A Comparative Study Between Novel Witricity and Traditional Inductive Magnetic Coupling in Wireless Charging

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A non-radiative energy transformer, commonly referred as Witricity and based on 'strong coupling' between two coils which are separated physically by medium-range distances, is proposed to realize efficient wireless energy transfer. The distance between the resonators can be larger than the characteristic sizes of each resonator. Non-radiative energy transfer between the first resonator and the second resonator is facilitated through the coupling of their resonant-field evanescent tails. The proposed system operates as traditional inductive magnetic coupling devices when the operating frequencies are not the resonant frequency. Corresponding finite element analysis (FEA) and experiments have been carried out to facilitate quantitative comparison. Compared with typical magnetic inductive coupling energy transmission devices, the efficiency of the proposed system is much higher. This investigation indicates that it is feasible to use wireless energy transfer technology to recharge batteries, particularly in implant devices.

***Index Terms*—Inductive magnetic coupling, resonant wireless energy transfer, strong coupling, witricity.**

I. Introduction

TRADITIONAL plug and socket charging method cannot keep up with demands of consumers for safety and fast charging. Thanks to the advent in power electronics, inductive charging, also known as wireless charging, has found much successes and is now receiving increasing attention by virtue of its simplicity and efficiency. The most important distinctive structural difference between contactless transformers and conventional transformers is that the two 'coils' in the former are separated by a large air gap.

Compared with plug and socket (i.e., conductive) charging, the primary advantage of the inductive charging approach is that the system can work with no exposed conductors, no interlocks and no connectors, allowing the system to work with far lower risk of electric shock hazards. As the charging system is often fully enclosed, wireless charging can be realized in waterproof packages and as such, wireless charging is attractive in situations at which rechargeable devices need to be frequently used near or even under water as well as in humid conditions. It is also a very attractive option in the medical field when the replacement of batteries for implant devices is very costly. The risk due to surgical operations is highly reduced if the batteries for the implant devices can be charged externally through wireless charging techniques.

Physical separation between the primary and secondary windings incurs proximity-effect winding losses. Poor coupling can result in poor transmission performance and low efficiency. Due to the large air gap between the primary and secondary windings, contactless transformers have large leakage inductances, small mutual inductance and low efficiency [1]–[3]. Compared to direct contact charging, inductive charging efficiency is lower and resistive heating is higher. Realization of low frequency inductive charging in electrical devices will lead to slow charging and heat generation.

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Fig. 1. Basic components of the Witricity system.

This paper reports the study on a topical mode of energy transmission using resonant technique, commonly known as Witricity (short form of wireless electricity) [4]. Detailed theoretical and numerical analyses reveal that Witricity is efficient and practical for mid-range wireless energy exchange. Unlike conventional inductive coupling methods, there are only very small energy dissipations in off-resonant objects for systems working on Witricity principle [5].

In this paper, a novel system based on Witricity is proposed for charging rechargeable batteries. The first resonator receives energy from an external power supply. It also includes a second resonator which is physically separated from the first resonator to supply useful working power to an external load. The distance between the two resonators can be larger than the characteristic sizes of each resonator. It transfers non-radiative energy between the first resonator and the second resonator through the coupling of their resonant-field evanescent tails. Fig. 1 shows the basic components of the Witricity system.

II. Theory and Design of the Proposed Witricity System

As a new wireless power transfer technology, Witricity is based on the concept of near-field and strongly coupled magnetic resonance. The fundamental principle is that resonant objects can exchange energy efficiently, while non-resonant objects only interact weakly.

Fig. 2 shows the basic design of the Witricity system consists of source and device resonators, a driving loop, and an output loop. The source resonator is coupled to the driving loop which is linked to an oscillator that supplies energy to the system. The

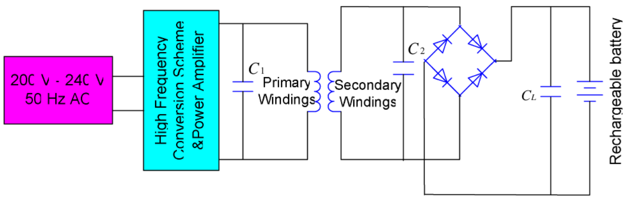

Fig. 2. The schematic diagram of the proposed system.

device resonator coil is coupled to the output loop to provide the power to an external load.

Due to its large physical separation, wireless inductive coupling transformers have large leakage inductances and small mutual inductance. Thus the coupling rates are very small, quite often less than 0.1, while those for conventional transformers are between 0.95–0.98 [6]. Judging on this aspect, inductive coupling technology is impractical. For the Witricity system, the coupling rate can however be as high as 0.7–0.9 by virtue of the strong resonant frequency coupling between primary and secondary windings.

To achieve high coupling rate and transmission efficiency, sources with certain resonant frequency (in the MHz range) is fed to the primary windings. Common formulas in the low frequency range to predict the performance of the system are inapplicable as the values of inductances and resistors vary greatly as frequency changes, especially at high frequency.

The coupling coefficient, k, between the transmitter and the receiver, represents the fraction of flux, created in the primary coil coupled into the secondary coil. It can be maximized by selecting the radius of the coils.

When the flux generated by the transmitter coil is only in itself and there is no common flux between the two coils, the coupling coefficient k is zero. k is equal to one when all of the fluxes created by the transmitter coil is in the receiver coil. Contrast to traditional wireless energy transmitting technology, the coupling coefficient of the proposed Witricity system is not only dependent on the geometry of the link, it also relies on the same intrinsic frequency of the transmitter and the receiver. Therefore, k is dependent on the design dimensions and the number of turns in either of the coils. An equation relating the inductances to the coupling coefficient is

$$k = \frac{M}{\sqrt{L_1 L_2}} = \frac{M_0 n_1 n_2}{\sqrt{n_1^2 L_{10} n_2^2 L_{20}}} = \frac{M_0}{\sqrt{L_{10} L_{20}}} \tag{1}$$

where M is the mutual inductance between the coils; L_1 and L_2 are the self-inductances of the coils; n_1 and n_2 are the number of the transmitter and the receiver turns, respectively; M_0 is the single turn mutual inductance; L_{10} and L_{20} are the single turn inductance of the transmitter and the receiver, respectively.

In the case being studied, the coupling rate has a relatively large value (about 0.81) when the distance is 5 cm for Witricity. It decreases gradually as the physical separation distance increases. This is easy to understand as magnetic flux coupled to another winding is expected to decrease markedly as separation distance becomes longer.

TABLE I
DIMENSION PARAMETERS OF THE TWO SYSTEMS

Primary winding / Secondary winding	Shape	Rectangular spiral winding
	Turns	6 turns
	Thickness of copper	0.04 mm
	Width of copper	6.35 mm
	Copper track separation	2 mm
	Maximum length	208 mm
	Minimum length	106 mm
Copper strip	Shape	Rectangle
	Number	4
	Thickness	0.04 mm
	Width	25.4 mm
	Length	50 mm

III. Quantitative Comparative Analysis Based on FEA Simulation

The proposed Witricity system uses a pair of rectangular spiral copper windings with the same shape and structure to achieve wireless energy transfer. Table I shows the parameters of the novel charging system which has identical parameters as those in a conventional system with the exception of the additional copper strips.

The amplitude of the exciting voltage, which is given by an amplifier, is 25 V at the frequency range from 0.01 MHz to 10 MHz. The induced electric field in the receiver is generated by variations in the magnetic flux produced by the transmitter coil. Particular attention is paid to the analysis of the voltage received by the receiver with different distances and different frequencies in order to find the energy transfer pattern.

Fig. 3 shows the electric field distributions of the conventional and Witricity systems at a frequency of 4.8 MHz with separation distances of 5 cm and 2 cm. It can be seen that the Witricity system has a relatively high electric field when compared with those of the traditional inductive magnetic coupling system at the resonant frequency of 4.8 MHz of the Witricity and efficient energy transfer is expected to occur, as most of the input energy is transferred from the primary coil to the secondary coil at the resonance frequency. In addition, it can be seen that the electric field strength is increasing gradually when the distance is reduced from 5 cm to 2 cm for both systems.

Fig. 4 shows the receiver output voltage (with a distance of 5 cm) versus frequency for both Witricity system and the traditional one. The frequency is varied between 0.01 MHz to 10 MHz. It can be seen that the induced voltage of the Witricity system has a large peak value of 18.23 V at a frequency of about 4.8 MHz. For the traditional magnetic coupling model, the receiver output voltage only increase slightly when the frequency rises from 0.01 MHz to 10 MHz.

For the proposed Witricity system, the receiver output voltage decreases regularly with an increase in the physical distance between the transmitter coil and the receiver coil. Although the receiver output for the traditional magnetic coupling model is relatively high at the beginning, the decreasing trend becomes much more noticeable as the physical distance is increased as shown in. Fig. 5.

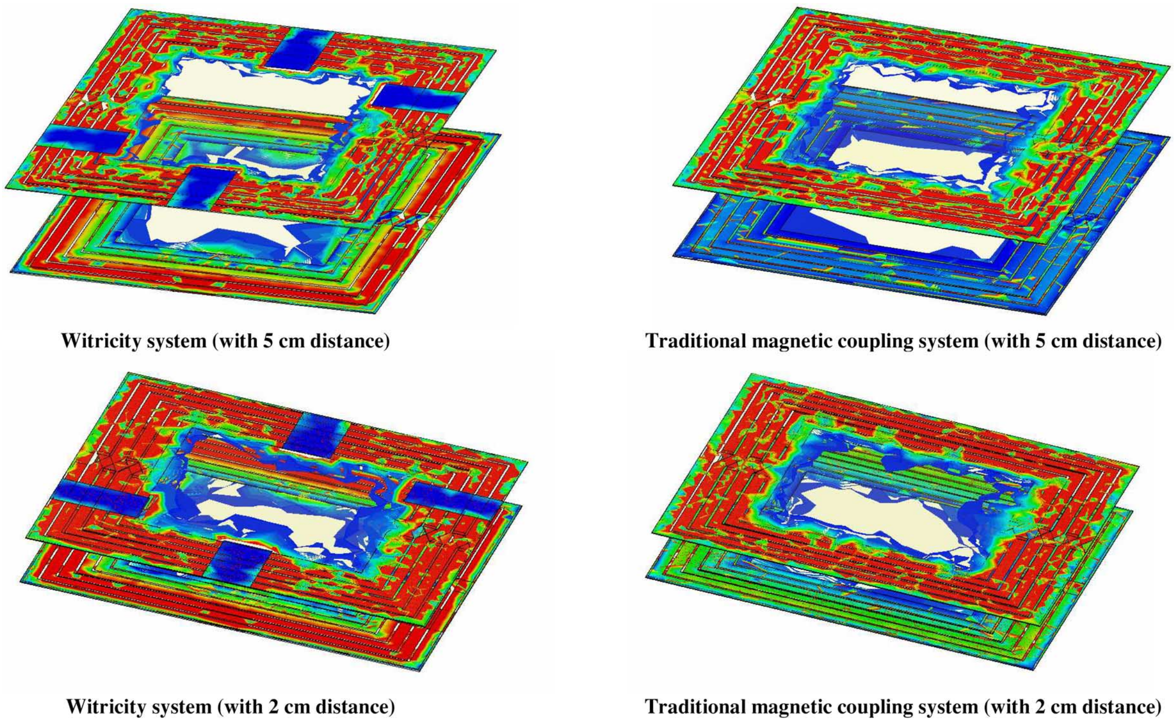

Fig. 3. The electric field distributions at frequency of 4.8 MHz for both two systems.

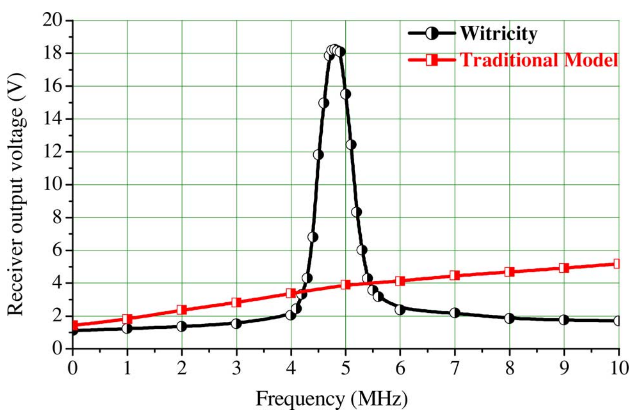

Fig. 4. Receiver output voltage versus frequency with a distance of 5 cm.

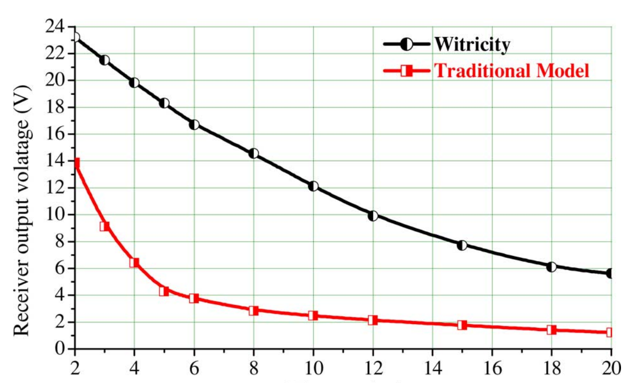

Fig. 5. Receiver output voltage versus distance with a frequency of 4.8 MHz.

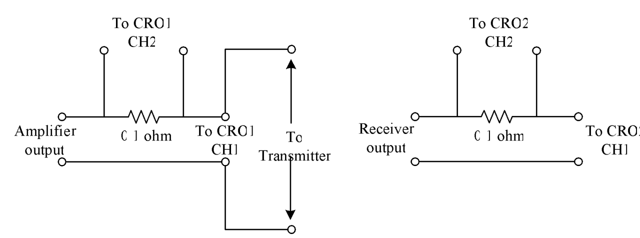

Fig. 6. Schematics of the system for experiment.

IV. Experiments

To verify the simulation result, a prototype model is built. Function generator and power amplifier are connected in series with the primary coil as shown in Fig. 6.

The function generator is connected to a power amplifier which generates a sinusoidal, 5.5 MHz, 0.5 W power supply. The middle layer, made from polymers, serves as a skeleton framework to function as an electrical isolation between the upper and lower layers. The magnetic field is generated by the upper layer which is fabricated by affixing spiral-type conductors consisting of 6 square turns with a separation distance of 5.0 mm between the conductors. The lower layer consists of several conductive strips in parallel with the radial direction of the cell, forming capacitors with the overlapped parts of the upper layer.

The measured and calculated values for the Witricity system and traditional model are presented in Table II.

The trends of the secondary apparent power for the two systems as a function of distances are shown in Fig. 7. Though both of them decrease when the distance increases, the apparent power of the proposed Witricity system are much higher than that of the traditional model, especially in the distance range

TABLE II
RECEIVER OUTPUT VOLTAGES AND CURRENTS OF THE TWO SYSTEMS

Distance (cm)	Witricity		Traditional model	
	Voltage (V)	Current (A)	Voltage (V)	Current (A)
2	17.590	0.479	13.07	0.412
3	17.160	0.477	10.34	0.327
4	16.800	0.476	8.76	0.212
5	16.200	0.476	6.01	0.196
6	15.300	0.475	4.13	0.161
7	14.670	0.471	3.35	0.133
8	13.800	0.466	3.17	0.116
9	13.200	0.464	2.85	0.107
10	12.350	0.459	2.62	0.104
11	11.600	0.455	2.48	0.101
12	9.400	0.446	2.24	0.0985
13	8.520	0.438	2.1	0.0962
14	7.260	0.408	1.96	0.0938
15	6.210	0.391	1.87	0.0941
16	5.600	0.365	1.65	0.0926
17	4.650	0.349	1.52	0.0932
18	4.250	0.342	1.41	0.0927
19	3.920	0.332	1.23	0.0913
20	3.430	0.322	1.09	0.0922

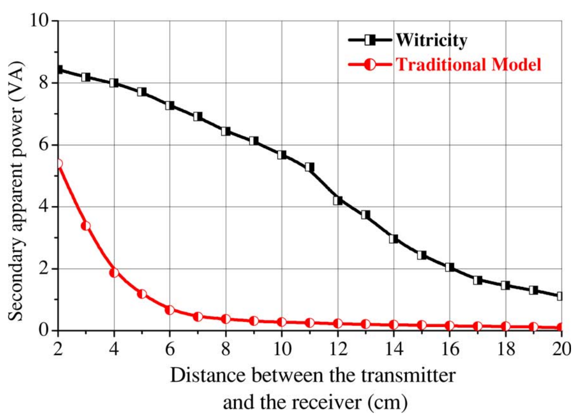

Fig. 7. Secondary apparent power versus distance.

of 2 cm to 10 cm. In general, the secondary apparent power in traditional inductive magnetic coupling model decreases very rapidly as the distance increases.

It can be seen from Fig. 8 that the efficiency of Witicity is 73% at 5 cm and 24% at 15 cm. In comparison, when the traditional inductive coupling method is used, the physical separation distance must be limited to less than 1 cm and 4 cm, respectively, in order to realize the same efficiencies. The studies indicate that Witricity is a suitable and practical technology for providing wireless power to charge a wealth of electrical devices.

Fluctuations of the output voltage, output power and efficiency of the transmission, which may lead to instability in the whole system, will appear because of changes in the coupling

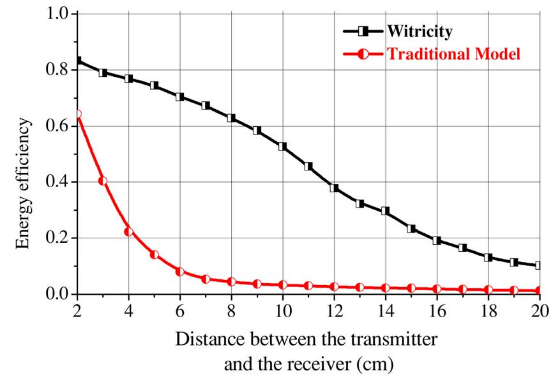

Fig. 8. Efficiency comparison between the two systems.

rate. Therefore this point must be fully addressed to enhance the stability of Witricity systems. Carefully parameter design is also necessary, especially for energy transmission over a relatively large distance.

V. CONCLUSION

In this paper, a wireless energy transfer system based on Witricity technology for power transmission and recharging of electrical devices is studied. In order to showcase its performance, comparable traditional inductive magnetic coupling model is built. Experiment and simulation results are reported to demonstrate the effectiveness and characteristics of the proposed method. In summary, the feasibility of this system is demonstrated using practical measurements in order to make meaningful performance comparisons.

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