, it did not attract substantial attention until 2007, when a group of experimenters from MIT aimed to produce an effective wireless power transfer system able of powering a 60W bulb from a distance of two measures [10]. This progress is abetting the electrification of transportation systems through the wireless recharging of batteries that power vessels and electric vehicles [11]. Scientists prognosticate that wireless power transfer will be vital in the technologically advanced societies of the future. Sir Oliver Lodge showcased the effective operation of high- frequency alternators driven by interspersing current to shoot wireless telegraph signals in 1894 [12]. These trials laid the root for contemporary wireless power transmission (WPT), including those performed by Elisha Gray in 1878. While substantially honored for his benefactions to telephone technology, Gray also managed to transmit interspersing current using a spark gap transmitter made up of an induction coil and capacitor [13]. The discharge produced oscillations that eased power transfer between electrodes, performing in sparks; this illustrates the early stages of what we now relate to as wireless power transmission. The conception of transmitting power without cables is not a ultramodern development; as beforehand as 1878, electrical energy was conveyed through natural mediums [14]. This natural medium encompassed the Earth and its atmosphere, and exercising it allowed early researchers to successfully transmit electricity. Table 1 outlines the literal timeline of inventions related to wireless power transfer.

TABLE 1. HISTORY OF WIRELESS POWER TRANSFER [15].

Year	Inventor	Contribution	Significance
1820	André-Marie Ampère	Discovery of electromagnetism	Understanding electromagnetic fields, crucial for WPT.
1831	Michael Faraday	Discovery of electromagnetic induction	A key principle for WPT.
1864	James Clerk Maxwell	Formulation of Maxwell's equations	providing the theoretical basis for wireless energy transfer.
1891	Nikola Tesla	Tesla Coil and experiments with wireless power	first practical demonstrations of wireless power transfer using resonant inductive coupling.
1893	Nikola Tesla	World's Columbian Exposition	power transfer, lighting lamps wirelessly.
1899	Nikola Tesla	Wardenclyffe Tower	build a global wireless power transmission system,
1961	William C. Brown	Microwave-powered helicopter	using microwaves, a precursor to modern WPT technologies.
1975	Raytheon and NASA	Solar Power Satellite Concept	proposed beaming solar power from space to Earth using microwaves.
2007	MIT Research Team	WiTricity (Resonant Inductive Coupling)	efficient wireless power transfer over mid-range distances using resonant coupling.
2009	Wireless Power Consortium	Qi Standard for Inductive Charging	first widely adopted standard for wireless charging of consumer electronics.
2010	Various Companies	Commercial Wireless Chargers	wireless charging pads for smart-phone, toothbrushes,
2015	Energous Corporation	Watt up Technology	RF-based WPT for charge devices over the air.

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2017	Apple Inc.	iPhone 8/X with Qi Wireless Charging	WPT charging in mainstream consumer electronics .
2020	Xiaomi	Mi Air Charge	long-range wpt charging using beamforming technology.
2021	Ossia Inc.	Cota Real Wireless Power	Wireless power delivery over distances using RF signals.
2022	NASA	Space Solar Power Project	advanced research on beaming solar power from space to Earth.
2023	Samsung	Long-Range Wireless Charging	introduced devices charge multiple meters away.
2024	Various Research Teams	Advancements in WPT for EVs and IoT	efficient wireless charging for electric vehicles and IoT devices, integrating AI for optimization.

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III. WPT TECHNOLOGIES

The transmission of electrical energy without requiring direct metal-to-metal contact made possible through Wireless Power Transfer (WPT) technology. WPT employs energy fields to facilitate this process, and magnetic coupling connects primary and secondary coils through a shared flux in a method referred to as Inductive Power Transfer (IPT). IPT typically takes place across considerable air gaps separating the two sets of coils. Fig.1 illustrates the physical representation of a standard IPT system.

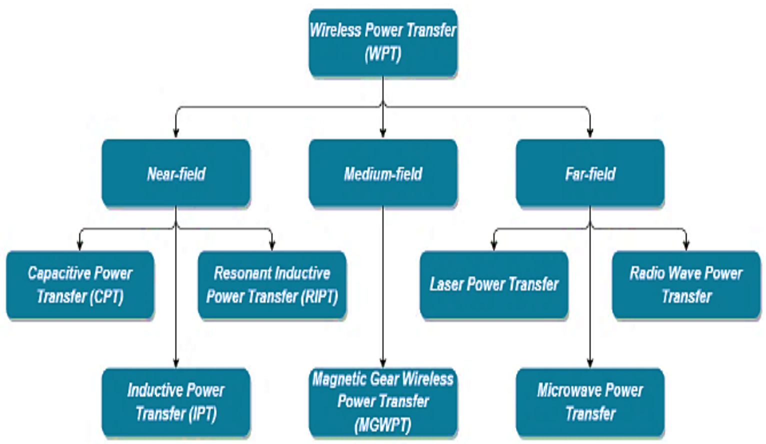

Fig. 1. A typical IPT system.

The WPT systems can be classified below as:

- Inductive coupling
- Resonant inductive coupling
- Radio frequency energy harvesting
- Laser-based power transmission

A Physical representation of IPT with circuit representation in Fig. 2.

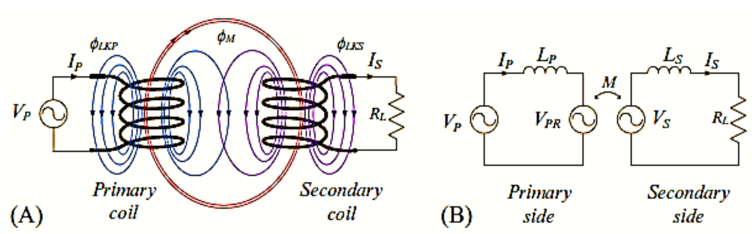

Fig. 2. (A) Physical representation of IPT, (B) circuit representation

Where:

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I_P = Primary current, ϕ_M = Mutual flux, R_L = resistive load, ϕ_{LKP}= flux occurs on the primary and, ϕ_{LKS} = flux occurs on the secondary, L_P and L_S are the primary and secondary self-inductances, M is the mutual inductance (H), V_P and V_S voltages induced in the primary and secondary windings, I_{SC} the current source [16].

The primary and secondary windings of the transfer power system are connected through Equations 1 and 2, which relate to the induced voltages at V_{PR} and V_S (in volts) on both sides of transmission from the transmitter to receiver.

$$V_{PR} = \_j\omega M\, I_S \quad (1)$$
$$Vs = j\ \omega M\, I_p \quad (2)$$

In Fig. 2. The circuit's secondary side is illustrated where the current source I_{SC} (A) varies based on both the open circuit voltage at the terminals of its secondary winding and impedance of its secondary coil when those terminals are shorted - neglecting any winding resistance.

$$I_{SC} = j\omega MI_P = M\, I_P \quad (3)$$
$$j\omega\, L_S = L_S \quad (4)$$

By leveraging the coupling properties of electric, magnetic, and combined electromagnetic fields, WPT systems demonstrate a common trait of energizing their surrounding environment through transmission. Numerous researchers have investigated various methods to implement WPT technology over the years. Fig. 1 summarizes the different types of WPT that can be employed. There are two categories of Far-field wireless power transfer systems: Microwave power transfer (MPT), which utilizes microwaves for energy transmission, and laser power transfer (LPT). Near-field wireless power transfers can be divided into inductive power transfer (IPT), which employs magnetic fields, and capacitive power transfer (CPT), which uses electric fields. Specifically in IPT technology, there are two approaches for energy transmission: coupled wireless transmission (CWTP), where the transmitter is directly connected to the receiver, and magnetically coupled resonance wireless transmission (MCRWTP) [17]. The energy stored per unit volume of space varies between capacitive and inductive power transfers:

$$W_o = \frac{1}{2}\,\varepsilon_o\, E^2 \quad (5)$$
$$W_m = \frac{1}{2}\,\mu_o\, H^2 \quad (6).$$

Where:

E and H are the intensity of the electric and magnetic fields, and, $\boldsymbol{\varepsilon_o}$, $\boldsymbol{\mu_o}$ are the permittivity and the permeability of the free space. On account of the values of $\boldsymbol{\varepsilon_o}$, $\boldsymbol{\mu_o}$, and the acceptable voltages across and current into the coupling devices. In free space, the magnetic field can reach an energy density that is roughly 104 times greater than that of the electric field. During the transfer of radiant power, significant values of electromagnetic fields are focused along the transmission path, resulting in energy concentration. The typical configuration for wireless power transfer (WPT) consists of a transmitting coil (Tx) connected to a high frequency (HF) source, and a receiving coil (Rx) linked to an electric load. When high frequency current flows through Tx, it generates electromagnetic energy that couples with Rx, leading to the generation of voltage across the latter. Ideally, there should be some distance between Tx and Rx, which results in a loose coupling during practical applications [17]. Additionally, Fig. 3 illustrates that there may be extra components such as rectifiers or converters that manage the power flow from both coils into various output circuits based on demand.

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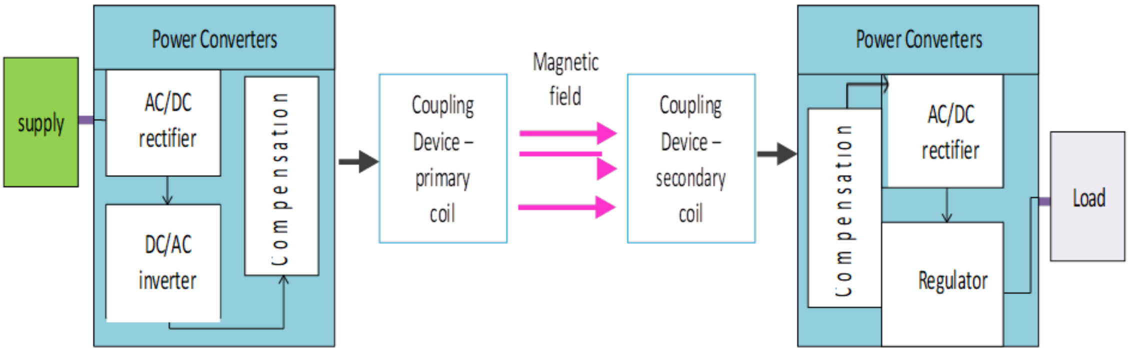

Fig. 3. A typical system of WPT

The power converter linked to Tx transforms the primary power source (AC or DC battery) into high frequency, while a rectifier/charger circuit is connected between Rx and the electrical load. To ensure optimal energy transfer, it is crucial for Rx to resonate at the same frequency as the high-frequency source. In cases where the operating frequencies are considerably lower than the natural resonant frequencies of the WPT coils, additional compensation capacitors must be utilized to establish resonance on both Tx and Rx sides. The wireless connection that includes all components, such as compensation circuits in this system from Tx to Rx, is referred to as such [18].

When the WPT Rx remains stationary while receiving power, it referred to as a fixed WPT pattern. This fundamental configuration, which consists of a single Tx and a single Rx, has progressed into multi-Tx and multi-Rx arrangements [19]. The Dynamic WPT (D-WPT) represents an advanced extension of the stationary system, aimed at delivering wireless power to mobile Rxs. The applications for static systems include medical implants [20], EV charging stations [21], consumer products, and industrial applications [22]. Conversely, the promising applications of D-WPT encompass electric vehicles [18], biomedical applications, robotics, and manufacturing applications [23].

IV. COIL DESIGN OF WPTS SYSTEMS

This section discusses the design process for WPTS coils. There are several design alternatives available to maximize power transfer efficiency. A variety of studies have thoroughly examined and compared different coil designs for both transmitter and receiver pads [24]-[26]. The design characteristics of near-field WPT techniques that utilize inductive coupling can also be applied to those employing electric fields, such as CPT. The research [27] supports the effectiveness of CPT as a practical WPT method and offers an analysis of power flow within such systems.

The suggested charging platform features a dynamic soft switching transformer with output-voltage regulation, specifically engineered to manage power flow under various operational conditions. During its operation, electricity passes through the primary coil, creating a time-varying magnetic flux. This fluctuating field induces electromotive force (e.m.f.) in the secondary coil, influenced by several factors, including the air gap between coils, the number of turns around each other, and the rate of change of magnetic fields per distance traveled, leading to current generation throughout its wiring lines.

The implementation of dual charge operations via wireless technology is expected to result in even higher growth rates. The analysis focused on two types of coupling structures: helix and spiral. By employing a Finite Element Method (FEM) code, the inductive parameters were assessed based on variables such as coil distance, number of turns, turn distance (specifically for spiral coils), and axial misalignment [28]. Generally, WPTs can be categorized into two groups: far-field WP and near-field WPT [29]. Fig. 4 illustrates the potential applications of WPT systems.

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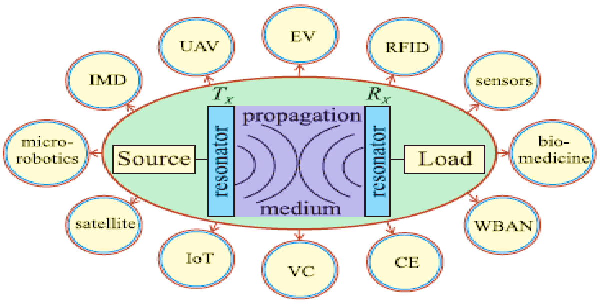

Fig. 4. The potential applications of the WPT systems.

In the field of near-field wireless power transfer (WPT), three primary techniques that involve inductive and magnetic coupling are frequently used in wireless power systems [30]. Additionally, the capacitive method is recognized for its compact dimensions upon review. When assessed against other methods, there is a significant difference in the power transfer range, which in turn restricts its practical application. On one hand, there are sequential processes, while on the other hand, inductive and resonant methods are utilized. Coupling-dependent WPTs employ a relatively long-range power transmission approach. The operational distance is determined using metallic coils [31].

Many improvements have made to these methods, especially as technological progress has facilitated the creation of micro strip lines (MLs) instead of printed coils and spirals [32]. Various design documents concerning resonance were cited. Coupling-based systems for wireless power transfer concentrate energy on specific transmitting devices. The efficiency of the system influenced by its frequency, resulting in enhanced performance in these WPTs. Unlike systems that rely on inductive coupling, this leads to a coupling sound typically associated with resonance.

A planar structure [33] is necessary for this to take place. For effective coupling, both a resonator and a defected ground structure (DGS) must be included based on the number of sources. Utilizing the DGS technique may assist in fostering the development of quasi-lumped resonant resonators, which are crucial for circuit behavior analysis [34]. The improvement depends on the resonant circuit possessing a high-quality factor (Q). The implementation of a double-sided substrate integrated design results in an exceptionally user-friendly layout. The technology of suspended lines is employed to enhance the Q factor in systems [35]. Researchers have noted that conventional printed spiral inductors have certain drawbacks [36]. WPT systems that use spirals were specifically tailored for certain applications, including benchmarks and enhancements in circuitry.

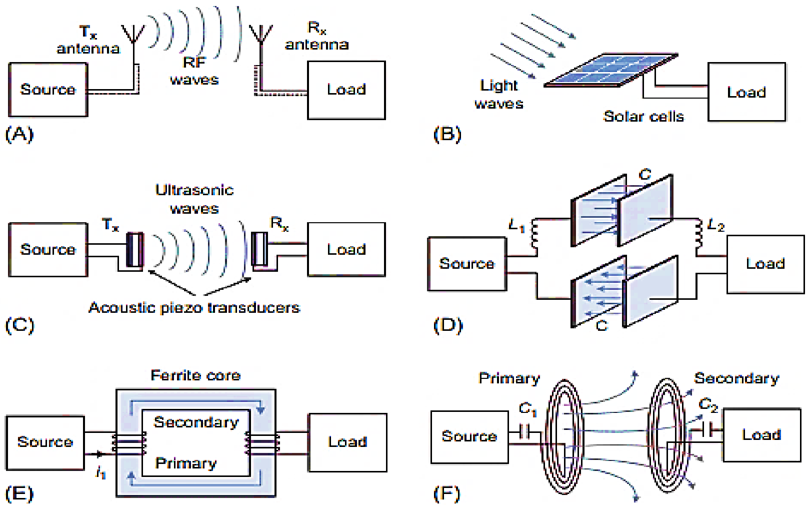

Fig. 5. Several methods of wireless power transfer. (A) WPT in radio-frequency waves, (B) solar radiation in optical WPT, (C) WPT using ultrasonic waves, (D) capacitive power transfer, (E) tightly coupled inductive power transfer, and (F) loosely coupled resonant inductive power transfer

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V. ELECTRICAL VEHICLE TECHNOLOGY

Electric Vehicle (EV) technology signifies a revolutionary change in the automotive and transportation sectors, motivated by the demand for sustainable and energy-efficient mobility options. EVs operate using electric motors that obtain energy from rechargeable battery packs, fuel cells, or hybrid systems, either replacing or enhancing traditional internal combustion engines (ICEs). This technology plays a crucial role in significantly lowering greenhouse gas emissions, reducing dependence on fossil fuels, and supporting global initiatives to tackle climate change.

Key elements of EV technology consist of:

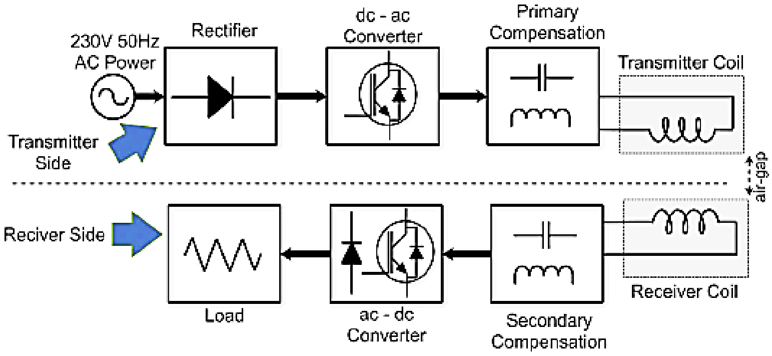
• Electric Motors: Generally AC induction or permanent magnet synchronous motors, recognized for their high efficiency and torque.

• Battery Systems: Lithium-ion batteries are prevalent due to their high energy density, although solid-state and other advanced battery technologies are currently in development.

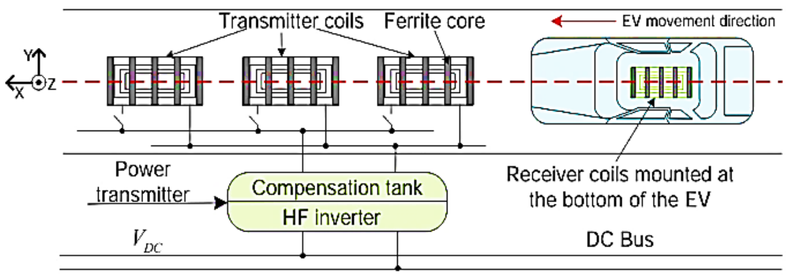
• Power Electronics: Inverters, converters, and controllers regulate energy flow between the battery, motor, and other components.

• Charging Infrastructure: Comprises Level 1, Level 2, and DC fast chargers, enhanced by smart grid integration for effective energy management.

The EV technology is swiftly advancing, with improvements in battery chemistry, energy storage, and autonomous driving technologies. Issues such as range anxiety, charging duration, and infrastructure development are being tackled through innovation and supportive policies. Fig. 5 illustrates the proposed technology implemented in Dynamic Road Electrical Vehicle [37].



(a)



(b)

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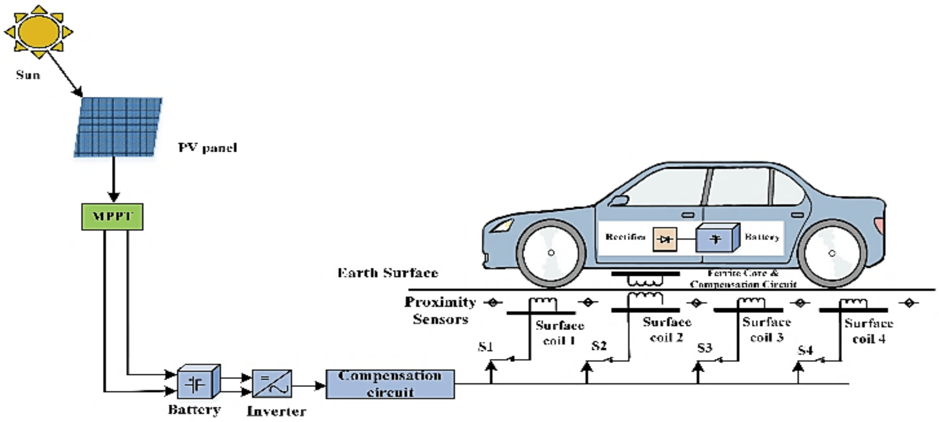

(c)

Figure 5 the proposed technology implemented in Dynamic Road Electrical Vehicle.
a) Transmitter and Receiver process, b) and c) installation system in road.

To attain peak performance in a WPT system, it is vital to take into account various factors that influence its operation. Besides transmission distance, misalignment tolerance and load variation tolerance are critical application-level requirements that significantly affect overall performance. Thus, considering all these elements is necessary for achieving the best outcomes from the WPT system. The speed of PTE and TP is largely dependent on specific application requirements. Their efficiency decreases markedly with increased transmission distance and misalignment. Numerous strategies have suggested enhancing their performance, such as developing compensation networks or circuits [38].

VI. COMPARISION OF POWER TRANSMISSION METHODS

Methods presented in preceding subsections are compared briefly in this subsection. Each and every method has its own advantages and disadvantages including cost, range and health hazards. Comparison is summarized in Table 2.

TABLE 2. COMPARISON OF POWER TRANSMISSION METHODS

Magnetic Resonance Method	**Microwave Method**	**Laser Method**
• It is economical as the equipment used • Is cheap and easily available	Relatively expensive as compared to other methods	Implies same economic conditions of mutual inductance
Useful for implementation of the small distance applications	This method implies for long distance applications	Useful for small distance, but could be used for longer when high distance beam is involved
It is safe from biological point of view	Injurious for health because of high frequency rays	This method is also injurious to human health

VII. CONCLUSIONS

The wireless power transfer technology regarded as one of the most promising innovations and holds potential for the future. Although this technology not yet extensively utilized for high levels of electric power over long distances, there are indications that research in this area is robust and ongoing. When comparing wireless energy transfer to traditional electrical energy transmission via high voltage lines, a contactless approach not only reduces the construction costs of power lines but also offers unconventional solutions. For instance, it can facilitate the rapid transfer of the highest power from one location on Earth to another. This advancement will lead to savings in money, time, materials, and natural resources.

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