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Dynamic Wireless Power Transfer in Electric Vehicles using Magnetic Resonance: A Case of Developing Countries

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***Abstract*—Power pads for charging batteries of electric vehicles in the garage have been in existence for many years but they have not solved the problems facing the users. Electric vehicles stop anywhere on the road as soon as the energy stored in the batteries is exhausted. Stationary charging systems are common and usually located at designated charging stations. To overcome the problems associated with the stationary charging system especially in developing countries, we propose the design of power pad for dynamic battery charging system. This model employs wireless power transfer mechanism, utilizing high quality magnetic resonance. The work leverages on the ability of energy to be transferred efficiently between two magnetically coupled resonating coils in a complex electromagnetic environment. A prototype of the dynamic battery charging system was designed and constructed.**

***Index Terms*— Electric vehicles, magnetic resonance, power pad, wireless power transfer**

I. Introduction

THE notion of wireless power transfer for charging of electric vehicles dates back to 19th century through the concept of power distribution for wireless bulbs [1]. Power pads for wireless charging of electric vehicles (EVs) were made possible with the aid of wireless power transfer (WPT) technology. This technology tackles challenges of power pad for charging of electric vehicles which was a major impediment for owners of EVs. The technology for wireless charging can either be magnetic induction or radio frequency, through either stationary or dynamic wireless power transfer system; where magnetic induction powers the charging pads which transform electrical energy to magnetic energy and enables transmission over an air gap, typically short to mid-range. In the case of radio frequency (or microwave), the parabolic dish focuses on the radio waves which are normally long range waves towards intended target. In a stationary wireless power transfer (SWPT) method, drivers could park their cars and leave, but for the dynamic method, the EV is powered while driving, and the driver could change lane when vehicle is fully charged. This is referred to as dynamic wireless power transfer (DWPT).

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Wireless power transfer technology adopts both Faraday's and Ampere's laws as magnetic field induces a voltage in receiver coil, and current in transmitter coil can develop the capacity to produce magnetic field or magnetic induction which could be viewed in two categories: Magnetic Induction Coupling (MIC) and Magnetic Resonance Coupling (MRC). In MIC, the source drives primary coil resulting to a sinusoidal magnetic field which induces voltage across terminals of secondary coil which transfers power to the load [2]. The type of mechanism is used in transformer where the magnetic field is confined to a high permeability core. MRC has an extended range alignment insensitivity and potential to support multiple receivers than MIC.

Oil reserves are not unlimited, but they are so necessary to find supplementary energy sources [3]. This has become compulsory and urgent due to the fact that the burning of oil in the Niger Delta region of Nigeria and all other oil producing countries provides a negative environmental impact like huge carbon emission and other harmful gas emissions. Transportation sector is the largest consumer of fossil fuel worldwide and thus an important factor in reducing fossil fuel demand. Pollutant emissions and oil consumption are mostly caused by transportation sector. It is therefore necessary to combat this unpleasant situation in order to save energy and preserve the environment as well. In order to stand against environmental pollution, EVs were conceived. But the high flexibility makes it difficult to get power in a similar way electric trains that run on a fixed track do. Instead, a high power and large capacity battery pack is usually equipped as an energy storage unit to make an EV to operate for a satisfactory distance.

This paper contributes an effort to make wireless power pads for EVs future plan for dynamic charging systems. It is therefore our proposal for DWPT systems to be designed, manufactured and installed locally in developing countries. This will save cost and increase customer demands for the vehicles. It will also alert governments and stakeholders to take drastic steps to adjust the economy in the realities of falling oil prices, and also to save the environment from toxic pollutions. The major challenges are: electricity storage technology (in situation of epileptic power supply), insufficient energy density, limited life time and high cost.

The remainder of this paper is organized as follows: Section II provides a background study of the work; Section III describes the materials and method used in the work;

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Chapter IV presents and discusses the results of the work, while Chapter V concludes with recommendations.

II. Background of the Study

WPT is the transmission of electrical power from the power source to an electrical load without the use of physical connectors. History of WPT dates back to Maxwell's radio waves equations in 1862, and Poynting's energy flow theorem in 1884. Nikola Tesla investigated the principle of WPT at the end of the 19th century, but was not exploited to a commercial level because of its seemingly unsafe nature, low efficiency, and financial constraints [4]. Subsequent upon this, electromagnetic waves were used for wireless communications and remote sensing applications.

With the advent of advanced semiconductor technologies, Tesla's proposition has now become a reality. The wireless nature of this transmission makes it useful in environments where implementation of physical connectors can be inconvenient, hazardous or impossible, particularly in EVs. Research showed that Inductive Power Transfer (IPT) has wider applications [4]-[6]. The Wireless Power Transfer session of IEEE Antenna and Propagation Symposium in 2012 showcased many designs of IPTs for different applications [7][8]. However, all of these works focused on investigation, realization and improvement on efficient power transfer. Reference [9] investigated the requirements for electric vehicle charging and gave power level at 3 kW to7 kW residential for stationary garage charging and 60 kW to a little over100 kW for on-road dynamic charging. According to the authors, it must be safe, solid and efficient in order to be convenient for consumers. As brilliant as this idea was, it could not provide robust safety considerations, including electromagnetic fields exposure, electrical shock, fire hazards and flood hazards. This paper addresses these issues.

Electromagnetic field exposure (EFE) is a major concern for wireless charging of EVs' batteries. EFE exposure need to be rigorously analyzed to be within acceptable levels specified by safety standards both under normal conditions as well as unusual conditions such as during abnormal operation. There is a possibility that humans or animals may be present underneath the car during charging and therefore be exposed to high levels of electromagnetic radiation. The electromagnetic radiating field describes the behavior of the power pad:

- The mains voltage is converted into high frequency alternating current.
- The alternating current is sent to the transmitter coil by the transmitter circuit.
- The alternating current flowing within the transmitter coil creates a magnetic field which extends to the receiver coil (when within a specified distance).
- The magnetic fields generate current within the receiver coil of the device.
- The current flowing within receiver coil is converted into direct current by the receiver circuit, thus charging the battery of the device.

The wireless system relies on the well-known principle of electromagnetic induction. A magnetic field generated by an alternating current in a primary coil induces a current in a nearby secondary coil.

III. Materials and Method

The source of energy for EVs is the power pad, both in the stationary or dynamic modes. Power is transferred between transmitting and receiving pads. Vehicles have height difference from the ground level to chassis (Short range view and mid-range view). The case of vehicle-to-ground arrangement is not the same because it has to do with height variation and when height or distance is involved, efficiency of the power transferred is vital, as shown in Figs. 1 and 2.

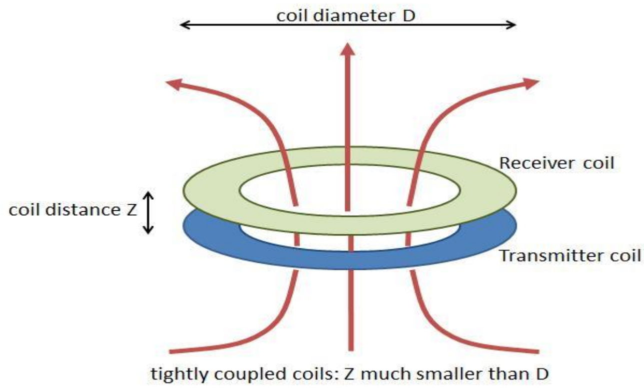

Fig. 1. Inductive coupling for short-range view

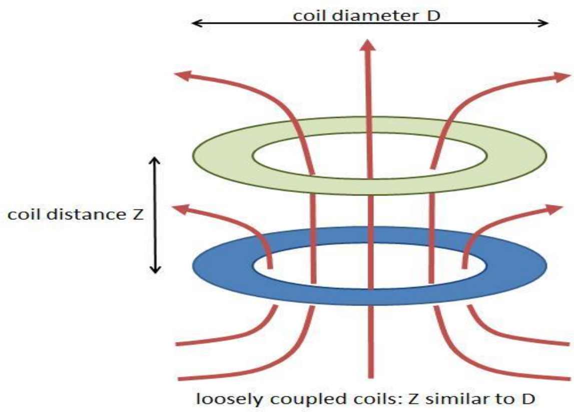

Fig. 2. Inductive coupling for mid-range view

WPT for charging EVs has many advantages compared to wired-plug-in electric vehicle (PEV) charging. Inconveniences in wired PEV charging process is major impediments in gaining interest of consumers. Due to industrial requirements and advancements in technology, power transfer distance in wireless power transfer systems has increased from certain millimeters to centimeters. Although researchers are improving on the wireless power transfer systems technology, there are still numerous challenges to overcome in order for it to be commercialized. To estimate maximum efficiency power transfer at certain distance between air gaps requires employing most efficient approach to actualize.

Using resonant induction for mid-range and Electromagnetic wave power transfer technology, there is possibility to supply power to places, which is difficult using conventional wires. The use of inductive coupling is

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currently in its developmental and research phases. Major technical challenges affecting power transfer efficiency are high transfer range, increasing power level, misalignment tolerance and safety considerations. Demonstrated research works have shown promises that the wireless power transfer can be brought into commercial level within a reasonable cost. Wireless power transmission is an efficient way for electric power transmission from one point to another through a medium or an atmosphere without the use of wires. By using wireless power transmission, power can be transferred through inductive coupling for short range as shown in Fig. 1.

Electromagnetic induction and the microwave power transfer are the most common WPT technologies. The system must satisfy three conditions for efficient mid-range power transfer as shown in Fig. 2, namely: high efficiency, large air gap and high power. Since microwave power transfer has a low efficiency for near field power transfer, this method may be inefficient as it involves radiation of electromagnetic waves. Although WPT can be done via electric field coupling, it does also provide an inductively loaded electrical dipole (also called a dielectric disk, or an open capacitor). Objects which are extraneous may provide a relatively strong influence on electric field coupling. Hence magnetic field coupling may be preferred, since an empty space magnetic field has the same properties as that of the magnetic field of extraneous objects. The range of electromagnetic induction method is short range as shown in Fig.1. Magnetic field coupling has higher efficiency, since it is a non-radiative power transfer method. But power transfer range can be increased by the application of magnetic coupling with resonance phenomenon on a magnetic field and is generated when electric charge moves through space or within an electrical conductor. The magnetic flux lines produced which is geometric in shapes by moving charges (electric current) has almost similar shapes to the flux lines in an electrostatic field.

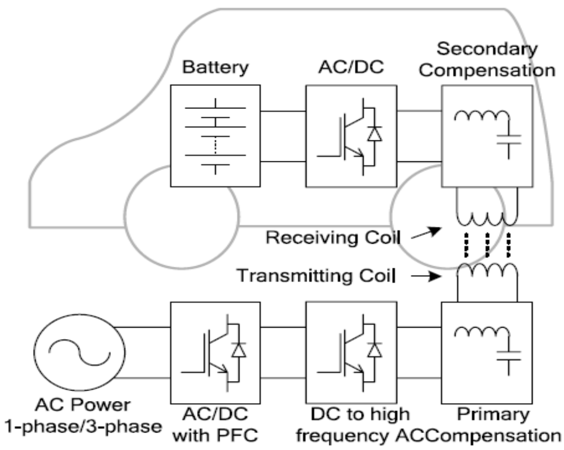

Fig. 3. Block diagram of the wireless power transfer system

Power transfer efficiency (PTE) always occurs at the resonance frequency for a two-coil system. This decreases with the coupling coefficient between transmitter and receiver, and output power is not always the maximum at the resonance frequency. It is important to consider transferred power as it determines voltage ampere ratings, which implies the component ratings, the series capacitor ratings and power converter switches when the maximum power is drawn from the source, transferred power tends to maximum. This happens when the source impedance matches the input impedance of the coil system.

When the system is operating at self-resonance frequency, maximum power transfer is reached at a coefficient value known as the critical coupling point. Critical coupling equals to coupling coefficient at a certain distance. Whereas in DWPT, wireless power transfer distance and coupling coefficient are vary continuously, thus operating at critical coupling point is not desirable.

The design and construction of dynamic power pad for charging electric vehicles battery is achieved by the use of the following materials:

i. Copper strip board - for manual soldering of electronic components.
ii. Lead - a melting material, soldering is used with it to firmly hold down electronic components on copper strip board.
iii. A toy car - the receiving circuit is constructed and mounted inside the car.
iv. Wooden road - where the transmitter coil is fixed for transmission.
v. Resistors, capacitors, inductors, diodes, LED and transistors - power pad components.
vi. Connector or jumper wire - to link or connect nearby and distance components.
vii. 9 volts battery - for the receiver and the transmitter.

The N-Channel metal oxide semiconductor field effect transistor (MOSFET) used in the circuit diagram has high speed variation (Fig. 6). They are of high power dissipation and they perform better in the circuit due to their low drain-to-source resistance. As for their operation, a MOSFET and coil heats up rapidly but before that the transmitter circuit did not oscillate. When the oscillator circuit begins to oscillate, very low power gets to the load coils and the receiver coil, which was slightly out of resonance, at the start of the operation, does not power up as expected. This was solved by building both LC-tank circuits with identical loops and capacitances, so that both the circuits have the same resonant frequency.

$$\omega_o = \frac{1}{\sqrt{L1C1}} = \frac{1}{\sqrt{L2C2}} \tag{1}$$

$$Q = \frac{\omega L}{R} \tag{2}$$

$$K = 1 / [1+ 2^{2/3} (D/ \sqrt{R1R2}\,)^2]^{3/2} \tag{3}$$

Where:
L_1=L_2 is self-inductance transmitting coil and receiving coil;
C_1=C_2 is C series capacitance;
ω is the frequency in radian per second;
L is the self – inductance of the coil;
R is the series resistance for considering the coil;
K is the coupling coefficient;
D is the physical distance between transmitter coil and receiver coil;
R1 and R2 are radius of loop-1 and radius of loop-2 respectively.

Fig. 5 shows inductive circuit diagram for both the transmitter and receiver based on Kirchhoff's current and voltage laws (around a closed loop, applied to four loops), with the loop equations from the resonating coils given by equations (4) to (11). The voltage at the terminal of each coil is described as the Time rate of change of flux (^).

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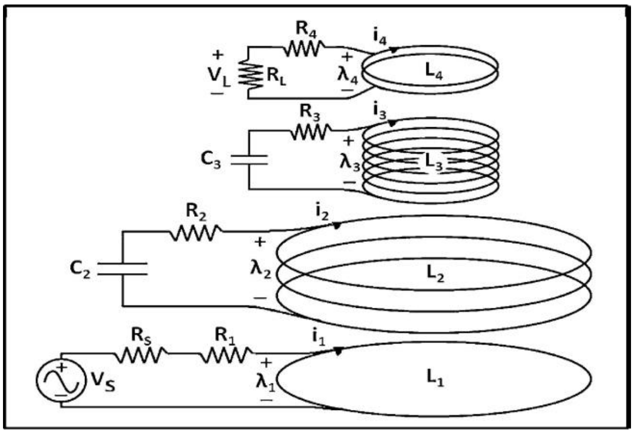

Fig. 5. Inductive circuit diagram for transmitter and receiver based on Kirchhoff's current and voltage laws

$$Vs = i_1Rs + i_1R_1 + j\omega\wedge_1 \tag{4}$$

$$Vs = i_1 (Rs + R_1) + j\omega\wedge_1 \tag{5}$$

$$0= i_2R_2 + i_2 (j\omega C_2) + j\omega\wedge_2 \tag{6}$$

$$0 = i_2[Rs + (j\omega C_2)] + j\omega\wedge_2 \tag{7}$$

$$0 = i_3R_3 + i_3 (j\omega C_3) + j\omega\wedge_3 \tag{8}$$

$$0 = i_3[Rs + (j\omega C_3)] + j\omega\wedge_3 \tag{9}$$

$$0 = i_4 R_4 + i_4 R_L + j\omega \wedge_4 \tag{10}$$

$$0 = i_4 (R_4 + R_L) + j\omega \wedge_4 \tag{11}$$

The four indications ($\wedge_1$, $\wedge_2$, $\wedge_3$ and $\wedge_4$) and four current loops (i_1, i_2, i_3 and i_4) represent complex amplitudes of flux linkages and currents in each of the four coils. Vs represent the complex amplitude of the ideal voltage source with resistances R_1 through R_4, Rs, R_L and capacitances C_2, C_3; at frequency (ω). Each of these coils is inductively coupled to the other. The relationship between the current and flux is symmetrically established using 4 x 4 inductance matrix.

$$\left| \cdot \begin{bmatrix} \Lambda_1 \\ \Lambda_2 \\ \Lambda_3 \\ \Lambda_4 \end{bmatrix} = \begin{bmatrix} L_{11} & M_{12} & M_{13} & M_{14} \\ M_{12} & L_{22} & M_{23} & M_{24} \\ M_{13} & M_{23} & L_{33} & M_{34} \\ M_{14} & M_{24} & M_{34} & L_{44} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \end{bmatrix} \right| \tag{12}$$

For known resistances, capacitances, self and mutual inductances and ideal source voltage substituted for flux linkages comprise of four simultaneous equations that determine the current i_1 to i_4 and the complex amplitude of the load voltage.

$$V_L = - i_4R_L \tag{13}$$

IV. RESULTS AND DISCUSSION

Power pad design for dynamic or in-motion electric vehicle was maximally achieved by the application of resonance magnetic circuit to efficiently maximize power transfer inductively. There are two resonators: the source and the receiver. The body of the vehicle is roughly represented by a big metallic plane. All materials are assumed to be copper. The central operation frequency is 10MHz. The work is based on Compensation Network Approach, which comprises of maximum power efficiency calculation.
The sending and receiving coils have a quality factor of 300; the theoretical maximum power transfer efficiency was about 96.7%.

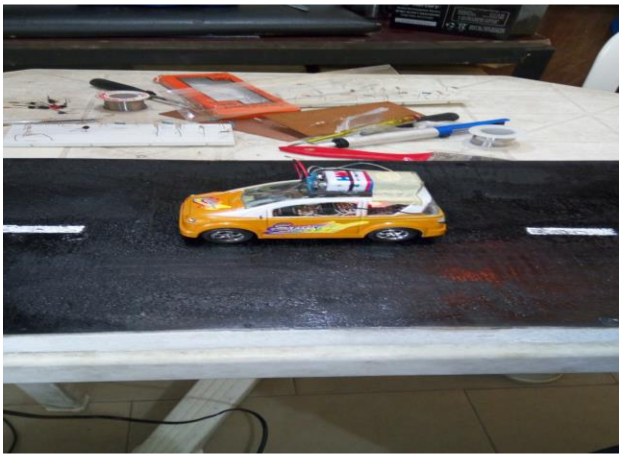

Fig. 6. Project prototype

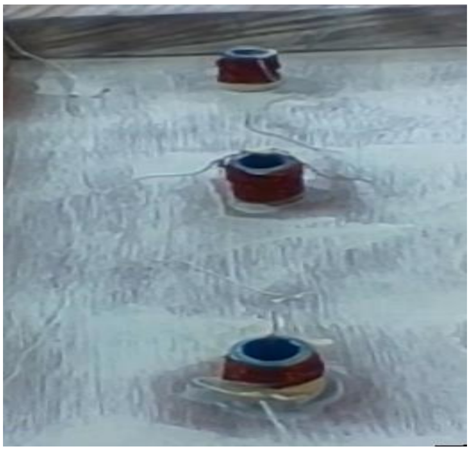

Fig. 7. Transmitter coil

Fig. 8. Receiver circuit

Transmitting power wirelessly is a technology which is applied in many fields and products. With the prevalence of mobile electronic products i.e. cell phones and PDAs, eliminating the wired bridge (power cord) tends to a natural progression of achieving ultimate mobility as the name implies of the product. Charging Electric Vehicles (EVs) wirelessly is a convenient feature, which will eradicate any need to remember to plug in a power cord after parking the vehicle. Additional safety advantages may also be achieved

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due to eliminating exposed contacts. Wireless charging for Electric Vehicles requires high electrical power (up to hundreds of kilowatts) and vast area of wireless power transmission which in turn increases electromagnetic field exposure. Thus, application of wireless charging to an Electric Vehicle requires a comprehensive safety analysis to ensure consumer protection.

The results demonstrate that the frequency is required to be resonant so that the maximum power can be transferred from transmitter to receiver. The design of inductive pad in transmitter side in parking slot may unique of capacitance, inductance as well as resistance whereas receiver side of different brands vehicle with different power ratings must not be same. Therefore, it is also desirable to tune the proper value of impedance to create resonance response. Integration of other supporting apparatus or tuning sub-circuit for appropriate frequency matching inside the vehicle can be causes to increase vehicle weight as well as cost rather than installation of tuning circuit at transmitter side.

V. Conclusion and Recommendation

Efficiency, transferred power, ranges and misalignment tolerance are identified as the performance indices for dynamic wireless power transfer in electric vehicles. A detailed analysis of dynamic wireless power transfer system has been presented, highlighting the contributions by the research community. Modeling methods and their own merits are presented, as well as design challenges. Dynamic wireless power transfer for electric vehicles is the next generation of transportation for road vehicles.

In order to minimize carbon emission, from public transport points of view, it is needed to find alternative source of energy. Electric vehicle can be way of minimize the carbon emission without burning of conventional petroleum. To facilitate the charging system of electric vehicle more efficiently, user friendly and with no hassle, wireless charging system can be very effective solution. The simulation results shows non-radiative wireless power is transferred through the air-gap at resonant frequency matching. Approximately 95% efficiency of power transfer is obtained at distance of 25cm. Moreover, coupling coefficient is increased with the decrease of distance between two coils for a given diameter of copper conductor in both side of transmitter and receiver. On the contrary mutual inductance between two coils is also increased with the decrease of distance between coils. Consequently, to achieve the optimum amount power transfer at optimum distance of coil between parking and bottom of vehicle is to be considered around 25cm. Where simulation shows that after rectification the received signal into DC signal can be obtained approximately 19.56 Watt at resonant frequency. The future work involve this project would be to design and simulate the vehicle-to-grid system, automatic ranging of resonant frequency in case of variable vehicle distance instead of alignment of antenna mechanically in addition communication between coils for transmitting power more efficiently.

We have shown and tested that power can be delivered wirelessly from a main coil to a load coil with a third coil placed intermediately between the source and load coil through magnetic resonant coupling and with capacitors at the coil terminals providing a sample means to match resonant frequencies for the coils. The mechanism has a robust potential to deliver wireless power to a receiver from a source coil.

Further research may be through the communication system between transmitter and receiver to match their tuning frequency of signal is need to be transmitted through the link, required power level, billing system and other supportive tasks. Recently, the applications of smart grid (SG) are grid-to-vehicle and vehicle-to-grid technology. It can be part of SG where the inductive pad can be used to transmit the signal to the vehicle battery and stored excess charge can be also feed to the grid simultaneously by allowing bi-directional power flow having both sides with charge controller.

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