A Consideration of Helical Antennas for Coupled Resonant Wireless Power Transfer Using Equivalent Circuit

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1. Introduction

Recently, wireless power transfer (WPT) systems are getting large interest for charging an electric vehicle. Coupled resonant WPT proposed by MIT has considerable advantages because of its mid range transfer distance and high transmission efficiency [1][2]. In order to put this method in practical use, design criteria of antenna should be established. Various kinds of antenna have been reported [3]. However, suitable antenna shape for an individual requirement is not cleared.

Assuming that the coupled-resonant WPT is a kind of magnetic induction, using short-end helix as an inductor is natural. In this case, external discrete capacitor is used to resonate. On the other hands, assuming that the coupled resonant WPT utilizes coupling of resonators, using open-end helix, which has self resonant frequency, is natural. We have been investigated open-end and short-end type helical antennas [4]. In this report, difference between open-end and short-end antenna is considered by using equivalent circuit.

2. Analysis models

Consideration models are shown in Fig. 1. Open-end model shown in Fig. 1(a) consists of two helices. Transmitting (TX) helix has port 1 and receiving (RX) helix has port 2. The input impedance of this model only for the TX helix (i.e. no coupling between TX and RX) is shown in Fig. 2(a). Self-resonant frequency of 11.6MHz is observed.

Figure1(b) shows short-end model in which both ends of the helical antennas are shorted. The input impedance of the short-end model is shown in Fig. 2(b). For the short-end model, input impedance is capacitive at 11.6 MHz, which is a self-resonant frequency of the open-end model. However, to use the helical antenna as an inductor, input impedance should be inductive. Therefore, series capacitor of 7.174pF is connected to the feeding point of the TX and RX helices to resonate at 8MHz.

These models are analyzed by using method of moment (MoM). Voltage source of output impedance 50Ω is connected to the Port1. Load resistance 50Ω is connected to the Port 2. Antennas are assumed to be perfect electric conductor.

3. Equivalent circuit

Equivalent circuits of the analysis models are shown in Fig. 3 in which both the electric and the magnetic field coupling are considered. The $k_l$ and $k_e$ show magnetic and electric coupling coefficient, respectively. The parameters of the equivalent circuit were obtained by the even and odd mode analysis of the models[5]. The parameters of the equivalent circuit are shown in Table 1 for a distance between antennas $D=300$mm. The frequency characteristic of S-parameters calculated by the equivalent circuit(E.C.) is compared with MoM in Fig. 4. It is found that the results of the equivalent circuit and MoM are in good accordance. Therefore, the equivalent circuit is regarded to express the physical phenomenon for coupled resonant WPT.
Figure 1: Analysis models

Figure 2: Input impedance

Figure 3: Equivalent circuit models
Table 1: Equivalent circuit parameters

<table>
<thead>
<tr>
<th>(a) open-end model</th>
<th>(b) short-end model</th>
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<tbody>
<tr>
<td>$L [\mu H]$</td>
<td>5.1858</td>
</tr>
<tr>
<td>$k_l$</td>
<td>$-0.0765$</td>
</tr>
<tr>
<td>$C_p [pF]$</td>
<td>12.6367</td>
</tr>
<tr>
<td>$k_c$</td>
<td>$-0.0038$</td>
</tr>
</tbody>
</table>

Figure 4: Scattering parameters ($| S_{11} |, | S_{21} |$)

4. Considerations

Distance property of the coupling coefficients $k_l$ and $k_c$ are shown in Fig. 5. The $k_l$ is greater than the $k_c$ in both models. Thus, both models are coupled mainly by magnetic field. It is remarkable that the distance property of the coupling coefficients $k_l$, $k_c$ is almost identical for two models.

The differences between two models are explained not by coupling coefficient but by the inductance of the system shown in Table 1. Inductance of the short-end model is 3.99 times greater than the open-end model. Thus, it is considered that the magnetic field coupling of the short-end model is stronger.

Distance property of $S_{21}$ is shown in Fig. 6. Transmission distance at which the $S_{21}$ becomes $-3$dB of the open-end model is 142% greater than the short-end model.

5. Conclusion

In this paper, we compared the open-end self resonant helical model with the short-end external resonant helical model by using the equivalent circuit. As a consequence, we found that the open-end and the short-end models are almost identical in distance characteristics of electric and magnetic coupling coefficient. Self-inductance of the short-end model is 3.99 times larger than the open-end model. Difference between the two models is mainly caused by the self-inductance in the equivalent circuit. As a result, transmission distance of the short-end model is 142% greater than the open-end model.

Investigation of transmission loss of open-end and short-end model is further study.
Figure 5: Coupling coefficient

Figure 6: Distance property of transmission coefficient

References


