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Selection of maximum power transfer region for resonant inductively coupled wireless charging system

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ABSTRACT

In order to uphold the maximum power transfer in a resonant inductively coupled wireless power transfer system, an operating region has been proposed based on the coupling coefficient, frequency and electric load. The effectiveness of the proposed condition has been examined both theoretically and experimentally. The obtained results are in well agreement with each other. It has been seen that the operating frequency region is different for different electric loads corresponding to the coupling coefficient between the transmitter and receiver coils of the resonant inductive link. The operating frequency region shifts to lower frequency side for lower value of electric load at larger value of coupling coefficient even maintaining the optimum power transfer. The obtained knowledge reveals the design modus operandi through which an effective wireless charging system can be intended not only for low power device applications but also for high power EV charging.

1. Introduction

Electric vehicles (EVs) are seen as next generation transportation for sustainable living and low carbon mobility [1–2]. The tribulations associated with the presently available plug-in or conductive chargers necessitate the pursuit of wireless power transfer (WPT) technology [3–5]. Being a convenient, cordless, hand-free, no touch, park and charge, reliable, safer, and suitable for all-weather conditions, wireless power transfer (WPT) system has been fetched to the forefront providing the ultimate convenience for powering/charging the electrical and electronic devices [6–10]. The inductive coupling based WPT system has been considered as a conventional means for WPT but not been adopted world-wide for EV charging due to its efficiency [11–13]. So, resonant circuits have been employed in the primary and secondary coils of WPT system to boost the power transfer capability and to minimize the voltage and current ratings of the source power supply [14–15]. Even though the primary and secondary resonant circuits are designed to operate at a particular frequency, the system performance may deviate if the coupling coefficient is not properly chosen corresponding to the electric load in order to uphold the maximum power transfer capability [16–17]. Based on the mutual coupling between the coils, generally, the WPT works in three different coupling regions like critically coupled, over coupled and under coupled regions [18–19]. In the under coupling regime, the reflected receiver coil impedance seen at the transmitter coil is lower than the transmitter coil impedance resulted from the decreased coupling coefficient. As a consequence, both the transfer power and transfer efficiency are reduced. In the over coupled regime, the reflected receiver coil impedance seen at the transmitter coil is higher than the transmitter coil impedance resulted from the increased coupling coefficient. As a result of which, the transfer efficiency increases while the transfer power decreases. In the critically coupled state, the WPT attains the maximum value whereas the transfer efficiency is nearly 50% that is resulted from the impedance matching because at least half of the power is dissipated in the source resistance. This maximum power transfer principle is a common practice used in many radio frequency (RF) circuit designs where the source impedance is considered to be fixed [20–21]. Nevertheless, the power transfer efficiency of WPT system can be enriched by keeping the source resistance as low as possible, and the load impedance comparatively higher than the source impedance. The maximum power transfer efficiency doesn't necessarily ensure maximum overall efficiency of the WPT system because there may be possibilities that a significant amount of power consumed by the source resistance itself. Rather emphasizing on the power transfer efficiency, the maximum power transfer condition can be thought of as a meaningful approach in designing an effective RF link even under poor coupling regime and when the load is not matched properly. In order to make the wireless charging system more viable, it's becoming essential to analyze and reveal the

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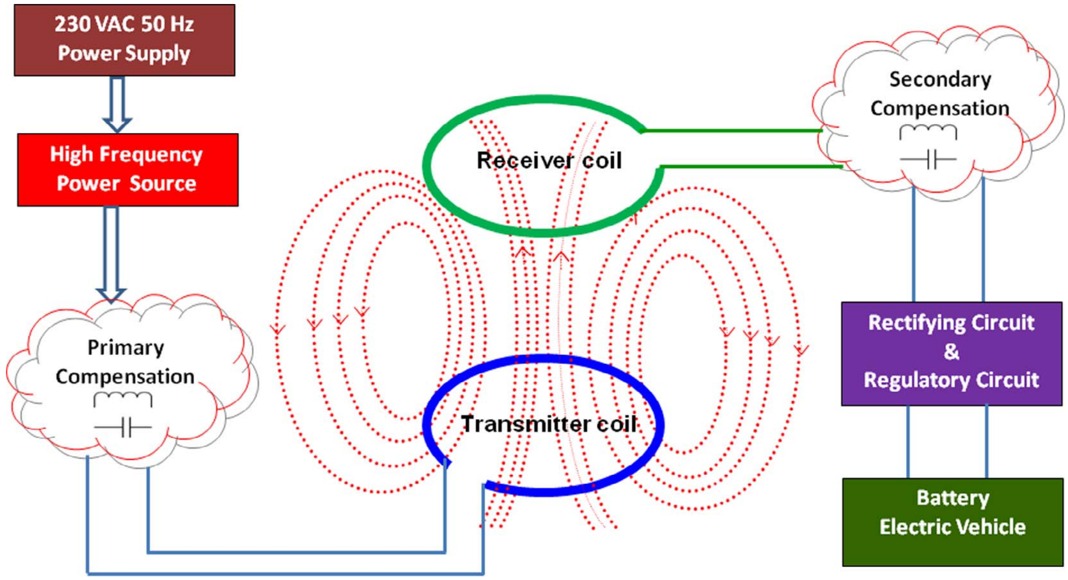

Fig. 1. Procedure involved in the resonance based wireless EV charging system.

condition to uphold maximum power transfer even under non-ideal charging scenarios which is a major concern. Therefore, the research interest has been laid to derive an operating regime for which maximum power transfer can occur. The correlation between the maximum power transfer ability with the operating frequency as well as coupling coefficient under different electric load conditions has been outlined. Both simulation and experimental investigations have been carried out to reveal the selection of maximum power transfer condition. The obtained knowledge presents the design modus operandi through which an effective wireless charging system can be intended not only for powering or charging of low power devices such as solid state devices, sensors, actuators, mobile robots, and biomedical implantable electronics but also for EV charging.

2. Experimental design and operating mechanism

The general procedure involved in the resonance based wireless EV charging system is shown as block diagram in Fig. 1. But in order to carry out the investigation for driving the optimal condition of maximum power transfer, an experimental set up has been built which is shown in Fig. 2. The system comprises of three major parts such as the associated power electronics circuitry in transmitter side, the inductive link, and the electronic circuitry connected to the receiver of vehicle side. A frequency converter circuit is used which converts the grid supply (230VAC 50 Hz) to a high frequency current source that is fed through a compensation network to the transmitting coil. The resonant inductive link comprises of mutually coupled transmitting and receiving coils. The receiver coil is connected to a compensation network in order to enhance the power transfer capability of this system. Finally, the voltage at the output of compensation network is rectified and processed through a charging circuit to feed the battery (load).

The fundamental principle behind this WPT concept is magnetic resonant inductive coupling. When the transmitting and receiving charging coils of the WPT system are in the midrange proximity (separated away from each other over a distance in the order of the coil size) their near magnetic fields will strongly couple with each other at a certain resonant frequency. The strong magnetic field coupling between

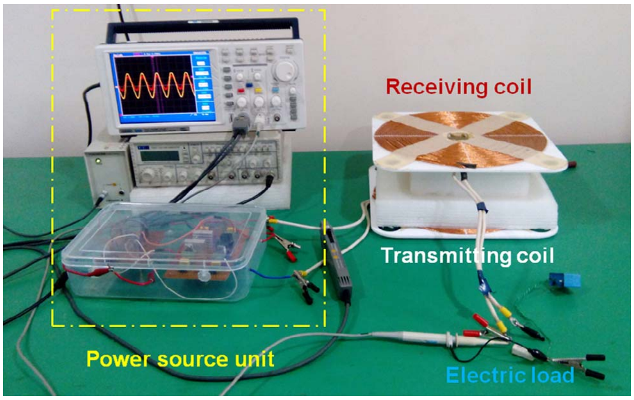

Fig. 2. Experimental setup of magnetic resonance based wireless power transfer system.

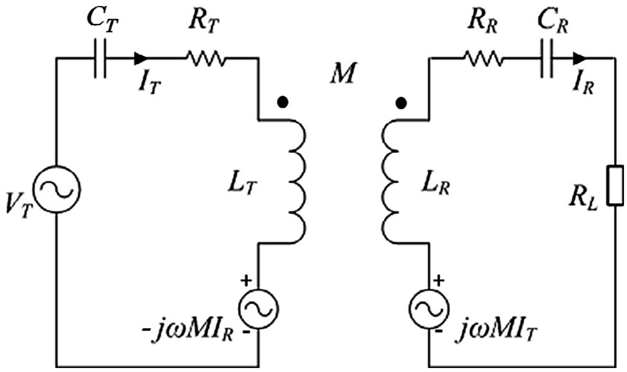

Fig. 3. Electrical equivalent circuit model of a series-tuned wireless power transfer system used for EV charging.

Table 1
Operating parameters used for calculation.

Parameters	Symbol	Value
Input DC voltage	V_T	4.12 V
Transmitter coil inductance	L_T	168 µH
Receiver coil inductance	L_R	168 µH
Transmitter tuning capacitance	C_T	330 nF
Receiver tuning capacitance	C_R	330 nF
Load resistance	R_L	50 Ω
Transmitter coil ESR	R_T	192 mΩ
Receiver coil ESR	R_R	192 mΩ
Operating resonant frequency	f_0	21.375 kHz