Energy Conversion and Management 65 (2013) 487–496

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Efficiency analysis of contactless electrical power transmission systems

Saeed Hasanzadeh, Sadegh Vaez-Zadeh *

School of Electrical and Computer Engineering, Faculty of Engineering, University of Tehran, North Kargar Ave., P.O. Box 14395/515, Tehran, Iran

ARTICLE INFO

Article history:
Received 25 May 2010
Received in revised form 18 June 2012
Accepted 12 July 2012
Available online 17 October 2012

Keywords:
Contactless electrical power transfer system
Inductive power transfer
Optimal resonance frequency
Maximum efficiency

ABSTRACT

In this paper, efficiency analysis and design of contactless electric power transfer systems working based on an inductive method are elaborated. Large leakage inductances of the systems are compensated to achieve resonance conditions for maximum efficiency. Considering the circuit models of a contactless system, the effects of different parameters including the compensating capacitors are analyzed for a specified frequency range and coupling coefficient. An algorithm is proposed to determine the optimal capacitors and resonance frequency. It is verified by experimental results.

1. Introduction

In recent years, with the growth of portable electronic equipment such as notebooks and cell phones, new demands for contactless electrical power transfer (CEPT) are developed and the research on this kind of power transfer is gained more attentions. The CEPT may be achieved by different methods including microwave radiation [1], capacitor power transfer [2] and inductive power transfer (IPT) [3]. Inspiring by the concept of mutual induction and resonance phenomenon, the IPT systems are attractive as a re-emerging technology. The IPT systems have many low and high power applications. They can be utilized to supply high power moving objects such as railway transportation systems [4]. Also, the systems can be applied to electric vehicles [5]. They can reduce the battery volume in hybrid electric vehicles [6] as well as hazards associated with plug-in vehicles [7]. The systems may have disadvantages such as effects of high electromagnetic fields on human health as a set of standards have been developed by the International Commission on Non Ionizing Radiation Protection (ICNIRP) [8].

An IPT system is composed of at least two coils, i.e. sender (primary) and the receiver (secondary) separated by an air gap. The most important aspect affecting a future wide spread application of such a system is the overall system efficiency. The IPT efficiency decreases rapidly by an increasing system air gap, which in turn increases the leakage inductances and magnetizing current. The efficiency also depends on the system operating frequency as the most influential factor to intensify the magnetic coupling between the primary and secondary sides. It is known that resonance frequencies on both sides contribute to a strong coupling, especially when the resonance frequencies are the same [9]. Compensating (resonant) circuits of different structures can be used in primary and secondary to achieve resonance conditions. Depending on the series (S) or parallel (P) connections of capacitors in the primary and secondary; four structures as SS, SP, PS and PP are built [10,11]. The combination of series and parallel connections are also used [12,13].

Different aspects of IPT systems are studied recently. A comparative study between resonance and non-resonance based inductive magnetic coupling methods is elaborated [14]. However, optimum resonance frequency for obtaining high efficiency is not considered. A contactless power delivery system is presented to transfer power to moving objects [15]. However, the optimal conditions are not investigated. An IPT system is proposed for a rotatable transformer in which the effects of load and air gap variations are studied for different compensation structures [10]. However, the effect of changing the operating frequency on the system efficiency is not studied. An IPT optimization algorithm is utilized to design an inductively coupled power transfer, with four compensation structures for a public transportation system [11]. But, the system efficiency is not analyzed for different operating conditions under varying coupling coefficient and frequency. A boundary frequency is found for optimal operation of contactless transformers under different loading conditions [16]. However, system parameters are not adjusted to obtain high efficiency for different cases. Keeping in mind this critical review, a thorough analysis of the factors influencing the IPT power transfer efficiency is essential for a practical system design.

* Corresponding author.
E-mail addresses: shasanzadeh@ut.ac.ir (S. Hasanzadeh), vaezs@ut.ac.ir (S. Vaez-Zadeh).
URL: http://eng.ut.ac.ir/ece/vaez-zadeh (S. Vaez-Zadeh).

0196-8904/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2012.07.007

In this paper the efficiency of an IPT system is obtained analytically in terms of coupling coefficient and resonance frequency; the former being a function of air gap, system structure and self and mutual inductances. A rather deep analysis is carried out to investigate the influences of the parameter variations on the system characteristics including efficiency and coupling coefficient. It is also shown that the efficiency strongly depends on the resonance frequency. An algorithm is developed to determine the optimal compensating capacitor and system resonance frequency. Finally, simulation results are verified by experimental results.

2. System model

An IPT system with a high frequency power source, two resonance circuits, a power conditioner and a load are shown in Fig. 1a. In Fig. 1b a system model with series resonant capacitors for the primary and secondary coils (SS), is shown. Also, Fig. 1c shows a model with a series resonant capacitor and a parallel capacitor (SP) for the primary and the secondary coils respectively. R_1 and R_2 are the resistance of the primary and the secondary sides, L_1 and L_2 are the self-inductances of two coils respectively; C_1 and C_2 are the resonant capacitances, M is the mutual inductance between the coils and R_L is the resistance of the load.

The power converter (inverter) is modeled by a sinusoidal voltage source with an internal resistor (R_{loss1}). The inverter switching losses can be included into R_{loss1}. The power conditioner loss in the secondary is also modeled by a resistor (R_{loss2}). The windings resistors (R_{cu}) depend on the system operating frequency due to skin effect. Therefore, the following equations are valid:

$$\begin{aligned} R_{1,2} &= R_{cu1,2} + R_{loss1,2} \\ R_{cu1,2} &= R_{ac1,2} = F_R(X) R_{dc1,2} \end{aligned} \tag{1}$$

where $F_R(x)$ represents the ratio of ac to dc resistances. The core losses are ignored due to a rather large air gap and the use of ferrite material in the core.

The efficiency of the system in SS structure is obtained as [17]:

$$\eta_s = \frac{R_L}{(R_2 + R_L) + \frac{R_1}{(\omega M)^2}\left[(R_2 + R_L)^2 + \left(L_2\omega - \frac{1}{C_2\omega}\right)^2\right]}. \tag{2}$$

$$\frac{1}{\sqrt{L_1 C_1}} = \omega_1 = \omega_0 = \omega_2 = \sqrt{\frac{1}{L_2 C_2}} \tag{3}$$

If (3) is satisfied, the efficiency of the system with SS structure is obtained as (4):

$$\eta_S = \frac{R_L k^2 \omega_0^2 L_1 L_2}{(R_L + R_2)(R_1 R_L + R_1 R_2 + k^2 \omega_0^2 L_1 L_2)} \tag{4}$$

where $\omega_0 = 2\pi f_0$ is the angular resonance frequency in rad/s and $k = M/\sqrt{L_1 L_2}$ is the coupling coefficient.

The efficiency of the system with SP structure is given by:

$$\eta_P = \frac{R_L}{[R_L + R_2(1 + (R_L C_2 \omega)^2]) + \frac{R_1}{(\omega M)^2}[(R_L + R_2 - R_L C_2 L_2 \omega^2)^2 + \omega^2 (L_2 + R_L C_2 R_2)^2]}. \tag{5}$$

$$\frac{1}{\sqrt{L_1 C_1}} = \omega_1 = \omega_0 = \omega_2 = \sqrt{\frac{1}{L_2 C_2} - \frac{1}{R_L^2 C_2^2}} \tag{6}$$

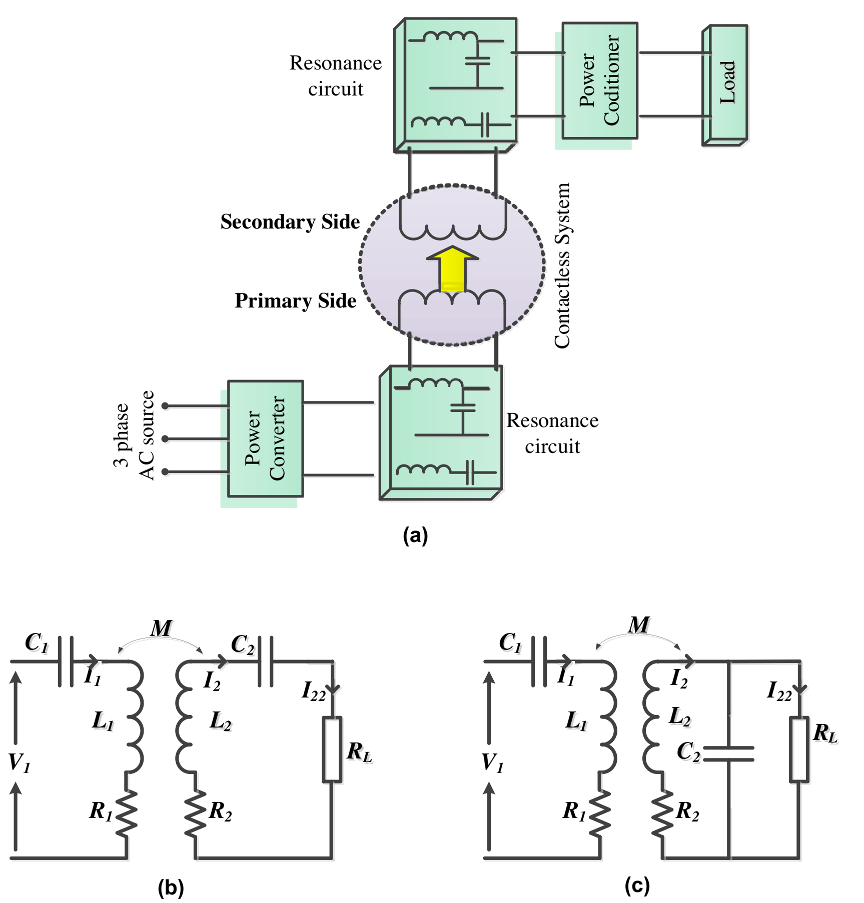

Fig. 1. System diagram (a) and circuit model of the contactless power transfer, (b) SS and (c) SP structures.