Research on Meander-type Coupled Structure of Capacitively Coupled Power Transfer System

SHIYUN XIE, YUGANG SU, CHUNSEN TANG, LONG CHEN
Automation college of Chong Qing university, China
xieshiyun1987@gmail.com, su7558@qq.com

Abstract: Capacitively coupled power transfer(CCPT)system is an alternative solution to tranditional inductive power transfer (IPT) system in certain high Electromagnetic compatibility applications with the advantages of being able to transfer power across metal barriers and having low standing power losses. Aiming at the problem of low transporting capacity and efficiency of typical CCPT system based flat elcctrodes in the loosely coupled mode, a new meander-type laminated coupled structrue was proposed in this paper. The equivalent circuit model of the new meander-type laminated structure was established, and the simulation analysis results showed that output power of the system with the new structure is two times higher than that of the traditional type. Finally, the experiment results verified the availability of the new structure and the theory analysis method.

Key word:- Capacitively coupled power transfer(CCPT), meander-type, laminated coupled, efficiency

1. Introduction

Contactless/wireless power transfer technologies have been developed to supply movable loads without direct electrical contacts for years. Based on magnetic field coupling, inductive power transfer (IPT) is widely accepted for achieving contactless power transfer with successful applications in material handling systems, contactless battery chargers, electric vehicles[1-4]. However, IPT cannot be used to transfer power across metal barriers, and power losses are of concern even when metal materials are present close to the magnetic field. Capacitively coupled power transfer (CCPT) employs electric field to be energy carrier, so that metal barriers and surroundings become less of an issue[5]. In addition, CCPT also has the potential to reduce standing power losses and pickup sizes [6]. Some successful prototypes using CCPT technology have already been developed to supply power wirelessly to LED lamps[7], soccer-playing robots[8], sensors for respiratory devices[6]etc.

Fig.1 shows the coupled structure of CCPT system that commonly used flat metal plate as electrodes. Because the majority of electric flux exists between the electrodes, the coupled structure based flat elcctrode has high efficiency in the case of tightly coupling[9]. However,when the system is operating in loosely coupling state, the electric field between the electrodes is composed of vertical field component and parallel field component. With the increase of coupling distance the density of vertical field component drops dramatically, and the consistency of parallel field component become poor at the same time. These two factors result in that the transfer efficiency of coupling structure is extremely low.

A new meander-type laminated coupled structrue is presented in this paper. The transmitting electrodes are designed as meandering windings which are connected parallelly and effectively improve the parallel field component of coupling structure and enhance the strength of the vertical field component. The equivalent circuit model of the coupling structure is established and the simulation analysis results show that with the new structure output power of system is two times higher than that of the traditional type, and the efficiency can also be improved. Finally, the experiment results verify the availability of the new structure and the analysis method.

Fig. 1 shows the block diagram of a typical CCPT charging system. A DC power supply is converted to a high-frequency ac voltage which is then supplied to two primary metal plates (charging pad). When two pickup plates are placed close to them, alternating electric field is formed between the plates, and causes the displacement current between the plates. Thus, power can be transferred from the source to a load without direct electrical contacts. To obtain sufficient amount of power as well as provide electric isolation, good dielectric materials are usually coated on the surfaces of the coupling plates. A compensation inductor is usually placed in series with the lo ad to compensate for the equivalent coupling capacitance. D_0 in Fig.1 is the distance between plates, and S is the coupled area. In the condition of $D_0^2 \ll S$, the coupled structure can be seen as lumped capacitor. The corresponding equivalent topology of typical CCPT system is showed as Fig.2.

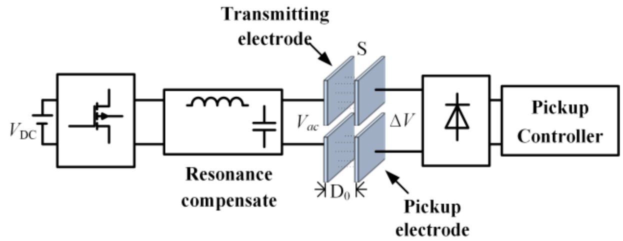


Fig.1. Schematic diagram of CCPT system based flat electrodes

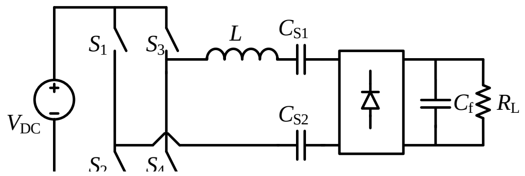


Fig.2. Topology of typical CCPT system based flat electrodes

Table.1. Parameters of a meander-type laminated electrode

L_P /cm	W_P /cm	d /mm	r /mm	f /KHz	V_{AC} /V
[illegible]	[illegible]	1	1	[illegible]	500

Through the AC impedance analysis method, the efficiency and transmission power of CCPT system can be expressed as (1), (2) where $\omega^2 LC_S=1, C_S=C_{S1}+C_{S2}$.

$$P_f = \frac{8\pi^2 V_{DC}^2}{\pi^2 r_{Cs} + 8R_L} \tag{1}$$

$$\eta_f = \frac{8R_L}{\pi^2 r_{Cs} + 8R_L} \tag{2}$$

The transmission efficiency of the CCPT system based flat elcctrode can be up to 90% in the tightly coupled area as Fig.3 showed. However, with the coupled distance D_0 increased, density of the coupled electric flux drops dramatically. And the consistency of parallel field component excited by fringe effect of the primary metal plates gets worse, therefore the transmission efficiency is extremely low.

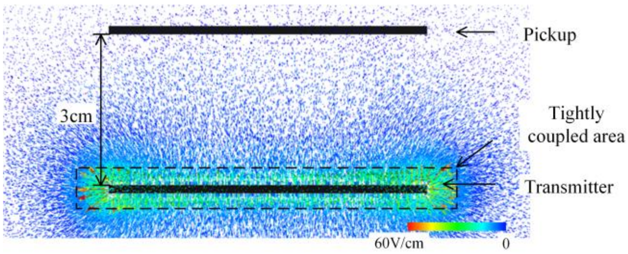


Fig.3. Electricfield distribution of flat electrod loosely coupled

2. Meander-type Coupled Structure

2.1 Electromagnetic Property of Meander Type Coupled Structure

As Fig. 4(a) shows the meander-type coupled structrue cons ists of two sub-electrodes made of *N* thin copper segments whose length is W_p and width is *d*. The feeding point of electrodes is connectted with the high frequency inverter link V_{ac} of the system. The pickup electrodes is made up of two flat metal plates whose separate distance is d_s as Fig. 4(b) shows, where *A* is the cross section area. The coupled structure of CCPT system is consist of multiple layers of meander electrodes and pickup plates. In this paper the primary meander electrodes and pickup plates have the same size, and d_p, d_s are large enough so that cross coupling between the electrodes could be ignored.

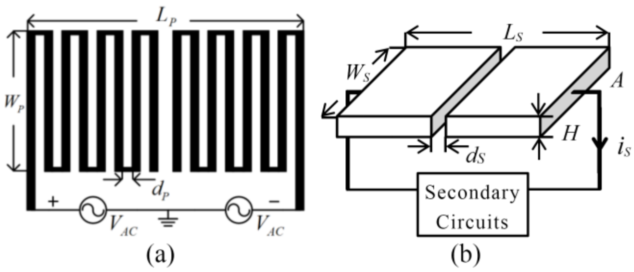


Fig. 4. Structure of meander-type transmitting and receiving electrodes

Through finite element simulation platform Ansoft, a meander-type coupled structure is developed which is consisted of three layers meander electrodes without electric contact between each other. Fig.5 is the spatial distribution of coupled electric field excited by primary meander electrodes. It can be seen that the vertical field component is mostly distributed near the edge of the electrode and parallel field component has better consistency than that showed in the Fig.3.

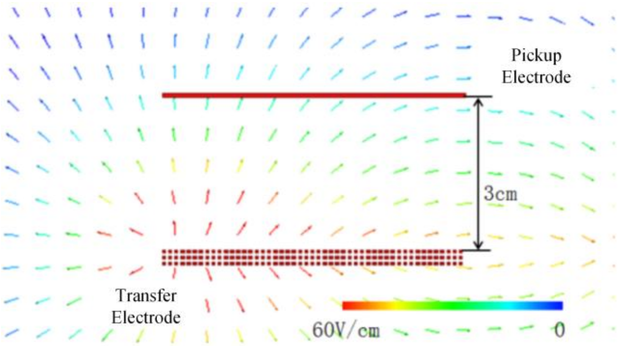
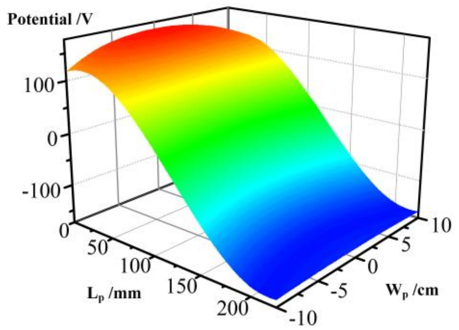


Fig.5. Electricfield distribution of meander-type coupled structure

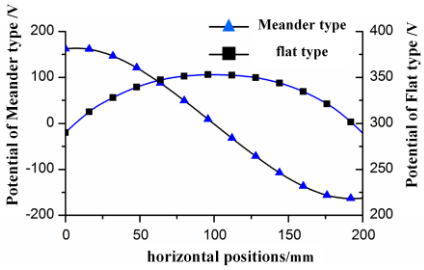
Under the effect of parallel field component, the pickup electrodes obtain induced current satisfied expression (3), where ∇*V*, ε_0 , *J* is potential variation, permittivity of vacuum and current density respectively.

$$i_{SS} = \int_A J \cdot dA = \frac{\sigma \varepsilon_0 A}{L_S} \Delta V \cos \omega t \qquad (3)$$

The electricfield distribution of 3cm high above meander electrodes is showed as Fig.6(a). It can be found that gradient of the electricfield is basically constant in the L_p dimensions. The reason is that the charge distribution of meander electrodes is similar to short electric dipoles. Fig.6(b) is the comparision between the electricfield distribution of meander electrodes and flat plate electrodes along centerline. The variation of potential of meander electrodes along the centerline is kept on a steady value 2.57, so the conduction current in the corresponding pickup electrodes can obtain stable value. As to the potential excited by the flat plate electrodes, although it is two times higher than that of meander electrodes, the induced current of pickup electrodes is very low due to the potential distribution has the parabolic type characteristic as the Fig.6(b) showed. Compared with flat plate electrodes, the parallel field component of meander electrodes has a better energy transmission characteristic.



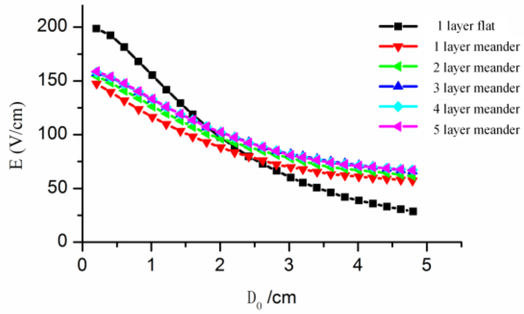
(a) Electricfield distribution above meander electrodes



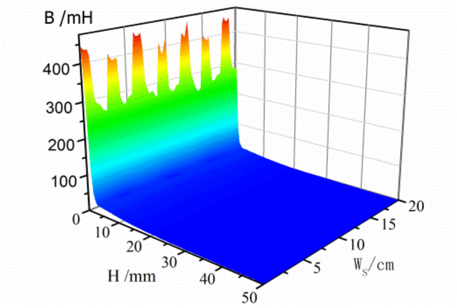
(b) Comparison between meander type and flat type electrodes

Fig.6. Electricfield distribution of meander-type electrode and comparison with flat electrode

Distribution characteristics of the vertical field component of two different type electrodes is showed as Fig.7(a). It can be seen that the electric field intensity of meander electrodes is higher than flat plate electrodes when the height exceed the range 200mm. And for the meander type electrodes, electricfield excited by the laminated structure is more stronger than the single layer structure. However affected by multiple factors(spacing *d*, diameter *r*) , there is no more increase of the strength of electricfield when the number of electrodes layer exceeds a special values(it is three in this paper). In addiction, magnetic flux density between the copper arms of meander electrodes is relatively large, but it can be ignored outside the bounds of 1cm vertical dimension as Fig.7(b) shows. So it can be seen that meander type electrodes have good EMC property.



(a) Vertical electricfield distribution of meander electrodes



(b) Magnetic distribution of meander electrodes

Fig.7. Electromagnetic characteristic of Meander-type electrode

2.2 Equivalent Circuit Modeling

As Fig.5 shows the electricfield excited by meander electrodes includes vertical field component and parallel field component which both can induce current in the pickup plates. Due to the distribution characteristic of electricfield is influenced by various aspects such as copper arm spacing d_p , coupled distance D_0, the potential difference of pickup plates only can be expressed in the closed form. The induced current in the pickup plates can be expressed as (4) based on the distribution characteristic of electricfield.

$$I_{S\parallel} = \frac{2\int \vec{\mathbf{E}} \cdot d\vec{\mathbf{l}}}{R_S + R_L} \tag{4}$$

According to the definition of capacitor, The equivalent capacitor of vertical field component can be expressed as (5) combined Gauss theorem of electricfield.

$$C_\perp = \frac{\oint_S \varepsilon E d\tau}{U} \tag{5}$$

Therefore the short-circuit current in the pickup plates can be expressed as follows.

$$I_{S\perp} = \frac{V_{AC}}{\sqrt{R_Z^2 + \left(1/\omega C_\perp\right)^2}} \tag{6}$$

Total current in the pickup electrodes I_{SS} is expression (7)

$$I_{SS} = \frac{2\int \vec{\mathbf{E}} \cdot d\vec{\mathbf{l}}}{R_S + R_L} + \frac{V_{AC}}{\sqrt{R_Z^2 + \left(1/\omega C_\perp\right)^2}} \tag{7}$$

The effect of primary electrodes on pickup plates can be represented by induction coefficient M_C.

$$M_C = \frac{I_{SS}}{j\omega V_{AC}} \tag{8}$$

Hence, the equivalent circuit of meander type electrodes can be found as Fig.8.

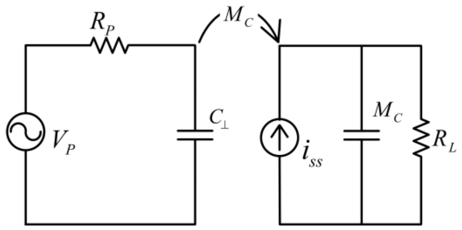


Fig.8. Equivalent circuit model of meander-type coupled structure

2.3 Comparison between Meander Type Coupling Structure and Flat Plate Type

The equivalent circuit of flat plates coupled structure is showed as Fig.9, where C_p, C_s is coupled capacitor of the primary electrodes and coupled capacitor of the pickup electrodes respectively, M_c represents the functions of primary electrodes on the pickup electrodes[10].

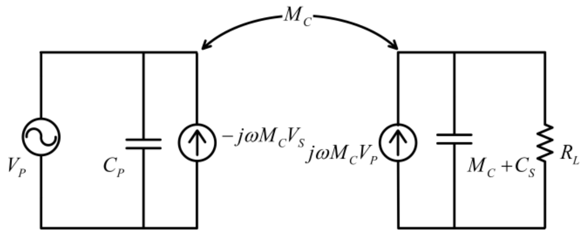


Fig.9. Equivalent circuit smodel of flat-type coupled structure

Because the distance between the primary electrodes is large enough, C_p, C_s can be ignored. The transfer power of flat plate type CCPT system can be expressed as (9)

$$P_f = \frac{R_L V_P^2}{R_L^2 + \left(1/\omega C_f\right)^2} \tag{9}$$

Through vertical field component and parallel field component, meander type coupled structure transfers power which is showed as expression (10) .

$$P_M = \frac{4\left(\int \vec{\mathbf{E}}_\parallel \cdot d\vec{\mathbf{l}}\right)^2}{R_L} + \frac{R_L V_P^2}{\sqrt{R_L^2 + \left(1/\omega C_\perp'\right)^2}} \tag{10}$$

Spacial electricfield $\vec{\mathbf{E}}_\parallel, \vec{\mathbf{E}}_\perp$ is a complex 3D vector field which can be solved only by numerical value analysis. According to Gauss theorem of electricfield, the spacial potential of coupled structure is satisfied expression (11), where $\phi(x, y, z)$ is scalar potential, $\varepsilon_r(x, y, z)$ is relative dielectric constant, ε_0 is permittivity of vacuum, ρ_υ is volume charge density. Through the Finite Elements solver in Ansoft package, the transmission power of meander type coupled structure can be found as follows based Table.1

$$\nabla\left(\varepsilon_r \cdot \varepsilon_0 \nabla \phi\right) = -\rho_\upsilon \quad (11)$$

The curve of the output power of the flat type and meander type structure changes with the distance is found as Fig.10. It can be seen that compared with flat type structure, deterioration rate of transmission power of meander type structure is slower when coupled distance increasing, particularly in the range of 2-4mm, transmission power of the meander electrode is three times higher as that of the flat type. Therefore, meander electrodes can essentially improved the transmission power of CCPT system in loosely coupled case.

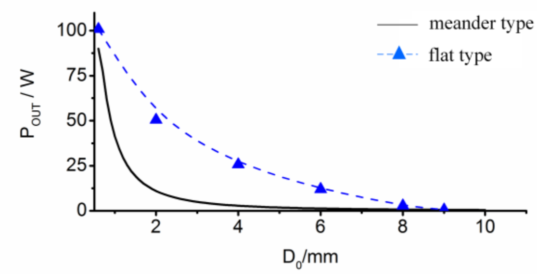


Fig.10. Transfer capability curves of meander-type CCPT system varying with D

3. Experimental Verification

To check the validation of meander type laminated coupled structure, a experimental equipment based E class converter is developed as Fig.11 shows. The parameters of system is listed in Table.2 and the switching devices used is the IPP096N03 MOSFET. Meander electrodes are wound by Litz wries and fixed on a 20cm×20cm cardboard. Because the output is pure resistant load, induced current in the pickup plates can be connected with output without rectifying circuit. The waveforms of excitation voltage U_p, pickup voltage U_s and output voltage after entered steady state is showed as Fig.11.

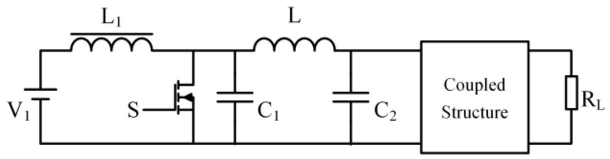
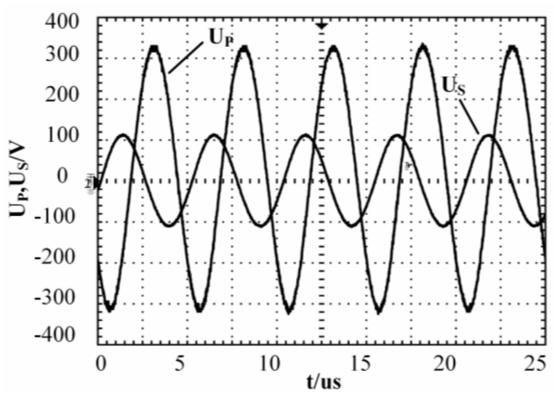


Fig.11. CCPT experiment equipment based E-class converter

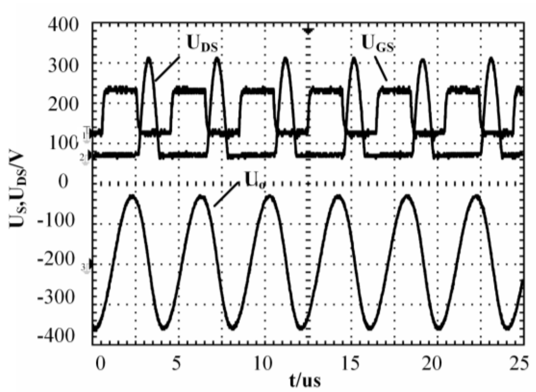
Table.2. Given parameter of experiment equipment

Parameter	Value	Parameter	Value
V_i/V	19	R_L/Ω	500
f /kHz	264	C_1/nF	2
L_1/uH	420	C_2/nF	1
L/uH	300	ε_r	3

It can be seen that the excitation voltage U_p and pickup voltage U_s are relatively stable without harmonic distortion as Fig.12 shows. The experiment results show that CCPT system with meander type coupled structure can work on a relatively stable state.



(a) Voltage waveform of transmitting and pickup electrodes



(b) Drive signal U_{GS} and output U_o

Fig.12. Experiment results of the new coupled structure

To verify the energy-efficiency property of meander type system, transmission efficiency and power of the meander electrodes is analyzed and compared with the flat type structure based on the system parameters as Table.3 shows. As Fig.13 shows that for different conditions of coupled distance the transmission efficiency and power of the meander electrodes is in concordance with the result of calculation.

Table.3. Comparison between transmission efficiency of meander-type system and flat-type

D /mm	P_f /W		P_M /W	
	Caculated Value	Experiment Value	Caculated Value	Experiment Value
0.5	89.6	91.3	110.0	104.2
2	11.0	13.2	55.7	51.6
4	2.7	5.0	28.3	22.1
6	1.2	3.4	13.5	9.8
8	0.7	2.4	3.1	2.6
10	0.4	1.6	1.6	0.9

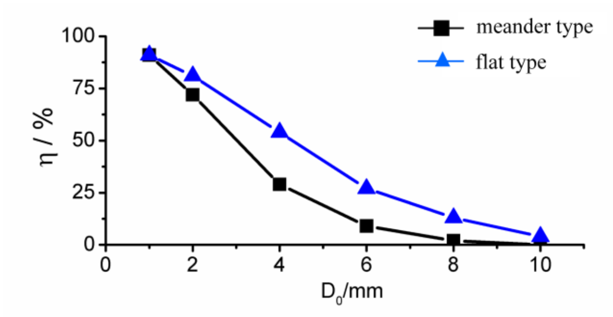


Fig.13. Comparison between transmission efficiency of meander-type CCPT system and flat-type

Experimental results were also given to confirm the correctness of analysis and the validity of proposed scheme. It was practically neglected that distribution of surface charges is nonuniform caused by the fringe effect of coupled structure, so that there is deviation between experiment results and analysis results. But generally speaking, meander type coupled structure can transfer power efficiently.

4 Conclusion

For the problems of low transporting capacity and efficiency of typical CCPT system based flat elcctrode coupled structure, a new meander-type laminated coupled structrue is proposed in this paper, which can effectively increase the electric flux density of the vertical field component and improve the consistency of parallel field component. Compared to traditional methods of increase of excitation voltage and coupled area, the CCPT system used meander type electrodes has higher transmission efficiency and power.

Reference

[1] Lee W Y, Huh J, Choi S Y, Thai X V, Kim J H, Al-Ammar E A, El-Kady M A, Rim C T, "Finite-Width Magnetic Mirror Models of Mono and Dual Coils for Wireless Electric Vehicles", IEEE Transactions on Power Electronics, vol. 28, no. 3, pp.1413-1428

[2] Choi S Y, Huh J, Lee W Y, Rim C T, "Asymmetric Coil Sets for Wireless Stationary EV Chargers With Large Lateral Tolerance by Dominant Field Analysis", IEEE Transactions on Power Electronics, vol. 29, no. 12, pp.6406-6420

[3] Choi S Y, Gu B W, Lee S W, Lee W Y, Huh J, Rim C T, "Generalized Active EMF Cancel Methods for Wireless Electric Vehicles", IEEE Transactions on Power Electronics, vol. 29, no. 11, pp.5770-5783

[4] Hui S, Zhong W, Lee C, "A critical review of recent progress in mid-range wireless power transfer", IEEE Trans. On Power Electronics, vol. no. pp.1

[5] Chao L, Hu A P, Covic G A, Nair N C, "Comparative Study of CCPT Systems With Two Different Inductor Tuning Positions", IEEE Transactions on Power Electronics, vol. 27, no. 1, pp.294-306

[6] Chao L, Hu A P, Wang B, Nair N C, "A Capacitively Coupled Contactless Matrix Charging Platform With Soft Switched Transformer Control", IEEE Transactions on Industrial Electronics, vol. 60, no. 1, pp.249-260

[7] Theodoridis M P, "Effective Capacitive Power Transfer", IEEE Transactions on Power Electronics, vol. 27, no. 12, pp.4906-4913

[8] Hu A P, Chao L, Hao L L. A Novel Contactless Battery Charging System for Soccer Playing Robot. 2008 15th International Conference on Mechatronics and Machine Vision in Practice, ., 2008, 2008:646-650

[9] Ludois D C, Erickson M J, Reed J K, "Aerodynamic Fluid Bearings for Translational and Rotating Capacitors in Noncontact Capacitive Power Transfer Systems", IEEE Transactions on Industry Applications, vol. 50, no. 2, pp.1025-1033

[10] Bondar H, Oree S, Jagoo Z, Ichikawa K, "Estimate of the maximum range achievable by non-radiating wireless power transfer or near-field communication systems", JOURNAL OF ELECTROSTATICS, vol. 71, no. 4, pp.648-655