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Optimization and Robustness Analysis of a Spiral Resonators Array for Misalignment Recovering purposes in WPT Systems

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Abstract

The aim of the manuscript is to present a feasibility analysis for misalignment recovering purposes in a two coils Wireless Power Transfer system with the presence of a Spiral Resonators Array. The misalignment is faced by opportunely varying the values of capacitive loads with an *ad-hoc* optimization procedure. In a previous work, the authors have already presented a methodology able to compensate the system efficiency drop by applying a post-processing approach based on an S-parameters matrix circuit representation of the entire system, and by changing the values of the capacitors which opportunely load each element of the SRA structure. Here, an optimization procedure followed by a Montecarlo method have been used in order to investigate the effect of the components tolerances and the sensitivity of the system. In this way, a more realistic modelization can be accomplished, guiding the designer to the realization of a more robust system.

1 Introduction

In literature, many examples of using a matrix of resonators tuned at a given frequency for improving the performance of a WPT system have been presented. Typically, the matrix of resonators is generally addressed as meta-surface or metamaterial. These solutions are very often adopted with the specific purpose of enhancing the magnetic field focusing produced by the source coil (also called driver), thus increasing the overall efficiency of the system. In a general arrangement, metamaterials are inserted in between driver and receiver coils.

The authors in [2] demonstrated that magnetic metasurfaces are also able to reduce the electric field strength in a typical WPT coaxial system. In this way, possible safety issues which could arise, for instance, in vehicles charging systems (power up to the kW range) or biomedical implants can be addressed. Hence, magnetic metasurfaces are suited to be adopted in all the WPT applications planned to be used in the proximity of human body.

As a matter of fact, the scientific community is also very active on searching the best design for WPT systems, maximizing the performance. In this sense, the misalignment issue is one of the most important concerns;

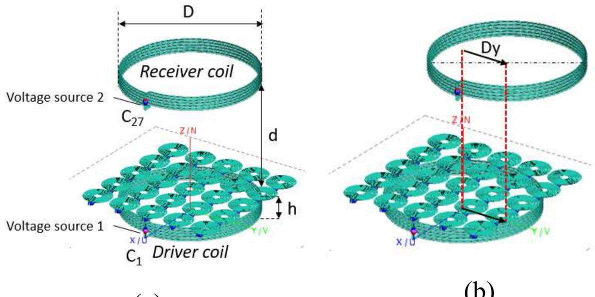


Figure 1. Numerical CAD models of the proposed WPT system with SRA configurations: (a) coaxial; (b) with a *Dy* misalignment along *y* axis.

indeed, when the coils are not placed in a perfect coaxial arrangement, this problem causes a reduction of the coupling coefficient, and, consequently, a degradation of the global WPT performances.

Robustness to misalignment cannot always be solved by the use of a “forced positioning” (see for instance the widely available wireless chargeable electric tooth brushes). Especially when more flexibility is required, new approaches should be investigated. Some authors demonstrated that the insertion of a slab of resonators between driver and receiver coils also mitigates the efficiency drop problem that arises from the misalignment between driver and receiver coils in a common inductive WPT system [1].
Other research groups proposed a tunable active version of the resonator’s matrix, with the same purposes [3] - [4].

In this contribution, a study on a passive resonator’s matrix is accomplished, in order to address the misalignment recovering purpose: this avoids the presence of complex power supply networks for loading capacitors. Thus, we first conduct a preliminary optimization of the best system topology, by employing only one full-wave simulation, and then, by analysing the system through a post-processing passive circuital point of view. By exploiting such approach, the system optimization (in terms of robustness to misalignment) by using a computationally efficient procedure is achieved. This feature can be of great help during the design phase of the system.

2 Methods

The method consists in representing the system reported in Fig. 1 through a suitable S or a Z parameters matrix relative to a number of ports equal to N = P+L (P = number of active ports and L = number of lumped elements, as shown in Fig 2) (Fig. 2), as already described in [5].

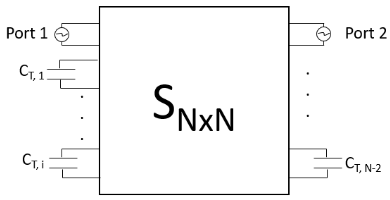


Figure 2. Circuital representation of the system; the tuning capacitors are highlighted.

The N×N S-matrix representation has been obtained by performing only one full-wave simulation based on a Method of Moments procedure of the entire WPT system consisting in the driving and receiving coils with the SRA placed in between them (Fig.1 (b)): the analysis has been carried out on the misaligned configuration (described in Figure 1).

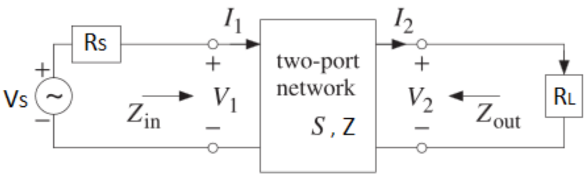


Figure 3. Circuital representation of the system as a two-ports.

The calculation has been carried out by using the Keysight Advanced Design System (ADS) software; they were performed with the purpose of both optimizing the system and obtaining an insight relative to the sensitivity of the SRA.

Starting from the capacitance values of the tuning capacitors used in the configuration presented in [5] (which consisted in choosing the SRA tuning capacitors to recover the efficiency drop due to the misalignment), we performed the following steps:

1. We optimized the values of those components, with the goal of maximizing the value of the obtained efficiency level of the system.
2. We performed a Montecarlo analysis of the results obtained from point 1, by choosing a commercial value of the capacitors characterized by a given tolerance. This is helpful to characterize the SRA sensibility to lumped elements tolerances.

The efficiency of the system has been evaluated as reported in (1), and well-described in [6].

$$\eta = \frac{P_{out}}{P_{in}} = \frac{|I_2|^2 R_L}{\Re\{V_1 I_1\}} = \frac{R_L |\bar{Z}_{21}|^2 \Re\{\bar{Z}_{in}\}}{|\bar{Z}_{22} + R_L|^2 |\bar{Z}_{in}|^2} \qquad (1)$$

2 Numerical design

The numerical simulations were carried out with an electromagnetic solver based on the Methods of Moments (Feko suite, Altair, Troy, MI, USA).
The design is a classical 2-coils system which represents the most common configuration adopted in WPT applications. Instead, the array was composed by a 5×5 matrix of passive resonant planar spirals and the design is well-described in [5]. In the present solution we neglected the losses of the tuning capacitors, which is realistic if we consider high quality commercial values of the component presenting a low Equivalent Series Resistance. Conversely, we studied the effects that typical capacitors' tolerances have on the designed SRA.

3 Results and Discussion

The feasibility analysis has been applied to the tuning capacitors configuration of the array (similar to the one obtained in [5]), and we chose not to load the spirals in light grey color, whereas the values of the capacitors under the receiver (dark grey color ones in Fig. 4) has been set equal to 575pF for, as reported in Fig. 5 (a).

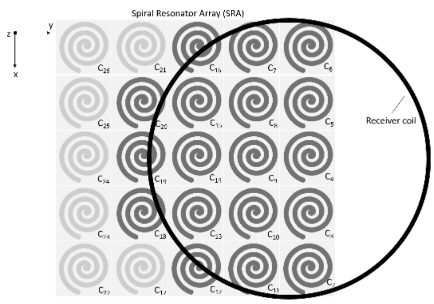
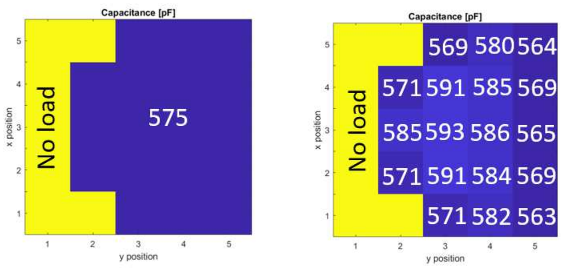


Figure 4. Schematic representation of the SRA with respect to the receiver translation: z = 0 plane (drawings not in scale).

The system in the last configuration has been optimized with the goal of obtaining the maximum efficiency level at 6MHz, which is the tuning and operating frequency of our system. The optimized method we adopted is a gradient based and a stochastic algorithm, both already implemented in ADS tool. After the optimization, the new values of the tuning capacitors in the array are shown in Fig. 5 (b).
Therefore, a Montecarlo analysis was applied to both configurations of the capacitors in the array. As it can be seen from the results shown in Fig. 6 (a) and Fig. 6 (b), by choosing for both configurations a Gaussian distribution of capacitors values with a tolerance equal to 1%, the optimized values (Fig. 6 (b)) are more confident if compared to the first configuration, which consisted in a manual optimization of capacitors values for misalignment compensation purposes.



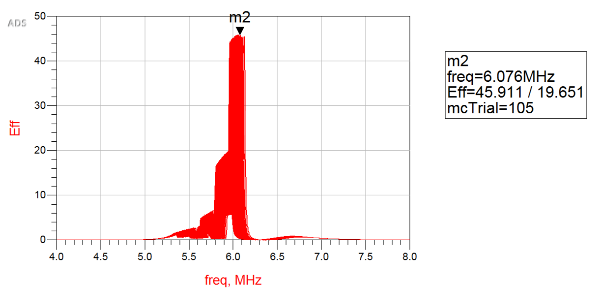
(a) (b)

Figure 5. Values of the tuning capacitors in the Spiral Resonators Array (SRA): (a) manual optimization [5]; (b) optimization obtained with ADS tool.

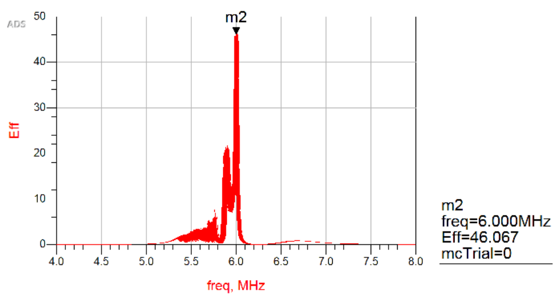
The last result suggested us to proceed with a realization of the new array in the optimized version since it provides a very good prediction of the performance of the system with commercial typical tolerance of the capacitors. By considering that the present system is narrowband, so very sensible to the tuning condition of use, the last result is quite important in the manufacturing process, suggesting us that an optimization of the design is essential. The values of the maximized efficiency are reported in Table I, for all the cases we analyzed.

TABLE I
EFFICIENCY OF THE ANALYZED SYSTEMS

	Manual optimization	*ADS optimization*
Efficiency [%]	*44*	*46*



(a)



(b)

Figure 6. Efficiency results according to the frequency of the Montecarlo analysis performed on the configuration in ADS: (a) design reported in Fig. 5(a); (b) with the values of the capacitors optimized through ADS tool.

4 Conclusion

In this paper we presented a study for misalignment recovering in a 2-coil Wireless Power Transfer system with the adoption of Spiral Resonators array (SRA).
We developed a procedure based on an optimization procedure varying the capacitive loads values by also using a Montecarlo method.
We demonstrated that this procedure can guarantee a more realistic modelization by considering also the typical tolerances of commercial capacitors used for unit-cells loading in the SRA structure.
This work can pave the way to a novel approach in order to enhance the performance and the potential applications of magnetic metasurfaces in resonant inductive Wireless Power Transfer, guiding the designer along the accomplishment of a more robust and effective system.

5 References

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