Indian journal of
Engineering

Static and dynamic wireless charging of electric vehicles using inductive coupling

Sanchit Garg, Stuti Khare, Jaydeep Kshetre, Ritika Sahu, Kapil Thakur, Ankit Singh, Sandeep Bhongade

To Cite:
Garg S, Khare S, Kshetre J, Sahu R, Thakur K, Singh A, Bhongade S. Static and dynamic wireless charging of electric vehicles using inductive coupling. *Indian Journal of Engineering*, 2023, 20, e25ije1656
doi: https://doi.org/10.54905/disssi/v20i53/e25ije1656

Author Affiliation:
Department of Electrical Engineering, Shri G S Institute of Technology & Science, Indore-452003, Madhya Pradesh, India

Peer-Review History
Received: 05 May 2023
Reviewed & Revised: 09/May/2023 to 10/June/2023
Accepted: 14 June 2023
Published: 18 June 2023

Peer-Review Model
External peer-review was done through double-blind method.

Indian Journal of Engineering
pISSN 2319–7757; eISSN 2319–7765

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ABSTRACT

In last few years we saw a significant development in the Electric Vehicle Industry. With this we needed faster, safer and more reliable charging systems. Wireless power charging seems to be the best option for solving most of the charging issues. One of the best methods WPT is Inductive Coupling. This technique is applicable for static and dynamic charging both. By using high frequency transformers, we can change the frequency of the supply AC which could save us a lot of energy. This energy could be enough to charge vehicle's batteries. This technique will have a big impact on charging time issues and reliability of electric vehicles in long distance.

Keywords: Electric vehicle charging, wireless power transfer, inductive wireless charging, dynamic charging, CPT (Capacitive Power Transfer), filamentary coils, lateral misalignment.

1. INTRODUCTION

Transportation systems are a vital aspect of our daily routine, but they are also responsible for a significant portion of global energy consumption, with petroleum accounting for more than 90% of this energy usage. This dependence on fossil fuels results in the transportation sector being a leading contributor to greenhouse gas (GHG) emissions and air pollution (Morrow et al., 2010). To reduce this negative impact, it is imperative to adopt clean transportation technologies that minimize the reliance on the presently available fossil fuels and limit GHG emissions. Therefore, for reaching a constant plummet in our dependence on fossil fuel-based energy sources and to reduce its harmful and horrific impacts on the atmosphere, there is a strong need for alternative solutions such as EVs charged on renewable energy sources or greener energy sources (Eshani et al., 2004).

As the availability of fossil fuel is plummeting and future of transportation is undoubtably uncertain. EVs seem to be the single ray of light. Especially in India the 2030 target of the government is to generate 450GW of Power via renewable sources alone. So, we will greener and cleaner energy, as a substitute of fossil energy. We could easily consume this power using EVs (Kumar, 2023). But the major drawback with EVs is their unreliability and distrust of the mass on them. Most of these issues find their origin in EV

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charging and battery issues. Slow charging speed, scarce charging station and batteries of deteriorated qualities because of maximizing their limit beyond their capacities. Most of these issues could be solved by wireless charging (Collin et al., 2019).

Presently, electric vehicles (EVs) predominantly rely on lithium-ion batteries, which have a limited capacity that restricts the driving range. Increasing the battery capacity can improve the range, but this also results in a heavier and more expensive vehicle (Mak et al., 2013). The technology of wireless power transmission (WPT) eliminates the risks associated with electric shock, short circuits and sparks, while also enabling prompt response to user demands. The technology has the potential to substitute traditional plug-in interfaces with transmitters and receivers, enabling the transfer of power without physical contact through the use of electromagnetic or static waves, as in (Figure 1).

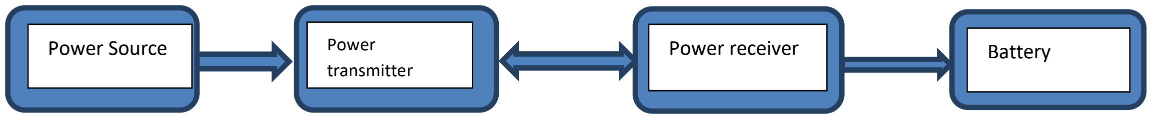

Figure 1 Basic structure of WPT system

Brown, (1996) classified the history of wireless power transfer into three distinct timelines, as documented in the literature. The initial period of wireless power transfer was associated with the contributions of Maxwell and Hertz. In 1873, Maxwell introduced equations describing the transmission of electromagnetic energy through free space. Later, between 1885 and 1889, Hertz conducted a series of experiments that confirmed Maxwell's predictions and the existence of electromagnetic radiation. The second phase of wireless power transfer is primarily linked to Nikola Tesla, who invented the Alternating Current (AC) and polyphase systems and aimed to transmit energy to any location on Earth by utilizing the planet and its atmosphere as a conductor (Brown, 1996).

According to Brown, (1996) the third and current phase of wireless power transfer (WPT) history began during World War II, when researchers utilized curved reflectors to focus energy into a small area. In his research, Brown, (1996) and Nambiar, (2015) examined the accumulation of energy using solar cells installed on satellites and then transmitted to Earth by beaming, with the beamed energy being converted into Direct Current (DC) upon arrival. The main drawback of wireless charging system is the time it takes in charging and the wireless charger produces significant electromagnetic interference (EMI), which can potentially result in safety hazards for humans and cause malfunctions in adjacent electric circuits.

Wireless charging for electric vehicles (EVs) can be performed in either a stationary or dynamic mode. Stationary wireless charging requires EVs to be parked in a specific location, but the development of this technology is limited by battery capacity and energy density constraints (Maglaras et al., 2014; Lukic and Pantic, 2013). On the other hand, dynamic wireless charging technology involves the installation of cable lines under the road surface, enabling EVs with receiver coils to be charged while in motion.

Wireless Charging Methods for EVs

Various techniques exist for wireless power transfer (WPT) (Mahesh et al., 2021), which are dependent on the technology and frequency level used for transmission. These techniques can be broadly classified into two categories based on the transfer mechanism: 1) Near-field or coupling and 2) Far-field or radiative.

Microwave Power Transfer (MPT)

MPT is a micro wave based WPT technology in a far- field context (Popovic, 2013). With minimal modifications, this approach can also be used in the radio-frequency (RF) range. The method involves a high-voltage DC generator that supplies a magnetron (a vacuum-based oscillator) to produce a microwave signal.

Optical WPT

This technique uses a transmitter that includes a laser diode to produce a light beam with a predetermined strength and wavelength. The electromagnetic waves that are created by optical wireless power transfer (WPT), sometimes referred to as laser-based power transmission are in the THz range, which implies that they exist as light. The laser diode is adjusted and the light beam's direction is managed by a beam director. The photovoltaic (PV) cell and rectifier make up the system's secondary side. The PV cell receives the light beam and transforms it into a power signal.

Inductive WPT

Inductive wireless power transfer (IWPT) systems operate on the principles of electromagnetic waves and function similarly to traditional transformers. In these systems, an Alternating Current (AC) on the primary side generates a magnetic field around the conductor (primary side coupler) based on Ampere's law. This time-varying magnetic field is linked to the magnetic coupler on the secondary side, which induces a voltage across the secondary coil in accordance with Faraday's law.

The induced voltage in the secondary coil is rectified to produce a DC power signal, which can be used to charge the battery. Tuning the frequency of the secondary coil to match the operating frequency can significantly improve the efficiency of the system (Wei et al., 2014). However, when operating in the radio frequency range, the limit of the air gap can extend up to 20 cm at the expense of lower efficiency (Sample et al., 2008).

Capacitive WPT

As a transmitter and receiver, two parallel metallic plates facing each other are used in electrostatic field-based systems, sometimes referred to as Capacitive Wireless Power Transfer (CWPT) systems, to create an equivalent capacitor for the transmission of power in the form of electrostatic energy. Inductive compensation, which involves adding extra inductors to the capacitor plates on either side, lowers impedance. This improves power transfer efficiency and permits gentle switching operation (Theodoridis, 2012).

Magnetic Resonance WPT

The Resonant Inductive Wireless Power Transfer (RIPT) system represents an improved version of the traditional IWPT, offering enhanced power transfer capacity, design and coupler coils. The existing grid voltage is converted into high-frequency AC (HFAC) using power electronics converters, which is then delivered to the coupler coil. The secondary coupler coil generates a voltage through linked magnetic fields, which is converted to DC power using power electronics converters and filter circuitry for use in charging the battery (Triviño-Cabrera et al., 2020).

We'll be further discussing IPT in this paper; an IPT system consists of two electrically isolated sides, with the transmitter side comprising a transmitter pad that is supplied with a high-frequency (HF) AC current. A compensation transmission network and HF inverter (10-100 kHz) are used to control the HF Alternating current, as in (Figure 2).

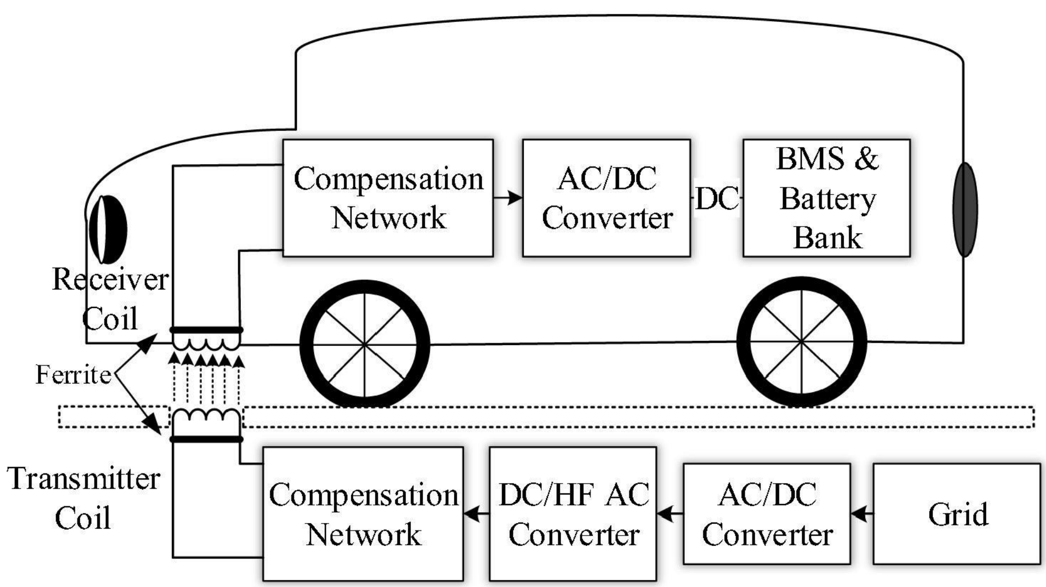

Figure 2 Basic block diagram of wireless charging system for EVs

The voltage is induced in the receiver coil as a result of the mutual coupling between the transmitting and receiving coils. Therefore, the relative position of the transmitting and receiving coils plays a crucial role in determining the transmission power and overall system efficiency (Mohamed et al., 2020).

2. METHODOLOGY

Three typical methods are used in DWPT systems for EV charging: Linked magnetic resonance, inductive power transfer and capacitive power transfer. IPT and CPT techniques have excellent efficiency but have a limited power transmission range. Because it can transmit more power at a faster pace than the CPT technique, the IPT method is preferred for charging EVs. The IPT technique is thought of as a specific case of coupled magnetic resonance, but with a medium range of power transmission. DWPT systems based on coupled magnetic resonance may operate at high frequencies up to 10 MHz and have a high-quality factor Q (Mi et al., 2016).

For wireless charging of a car there is fundamentally a very simple process. Current travels through the underground or overhead lines from the generating stastions. Then goes into the ground under the road. Their a system conditions it so that it is suitable for Electromagnetic induction. Then a coil under the road and the coil over the road form a transformer like structure to transfer power from underground line to car and process ends (Kallel et al., 2014; Mou and Sun, 2015).

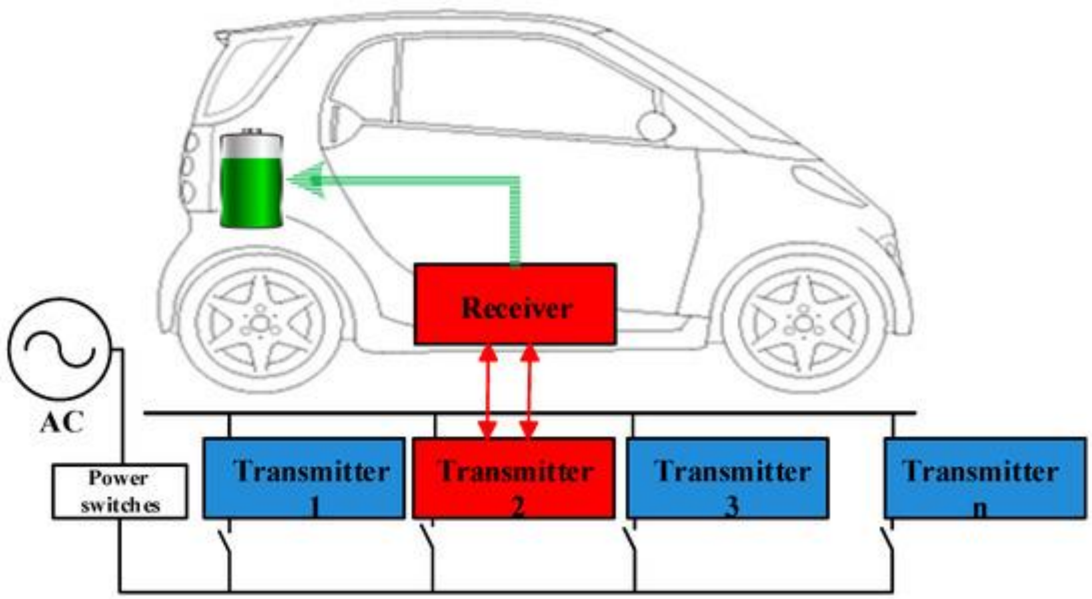

Figure 3 Application design of Dynamic Wireless Charging

Working principal of IWPT (Inductive wireless Power Transfer) is same as that of Transformer. As in Figure 4 AC current creates a time varying magnetic field on the primary side and it gets linked with secondary side. Power Converters are employed on both sides for Voltage regulation and rectification purposes (Mahesh et al., 2021).

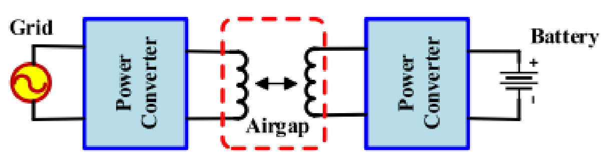

Figure 4 Diagram of Inductive WPT

But the details in between are most importanat. What power should we give. In which form, frequency etc. And most importantly proper coupling becomes the issue.

Here, In our model we have 4 important components

Road Rectifier

High Frequency Inverter

MI Coils

Car Rectifier or charging system

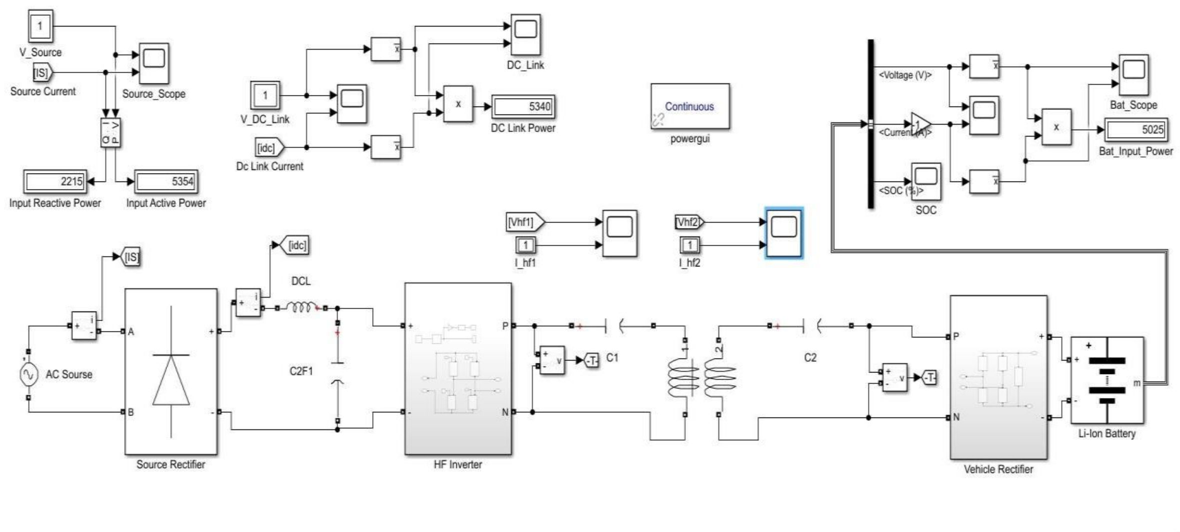

Figure 5 Simulation of Proposed System

Source supplies to the rectifier, which converts the power into Dc. Then it is filtered and fed into High Frequency Inverter which converts it into High Frequency AC. Then this HF Power is transfered from ground to car by two mutually coupled inductive coils. Transferred power is utilized by car battery charger.

Now the first question that arises is why high frequency? Why is it that we can't just feed the coils with our normal supply? We'll avoid a lot of difficulty this way. Thus, the following inquiries come up... Why Use High Frequencies? Impact of repetition at a certain flux, a coil's EMF rises with frequency. Transformers can be physically smaller by being run at higher frequencies since a particular core can handle more power without becoming saturated and fewer turns are required to attain the same impedance (Kallel et al., 2014).

When the switching frequency is doubled in a design, the flux density for a specified number of transformer turns is halved. Therefore, the designer has the option of reducing the core size, the number of turns or both proportionately. The first advantage of operating at a higher frequency is size. The smaller the transformer can be for a given power rating, the higher the frequency. Second, because the transformer is smaller, less copper is required, which lowers losses and increases the transformer's efficiency. Therefore, by reducing the number of wires turns of primary and secondary, you may raise the frequency while reducing the coil size and volt-seconds.

As in Figure 6, we made the prototype of the simulated model using presently available modules. For prototyping we used 12V battery supply. We employed KA3525 SMPS Controller based AF198 UPS module for providing power to the transmission coils. It had full wave centre taped Inverter formation. Each transmission coils had 20 turns. 20 each for both polarities and car had 60 turns. Full wave bridge rectifier was used in car for conversion of input into DC. In the car below L298n motor driver was employed in the car for motor controlling, Atmega microcontroller for processing and HC-05 as Bluetooth receptor.

We can eliminate the primary rectifier and directly feed the inverter with DC. During Implementation, a very long network of lines would be required to be laid we could easily supply DC power to them directly. This will save the rectifier losses. By 2030 India is planning to generate 450 GW of Power through renewable sources of energy. Most of this power could easily be in DC form, hence no losses in conversion. DC transmission will also have some other benefits, like;

Small conductor size

No Corona losses

Skin effect

No Frequency Issue

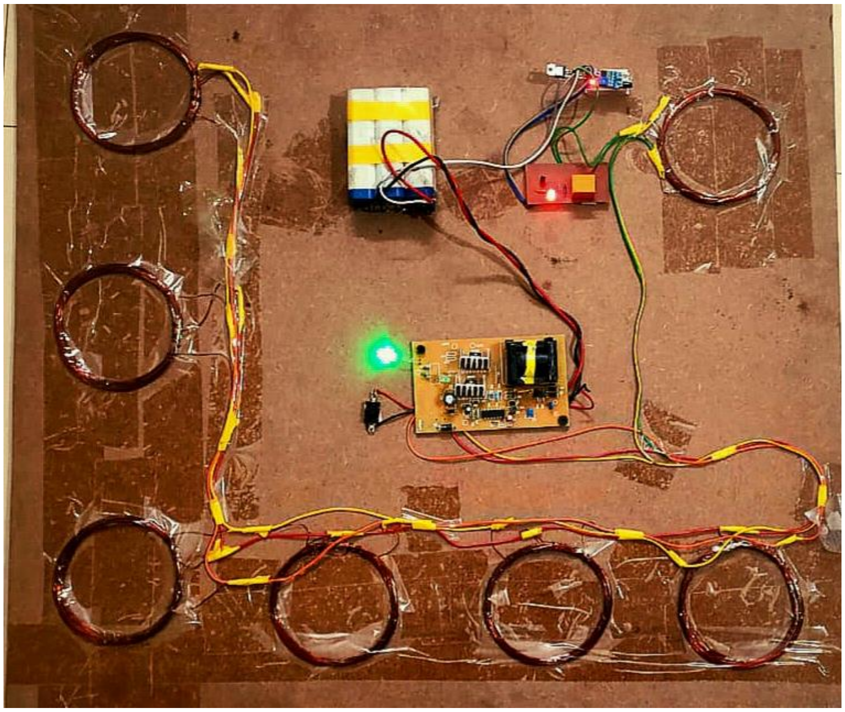

Figure 6 Track for wireless inductive charging

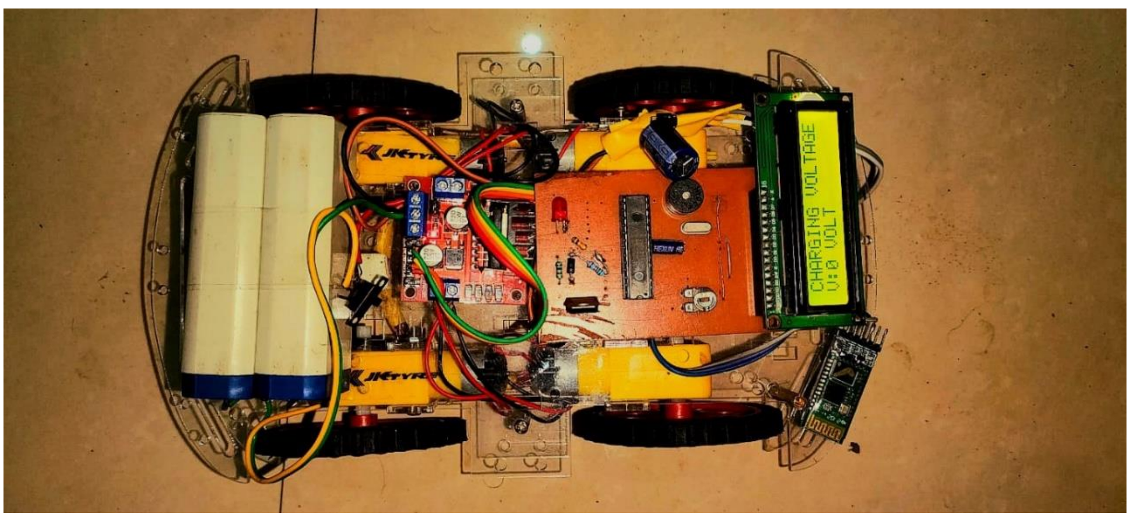

Figure 7 Bluetooth Controlled Induction Charged Car

3. FORMULATION

It was discovered that the efficiency greatly relies on the transmitting and receiving coil designs. Specific factors that have a significant impact on both self and mutual inductances include coil shape, material, shielding and size, as well as lateral and axial displacements between primary and secondary inductors. There are various widely used techniques to calculate a coil's self-inductance L and its quality factor Q, which were extensively documented in (Greenhouse, 1974; Yu and Han, 1987).

Since the inception of the idea various shapes of coils have been researched. However, Luo and Wei, (2018) claimed that circular coils provide highest efficiency and performance. Use of Circular coils leaves us with the challenge of calculation of mutual inductance between the coils. Most of our literature only dealt with axially symmetrical coils but in the case of dynamic charging that won't always be the case.

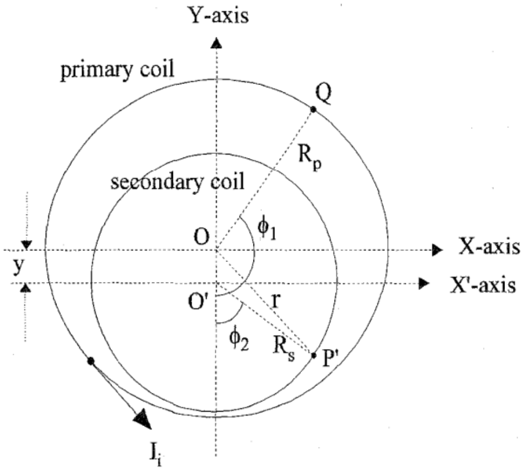

Figure 8 Front View of two filamentary coils

For these calculations various methods have been proposed. One of them is calculation with complete elliptic integrals and mesh-matrix method (Kim et al., 1997). It is a highly complex method with rigorous calculations involved. Originally it was Grover, (1944), who developed general method for determining the mutual Inductance between two inclined circular filaments. But now with the development of more powerful calculation tools faster and easier methods have been developed (Babic et al., 2010). Today we have computer aided tools which can perform these tasks in no time.

The efficiency and performance of the system is highly dependent on the coil radius. Figure 9 shows that the coefficient of coupling (k) and mutual inductance (M) of the WPT system with various coil radii decrease as the distance increases. Each WPT system's Mutual Inductance and coupling coefficient values rapidly decline with increasing transfer distance and the values with radii of 5 and 25 cm have lesser values. Before the transmission distance surpasses 20 cm, the values of M and k with a radius of 15 cm are bigger (Li et al., 2019).

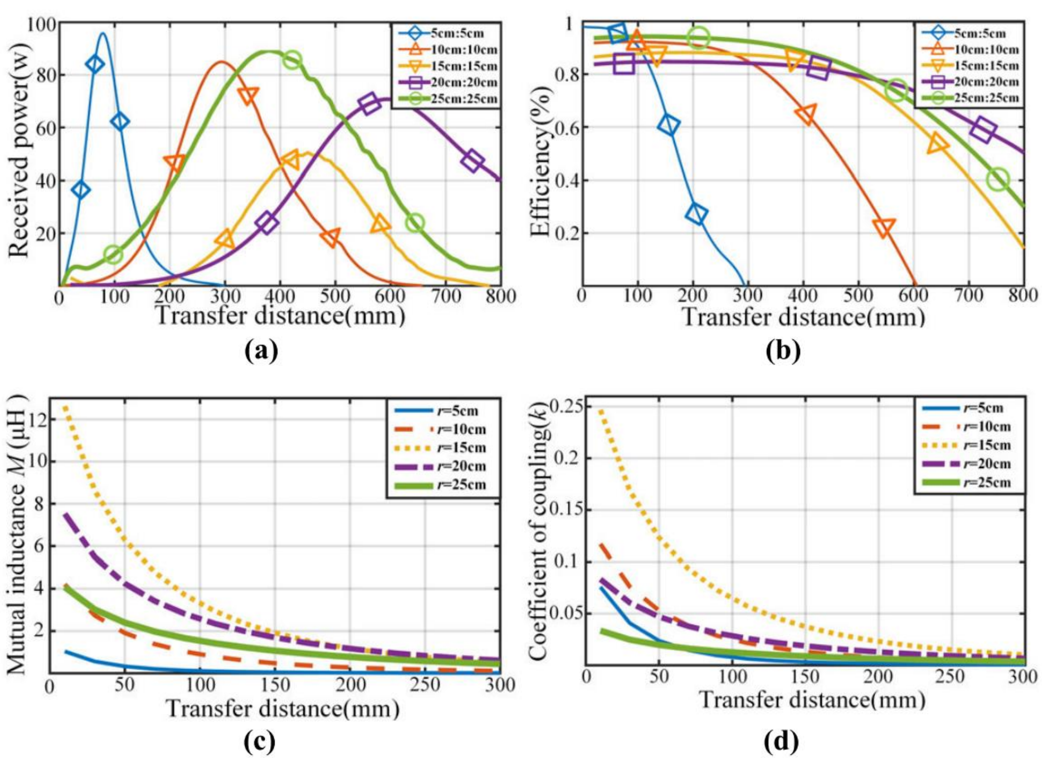

Figure 9 Simulation results of Power, Efficiency, M and k

In Rakhymbay et al., (2018) change in M with change in distance between two coils had been investigated. Figure 10 depicts how the mutual inductance of the circularly formed coils is affected by the distance y. As can be observed, when this distance is zero, the mutual inductance reaches its maximum value of 22.100 H. The mutual inductance reduces as the distance between two transmitter coils grows. When the displacement between the transmitter coils is adjusted to 160 mm (or 50% of the coil's diameter), the mutual inductance becomes almost negligible.

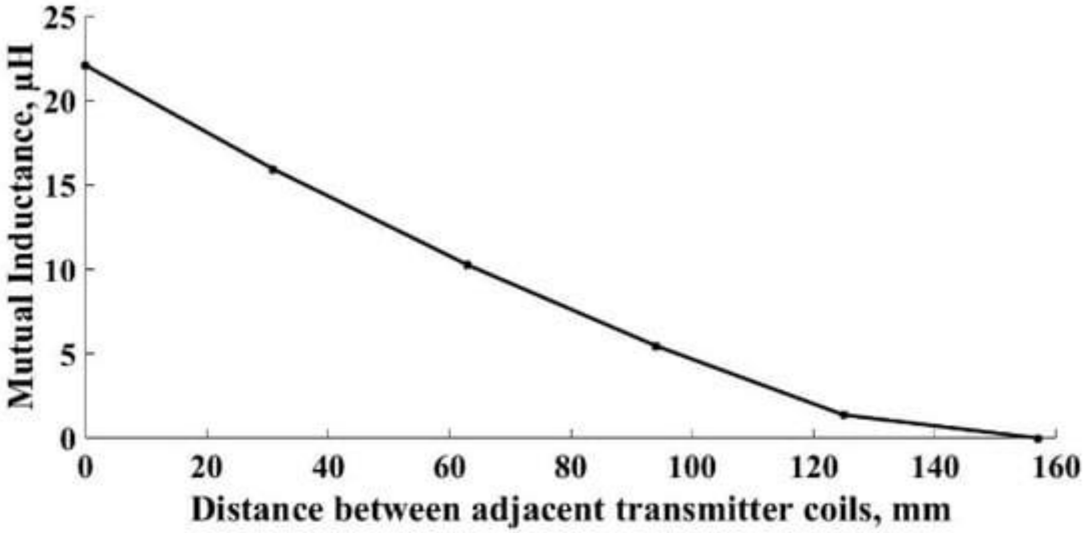

Figure 10 Effect of displacement between transmitters on the mutual inductance for circular shaped coils

Figure 10 is applicable for coaxial coils. But in dynamic charging coils misalign with the movement of the car. A generalised case is in (Figure 11). With the movement the M constantly varies and the result of the same is in (Figure 12).

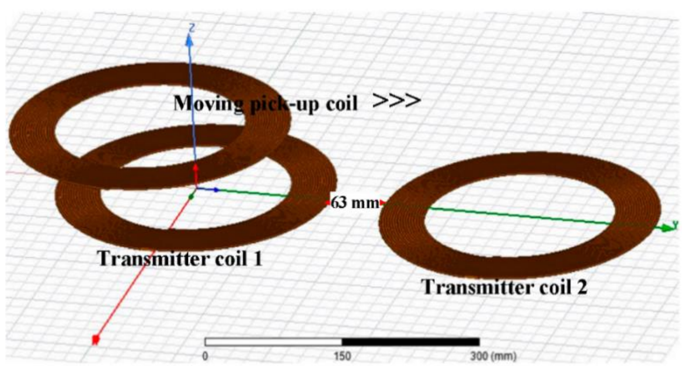

Figure 11 3-D view of circular shaped coils

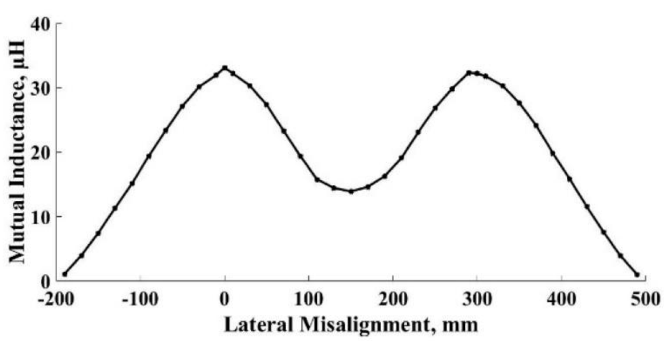

Figure 12 Plot of mutual inductance change with respect to lateral misalignment

Distance between the transmission coils is a big differentiator when it comes to system efficiency. Continuous working of these coils causes power wastage. Selective switching of these coils can increase the efficiency of the system. Proper separation between two consecutive rows of transmission can improve the transmission stability and reduce the fluctuations (Zhang et al., 2016).

4. CONCLUSION

The dynamic and static wireless charging is poised to play a significant role in electrification of transportation.

These WEVCSes provide an easy, quick and hands-free way to charge electric vehicles with the same effectiveness and rapidity as conventional AC chargers which require physical contacts.

Wireless charging of electric cars employing WPTs technologies has been examined in a wider context and its many varieties have been researched.

Road transport might be revolutionised by electric car charging that is dynamic, safe and high-performing. The question of the hour is how to combine capacitive and inductive WPT to possibly allow this transformation. Both technologies have enormous potential for R & D, particularly in the fields of high-frequency power electronics and near-field coupler design.

outcomes of Research on the health implications of prolonged exposure to weak electric and magnetic fields has not yet been completed and developing techniques to identify live things and foreign items near WPT systems would be a significant task. Techniques to choose the best charger power levels and spacing for economy are also required.

Techniques for integrating WPT technologies into roads and methods for analysing the effects of deploying large-scale WPT systems on the electric grid.

Dynamic electric vehicle charging methods are the cornerstone for wirelessly powered biomedical implants and amazing supersonic hyper loop transportation.

Ethical issues

Not applicable.

Informed consent

Not applicable.

Funding

This study has not received any external funding.

Conflict of Interest

The author declares that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

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