Investigation of the effects of common and separate ground systems in wireless power transfer

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Abstract
This article presents an investigation of the effects on a grounding system of wireless power transfer (WPT) when transmitting over relatively far distances, that is, up to 1.25 m. Conventional two-coil WPT systems are sufficiently commercialized in strong coupling range, but it is important to accomplish the long-range WPT in weak coupling range for further various applications. This system depends on the coupling effect between the two coils that the grounds of the transmitting and receiving coils should be completely separated. However, when evaluating the performance of two-coil systems with the instrument consisting of two ports and one common ground, undesirable problems occur in weak coupling ranges, for example, obtaining disagreeable transmission efficiency and degrading system stability/reliability. We investigate the problems of the leakage power from common ground systems and provide a practical solution to obtain a reliable WPT system by using an isolation transformer. The usefulness of this approach is that it is possible to achieve the stability of the system with relatively far transmitting distances and to determine the exact transmission efficiency.

KEYWORDS
ground, isolation, measurement, transformer, wireless power transfer (WPT)

1 | INTRODUCTION

Wireless power transfer (WPT) has been developed to utilize wireless charging for mobile phones, electric vehicles, and various electronic devices. There are several different concepts for representative WPT [1–4]; one of these is a method of transferring electric power using a magnetic field induced in a coil in a magnetic induction coupling. Its fundamental property is that the self-resonance frequency of the coils is different from the operating frequency within the energy transmissions. In Kurs et al. [5], there was demonstrated the wireless transmission of 60 W of power at a distance of 2 m using magnetic resonance coupling (MRC). It was based on magnetic resonance mode coupling between the transmitter (TX) and receiver (RX) using the same resonance frequencies for both the coils and the energy transmission. An MRC-based WPT system is advantageous in terms of transmission distance due to the high quality factors \((Q)\) of the coils with magnetic resonance [6]. For extending the applications of WPT schemes, there have been several studies on the transmission distance of WPT in strong coupling range via effective transfer distance [7–10]. However, the WPT system in weak coupling
range might be low stability [11], high sensitivity [12], and unstable transfer efficiency [13]. Correspondingly, it is necessary to consider a WPT system with both extended transmission distance and supplied stable system characteristics.

Figure 1 shows that the grounds of the two coils are completely separated. Indeed, the ground of the TX is connected to the source side, and the RX is referenced to the load. This ground system does not distribute a balanced ground loop. Typically, there would be only one common ground to instrumentally evaluate the performance of two-coil systems. However, if the transmission distance increases, the stored energy of the coil is not consumed by the transmission; it can then flow out to the common ground in terms of leakage currents. Thus, a measurement error occurs and leads to the defect of the WPT system from an engineering perspective.

In this article, we present our investigation of the effects of a separately grounded WPT system. This method analyzes using the proposed measurement procedure and provides a practical solution. The proposed coil is specially made of copper sheet to reduce the resistance loss of itself [14]. To realize stable transmission efficiency, the alignment between the two coils was fixed [15]. The Q values of each experimental case with/without isolation was evaluated to analyze the undesirable transmission efficiency occurring in the unbalanced ground between the two coils. A proposed 1:1 transformer is used to provide isolation and the conversion of balanced impedance to unbalanced. If this is used, the efficiency of the WPT may be reduced depending on the loss of the isolation transformer, but it is possible to determine the proper transmission efficiency of the isolated ground system and obtain the reliability of the system.

### Table 1 Circuit parameters of coils

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TX ($i = 1$)</th>
<th>RX ($i = 2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_i$</td>
<td>34.51 uH</td>
<td>34.48 uH</td>
</tr>
<tr>
<td>$R_i$</td>
<td>41.87 mΩ</td>
<td>41.64 mΩ</td>
</tr>
<tr>
<td>$C_i$</td>
<td>16.17 pF</td>
<td>16.66 pF</td>
</tr>
<tr>
<td>$f_0$</td>
<td>6.64 MHz</td>
<td>6.64 MHz</td>
</tr>
</tbody>
</table>

2 | WPT SYSTEM CONFIGURATION

As shown in Figure 1, the MRC-based WPT system is composed of a source, a load, a set of TX/RX coils, and compensation networks. The equivalent circuit model of the MRC-based WPT system is constructed with the load resistance $50$ ohms ($R_L$) at the RX, the self-resistances ($R_1$, $R_2$), the self-inductances ($L_1$, $L_2$), the mutual inductance ($M$) between the TX and RX coils, and the compensation capacitances ($C_1$, $C_2$), respectively. The magnetic resonance can be obtained by compensating the imaginary part of the impedance with a combination of L-C at a certain frequency as follows,

$$f_0 = \frac{1}{(2\pi\sqrt{L_i C_i})}, \quad \text{where } i = 1, 2. \quad (1)$$

Table 1 shows the values, measured by using an LCR meter (HIOKI IM3536), of the circuit parameters corresponding to the proposed MRC-based WPT system.

This article proposes a coil suitable for the investigation of MRC-based WPT systems. The proposed coil was fabricated by winding copper sheet to minimize ohmic loss. The thickness and width of each coil were $0.15$ mm and $24$ mm, and the inner and outer diameter of each copper tape were $90$ mm and $250$ mm, respectively. The number of turns was $15$ with a $5$-mm pitch by putting polystyrene-foam between the layers of copper sheet as it was wound.

In the general WPT system, the $Q$ depends on the circumstances of both the TX and RX systems. Although a low $Q$ is sufficient in the inductive coupling system, it is necessary to obtain a higher $Q$ for the resonance coupling system. Thus, a high-$Q$ WPT system would be more difficult to adjust but have advantages with respect to selectivity and increased wireless transmission distance. We considered the definition of $Q$ [16] that generalized in application to coil resonant circuits as follows:

$$Q = 2\pi f \times \frac{\text{Energy stored}}{\text{Energy dissipated}}. \quad (2)$$

The stored energy in the coil is the sum of energies stored in the imaginary part of the impedance within inductors and capacitors. The dissipated energy for wireless
transmission is the sum of the energies lost in resistors at a resonance frequency. Although this physical notion enables wireless energy transmission between the TX and RX coils, the reliability of the $Q$ value in the WPT system is necessary. This definition proves useful in the subsequent analysis in the next section.

3 | EXPERIMENTAL RESULTS

As shown in Figure 2, the transmission efficiency is observed according to the distance, $d$, between the TX and RX coils. $d$ is from 0.25 m to 1.25 m, that is, the ratio of the diameter of the coil to the transfer distance, 1 to 5. To measure the transmission efficiency, the coils were located by plastic supporters and connected to a network analyzer (Keysight E5071C). While the TX coil was fixed, the RX coil was moved from the observation start to end by placing it at intervals of half of the diameter of the coil.

3.1 | Common ground system

Now, we investigated two cases of the configurations in Figure 2. Specifically, we considered a configuration of the separated ground system in which the isolation transformers (Mini-circuits T1-1-KK81+) were connected to both the TX and RX coils. This isolation transformer is a commercial product that is an RF 50-ohm transformer available up to 0.25 W [17]. It implies an alternative method with respect to the ground separation. The two-port S-parameters in the vicinity of $f_0$ were obtained to evaluate the transmission efficiency corresponding to the two cases of with/without isolation. This experimental results were illustrated as a contour plot as a function of both frequencies and distances in Figure 3. When the coils were close to each other, the red regions in Figure 3A,B were spread out based on $f_0$. This demonstrates frequency splitting for a typical WPT system [7]. When the transmission distance was increased, the maximum transmission efficiency was collimated to one single frequency range. In Figure 3A, the transmission efficiency tended to hold relatively well compared to Figure 3B at the ratio from 2 to 5. However, these performances should be interpreted carefully. Due to the common ground and unbalanced impedance configuration at each coil, they may agree with undesired efficiency. Although the resonance frequency in Figure 3B was shifted to 6.78 MHz because of the property of the isolation transformers, this does not affect the transmission property. Rather, the WPT system loss may increase due to the attenuation of transformers, at about 1.1 dB at the transfer frequency band. Thus, it is obvious that the transmission efficiencies with/without isolation are not consistent with respect to the case of a far transfer distance, as well as the relatively low power isolation is
sufficient to investigate the ground effects of the WPT system.

Figure 4 shows the computed $Q$ values according to isolation at the maximum transmission frequencies. This $Q$ value was obtained by the WPT transfer function $S_{21}$ with frequency dependence that is the left and right frequencies with 3 dB of attenuation from the center frequency $f_0$. The red curve with squares has low $Q$ values in a far transfer distance without isolation, whereas the other curve (marked with triangles) obtained relatively high-$Q$ values. When the transmission distance increases, the energy to be transmitted in the nonisolated system might be combined with both the reactive energy of the coil to be dissipated and the undesirable energy due to the unbalanced ground loop. This occurred the degradation of the $Q$ compared with the case of the isolated system. When the transmission distance is short and the coupling coefficient $k$ is high, both $Q$ values agree well with each other. It shows that the effect of an unbalance ground is weak in the case of a high $k$. This phenomenon is investigated specifically in the next subsection.

### 3.2 Separate ground system

Based on the phenomenon described in the previous subsection, the practical solutions were performed with the goal of better practical understanding. Figure 5 describes the separate ground system from a practical perspective. The TX coil is connected to a signal generator (Keysight E8257D), whereas the RX system is completely separated from the transmitting system. A portable spectrum analyzer (Rohde & Schwarz FSH13) was now used to measure the transmission efficiency instead of the network analyzer. The TX and RX are independent in the WPT link that implies that all transmitting power might be into the RX in a separate ground system. When the TX transmitted 0-dBm power from the signal generator, the RX received power from a completely separated WPT link. Even it is not performed to exploit the relatively high power in this article, it is sufficient to evaluate the WPT efficiency with common and separate ground effects.

Figure 6 shows the transmission efficiencies corresponding to the common ground systems with/without isolation and the separated ground system. The red curve with squares and the black curve with triangles measured the S-parameters from the network analyzer without or with isolation at one single resonance.
frequency, which was 6.64 MHz or 6.78 MHz, respectively. The green curve with reverse-triangles obtained the maximum power spectrum level from the spectrum analyzer at the resonance frequency 6.64 MHz with consideration of the cable loss of 0.3 dB at both the TX and RX. It is obvious that the transmission efficiency from the separate ground system agreed well with the common ground system with isolation when considering the 1.1 dB loss at the transformers. In the near transmission distance, the efficiencies of the separate ground and common ground system with isolation were better than the case of the nonisolation system. This implies that the effect of the frequency splitting was reduced due to the balanced ground system. However, when the transmission distance increased, the efficiency of the nonisolated ground system was higher than the others. This undesirable result implies that the energy of the coil to be dissipated might be flowing out to the unbalanced ground.

To validate and clarify the results due to the unbalanced ground, we considered an experiment to find the energy of the coil to be dissipated and transmitted. The separately grounded WPT system in Figure 5 was used again, but the ground of the spectrum analyzer was connected to the ground of the signal generator to reproduce the circumstance of the common ground transmission system. In this configuration, the energy of the coil to be dissipated would be flowing out to the unbalanced ground loop. This leakage power at the unbalanced ground and the transmission power would be measured by the spectrum analyzer; see the blue curve with circles in Figure 6.

Table 2 shows the comparison of the leakage power with respect to the common/separate ground systems. It shows that the transmission power levels in cases of the common ground system without isolation and separate ground system with connected both grounds were similar within 2 dB in all of the ratios at the single resonance frequency. However, in the separate ground and common ground system with isolation, the transmission power levels were different from the previous cases. This implies that the difference in the transmission power level between the former and latter was the leakage power at the unbalanced ground. The leakage power levels in the far transmission distance, the ratio from 3 to 5, agreed well, respectively, but it was not appropriate in the near transmission distance due to less leakage power in strong coupling ranges. In other words, this analysis revealed that it was a quantitative interpretation when measuring the MRC-based WPT system with regard to the transmission distance.

Consequently, the results without isolation showed that the energy of the coil to be dissipated flows out to the unbalanced ground of the instruments, and this leakage power affects the transmission efficiency of both the TX and RX systems. It implies that the grounds in the TX and RX should be separated by using an isolation transformer when measuring the transmission efficiency with the instrument consisting of two ports and one common ground. Specifically, the comprehensive results should be considered as an essential notion for the long/midrange WPT applications.

### Table 2  
Comparison of leakage power with respect to isolation

<table>
<thead>
<tr>
<th>Ratio&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Transmission power level (dB)</th>
<th>Leakage power level (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Common ground system without isolation</td>
<td>Common ground system with isolation</td>
</tr>
<tr>
<td>1.0</td>
<td>-7.9</td>
<td>-3.8</td>
</tr>
<tr>
<td>1.5</td>
<td>-4.3</td>
<td>-1.3</td>
</tr>
<tr>
<td>2.0</td>
<td>-3.9</td>
<td>-4.5</td>
</tr>
<tr>
<td>2.5</td>
<td>-4.6</td>
<td>-8.7</td>
</tr>
<tr>
<td>3.0</td>
<td>-5.4</td>
<td>-12.7</td>
</tr>
<tr>
<td>3.5</td>
<td>-6.0</td>
<td>-16.2</td>
</tr>
<tr>
<td>4.0</td>
<td>-6.5</td>
<td>-18.9</td>
</tr>
<tr>
<td>4.5</td>
<td>-6.9</td>
<td>-21.2</td>
</tr>
<tr>
<td>5.0</td>
<td>-7.5</td>
<td>-23.1</td>
</tr>
</tbody>
</table>

<sup>a</sup>Ratio of distance to diameter, the distance from 0.25 m to 1.25 m.  
<sup>b</sup>Difference of the transmission efficiency from the network analyzer in dB scale between without and with isolation in the common ground system; see the red curve with squares and black curve with triangles in Figure 6.  
<sup>c</sup>Difference of the transmission efficiency from the spectrum analyzer in dB scale between connected and isolated grounds in the separated ground system; See the blue curve with circles and green curve with reverse-triangles in Figure 6.
This article presents a practical investigation of MRC-based WPT using the concept of a separated ground system. Comprehensive case studies were validated constructively in terms of the measurement methods with respect to isolation between the TX and RX coils. We identified undesirable circumstances of the two-coil WPT system in weak coupling range and provided an effective solution. We believe that the results provide a practical sense of the grounding of an achievable WPT system at the far transmission distance. Furthermore, the proposed isolated ground configurations are effective and precise to be applied to general WPT systems.

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CONFLICTS OF INTEREST
The authors declare that there are no conflicts of interest.

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REFERENCES

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