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DOI
10.1109/ISCAS45731.2020.9181016

Publication date
2020

Document Version
Final published version

Published in
2020 IEEE International Symposium on Circuits and Systems (ISCAS)

Citation (APA)
https://doi.org/10.1109/ISCAS45731.2020.9181016

Important note
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Compensation Network for a 7.7 kW Wireless Charging System that uses Standardized Coils

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Abstract—Industrial wireless charging systems use standardized coils to guarantee interoperability between different manufacturers. In combination with these coils, the compensation network can still be designed and optimized. This paper explains the step-by-step design of the compensation network for a 7.7 kW wireless charging system (power class WPT2), which is composed of standardized coils. The compensation network must satisfy the output power and voltage requirements, the soft-switching of the inverter, and the limit of voltage and current stress on the components. The S-S compensation network is found to be unfeasible for those coils, and an optimized double-sided LCC compensation network is designed. The 3-phase grid connection is selected despite the 1-phase one because it gives the lowest total conduction losses. Finally, two parallel SiC MOSFETs C3M0075120K are chosen as inverter’s switch because of their low conduction losses. This solution can achieve a payback time within a year with respect to the cheapest one.

Index Terms—Compensation networks, electric vehicles (EVs), inductive power transfer, standardized coils, wireless charging.

I. INTRODUCTION

Nowadays, standards and regulations on wireless charging for electric vehicles (EVs) are well defined, such that interoperability is guaranteed between systems from different manufacturers [1]. Especially for what concerns the main magnetic coils, reference designs are specified in SAE 2954 [2] for the power levels up to 11.1 kW (WPT3). Each of them presents both mechanical and electrical specifications. This means that the specification already defines the values of the inductance and coupling of the coils. From an industrial point of view, manufacturers commercialize coils which are designed based on the reference designs to make sure that their products are compatible with the standards.

When designing a wireless charging system using standardized coils, the compensation network can be still optimized. The aim of the compensation network is to minimize the reactive power circulating in the charging system. In this way, it is possible to transfer the required power to charge the battery and achieve high power efficiency. At the required power level, the compensation network must also ensure that the DC output voltage is in the range of the battery voltage, which is typically around 400V. At the same time, the DC input voltage must be in the range of the rectified voltage from the AC grid, which is either 340-500V DC in case of a 1-phase connection or 650-870V DC in case of a 3-phase one, for a grid with phase-to-neutral potential of 230 V rms. Moreover, the inverter’s soft-switching needs to be guaranteed, and the voltage and current stress on all components must be within reasonable values. Therefore, given the geometry and the electrical specifications of the coils, the designed compensation network needs to satisfy all these requirements.

This paper explains the design and the optimization of the compensation network for a 7.7 kW wireless charging system, which is composed of standardized coils of the power class WPT2. The coils parameters and the design constraints are summarized in Section II. After this, Section III explains the step-by-step design and optimization of the compensation network. Then, the stress on the components is computed through an accurate circuital model and time-domain simulations. The well-known series-series (S-S) compensation network is proved to be unfeasible with selected standardized coils for the required power level, and the double-sided LCC compensation network is found to be suitable. Different designs are analyzed and compared for what concerns the soft-switching of the inverter, the voltage and current stress, conduction losses of the components and cost. Finally, in Section IV, conclusions are given on the design of a 7.7 kW compensation network.

II. DESIGN REQUIREMENTS AND CONSTRAINTS

The compensation network has to be designed and optimized for a 7.7 kW wireless charging system with given coils. The equivalent circuit of the system is shown in Fig. 1. Standardized coils are used according to the power class WPT2 of SAE J2954 [2]. In particular:

- **Transmitter:** the coil is sealed in a concrete block to facilitate its on-ground mounting. Its geometrical and electrical characteristics are based on the universal ground assembly (GA) coil. This coil has been manufactured by MAGMENT [3].
- **Receiver:** the coil is based on the geometrical and electrical characteristics of the WPT2/Z2 class. This coil has been manufactured by PREMO [4].

Fig. 2 shows the picture of the two coils of the wireless charging system. The coils’ parameters are constraints in the design of the whole wireless charging system. In particular, $L_1$ and $L_2$ define the transmitter (primary) and receiver (secondary) coil inductance; $R_1$ and $R_2$ are, respectively, their series resistances; $M$ is the mutual inductance between the coils, and $k$ is their coupling factor ($k = \frac{M}{\sqrt{L_1 L_2}}$).

For what concerns the requirements, the output power $P_{\text{out}}$ is defined by the receiver’s coil power class. The DC output
The DC input voltage of a conventional battery used in automotive applications.

is to have reasonable voltage and current stresses measured at the specified airgap and with perfect alignment. This property is preferable both in dynamic charging and when multiple receivers are present. After this, since the resonant voltage is shared by more components, their voltage stress is lower than in the S-S compensation. Moreover, since the components $L_{f1}$, $C_{f1}$ resonate at the nominal operating frequency, the inverter’s current high-order harmonic components are highly attenuated. This ensures low distortion of $I_1$ that is fundamental to fulfill the electromagnetic compatibility (EMC) limits for the radiated magnetic field [17].

First, it is verified the suitability of the S-S compensation network with the given coils. This is done by checking if it satisfies all the requirements in Table I. If not, the double-sided LCC compensation would be selected and designed.

### A. S-S compensation network

The resulting circuit’s parameters of the S-S compensation network are shown in Table II. By using (1) and (2), the S-S compensation network satisfies the output requirements on $P_{out}$ and $V_{out}$ specified in Table I. According to [5]–[10], the compensation capacitors of both the primary and secondary circuits are calculated as:

$$C_1 = \frac{1}{\omega^2 L_1}, \quad C_2 = \frac{1}{\omega^2 L_2}.$$  

In both circuits, the components’ voltages and currents can be computed with the Kirchhoff’s voltage law in (3) and (4). These equations use the phasor convention, where all voltages and currents are assumed to be $85\text{ kHz}$ sinusoids, and $V_{AB}$ is taken as reference such that $V_{AB} = V_{AB}\phi$. The DC input voltage $V_{in}$ can be found by using (5). Both (2) and (5) are based on the first harmonic approximation (FHA) [11], [18].

1b) [12]–[16]. According to [12], this network has several features. First, the current flowing through the primary coil does not depend neither on the coupling nor on the load condition. This property is preferable both in dynamic charging and when multiple receivers are present. After this, since the resonant voltage is shared by more components, their voltage stress is lower than in the S-S compensation. Moreover, since the components $L_{f1}$, $C_{f1}$ resonate at the nominal operating frequency, the inverter’s current high-order harmonic components are highly attenuated. This ensures low distortion of $I_1$ that is fundamental to fulfill the electromagnetic compatibility (EMC) limits for the radiated magnetic field [17].

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### III. Design Procedure

It is always preferable to choose a compensation network with the minimum number of components, such that the losses can be contained. From the literature, it is well-known that at least one capacitor must be connected to each coil. In this way, the reactive power that circulates in the system is minimized, and the power factor is close to unity at both the input and output of the resonant stage. Depending on the type of connection, the most basic compensation network can be either series-series (S-S), series-parallel (S-P), parallel-series (P-S) or parallel-parallel (P-P) [5]–[10]. Among these combinations, the S-S compensation is the most used in wireless charging because the required value of both capacitors is independent of both coupling and loading condition [5], [9]–[11]. Its schematic is shown in Fig. 1a).

Compensation networks with multiple components can be also found in the literature, such as the double-sided LCC compensation network which the schematic is shown in Fig.

### Table I

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{out}$</td>
<td>7.7 kW</td>
</tr>
<tr>
<td>$V_{out}$</td>
<td>490 V</td>
</tr>
<tr>
<td>$V_{in}$</td>
<td>340–500 V (1s) or 650–870 V (3s)</td>
</tr>
<tr>
<td>$f_0$</td>
<td>85 kHz (79–90 kHz)</td>
</tr>
<tr>
<td>$V_r, I_r$</td>
<td>$&lt; 5$ kW, $80$ A</td>
</tr>
<tr>
<td>$V_{out}$</td>
<td>$V_{out}$</td>
</tr>
<tr>
<td>$I_{out}$</td>
<td>$I_{out}$</td>
</tr>
<tr>
<td>$Q_1, Q_2$</td>
<td>Soft-switching</td>
</tr>
<tr>
<td>$C_{1, 2}$</td>
<td>$C_{1, 2}$</td>
</tr>
<tr>
<td>$R_{1, 2}$</td>
<td>$R_{1, 2}$</td>
</tr>
<tr>
<td>$L_{1, 2}$</td>
<td>$L_{1, 2}$</td>
</tr>
<tr>
<td>$M$</td>
<td>$M$</td>
</tr>
<tr>
<td>$k$</td>
<td>$k$</td>
</tr>
</tbody>
</table>
of coils’ current. In this case, the coils are chosen to carry a symmetrical system, and not for a generalized approach. The double-sided LCC compensation can be found in [12]. The requirements on \( V_{in} \) are not preferable in this application. This means that the double-sided LCC compensation network should be investigated.

B. Double-sided LCC compensation network

The circuit parameters’ definition and detailed analysis of the double-sided LCC compensation can be found in [12]. The parameters’ definition is summarized in (6). However, in [12], the value of the parameters is chosen only for a completely symmetrical system, and not for a generalized approach.

\[
L_{f1}C_{f1} = \frac{1}{\omega_0^2}, \quad L_i - L_{f1} = \frac{1}{\omega_0^2C_i} \quad i = 1, 2 \tag{6}
\]

The values of \( L_1, L_2, and M \) are known, which are listed in Table I. The values of \( L_{f1}, L_{f2} \) need to be selected according to the requirements on \( P_{out} \) and \( V_{out} \). After this, the values of \( C_1, C_2, C_{f1} \) and \( C_{f2} \) can be computed as shown in (6).

The double-sided LCC compensation has a constant-current output characteristic, since \( I_{L_{f2}} \) is load-independent [12]:

\[
I_{L_{f2}} = \frac{M}{\omega_0^2} \frac{V_{in}}{L_{f1} L_{f2}} \tag{7}
\]

To make sure that the double-sided LCC meets the output requirements, the relation between \( I_{L_{f2}} \) and \( I_{out} \) is described by (8). This is based on [18] that assumes a continuous conduction of the rectifier’s diodes in Fig. 1a).

\[
I_{L_{f2}} = \frac{\pi}{2} I_{out} \tag{8}
\]

By substituting (7) and (1) into (8), it can be found that

\[
L_{f1} L_{f2} = \frac{8}{\pi^2} \frac{M V_{in} V_{out}}{\omega_0 P_{out}} \tag{9}
\]

In (9), there are two unknown variables: the ratio between \( L_{f1} \) and \( L_{f2} \), and the input voltage \( V_{in} \). The ratio between \( L_{f1} \) and \( L_{f2} \) can be found by choosing the desired amount of coils’ current. In this case, the coils are chosen to carry the same amount of current to keep the components’ voltage and current stress under control. Since [12] defines \( I_1 \) and \( I_2 \) as in (10), the condition that makes \( I_1 = I_2 \) is (11). At this point, \( L_{f1} \) and \( L_{f2} \) can be calculated by using (9) and (11). However, before that, the proper \( V_{in} \) needs to be selected.

\[
\hat{I}_1 = \frac{\pi}{2} \frac{V_{in}}{\omega_0 L_{f1}}, \quad \hat{I}_2 = \frac{\pi}{2} \frac{V_{out}}{\omega_0 L_{f2}} \tag{10}
\]

\[
\frac{L_{f2}}{L_{f1}} = \frac{V_{out}}{V_{in}} \tag{11}
\]

According to (9), it can be found that \( V_{out} \) is directly proportional to both \( M \) and \( V_{in} \). This means that, when the coils become more misaligned, the target \( P_{out} \) can be reached by increasing \( V_{in} \). Therefore, at the highest coupling condition, the compensation network has to be tuned at the minimum \( V_{in} \).

Table I shows two possible ranges of \( V_{in} \), depending on the grid connection. Herein, it is assumed an operation at \( V_{in} = 380 \) V for the \( 1\phi \) grid connection, while \( V_{in} = 650 \) V for the \( 3\phi \) grid connection. To identify which grid connection is the most suitable, a double-sided LCC compensation network is designed for both minimum values of \( V_{in} \) based on (6), (9) and (11). Circuit simulations in the time domain show that \( I_{L_{f1}} \) and \( I_{L_{f2}} \) are distorted. This happens because the LCC components have multiple frequencies that influence the resonance at 85 kHz. This means that (9) and (11) are not accurate since they are based on the FHA. Therefore, to reach \( P_{out} = 7.7 \) kW, a higher value of \( P_{out} \) has been used in (9).

To make a fair comparison, both solutions are designed to have soft-switching operation. As explained in [12], [18]–[21], the zero-voltage switching (ZVS) turn-on can be realized by switching off the inverter legs at a turn-off current \( I_{OFF} \) that is high enough to completely discharge the equivalent drain-source internal capacitance \( C_{ds} \) of the MOSFETs during the dead time \( t_{dead} \). To perform the comparison, the two designs are tuned to the same \( I_{OFF} \) as it is shown in Fig. 3. By using (6), (9) and (11), the design at \( V_{in} = 650 \) V reaches the operating condition shown in Fig. 3b). On the other hand, at \( V_{in} = 380 \) V, to realize the same \( I_{OFF} \), the capacitance \( C_2 \) has been increased by 0.1 nF as explained in [12]. Since the value of \( I_{OFF} \) depends on \( V_{ds,off}, C_{ds} \) and \( t_{dead} \), \( I_{OFF} \) varies for different MOSFETs and \( V_{in} \). Hereby, this is not considered because it is out of the scope of the paper.

The components used for both the inverter and the compensation network are listed in Table III. For both possible \( V_{in} \), two SiC MOSFETs are considered that differ in current rating and, consequently, in price. The resulting circuit’s parameters for both designs of the double-sided compensation network are shown in Table IV, where the number and type of passive components are specified within the brackets. The two designs are analyzed for what concerns the components’ voltage \( \hat{V} \) and

| \( V_{in}, C_i \) | \( 112.3 \text{V} \) |
|\( C_1, C_2 \) | 55.34 mF, 80.5 mF |
|\( I_1, I_2 \) | 120.7 A, 50.2 A |
|\( V_{L1}, V_{L2} \) | 4.4 kV, 703 V |
|\( V_{C1}, V_{C2} \) | 4.4 kV, 703 V |
current $I$ stress, conduction power losses $P_{loss}$ and total cost. Table V shows the total $P_{loss}$ and cost of all designs, where the partial quantities of the main coils, compensation network and inverter are highlighted. The cost of the main coils is not considered here, because it is the same for all designs and it is not interesting for the comparison. Additionally, the details of each passive component are shown in Table VI. At $V_{in} = 650 \, V$, the current stress on the inverter $I_{L_{f1}}$ is about 30% lower than in the case of $V_{in} = 380 \, V$. On the other hand, at $V_{in} = 380 \, V$, the current stress on both the main coils $I_1, I_2$ is about 3% lower which leads to lower $P_{loss}$ than in the case of $V_{in} = 650 \, V$. From Table V, it can be concluded that the total $P_{loss}$ on the passive components $\Sigma_{L,C}$ is slightly lower (0.65%) for the 3φ grid connection ($V_{in} = 650 \, V$) at a cost that is 11% higher. Considering also the $P_{loss}$ of the inverter, the case of $V_{in} = 380 \, V$ with SW4 leads to the lowest total losses and most expensive design. To evaluate if the extra cost can be amortized with the time, the economical analysis of all the designs is performed in Table VII. The payback time is calculated taking as a reference the most affordable design ($V_{in} = 380 \, V$ with SW1). As a result, the payback time of the most expensive and efficient solution with $V_{in} = 650 \, V$ and SW4 is less than one year, which is much lower than the design lifetime of the wireless charging system. In a future work, this analysis will be verified experimentally with a prototype, where the primary circuitry is shown in Fig. 4.

IV. CONCLUSION

This paper explains the design and optimization of the compensation networks for a 7.7 kW wireless charging system which uses standardized coils of the power class WPT2. The conclusions can be summarized as follows:

- The series-series compensation network is proved to be unfeasible with the selected coils because, to match the output requirements, it demands a DC input voltage that is below the minimum value allowed by any grid connection. It also causes a high current stress at the primary circuit which is higher than the coil’s rated value.
- The double-sided LCC compensation network is found to be more suitable for this application. The 3-phase grid connection is selected, because the DC input voltage range 650-870 V ensures soft-switching of the inverter at 85 kHz, low current stress on the inverter and the lowest total conduction losses on the passive components.
- Two parallel 1200V SiC MOSFETs C3M0075120K are chosen as switch of the inverter because of their low conduction losses. Taking as a reference the cheapest design, this solution has a payback time less than one year.
REFERENCES


