LETTER

Performance of Data Transmission in Wireless Power Transfer with Coil Displacements

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SUMMARY This letter investigates the relationship between antenna position and data communication performance in a magnetic resonance wireless power transfer (MRWPT) system. In MRWPT information such as the types of equipments, the required amount of electrical power, or the timing of power transfer should be exchanged. It is assumed here that power transfer coils in the MRWPT system are employed as antennas for data communication. The frequency characteristics of the antennas change due to coil displacements. The power transfer coils are modeled as a band pass filter (BPF) and the frequency characteristics of the filter are presented in this letter. The characteristics of the filter are derived through circuit simulation and resulting data communication performance is evaluated. Numerical results obtained through computer simulation show that the bit error rate (BER) performance can be improved by controlling the center frequency of the communication link.

key words: wireless power transfer, antenna position, power efficiency, coupling coefficient, BPF

1. Introduction

There is an increasing demand for wireless power transfer systems embedded in electric devices. In 2006, the Massachusetts Institute of Technology announced a wireless power transfer technology called magnetic resonant coupling [1]. Magnetic resonance wireless power transfer (MRWPT) system is considered as a promising method to achieve high transmission efficiency at a long distance [2], [4]. In this system, two coils are tuned at the same resonant frequency and the power transfer efficiency is approximately 50\% over a distance of several tens of centimeters.

In the MRWPT system information such as the types of equipments, the required amount of electrical power, or the timing of power transfer should be exchanged. Additional information including identification information, images, or data files may also be transmitted depending on the applications of electrical equipments [3]. MRWPT uses both the receiving and transmitting self-resonant coils as the LC resonant circuits [4]. The frequency characteristics between the coils are affected by their distance [5], [6]. In this letter, the power transmitter coils are used as the transmitting and receiving loop antennas for data communication [7]. Here, it is assumed that the data communication mode and the power transmission mode are separated and are not operated at the same time.

Our recent investigations have demonstrated the performance of data communication in MRWPT [8], [9]. However, the effect of antenna position is not considered in the previous work. In this letter, the bit error rate (BER) is used to benchmark the performance of data communication with antenna displacements. The equivalent circuit of the transmitting antenna and the receiving antenna in MRWPT is modeled as a band pass filter (BPF) that is calculated using PSpice [10]. Orthogonal frequency division multiplexing (OFDM) is used for data communication to control this system. To achieve reliable data communication, the center frequency is varied depending on the frequency characteristics.

This paper is organized as follows. Section 2 introduces the system model. In Sect. 3, numerical analysis of the coupling coefficient and the frequency characteristics of BPF gain is explained. Section 4 describes simulation results obtained using computer simulation and Sect. 5 gives our conclusions and directions for future work.

2. System Model

The model of antenna elements and their positions assumed in this letter are shown in Fig. 1. The antenna conditions are shown in Table 1. In Fig. 1, \(d\) represents the gap of the central axes of the antennas and \(h\) represents the spacing distance of the antennas. The equivalent circuit of a communication module in the MRWPT system is shown in Fig. 2 [11]. In this system, the data communication mode

\[\text{Fig. 1 Loop antenna and position.}\]

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and power transfer mode are selected by the switches. In Fig. 2, \( L \) represents self-inductance, \( M \) represents mutual inductance, \( Z_0 \) represents the characteristic impedance, and \( C \) represents the capacitance of the antenna. The conductor losses and the internal resistance are ignored in this system. From Neumann's formula, the self inductance of the antennas \( L \) is given by
\[
L = \frac{\mu_0}{4\pi} \int_0^{2\pi} \int_0^{2\pi} \frac{R^2 \cos(\theta - \theta_2)}{\sqrt{x^2 + y^2 + z^2}} d\theta_2 d\theta_1,
\]
where \( G \) is the radius of the wire, \( W \) is the winding number of the antenna, \( R \) is the radius of the antenna, and \( P \) is the pitch of the antenna [12]. \( C \) and \( Z_0 \) are set to 20.482 \( \text{pF} \) and 50 \( \Omega \) in order to make the resonance frequency be 13.56 MHz in this letter [13]. The parameters of the equivalent circuit are shown in Table 2.

### Table 2: Equivalent circuit parameters.

<table>
<thead>
<tr>
<th>( L ) [( \mu \text{H} )]</th>
<th>( C ) [( \text{pF} )]</th>
<th>( Z_0 ) [( \Omega )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.726</td>
<td>20.482</td>
<td>50.0</td>
</tr>
</tbody>
</table>

3. Numerical Analysis

3.1 Coupling Coefficient

The mutual inductance between the antennas is given by
\[
M = \frac{\mu_0}{4\pi} \int_0^{2\pi} \int_0^{2\pi} \frac{R_1 R_2 \cos(\theta - \theta_2)}{\sqrt{x^2 + y^2 + z^2}} d\theta_2 d\theta_1,
\]
where \( x' = d + R_2 \cos \theta_2 - R_1 \cos \theta_1 \),
\[
y' = R_2 \sin \theta_2 - R_1 \sin \theta_1,
\]
\[
z' = h + W_1 P_1 - (P_1 \theta_1 - P_2 \theta_2)/2\pi,
\]
and
\[
M = k \sqrt{L_1 L_2},
\]
where subscript 1 means the transmitting side and subscript 2 means the receiving side. \( L_{1,2} \) are given by Eq. (1). \( k \) is the coupling coefficient, which varies depending on the relative antenna position. In this letter, it is assumed that \( L_1 = L_2 \). The calculated theoretical value of the coupling coefficient and the relationship with the relative antenna position is shown in Fig. 3. The negative value indicates the reversal of current direction.

3.2 \(|S_{21}|\) Characteristic

In this letter, the frequency characteristics between the antennas as BPF gain \( \eta_B \) is given by
\[
\eta_B = 20 \log_{10} |S_{21}(\omega)|.
\]
Here,
\[
S_{21}(\omega) = \frac{2 j \omega MZ}{M^2 \omega^2 + [Z + j \omega L - (1/\omega C)]^2},
\]
where \( L \) and \( M \) are given by Eq. (1) and Eq. (5), respectively [11]. The transfer function \( S_{21} \) is calculated by circuit simulation and the relationship between the coupling coefficient and the BPF gain is shown in Figs. 4 and 5, in which \( k \) is a function of \( M \) and \( L \). From the frequency characteristics, the double-humped resonance response is observed at \( k \) of more than 0.1. In this letter, the frequency of the lower peak is written as \( f_L \) and the higher one is indicated as \( f_H \).

4. Simulation Results

4.1 Simulation Condition

BER performance is evaluated through computer simulation. The OFDM system for data transmission assumed here is the same as those in [8] and [9]. The simulation conditions are shown in Table 3. Information bits are modulated with quadrature phase shift keying (QPSK) on each subcarrier. The center frequency of signal is set to 13.56 MHz, \( f_L \), or \( f_H \). Coupling coefficient, \( k \), is set from 0.02 to 0.6. The number of discrete Fourier transform (DFT) points is set to 64 and is fitted to the bandwidth. Here, the bandwidth is 1 MHz to fit in half-gain points (3 dB) from the the composite filter peak at \( k = 0.08 \), which has the highest gain without
the double-humped resonance characteristics. The guard interval is set to 16, which is 1/4 of the number of subcarriers $N$. The channel model between the transmit antenna and the receive antenna is assumed as a quasi-static multipath channel. The phase compensation is assumed to be perfect.

4.2 BPF Gain

The relationship between the $|S_{21}|$ characteristics and the center frequency of data communication, $f_c$, is shown in Fig. 6. The mean values of the BPF gain with 1 MHz bandwidth are shown in Table 4. When the center frequency is chosen at 13.56 MHz or $f_L$, the mean value of the gain becomes the highest at $k = 0.1$ since the frequency character-

4.3 BER Performance

The BER performances based of the BPF gain are shown in Figs. 7 to 10, in which the center frequency is set to 13.56 MHz, $f_L$, or $f_H$. In these figures, $x$ axis means supplied bit energy per noise ($SE_{b}/No$) at the transmitting end. In Figs. 7 and 8, the BER curves are close to the AWGN theoretical performance when the coupling coefficient is $k = 0.1$. This is because the passband is not affected by the double-humped resonance characteristics. Therefore, when the center frequency is fixed at 13.56 MHz, the spacing distance or the gap of the central axes between the antennas should be around 15 cm for reliable data communication.

Table 3 Simulation conditions.

<table>
<thead>
<tr>
<th>Number of OFDM symbols</th>
<th>1,000,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation scheme</td>
<td>QPSK + OFDM</td>
</tr>
<tr>
<td>Center frequency of data communication</td>
<td>13.56 [MHz] ($k = 0.02 \sim 0.08$)</td>
</tr>
<tr>
<td></td>
<td>13.56 [MHz], $f_L$, $f_H$ ($k = 0.1 \sim 0.6$)</td>
</tr>
<tr>
<td>Coupling coefficient</td>
<td>0.02 $\sim$ 0.6</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>1 [MHz]</td>
</tr>
<tr>
<td>DFT size</td>
<td>64</td>
</tr>
<tr>
<td>Number of data subcarriers</td>
<td>64</td>
</tr>
<tr>
<td>Number of guard interval</td>
<td>16</td>
</tr>
<tr>
<td>Channel model</td>
<td>Quasi-static multipath channel</td>
</tr>
</tbody>
</table>

Table 4 Mean value of BPF gain.

<table>
<thead>
<tr>
<th>$k$</th>
<th>$f_L$</th>
<th>$f_H$</th>
<th>$f_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>0.13950</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.04</td>
<td>0.45531</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.06</td>
<td>0.76401</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.08</td>
<td>0.94495</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.1</td>
<td>0.98950</td>
<td>0.92861</td>
<td>0.94879</td>
</tr>
<tr>
<td>0.2</td>
<td>0.56682</td>
<td>0.81346</td>
<td>0.89564</td>
</tr>
<tr>
<td>0.3</td>
<td>0.29729</td>
<td>0.77393</td>
<td>0.90832</td>
</tr>
<tr>
<td>0.4</td>
<td>0.17720</td>
<td>0.74531</td>
<td>0.92751</td>
</tr>
<tr>
<td>0.5</td>
<td>0.11641</td>
<td>0.71864</td>
<td>0.94691</td>
</tr>
<tr>
<td>0.6</td>
<td>0.08203</td>
<td>0.69671</td>
<td>0.96460</td>
</tr>
</tbody>
</table>
The reason is that the coupling coefficient is close to 0.1 as shown in Fig. 3, which realizes the largest BPF gain as shown in Table 4. On the other hand, in Figs. 9 and 10, the BER curves are improved compared to those in Figs. 7 and 8. This is because the gain in the bandwidth stays high by changing the center frequency to $f_L$ or $f_H$. In Fig. 10, the BER curves are close to the AWGN theoretical performance when the coupling coefficient, $k$, is set to 0.6. The bandwidth reduces at $k$ of more than 0.08. When the center frequency is set to $f_H$, the BER performance improves even if the spacing distance or the gap of the central axes is narrow.

5. Conclusion

In this letter, the effect of coil displacements in data transmission for wireless power transfer systems has been investigated. The coupling coefficient is derived from the theoretical formula and the BPF gain is calculated based on the equivalent circuit model when the coupling coefficient is changed. In the data communication, OFDM is used as the modulation scheme and the BER performance is evaluated. From simulation results, BER curves are close to the AWGN theoretical performance when the center frequency of the data communication is set to $f_H$. This is because the highest BPF gain is selected. To conclude, the same BER can be achieved when the center frequency of the data communication is shifted. Further work will consider the detection and the control of the frequency characteristics.

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References

