Method of Wireless Power Transfer for High Efficiency and High Output Stability

Y. Ota, N. Aruga, S. Miyahara*, F. Sato, and H. Matsuki*

Graduate School of Engineering, Tohoku Univ., 6-6-05 Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan
* Graduate School of Biomedical Engineering, Tohoku Univ., 6-6-05 Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan

Wireless power transfer (WPT) systems transmit electrical power to devices via a high-frequency electromagnetic field. The load conditions of devices change dramatically depending on their operating conditions; however, these systems must supply a constant output voltage that is stable regardless of the load. This paper describes a method of using the LC-booster to stabilize the output voltage while maintaining efficiency. The LC-booster contains two secondary coils, where one is connected to the load and the other is connected to the capacitor to create a resonator. This allows the optimized load of the LC-booster to be adjusted. We demonstrate that the LC-booster can stabilize output voltage over a wide range of loads and is thus a promising method of versatile stabilization method.

Keywords: wireless power transfer, electromagnetic induction, resonance circuit, LC-booster method, output stabilization.

1. Introduction

Technology for wireless power transfer (WPT) via electromagnetic fields is expected to be useful for many kinds of equipment, such as mobile devices, electric vehicles, and health care devices. Today, various methods have been proposed for this technology, including electromagnetic induction\(^1\), electric field coupling\(^2\), and magnetic resonance transmission\(^3\). Our group has researched the electromagnetic induction method for wide-area high efficiency transmission.

A block diagram of a typical WPT system is shown in Fig. 1. In this system, electric power is transmitted via a high-frequency electromagnetic field and it passes through a rectifier and other control circuits before reaching the target devices. The load conditions of devices change dramatically depending on their operating conditions, and the devices require a constant voltage power supply. Therefore, the voltage of the transmitted power should be controlled by a power management device such as a DC-DC converter. However, the voltage limit is set for each control circuit and changing the load conditions affects the output voltage. Therefore, the output voltage should be stabilized regardless of the load value.

The load-output characteristics under constant excitation current conditions have been reported in our previous work\(^4\). Depending on the target, the power supply on the primary side must be a standard constant voltage source. Accordingly, in this paper we have developed a method of circuit construction to stabilize the output voltage while maintaining the efficiency by comparing various matching circuits.

2. Matching method for WPT via electromagnetic induction

2.1 Series and parallel resonance

Generally, in the electromagnetic induction method, one capacitor is connected in series or in parallel with the secondary coil in the matching circuits. The equivalent circuit is shown in Fig. 2. The maximum efficiency, optimized load, and preferred capacitance of the secondary circuit for each circuit are presented in Table 1. The load-efficiency characteristics in Fig. 3 show series resonance matches a heavy load and parallel resonance matches a light load. However, according to Table 1, the optimized load value is limited by the equivalent series resonance (ESR) of the coils, \(r_2\).

![Fig. 1 Block diagram of WPT system.](image)

![Fig. 2 Equivalent circuits.](image)

**Table 1 Optimized parameters for each circuit.**

<table>
<thead>
<tr>
<th></th>
<th>Series(^0)</th>
<th>Parallel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimized Load</td>
<td>(r_2\sqrt{1+\alpha})</td>
<td>(r_2\left(\sqrt{1+\alpha} + \frac{Q_{l2}}{\sqrt{1+\alpha}}\right))</td>
</tr>
<tr>
<td>(C_2)</td>
<td>(\frac{1}{\omega^2 L_2})</td>
<td>(\frac{Q_{l2}}{\omega r_2(1+\alpha+Q_{l2}^2)})</td>
</tr>
<tr>
<td>Maximum Efficiency</td>
<td>1</td>
<td>(1 + \frac{\alpha}{\omega} + \sqrt{1 + \alpha})</td>
</tr>
</tbody>
</table>

\(\alpha \equiv k^2 Q_{l1}^2 Q_{l2} Q_{ln}^2 = \frac{\omega L_n}{r_n}, \omega\): Drive frequency
2.2 LC-booster method

In the LC-booster method\(^6,7\), there are two coils on the secondary side: one coil is connected to the load and the other is connected to the capacitor to create a resonator, as shown in Fig. 4. The resonator circuit in this figure is called the LC-booster, \(L_2\) is the booster coil, and \(L_3\) is the pick-up coil. The optimized load, \(R_{\text{opt}}\), is calculated by

\[
R_{\text{opt}} = r_3 \sqrt{1 + \alpha + \frac{1}{1 + \beta \frac{Q_{L_3}}{\sqrt{1 + \alpha}}}}
\]

(1)

the resonance capacitor capacitance, \(C_2\), is calculated by

\[
C_2 = \frac{1}{\omega^2 L_2}
\]

(2)

and the maximum efficiency, \(\eta_{\text{max}}\), is obtained from

\[
\eta_{\text{max}} = \frac{\alpha \beta}{\beta + (1 + \alpha) \left( \beta + 2 \left(1 + \frac{1}{1 + \beta + Q_{L_3}^2 + \frac{1}{1 + \alpha} \frac{1}{\beta}} \right) \right)}
\]

(3)

\[\alpha \equiv k_{12}^2 Q_{L_1} Q_{L_2}, \quad \beta \equiv k_{23}^2 Q_{L_2} Q_{L_3}, \quad Q_{L_n} \equiv \frac{\omega L_n}{r_n}\]

Here, \(k_{12}\) is the coupling factor between coil \(L_1\) and \(L_2\), and \(k_{23}\) is the coupling factor between \(L_2\) and \(L_3\).

According to these equations, the LC-booster method can change the optimized load by adjusting performance index, \(\beta\), which is related to the mutual inductance, \(M_{23}\). Thus, the design of the LC-booster method is very flexible.

3. Output stabilization

3.1 Coil design

In this section, we discuss the circuit construction for stabilizing the output voltage while maintaining the efficiency by comparing the matching circuits. First, we constructed transmission coils to provide 5 W mobile devices (5 V, 5 Ω) with energy. The specification of the coil is shown in Table 2.

\[L_1\] was the transmission coil for all methods and \(L_2\) was the receiving coil for the series and parallel resonance circuits. In the LC-booster method, coil \(L_2\) was used as a booster coil and \(L_3\) was used as a pick-up coil. The drive frequency was set as 200 kHz and the resonance capacitor was selected for this frequency. In addition, the Ni-Cu-Zn ferrite plate was attached to the back of each coil.

### Table 2 Coil specifications.

<table>
<thead>
<tr>
<th></th>
<th>(L_1 / L_2)</th>
<th>(L_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter</td>
<td>40</td>
<td>47</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>14</td>
<td>40</td>
</tr>
<tr>
<td>(Q)</td>
<td>90</td>
<td>21</td>
</tr>
</tbody>
</table>

3.2 Relationship between load value and output voltage

To clarify the features of each method, the load-output voltage and load-efficiency characteristics were simulated with the PSPICE circuit simulator. The vertical gap was assumed to be 15 mm, thus \(k_{12}\) was set to 0.18. Coupling between the booster and pick-up coil was set to 0.54, which matched the 6.5 Ω load. The transmission coil was connected with a series resonance capacitor for a resonance frequency of 200 kHz, and the input voltage for the primary circuit was 5 V. The results are shown in Fig. 5.

The first goal was transmitting an output of 5 V for an assumed load of 5 Ω for the target device. This value determines the rated load of the circuit. The series, parallel, and LC-booster circuits achieved the desired output voltage at 5 Ω, although there were some differences that appeared for lighter loads. At 1 kΩ the maximum change in the output voltage was 68 V in the series resonance circuit. The variation in the voltage for the parallel resonance circuit was about 29 V at 1 kΩ. In comparison with these two methods, the voltage variation was small for the LC-booster method. For charging mobile devices, there is a no-load mode once charging is complete. Therefore, the output voltage characteristics of the LC-booster method are superior to those of the series and parallel methods.
To achieve high efficiency, the optimized load of the maximum efficiency was 3.3 Ω for series resonance, 108 Ω for parallel resonance, and 6.5 Ω for the LC-booster method. This indicates that the LC-booster method is the best way to stabilize the output voltage while maintaining efficiency under heavy loads.

To confirm this result, we conducted a feeding experiment as shown in Fig. 6. In this experiment, input voltage was limited to 1 V because of the current limit of the primary circuit. The figures show that the experimental results match the simulation results well.

3.3 Parameter settings of the LC-booster method

The experimental and simulation results show that the LC-booster is the best method to stabilize output. However, if this method is to be used for other applications, the relationship between the parameter settings and output characteristics must be determined.

Initially, the coupling factor, $k_{23}$, was set as the parameter to assess its effect on the output voltage in the LC-booster method. Fig. 7 shows the results calculated with PSPICE and demonstrates that $k_{23}$ can adjust the maximum output voltage while maintaining its stability. However, the efficiency is strongly correlated with $k_{23}$. To achieve both high efficiency and a stable output, changing only $k_{23}$ is insufficient.

Fig. 8 shows $L_3$ dependence on output voltage for the $L_3$ parameter set to 40 and 80 μH with $k_{23}$ of 0.54 and $Q_3$ of 100. The optimized loads were 100 and 200 Ω. This suggests that in the same coupling, the maximum voltage is higher for a light optimized load than a heavy optimized load.

According to the results, we calculated the ratio of the voltage of the light load at 1 kΩ, $V_{o}$, to the optimized load conditions, $V_{opt}$. The results are shown in Table 3. This ratio is very small in the parallel resonance and LC-booster methods, whereas the value of the series resonance method is more than ten times that of the other methods. In addition, the LC-booster can adjust the optimized load over a wide range, which makes this method very flexible.

4. Conclusions

We have reported a method of circuit construction for stabilizing the output voltage while maintaining the efficiency by comparing various matching circuits. In the LC-booster method, the output voltage remains stable over a wide range of loads. This is considered to result from the effect of $M_{12}$ in light load conditions. As shown in Figs. 2 and 4, the capacitor $C_2$ is inserted in parallel to the coil $L_2$ in parallel resonance and the LC-booster method. Therefore, the effect of $M_{12}$ becomes larger in light load conditions due to resonant currents; consequently, the voltage ratio in these two methods becomes lower than that in series resonance. Furthermore, with the LC-booster method, the optimized load can be changed; as a result, the output can be stabilized over a wide range of loads.

From these results, we can say that the LC-booster method is effective for stabilizing the output voltage while maintaining the efficiency.
Table 3 Voltage ratio of each method.

<table>
<thead>
<tr>
<th>Method</th>
<th>Vo/Vopt</th>
<th>Opt. Load R_{opt}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series</td>
<td>10–15</td>
<td>3.3</td>
</tr>
<tr>
<td>Parallel</td>
<td>1.1</td>
<td>108</td>
</tr>
<tr>
<td>Booster</td>
<td>1.1–1.2</td>
<td>3–200</td>
</tr>
</tbody>
</table>

Fig. 7 Load characteristics (k_{23}).

(a) Load-output voltage.

(b) Load-efficiency.

Fig. 8 Load characteristics (L_{3}).

(a) Load-output voltage.

(b) Load-efficiency.

References

1) NIKKEI ELECTRONICS 2009. 5. 4, p.38.

Received Oct. 17, 2014; Accepted Nov. 14, 2014