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近傍界結合による無線電力伝送のアンテナ設計法についての検討

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あらまし　近傍界結合による無線電力伝送の最大伝送効率を得るための送受信アンテナ設計法について，放射，導体損失，インピーダンスマッチングというアンテナ設計の観点から議論する．受信素子の負荷インピーダンスによって変化する伝送効率を最大化する最適負荷条件を検討し，伝送効率を最大とする最適な負荷の条件を導く．また，近傍電界結合と近傍磁界結合による電力伝送システムの伝送効率の違いを数値シミュレーションにより明らかにする．

キーワード　無線電力伝送，アンテナ，整合

Antenna Design for Near-field Coupled Wireless Power Transmission

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Abstract　A fundamental study is focused to investigate the power transmission efficiency of the wireless power transmission system by near-field coupling from a view point of antenna theory. Two types of antennas, dipole and loop antennas, are used as the transmitting antennas and receiving antennas for electrical near-field coupling and for magnetic near-field coupling, respectively. The relation is clarified between the power transmission efficiency and antenna geometry, antenna electrical size, impedance matching of the antennas, and ohmic loss in antennas and impedance matching circuits. Seveal observations have been obtained to demonstrate the influence on the power transmission efficiency from the impedance matching and ohmic loss in the wireless power transmission system by near-field coupling.

Key words　Wireless Power Transmission, Wireless Power Transfer, Antennas, Near-field Coupling, Efficiency, Conjugate Impedance Matching

1. Introduction

Wireless power transmission (WPT) technology attracts a great deal of attention for the applications to wirelessly charging electronic devices such as mobile music player, mobile phone, household robots and so on. It was experimentally demonstrated that a very efficient power transmission can be achieved by using the so-called evanescent resonant coupling method, showing its potentiality of practical application [1]. It was shown that the evanescent resonant coupling method can transmit the energy for longer distance than the previous near-field induction method [2], [3], and is more efficient than the far-field radiation method where vast majority energy is wasted due to the transmission loss [4]- [6].

There have been many researches following [1] in recent years. In [7], the power transmission efficiency (PTE) of two dielectric disks and two capacitive loaded conducting-wire loops were calculated by the resonance width and the coupling coefficient based on the coupled-mode theory (CMT), showing the applicability of the WPT system in the presence of extraneous environmental objects. However, because the approach was based on the CMT, it was difficult to explain how to make the transmitting or receiving element resonating at the desired frequency, and it was also difficult to give an optimum load for the receiving element which dominates the resonance width or resonant decay coefficient. The WPT via magnetic resonant coupling was experimentally demonstrated in a system with a large source coil and either one or two small receivers and resonance between source and load coils was achieved with lumped capacitors terminating the coils [8]. It was also demonstrated that the WPT system could be designed by the conventional circuit theory and the multistage filter theory in [9], [10]. We have presented a practical WPT system consisting of a large wire loop and a small wire loop with a parasitic square helical coil for an indoor application, and investigated the variation of the PTE when location of small loops is changed and resonance condition is destroyed by the nearby scattering objects [11].

This research is focused on the WPT system by near-field coupling, which is supposed to unify the concept of the evanescent resonant coupling method and the near-field induction method. The study is performed from the view point of antenna theory instead of the circuit theory, by investigating antenna parameters such as geometry of transmitting and receiving antennas, electrical size of antennas, impedance matching for antennas, distance between transmitting and receiving antennas, conductor loss (ohmic loss) of antennas, ohmic loss of matching circuits, and so on, in order to clarify the relation between the PTE and these parameters. Two types of antennas, dipole antennas and loop antennas are used as a conical model to obtain some general conclusions. The PTE is strictly defined as the ratio of the receiving power at the receiving antenna and the input power at the transmitting antenna by considering the input impedance of antennas including the effect of near-field coupling. The WPT system including antennas is numerically analyzed by the method of moments (MoM).

2. Analysis model and method

In order to obtain a clear physical explanation to the relation between the PTE and antenna parameters, two simple antennas are used as the transmitting and receiving antennas: straight wire dipole with a length l shown in Fig. 1, and circular wire loop with a diameter of D shown in Fig. 2, operating as the antenna for electric coupling and magnetic coupling, respectively. The transmitting and receiving antennas are the same and separated with a distance d. The transmitting antenna is connected to a source with internal impedance of Z_s, while the receiving antenna is loaded with an impedance Z_l.

These two WPT systems can be expressed in form of a 2-port equivalent circuit shown in Fig. 3. The PTE can be

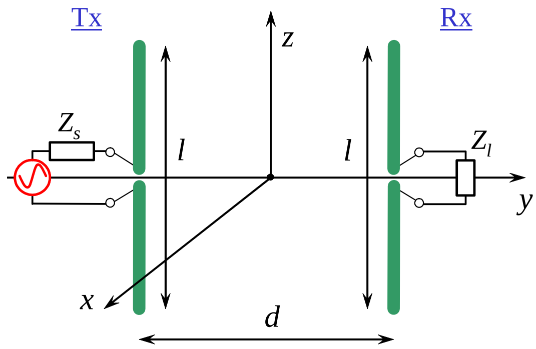

Figure 1 Wireless power transmission system using dipole antennas.

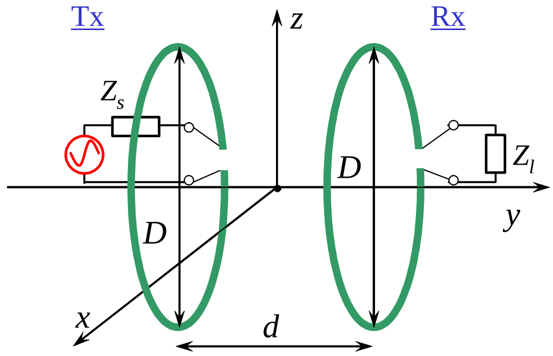

Figure 2 WIreless power transmission system using loop antennas.

evaluated by using the S-parameter of the circuit as

$$\eta = \frac{P_l}{P_{in}} = \frac{\mid S_{21} \mid^2 \left(1 - \mid \Gamma_l \mid^2\right)}{\mid 1 - S_{22}\Gamma_l \mid^2 \left(1 - \mid \Gamma_{in} \mid^2\right)} \tag{1}$$

where, Γ_l is the reflection coefficient at the load Z_l, and Γ_{in} is the reflection coefficient at port 1, caculaled by

$$\Gamma_l = \frac{Z_l - Z_0}{Z_l + Z_0} \tag{2}$$

$$\Gamma_{in} = S_{11} + \frac{S_{12}S_{21}\Gamma_l}{1 - S_{22}\Gamma_l} \tag{3}$$

respectively. Here, S_{11}, S_{21}, S_{12}, S_{22} are calculated by using the MoM, and characteristic impedance $Z_0 = 50\Omega$ is supposed to calculate the S-Parameter.

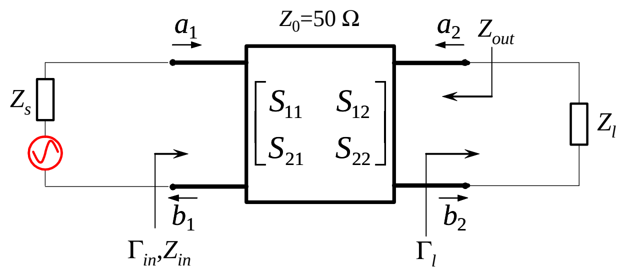

Figure 3 2-port equivalent circuit for analysis of wireless power transmission system.

3. PTE in case of conjugate-impedance-matching

In this section. the ohmic loss of antennas is ignored to simplify the investigation. As a result, there are two kinds of power loss left in the WPT system: the reflection loss and the radiation loss. When antenna geometry and antenna distance are given, the radiation loss is determined. In this case, if both of the transmitting and receiving antennas are perfectly impedance-matched with the feeding circuit and load impedance respectively, the PTE reaches the maximum value. The perfect impedance-match is realized when condition of the complex conjugate matching is satisfied at both port 1 and port 2. Because transmitting antenna and receiving antenna are the same, the condition of conjugate impedance matching at two ports is equivalent to the relation

$$Z_{in} = Z_l^* \tag{4}$$

where Z_{in} is the input impedance at port 1, aslo influenced by the reception port through near-field coupling, and Z_l^* is complex conjugate of the load impedance Z_l at the reception port. Because Z_{in} depends on Z_l, Z_l should be tuned to a value Z_l^o to satisfy the relation of Eq. 4. Z_l^o is called optimal load impedance, dependent on antenna geometry and antenna distance between transmission and reception. For the dipole system in 1, the PTE for different antenna length and distance is shown in Fig. 4 when the receiving antenna is loaded with optimal load impedance Z_l^o. It is found that the PTE can approach to 100% if the antenna is small enough and distance is short enough. A smaller dipole results in a higher efficiency when the dipole is electrically small. This result is theoretically true because the radiation power decreases when dipole length becomes short. It is found that a short dipole requires an extremely large value of reactance as the load impedance. In practice, this large admittance itself usually involves a large ohmic loss which reduces the PTE, which will be discussed in the next section.

For the loop system in 2, the PTE for different antenna diameter and distance is shown in Fig. 5 when the receiving antenna is loaded with the optimal load impedance Z_l^o. It is also found that the PTE can almost approach to 100% if the loop is small enough and distance is short enough. A smaller loop results in a higher efficiency when the loop is electrically small, approximately $D \leqq \lambda/2\pi$. As the same with the dipole case, a large value of reactance component as Z_l^o is required to obtain a high efficiency near 100% by using electrically small loop antennas.

It is known from the above results that a near-field coupling can result in an efficiency as high as 100% at a conjugate matching condition. Generally speaking, a larger area

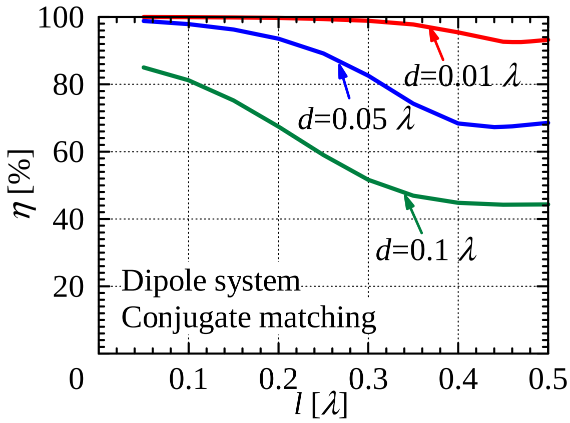

Figure 4 PTE versus dipole length for different antenna distance at condition of complex conjugate matching.

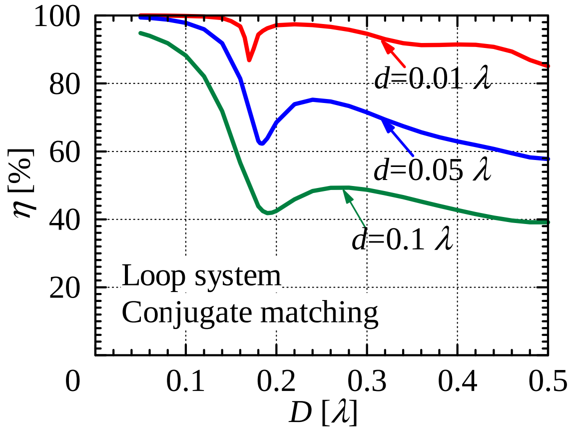

Figure 5 PTE versus loop diameter for different antenna distance at condition of complex conjugate matching.

of near-field which contains non-radiation inductive field, causes a longer distance of power transmission with high efficiency. The area of near-field is determined by antenna geometry and antenna size. Therefore, we have investigated the dependence of the PTE on the distance normalized by physical size of the antennas for both dipoles and loops to find which antenna is better in keeping high PET at a long transmission distance. We have found that if antennas are perfectly matched with a complex conjugate impedance and are made of perfect electric conductor (PEC), the PTE can approach to 100 % when transmitting and receiving antennas are small enough and located within the near-field region of each other. Furthermore, a smaller size of antennas results in a higher value of the PTE. However, it is well known that the ohmic loss cannot be ignored, and even becomes a key factor to determine the antenna performance especially for those small antennas from the view of antenna engineering. Therefore, we should continue this study with consideration of the ohmic loss of antennas.

4. PTE with consideration of ohmic loss in antennas

In this session, It is assumed that the antennas are made of good conductors and the condition of complex conjugate matching is satisfied to find the influence on the PTE due to the ohmic loss of conductor. Two kinds of conductivity are assumed in the numerical analysis. One is 5.8×10^7 S/m, equivalent to that of pure copper, and the other is 5.8×10^6 S/m, a more practical value for a good conductor. The frequency is assumed to be 13.56 MHz for calculating surface impedance of antennas in the numerical simulation.

The efficiency variation with antenna size at a distance d=0.05 λ for dipole system and loop system are shown in Fig. 6 and Fig. 7, respectively. Compared with the case of PEC plotted in these figures, the PTE is degraded due to the ohmic loss. The degradation due to the ohmic loss is dependent on the antenna type and size. A electrically small Loop antenna is more sensitive to the ohmic loss than a electrically dipole, because the electrically small loop has a lower input impedance than the dipole antenna.

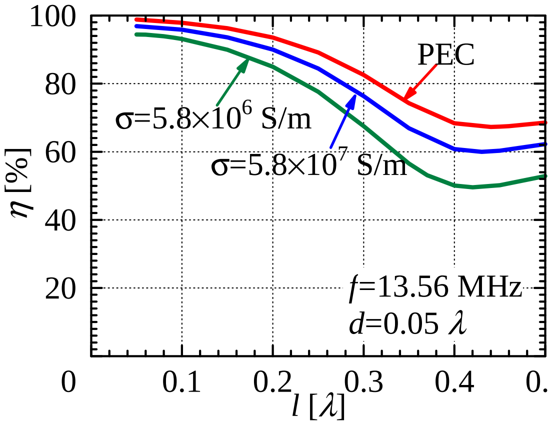

Figure 6 PTE versus dipole length for different conductivity of antennas when antenna distance is $d = 0.05\lambda$ and condition of complex conjugate matching is satified.

From the above study, it is found that the reactance part of optimal load impedance is very large, showing a large inductance value for electrically small dipole antennas, and a small capacitance value for electrically small loop antennas, to satisfy condition of the complex conjugate matching. The optimal load impedance should have a very low Q-value because the resistance component is relatively very small. However, it is practically very difficult to realize this large load impedance with a very low Q-value. In the next session, the matching circuits are added to the WPT system and the ohmic loss in the matching circuits is further considered in the numerical analysis.

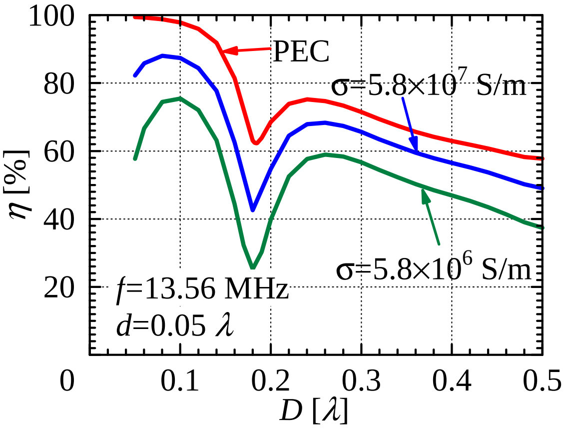

Figure 7 PTE versus loop diameter for different conductivity of antennas when antenna distance is $d = 0.05\lambda$ and condition of complex conjugate matching is satified.

5. PTE with consideration of ohmic loss in matching circuit

The matching circuit is usually used for 50 Ω matching, but it is introduced here for cancelling the large value of reactance component of the optimal load impedance. Therefore, the matching circuit can be very simple, just composed of only one lumped element of impedance Z_x, connected with load and source in series, as shown in Fig. 8. Introduction of the single-element matching circuit is equivalent to the concept of designing small antennas if the bandwidth is not the most important fact to be considered. The impedance Z_x has the same reactance component of Z_l^o, while its resistance is determined by Q-value of the lumped element, reflecting the ohmic loss of Z_x, defined as

$$Z_x = \frac{|X_l^o|}{\mathrm{Q}} + jX_l^o \tag{5}$$

where, X_l^o is the imaginary part of the optimal load impedance Z_l^o, Q is the Q-factor of the matching impedance Z_x.

Because of the existence of the matching circuit, the optimal load impedance to obtain the maximum PTE is changed and should be calculated with consideration of the matching circuit. If the equivalent circuit includes the matching circuit as shown in Fig. 8, the optimal load impedance $Z_l^{o\prime}$ for complex conjugate matching can be obtained according to the approach described above, if the S-parameter is evaluated from the circuit block including both transmitting and receiving antennas, as well as the matching circuits at the both ports.

The PTE for the dipole system and loop system with different Q-value in the matching circuit is shown in Fig. 9, and Fig. 10, respectively. Here, the ohmic loss in antennas is not considered in the simulation model. It is noted that

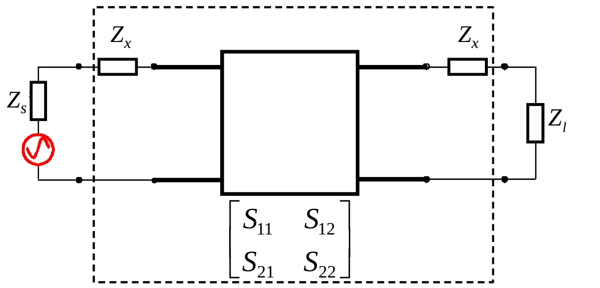

Figure 8 2-port equivalent circuit including matching circuit.

the lumped element is an inductor for the dipole system, while it becomes a capacitor for the loop system. The performance chart from those commercial products of inductors and capacitors for RF application shows Q-value of a capacitor is much higher than that of a inductor. Because of this fact, the range of Q-value for the dipole and loop system is different in the numerical experiment.

It is found that a small antenna is good at increasing the PTE as high as 100% in case of Q=Infinity, but if the ohmic loss is considered, the situation becomes quite different. The efficacy is degraded very much when antenna becomes small. It is also found the efficiency of the loop system is generally much higher than that of the dipole system if the Q-value difference between dipole and loop is considered. Even if the Q-value has the same value, the efficiency of loop system is also higher than that of dipole system, especially when the antenna is electrically small.

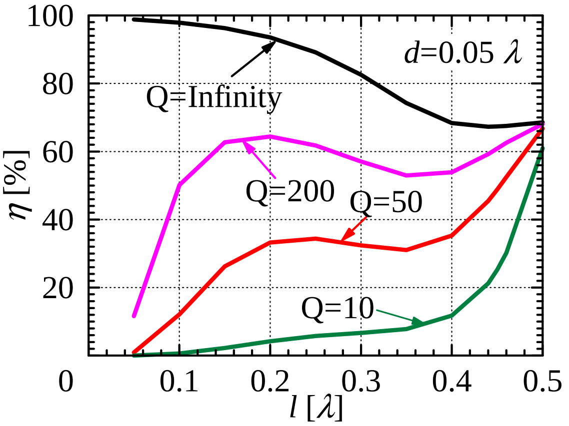

Figure 9 PTE versus dipole length for different Q-value in matching circuit when antenna distance is $d = 0.05\lambda$ and condition of complex conjugate matching is satified.

6. Conclusions

In this research, the wireless power transmission system was numerically analyzed by using a canonical model including a dipole system and a loop system to investigate the relation between the power transmission efficiency and antenna

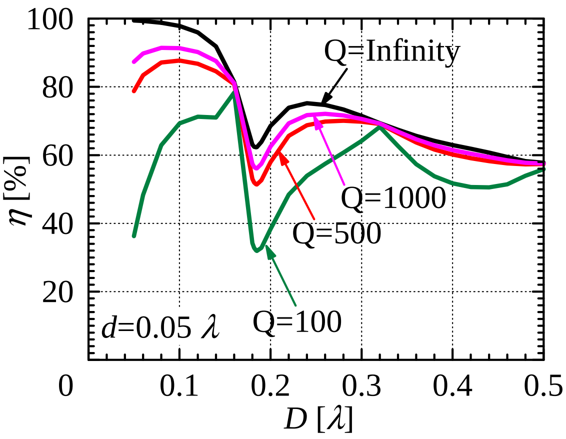

Figure 10 PTE versus loop diamneter for different Q-value in matching circuit when antenna distance is $d = 0.05\lambda$ and condition of complex conjugate matching is satified.

geometry, antenna size, antenna distance, ohmic loss in antennas and matching circuits. We can summarize the results as follows form the numerical experiment.

- It is theoretically true that the maximum efficiency can be obtained by loading the antennas with conjugate matching impedance if the antenna geometry and antenna distance are give.
- A high efficiency near 100% can be achieved in the near-field region when antenna is small enough under a assumption of ohmic loss free.
- The efficiency is degraded when the ohmic loss of antennas is considered. The loop system is much affected by the ohmic loss than dipole system.
- The loop system is superior to dipole system in achieving high efficiency if the ohmic loss of both antennas and matching circuits are considered. Superiority of the loop system is very obvious if the Q-factor of lumped electrical elements in matching circuits is defined in a practical range.
- An optimal size of loop exists to obtain maximum efficiency whose value is dependent on antenna distance.

Although a conical model of antennas was used in the numerical analysis model, these results and observations are general and fundamental, which provides a theoretical insight on how to design systems for the wireless power transmission using near-field coupling. In practice, the antenna geometry can be designed to be very complex. For example, a loop antenna together with a helical loop as a parasitic element was usually used in previous studies. However, the parasitic element in this case is theoretically equivalent to increasing electrical size of the original loop antenna, and the present results are still applicable.

お 断 り

本稿は，研究会における討論をスムーズに行えるための資料であり，論文ではない．著者は，本稿を一部加筆・修正したうえ，論文として他学会へ投稿する権利を保留する．

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