Wireless Power Transfer through Inductive Coupling

Mohamed A. Hassan, A.Elzawawi

Abstract

Wireless power transfer is a new technology to transfer electrical power without any physical contact between the source and the load. The aim of this paper is to propose the use of a simple, cheap and easy technique for charging any mobile. The various technologies available so far for wireless transmission of electricity and the need for a wireless system of energy transmission are discussed here. The main problem is how power is transferred wirelessly without any bad effect on environment and human. The core of the used technology is making use of the magnetic resonance concept for transmitting the power wirelessly for charging any mobile. Electric power is transferred at a frequency of about 100 kHz in a short distance range to charge a mobile making use of resonance. An impedance compensating network is used to achieve maximum power transfer. The practical results are very close to these obtained using the mathematical model and the theoretical calculations. The new applications of wireless power transfer technology (WPTT) are enumerated in this paper.

Keywords wireless power transfer technology (WPTT), inductive power transfer (IPT), capacitive power transfer (CPT), magnetic resonance.

I. INTRODUCTION

The transfer of electric energy from a power source to an electric load without a direct physical connection between them, usually via an electromagnetic field, is defined as Wireless Power Transfer Technology (WPTT).

Nowadays, electronic devices such as cell phones and laptops need WPTT for wireless charging with also the advantage of the protection from any faults at the power source.

In the 1890's, a wireless power transfer (WPT) system was demonstrated by Nikola Tesla using his demonstration on resonant transformers called Tesla coils.

In July 2007, a group of researchers at MIT presented a method of transmitting power wirelessly [1].The researchers used an electromagnetically coupled resonance system to power a 60W light bulb wirelessly from a distance over two meters away. The magnetic resonance coupling technology has been found to be viable for midrange energy transfer. It is used for charging the electric vehicles with energy efficiency up to 90% in a relatively short time. It is also used for low power wireless charging of mobile phones with a power up to five watts and energy efficiency up to 70%.

II. CATEGORIES OF WIRELESS POWER TRANSFER

Various methods used in WPTT mainly depend on the range between the transmitter and the receiver, operating frequency and the amount of transmitted power [2-5].

There are two fields of WPTT, Far Field WPTT (FFWPTT) and Near Field WPTT (NFWPTT). The main differences between the two types of fields are illustrated in Table I.

Table I
Main differences between FFWPTT and NFWPTT

WPT	Far Field	Near Field
Range	Long	Short-Mid
Phenomenon	Coupled mode theory	Induction theory
Frequency	Mega Hertz	Kilo Hertz
Efficiency	Low	High

FFWPTT is based on the electromagnetic radiation concepts which can be divided into microwave and laser according to the operating frequency. NFWPTT can be categorized as magnetic induction WPTT (MIWPTT) and electric induction WPTT (EIWPTT) .Energy transfer in MIWPTT depends on the mutual coupling between the coils which is known as inductive power transfer (IPT).In EIWPTT, energy is transferred through the electric field between the plates of the capacitor .This is known as capacitive power transfer (CPT). The main differences between the two induction methods are illustrated in Table II.

Table II
Comparison between IPT and CPT system

Technology	Performance		
	Efficiency	EMI	Frequency
Inductive Power Transfer (IPT)	Medium	Medium	10-50 kHz
Capacitive Power Transfer (CPT)	Low	Medium	100-500 kHz

III. SYSTEM DESCRIPTION

The WPT system consists of a power source which is a high speed switching circuit, primary impedance compensating

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network, two magnetically coupled coils, a secondary impedance compensating network, a high frequent rectifier, a voltage regulator and a DC load. The schematic diagram of WPT system is illustrated in Fig.1.

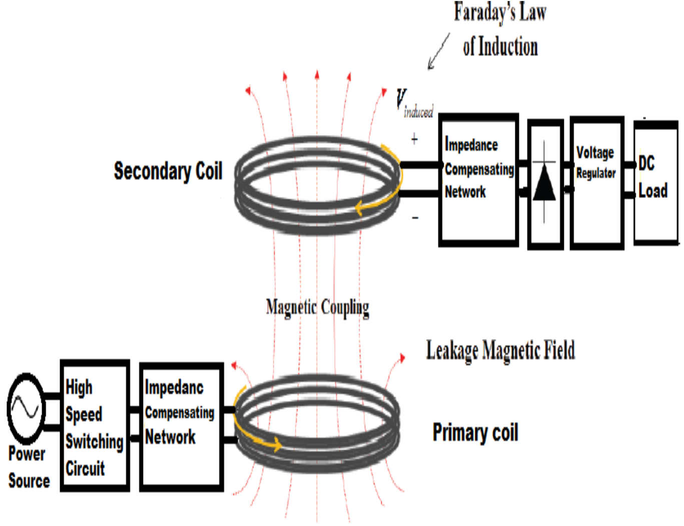

Fig. 1 Schematic diagram of WPT system

The high speed switching circuit is a single-ended high frequency quasi resonant inverter that consists of power MOSFETs and triggering circuits. A power MOSFET is a Metal Oxide Semiconductor Field Effect Transistor (MOSFET) designed to handle significant power levels and can operate at high frequencies up to hundreds of kilo Hertz. Now, the power electronics development reaches to a new power MOSFET (SiC MOSFET) that can operate at frequencies up to Mega Hertz which is used for high switching frequency applications [6].

The impedance compensating network (matching network) has a very important role in WPT system .It reduces the volt-ampere rating of the power source by minimizing the reactance of input impedance and increase the power transfer efficiency by utilizing the magnetic field resonance.

The time varying magnetic field is generated from the primary coil and is gathered at the secondary coil to transfer the average load power [7-8].

A high frequency rectifier is used to convert high frequency AC power into a DC power. There are two lose contributions associated with the diodes in a high frequent rectifier; losses due to the forward conduction of the diodes and the high frequent loss according to the switching time of the diodes. These losses act as a consequence of the reverse recovery time of the diodes. To eliminate the loss effect, Schottky diodes or ultrafast diodes are used in the rectifier circuit instead of normal diodes [9].

The voltage regulator is used to stabilize and control the DC voltage level according to the required load voltage.

The load is generally an electrical load that consumes certain electric power. The mobile battery is a common load in a WPT system as charging a mobile wirelessly means no need to connect the mobile charger to a mobile phone. The mobile phone is put on the charging pad and the charging operation starts till the phone is fully charged. The transfer circuit is attached to the charging pad and the receiving circuit is included inside the mobile.

The Wireless charging for a mobile via inductive coupling is illustrated in Fig.2.

Fig. 2 Inductive coupling between charging pad and phone

IV. MATHEMATICAL MODEL

The mathematical model of the wireless power transfer system through inductive coupling method is illustrated in this section.Fig.3 shows the simplified equivalent circuit model of the wireless power transfer system with two series resonant coils. The load power is increased by increasing by the frequency or the mutual inductance or the magnitude of source current [10].

The loop equations of the equivalent circuit are given by:

$$V_1 = Z_1 I_1 - j\,\omega\,M\,I_2 \qquad (1)$$

$$|I_2| = \frac{\omega\,M}{Z_2} I_1 \qquad (2)$$

As, V_1 is the supply voltage. I_1 and I_2 are the passing currents in the primary and secondary coils, respectively. Z_1 and Z_2 are the equivalent impedances of the transfer and receiving circuits, respectively. M is the mutual coupling between the two coils and depends on the coupling coefficient between them and the self INDUCTANCES l_1 AND l_2.

$$M = k\sqrt{l_1 l_2} \qquad (3)$$

At resonance frequency the equivalent impedances Z_1 and Z_2 can be simplified and approximated to

$$Z_1 = R_s + R_{1ac} \qquad (4)$$

$$Z_2 = R_l + R_{2ac} \qquad (5)$$

Where R_{1ac} and R_{2ac} are the series resistances of the primary and secondary coils, respectively. R_s and R_l are the source and load resistances, respectively.

The resonant frequency ω is defined as

$$\omega = \frac{1}{\sqrt{l_1 c_1}} = \frac{1}{\sqrt{l_2 c_2}} \qquad (6)$$

The load power can be deduced as

$$P_l = \frac{\omega^2 M^2}{(R_l + R_{2ac})^2} I_1^2 R_l \qquad (7)$$

The power transfer efficiency is given by

$$\eta = \frac{\omega^2 M^2 R_l}{(\omega^2 M^2)(R_l + R_{2ac}) + (R_s + R_{1ac})(R_l + R_{2ac})^2} \qquad (8)$$

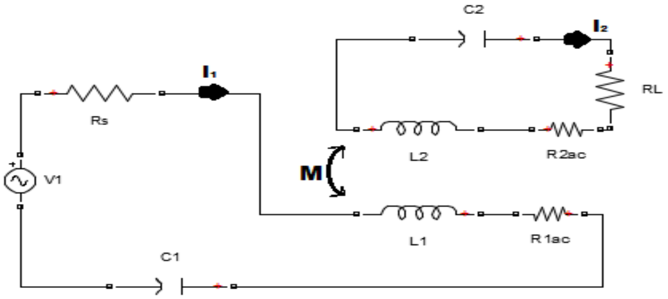

Fig. 3 Equivalent circuit of series-series resonance wireless power transfer system

From equations (7) and (8), the load power increases by increasing the frequency or the mutual inductance or the magnitude of source current. From equation (8), the efficiency increases by decreasing the parasitic resistance, increasing the frequency and the mutual inductance.

The losses due to the parasitic resistance R_{1ac} and R_{2ac} can be decreased by using Litz wire in coils design. Litz wire is used to mitigate the skin and the proximity effects. Generally, coupling is the interaction between two devices or circuits. The phenomenon of energy coupling explains how electrical energy is transferred from one device to another. When the interaction between the couplers is due to the magnetic field of one of the couplers, the coupling is known as a magnetic coupling. In magnetic coupling, the magnetic field of one of the devices induces current in the other device of the coupling system. Therefore, power can be transferred from a sending unit to a receiving one. The more flux reaches the receiver; the better the coils are coupled. The degree of coupling is expressed by the coupling factor k. From equation (3), it is clear that the coupling coefficient k depends on the medium between the two coupled coils and their parameters such as the number of turns, cross section area and coils lengths. In wireless charging the relative permeability is one. The use of two identical coils with a small spacing between them relative to the coils diameters ensures large coupling coefficient between them [11-12]. By increasing the coupling coefficient between the two coils, the power transfer efficiency will increase as illustrated in Fig.4.

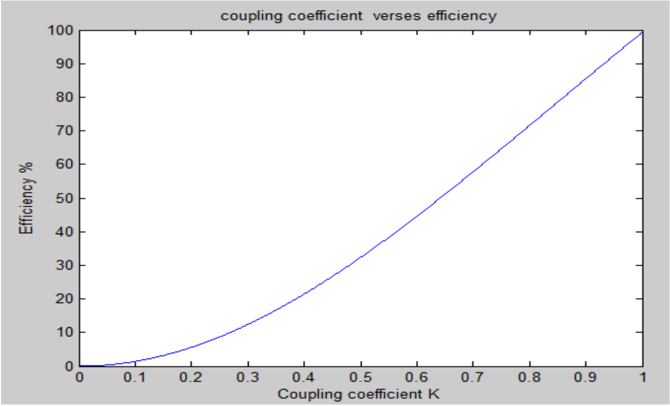

Fig.4 Relation between coupling coefficient and the power transfer efficiency in the simplified wireless charging model

V. EXPERIMENTAL WORK

The transfer coil is connected to the power source through a high speed switching circuit which operates at 112 kHz and a compensating network to achieve the resonance in the primary circuit. The receiver coil is connected to a mobile phone Nokia N70 through three stages. The first stage is a compensating network to maximize the induced current at the secondary by a series capacitor with the receiving coil. The second stage is a high frequent full wave rectifier designed using group of four Schottky diodes. The last stage is a voltage regulator and a charging system. The wireless charging system for a mobile Nokia N70 is illustrated in Fig.5.

Fig.5 Wireless charging system for Nokia N70

Fig.6 shows the relation between the load power and the loss power in the receiver circuit verses the angular frequency. It is clear that the maximum transferred power is achieved at the resonance frequency around w=700k rad/s related to the operating frequency of 112 kHz.

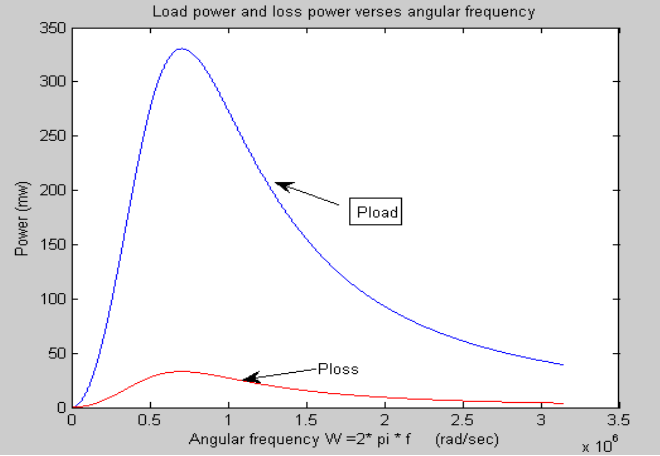

Fig.6 Load power and loss power distribution versus ω

VI. APPLICATIONS OF WPTT

There are many applications of WPTT such as:

1- Automatic wireless charging of mobile electronics

2- Robots, packaging machinery, assembly machinery and machine tools can take advantage of this technology.

3- Direct wireless power for wireless sensors and actuators, eliminates the need for expensive power wiring or battery replacement and disposal.

4- Automatic wireless charging for future hybrid and all-electric passenger and commercial vehicles, at home or in parking garages.

The IPT system is the world's first commercially wireless electric car charging system. It is described as the safest, most efficient and most effective way to transfer power without wires. The Wireless electric vehicles charging system is illustrated in Fig.7.

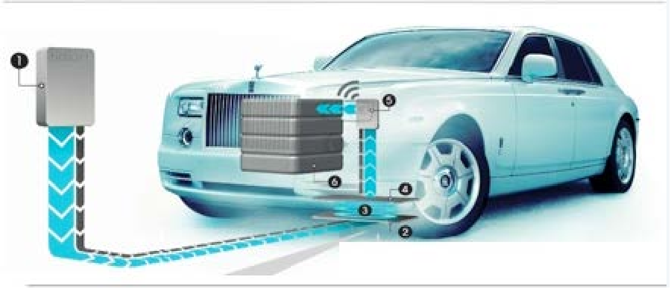

Fig.7 Wireless electric vehicles charging system

VII. CONCLUSION

Wireless mobile charging is an application of low power, short range WPTT .Our simplified model depends on series-series (SS) topology to transfer the needed power for charging inductively at resonance frequency with high coupling coefficient. The future work will be more development of this model to be of lower cost, efficient, simpler and compatible with any mobile.

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