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Analytical study and corresponding experiments for a new resonant magnetic charger with circular spiral coils

Junhua Wang,[1,2,a)] Jiangui Li,[3] S. L. Ho,[1] W. N. Fu,[1] Zhigang Zhao,[4] Weili Yan,[4] and Mingui Sun[2,b)]

[1]*Department of Electrical Engineering, the Hong Kong Polytechnic University, Hong Kong*
[2]*Department of Neurological Surgery, University of Pittsburgh, Pittsburgh, Pennsylvania 15213, USA*
[3]*Department of Electrical and Electronic Engineering, the University of Hong Kong, Hong Kong*
[4]*Joint Key Laboratory of EFEAR, Hebei University of Technology, Tianjin 300130, China*

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This study proposes a new resonant magnetic charger comprising circular spiral coils that operate with a strong coupling effect between the transmitter and the receiver. The two spiral coils are fitted with additional copper tapes to serve as resonant transmitter and receiver coils. The magnetic flux distributions are calculated using temporal coupled mode theory. Analysis results show that the proposed system can dramatically improve the efficiency and extend the power transfer distance. Experiments have been carried out in order to verify the performance of the system. In particular, the trends of output voltages when either the operating frequencies or the transfer distances are changing are reported. The system efficiency obtained experimentally is also given. Both calculated and measured results are in good agreement. © *2012 American Institute of Physics*. [doi:10.1063/1.3670981]

I. INTRODUCTION

Because of the large air gap between the primary and secondary windings, contactless transformers generally have large leakage inductances, small mutual inductance, and low efficiency. Compared to direct contact charging, the efficiency of inductive charging is lower, and its resistive heating is higher. The realization of low frequency inductive charging in electrical devices will generally lead to slow charging and excessive heat generation.[1–3]

In July of 2007, Kurs *et al.*[4,5] reported a new method for wirelessly transmitting power over distances on the order of several times the physical size of the devices. This non-radiative field differs from the traditional "radiative" field in that the energy can be drawn from the non-radiative field only if an object is resonating with the transmitting object. All off-resonant objects acquire very little energy, and it would appear as though they do not exist in the energy transmission path.

Based on this novel technology, a new resonant magnetic charger with circular spiral coils for powering and recharging electrical devices is studied. Temporal coupled mode theory (CMT) for modeling and simulation is introduced in order to study the performance of the proposed system. Simulation and experimental results show that the system is effective in transferring power to wireless devices. The energy transfer efficiency with respect to the system dimensions and the distance between the source and the receiving cells are also studied analytically and experimentally. Figures 1 and 2 illustrate the block diagram and the circuit diagram, respectively, of a resonant magnetic charger with circular spiral coils.

II. THE PROPOSED RESONANT MAGNETIC CHARGER WITH CIRCULAR SPIRAL COILS

It is one of the key features in the design of regular coils meant to operate at specific resonating frequencies and to be used in applications in, for example, implant systems in the medical field. This technology is very different from traditional inductive energy transfer know-how, because it is necessary to design the system based on practical needs in terms of the area of the implant sites, for example, before the operation frequency is determined. In our study, the coupling uses two flat circular spiral inductors to create an inductively coupled link. Figure 3 shows an analytical model for a new resonant magnetic charger with circular spiral coils. The design parameters are shown in Table I.

III. ANALYTICAL FEM STUDY FOR THE SYSTEM

The well-known CMT is used as the analytical framework for modeling this resonant wireless power transfer process. The electromagnetic fields of the charger including two

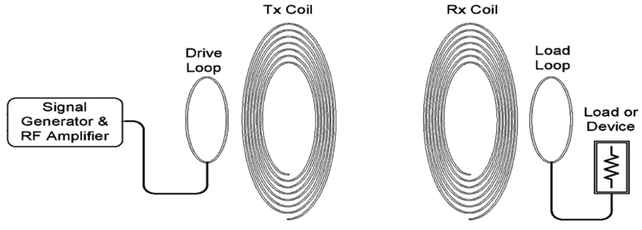

FIG. 1. Block diagram of the proposed resonant magnetic charger with circular spiral coils.

a)Present address: Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA. Electronic mail: junhua.wong@connect.polyu.hk.
b)Electronic mail: drsun@pitt.edu.

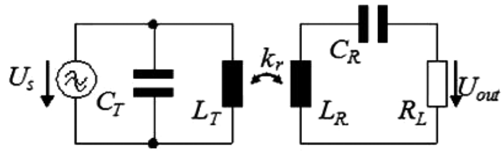

FIG. 2. Circuit diagram of a resonant magnetic charger.

resonant coils, a transmitter, and a receiver can be approximated by

$$\mathbf{F}(r,t) \approx a_S(t)\mathbf{F}_S(r) + a_D(t)\mathbf{F}_\mathbf{D}(r), \tag{1}$$

where $\mathbf{F}_S(r)$ and $\mathbf{F}_\mathbf{D}(r)$ are the respective eigenmodes of the transmitter and the receiver alone. Then the fields a_S and a_D can be shown[6] to satisfy

$$\dot{a}_S = (j\omega_S - \Gamma_S)a_S(t) + j\kappa a_D(t) + f(t), \tag{2}$$

$$\dot{a}_D = (j\omega_D - \Gamma_D - \Gamma_W)a_D(t) + j\kappa a_S(t). \tag{3}$$

The eigen-frequency is

$$\omega = \frac{\omega_S + \omega_D + \sqrt{4\kappa^2 - (\Gamma_S - \Gamma_D - \Gamma_W + j\omega_D - j\omega_S)^2}}{2} + j\frac{\Gamma_S + \Gamma_D + \Gamma_W}{2} \tag{4}$$

when the system is at resonance,

$$\omega_S = \omega_D = \omega_0, \tag{5}$$

and the working frequency is the real part of the eigen-frequency as follows:

$$\omega = \omega_0 \pm \sqrt{\kappa^2 - \left(\frac{\Gamma_S - \Gamma_D - \Gamma_W}{2}\right)^2}. \tag{6}$$

Moreover,

$$\frac{|a_D|^2}{|a_S|^2} = \frac{\kappa^2}{(\omega - \omega_0)^2 + (\Gamma_D + \Gamma_W)^2} = \frac{\kappa^2}{\kappa^2 - \left(\frac{\Gamma_S - \Gamma_D - \Gamma_W}{2}\right)^2 + (\Gamma_D + \Gamma_W)^2}. \tag{7}$$

Based on simulation results, the electric field distributions of the proposed charger at frequencies of 0.5, 3, 3.4, and 5 MHz with a distance of 5.5 cm are given in Fig. 4. There is a relatively large electric field when the frequency is at 3.4 MHz, which is near to the resonant frequency of the coils. The electric field strength also increases from 0.5 MHz to 3.4 MHz when the frequency approaches the resonant frequency of the coil. It decreases gradually when the frequency is increased beyond 3.4 MHz. This is accomplished mainly because of resonance, which creates magnetic fields that are largely governed by the electric distributions. When the transmitter and the receiver resonate with each other, most of the energy is transferred from the primary coil to the secondary coil.

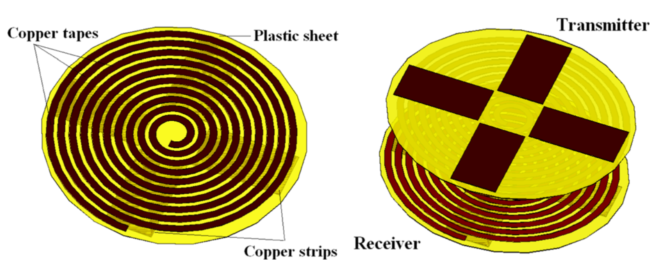

FIG. 3. (Color online) FEM schematics of the resonant magnetic charger.

TABLE I. System design parameters.

Primary winding/ secondary winding	Shape	Circular spiral
	Turns	10
	Thickness of copper	0.02 mm
	Width of copper	3.2 mm
	Copper track separation	1.4 mm
	Maximum diameter	132 mm
	Maximum diameter	40 mm
Copper strips	Shape	Rectangle
	Number	4
	Thickness of copper strips	0.04 mm
	Width of copper strips	25.4 mm
	Length of copper strips	50 mm
	Relative permittivity	3

IV. MEASUREMENT RESULTS

In order to evaluate the functionality of the proposed system, one practical model was designed and tested. Figure 5 presents the structure and one photo of the coils. The magnetic field is generated by the transmitter's upper layer, which is fabricated by affixing spiral-type conductors consisting of 10 spiral turns with a separation distance of 1.4 mm between the conductors. The lower layer consists of several conductive strips in parallel with the radial direction of

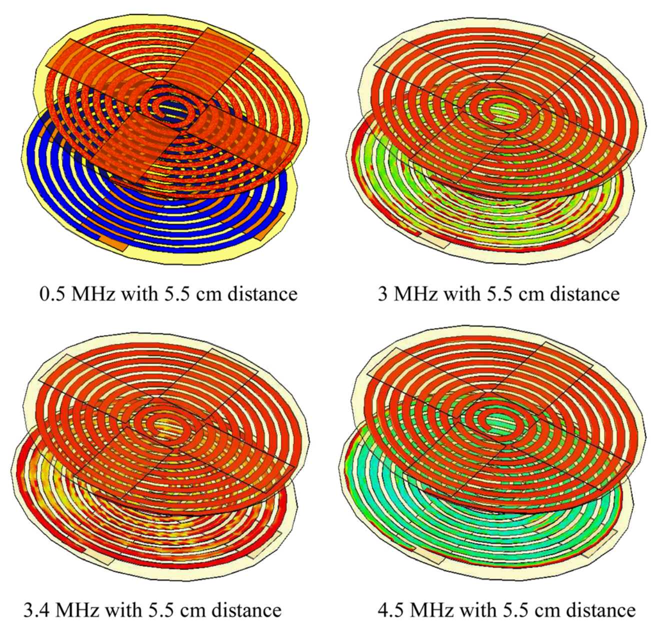

FIG. 4. (Color online) The electric field distributions at different frequencies.

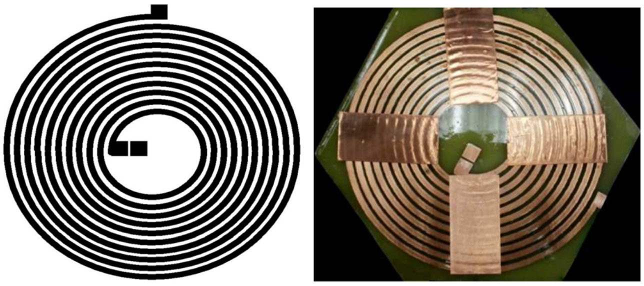

FIG. 5. (Color online) Photos of the proposed charger coils.

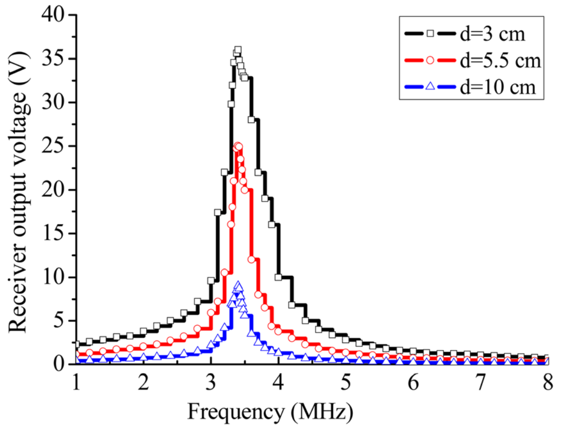

FIG. 6. (Color online) Receiver output voltage at different frequencies.

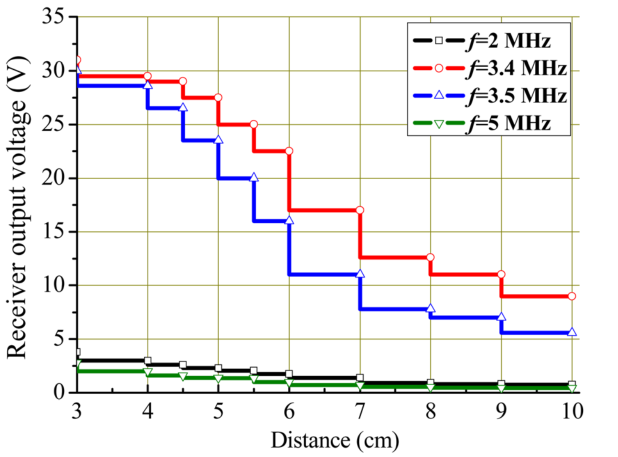

FIG. 7. (Color online) Receiver output voltage vs distance at a frequency of 3.4 MHz.

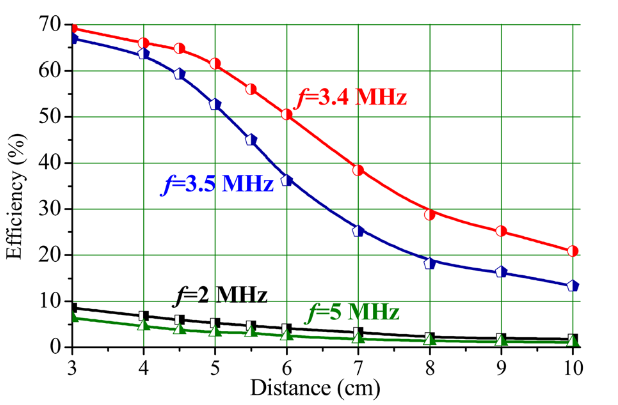

FIG. 8. (Color online) The system efficiency at 2, 3.4, 3.5, and 5 MHz with different distances.

the cell, forming capacitors with the overlapped parts of the upper layer. The receiver picks up the transmitted power through induced eddy currents. The output voltages of the receiver at different frequencies and various distances are given in Figs. 6 and 7, respectively.

The receiver's output voltages are collected at frequencies ranging from 1 to 8 MHz with the distance between the transmitter and the receiver being adjusted to 3, 5.5, and 10 cm. It can be seen from Fig. 6 that all of the three wave lines have a large peak value when the frequency is at about 3.4 MHz, and they are 36.2 V for 3 cm, 25.7 V for 5.5 cm, and 9.3 V for 10 cm. The appearance of these peak values is a result of the resonant condition, which electrically couples the transmitter coil and the receiver coil strongly.

Figure 7 shows the receiver's output voltages at frequencies of 2, 3.4, 3.5, and 5 MHz with the distance between the transmitter and the receiver ranging from 3 to 10 cm. When the distance is near 3 cm, the receiver attains the highest voltage; the voltage value is observed to have dropped to about 25.7, 20, 2.5, and 2 V at the four aforementioned frequencies when the distance is increased to 5.5 cm. Although the output voltage decreases when the distance is increased, the proposed system nonetheless is meaningful for practical applications in that a reasonable voltage can still be picked up, with relatively high efficiency, by the receiver with a separation of a few cm.

The energy transmission efficiency of the charger has also been evaluated and is shown in Fig. 8. At transmitter-receiver separations of 3 to 10 cm, the input and output power values are measured by a network analyzer, a high-frequency multimeter, and an oscilloscope in the laboratory. The efficiency with separation distances of 3 and 5.5 cm is up to 69% and 55% at a resonant frequency of 3.4 MHz. When the operating frequencies are 2 and 5 MHz, which are not the resonant frequency, the efficiencies are only about 7% and 4% with the same distances.

V. CONCLUSION

For most electric charging applications, such as implantable medical devices, an average distance of about 5 cm between the transmitter and the receiver is usually enough. The efficiency at that distance is up to 50% according to the analytical and experimental findings of the proposed system. Through careful design and calibration of the system, a higher efficiency is likely achievable.

ACKNOWLEDGMENTS

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