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WIRELESS POWER CHARGING OF ELECTRICAL VEHICLE THROUGH MAGNETIC COUPLING WITH EXPERIMENTAL ANALYSIS

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ABSTRACT

This paper presents an overview of current wireless power transfer (WPT) technologies for the application of electric vehicles (EV) wireless charging. The experiment is carried out on small sized antennas that can be equipped at the bottom of a four wheeler vehicle. The efficiency characteristics of contact less power transmitted wirelessly has been analysed by varyin g frequency of power, gap between receiving and transmitting coils and power to be transmitted. Technology such as coupled magnetic resonance is systematically reviewed. The feasibility of wireless power transfer with large air gaps and high effici ency by small sized antennas is proposed and analysed in this paper. The latest key technical issues, challenges and state-of-art researches are introduced.

Keywords- Contactless power transfer, magnetic resonance, coupling, battery charging, wireless power transfer, electric vehicle, wireless charging

I. INTRODUCTION

The biggest problem that the Electrical vehicle industry is facing today is the problem of charging. Wireless power transfer is a solution to this problem. Wireless technique requires no physical contact between vehicle and charging device, therefore overcomes the inconvenience and hazards caused by traditional conductive method. This system will enable the diffusion of Electric Vehicles (EVs) because it makes charging mechanism more convenient. Intelligent sensors are fitted in an Electric Vehicle to continuously monitor battery level and make the charging process fully automated. Electric Vehicles are automatically charged by wireless power transfer. In general, one would use a cord and plug in Electric Vehicle at home, but it is not necessary if wireless power transfer technology is used. The technology of wireless power transfer requires three main characteristics: large air gaps, high efficiency and a large amount of power. The electromagnetic resonance coupling is the only technology that meets these requirements. In this paper, the need and usefulness of wireless power transmission and the feasibility of using Electromagnetic resonance coupling as the means for wireless power transmission is investigated. There are multiple needs and uses for this technology. In this paper, current WPT technologies will be reviewed on the perspective of electric vehicle charging. For each technology, basic principle will be explained with summary of its potential and constraints on EV charging. For the two promising techniques, namely coupled magnetic resonance and magnetic gear; key issues, research challenges the latest developments will be noted. Finally, the technology trends will be introduced. For a better understanding of the power level, efficiency and application constraints of existing technologies, a classification should be carried out according to the physical mechanisms. For the time-varying electromagnetic field, there are two main types of WPT technologies, the near-field and the far-field. The near-field is non-radiative and can transfer energy over a distance of less than one wavelength. Inductive power transfer (IPT) is a popular near-field technology which is widely used in induction motors. It has normally employed in signal broadcasting where the required power is on microwatts level. Moreover, for charging application, the antennas should be large enough to satisfy the safety standards on EM radiation regulation, which makes it unsuitable for vehicle applicationCapacitive WPT technology uses alternating electric field to transfer energy. It has a smaller EMI than traditional electromagnetic-field-base also been used in wireless charging electronics, such as electric toothbrushes and cell phones. However, the transferred power decays rapidly as the distance increases ($1/r^3$). Therefore, the efficient operating range is always limited to several centimetres.

II. MECHANISM OF WPT AND EXPERIMENTATION

To transmit power an alternating current must be passed through a closed loop coil. The alternating current will create a time varying magnetic field. The flux generated by the time varying magnetic field will then induce a voltage on a receiving coil closed loop system. Magnetic coupling occurs when two objects exchange energy through their varying or oscillating magnetic fields. Resonant coupling occurs when the natural frequencies of the two objects are the same [1].

A. Magnetic Resonance coupling WPT

Basic Principles

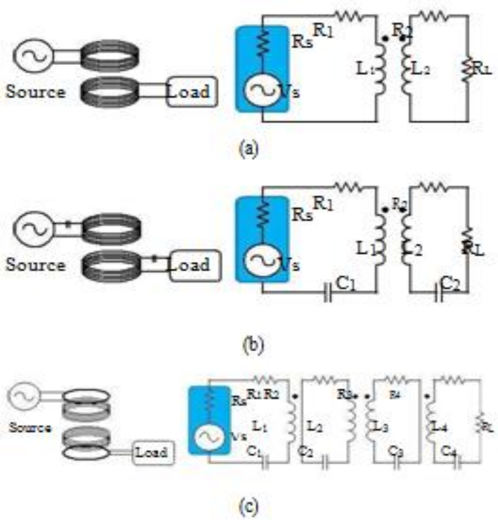

Fig. 1: Topologies and equivalent circuit models of near-field wireless power transfer technologies: (a) traditional IPT; (b) coupled magnetic resonance; and(c) strongly coupled magnetic resonance.

Coupled magnetic resonance is a near-field WPT technology but with some differences from traditional IPT, as shown in Fig. 1. Two or more pairs of RLC resonators are used to enhance power transfer efficiency and extend transfer range. As shown in Fig.1. b. the two capacitors connected in series. However, both primary and secondary side compensation capacitors can be connected in series or parallel, which results in four different prototypes. Intensive research has been done on analyzing and comparing those prototypes [16], [17]. Generally, the primary side is compensated to lower the reactive power and therefore lower the VA rating of the power supply. The secondary side is compensated so that the load acquires almost of the transferred power, enhancing the power transfer capability. The choice of topology is application oriented. Series compensation on secondary side is suitable for constant voltage application, while parallel topology is capable to support a constant current. The series-compensated primary can reduce the power supply voltage which is very attractive in long track application, while the parallel-compensated primary is capable to support a large supply current. Especially, by using 2 loops and 2 coils, the internal resistance of voltage source *RS* and the load resistance *RL* are excluded from the RLC resonators, which results a much higher quality factor of circuit (Q) than conventional 2 coils resonators. This means with the same coupling coefficient; more energy could be transferred to the load. Additionally, to improve the transfer efficiency, the internal resistance of RLC resonators is further reduced by replacing lumped resonant capacitors by coil parasitic capacitance (*C2* and *C3* in Fig.1. c.). Therefore, with a highly reduced resistance, the resonators can transfer energy efficiently even when the coupling coefficient is low.

B. BLOCK DIAGRAM OF WIRELESS POWER TRANSFER SYSTEM

The basic diagram showing the system of wireless power transfer is shown in Fig. 2. Antennas are used for transmitting and receiving the electrical energy. A high frequency power source distributes power through the transmitting antenna. Another antenna is fitted at the bottom of the Electric Vehicle which receives electric power from the transmitting antenna. This antenna is thus called receiving antenna. The transmitting antenna sends energy to a receiving antenna using electromagnetic resonance coupling wirelessly. The energy with high frequency is rectified and is used to charge the battery of the Electric vehicle [4]

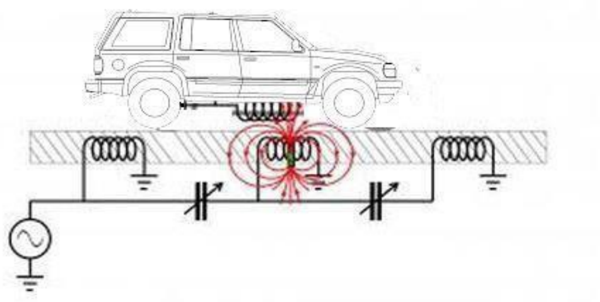

Fig. 2 Block diagram for contactless power transfer in Electric Vehicle.

In this paper, characteristics of antenna are studied because antenna characteristics decide the air gaps and efficiencies [5]. Antennas of 450mm diameter are considered so that the antenna can be fitted to the bottom of Electric Vehicles. Electromagnetic resonance couplings cannot radiate like microwave power transfer. Instead, Electromagnetic resonance couplings transfer power by connecting the electromagnetic fields of the two antennas to form a link that does not allow power to radiate outward, and thus conserves energy. The transmitting antenna is continuously fed power and this power is transferred to the receiving antenna via a wireless magnetic resonance coupling. Typical characteristics of antennas, inter-relation between air gaps, frequency and relation of power and efficiency are shown

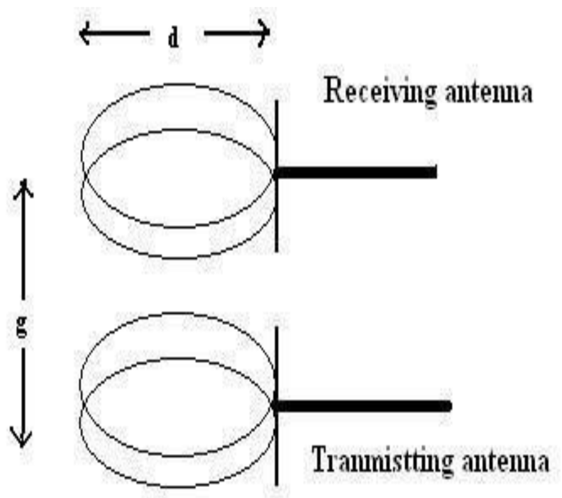

Fig. 3: Basic diagram of Antennas

In Fig. 3: diameter (d)=450mm, air gap is represented by (g) which is around 150mm to 500mm in our experiment.

C. EQUIVALENT CIRCUIT

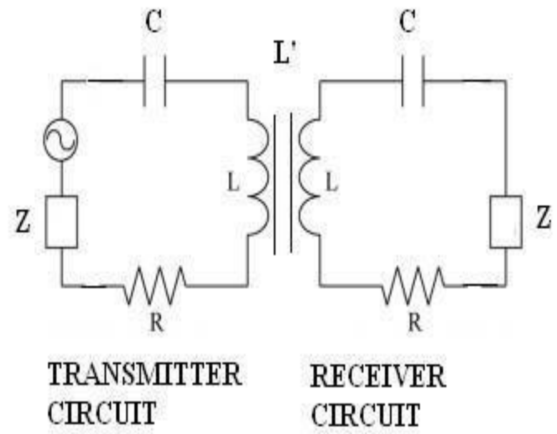

Fig. 4 Equivalent circuit of magnetic resonant coupling.

The above figure shows basic transmitter and receiver circuits. The resonance frequency can be calculated theoretically from the equivalent circuit.

III. ADVANTAGES OF THIS SYSTEM.

A. Power transfer system is invisible.

The principle of Electromagnetic resonance is invisible. The necessary equipment's are buried under the road. The receiving antenna is fitted under the vehicle. This facilitates invisible recharging. This system will be useful in areas where the installation of conventional overhead systems would be difficult or prohibited, such as heritage sites or parks.

B. Recharging on the go.

Waiting periods for charging of the battery can be avoided because high level of power transfer facilitates quicker recharging of the battery. Not just under the roads but the wireless charging equipment's must also be installed all along the public parking places like offices, universities,

theatres, shopping malls etc. so that when vehicles are parked they are charged automatically and ready to go long distances again [5]. This means that vehicle availability and service reliability can be ensured without employing extra fleet vehicles or batteries.

C. Fully Automated and Hassle Free. Intelligent sensors fitted in the vehicle continuously detect the battery level and make the charging process fully automated. Hence the driver does not require any special training to operate Electric Vehicles.

D. Cuts operating costs and Co2 emissions. Since the price of fossil fuels is ever-increasing, this system will comparatively reduce the overall cost of travelling to a great extent [6]. Overall energy consumption and emissions would diminish because of the higher efficiency of electric vehicles over the entire cycle as energy is not consumed while the vehicle is stationary, unlike internal combustion engines which consume fuel while idling. In addition, regenerative breaking avoids wastage of energy. The transportation system will be totally pollution free. Not just electric vehicles but wireless electricity makes everyday products more convenient, reliable, and environmentally friendly. With advancements in wireless power transfer technologies; cell phones, game controllers, laptop computers, mobile robots, will be capable of re-charging themselves without ever being plugged in [7].

IV. EXPERIMENTAL RESULTS

The experiment is conducted by taking two coils. The two transmitting and receiving coils are kept at a fixed air gap and by changing the frequency, the power at the receiving coil is continuously measured with a wattmeter. The air gap is fixed at 150mm. The frequency at the start of the experiment is 8MHz. At this frequency, no significant power is observed in the wattmeter connected to the receiver coil i.e. no significant power is transmitted. As the frequency of power supply is increased, the wattmeter reading also increases and reaches a maximum value at a particular frequency which is the resonant frequency of the two coils. From the oscilloscope, the resonance frequency is noted as 11.2MHz [8-9]. At this frequency, the power transfer between the coils is maximum and the efficiency of power transfer is found to be 97.1%. As the frequency is further increased the wattmeter reading connected to the power receiving coil first falls and then rises again to reach its maximum value. This is second resonant frequency. The second resonant frequency from the oscilloscope is noted as 13.1MHz. The graph of efficiency of power transmission [%] vs. frequency is plotted and is shown in Fig. 5.

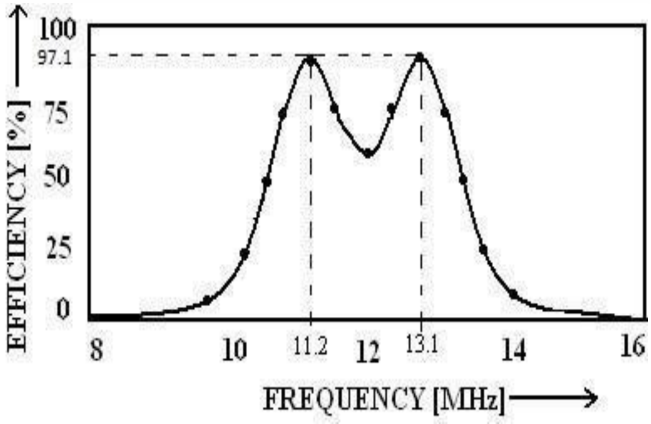

Fig.5: efficiency of power transfer (%) vs. frequency(MHz) at g=150mm.

The same experiment is repeated by changing the air gap between the transmitting and receiving coils to 250mm [11]. A graph of – efficiency of power transmission vs. frequency is drawn. It is found that the resonant frequency shifts towards right i.e. the resonant frequency increases. The resonant frequency from the oscilloscope is noted as 12.0MHz. Resonance occurs only at one frequency. Hence, the number of frequencies at which resonance occurs reduces from two to one at air gap of 250mm. The graph obtained is shown in Fig.6.

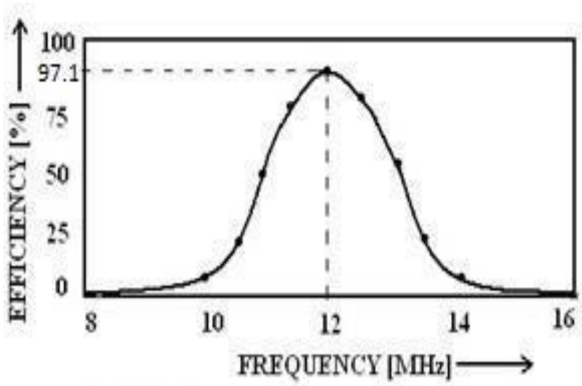

Fig.6: efficiency of power transfer (%) vs. frequency(MHz) at g=250mm.

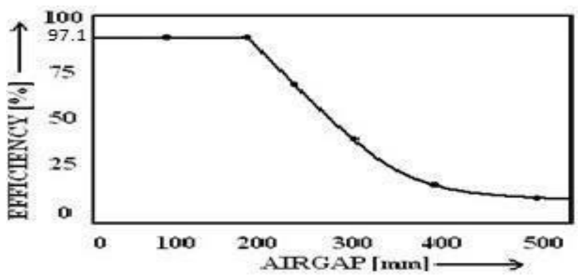

Fig. 7 Efficiency of power transfer vs. Air gap

Though the resonant frequency values have changed with change of air gap between the coils, the efficiency of power transfer remains constant at 97.1%. But, when experiment is conducted by increasing the air gap beyond 250mm, the amount of power transferred is reduced. Beyond air gap of 250mm, the longer the air gaps become, the more efficiency is lost [12]. The relation between maximum efficiency and airgap is shown in Fig.7.

Theoretically, the efficiency of power transfer does not depend on the amount of constant. Experimental verification is needed, however, because of the effect of heat etc. is not known until the experiment is practically performed. The air gap is 250mm and the frequency is set to resonant frequency of 12.0MHz for maximum efficiency as obtained earlier in above experiment by the Fig.- 6. The experiment is performed by steadily increasing the power to be transmitted. watt meters are connected across transmitting as well as receiving coils. By increasing the power in steps of 20W, both wattmeter readings are noted. The power is changed in equal steps from 5W to 100W and efficiency of power transmission is measured at every step from the readings of transmitted power and received power. In this case, when the input power is 100.0W, the received power 97.1W is recorded. Hence, the efficiency of power transmission is 97.1% and is found to be constant. Efficiency does not depend on amount of power transferred. The graph plotted between efficiency of power transmission and amount of power transmission.

V. KEY CHALLENGES OF COUPLED MAGNETIC RESONANT HIGH EFFICIENCY

The basic coupled magnetic resonance WPT system is consisted of 4 power stages, namely the power factor correction (PFC) converter, the RF amplifier, the coils or resonators, and the on- board rectifier. Fig. 8. shows the system schematic of a 4-coil strongly coupled magnetic resonance wireless EV charging system with uncontrolled pick-up. To archive 90% overall efficiency, both of the PFC and RF amplifier stages should have 97.1% efficiency at least, with the coil-to-coil efficiency higher than 96% and the rectifier efficiency close to 99%.The coil design is the most important part in the whole system. The dimension of coil will define the upper limit of the power capacity, and the efficiency will be affected by the quality factor of coils. For vehicle application, the coils normally consist of two parts, the wires and the magnetics. The coils will be operated from 10 kHz to several hundred Hertz. Under such high frequency, the skin effect will cause a very high AC resistance. So, Litz wire is often used. [13] Moreover, the alternating current flowing in one strand will generate an alternating magnetic field which will induce eddy current in its adjacent strands. This is called proximity effect and will also increase the AC resistance. When operating under MHz, a solid copper wire may have higher efficiency than Litz wire [14]. That's becausethe AC resistance may be dominated by proximity effect under such frequency. To eliminate this effect, wire coated with magnetic thin film is proposed to give shielding for the alternating magnetic flux and eliminates eddy current [15]. Some solutions turn to non -metallic materials such as graphene and carbon nanotube to completely eliminate the skin effect and proximity effect [16].

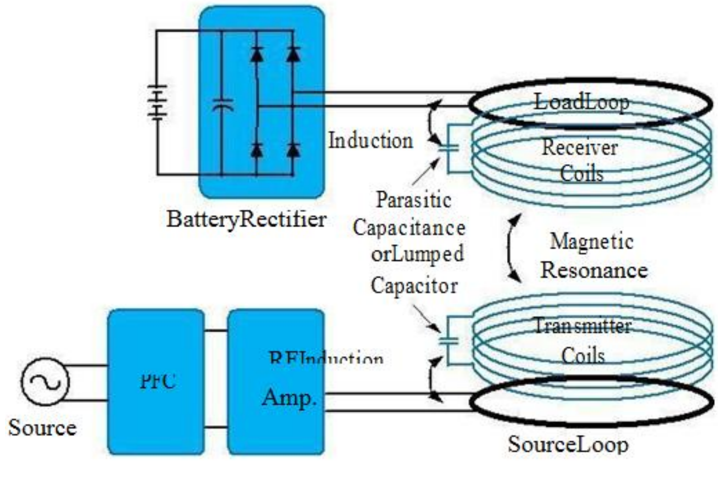

Figure 8: Schematics of strongly coupled magnetic resonance wireless EV charging system.

The magnetic structures are used to enhance coupling, reduce flux leakage and shape the magnetic field. There are two major types of magnetic structures, the track type and the lumped pad type [17][18]. The track type can provide an evenly distributed magnetic flux, which reduced the design and control complexity of the following stages. KAIST The magnetic field shape can be controlled by the configuration of the ferrite core in power supply and pick-up sides, as well as the distance and coils turns. So the Shaped Magnetic Field in Resonance (SMFIR) technology is proposed to offers a tool to optimally solve functional requirements and design parameters using an axiomatic approach, as defined in[19][20] .

The lumped pad is mostly used for stationary charging because when the displacement occurs, the mutual inductance of the primary and secondary coils will change, which will cause a fluctuation of the magnetic flux. And when it's used in dynamic charging there should be a control strategy which will tolerate or correct the flux fluctuation. And if the technique permits, this kind of structure will offer less restriction on vehicle movement and make the driving more freely.

A. Alignment Tolerance

Alignment tolerance is another important issue in EV charging application. One of the solutions is to adjusting configuration of the ferrite cores. By using a fish bone shaped primary core and flat E shaped pick-up, the alignment tolerance is nearly doubled than the former designs [21]

B. Dynamic Charging Control

Different charging control strategies are proposed, such as control on both primary side and secondary side with the help of wireless communication. However, this solution is not universal to all vehicle types, because the road side and on-board system has to be designed at the same time. A more promising solution for the future application is to use only road side control, as proposed by ORNL, although the wireless communication is also included [22]. This solution enables the on-board pick-up rectifier to be compact and reliable, and make the charging device universal to all types of vehicles.

C. Industry Trends and Vision on WPT Developments

In EV wireless charging area, great achievements have been made on various pre-commercial demonstrations and some ready commercial kits. The very short term development will be focused on mass adoption of existing stationary or semi-dynamic charging techniques into market available EVs. High power, high efficiency, misalignment tolerance and optimized charging control will still be emphasised issues. Researches include magnetic structure design, high efficiency RF amplifier and converter control strategy design. Besides, international standards and safety regulations are also speed up for the future application.

In the long term, the final objective of this technique is to allow wireless charging the EVs with freely driving on road. The multiple placed charging tracks is under demonstration. More attractive is the multiple lumped charging pad structure. Because every single pad can be separately turned on, this will lead to higher system efficiency and maximum driving freedom if control technique enables.

VI. CONCLUSION

In this paper, different wireless power transfer techniques are reviewed on the perspective of EV charging application. A classification is made first by energy carrying mediums and then by technologies. The coupled magnetic resonance and magnetic gear technologies are choosing out for detailed review, because their suitability for EV charging application in both power and range level. The basic principle of each technology is explained.

The feasibility of wireless power transmission through Electromagnetic resonance coupling is investigated in this paper. This consists of using a transmitting and receiving coils as the coupling antennas. The antenna's size is small enough to be equipped to the bottom of the Electric Vehicle. The efficiency characteristics of power transmitted under variable frequency, air gaps and power are determined. By increasing the length of air gap between transmitting and receiving coils from 150mm to 250mm, the number of frequencies at which resonance occur changes from two to one. The maximum efficiencies are constant for any air gap less than 250mm. Beyond 250mm, the longer the air gaps become, the more the efficiency falls. This technology can be built all along the existing roadway systems to charge an electric vehicle safely and efficiently roadway systems to charge.

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