High power compact contactless charging system.

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Abstract
We have been developed 3kW contactless charging system for EV. Recently the high output of contactless charging system has been requested growing for the charging time decreased. But there is a restriction mounting space of the vehicle when using a contactless charging system in the EV. The proposed contactless charging system is capable of 6.9kW output the same size of the secondary coil 3.3kW (Conforms to the input power class 2 of IEC standards). The basic configuration of proposed contactless charging system that the primary coil to the high frequency power source, load and the rectifier is connected to the secondary coil, resonance method is primary series secondary series. The primary drive voltage of proposed system is higher than the 3.3kW system, and changed to the double current rectifier from the full bridge rectifier of 3.3kW system. Characteristic of the double current rectifier is down voltage and rising current. Secondary coil does not problem of heat because the secondary coil current is equivalent to 3.3kW, so it isn't necessary to size up the secondary coil at 6.9kW. The proposed system was clarified that there is no decrease in efficiency with misalignment and gap change by the simulation and experiment. This system is an effective technology for EV contactless charging system with mounting space restriction of the vehicle.

Keywords: EV, Magnetic field type, Contactless charging system, Double current rectifier

1 Introduction
Research and development of contactless power transfer systems that are superior in convenience and maintenance for charging electric vehicles (EVs) and plug-in hybrid vehicles are gaining momentum.¹²³ We previously developed a 3 kW contactless power transfer system for normal charging. However, there is a growing need for increased output power to reduce the charging time. It is also preferable to realize high power output without increasing the size of the vehicle coil due to space limitations. This paper describes the development of a contactless charging system that conforms to Class 2 Input Power Class as shown in Table 1, its system configuration, power transfer efficiency, and leakage magnetic field characteristics.
The values of $C_1'$ and $C_2$ are determined based on Equations (1) and (2) so that they resonate with the primary and secondary coils respectively at power frequency $f_0$.

\[
x_{c_1}' = -\frac{1}{jL_0C_1} = x_0 + x_1' \quad \text{..............................................(1)}
\]

\[
x_{c_2}' = -\frac{1}{jL_0C_2} = x_0 + x_2 \quad \text{..............................................(2)}
\]

The values of $r_0$, $r_1$, and $r_2$ can be ignored because they are small compared to the corresponding inductance. Then Equations (3) and (4) hold between the voltage and current at the input and output.

\[
V_i = jx_0' I_2 \quad \text{..............................................(3)}
\]

\[
I_i = \frac{1}{jx_0} V_22 \quad \text{..............................................(4)}
\]

### 2.3 Conditions for the Maximum Efficiency Operation

$Q$ of the winding and coupling coefficient $k$ are defined by Equation (5). If Equation (6) holds, the maximum power transfer efficiency $\eta_{\text{max SS}}$ of the transformer and the load resistance $R_{\text{Lmax}}$ at that efficiency can be approximated by Equations (7) and (8).

\[
Q_i = \frac{\omega_0 L_0}{r_0} \quad Q_i = \frac{\omega_0 L_2}{r_2} \quad k = \frac{M}{\sqrt{L_1 L_2}} \quad \text{.................................(5)}
\]

\[
\frac{1}{k^2} \frac{Q_2}{Q_1} >> 1 \quad \text{..............................................(6)}
\]

\[
\eta_{\text{max SS}} = 1 - \frac{2}{k \sqrt{Q_1 Q_2}} \quad \text{.................................(7)}
\]

\[
R_{\text{Lmax SS}} = k r_2 \sqrt{Q_1 Q_2} \quad \text{.................................(8)}
\]

### 3 Outline of the 6.9 kW Contactless Power Transfer System

#### 3.1 Comparison of Different Systems

Table 2 shows a comparison of the characteristics of primary coil voltage $V_{\text{IN}}$, secondary coil current $I_2$, secondary coil voltage $V_2$, output current $I_o$, and output voltage $V_o$ between full-wave and current-doubling rectification. Since the battery voltage is constant regardless of the output, the same output
voltage $V_L$ is required even in the case of the increased-output transformer.

To generate output voltage $V_L$ in 6 kW full-wave rectification, which is the same as 3 kW full-wave full-wave rectification, the secondary coil current $I_2$ needs to be doubled. On the other hand, in 6 kW current-doubling rectification, the primary coil voltage $V_{IN}$ is doubled and the secondary coil $I_2$ is the same as 3 kW full-wave rectification. Therefore, it is possible to increase the output by using current-doubling rectification without expanding or changing the secondary coil.

### 3.2 Configuration of the 6.9 kW Contactless Power Transfer System

Figure 4 shows the proposed 6.9 kW contactless power transfer system. It consists of a high-frequency power supply comprising an ac-dc converter and full-bridge inverter, an SS-system contactless power transfer coil, and a current-doubling rectifier circuit composed of two diodes and two reactors.

### 4 Experimental Results of the 6.9 kW Contactless Power Transfer System

#### 4.1 Specifications of the Experimental System

As shown in Table 1, the Draft International Standard divides contactless power transfer systems into three classes according to the input voltage and specifies a system efficiency of 90% or higher. The output power is approximately 3.3 kW in Class 1, and 3.3–6.9 kW in Class 2. Our target was to build a contactless power transfer system with a maximum power transfer output of 6.9 kW.

Table 3 lists the specifications of the 6.9 kW contactless power transfer system that we developed, and Table 4 indicates the power transfer transformer constants. The output is 6.9 kW, output voltage 180–400 V, and the standard gap 135 mm. In the SS system and current-doubling rectifier circuits, the output voltage $V_L$ is $1/z_1$ times the effective value of the secondary coil voltage $V_2$, and the output current $I_L$ is $2/z_1$ times the effective value of the secondary coil current $I_2$. Equivalent load resistance $R_L$ at the highest efficiency is smaller than $R_{L\text{max}}$. In this system, load resistance $R_L$ is chosen so that the output voltage $V_L$ is kept within a range of 180 to 400 V. This circuit was designed based on the preliminary examination using a contactless power transfer system simulator.

#### 4.2 Appearance of the Primary and Secondary Coils

The size of the secondary coil and the outer appearance of the primary and secondary coils are shown in Figure 5.

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**Table 2. Comparison of System.**

<table>
<thead>
<tr>
<th>System</th>
<th>Circuit</th>
<th>$V_{IN}$</th>
<th>$I_1$</th>
<th>$I_2$</th>
<th>$k$</th>
<th>$V_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 kW full wave</td>
<td><img src="image" alt="High-frequency power supply" /></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>6 kW full wave</td>
<td><img src="image" alt="High-frequency power supply" /></td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>6 kW Double current</td>
<td><img src="image" alt="High-frequency power supply" /></td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table 3. Specifications.**

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>6.9 kW</td>
<td>6.9</td>
<td>180〜400</td>
<td>40</td>
<td>85</td>
<td>135±35</td>
<td>+100</td>
<td>+200</td>
<td>131</td>
</tr>
</tbody>
</table>

**Table 4. Transformer parameters.**

| $r_1$ [$\Omega$] | 277.6 | $r_2$ [$\Omega$] | 352.1 | $l_1$ [μH] | 153.6 | $l_2$ [μH] | 197.2 | $Q_L$ | 225.7 | $C_{SS}$ [nF] | 20.9 | $Q_2$ | 314.7 | $C_{SS2}$ [nF] | 27.0 | $\eta_{\text{max}}$ [%] | 96.8 |

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**Fig. 5. 6.9 kW coil appearance and dimensions.**
4.2 Results of Power Transfer Experiment

1) Operating Waveform

Figure 6 shows the simulated waveforms of inverter output voltage $V_{IN}$, inverter output current $I_{IN}$, secondary coil current $I_2$, and output current $I_L$ at 6.9 kW power transfer. For an inverter input voltage $V_{DC}$ of 337 V and a secondary coil current $I_2$ of 14.8 A, output current $I_L$ is 37.3 A, which is approximately 2.5 times larger. These values almost coincide with the actual measured values of $I_2$ of 14.8 A and $I_L$ of 36.9 A, as current-doubled characteristics.

![Fig. 6. Simulated waveforms.](image)

2) Comparison with the Simulation

Figure 7 compares output current $I_L$, output $P_O$, and overall efficiency $\eta$ between the power transfer characteristics during 6.9 kW power transfer to load resistance $R_L$ of 5Ω with a gap of 135 mm under the standard state without misalignment, and the results of simulation. The overall efficiency $\eta$ reaches 90.0% at an output $P_O$ of 6.9 kW, which is almost identical to the simulated overall efficiency $\eta$ of 89.9%.

![Fig. 7. Comparison of experimental results and simulation.](image)

3) Constant-Current Characteristics

Figure 8 indicates the changes in output current $I_L$ and overall efficiency $\eta$ when load resistor $R_L$ is changed. When the inverter input voltage $V_{DC}$ is kept constant at 300 V and load resistance $R_L$ is tripled from 3Ω to 9Ω, output current $I_L$ decreases from 34.9 A to 28 A.

![Fig. 8. Characteristics with $R_L$ change.](image)

4) Gap Change Characteristics

Figure 9 shows inverter current $I_{DC}$, output current $I_L$, and overall efficiency $\eta$ when the gap changes under 6.9 kW power transfer to load resistance $R_L$ of 5Ω. The average value of overall efficiency $\eta$ for a gap of 135±35 mm is 89.0%.

![Fig. 9. Characteristic with gap change.](image)

5) Power Transfer Characteristics with Misalignment

The power transfer characteristics at 6.9 kW power transfer to load resistance $R_L$ of 5Ω with a gap of 135 mm when a misalignment occurs are shown in Figures 10 and 11. The average value of overall efficiency $\eta$ is 87.4% for misalignment of 100 mm or smaller along the x-axis, and 87.9% for misalignment of 200 mm or smaller along the y-axis. This indicates that power is transferred without a significant decrease in overall efficiency from the standard state.

![Fig. 10. Characteristics with x change.](image)

This demonstrates that the circuit has almost constant-current characteristics, a feature of the SS system.
6) Evaluation of the Density of Leakage Magnetic Field

Figures 12 and 13 show the measurement results of leakage magnetic field density during 6.9 kW power transfer to load resistance \( R_L \) of 5Ω under the standard state. The vehicle is misaligned from the center of the coil by 750 mm in the front-and-back direction of the vehicle and by 600 mm in the width direction. The results satisfy the ICNIRP 2010 guideline level (27 μT). There is room for improved efficiency by decreasing the value of \( R_L \) in Figure 8. We believe that the leakage magnetic field can be reduced through the optimal design of the coil so that the load resistance at the highest efficiency in Equation (8) is the same as the equivalent resistance under a battery load.

\[
\begin{align*}
\text{Distance of coil center (mm)} &: Z=0, Z=500, Z=1000 \\
\text{Leakage magnetic field (μT)} &: 27μT
\end{align*}
\]

\[
\begin{align*}
\text{Distance of coil center (mm)} &: Z=0, Z=500, Z=1000 \\
\text{Leakage magnetic field (μT)} &: 27μT
\end{align*}
\]

\[
\begin{align*}
\text{Distance of coil center (mm)} &: Z=0, Z=500, Z=1000 \\
\text{Leakage magnetic field (μT)} &: 27μT
\end{align*}
\]

5 Conclusion

We have proposed a method for increasing the output of a contactless power transfer system without increasing the size of the secondary coil, and demonstrated the effectiveness of the method through simulation and experiments. The proposed system generates an output of 6.9 kW with a secondary coil of the same size as that for 3.3 kW output through an increase of the driving voltage of the primary side, and voltage-decreasing/current-increasing conversion using a current-doubling rectifier circuit connected to the secondary coil. Use of our technology is advantageous in contactless power transfer systems for charging EVs with space limitations.

References


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