A 3D Computational Model for Analysis of Wireless Power Transfer System Based on the Magnetic Resonance Coupling Method

M. Joler  B. Štih

Abstract — This paper presents a 3D computational model we have created to enable easier and more accurate analysis of the wireless power transfer (WPT) based on the magnetic resonance coupling method (MRC). The model enables time-efficient analysis of practical issues in the design of an MRC WPT system, such as: the optimal size of the MRC system on the transmitting (Tx)- or receiving (Rx)- side, the effects that the distance between the Tx- and Rx- resonator, or between the excitation loop and the resonator, have on the power transfer efficiency and resonant frequency of the system, to mention a few. Experimental verification of the results has been performed and showed a good agreement with the simulation.

1 INTRODUCTION

Wireless power transfer (WPT) has regained researchers’ interest in recent years due to the growing number of wireless gadgets that are to be charged in our daily routines. As there has not been a worldwide standard for a universal phone connector established till recently (yet to come into effect worldwide in the near future,) and different countries have different power outlets, it creates incompatibility issues and hassle for world travelers and we all share a common need for hassle-free charging of our mobile devices.

Moreover, various mobile applications, that simultaneously run in the background of our devices, tend to drain the battery fairly quickly, causing us the inconvenience of getting the device battery empty in the middle of the day at the places where we cannot afford to plug the device into the power outlet for re-charging.

These reasons motivate us to design wireless-charging solutions that will enable us to get our devices charged on-the-go, e.g. at the coffee shop or the restaurant, on the airplane, in the conference room etc. The challenge of getting a practically feasible system is to have a small receiver circuit inside our mobile devices and an efficient WPT circuitry mounted somewhere around us.

Amongst other methods of WPT [1–3], the magnetic resonance coupling (MRC) method has shown to be a viable approach for wireless charging of electronic devices on distances larger than just a few centimeters that the magnetic induction method can typically provide.

2 3D COMPUTATIONAL MODEL

While there have been experimental studies that have demonstrated the efficiency and range of the MRC [2,4], we felt a realistic computational model of the MRC system would be beneficial to ease the system design and analysis.

This parameterized 3D computational model, shown in Fig. 1, can provide us answers to a number of practical issues such as: the optimal (or required) size of the MRC system on the Tx- or Rx- side, the effect of the distance between the Tx- and Rx- resonator, or between the excitation loop and the resonator, on the power transfer efficiency and resonant frequency of the system, the effect of the discrete- and parasitic-capacitance on efficiency of the system, the effect of the spiral- or helix- resonator outer-to-inner radius ratio on the power transfer efficiency, the effect of the number of turns etc. We have created the computational mod-
approach comprising a directly excited resonator. Within the scope of this paper, we will discuss only the spiral resonator-based WPT system.

The MRC system comprises four principal elements (Fig. 1): the driver loop, the Tx- and the Rx- spiral resonator, and the load loop. Although a fairly simple configuration, the geometry of each element and the distance between each two elements must be judiciously designed in order to match all the components on the desired resonant frequency and maximize the system efficiency. The driver loop excites the primary resonator at the desired resonant frequency by its magnetic field lines. The primary resonator will transfer the field energy onto the secondary resonator, which will forward it to the load loop and the load connected to it. However, the distance chosen between the resonators will affect the resonant frequency value, as it will be shown later, while the separation between the loop and the resonator will affect the efficiency. Since it is a 3D computational model, the parameters of interest, i.e. the inductance $L$ and capacitance $C$ must be generated by proper dimensioning of the spiral resonator, primarily for $L$. As for $C$, the spiral will exhibit a small parasitic capacitance $C_p$ in the order of picofarads, which would shift the resonant frequency $f_r$ to higher values. To lower the resonant frequency down to about 10 MHz, that was chosen in this work, a discrete capacitor of the adequate value is added to the resonator and its value is calculated from the desired resonant frequency and the designed value of $L$.

The frequency band at about 10 MHz is convenient for WPT being far enough from the devices that could cause interference with the WPT system and for not being hazardous for health.

The self-inductance $L$ is here calculated using the Wheeler’s approximation formula [5], which showed to be accurate enough for this purpose:

$$L = 0.03937 \frac{r^2 N^2}{8r + 11w} \ [\mu H]$$  

where $r$ (in $mm$) designates the mean radius stretched from the center of the spiral to the center of the $N$ spiral turns, $N$ is the number of wire turns, and $w$ (in $mm$) is the width of one side of the spiral turns

3 RESULTS

The parameter values that were used are listed in Table 1, where $R_1$ and $R_4$ are the driver and the load loop radii, respectively, $R_{i2}$ and $R_{o3}$ are the inner radii of the Tx- and Rx-spiral, while $R_{o2}$ and $R_{o3}$ are the outer radii of the Tx- and Rx-spiral, respectively, $\rho$ is the wire radius, $N_2$ and $N_3$ are the number of turns of the Tx- and Rx-spiral, $L_2$ and $L_3$ are the self-inductances of the TX- and RX-spiral, and $C_2$ and $C_3$ are the calculated values of the discrete capacitors that are added to the Tx- and Rx-spiral respectively, to establish the desired $f_r$. $L_2 = L_3$ is evaluated using (1) and $C_2 = C_3$ is calculated by the expression for the resonant frequency

$$\omega_r = \frac{1}{\sqrt{LC}}$$  

3.1 Computational Analyses

Using the proposed model, we obtained the results presented in the following subsections. The parameter $S_{21}$ is the measure for the WPT efficiency between the Tx- and Rx-side.

3.1.1 Effects of the distance between the resonators

In this analysis, we investigated how the distance ($d_{23}$) between the resonators affects the power transfer. It was found that there was some threshold value for $d_{23}$, let us refer to it as $d_{th}$. When $d_{23} > d_{th}$, the $S_{21}$ curve will have a single peak at the designed $f_r$ and decay bilaterally around it. As $d_{23}$ increases, the curve will retain the shape, but keep continuously dropping to lower values. In the case $d_{23} < d_{th}$, however, the resonance splits into two resonant frequency that drift away from the original $f_r$ in the opposite directions, while the $S_{21}$ at the original $f_r$ drops. The smaller the $d_{23}$, the more the two resonant frequencies will drift away, but the shift is not significant overall. Each new $f_r$ was shifted a few hertz from the original $f_r$, as presented in Fig. 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1 = R_4$</td>
<td>6 cm</td>
</tr>
<tr>
<td>$R_{i2} = R_{o3}$</td>
<td>3 cm</td>
</tr>
<tr>
<td>$R_{o2}$</td>
<td>9 cm</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.1 cm</td>
</tr>
<tr>
<td>$N_2 = N_3$</td>
<td>5</td>
</tr>
<tr>
<td>$f_r$</td>
<td>10 MHz</td>
</tr>
<tr>
<td>$L_2 = L_3$</td>
<td>3.1 $\mu H$</td>
</tr>
<tr>
<td>$C_2 = C_3$</td>
<td>81.495 pF</td>
</tr>
</tbody>
</table>

Table 1: Parameters used in the model.
3.1.2 Analysis of the distance between the loop and the resonator

Another important parameter is the distance between the driver and/or the load loop and the respective resonator, that is $d_{12}$ or $d_{34}$, respectively. In this analysis, we set $d_{12} = d_{34}$. The results in Fig. 3 indicate a twofold behavior again. For larger values of $d_{12}$, the original $f_r$ splits in two $f'_r$s that drift away. When $d_{12}$ is smaller than some threshold value, a single resonance is achieved in the vicinity of the desired $f_r$ value and for some $d_{12}$, it will have its maximum. Further decrease in $d_{12}$ value will maintain the curve shape, but the efficiency will drop.

3.1.3 Analysis of the loop radius

In this analysis, we investigated the effect of the loop radius ($R_1$ or $R_4$) on the efficiency of the system. Figure 4 shows the results. Here, we also kept $R_1 = R_4$. It is evident that there is again some optimal value of $R_1$. For too small a value of $R_1$, the efficiency drops at the position of the desired $f_r$ and $f_r$ splits into two $f'_r$s which drift away. At some value (in this case $R_1 = 3$ cm), the WPT efficiency is at maximum and at the desired $f_r$ forming only one resonance peak. Further increase of $R_1$ will retain the shape of the $S_{21}$ curve, but the magnitude of $S_{21}$ will decay at the location of $f_r$.

3.2 Effect of wire thickness

In this part, we examined the effect of the wire thickness. Although the wire thickness is not explicitly included in (1), one is aware that different wire thickness will slightly affect the overall $L$ and $C_p$, which will then affect $f_r$, but the question is which parameter will prevail (keeping $N_1$, $R_{i2}$ and $R_{o2}$ fixed). Although there are formulas that include wire thickness in the evaluation of $L$ [6], it is still tricky to evaluate $L$ without a meticulous analytical procedure, due to the opposite trends of changes of the wire thickness and the gap between the wires (when $R_{i2}$ and $R_{o2}$ are kept unchanged). The results shown in Fig. 5 indicate that a thicker wire will actually increase $f_r$, which, without having one such 3D model, need not be obvious right away.

3.3 Measurements

To test the computational results, we built a laboratory prototype (Fig. 6) of the WPT system described here, with approximately the same design parameters as listed in Table 1. The early measurements show an agreement with the computationally obtained results in a qualitative sense (for closer quantitative agreement, voltage levels of the virtual model and the experimental setup need to be reconciled and we would need higher precision in the fabrication of the experimental WPT sys-
The magnitudes of $S_{21}$ in this measurement also take into account the effect of plexiglass plates that support the loops and resonators in this experimental setup. As the results in Fig. 7 suggest, the presence of the plexiglass plates reduces the $S_{21}$ magnitude for a few dBs.

4 CONCLUSIONS

In this paper, we presented a 3D computational model for the analysis of a WPT system based on the magnetic resonance coupling method. The computational model enables us to provide answers to a number of design-related issues in a substantially shorter time than it takes to assemble an experimental setup and conduct measurements and it also provides an insight into the aspects that are hard to verify or distinguish experimentally. We have also built and tested a laboratory prototype and obtained results that correspond to the simulated results.

References


