Lateral and Angular Misalignment Analytical Study for a Novel Witricity Charger

Junhua Wang[1], S. L. Ho[1], W. N. Fu[1], and Mingui Sun[2]

[1]Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong
[2]Department of Neurological Surgery, University of Pittsburgh, Pittsburgh, PA, USA
junhua.wong@polyu.edu.hk

Abstract —This paper presents an analytical model, based on Witricity technology, for resonant magnetic coupling to include misalignments between the transmitter and receiver. The relationship between the energy transfer efficiency and several key system parameters is analyzed using finite element method (FEM). Formulae to incorporate coil characteristics and misalignments are derived for the magnetic field computation of the receiver coil when it is laterally and angularly misaligned from the transmitter. Experiments have been carried out to facilitate quantitative comparison. It is shown that a maximum degree of misalignment can be defined in a given application. The reported finding allows a formal design procedure to be established for optimization of Witricity charger for a given application.

Index —Coupling efficiency, inductive coupling, misalignments, Witricity

I. Introduction

In contrast to traditional magnetic inductive coupling [1-3] in energy transmission for wireless non-radiative mid-range energy transfer, the well known oscillatory resonant electro-magnetic modes which are referred as Witricity modes have been investigated extensively with slow and localized evanescent field patterns. Detailed theoretical and numerical analysis reported in [4] reveals that such an efficient mid-range wireless energy exchange is practically realizable. There is only modest loss and very little energy is dissipated in other off-resonant objects. In essence, the exchange system of Witricity is carefully designed to operate in a regime of 'strong coupling' [4, 5]. In both traditional magnetic coupling and advanced Witricity systems, the transmitter and receiver coils are separated by a layer, in the range of 1 cm to 5 cm. The coils are usually misaligned, due to anatomical constraints and hence the coupling efficiency is inevitably impaired.

The contribution of this paper is to introduce a novel power transfer function to address misalignments of the Witricity coils. The analyzed results for the resonant power transfer developed will allow the designer to optimize the efficiency of the link and predict the effect of coil characteristics and misalignment on the coupling factor. An interpolative finite element analysis (FEA) modeling simulation is introduced to study the performance of Witricity systems with lateral and angular misalignments.

II. Modeling of the Witricity Charger

An FEM model for a Witricity system is presented in Fig. 1 and formula for expressing the power transfer from transmitter to receiver is derived based on the model. Extended model geometries for several turns of the transmitter coil and the receiver coil are also proposed with lateral and angular misalignments, respectively.

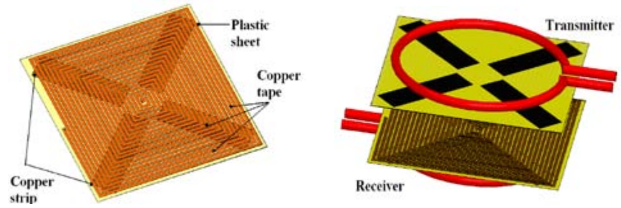


Fig. 1. FEM schematics of the Witricity charger.

Based on Biot-Savart law, the induced magnetic field at the receiver can be expressed as

$$\vec{H}_{induced} = \frac{I \cdot n_T}{4\pi} \oint \frac{d\vec{l} \times \vec{r}}{r^3} \tag{1}$$

where; n_T is the number of turns; $d\vec{l}$ is the tangential vector along the circular coil; r is the distance from the center of the receiver to the edge of the transmitter.

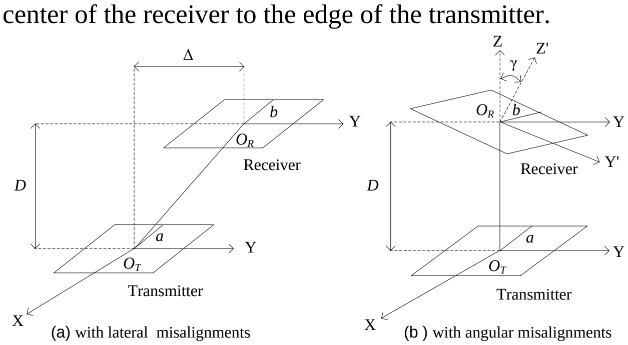


Fig.2. Configurations of the Witricity model with lateral and angular misalignments.

III. Lateral and Angular Misalignments

Configurations of the Witricity model with lateral and angular misalignments are shown in Figs. 2(a) and (b). A set of design formula is as given below, and the FEM analysis has been carried out to showcase the system performance.

A. *Lateral Misalignment*

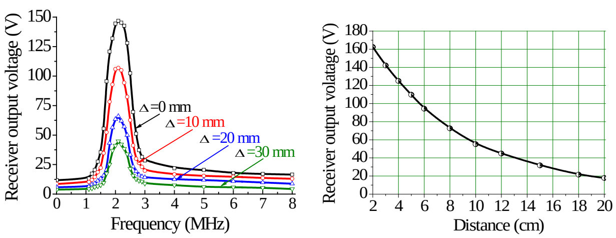
In the lateral misalignment case, the transmitter and the receiver coils are located in parallel planes and their centers are offset by a distance Δ. The *x* and *y* components of the magnetic field vector can be ignored because they are parallel to the plane of the transmitter coil. The component along z axis is

$$H_{z-induced} = \frac{\frac{a}{\pi}\sqrt{2m}}{\left(\frac{a}{\pi}\Delta\right)^{2/3}} \left(\Delta K(m) + \frac{\frac{4a}{\pi} m - (2-m)\cdot\Delta}{2-2m} \cdot E(m) \right) \tag{2}$$

where; *K(m)* and *E(m)* are the complete elliptic integrals of the first and second kind, respectively; *m* is the modulus ($0 \le m \le 1$).

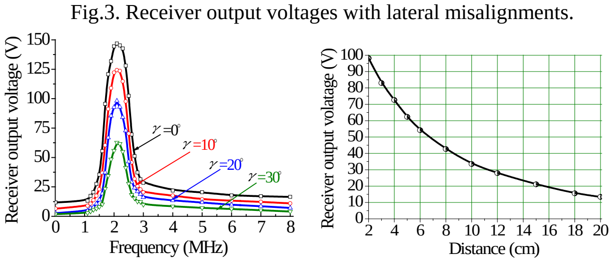
$$m = \left[\frac{\left(\frac{16a}{\pi}\Delta\right)}{(\frac{4a}{\pi}+\Delta)^2 + D^2} \right] \quad (3)$$

The distance between the two coils is fixed to 5 cm. Fig. 3(a) shows the receiver's output voltage at the frequency range from 0.01 MHz to 10 MHz, when the lateral misalignment between the transmitter and the receiver is 0 mm, 10 mm, 20 mm and 30 mm. It can be seen that all of the four wave lines have a large peak when the frequency is at about 2.03 MHz which are, namely, 146.84 V for 0 mm, 106.92 V for 10 mm, 66.03 V for 20 mm and 44.88 V for 30 mm. The receiver's output voltage values are recorded in Fig. 3(b) at the frequency of 2.03 MHz according to the FEM simulation, when the lateral misalignment is 10 mm and the distance between the transmitter and the receiver is changed from 2 cm to 20 cm. It can be seen that there are large peak when the frequency is at about 2.03 MHz, which are 109.35 V for 5 cm, 57.19 V for 10 cm, 31.84 V for 15 cm and 17.76 V for 20 cm.



(a) vs. frequency (b) vs. distance

Fig.3. Receiver output voltages with lateral misalignments.



(a) vs. frequency (b) vs. distance

Fig. 4. Receiver output voltages with angular misalignments.

B. *Angular Misalignment*

In the angular misalignment case the transmitter and the receiver coils are tilted to form an angle of γ. The *x* and *y* components of the magnetic field vector can be ignored due to the circular symmetry at the center of the receiver coil. The component along the *z*-axis is

$$H_{z-induced} = \frac{\frac{16a^2}{\pi}\cdot\cos\gamma}{\left(\left(\frac{4a}{\pi}\right)^2 + D^2\right)^{3/2}} \quad (4)$$

Fig. 4(a) shows the output voltage of the receiver at the frequency range from 0.01 MHz to 10 MHz, when the angular misalignments between the transmitter and the receiver are 10°, 15°, 20°and 30°. The distance between the two coils is also fixed to 5 cm. All the four waves have large peak values when the frequency is at about 2.03 MHz which are, namely, 146.84 V for 0°, 124.32 V for 10°, 98.14 V for 20° and 62.75 V for 30°. When the angular misalignment between the transmitter and the receiver is fixed at 30°, the receiver's output voltage values decrease from its peak value of 98.14 V to 13.42 V at the resonant frequency of 2.03 MHz as shown in Fig. 4(b).

IV. Experiment Results

A prototype model is built and experiments have been carried out corresponding to the FEM simulation setups. The distance between the two coils is fixed at 5 cm and the resonant frequency is 2.34 MHz, which is slightly different from the FEM results.

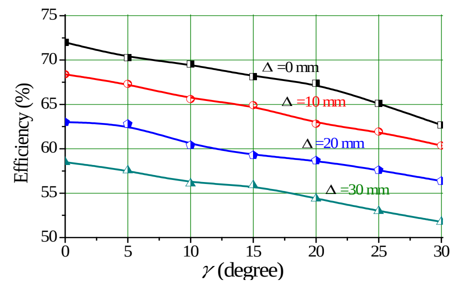


Fig. 5. The system efficiency versus distances with lateral and angular misalignments.

The most important parameters among these results are the efficiency against distance as shown in Fig. 5. Even when the lateral misalignment is 30 mm and the angular misalignment is 30°, the efficiency at 5 cm is up to 52.3% according to the test results of the system. It should be noted that by using traditional magnetic inductive coupling methods, the distance must be kept much shorter in order to obtain the same efficiency.

V. Conclusion

This paper presents a novel analytical model for Witricity, incorporating misalignment effects. FEM simulations and corresponding experiments for the magnetic field at the receiver under lateral and angular misalignments have been suggested. The analytical model introduced can be used to develop a design procedure for optimum power transfer in low power inductive links. It is the intention of this research to extend the model to study square and circular spiral coils.

References

[1] J. Murakami, F. Sato, T. Watanabe, etc., "Consideration on cordless power station - Contactless power transmission system," *IEEE Trans. on Magn.*, vol. 32, no. 5, pp. 5037 -5039, 1996 .

[2] H. Miura, S. Arai, Y. Kakubari, F. etc., "Improvement of the Transcutaneous Energy Transmission System Utilizing Ferrite Cored Coils for Artificial Hearts," *IEEE Trans. on Magn.*, vol. 42, no. 10, pp. 3578-3580, 2006.

[3] H. Matsuki, Y. Yamakata, N. Chubachi, etc., "Transcutaneous DC-DC converter for totally implantable artificial heart using synchronous rectifier," *IEEE Trans. On Magn.*, vol. 32, no. 9, pp.5118 -5120, 1996

[4] A. Karalis, J.D. Joannopoulos, and M. Soljacic, "Efficient Wireless Non-radiative Mid-range Energy Transfer," *Annals of Physics*, vol. 323, pp. 34-48, January 2008.

[5] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, "Wireless power transfer via strongly coupled magnetic resonances," *Science*, Vol. 317, pp. 83-86, July 2007.