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# Wireless Power Transfer Technology

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**Abstract--The advent of several wireless technologies represents a significant discovery in the realm of communication. Wireless technology facilitates the transmission of electrical power without the need for physical connections, thereby minimizing the losses typically associated with power transmission through conventional wiring. This paper offers a comprehensive review and in-depth analysis of the various techniques employed in wireless power transmission. It includes a comparative assessment of different wireless power transmission (WPT) methods, discussing their respective advantages and disadvantages, while also exploring prevalent perceptions and fundamental understanding of WPT. Furthermore, it examines both short-range and long-range power transmission technologies, considering the effects of various parameters. This review highlights the latest advancements in wireless energy conversion designs, including** applications 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 evolution of power transmission to various electronic loads has been a continuous process since the discovery of electricity in the 18th century. Particularly, Michael Faraday introduced a form of wireless power transfer (WPT) in 1831, when he discovered electromagnetic induction. This principle remains the foundational technique employed by contemporary WPT methods, and dominated the field for approximately seventy years following its initial discovery [1].
The WPT system represents a revolutionary approach to power transmission, employing electromagnetic fields to convey electricity across networks without the necessity of physical cables, or direct contact. The origins of this technology can be traced to the 19th century, marked by the introduction of Maxwell's equations in 1864 [2], and Henry Poynting's interpretation of electric waves as energy flows which laid the foundation for his theorem in 1884 [3]. Nikola Tesla expanded upon this concept towards the conclusion of the same century [4].

Although there were several unsuccessful experiments during Tesla's era, his vision has ultimately materialized with the advent of sophisticated semiconductor technology. Currently, the WPT technology is extensively utilized owing to its practicality. Various methods including laser, radio wave, microwave, capacitive coupling, and inductive coupling, have been developed to facilitate this technology [5]. Resonance-based inductive coupling is particularly notable among various techniques for its efficient power transmission capabilities. These methods is advantageous in numerous settings where the absence of wiring and exposed contacts is beneficial, such as in sparkling factories, mining operations, and underwater environments. Additionally; as ships and electric vehicles increasingly depend on wireless battery charging to enhance global transportation electrification, WPT is set to assume a crucial role. Consequently; it is expected that technologically advanced societies will embrace this technology on a global scale in the future [5]. This paper introduces the significance of WPT and compares various theoretical techniques employed across different WPT applications, with a specific focus on the Dynamic E-Road Electrical Vehicle (DEREV), which represents a significant future application of WPT Widespread commercial adoption necessitates the resolution of numerous challenges. A primary design difficulty is the enhancement of power transmission distance without compromising performance. Additionally; improving misalignment tolerance and load characteristics are critical considerations [6]. This paper is structured as follows: Section II explores literature review, while Section III explores various WPT techniques and technologies. Section IV offers theoretical understandings into coil design within WPT systems. The pros and cons of wireless charging are examined in Section V, and Section VI highlights different WPT systems implemented for Dynamic E-Road Electrical Vehicle (DEREV) applications.

## II LITERATURE REVIEW.

Nikola Tesla, a Serbian inventor, was a pioneer in the field of electricity transmission through electromagnetic flux density, notably with the invention of the Tesla coil in 1891 and the construction of the Wardenclyffe Tower,


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which stood approximately 57 meters tall. This groundbreaking apparatus was powered by a 300-kW signal operating at a frequency of 150 kHz, allowing it to transmit energy over distances of up to three kilometers without the need for traditional connections [7]. Despite his vision of creating a widely adopted wireless power transmission system that included both transmitters and receiving towers. Tesla was ultimately unable to realize this goal due to financial constraints. By 1906, progress on his research had effectively ceased, leading to the sealing of essential materials by officials, which culminated in the tower's destruction in 1916. Initially; the concept of wireless power transfer technology was introduced by John Schuder in 1961[8], followed by William Brown in 1964, and Peter Glaser in 1968[9]. However, it did not garner significant interest until 2007, when a team of researchers from MIT sought to develop an efficient wireless power transfer system capable of illuminating a 60W bulb from a distance of two meters [10]. This advancement is contributing to the electrification of transportation systems through the wireless recharging of batteries that power ships, and electric vehicles [11]. Scientists anticipate that wireless power transfer will play a crucial role in the technologically advanced societies of the future.

Sir Oliver Lodge demonstrated the successful use of high-frequency alternators powered by alternating current to transmit wireless telegraph signals in 1894 [12]. These experiments paved the way for modern-day WPT, such as those conducted by Elisha Gray in 1878. Although primarily known for his work on telephone development, Gray also transmitted AC through a spark gap transmitter composed of an induction coil and capacitor [13]. The discharge generated oscillations that transferred power between electrodes causing them to emit sparks, this exemplifies early forms of what is now considered wireless power transmission. The transmission of power without wires is not a recent innovation, as far back as 1878, electrical energy was transmitted through the medium found in nature [14]. This natural substance encompassed the earth and its surrounding atmosphere, utilizing this medium led to early experimenters transmitting electricity with great success. Table 1 indicate the history of wireless power transfer inventions with work.

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. |
| 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 transfer of electric power without the need for direct metal-to-metal contact is achievable through WPT technology. WPT utilizes energy fields to accomplish this task and magnetic coupling links primary and secondary coils via a mutual flux in an approach known as Inductive Power Transfer (IPT). IPT usually occurs across significant air gaps between both sets of coils. Fig.1 shows the physical representation of a typical IPT system.


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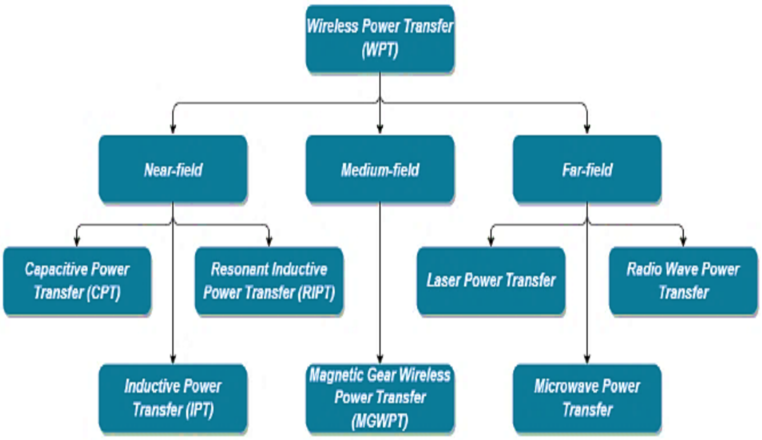


Fig. 1. A typical IPT system.

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.

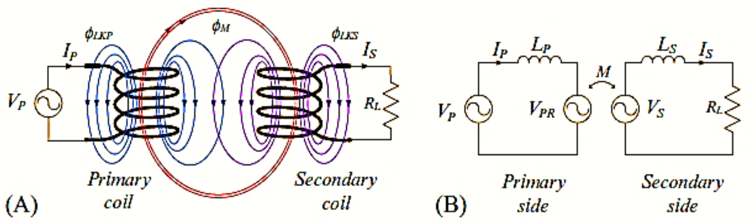


Fig. 2. (A) Physical representation of IPT, (B) circuit representation

Where:

$I_P$ = Primary current, $\phi_M$ = Mutual flux, $R_L$ = resistive load, $\phi_{LKP}$= flux occurs on the primary and, $\phi_{LKS}$ = 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.

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

$$j\omega\, L_S = L_S \quad (4)$$

By utilizing the coupling characteristic of electric, magnetic, and combined electromagnetic fields, WPT systems exhibit a shared characteristic of energizing their surrounding space through transmission. Countless researchers have explored various techniques to implement WPT technology over time Fig. 1 provides a summary of the various types of WPT that can be utilized. There are two types of Far-field wireless power transfer systems. Microwave power transfer (MPT), which uses microwaves to transmit energy, and laser power transfer (LPT). Near-field wireless power transfers can be classified into inductive power transfer (IPT) that uses magnetic fields or capacitive power transfer (CPT) that utilize electric field. In IPT technology specifically, there are two methods for transmitting energy coupled wireless transmission (CWTP), where the transmitter is directly linked to the receiver and magnetically coupled resonance wireless transmission (MCRWTP) [17]. The energy stored per unit volume of space is different for capacitive and inductive power transfers:


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$$W_o = \frac{1}{2}\,\varepsilon_o\,E^2 \qquad (5)$$

$$W_m = \frac{1}{2}\,\mu_o\,H^2 \qquad (6).$$

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 achieve approximately 104 times higher energy density compared to the electric field. During radiant power transfer, high values of electromagnetic fields are concentrated along the transmission path leading to a concentration of energy. The standard setup for wireless power transfer WPT includes a transmitting coil (Tx), linked to a high frequency (HF) source, and a receiving coil (Rx), connected to an electric load. When current of high frequency runs through Tx, it produces electromagnetic energy that couples with Rx resulting in the production of voltage over the latter. It is ideal for there to exist some distance between Tx and Rx which causes them only loosely coupled during practical applications [17]. Moreover; Fig. 3 shows how there could be additional attachments such as rectifiers or converters working power flow coming from both coils into various output circuits depending on demand.

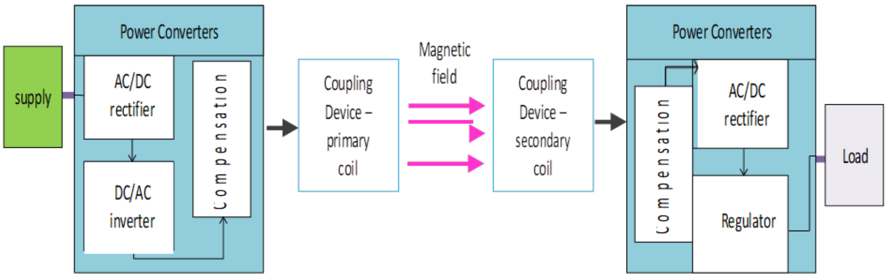


Fig. 3. A typical system of WPT

The power converter connected to Tx converts the main power (AC or DC battery) into high frequency, while a rectifier/charger circuit is linked between Rx and the electrical load. To achieve maximum energy transfer, it's essential that Rx resonates at the same frequency as that of the high-frequency source. In situations where operating frequencies are significantly below natural WPT coil resonant frequencies, additional compensation capacitors must be employed for resonance formation on both sides of Tx and Rx. The wireless link comprising all components like compensation circuits in this system from Tx to Rx is termed as such [18].

When the WPT Rx stays in one location while receiving power, it is known as a fixed WPT pattern. This basic setup, consisting of only one Tx and one Rx, has evolved into multi-Tx and multi-Rx schemes [19]. The Dynamic WPT (D-WPT) is an innovative continuation of the stationary system designed to transmit wireless power to mobile Rxs. Applications for static systems span across medical implants [20], EV charging stations [21], consumer products and industrial use [22]. On the other hand, promising applications of D-WPT include electric vehicles [18], biomedical applications robotics and manufacturing applications [23].

## IV. COIL DESIGN OF WPTS SYSTEMS

In this section, the process for designing WPTS coils is addressed. Multiple design options are available to achieve optimal power transfer efficiency. Numerous studies have explored and compared various coil designs for transmitter and receiver pads in great detail [24]-[26]. Design features of near-field WPT methods using inductive coupling can be applied to those that use electric fields (such as CPT). The study [27] advocates for CPT's effectiveness as a viable WPT method while also providing an analysis of power flow within such a system. The proposed charging platform consists of a dynamic soft switching transformer with output-voltage regulation designed specifically to control power-flow across diverse operational conditions. During operation, electricity flows through the primary coil which generates varying magnetic flux over time. This changing field induces electromotive force (emf) into the secondary coil based on several factors including air gap length between coils, number of turns made around each other or rate at which magnetic fields change per distance traveled etc., precipitating current generation throughout its wiring lines counterparts implementing dual charges operations via wireless technology predict even greater rates growth emergence. The analysis involved two types of coupling structures, specifically helix and spiral. Utilizing a Finite Element Method (FEM) code, the inductive parameters were determined based on factors such as coil distance, turn number, turn distance (solely for spiral coils), and


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axial misalignment [28]. In general, it is feasible to divide WPTs into two categories, namely, far-field WP and near-field WPT [29]. Fig. 4. shows the potential applications of the WPT systems.

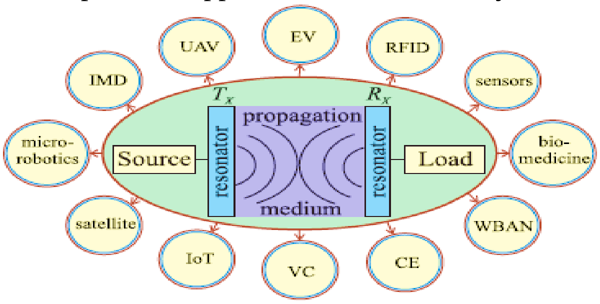


Fig. 4. The potential applications of the WPT systems.

In the region of near-field WPTs, there exist three distinguishable inductive, and magnetic coupling techniques, are widely used in wireless power transfer systems [30]. Additionally; the capacitive one has a smaller size when explored. In comparison with the other methods, there is a difference in power transfer range. hence, has limited practical applicability. On the one hand, there are successive actions. On the other hand, inductive and resonant processes exist. Coupling-dependent WPTs that utilize a relatively extended power transmission. The distance of the mission is constructed using metallic coils [31]. There have been several improvements in these methods, con-Considering that advancements in technology have facilitated the creation. Using microstrip lines (MLs) instead of printed coils and spirals [32]. refer to various design reports associated with resonance. Coupling-based systems for wireless power transfer concentrate energy on specific transmitting devices. The efficiency of the system is influenced by its frequency. As a result, these WPTs demonstrate an enhanced performance. When compared to systems that rely on inductive coupling, give rises to a pling sound, which is typically associated with resonance. plane structure [33] to be present. In order for coupling to occur, both a resonator and a defected ground structure (DGS) must be in place as per source number. The use of the DGS technique may assist in fostering the advancement of Quasi-lumped resonant resonators are required to consider the behavior of circuits [34]. Enhancement is dependent on the resonant circuit possessing a high-quality factor (Q) The utilization of a double-sided substrate integrated results in an exceptionally intuitive design. The technology of suspended lines is used to improve the Q factor in systems [35]. Scientists has indicated that conventional printed spiral inductors have limitations [36]. WPT systems based on spirals were designed for specific applications, such as standards and improving the circuit design the circuit design was improved by taking into account various standards, resulting in a high-efficiency WPT for IMDs. Standardized frequencies [36] along with distinct signal carriers After conducting a brief survey on the WPT systems that utilize coils. Several methods of wireless power transfer shown in Fig. 5.

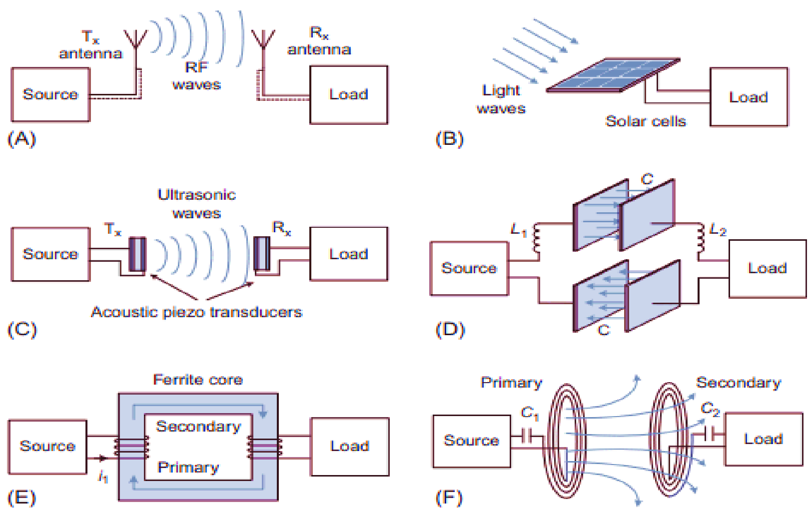


Fig. 5. Several methods of wireless power transfer. (A) WPT in radio-frequency waves, (B) solar radiation in optical WPT, (C) WPT using ultrasonic waves, (D) capacitive power transfer, (E) tightly coupled inductive power transfer, and (F) loosely coupled resonant inductive power transfer

## V. ELECTRICAL VEHICLE TECHNOLOGY

Electric Vehicle (EV) technology represents a transformative shift in the automotive and transportation industries, driven by the need for sustainable and energy-efficient mobility solutions. EVs are powered by electric


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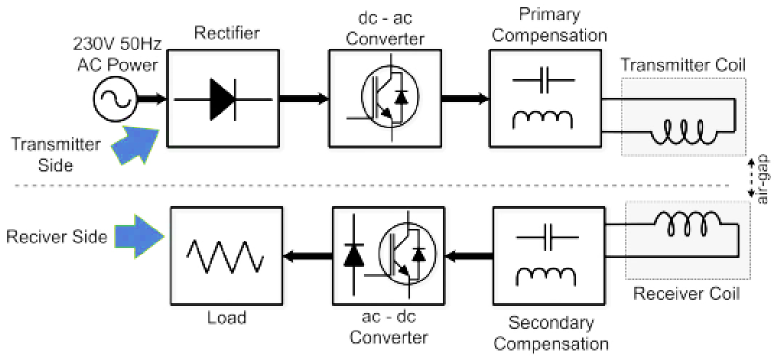
motors, which draw energy from rechargeable battery packs, fuel cells, or hybrid systems, replacing or supplementing traditional internal combustion engines (ICEs). This technology significantly reduces greenhouse gas emissions, decreases reliance on fossil fuels, and aligns with global efforts to combat climate change.

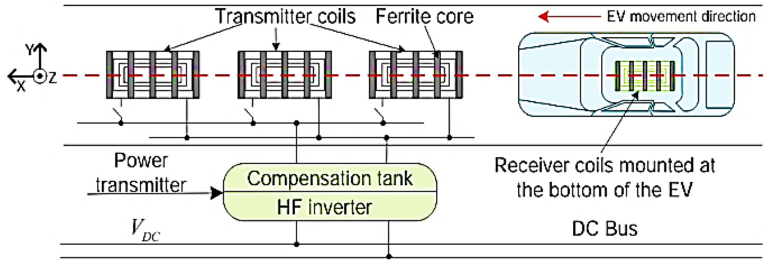
Key components of EV technology include:

- Electric Motors: Typically AC induction or permanent magnet synchronous motors, known for their high efficiency and torque.
- Battery Systems: Lithium-ion batteries dominate due to their high energy density, though solid-state and other advanced batteries are under development.
- Power Electronics: Inverters, converters, and controllers manage energy flow between the battery, motor, and other systems.
- Charging Infrastructure: Includes Level 1, Level 2, and DC fast chargers, supported by smart grid integration for efficient energy management.

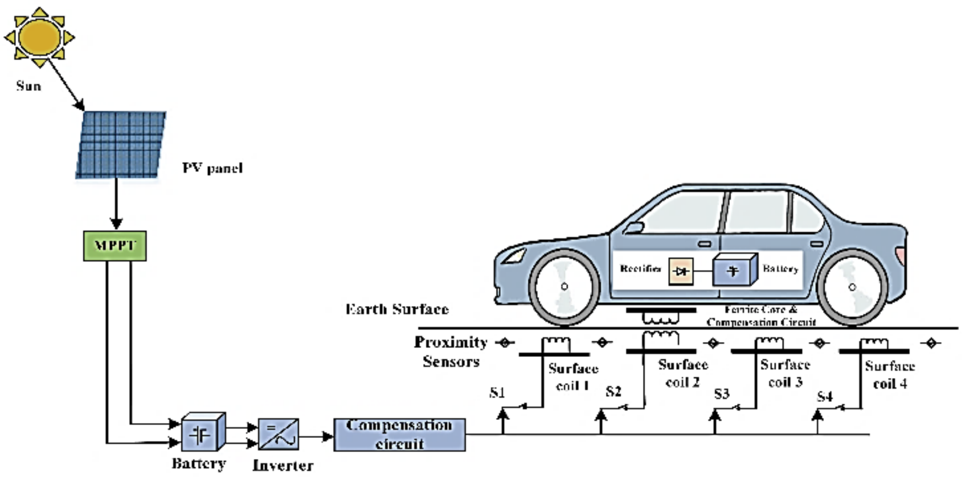
EV technology is rapidly evolving, with advancements in battery chemistry, energy storage, and autonomous driving systems. Challenges such as range anxiety, charging time, and infrastructure development are being addressed through innovation and policy support. Fig. 5. illustrate the proposed technology implemented in Dynamic Road Electrical Vehicle [37].




(a)




(b)




(c)

Figure 5 the proposed technology implemented in Dynamic Road Electrical Vehicle.
a) Transmitter and Receiver process, b) and c) installation system in road.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To achieve optimum performance in a WPT system, it is crucial to consider multiple factors that impact its functioning. In addition to transmission distance, misalignment tolerance and load variation tolerance are application-level requirements that also contribute significantly towards overall performance. Therefore, taking all of these aspects into consideration is essential for achieving optimal results from the WPT system. The swiftness of PTE and TP is heavily contingent on particular application demands. Their effectiveness diminishes considerably with greater transmission distance and alignment. A plethora of methodologies have been proposed to augment their performance, including devising compensation networks or circuits [38].

## V. 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<br>• 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 |

## V. **CONCLUSION**

The wireless power transfer of is considered one of the most attractive new technologies, and does have its place in future. Even though this technology is still not widely applied for high level of electric power, and large distance, there are symbols that the research in this direction is demanding, and has never stopped. Comparing the wireless energy transfer to the classical electrical energy transport by high voltage lines, a contactless technology is capable not only of cutting down the construction expenses of power lines, but also of providing unconventional solutions, e.g. capable of switching the highest power supplied to one point of the Earth to another point on the Earth in the shortest possible time. All this will save money, time, material, and natural resources.

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