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Design and analysis of a wireless power transfer system with alignment errors for electrical vehicle applications

Sakir Kuzey [a], *Selami Balci* [b], *Necmi Altin* [c,*]

[a] *Giresun University, Sebinkarahisar Vocational Schools of Technical Sciences, Electricity and Energy Department, 28400, Giresun, Turkey*

[b] *Ministry of National Education, Ankara, Turkey*

[c] *Gazi University, Faculty of Technology, Electrical and Electronics Engineering Dept., 06500, Ankara, Turkey*

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ABSTRACT

In this study, a 15 kW wireless power transfer system with high frequency and large air gap for electrical vehicle battery charge systems is designed and co-simulations with ANSYS-Maxwell and Simplorer software are performed. The air gap between the primary and the secondary windings are determined as 20 cm for the 15 kW wireless power transfer system. Operation of the designed system for different operation conditions such as completely aligned windings (ideal condition) and windings with alignment errors, which can occur because of user error or another reason, are analyzed and obtained results are reported. The resonant frequency of the designed system which has a 60 × 60 cm secondary winding and a 60 × 100 cm primary winding is 17.702 kHz, and the maximum efficiency of the system is obtained as 75.38% for completely aligned windings. The distribution and density of the electromagnetic flux, and variation of efficiency versus load level of the system and responses of the system in case of different alignment errors are also investigated and reported for both ideal operation conditions and in case of alignment errors.

Introduction

Nowadays, reasons such as increase in the price of oil and its derivatives, extinction of fossil fuels and global warming increase the attention on electrical vehicles (EVs). Environmental friendly EVs have become the main driving force for automotive industry with their zero emission feature [1–3]. While the battery bank of the conventional EV is charged through the grid with a power cable and a plug, more safe wireless charge systems have become to use for the same purpose with the improvements in technology.

Similar to electrical machines and transformers, power transmission from one winding to the other one, which are magnetically coupled, is essentially known method. The overall objective of the inductively coupled power transfer (ICPT) systems is to provide wireless power transfer efficiently. The inductive coupling coefficient is one of the most important parameter of these systems. Since the power is transferred form primary winding to the secondary winding

* *Corresponding author.*
E-mail address: naltin@gazi.edu.tr (N. Altin).

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through the air gap according to the magnetic induction principle, the electromagnetic coupling coefficient is decisive variable that affects the system performance. Therefore, many studies have been proposed on determining optimal coupling coefficient and power factor compensation to obtain efficient power transfer [4].

Effects of ICPT systems on human body is an important issue and should be examined. These systems should comply with standards defined by International Commission on Non-Ionizing Radiation Protection (ICNIRP). Many studies have been performed to analyze effects of electromagnetic systems on human body. Although the operation frequency of communication systems is in range from MHz to GHz, the operating frequency values of the ICPT systems are usually lower than a few kHz because of efficiency and power level limitations. It is reported that, a proper designed ICPT system comply with the standards and they do not have hazardous effects on the human health [5].

ICPT systems are usually designed as spiral circles and rectangle geometries. The mutual inductance value of a ICPT system with spiral circles is also 45–50% higher than the ICPT system with rectangle geometries. Although, magnetic coupling value of the ICPT system with the spiral circles is higher, the ICPT system with rectangle geometries have better performance under alignment errors. Therefore, rectangle geometries are more common in EV applications [6]. In addition, ferrite core can be used in primary and secondary windings to increase the coupling coefficient [7]. In this condition, windings can be designed in different forms to obtained maximum efficiency. However, in this case, increasing core temperature triggers some disadvantages such as decreasing on coupling coefficient and linearity reduction on system control [8–10].

Enlarging size of the primary winding will not increase the system efficiency. In addition, this increases the system cost because of increasing conductor length and size of mechanical design. At this point, concordance between primary and secondary windings has come to the forefront. The maximum system efficiency is obtained with optimum inductive coupling coefficient, proper compensation topology, and providing operation at resonant frequency [11,12].

Since these ICPT systems are supplied with high frequency voltage, resonant converters, which are commonly used in different applications such as induction heating, electronic ballasts, power supplies, etc., are used at the converter stage to obtain higher efficiency values [13,14]. Therefore, there are number of studies on electromagnetic design of the ICPT system [15,16], converter and resonator circuit design issues [17,18]. In addition, the placement of the ICPT system receiver and transmitter windings directly affects the system performance. Alignment errors are very common in a practical wireless power transfer system for EV applications Therefore, some studies on auto-alignment of the EVs are also proposed [19]. However, effects of different alignment errors on system performance are rarely analyzed.

In this study, a 15 kW ICPT system with 20 cm air gap is designed. Then the designed system is simulated with finite element analysis software. The model of the ICPT system is also co-simulated with inverter and compensation circuits to obtain more realistic results. Besides the ideal operation conditions without any alignment error, presence of different alignment errors between the windings are also analyzed. The flux distribution, and efficiency of the ICPT system are interpreted. In addition, efficiency variation versus load is also analyzed. It is seen from the simulation results that the proposed system is low magnetic coupled systems with 0.1556 electromagnetic coupling coefficient. In addition, the maximum efficiency value of the ICPT system is obtained as 75.38% for ideal condition, and 33.35% and 46% for alignment error and 2-degree gradient alignment error conditions, respectively.

Inductive magnetic coupled power transfer systems

Uncompensated circuit model of inductive magnetic coupled power transfer system, which makes understanding the system easy is seen in Fig. 1. This is the most fundamental figure [20]. Here, V_p is rms value of sinusoidal signal applied to primary winding. Assuming that voltage and current are sinusoidal, the induced voltage in secondary winding due to the primary current I_p is $j\omega MI_p$, reflected voltage in the primary winding due to the secondary current I_s is $-j\omega MI_s$ where "M" is on the mutual inductance and ω is the operation frequency [21].

Mathematical equation of system's equivalent circuit must be derived in order to follow power flow of ICPT system. According to equivalent circuit, Eq. (1) can be written for input voltage V_p [7,8,11].

$$V_p = [R_p + j(\omega L_p)]I_p - j\omega MI_s = (R_p + jX_p)I_p - j\omega MI_s = Z_pI_p - j\omega MI_s \quad (1)$$

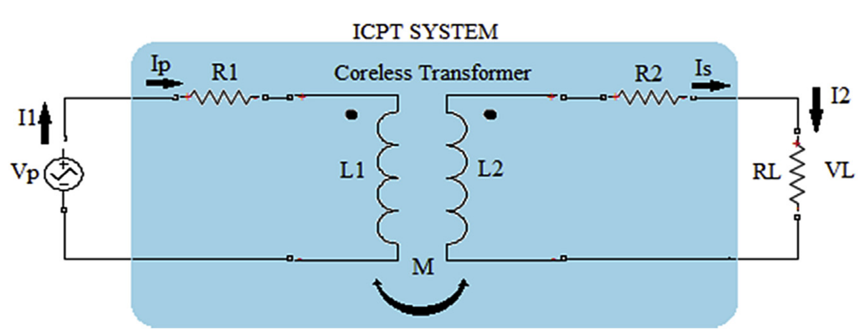

Fig. 1 – Electrical equivalent circuit of ICPT system.