Improvement of Efficiency of Multi-Parallel Dynamic Wireless Power Transfer System with LCC Topology

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Abstract—Wireless power transfer (WPT) for moving electric vehicles has been widely studied. LCC topology was proposed as a novel compensation circuit for dynamic WPT (DWPT) because inverter current is suppressed automatically according to the decrease in coupling coefficient. In addition, its characteristic enables a DWPT system to connect multiple transmitter coils to a single inverter. This paper proposed an optimal load condition under a multi-parallel operation considering waiting loss. Moreover, two types of LCC topologies are approximated into a Series-Series compensation topology, and the effective range of that approximation is derived. Calculation results revealed the effective range of the approximation. The proposed method improved transmission efficiency by up to 7% in the experiment.

Index Terms—Efficiency, Electric vehicle, Inductive power transfer, Optimal load condition, Wireless power transfer

I. INTRODUCTION

Electric vehicle (EV) is expected to be the transportation of the next generation because of its high kinematic performance and efficient operation [1]. In order to extend the driving range of EV without any increase in the amount of battery, dynamic wireless power transfer (DWPT) technology, which enables EVs to be charged in motion, has been studied intensively [2], [3]. In DWPT, energy is transferred via magnetic flux generated by transmitter and receiver coils. Because those main coils can be covered with an insulator, and their electrical terminals are not exposed, EV can be charged safely.

Various compensation topologies which are connected to the main coils to obtain desired characteristics such as unity power or high output power have been investigated in wireless power transfer (WPT). Series-Series (S/S) compensation topology, which employs series resonance at both primary and secondary sides by adding capacitors in series, is widely applied in a static WPT charging system because it has a simple structure and achieves unity power factor regardless of a coupling factor between the main coils and the load. However, one of the major drawbacks of the S/S topology is that inverter current drastically increases in the light load or no load condition. Therefore, the inverter should be controlled appropriately according to the moving secondary coil. Accurate detection of a position of the secondary coil requires a complicated system with sensors or a practicable detection algorithm [4], and those systems push up a cost of construction and maintenance of a total DWPT system.

To solve the problems described above, a novel compensation topology called LCC, which consists a series inductance $L$, a parallel capacitor $C$, and a series capacitor $C$, was proposed [5]–[10]. In the topology, inverter current decreases automatically according to the decrease in the coupling of coils. Moreover, the transmission efficiency of LCC at light load condition is higher than that of S/S [5]. Due to the stability and its superiority over S/S in light or no-load conditions, a parallel structure as shown in Fig. 1 without additional switches or sensors can be realized [6]–[8]. This structure can realize a simple control system and reduction of the number of inverters. The prototype of LCC was constructed, and its verification was conducted [9].

In WPT, an optimal condition of the load, which maximizes transmission efficiency, is determined uniquely in a specific coupling condition. The coupling condition and load condition vary dynamically in the DWPT system. As a result, the optimal condition also changes. If the optimal condition and real one are different significantly, system efficiency lowers. Therefore, optimal tracking control with an active rectifier is usually applied to maintain high-efficiency [10], [11]. The optimal condition, which must be derived to implement the control, for S/S topology was obtained, and several control methods have been demonstrated experimentally. On the contrary, that
In this paper, the primary and secondary coils are magnetically connected and their mutual inductance is \( L_m \). AC equivalent load resistance is \( R_L \). Compensation components are chosen to be resonant at source frequency as shown (1) - (2).

\[
\omega L_1 = \frac{1}{\omega C_{1p}} \tag{1}
\]
\[
\frac{1}{\omega C_{1p}} = \omega L_1 - \frac{1}{\omega C_{1s}} \tag{2}
\]

Secondary resonant condition for LCC/S is (3) and ones for LCC/LCC are (4).

\[
\text{LCC/S} \quad \left\{ \begin{align*}
\omega L_2 &= \frac{1}{\omega C_2} \tag{3} \\
\omega L_{2s} &= \frac{1}{\omega C_{2s}} \tag{4}
\end{align*} \right.
\]

Under the resonant condition, LCC/S and LCC/LCC can be transformed as Fig. 3 step by step. Subscripts of stray resistance are same as ones of self-inductance of coils. Transmission efficiency is defined by a ratio of output power to input power. In each red square represented in Fig. 3, input power is divided into stray resistance and transformed impedance inside of the red square of the middle circuit. By doing as do at the secondary LCC, finally, simple equivalent circuit can be obtained as shown in the right bottom circuit.

For LCC topology was calculated under some approximated conditions [12] because the topology has many electric components, and its optimal condition is too complicated to use for designing a controller.

In addition, the optimal condition has been derived only for a simple case in which a single transmitter and a single receiver exist. However, LCC topology is expected to be operated as the parallel system as shown Fig. 1. Thus, the effect of other transmitter units connected in parallel on the efficiency of the system must be considered.

This paper clarifies the optimal load conditions to achieve the maximal efficiency for two kinds of topologies of LCC and transforms them into approximate ones, and the effective range of the approximations and its conditions are discussed. After clarifying the conditions, a shift of the optimal load condition for the multi-parallel operation system is demonstrated by considering power loss at parallel transmitter units. Finally, this paper proves that the improvement of efficiency can be achieved by considering the shift.

The precise and approximate optimal load conditions for LCC topology are derived, and the effective range of the approximation is revealed by numerical calculation in Section II. By considering the effects of waiting loss, the optimal load condition is modified in Section III. In Section IV, experimental verification is demonstrated, and Section V concludes this paper.

II. OPTIMAL LOAD CONDITION OF LCC TOPOLOGY

A. Efficiency definition and optimal load condition

There are two main types including LCC topology as shown in Fig. 2. Each configuration is named after primary and secondary circuit topologies. First one is LCC/S. The other is usually called double-sided LCC or double LCC, but to avoid misunderstanding, in this paper it is called LCC/LCC. In WPT,
\[ \eta_{\text{LCC/LCC}} = \frac{R_{\text{in}} R_{\text{eq}} R_{\text{ref}}}{R_{\text{in} s} + R_{\text{in}} R_{\text{ref}} R_{\text{ref}} R_{\text{eq}} R_{\text{eq}} R_{L s} + R_{L}} \] (5)

where \( R_{\text{eq}} = \frac{(\omega L_{2 s})^2}{R_{2 s} + R_{L}} \), \( R_{\text{ref}} = \frac{(\omega L_{1 s})^2}{R_{1 s} + R_{\text{ref}} R_{\text{ref}} R_{2} + R_{L}} \).

As do in case of LCC/LCC, the transmission efficiency for LCC/S \( \eta_{\text{LCC/S}} \) can be derived as (7).

\[ \eta_{\text{LCC/S}} = \frac{R_{\text{in}} R_{\text{ref}} R_{\text{ref}} R_{L}}{R_{\text{in} s} + R_{\text{in}} R_{\text{ref}} R_{\text{ref}} R_{\text{ref}} R_{\text{ref}} R_{\text{eq}} R_{\text{eq}} R_{L s} + R_{L}} \] (7)

where \( R_{\text{ref}} = \frac{(\omega L_{1 s})^2}{R_{1 s} + R_{\text{ref}} R_{\text{ref}} R_{2} + R_{L}} \), \( R_{\text{in}} = \frac{(\omega L_{1})^2}{R_{\text{ref}} + R_{1}} \).

To obtain the optimal condition, \( \frac{dn}{dR_{\text{in} s}} = 0 \) should be solved.

The optimal load condition for LCC/S \( R_{\text{opt}}^{\text{LCC/LCC}} \) is obtained in [13] as follow:

\[ R_{\text{opt}}^{\text{LCC/LCC}} = R_{2 s} \sqrt{\left(1 + F_{k}\right) \left(1 + F_{k} \frac{1 + F_{k}}{1 + F_{k}}\right)} \] (8)

where \( F_{k} = k^2 Q_{1} Q_{2}, \) \( F_{o} = \alpha Q_{1} Q_{1} \) and \( \alpha = L_{1 s}/L_{1} \). \( Q_{i} \) is quality factor of inductor \( i \) and defined as

\[ Q_{i} = \frac{\omega L_{i}}{R_{i}} \] (9)

The optimal load condition for LCC/LCC \( R_{\text{opt}}^{\text{LCC/LCC}} \) is obtained in [14] as follow:

\[ R_{\text{opt}}^{\text{LCC/LCC}} = R_{2 s} \sqrt{\left[1 + F_{\beta} + F_{k}\left(1 + F_{k}\right)\right]} \] (10)

where \( F_{\beta} = \beta Q_{2} Q_{2} \) and \( \beta = L_{2 s}/L_{2} \). Those \( F \) values represent how lossless those parts of the WPT circuit are, and \( F_{k}, F_{o}, \) and \( F_{\beta} \) are the values of coupling part, primary LCC part and secondary LCC part respectively.

**B. Approximation of optimal load condition**

Because the optimal conditions for LCC topologies are complicated, LCC topology is often approximated to S topology. If the optimal load conditions for LCC can be approximated to that of S/S, it is possible to apply optimal tracking control for S/S to LCC topology. In this study, two cases are investigated. One is that LCC/LCC is approximated into S/S, the other is that LCC/S is approximated into S/S. Both cases are discussed in the previous studies.

Their optimal load conditions are represented by coupling factor \( k \) and quality factor \( Q \) of inductors as discussed in the previous subsection. Their quality factor used in WPT usually reaches several hundred, and the typical maximal coupling factor of DWPT for EVs is from 0.2 to 0.3. Thus, the value of \( F_{o}, F_{\beta} \), and \( F_{k} \) can be assumed much larger than 1. Then, LCC/S can be transformed into S/S, and \( R_{\text{opt}}^{\text{LCC/S}} \) becomes the same optimal load condition for S/S \( R_{\text{S/S}}^{\text{opt}} \) as shown in (11) when (12) is true.

\[ R_{\text{opt}}^{\text{S/S}} = R_{\text{LCC/S opt}}^{\approx} = R_{2 s} \sqrt{1 + F_{k}} \] (11)

LCC/LCC can be transformed into S/S by calculating a combined impedance of the right-hand part of secondary LCC [12]. If \( R_{2 s} \) can be ignored in (6), \( R_{\text{LCC/LCC opt}}^{\approx} \) is shown in (13). Then \( R_{\text{LCC/LCC opt}}^{\approx} \) is identical to (6) as shown in (13).

\[ R_{\text{opt}}^{\text{LCC/LCC}} = R_{2 s} \sqrt{\frac{(\omega L_{2 s})^2}{R_{\text{LCC/LCC opt}}^{\approx}} + \frac{(\omega L_{1 s})^2}{R_{\text{LCC/LCC opt}}^{\approx}}} \] (13)

If \( F_{o} F_{\beta} \gg F_{k} \) is true, (10) can be

\[ R_{\text{opt}} = R_{2 s} \sqrt{1 + F_{k}} \sqrt{1 + r F_{k} + F_{\beta}} \] (14)

where \( r = F_{o}/F_{\beta} \). If \( r \approx 1 \) is true, \( R_{\text{LCC/LCC opt}}^{\approx} \) becomes

\[ R_{\text{LCC/LCC opt}}^{\approx} = R_{2 s} \frac{F_{\beta}}{\sqrt{1 + F_{k}}} \] (15)

The summary of the approximations and the conditions for those approximations to be valid are shown in TABLE I.

**C. Effective range of approximations**

Those approximations are established under some conditions. Therefore, the effective range of them should be considered. The difference ratio of the approximated optimal load conditions to precise ones in case of LCC/S and LCC/LCC are shown in Fig. 4 and Fig. 5. The values used in the calculation is shown in TABLE II. When the ratio is 1, the approximated condition is identical to the precise one.

![Image](image_url)

**TABLE I**

<table>
<thead>
<tr>
<th>Approximation</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCC/S approximated to S/S</td>
<td>( F_{o} \gg F_{k} )</td>
</tr>
<tr>
<td>LCC/LCC approximated to S/S</td>
<td>( F_{o} F_{\beta} \gg F_{k}, r \approx 1 )</td>
</tr>
</tbody>
</table>

**TABLE II**

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Name</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_{1} )</td>
<td>156 [\mu H]</td>
<td>( R_{1} )</td>
<td>0.30 [\Omega]</td>
<td>( f )</td>
<td>85 kHz</td>
</tr>
<tr>
<td>( L_{1 s} )</td>
<td>60 [\mu H]</td>
<td>( R_{1 s} )</td>
<td>90 [m\Omega]</td>
<td>( k )</td>
<td>0.1, 0.2, 0.4</td>
</tr>
<tr>
<td>( L_2 )</td>
<td>163 [\mu H]</td>
<td>( R_2 )</td>
<td>0.32 [\Omega]</td>
<td>( V_{DC} )</td>
<td>20 V</td>
</tr>
<tr>
<td>( L_{2 s} )</td>
<td>50 [\mu H]</td>
<td>( R_{2 s} )</td>
<td>80 [m\Omega]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
It can be said that this approximation is valid when $F_\alpha/F_k$ is about more than 5.

The characteristics of primary LCC is that current circulating in the transmitter coil is constant regardless of the coupling between the main coils [14]. Moreover, especially in the small coupling coefficient region, the power consumption of $L_{1s}$ is relatively lower than one at the transmitter coil as shown in Fig. 6. Therefore, power loss at primary side $P_1$ can be seen almost constant, and $P_{in}$ can be approximated as (18). On the other hand, loss at secondary side $P_2$ and output power $P_{out}$ can be approximately represented as (19) and (20) by considering $R_L \gg R_2$, where $P_{trans}$ is power the receiver coil receives.

\[
P_{in} = P_{out} + P_1 + P_2 \approx P_{out} + P_{wait} + P_2 \quad (18)
\]

\[
P_2 = \frac{R_2}{R_2 + R_L} P_{trans} \approx \frac{R_2}{R_L} P_{trans} \quad (19)
\]

\[
P_{out} = \frac{R_L}{R_2 + R_L} P_{trans} \approx P_{trans} \quad (20)
\]

Thus, (17) can be approximated as a function to $R_L$ as shown in (21), where $a_1$ and $a_2$ are defined by (22) and (24).

\[
\eta_{total} \approx \frac{P_{out}}{P_{in} + P_2 + N P_{wait}} = \frac{a_1}{R_L} + \frac{a_2}{R_T} + N P_{wait} \quad (21)
\]

\[
P_{out} \approx k^2 \frac{L_2}{L_1} \frac{V_{in}^2}{R_L} = \frac{a_1}{R_L} \quad (22)
\]

\[
P_1 \approx P_{wait} \quad (23)
\]

\[
P_2 = \frac{R_2}{R_L} P_{out} = \frac{a_2}{R_L^2} \quad (24)
\]

When the differentiated value of (21) by $R_L$ equal to 0, efficiency becomes maximal and the value is

\[
R_{Lopt}^{LCC/S} (N) = \sqrt{\frac{a_2}{P_{wait} N}}. \quad (25)
\]

The optimal load condition under the multi-parallel operation changes depending on the number of transmitter units. In addition, $R_{Lopt}^{LCC/S} (N)$ can be easily calculated by dividing $R_{Lopt}^{LCC/S} (1)$ by the square root of $N$ as (26) because the $R_{Lopt}^{LCC/S} (1)$ must be identical to (8) when $N$ is 1. In case of LCC/LCC, based on the analysis of (13), $R_{Lopt}^{LCC/LCC} (N)$ is
exhaustive search and approximated optimal load respectively. A precise optimal load condition determined by parameters for the simulations are shown in Fig. 7 and TABLE II as (27).

\[ R_{\text{LCC}}^{\text{approx}}(N) = \frac{R_{\text{Lopt}}^{\text{LCC}}(1)}{\sqrt{N}} \]  
\[ R_{\text{Lopt}}^{\text{LCC}}(N) = \sqrt{N} R_{\text{Lopt}}^{\text{LCC}}(1) \]  

Calculation results under multi-parallel operation and parameters for the simulations are shown in Fig. 7 and TABLE II respectively. A precise optimal load condition determined by exhaustive search and approximated optimal load \( R_{\text{Lopt}}^{\text{LCC}}(N) \) and \( R_{\text{Lopt}}^{\text{LCC}}(N) \) calculated by (26) and (27) are consistent with each other. Moreover, transmission efficiency decreases as the number of transmitter units increases. Therefore, there is a trade-off relation a designer should consider between the number of them and efficiency.

IV. EXPERIMENTAL VERIFICATION

In this section, the improvement of transmission efficiency under a multi-parallel operation is verified by the experiment.

A. Experimental setup

The circuit diagram of a whole experimental system is shown in Fig. 8. SCT2080KE N-channel SiC MOSFETs (ROHM Co., Ltd.) are used as power switching devices. AWG38 160 strands Litz wire is used for coils, and specifications of those coils and capacitors which are calculated by (1) - (3) are shown in TABLE III. The size of primary and secondary coils are 200×300 mm and 200×200 mm respectively.

B. Experimental results

Fig. 9 shows the accuracy of the approximation to calculate \( R_{\text{Lopt}}^{\text{LCC}} \). As explained in the previous section, the approximated optimal load \( R_{\text{Lopt}}^{\text{LCC}/\text{LCC}} \) and measured one are 40.5 \( \Omega \) and 40 \( \Omega \) respectively under \( r \approx 1 \) condition, and the approximation is valid. On the other hand, \( R_{\text{Lopt}}^{\text{LCC}/\text{LCC}} \) is much different from the measured one when \( r \) is much larger than 1. In other words, \( R_{\text{Lopt}}^{\text{LCC}/\text{LCC}} \) is invalid in large \( r \), and \( R_{\text{Lopt}}^{\text{LCC}/\text{LCC}} \) should be used to calculate the optimal condition instead of the \( R_{\text{Lopt}}^{\text{LCC}/\text{LCC}} \). To increase \( r \), 1 \( \Omega \) series resistance is added to \( R_{2s} \) in this experiment.

Experimental results under multi-parallel operation are shown in Fig. 10 and TABLE IV. Comparing cases of \( N = 1 \) and \( N = 4 \) in Fig. 10, maximal efficiency of \( N = 1 \) is always higher than that of \( N = 4 \). Moreover, the optimal loads for \( N = 4 \) apparently are smaller than those of \( N = 1 \). When the effect of \( P_{\text{wait}} \) is ignored, and the optimal load for \( N = 1 \) is adopted to an \( N = 4 \) multi-parallel system, the transmission efficiency is not maximal. Therefore, by considering \( P_{\text{wait}} \), maximal efficiency at \( N = 4 \) can be achieved and improves by 7%, 1%, and 3% respectively comparing to the case that optimal load at \( N = 1 \) is used as shown in Fig. 10.

TABLE IV is a summary of the optimal conditions in the
In this paper, an effective range of the approximated optimal load conditions for LCC/LCC and LCC/S are investigated. The conditions are also derived in the case of the multi-parallel load conditions for LCC/LCC and LCC/S are investigated. The investigation reveals the approximation conditions are also derived in the case of the multi-parallel structure system. The approximation of LCC/LCC is valid as long as \( F_\alpha \approx F_\beta \) is true, and that of LCC/S is valid as long as \( F_\alpha \gg F_k \) is true. Moreover, the optimal load condition changes according to the number of idling transmitter units which are irrelevant to power transmission. This paper proposes the estimation method of the optimal condition of a multi-parallel system with \( N \) transmitter units from that of single transmitter and receiver. Finally, experimental verification is conducted and shows that the shift of the optimal load condition can be predicted by the proposed method. Besides, the improvement of efficiency by up to 7% was achieved by considering the shift effect.

The symmetrical design of \( F \) values makes the optimal condition of LCC/LCC as simple as that of S/S, and its accuracy is ensured. Then achievements of optimal tracking control for S/S can also be utilized to LCC/LCC. Moreover, this paper enables us to operate the multi-parallel system with LCC topology more efficiently by applying the proposed modified optimal condition.

### V. CONCLUSION

In this paper, an effective range of the approximated optimal load conditions for LCC/LCC and LCC/S are investigated. The conditions are also derived in the case of the multi-parallel structure system. The investigation reveals the approximation of LCC/LCC is valid as long as \( F_\alpha \approx F_\beta \) is true, and that of LCC/S is valid as long as \( F_\alpha \gg F_k \) is true. Moreover, the optimal load condition changes according to the number of idling transmitter units which are irrelevant to power transmission. This paper proposes the estimation method of the optimal condition of a multi-parallel system with \( N \) transmitter units from that of single transmitter and receiver. Finally, experimental verification is conducted and shows that the shift of the optimal load condition can be predicted by the proposed method. Besides, the improvement of efficiency by up to 7% was achieved by considering the shift effect.

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### REFERENCES


