http://ansinet.com/itj

ITJ

ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 12 (23): 7148-7151, 2013
ISSN 1812-5638 / DOI: 10.3923/itj.2013.7148.7151

Consistence Analysis and Validation of Non-radiative Wireless Power Transmission via Resonant Coupling

Zhang Xian, Yang Qing-Xin, Zhang Xin, Zhang Peng-Cheng, Li Yang and Jin Liang
Tianjin Key Laboratory of Advanced Electrical Engineering and Energy Technology,
Tianjin Polytechnic University, 300387, Tianjin, China

Abstract: In this study we investigate the fundamental issues of near-field wireless power transfer (WPT) through two kinds of coupled mode theory which are coupling in time formalism and coupling in space. A series of key factors that affect system performance are discussed, so as the effective range of activity. It is shown that the conclusion can be applied to other non-radiative power transfer system via Electro-Magnetic (EM) fields and proved by simulation and experimental results.

Key words: Resonantly coupling power transmission, coupled mode theory, critical strong coupling, three-coil wireless power link, optimal impedance feed

INTRODUCTION

As novel technology for energy storage, conversion and transmission wireless power transmission technology, which has wide prospect on electric vehicles, aerospace, power systems, biomedical, communications technology, is paid more and more attention by researchers of many countries (Zhang *et al*., 2010; Kurs *et al*., 2007; Karalis *et al*., 2008). According to its different application situations, it can be divided into three patterns which are which are Inductive Power Transmission (IPT) (range of a few hundred kHz), Resonantly Coupling Power Transmission (RCPT) also called as witricity (range of several MHz) and directly microwave radiation (range above Ghz) (Elliot *et al*., 2006; Hamam *et al*., 2007). Among them, RCPT is based on strongly coupled magnetic resonances to transfer energy wirelessly via non-radiative near field between them. Compared with IPT, the transmission distance in RCPT is expanded to the order of meter so that it is more convenient to recharge the electrical equipment.

In this study, we focus on non-radiative power transmission technology through which wireless electrical devices can be charged freely and efficiently. It supplies energy to electrical devices that work in vivo studies or under some harsh environments with advantages of simple structure and high reliability than power transmission via EM radiation or laser (Takagaki *et al*., 2006). However, theoretical system of WPT is still incomplete, though some products based on this technology have been developed. The discussion of coupling mechanism is based on lumped parameter equivalent circuit model (Elliot *et al*., 2006), in which the influence of frequency change to system has been ignored. And power transfer in time domain is studied by Kurs *et al*. (2007) and Karalis *et al*. (2008) without considering the fluctuation of high-frequency electro-magnetic fields in space. Therefore, consistent analysis is necessary to search for associations in various WPT forms and improve system performance.

RANGE DETERMINATION OF NON-RADIATIVE WPT

It is in essence different from EM radiation or laser that power is picked up from the near field of an oscillating source. And there is no determined proportion between electric field strength and magnetic field strength. (Sample *et al*., 2008)

Considering a current loop surrounded by linear isotropic homogeneous medium in x-y plane of infinite space, the wave impedance is expressed as (1) and the relationship with k*r is shown in Fig. 1:

$$Z_H(r) = \left|\frac{\boldsymbol{E}_\varphi(r)}{\boldsymbol{H}_\theta(r)}\right| = \eta_0 \left|\frac{1+\dfrac{1}{jkr}}{1+\dfrac{1}{jkr}+\dfrac{1}{(jkr)^2}}\right| \qquad (1)$$

where, wave number $k = 2\pi/\lambda$; η_0 is the free-space impedance; r is the distance from the source to the observation point in meters.

Corresponding Author: Zhang Xian, Tianjin Key Laboratory of Advanced Electrical Engineering and Energy Technology, Tianjin Polytechnic University, 300387, Tianjin, China

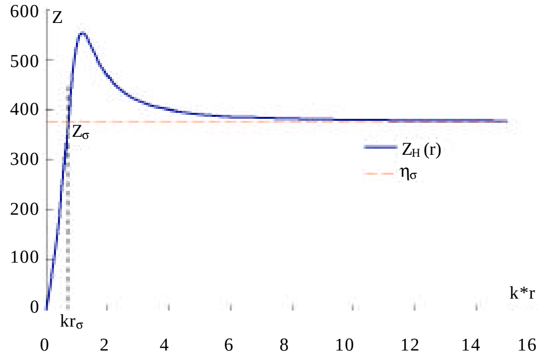

Fig. 1: Wave impedance of current loop

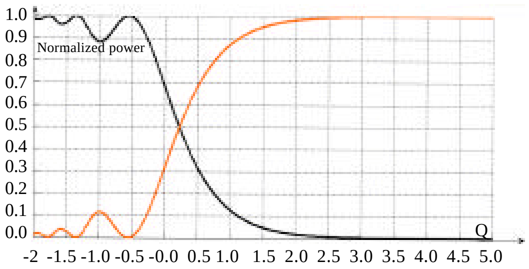

Fig. 2: Normalized power as a function of Q

When the wave impedance increases to Z_0, EM field behaves like wave propagation in free space. Here, $r_0 \approx 0.8*2\pi/\lambda$ and power density of near field is $S_{av} = \frac{1}{2}*\mathrm{Re}\,[E\times H^*] \approx 0$. Note that there is still some power radiated from the region, which can be described as a radiation resistance.

When the coupling between the two waveforms is taken into account, (2) is proposed where α and α^* are two reverse rotated vectors; κ is the coupling coefficient in unit length; and the propagation constant $\beta = \pm\omega\sqrt{LC}$ (Haus, 1983):

$$\begin{cases} \dfrac{da_1(z)}{dz} = -j\beta_1 a_1(z) + j\kappa a_2(z) \\ \dfrac{da_2(z)}{dz} = -j\beta_2 a_2(z) + j\kappa a_1(z) \end{cases} \tag{2}$$

When boundary conditions of (3) is added, the solution of (2) is achieved, where Q is expressed as (4):

$$\Omega: \quad a_1(0) = 1 \qquad a_2(0) = 0 \tag{3}$$

$$Q = \frac{2\kappa}{\beta_1 - \beta_2} = \frac{2\kappa}{\Delta\beta} \tag{4}$$

It can be seen that when Q is large enough and $\kappa z = n\pi/2$, (here n = 1, 2 ,3…), power in wave No.1 is completely transferred to wave No. 2. And their relationship with Q is shown in Fig. 2 where Q is represented by logarithmic coordinates and power is normalized.

Therefore, coupling or power transmission between waveforms do not only depend on coupling coefficient, but also depends on their Q, which can be called as coupling capability factor. At the same time, when waves coupling is discussed in time domain using coupled mode theory, the coupling capability factor is correspondingly changed into $Q = 2\kappa/(\omega_1-\omega_2) = 2\kappa/\Delta\omega$ where $\omega_{1,2}$ are angular frequencies of the two waves. (Yang *et al.*, 2010) At the time when t = 0 if the initial condition is as (5), the time-domain solution of the oscillation modes is achieved, (6):

$$\Gamma: \quad t = 0, \quad a_1(t) = A_1(0); \quad a_2(t) = 0 \tag{5}$$

$$\begin{cases} |a_1(t)| = \left|A_1(0)[\cos(\Omega t) + j\dfrac{\omega_{10} - \omega_{20}}{2\Omega}\sin(\Omega t)]\right| \\ |a_2(t)| = |A_1(0)\kappa_{21}\sin(\Omega t)/\Omega| \end{cases} \tag{6}$$

If there is a sustained oscillation, one of the characteristicroots is a non-negative number at least. Additionally from (6), we can get that the condition to maximum the amount of power exchange is to keep the resonators working at the same resonant frequency. Based on theaboveanalysis,the prerequisite for power exchange in a RCPT system is shown in (7) as:

$$\begin{cases} |\kappa_{12}\kappa_{21}| > 1/(Q_1 Q_2) \\ \omega_{10} = \omega_{20} \end{cases} \tag{7}$$

According to the derivation, the factors constrain power exchange include mode coupling coefficient, the resonant angular frequency and quality factor. The relationship of normalized power exchange of the resonant modes is shown in Fig. 3 where $|\alpha_1|^2$, $|\alpha_2|^2$ and $|\alpha_1+\alpha_2|^2$ denote, respectively the energy of α_1, α_2 and the whole system. According to the derived equations, the factors that restrict power exchange include angular frequency, quality factor and mode-coupling factor. Among them, the energy acquired by the receiving end becomes a smallvalue if angular frequencies differ from each other or mode-coupling factor are not large enough. Additionally the total energy declines sharply if the quality factor is too low. As soon as the requirements of (4) are met, it is working under the strong coupling state in which the proportion ofenergy exchange reaches 100% theoretically. And the total energy is decreased under exponential law because the sense of Joule loss and a small portion of radiationloss.

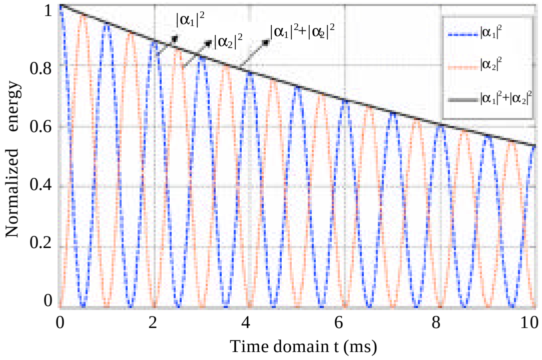

Fig. 3: Schematic of normalized power exchange

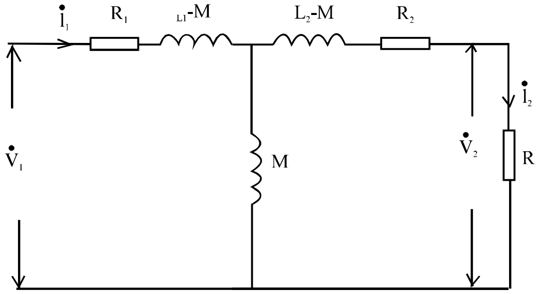

Fig. 4: Equivalent circuit of WPT in less coupling region

When the phase delay effect can be ignored, power transmission system is represented as an equivalent circuit of loosely coupled transformer as Fig. 4:

$$P_{omax} = \frac{V_1^2 M^2}{2\omega L_1 (L_1 L_2 - M^2)} = \frac{V_1^2}{2\omega L_1 (\frac{L_1 L_2}{M^2} - 1)} \quad (5)$$

Here, the coupling coefficient is:

$$\kappa = M/\sqrt{L_1 L_2} \quad (6)$$

When κ reaches to 1, output power goes to maximum. κ is increased when the loops is as close as possible and placed asymmetrically. When power density is still not enough in near field, iron core is applied in system. It should be noted that, (6) is only applicable to the less coupling region in which there is no frequency splitting.

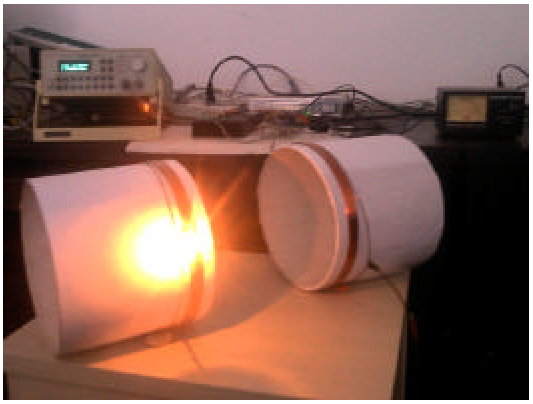

Fig. 5: Supply power to the 24 V/20 W bulb 30 cm spaced

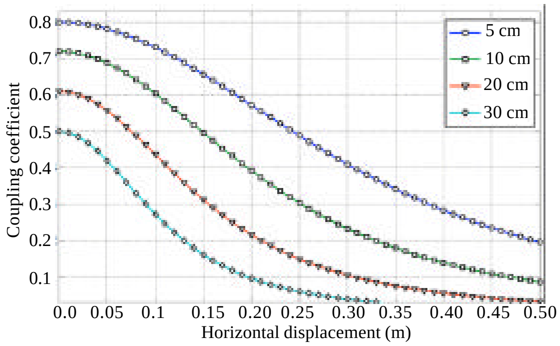

Fig. 6: Coupling coefficient change with horizontal displacement

Table 1: Parameters of RCPT system composed of helical resonators

Source/device coil	Parameters	Resonator	Parameters
Diameter (mm)	2	Diameter (mm)	2
Radius (mm)	125	Average radius (mm)	125
Inductance (μH)	0.75	Inductance (μH)	4.81
Resistance (Ω)	0.096	Resistance (Ω)	1.16
Conductivity (S/m)	5.98×10^7	Conductivity (S/m)	5.98×10^7
Load resistance (Ω)	40	Resonant frequency (MHz)	10
Spacing (mm)	300	Capacitance (pF)	60.6
Error range	±2.5%	Wire spacing(mm)	1
Skin depth (mm)	0.021	No. of turns	10

SIMULATION AND EXPERIMENT VALIDATION

In order to verify the accuracy of this model, a resonantly coupling system contains helical oscillators is designed whose detailed parameters are shown in Table 1. We built a strongly coupled model of WPT which lights up a bulb about 20W 30 cm away from the source considering phase and time delay effects. When system operates in low frequency, iron core is added to increase the power density. The transmitter and receiver have symmetric structure and are placed coaxially.

The physical diagram and structure of helical oscillators, which had been tuned into the same resonant frequency, are shown in Fig. 5 where the single coils indicate the source and device coil. The device coil is connected to a 24 V/20 W bulb from which the active power can be displayed by the brightness. Coupling coefficient change with horizontal displacement is shown in Fig. 6.

It is shown that system performance is mainly subject to drive power, coupling coefficient and quality factor.

CONCLUSION

Non-radiative WPT technology sends power to the device that in a certain range which depends on wavelength of the field emission source. It reflects essential difference from antenna that reactive power in the near field is employed rather than EM radiation in far field. The principle of coupling is proposed by coupled mode theory in space domain and in time domain. Accordingly, it proved that not only coupling coefficient is a key factor should be considered, but also phase delay and time delay effects. When system runs in a frequency that is low enough to ignore phase delay, it is called as loosely coupling in which the drive power, coupling coefficient and quality factor are main factors to system performance. Strongly coupling theory and coupling coefficient in loosely coupling system are validated by the results of experiment and simulation.

ACKNOWLEDGMENTS

This Project was supported by the National Natural Science Foundation of China under grant No. 51237005 and 51307120; Tianjin Education Commission research project 20120416.

REFERENCES

Elliot, G.A.J., J.T. Boys and G.A. Covic, 2006. A design methodology for flat pick-up ICPT systems. Proceedings of the 1st IEEE Conference on Industrial Electronics and Applications, May 24-26, 2006, Singapore, pp: 1-7.

Hamam, R.E., A. Karalis, J.D. Joannopoulos and M. Soljacic, 2007. Coupled-mode theory for general free-space resonant scattering of waves. Phys. Rev. A, Vol. 75. 10.1103/PhysRevA.75.053801

Haus, H.A., 1983. Waves and Fields in Optoelectronics. 3rd Edn., Prentice-Hall, New Jersey, ISBN-13: 978-0139460531, Pages: 402.

Karalis, A., J.D. Joannopoulos and M. Soljacic, 2008. Efficient wireless non-radiative mid-range energy transfer. Ann. Phys., 323: 34-48.

Kurs, A., A. Karalis, R. Moffatt, J.D. Joannopoulos, P. Fisher and M. Soljacic, 2007. Wireless power transfer via strongly coupled magnetic resonances. Science, 317: 83-86.

Sample, A.P., D.J. Yeager, P.S. Powledge and A.V. Mamishev, 2008. Design of an RFID-based battery-free programmable sensing platform. IEEE Instrumentation Measure. Trans., 57: 2608-2615.

Takagaki, T., T. Yamamoto, K. Fujimori, M. Sanagi and S. Nogi, 2006. Efficient design approach of mW-class RF-DC conversion rectenna circuits by FDTD analysis. Proceedings of the Asia-Pacific Microwave Conference, December 12-15, 2006, Yokohama, Japan, pp: 1945-1948.

Yang, Q., G. Xu, J. Jin, D. Geng, W. Fu, W. Yan and M. Sun, 2010. Optimal design of energy transmission system for implantable device base on WiTricity. Proceedings of the 14th Biennial IEEE Conference on Electromagnetic Field Computation, May 9-12, 2010, Chicago, IL., USA., pp: 1-1.

Zhang, X., Y. Li, H.Y. Chen, Y. Li and Z. Yan, 2010. The application of non-contact power transmission technology (NPT) in the modern transport system. Proceedings of the International Conference on Mechatronics and Automation, August 4-7, 2010, Xi'an, China, pp: 345-349.