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Two Receiver Coil Based Wireless Charging System with Economic Analysis for Electric Vehicle

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ABSTRACT

Electric vehicle systems are based on various modules that should guarantee the high power and stability of the vehicle on the track. The majority of these components are related to the charging mechanism. In this concern, dynamic wireless power transfer is a practical method to solve electric vehicle range anxiety and decrease the cost of onboard batteries. The constant research to eliminate wires in our everyday life has been going on for years now. When the telephone was first invented, wires were needed to transmit communication between parties. Now, wireless power transfer is very favorable for society. Wireless power transfer is already being implemented in today's world in some cases, but it is not part of the "mainstream". Various wireless power transfer (WPT) methods for electric vehicles charging are conferred in brief with some scientific examples and approaches. Inductive wireless power transfer is used here. Finally, some future points are mentioned in brief. Wireless recharging has long been common with pure electric vehicles and is designed to permit charging even when the vehicle is in motion. However, it is hard to analyze this method since its operating philosophy is difficult, particularly with the existence of several variables and parameters. Also, the state of the vehicle, whether it is in motion or not, defines some parameters such as the vehicle speed as well as the sizes and dimensions of the coil receivers. This paper presents a novel method to increase the performance of the dynamic wireless recharge system. In the proposed system, receiver coils have been added to maximize charging power by offering a dynamic mathematical model that can describe and measure source-to-vehicle power transmission even though it is in motion. In the proposed mathematical model, all physical parameters describing the model were presented and discussed. The results showed the effectiveness of the proposed model. The simulation results are obtained by providing two coil receivers under the vehicle.

Keywords: *Coils, Electric vehicles, Mutual inductance Mathematical model, Wireless charging systems*

I. Introduction

The scarcity of fossil fuels, as well as environmental concerns, point to new energy challenges. Overall, the traditional transport industry absorbs half of the world's oil production, resulting in massive emissions [1]. Taken together, these issues have an impact a new concept of "wireless electric vehicles (WEVs)," which is coined by the author, is introduced, and wireless power transfer (WPT) technologies including inductive power transfer (IPT) and capacitive power transfer (CPT) are explained. Then, introduction to electric vehicles (EVs) is briefly provided. On the automotive industry and are also important for the research and development of electric vehicle (EV) technologies as a solution to these problems. Electric power storage is also one of the main research topics these days [2,3]. Technological advances in electrical energy storage have culminated at a sufficient mass density of energy and power to meet automotive needs [7–11]. The biggest drawback of these storage technologies is their high production expense [4,5]. Nowadays, researchers are attempting to build good storage solutions and enhance their charging strategy and reliability to reduce the overall cost of the vehicle. Many technology storage systems have been developed in this area and integrated into the power train system, resulting in positive performance [6,7,8].

The perfect control of the main electrical engine, or the perfect control of the battery recharge system, helps reduce the vehicle's power system's loss [9]. In [10], the authors have investigated A detailed mathematical model explaining how the recharging method operates is presented. It also provided useful findings demonstrating the effectiveness of the physical equations used. It has been accomplished in two ways: first, when the vehicle is in stop mode, and second when the vehicle is in motion. This analysis also puts two wireless receivers in the car for testing, and the results obtained show how useful this proposed model is. As the vehicle's speed changes, the positioning of the receiver with respect to the transmitter was investigated, and the consequences of the vehicle's autonomy were addressed and discussed. These findings are compared to current methodologies. Thus, the results revealed in this paper demonstrate the effectiveness of having two receivers underneath the vehicle. Experimental examination of the proposed model using a prototype has verified the obtained results.

This manuscript is organized as follows. Following the introduction, the second section is dedicated to the definition of the wire- less charging device. The third section clarifies the mathematical model and the objectives of the work. The fourth section shows and discusses the simulation findings, and the results. Then, the conclusions are given in the last section.

II. The Needs for Wireless Electric Vehicles

Why most people are still not daily driving an electric vehicle? As a customer, I feel that EVs are still very expensive and inconvenient compared with existing conventional internal combustion engine (ICE) vehicles. The structure of an EV is relatively simple and easy to have maintenance; however, it is not cheap and heavy because of its onboard batteries. Still, most EVs have much shorter driving distance for a full charge compared with ICE vehicles. Therefore, it can be said that EVs have not been widely commercialized because of battery and charging problems. Remark that battery EV (BEV) had been commercialized since the late 19th century, which is about 20 years earlier than the commercialization of ICE vehicles. The original BEVs disappeared from markets because the battery was too heavy, required long time to recharge, had a relatively short driving distance, and was expensive. Amazingly, these problems of battery still exist compared with current ICE vehicles nevertheless the drastic improvement of EV batteries. The expensive price of EVs is mainly due to battery price. The improvement of battery is very slow and does not follow the Moore’s law because it is not governed by electronics but governed by chemistry. Another major obstacle for commercialization of EVs is the charging problem. Even though innovative batteries will become available, still we have charging problems. We should have 30 C (1 C corresponds to the rated power or energy capacity of a battery for an hour) charging capacity in order to recharge an EV in 2 min in case we have such a good battery. For a 50 kWh battery example, which is common to a long distance EV now, we should have at least 1.5 MWpower rating charger and power distribution facility to support it. In practice, we should recharge an EV frequently in order to avoid the battery empty. If a cable charger is used, it is very inconvenient to plug in and plug out daily, and it is potentially dangerous to deal with the connector of a cable manually under wet conditions. Currently, a quick charger can recharge an EV battery up to 80% within 20 min, which is still too long time for customers accustomed to 2 min refueling. The first solution is to adopt the road-powered EV (RPEV) [11,12] or online electric vehicle (OLEV) [13-18], which does not rely on the battery but gets power directly from roadway power supply rails. This charging method is often referred “the dynamic wireless charging” or simply “dynamic charging” because power is delivered to an EV when it is in motion. An RPEV has a battery for temporary energy storage, but its size is a few times smaller than a BEV, which is not an obstacle for commercialization. RPEVs have replaced conventional conductive EVs that have wearable pantographs and cumbersome power lines. The second solution is stationary wireless charging [19-23], often called as “static charging,” by which the inconvenient and dangerous cable charging problems can be completely solved. The stationary wireless charging can be applicable to both plug-in EVs (PHEVs) and BEVs. Of course, the slow charging problem cannot be directly solved by the wireless charging, and it must be mitigated by other means such as “interoperable road-powered supply rails [24],” on which this stationary wireless charging is also made together with RPEVs. I would like to call the stationary and dynamic charging EV solutions as wireless EVs (WEVs), which embrace WPT and wireless communications for EVs. As EVs evolve to information platforms in the future, wireless communications will be essential to every EV, which results in ubiquitously connected cars. WPT will make the WEV complete.

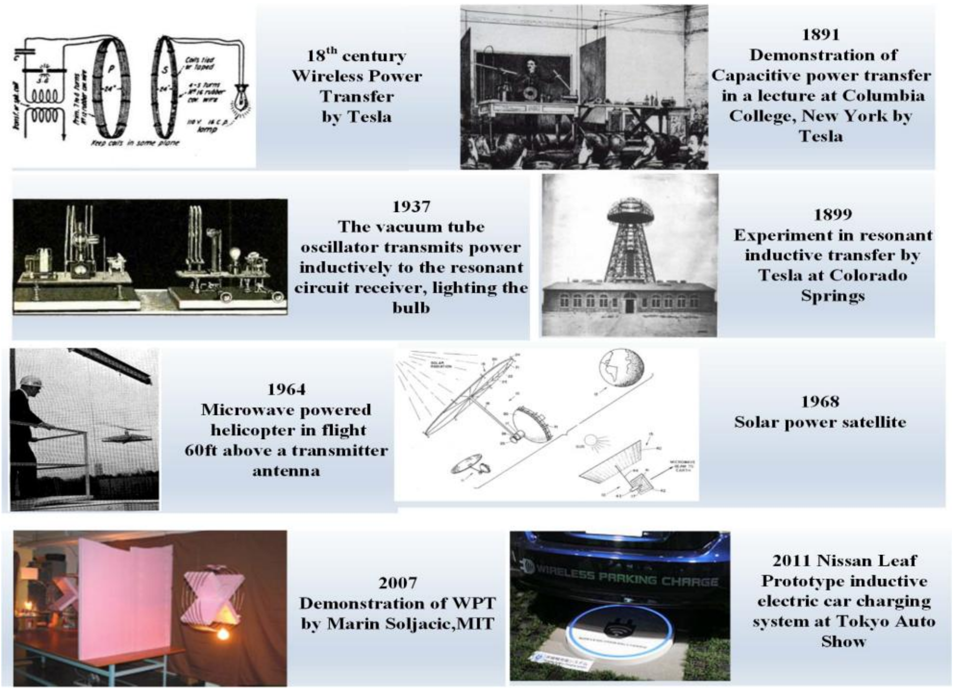

Fig.1. Timeline diagram of development of the WPT

III. Wireless Charging Methods for EVS

In Figure 1, classification of wireless charging is shown. The electromagnetic fields produced by an antenna device (transmitter) by a moving electric charge are divided into two regions: (a) Non-Radiative region or Near field (b) Radiative or Far field region. In this section, only wireless power transfer methods for wireless charging of EV are discussed.

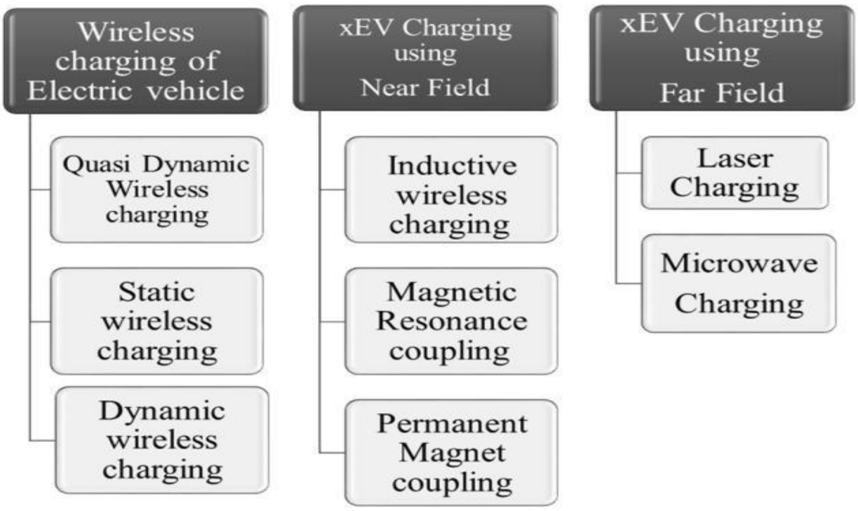

Fig.2 Types of Wireless Charging and Different EVs Charging Methods

A. Wireless Charging using Near Field Wireless Technology

Near field means the energy remains within a small region of the transmitter. The transmitter doesn't emit power if there is no receiver range. The range of these fields is very small and depends on the size and shape of the transmitter and receiver. In the near field region, the electric and magnetic fields are separate, hence power can be transferred through the electric field via electrodes and the magnetic field via coils. Power decays by (1/r3) factor, with an increase in distance (r), and energy remains at short distance between transmitter and receiver. Electric field WPT can transmit power to a very less distance due to a very high decay rate, but magnetic field WPT can transmit power at a distance more than electric because of the ability that magnetic field can penetrate the wall, furniture, and people.

1) Inductive Power Transfer (IPT) based Wireless charging

IPT based wireless charging uses the principle of magnetic induction to transmit power without a medium [8]–[11]. It is based on Lenz's Law and Faraday's Law where a time variant current in a conductor creates the magnetic field around the conductor, and a secondary loop (receiver) gets voltage generated due to time variant magnetic flux [13]. The receiver is connected to the load which closes the circuit to transfer the power without wires. In 1819 H. C. Oersted had discovered the concept of generation of the magnetic field around the current carrying conductor and was the beginning of electromagnetism. Ampere's Law, Faraday's Law, and Biot-Savart's Law were the results of the property of the magnetic field. With the introduction of Maxwell's equation in 1864, the relationship between electric and magnetic fields was developed. Later in 1873 J. C. Maxwell combined the study of electricity and magnetism in his book, "A Treatise on Electricity and Magnetism". These are some basic inventions which lead to the concept that electricity and magnetism are derived from the same forces and established a modern theoretical foundation of electromagnetism and the beginning of wireless transmission of electricity. In 1888, H. R. Herts had transmitted the electricity over a minimal gap using an oscillator by connecting it with induction coils. In 1894, Hutin Le-Blanc effectively patented for improvement in electric traction for a vehicle using wireless power transfer. In 1971 Prof. Don Otto, from University of Auckland, developed a small trolley bus based on WPT and patented on it. At the same time in California USA, PATH (Partner for Advanced Transit and Highways) Project was instigated. In 1982, PATH performed a successful experiment of running an EV at frequency 400 Hz for 50-100 mm air gap distance with a 60% efficiency. In the 1990s, Groupe PSA (informally PSA; known as PSA Peugeot Citroën from 1991 to 2016) directed a scheme named Tulip (Transport Urban, Individual et Public) in France, and Wampfler Co. in Germany established an IPT system. In 2009 Showa Aircraft Co. Japan developed the IPT system of 30 kW power for EVs at 22 kHz frequency for an approximate air gap of 14 cm with an overall efficiency of 92%. Wireless Power Transfer used for communication requires minimal power, hence electronic objects, such as a RFID system, can work efficiently [15]. However, for applications such as running appliances, a high power level may be required. The IPT system gets upgraded with just resonance and termed as coupled magnetic resonance, i.e. coupling at resonance.[23]

2) Coupled Magnetic Resonance (CMR) based Wireless Charging:

Magnetic resonance was developed by MIT USA and consists of transmitting and receiving coils and capacitances for the purpose of compensation and power factor correction, finally creating a resonant condition for maximum power transfer. In Korea, On Line Electric Vehicle (OLEV) is running based on resonance coupling and using dynamic wireless charging of EVs. The OLEV is among the top 50 inventions of 2010 worldwide. Commercialization of OLEV is in progress. Global motor companies, such as Tesla, Toyota, Nissan, and so forth, are employing magnetic resonance coupling for WPT. Various research are working on two major aspects, (1) as magnetic resonance coupling by Tokyo and Nagano Japan Radio Co. Ltd., and (2) is electric resonance coupling for EV by the Toyohashi University of Technology. The University of Tokyo, in collaboration with Nagano Japan Radio Co. Ltd, has developed a WPT system for EVs based on resonance coupling and transmitted a power of 1kW at the back side of the wall at 13.56 MHz frequency at a distance of 30 mm, with an efficiency of 88%. CMR technology follows coupled mode theory which can transfer power to a significant distance. In [16] C. Wang et al developed a dynamic WPT system with 90% efficiency for the range of 1 meter and developed the system having two antennas which resonate at the same frequency in MHz range.

3) Permanent Magnet Coupling based Wireless Charging

The University of British Columbia has developed a method which relies on the “magnetic gear effect,” where a permanent magnet (Neodymium permanent magnets) acts as a magnetic coupler [17]. The primary side permanent magnetized rotor rotates the secondary rotor with the same speed, known as synchronous speed. A permanent magnet WPT prototype was developed by which transfers the power with 81% efficiency at 150 Hz frequency for 150 mm distance. There are many drawbacks to this system because of vibrations and noise of many mechanical components. Another major problem with this scheme is alignment and maintenance issues. For EV charging application, this method is not suitable due to the large system, low efficiency, mechanical rotation, etc. In [17], Weilai Li has stated a power flow diagram (Figure 5), mechanism of wireless power transfer and its implementation, and have proposed three types of magnetic gear. Figure 5 (e) shows the magnetic gear orientation. PMC requires a large sized Permanent magnet for high power transfer. In most of the wireless charging methods, misalignment is a critical issue, but in the case of PMC wireless charging, misalignment is not a big issue.

B. Wireless Charging Using Far Field Wireless Technologies

Far field technology involves three major steps to process: firstly, conversion of electrical energy to radio frequency, microwave or laser; secondly, transmission of converted energy to another through space; and thirdly, collection of power at destination and conversion into electrical energy. There are mainly two types of far field power transfer technologies 1) microwave or radio wave and 2) laser. Below, a brief literature survey is given on these technologies for wireless power transfer.

1) Wireless Charging using Microwave and Radio Wave

WPT using far field technology is the oldest method because, initially, it was developed for wireless communication. In 1904 Nikola Tesla was the first to transfer power using radio waves at 150 kHz. In 1964, W. C Brown invented and glided a wireless helicopter without a battery, using 2.45 GHz magnetron. R. Dickson realized Maximum Power Transfer with parabolic antenna and Klystron for a distance of 1.6 km at frequency 2.45 GHz, transmitting power of 450 kW in Goldstone, USA . After the 1980s, development of WPT was amplified in Solar Power Satellite (SPS) research in Japan. Most of the work is conducted in Japan by Kyoto University.Between 2003 to 2008, N. Shinohara worked together with Nissan Motors and developed a road to vehicle WPT system at 2.45 GHz, using slot antennas and magnetron to reduce the cost and microwave to charge the battery at an efficiency of 76% [104], which is high and appropriate to realize charging of EVs wirelessly using the microwave. They developed a GaN (Gallium Nitride) Schottky diode to rectify the power in order to increase the efficiency and reduce the charging time. After 2006, Mitsubishi Heavy Industries, Ltd. directed a project on MPT for EVs with Daihatsu Motor Co. Ltd., Fuji Heavy Industries, and Mitsubishi Motors Co in Kyoto University Laboratory. Due to the directional behavior of the microwave, it can be used for long distance power beaming. The previous microwave was utilized in the transmission of energy to and from a solar powered satellite to Earth. Far field technology includes a laser to transmit very high power to a focused location.

2) Wireless Charging using Lasers

Laser technology can transmit power to a considerable distance, but with limited efficiency. EV charging is not very feasible using a laser. Since the mechanism of transfer of power using laser is also a complex phenomenon, where power can be transferred by converting electrical current into a laser beam, the beam is focused on the photovoltaic cell. Since the power transferred at the receiver end, hence it is known as power beaming. Electromagnetic radiation spectrum for the laser is closer to the visible region of the spectrum. For this application, extraordinary photovoltaic laser power converters are used which are optimized for light conversion of monochromatic light. Extreme precautions are required to increase efficiency; any miss directionality of the laser beam could cause danger to life and loss of energy.

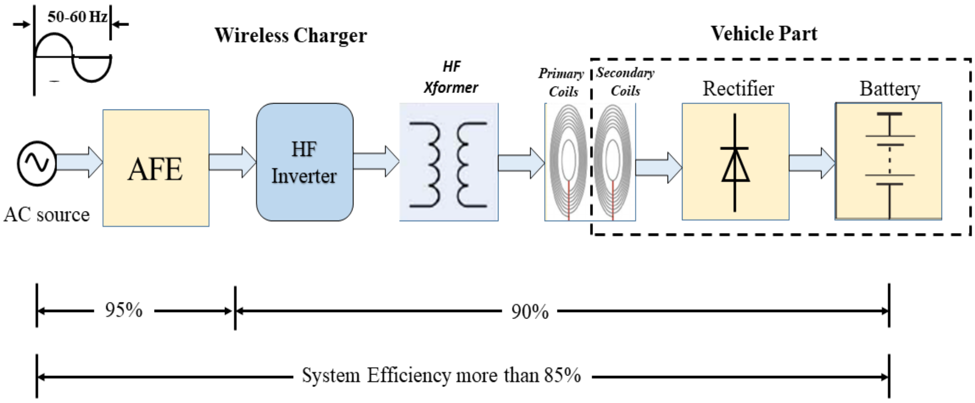

Fig.3Block Diagram of a Wireless Charging System

IV. Dynamic Wireless Charging

Dynamic wireless charging charges the EV while driving. There is no need to stop and wait for charging. This concept was given by J. G. Bolger et al in 1978, in which the energy is transferred to the vehicle while driving. Development of Dynamic Wireless Charging is led by a research team at KAIST since 2009. Many major problems have been solved by this project such as continuous power transfer, high frequency current controlled inverter, and different EMF characteristics. Choi et al have given a beneficial survey of OLEV. Dynamic wireless charging overcomes most of the problems of the Electric vehicle, such as range anxiety, battery size, battery cost, etc. Existing models of dynamic wireless charging are based on inductive the wireless power transfer method. This technology relies on the magnetic coupling existing between the coils installed under the road surface and supplied with a high-frequency current generating electromagnetic field, and a pickup coil fitted in the EV. Figure 3 shows the block diagram of DWC. The on-road coils constitute a track that continuously transfers power to the pickup coil. The power captured by this coil, after being suitably conditioned, charges the EV battery. Low power wireless systems have also been developed to transfer power to a device with an embedded pickup coil and over a surface containing a transmitter coil and many resonators, but these systems are not suitable for EVs since they move along a path. There are two types of the track which have been devised for the DWC systems: stretched and lumped differentiated by shape. A stretched track is constituted by a transmitter coil whose dimension is considerably longer than the pickup coil; a lumped track, instead, is built up with a string of coils having dimensions comparable to the pickup coil. Research on the stretched tracks has led to the development of the OLEV (On-Line Electric Vehicle) prototype by KAIST, while research on lumped tracks has been initiated by a research group at Auckland University. For the lumped track, only a portion of the track has the transmitter coil which is coupled and hence, supplies power to the receiver coil. This supply solution, commonly termed as segmentation, is useful both to increase the DWC efficiency and to avoid the radiation of electromagnetic fields from the non-coupled track portions. Previous works on coil sizing have mainly focused on dimensioning the coils and on analyzing the effects of misalignment between the coil axes for static wireless charging systems. Regarding DWC systems, some works have focused on evaluating the optimal length of the coils in a stretched track or have dealt with lumped tracks made of coils deployed side-by-side

1) Fundamental Principle of Wireless Charging

Fundamentals of wireless power transfer are similar to a transformer application, and coupling between primary and secondary coils is through the air as the core. Simple analysis of wireless charging with separate compensation network of coil is shown in Figure 3, neglecting the coil resistance and magnetic losses. The calculation of exchanged complex power from Lp to Ls. From Lp and Ls we can get the exchanged complex power as follows:

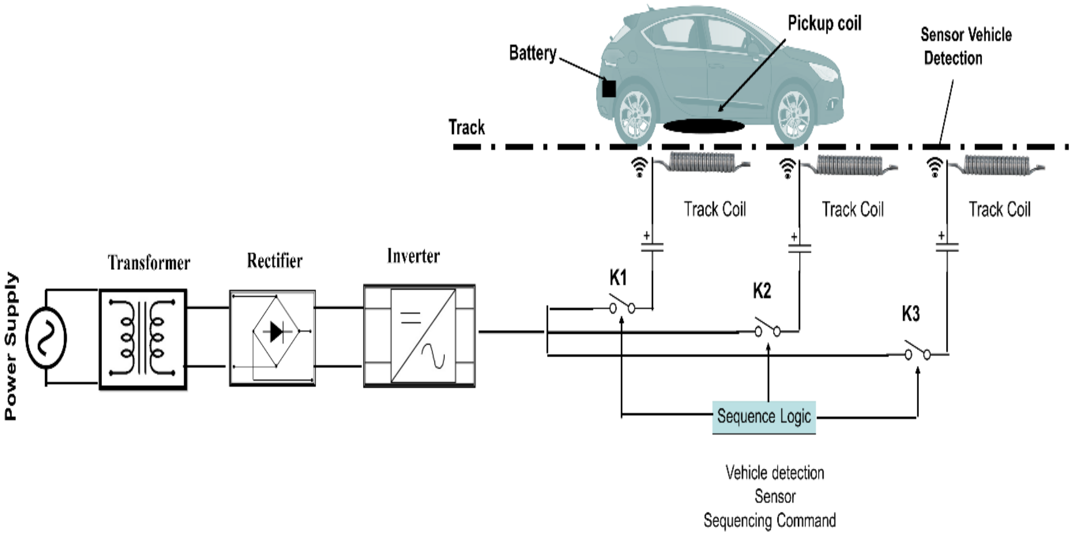

Fig.4 Block Diagram of Dynamic Wireless Charging

Quasi-Dynamic Wireless Charging

Quasi-Dynamic wireless charging of electric vehicles (EVs) will be easily feasible when both SWC and DWC would be available all over the place. In Young Jae Jang et al have defined QWC as the vehicle charging when it is moving slowly or stop and go position. They have compared and performed cost analysis and developed optimization models for each system on an initial investment of SWC, QWC and DWC for the public transportation system. This is basically to design such a system that is an auto detective for the condition of charging. If there is dynamic charging available, it can start charging wirelessly on the dynamic track, but if the dynamic track is not available, the same system manages automatically to charge the EV in a stationary position. This system will not only take the advantages of DWC but simplify the control complexity, a significant reduction in the cost of the infrastructure system and an increase in the alignment of the system. Implementation of QWC at traffic signals could a very beneficial where each stopping lane will be installed with primary power pads, each power pad could be controlled with an individual converter or few pads with a single converter. The activation and deactivation of the pads could be controlled with the controller coupled with traffic light controllers. A. Mohamed et al have used the above concept to design a model of QWC and performed a feasibility study for validation. Three different scenarios were implemented for analysis (i) EV charges at a fixed power level at interconnections resulted in an increase in driving range, increase in the efficiency. (ii) A variable power charging profile is applied (iii) V2G and G2V operations were tested. They have achieved very prominent results for its implementation. This method of charging would be very much beneficial in bus systems. Since buses stop at regular distances, hence on bus stands, static charging coils can be fixed inside the road. A. Ahmad et al have proposed a QWC system at traffic lines when vehicles stop at traffic signals. KAIST OLEV system as described on their website and videos as dynamic charging at low power levels during driving conditions and high power charging at bus stops, which can be considered as quasi-dynamic charging

Table1. Classification and Comparison of Different WPT Technologies for EV Charging

Energy carrying medium	**Technology**		**Power**	**Range**	**Efficiency**	**Comments**
Electromagnetic field	Near field	Traditional IPT	High	Low	High	Range is too small for EV charging.
		Coupled Magnetic Resonance	High	Medium	High	Capable for EV charging
	Far field	Laser, Microwave,	High	High	High	Need direct line-of-sight transmission path, large antennas, and complex tracking mechanisms
		Radio wave	High	High	Low	Efficiency is too low for EV charging.
Electric field	Capacitive power transfer	Low	Low		High	Both power and range are too small for EV charging.

Mechanical force	Magnetic gear	High	Medium		High	Capable for EV charging

V. EV Wireless Charging Standards

As wireless charging is becoming a pioneer in the field of EV charging, standardization is required for reliable commercialization of high voltage and high power WPT for EV charging. Standardization includes the safety criteria, efficiency, electromagnetic limits, and interoperability targets, along with test setup for getting wireless charging. Ubiquity is a very important requirement for EV which is possible after standardization. Customers need not worry about its compatible charging station. IEC-61980-1 standard contains the total system of wireless power transfer from supply network to EVs charging the battery or any equipment of the same at the standard supply of 1000 V AC or 1500 V DC. These all are addressed by SAE in its standard SAE TIR J2954. This is the first standard developed by SAE in Wireless Power Transfer for an EV charging application. This standard is developed specifically for static wireless charging. The frequency band, interoperability, safety, coil definitions, as well as EMC/ EMF limits from SAE TIR J2954 allow any attuned vehicle to charge wirelessly from its wireless home charger, office, or a commercial charger, etc. with the same charging ability. The standard frequency range for SAE 2954 is 85 kHz (81.39 kHz-90 kHz) for all light-duty Electric Vehicles.

(i)Economic Analysis of the Wireless Charging for Electric Vehicle

EV initial investment involves the vehicle cost and charging infrastructure, splitting the vehicle cost into a battery, vehicle parts, power train and charging components. For the analysis of wireless charging systems, only battery and charging components are considered. Here, we consider a service route of operation for EVs in order to analyze wireless charging schemes. The total cost of EV *Ts* for three types of charging (SWC, QWC, and DWC) involves storage cost and charging unit installation cost to establish a minimum investment in fulfilling the charging requirement for EV. Three wireless charging modes are demonstrated, it is clearly visible the charging lane for DWC requires the highest number of infrastructure but a very small battery is enough. For SWC heavy large size battery is required to complete the whole journey since there is no charging in between. In the case of QWC, each bus stops are having charging systems installed smaller battery size is required.

Economic Feasibility of Static Wireless Charging:

The static wireless charger is the most adopted form of wireless charging for the existing EV technology. KAIST University, Korea has developed a system that can transmit power up to 5 m of range using the dipole coil resonance system. Oakridge National Labs USA has also developed and tested various prototypes for the static and quasi dynamic wireless charger deployment. Many other companies and industries like Tesla, Nissan, Qualcomm, and WiTricity are working in this field to ensure commercially viable deployment of EV wireless charging. Still, the electromagnetic emissions and the coil misalignment pose a challenge for its future adoption into the commercial space. Figure 5 shows a schematic diagram of static wireless charger deployment at some stationary point. Grid side supply is connected to a high-frequency converter. This high-frequency supply is fed to the primary pad (transmitter). Both coils (primary and secondary) are coupled with magnetic resonance. The load side also has an AC-DC converter to supply the power directly to the battery. The battery has a Battery Management System (BMS), which controls the battery state of charge (SOC), the state of health. BMS is connected with the vehicle Controller Area Network (CAN), which controls the sensing of the vehicle and through radio signals, the vehicle is connected to the wireless charging regulation pole. Alternatively, if the vehicle battery management system does not allow sending power directly to the battery, one needs to use another DC-DC converter. The whole static wireless charging deployment system is operator free. There is no human interference; all payment charging could be automatically possible with a smart control system connected with BMS and CAN. The commercial viability of the wireless charging of electric vehicles is only possible if, economically, it gives more facility at less price.

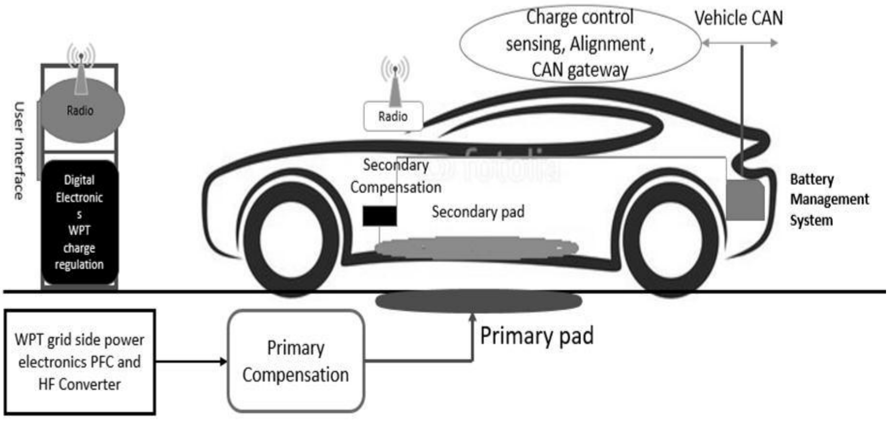

Fig.5

Economic Feasibility of Dynamic Wireless Charging System:

The DWC system also has various advantages over other charging techniques. DWC is very feasible on highways, large area institutions, industries, etc. because it requires a big area for the installation of charging lanes. One major disadvantage of EV over gasoline vehicles is the range-anxiety, which can be reduced if DWC is installed over highways. In [23], S. Jeong et al gave some mathematical optimization models to reduce the battery size and compared the total cost of the SWC and DWC system, as shown in Figure 6. This comparison is on the basis that they had operated 18 buses for 10 years. There was a difference of $ 2,462,268 for the total cost of operation between SWC and DWC, which is a 20.8 % reduction in the implementation of DWC. DWC requires a huge amount for track installation, but this was due to the huge cost of battery used in SWC

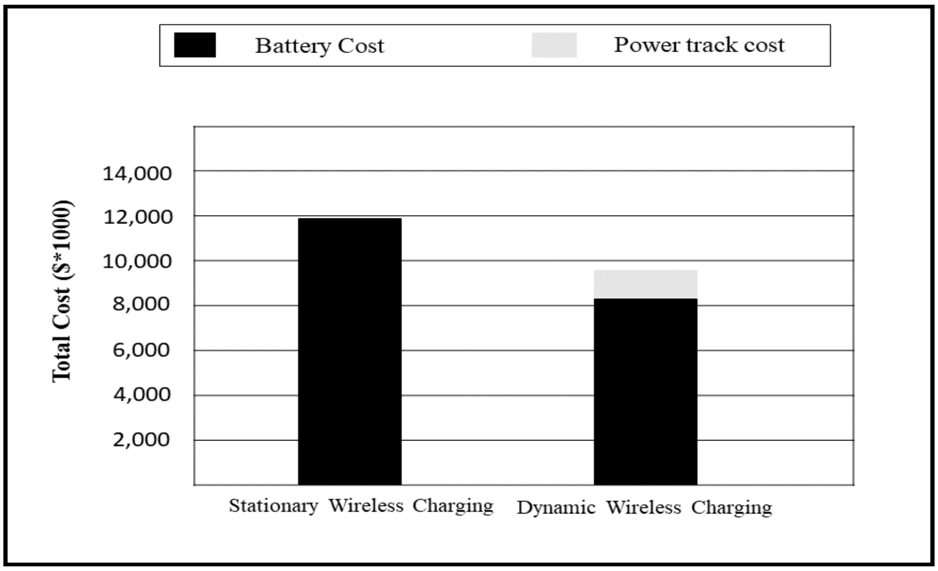

Fig.6 Comparison of Cost in the Installation and Operation of SWC and DWC for 10 years [26]

VI. Mathematical model of the wireless charging system

Static and dynamic models are detailed in the following subsections, to describe the mathematical model of each case

(a) Mathematical expressions of the static model

As the EV system is the main application of this study, the wireless recharge system's interior architecture is connected to the battery pack where the electronic components comprise an AFE converter delivering the DC bus to a high frequency inverter. It is connected to the coil through the SS compensation topology. Based on the previous explanations of the compensation topologies the SS model is selected. Hence, the corresponding model is given taking into consideration all the parameters as the resistances, inductances, and mutual inductance. Firstly, La = Lp-M and Lb = Ls-M, where La and Lb denote the primary and secondary winding leakage inductances, respectively. In this model, the primary voltage of the coil is denoted as Vp, which is obtained from a sinusoidal voltage source denoted V1. Here, RL represents a series resistive load used to obtain the final expression of global yield value. Eq. (1) shows the power consumption formula (Pwr) if a resistive load is connected, considering the mutual inductance parameter as a function of the primary current.

$$P_{wr}=I_p^2\left(\frac{(\omega M)^2}{R_L}\right) \quad (1)$$

The global impedance of the primary coil is expressed in (2) .So, the corresponding primary current can be evaluated as given in (3).

$$Z_1=X+Y \quad (2)$$

$$I_p=\frac{V_1}{Z_1} \quad (3)$$

The primary and secondary capacitance denoted Cp and Csshould be evaluated under a null imaginary part of Z1. The corresponding equation of the related capacitance can then be expressed as given in Eq. (4).

$$c_p' = c_s\frac{1}{\omega^{2(L_b+M)}} \quad (4)$$

$$\frac{R_L}{R_L+R_S+\left(\frac{R_p(R_S+R_L)^2}{(\omega M)^2}\right)} \quad (5)$$

The secondary side load impedance, RS and RP are the internal impedance of the secondary and the primary sides, respectively. When the charging system is definite, the load and the internal impedance are constant. It can be concluded that the system efficiency is only related to the mutual inductance between the primary and the secondary side coils Based on (5), it is clear that the only parameter that can be handled is the mutual inductance M. If this parameter increases, the global energetic efficiency will increase. Consequently, in the next part, M is multiplied by two after using the second receiver coil. This proposition's effectiveness will be investigated, and the simulation results will address their energic performances. Besides, a shield can increase M by increasing the magnetic flux between the coils and adding another receiver coil to improve the coupling between the coils. With more than one receiver used, the total reflected impedance can be expressed as given in (6), where nc is the number of receiver coils.

$$\sum_{i=1}^{n_c} Z_{ri} = n_c\left(\frac{\omega^2 M^2}{Z_s}\right) \qquad (6)$$

The new equivalent magnetic coupling coefficient (knc) is then expressed in (7), and the unique mutual inductance (Mnc) is expressed in Eq. (8).

$$K_{nc} = \sqrt[K]{n_c} \text{ with } 0 \leq K \leq 1 \quad (7)$$

$$M_{nc} = \sqrt[M]{n_c} \qquad (8)$$

VII. Simulation results

The simulation work was applied to two different cases – with one receiver, and two receivers. This simulation aims to optimize WPT performance if a vehicle is in motion. In the simulated model, the coil diameter is set to 0.5 m, and there is a free space of 1.5 m between two successive transmitters. Two different speeds were investigated – a low speed (set to 10 km/h) and a high speed (set to 100 km/h) to test the efficiency of the system.

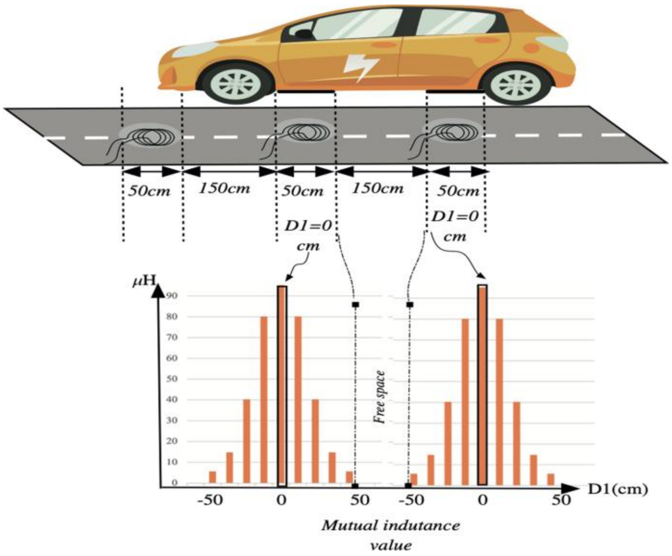

Fig.7Two receivers case Mutual inductance

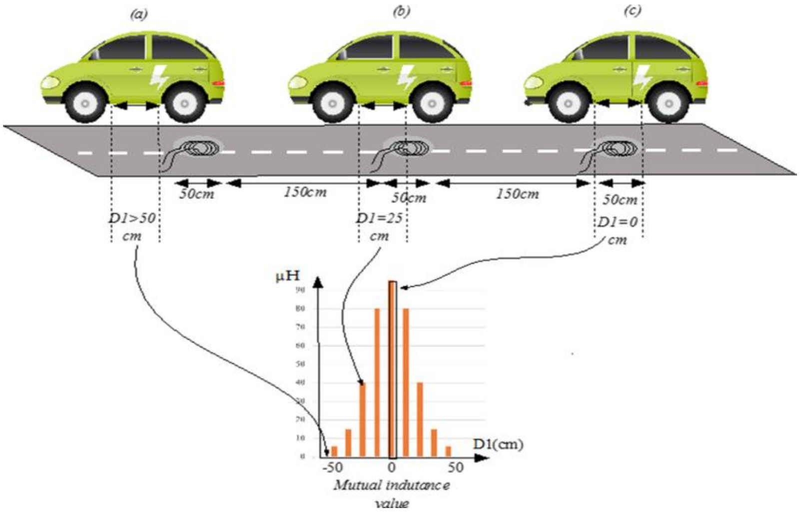

Fig.8 One receivers case Mutual inductance

Case 1: one receiver used

One receiver case was applied in two steps. Initially, the mutual inductance value was extracted to show the possible value concerning the D1 parameter variation. Fig.2 shows the mutual inductance value for a various receiver/transmitter positions. This depends mainly on the D1 parameter. If it is null, then case (c) is employed, and the mutual inductance value will be at the highest rate. However, if it is in case (a), the mutual inductance value will be null. The mutual inductance varies according to the speed motion when the secondary coil passes on the primary coil. Note that the maximum value of the mutual inductance remains constant at 95.3 lH in a fixed and centralized EV case. Otherwise, the mutual inductance value decreases based on the D1 values. If the vehicle moves, the form of mutual inductance is the same in all receiver and transmitter combinations. However, the value of mutual inductance will increase according to the number of coil transmitters. Fig. 3 represents the effect of the vehicle speed on the mutual inductance. So, the number of the used coils was varied, as shown in Fig. 3a, where the speed is 10 km/h. When two transmitters were used, the global mutual inductance had two sinusoid forms in a period of 1 s, which represents 2.5 m as a road distance. When the vehicle speed increases as shown in Fig. 3b (the vehicle speed is 100 km/h and the number of the coils used is 14 transmitters), the vehicle will cover 26.5 m.

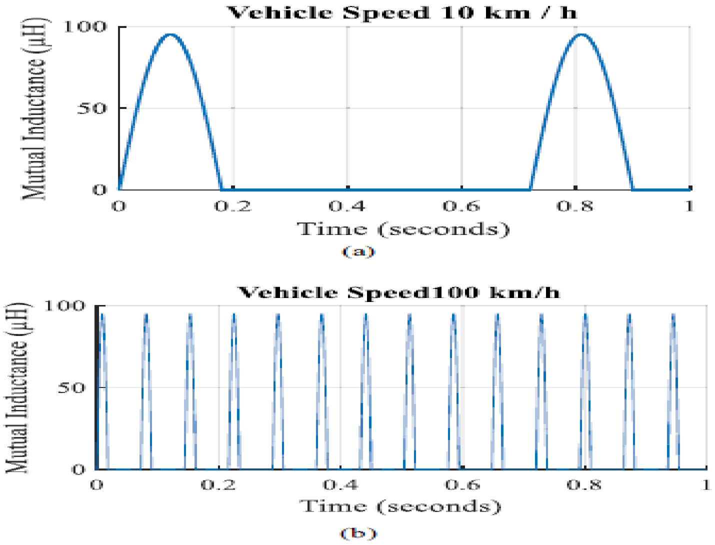

Fig.9 One receivers case influence of speed on the value of the mutual inductance

Case 2: Two receivers used

Fig. 1 shows the effect of the two receivers' position on the mutual inductance. Note that the maximum value of the mutual inductance is extracted in Fig. 2 because we have conserved the sizes and forms of the same coils. But the value of the mutual inductance will be multiplied by two, which helps increasing extracting power from the transmitter. For the same test applied before, Fig. 4 showed that the value of mutual inductance would be multiplied by two. In a situation where the vehicle has a speed of 10 km/h, the vehicle passes through two transmission coils for the same road distance. The results showed that the gain used three transmitters, unlike in the previous case where only two transmitters were used. The same conclusion can be drawn if the vehicle has a speed of 100 km/h and there have been 28 flow transmissions with 14 transmission coils for the same previous road situation.

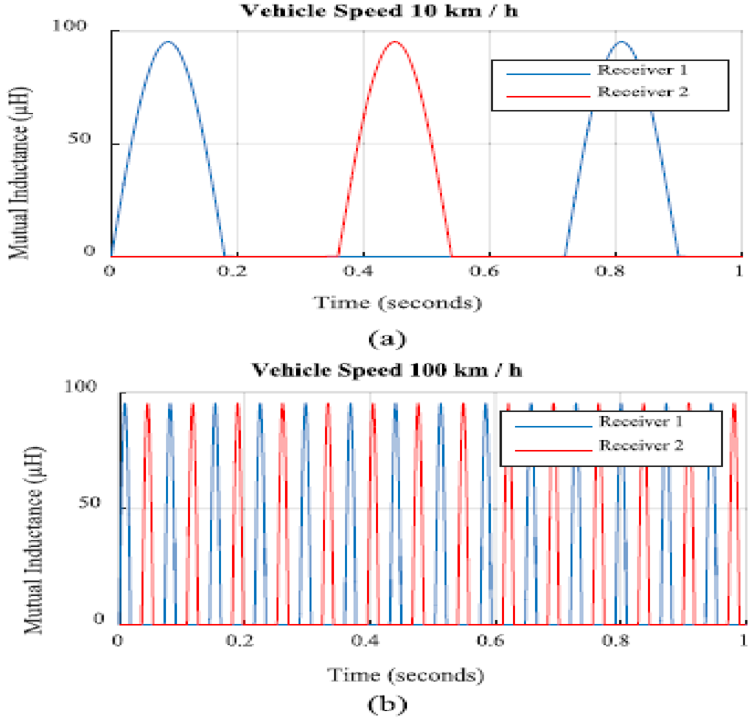

Fig.10 Two receivers case influence of speed on the value of the mutual inductance

VIII. Conclusion

The use of WPT systems for EVs was the focus of this article. The key components of the WPT were studied with respect to the compensation topology and the coil construction. The key result of this study is concerned with the static and dynamic modeling of the proposed WPT method. A new model is developed and defined that incorporates both static and dynamic problems. On laboratory work, this model was experimentally validated. The results obtained were satisfactory and confirmed the effectiveness of the reported observations. This was done all over a single receiver coil. The mutual inductance enhanced value determines the efficiency. Furthermore, having two coil receivers under the EV is an upgrade to the methodology and it was discussed in detail. The mutual inductance is an important parameter in the WPT scheme. As a result, the considered one or two coils cases were extended to derive the used mutual inductance values. An assessment technique was addressed, and the two cases were compared and concluded. The presented work included developing a new type of WPT device to ensure high-efficiency EV battery charging. Extracted data from laboratory setup and simulation experiments demonstrate the overall good performance of the proposed algorithm. The results obtained show that it is possible to increase 100% of the efficiency of the wireless recharge system if a dual-receiver is installed. The results obtained also show that as the speed increases, the efficiency of the recharge system decreases. Finally, the efficiency of the proposed method is 90% of global efficiency, which helps improve battery life. As a follow-up, a study will address issues related to the efficiency of the used converters while considering the system control difficulties and drive pattern issues. On the other side, integrating renewable energy systems, as solar photovoltaic systems, in this kind of recharge tool appears a serious challenge that can reduce the grid load in such cases.

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