Proposed Equivalent Circuit and Parameter Identification Method for Electro-Magnetic Resonance Based Wireless Power Transfer

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Abstract – The proper equivalent circuit is newly presented for electro-magnetic resonance based wireless power transfer. Based on the proposed equivalent circuit of open-ended helical antennas, the parameter identification of helical antennas can be well derived for highly efficient wireless power transfer. The well-established equivalent circuit in high frequency ranges is developed for analyzing a resonance enhanced-electromagnetic coupling helical antennas and the unknown parameters for helical antennas are identified by experiments. The effectiveness based on the proposed equivalent circuit is verified through experiments.

Keywords: Wireless power transfer, Electro-magnetic resonance coupling, Equivalent circuit, Parameter identification

1. Introduction

Wireless power transfer (WPT) is the transmission of electrical energy from a power source to an electrical load without artificial interconnecting conductors. Wireless power transfer is useful in cases where interconnecting wires are inconvenient, hazardous, or impossible [1]. If WPT method is commercialized, most of application fields such as electric appliances, industries, aerospace, military, and others may open a new era for stepping forward developments.

In 1900s, Dr. Nikola Tesla already demonstrated the illumination of wireless lamps by energy that was coupled to them through an alternating electric field [1]. Recently worldwide researchers and developers have been much focusing on a long wireless power transfer since innovative transfer was released by Karalis et al [2] of MIT in 2006. The released WPT method is based on resonance enhanced-electromagnetic coupling and could get 45~50% efficiency and 60W power transfer on condition of 2 meter long distance. On the contrary, other WPT methods such as electromagnetic radiation in the form of microwave or laser had limitation which could not satisfy both a long distance transfer and high efficiency simultaneously. MIT's released WPT method was the key turning point for improving both a long distance and high efficiency in a wireless power transfer.

The frequency range is 10MHz~100MHz and the distance may be within a few meters. This resonance enhanced WPT makes a long distance transfer possible, while the conventional WPTs have a limitation of the air

gap distance in 100kHz frequency range [3, 4].

The efficiency in WPT consisting of high frequency electrical circuit is evaluated through S_{21} parameter, which is one evaluation parameter of scattering matrix (S-parameter matrix). It is very important to identify the exact information on electrical circuit model and all parameters, but the parameter identification is not easier due to the uncertain electrical circuit model. Therefore S_{21} parameter is measured only through experiments. Imura et al [5, 6] performed several experiments regarding helical antennas (short-end or open-end) based on the principle in the reference [2], and presented several related experimental reports. In the reference of [7], a capacitor insertion in series in the antenna equivalent circuit was presented to improve the high frequency equivalent circuit analysis regarding a pair of helical antennas. Authors also released the related experimental reports without theory [8].

To clear the above mentioned problems and increase efficiency in wireless energy transfer, authors do analyses of the open-end typed helical antennas to find the well-established high frequency equivalent circuit, in the basis of which all parameters can be optimized for highly efficient transfer [11]. In these analyses, the proper equations based on the well-established high frequency equivalent circuit can be derived and it is revealed that five key parameters are important. Also theoretical design procedure for making transfer efficiency higher can be derived to find parameter identification. Based on these procedures, experiments are carried out to prove the above mentioned validity.

2. Wireless Power Transfer System

Fig. 1 shows the overall wireless power transfer system consisting of the followings [11]; (a) HF (high frequency)

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Fig. 1. Overall configuration of wireless power transfer system

inverter for transmitter power source, (b) primary impedance matching stage, (c) primary helical antenna, (d) secondary helical antenna, (e) secondary impedance matching stage, (f) HF rectifier for load. All of these categorized components are very important to make WPT system highly efficient. The electro-magnetic resonance based antenna will be mainly discussed in this paper.

2.1 Enhanced-electromagnetic coupling antennas

Two types of wireless power transfer systems are largely classified according to frequency ranges; one is the electromagnetic induction used in ranges of 50~20kHz and the other is the electromagnetic resonance used in ranges of around 10MHz. The resonance enhanced-electromagnetic coupling antenna utilizes a resonance phenomenon between L and C to secure a highly efficient energy transfer even though longer distance between the primary transmitter and the secondary receiver.

The electro-magnetic coupling antenna with induction method or resonance method is shown in Fig. 2. In case of electromagnetic induction, each quality factor Q of transmitter and receiver in (1) is lower. So the higher coupling coefficient k between transmitter and receiver in (2) should be required for highly-efficient WPT. But the coupling coefficient k is reversely proportional to an air-gap distance between transmitter and receiver. Thus, the conventional electromagnetic induction is not unsuitable to the purpose of a longer distance WPT. On the contrary, the resonance enhanced-electromagnetic coupling antenna can overcome the above mentioned problems in the longer distance power transfer. Even though coupling coefficient is lower, each quality factor Q of transmitter and receiver can be much increased by resonance phenomena between L

Fig. 2. Configuration of electro-magnetic coupling antenna for WPT

and C in open-ended helical antennas to secure highly efficient wireless energy transfer in a few meter long distances.

$$Q = \frac{\omega_0 L}{R} = \frac{1}{R} \sqrt{\frac{L}{C}} \quad (1)$$

$$k = \frac{\omega L_m}{\sqrt{L_1 L_2}} \quad (2)$$

$$L_m = \frac{\pi \mu_0 N_1 N_2 (r_1 r_2)^2}{D^3} \quad (3)$$

where ω_0 : resonant frequency
 L : leakage inductance
 L_m : magnetizing inductance
 L_1 : self inductance of transmitter
 L_2 : self inductance of receiver
 μ_0 : permeability of air
 N_1 : the turn number of transmitter coil
 N_2 : the turn number of receiver coil
 r_1 : radius of transmitter coil
 r_2 : radius of receiver coil
 D : transmission air-gap distance

2.2 Equivalent circuit of open-ended helical antennas

A helical antenna is consisting of a conducting wire wound in the form of an open-ended helix and a RITZ wire is especially used as a conducting wire in applications of a long distance wireless power transfer. It is so complicated to analyze the unknown parameters of a helical antenna. First of all, an equivalent circuit suitable to the open-ended helical antenna should be introduced to analyze the given antennas and make highly efficient wireless energy transfer.

The experimental prototype of an open-end helical antenna is depicted in Fig. 3, where (a) and (b) are appearances and structures, individually. The conventional equivalent circuit representing the given antenna prototype is shown in Fig. 5 and the parameters are defined as follows:

C : series capacitance element in antenna
 L : inductance element in antenna
 L_m : magnetizing inductance between a pair of antennas
 R : loss resistance of antenna

Fig. 3. Experimental prototype of open-end helical antenna: (a) appearances; (b) structure

R_{in} : copper loss of antenna
 R_{rad} : radiation loss of antenna
 R_x : load resistance
 Z_0 : internal impedance ($=50\ \Omega$)

2.2.1 Impedance analysis of open-ended helical antennas

Using Network Analyzer, impedance Z_{11} or Z_{22} of one helical antenna can be measured for analyzing “real part” and “imaginary part”. These experimental results regarding one helical antenna are presented in Fig. 4.

The real part $\text{Re}[Z_{11}]$ and the imaginary part $\text{Im}[Z_{11}]$ in Fig. 4 are used for finding the anti-resonant frequency and the resonant frequency, respectively. Through this figure, the anti-resonant frequency and the resonant frequency can be observed as 17.6 MHz and 14.0 MHz, respectively. However, when a pair of helical antenna is practically designed as the prototype, both helical antennas have not the same anti-resonant and resonant frequencies each other. Based on two impedances Z_{11} and Z_{22} of a pair of helical antennas, the average values of both antennas, which is practically designed as the prototype primary and secondary antennas, are used for determining the anti-resonant frequency f_a , the resonant frequency f_0 , $\text{Re}[Z_{11}]$ at the resonant frequency, and $\text{Im}[Z_{11}]$ at the resonant frequency. These average values are listed in Table 1.

(a) real part $\text{Re}[Z_{11}]$

(b) imaginary part $\text{Im}[Z_{11}]$

Fig. 4. Impedances of one helical antenna measured by Network Analyzer

Table 1. Average impedance, and average anti-resonant and resonant frequencies of a pair of helical antennas

item	unit	average measured value
F_0	MHz	14.28
f_a	MHz	18
$\text{Re}[Z_{11}]$	Ω	3.9
$\text{Im}[Z_{11}]$	Ω	-j0.06

The anti-resonance can be figured out as the frequency point when “real part” value is at the maximum or “imaginary part” value is sharply inverse-changed from positive maximum to negative maximum. And the resonant frequency can be figured out as the frequency point when “imaginary part” is zero.

2.2.2 Conventional equivalent circuit

The equivalent circuit is very helpful tool to evaluate the characteristics of helical antennas and design a highly-efficient WPT system. The equivalent circuit for a pair of helical antennas can be modeled on the basis of the measured parameters.

The conventional equivalent circuit [7] for a pair of helical antennas is shown in Fig. 5. The coupling coefficient and the magnetizing inductance of the conventional equivalent circuit in Fig. 5 are defined as (2) and (3) respectively [2]. Self inductance in the conventional equivalent circuit consists of magnetizing inductance L_m and leakage inductance $L_l (= L - L_m)$, and Fig. 5 (a) can be represented as T type equivalent circuit shown in Fig. 5 (b).

Generally, the anti-resonant frequency doesn't exist in the conventional equivalent circuit. However the anti-resonant frequency exists in the analyzed data of Fig. 4. Thus there is a mismatch between the experimental results and the established conventional equivalent circuit. This conventional equivalent circuit is not suitable and then the

(a) practical

(b) T type

Fig. 5. Conventional equivalent circuit of a pair of helical antennas

Fig. 6. Proposed equivalent circuit of a pair of helical antennas

proper modification regarding the equivalent circuit should be required for two kinds of resonance frequencies to exist in the modified equivalent circuit.

2.2.3 Proposed equivalent circuit

To clear the above mentioned mismatching problem, authors propose the proper equivalent circuit regarding a pair of helical antennas for a long distance WPT system in Fig. 6 [8]-[10]. And the proposed T type equivalent circuit representing Fig. 6 (a) is shown in Fig. 6 (b). It is noted that C_t is parallel capacitance element in the antenna.

This equivalent circuit has two kinds of resonances, which can be expressed as follows respectively:

$$\begin{aligned} \omega_1 &= \frac{1}{\sqrt{(L+L_m)C}} \\ \omega_2 &= \frac{1}{\sqrt{(L-L_m)C}} \end{aligned} \quad (4)$$

where $I_1 = I_3$

in case of resonant frequency ω_1 : $I_2 = I_1 + I_3 = 2I_1$
 in case of resonant frequency ω_2 : $I_2 = I_1 - I_3 = 0$

When the distance between the primary helical antenna and the secondary helical antenna becomes much longer, the term in (3) becomes almost zero. Thus, these two resonant frequencies (ω_1 for the primary antenna and ω_2 for the secondary antenna) merge to one resonant frequency ($\omega_0 = 1/\sqrt{LC}$), which is called a resonant frequency for highly efficient energy transfer.

2.3 Efficiency evaluation by s-parameter matrix

S-parameter matrix is very useful to evaluate the circuit characteristics in the MHz high frequency ranges. The reflection power and the transfer power between a pair of antennas can be easily measured by network analyzer. These two S-parameters for helical antenna WPT evaluations can be theoretically expressed as (5), once the equivalent circuit in Fig. 6 is correctly established. S_{11} is the power reflection, which is the ratio of the receiving power at the transmitter divided by the transmitting power at the same transmitter. S_{21} is the power transfer, which is the ratio of the receiving power at the receiver divided by the transmitting power at the transmitter [9].

$$\begin{aligned} S_{11} &= \frac{(Z_{11} - Z_0)(Z_{22} + Z_0) - Z_{12}Z_{21}}{(Z_{11} + Z_0)(Z_{22} + Z_0) - Z_{12}Z_{21}} \\ S_{21} &= \frac{2Z_0Z_{21}}{(Z_{11} + Z_0)(Z_{22} + Z_0) - Z_{12}Z_{21}} \end{aligned} \quad (5)$$

where Z_{11} , Z_{12} , Z_{21} , Z_{22} are called Z-parameters. In addition, Z_0 is the internal or reference impedance to define S-parameters and is generally set as 50Ω in high frequency circuit.

The power reflection loss η_{11} and the power transfer efficiency η_{21} can be calculated on the basis of S-parameter matrix, which are measured by Network Analyzer [9]. They are expressed as (6). The power reflection acts as the active power and the reflection power acts as the reactive power. The measured values of S_{11} and S_{21} by Network Analyzer are displayed as the unit of decibel.

$$\begin{aligned} \eta_{11} &= \left(\frac{S_{11}}{10^{20}} \right)^2 \times 100[\%] \\ \eta_{21} &= \left(\frac{S_{21}}{10^{20}} \right)^2 \times 100[\%] \end{aligned} \quad (6)$$

Through two types of S-parameter matrix (S_{11} and S_{21}) mentioned above, it is well known that the power reflection S_{11} should be completely reduced for achieving higher efficient power transfer. In other words, the lower the power reflection is reduced, the higher the power transfer efficiency is improved for commercialized WPT system.

2.4 Proposed parameter identification

For optimizing the power transfer S_{21} , several sub-tasks are prepared. One is to obtain the values of the unknown parameters. As shown in (5), S_{21} consists of Z-parameters, thus the values of Z-parameters are required. Z-parameters are consisting of parameters in Fig. 6.

Fig. 7. Equivalent circuit of half helical antenna

For simplicity, a pair of helical antennas (transmitting antenna and receiving antenna) can be divided into the identical half antenna. Thus the equivalent circuit regarding the identical half antenna can be depicted as shown in Fig. 7 which has the four unknown parameters C , C_t , R , and L . Magnetizing mutual inductance L_m becomes zero in this half antenna. Z_{11} can be easily derived using these parameters [9].

$$\text{Re}[Z_{11}] = \frac{R}{\{1 - \omega C_t(\omega L - \frac{1}{\omega C})\}^2 + (\omega R C_t)^2} \quad (7)$$

$$\text{Im}[Z_{11}] = \frac{j(\omega L - \frac{1}{\omega C})\{1 - \omega C_t(\omega L - \frac{1}{\omega C})\}^2 - j\omega R^2 C_t}{\{1 - \omega C_t(\omega L - \frac{1}{\omega C})\}^2 + (\omega R C_t)^2} \quad (8)$$

Since the four parameters are unknown, four equations are required for unique determination of them. The following four steps are introduced in experiments to calculate the values of the unknown parameters based on the proposed equivalent circuit.

STEP 1 : Based on the resonant frequency condition in (9), the resonant frequency ω_0 of each open-ended helical antenna is calculated as (10).

$$0 = \omega L - \frac{1}{\omega C} \quad (9)$$

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad (10)$$

STEP 2 : Putting the resonant frequency condition (9) into (7) and (8), the real part and the imaginary part of impedance Z_{11} at the resonant frequency ω_0 are respectively calculated as,

$$\text{Re}[Z'_{11}] = \frac{R}{1 + \frac{1}{LC} R^2 C_t^2} \cong R \quad (11)$$

$$\text{Im}[Z'_{11}] = \frac{-jR^2 \sqrt{\frac{1}{LC}}}{\frac{1}{C_t} + \frac{1}{LC} R^2 C_t} \cong 0 \quad (12)$$

where C_t is much smaller than unity ($C_t \ll 1$), $\text{Re}[Z_{11}]$ is resistance, and $\text{Im}[Z_{11}]$ is reactance.

STEP 3 : Based on the anti-resonant frequency condition in (13), the anti-resonant frequency ω_a of each open-ended helical antenna is calculated as (14).

$$0 = 1 - \omega C_t(\omega L - \frac{1}{\omega C}) \quad (13)$$

$$\omega_a = \sqrt{\frac{1}{L}(\frac{1}{C_t} + \frac{1}{C})} \quad (14)$$

STEP 4 : Putting the anti-resonant frequency condition (7) into (8) and (14), the real part and the imaginary part of impedance Z_{11} at the anti-resonant frequency ω_a are respectively calculated as,

$$\text{Re}[Z''_{11}] = \frac{1}{\frac{1}{L}(\frac{1}{C_t} + \frac{1}{C}) R C_t^2} \quad (15)$$

$$\text{Im}[Z''_{11}] = \frac{-j}{C_t \sqrt{\frac{1}{L}(\frac{1}{C_t} + \frac{1}{C})}} \quad (16)$$

As mentioned in the subsection 2.2.1, the values of the anti-resonant frequency and the resonant frequency can be confirmed through the experimental results regarding $\text{Re}[Z_{11}]$ and $\text{Im}[Z_{11}]$ in Fig. 4 and Table 1.

STEP 5 : Based on the four equations derived in the previous steps, the unknown four parameters regarding the open-ended helical antenna for WPT system can be estimated by the following Eqs. (17-20). The estimated parameters (L , C , C_t , R) are listed in Table 2.

Table 2. Parameters estimated by proposed parameter identification

parameter	unit	value
L	mH	30.2
C	pF	163.0
C_t	pF	276.0
R	Ω	3.9

Through the data in Table 1, the anti-resonant frequency and the resonant frequency can be confirmed as 18.0MHz and 14.28MHz respectively. And also the real part impedance $\text{Re}[Z_{11}]$ at the resonant frequency, and the imaginary part impedance $\text{Im}[Z_{11}]$ at the resonant frequency can be found and used for estimating the four unknown parameters of each helical antenna.

$$\omega_0 = \frac{1}{\sqrt{LC}} = 14.28 \times 10^6 \text{ Hz} \quad (17)$$

$$\omega_a = \sqrt{\frac{1}{L}(\frac{1}{C_t} + \frac{1}{C})} = 18 \times 10^6 \text{ Hz} \quad (18)$$

Fig. 8. Impedance of helical antenna equivalent circuit calculated by simulation analysis

$$\text{Re}[Z'_{11}] = \frac{R}{1 + \frac{1}{LC} R^2 C_t^2} = 3.9\Omega \quad (19)$$

$$\text{Im}[Z'_{11}] = \frac{-jR^2 \sqrt{\frac{1}{LC}}}{\frac{1}{C_t} + \frac{1}{LC} R^2 C_t} = -j0.06\Omega \quad (20)$$

Putting these estimated four parameters into the proposed equivalent circuit Eqs. (7) and (8), the frequency response of Z_{11} can be calculated by simulation analysis, and the simulation results regarding the impedance Z_{11} of each open-ended helical antenna are shown in Fig. 8.

It can be observed that these simulated curves regarding the impedance Z_{11} of each open-ended helical antenna match very well to those of experimental results in Fig. 4. This implies that the proposed equivalent circuit in Fig. 6 can explain the physical phenomena of helical antenna very well and also the proposed procedure for calculating the unknown four parameters are practically acceptable. Based on the proposed equivalent circuit, the design of open-ended helical antennas with higher WPT efficiency can be easily obtained.

2.5 Parameter optimization for power transfer efficiency

When the power source frequency is adjusted at the resonant frequency ω_0 and the resistance R is zero, the power reflection loss S_{11} and the power transfer efficiency S_{21} of a pair of the open-ended helical antennas in Fig. 3 can be expressed with the estimated four parameters and the known reference impedance Z_0 . It is noted that the magnetizing mutual inductance L_m is included in (21) and (22).

$$S_{11} = \frac{CLL_m^2 - (CLZ_0)^2 + (L_m C_t Z_0)^2}{CLL_m^2 + (CLZ_0)^2 + (L_m C_t Z_0)^2 + 2jL_m^2 C_t Z_0 \sqrt{LC}} \quad (21)$$

$$S_{21} = \frac{2jL_m^2 C_t Z_0 LC \sqrt{LC}}{CLL_m^2 + (CLZ_0)^2 + (L_m C_t Z_0)^2 + 2jL_m^2 C_t Z_0 \sqrt{LC}} \quad (22)$$

To maximize the power transfer efficiency, the power reflection S_{11} should be zero and the power transfer S_{21} must be unity. Putting zero power reflection into (23), (24) is derived for optimizing the magnetizing inductance L_m .

$$0 = LCL_m^2 - (LCZ_0)^2 + (L_m C_t Z_0)^2 \quad (23)$$

$$L_m = \frac{LCZ_0}{\sqrt{C_t^2 Z_0^2 + LC}} \quad (24)$$

Also putting (24) into (22), (25) is derived and the absolute value of S_{21} is expressed as (26).

$$S_{21} = \frac{C_t Z_0 + j\sqrt{LC}}{\sqrt{C_t^2 Z_0^2 + LC}} \quad (25)$$

$$S_{21} = \sqrt{\left(\frac{C_t Z_0}{\sqrt{C_t^2 Z_0^2 + LC}}\right)^2 + \left(\frac{\sqrt{LC}}{\sqrt{C_t^2 Z_0^2 + LC}}\right)^2} = 1 \quad (26)$$

In short, it is confirmed that the following conditions should be satisfied to maximize the power transfer efficiency. The magnetizing inductance L_m is a function of the distance D in (3) and a variant parameter. The other parameters are constant once the antenna geometry is designed. Therefore, the procedures regarding parameter optimization are summarized as follows:

- minimizing the antenna internal resistance
- tuning the magnetizing inductance L_m for satisfying (24)

3. Experiments

3.1 System configuration

The experimental system configuration for power

reflection loss and power transfer efficiency is illustrated in Fig. 9, which is consisting of RF power source, SWR meter, impedance matching system, a pair of helical antennas, load. In addition, Network Analyzer is used for measuring the power reflection and the power transfer.

In the experimental system, the SWR(Stand Wave Ratio) meter is used to confirm the system impedance matching level as analogue-observing both the power reflection and the power transfer by adjustment of impedance matching system, the impedance matching system is used to match the impedance between RF power source and WPT, RF power source is used as the high frequency (1.8MHz ~ 54MHz) power source for WPT system, and the load at the secondary antenna is an incandescent light bulb.

Based on the proposed equivalent circuit regarding a pair of the open-ended helical antennas for higher efficient WPT, the power reflection loss and the power transfer efficiency power transfer according to the distance D between the primary antenna and the secondary antenna are surveyed at 14.28MHz resonant frequency of RF power source.

3.2 Experimental reviews on power reflection and power transfer

Power reflection and power transfer in Fig. 9 are dependent on the distance D between the transmitting

Fig. 9. Overall system configuration for measuring power reflection loss and power transfer efficiency in experiments

Fig. 10. Power reflections S_{11} and S_{22} of each helical antenna independently measured by Network Analyzer; S_{11} is power reflection of the primary antenna, S_{22} is power reflection of the secondary antenna

(a) $D=8\text{cm}$

(b) $D=12\text{cm}$

(c) $D=16\text{cm}$

(d) $D=20\text{cm}$

Fig. 11. Power reflection S_{11} and power transfer S_{21} measured according to distance D

antenna and the receiving antenna. These influences are surveyed by Network Analyzer (R&S ZVL) measurements of S_{11} and S_{21} under input power 100W which is supplied by HF based power source (YAESU FT-2000, 100W, max. 50MHz). Fig. 10 shows each measured power reflection of transmitting antenna and receiving antenna independently. It can be confirmed that the power reflection is lower at around the resonant frequency 14.28MHz of power source than other frequency ranges. This means that the lower level at around the resonant frequency has the lower power reflection loss. Therefore the power can be transfer to the secondary antenna from the primary by the electro-magnetic resonance coupling antennas.

Fig. 11 shows the measured reflection transfer and the measured power transfer between transmitting antenna and receiving antenna. It is confirmed in this figure that power transfer S_{21} is changed according to the distance which influence L_m is related to power transfer efficiency.

3.3 Experimental reviews of power transfer efficiency

The power transfer efficiency is measured under conditions of several different distances, which are shown in Fig. 12.

In case that the distance D is below 20cm, the power transfer efficiency can be secured above about 90%. But in case that the distance is above 20cm, the power transfer efficiency has the sharp decrease curve as shown in Fig. 12. Thus it can be predicted that there exists the most suitable distance for the optimized power transfer efficiency.

Fig. 12. Power transfer efficiency measured according to distance

5. Conclusion

This paper proposed both the electrical equivalent circuit of open-ended helical antenna and the parameter identification for higher wireless power transfer and the followings were in detail discussed.

- The well-established equivalent circuit in high frequency ranges is developed for analyzing a resonance enhanced-electromagnetic induction coupled by helical antennas
- The unknown parameters are identified via experiments and it is revealed that their parameters are measurable
- Based on the well-derived electrical equivalent circuit in high frequency ranges, the basic key-design for optimizing antenna's parameter can be provided

It is verified through the experimental data and the simulation analysis that the proposed methodology to identify the unknown parameters regarding a pair of the open-ended helical antenna for high efficient wireless power transfer is effective.

References

- [1] C. K. Lee, W. X. Zhong, and S. Y. R. Hui, "Recent Progress in Mid-range Wireless Power Transfer," in *Proceedings of ECCE*, pp. 3819-3824, 2012.
- [2] Karalis et al, "Efficient Wireless Non-radiative Mid-range Energy Transfer," *Annals of Physics*, pp. 34-48, 2007.
- [3] A. Kawamura, K. Ishioka, and J. Hirai, "Wireless Transmission of Power and Information through One High Frequency Resonant AC Link Inverter for Robot Manipulator Application," *IEEE Trans. on IA*, Vol. 43, No. 3, pp. 503-508, 1996.
- [4] Shigeru Abe and Yasuyoshi Kaneko, "Wireless Power Transfer Technology," *IEEJ Trans. on IA*, Vol. 128, pp. 796-799, 2008.
- [5] T. Imura, "Experimental Analysis of High-Efficiency Power Transmission Using Resonance of Magnetic Antennas for the Near Field; Geometry and Fundamental Characteristics," in *Proceedings of JIASC*, No. 2-62, pp. 539-542, 2008.
- [6] Takehiro Imura, "Transmission Technology by Resonant Coupling of Electromagnetic," *IEEJ Trans. on IA*, Vol. 129, pp. 414-417, 2009.
- [7] T. Imura, H. Okabe, T. Uchida, and Y. Hori, "Study on Open and Short End Helical Antennas with Capacitor in Series of Wireless Power Transfer using Magnetic Resonant Couplings," in *Proceedings of IECON*, pp. 3848-3853, 2009.
- [8] H. Kurata and A. Kawamura, "Parameter Optimization of Wireless Power Transmission in 10MHz and 1m Distance Range Experiment Based on Electrical Equivalent Circuit," in *Proceedings of IIC*, IIC-10-15, 2010.
- [9] K. Ichikawa and Y. Ichikawa, "The S Parameter Demystified for Design of High-Frequency Circuit," *CQ Publisher*, 2008.
- [10] T. Kawaguchi, Y. Kobayashi, and Z. Ma, "A Study on Equivalent Circuit Expression of Electromagnetic Coupling between Distributed Resonators," *IEIC*

Technical Report, Vol. 103, No. 370, pp. 1-6, 2003.

- [11] T. Anazawa, A. Kawamura, and T. W. Kim, "Optimized Antenna Design for Wireless Power Transmission and Efficiency Analysis of HF Rectifier," in *Proceedings of JIASC*, pp. 491-496, 2011.

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