On the Spiral Resonator Arrays Size Analysis for Misalignment Compensation in Wireless Power Transfer Systems

Nunzia Fontana
Department of Energy, Systems, Territory and Construction Engineering
University of Pisa
Pisa, Italy
nunzia.fontana@unipi.it

Sami Barmada
Department of Energy, Systems, Territory and Construction Engineering
University of Pisa
Pisa, Italy

Marco Raugi
Department of Energy, Systems, Territory and Construction Engineering
University of Pisa
Pisa, Italy

***Abstract*— In this study the authors aim to use a metasurface as an additional component of a two-coil Wireless Power Transfer (WPT) system and to provide a robustness analysis to misalignment between the transmitter and the receiver coils. The analysis between metasurfaces of different size and their optimization performed to improve misalignment robustness is proved by numerical and easy circuital simulations with the aim of predicting the loads to be considered for the single unit-cell to properly control the WPT system and make it more tolerant to misalignment.**

Keywords—Wireless Power Transfer, Metamaterials, Metasurfaces, Misalignment Compensation

I. INTRODUCTION

Wireless Power Transfer (WPT) systems based on resonant multicoil are becoming popular devices. Especially for low power applications [1], WPT can be already considered as a consumer ready product. At the same time, power levels up to hundreds of kilowatts can be delivered with the same concept (with different and more complex systems) for applications like e-mobility. In this latter case, more aspects should be considered in the design phase of the WPT system, such as electromagnetic shielding and cooling issues [2]-[3]. Electromagnetic shielding is a particularly important aspect when WPT apparatuses are used to power biomedical devices or implants, since the closeness to human tissue is maximum. Several solutions for the reduction of magnetic field leakage are available in the literature, employing shields and passive or active coils arrangements [4]. In addition, in [5] and [6] the authors demonstrated that the use of a metasurface can also improve the system's performance from the EMC point of view by reducing the electric near field produced by the transmitting side of a WPT system and due to an interference. Nevertheless, all the above-mentioned applications critically suffer for misalignment between the transmitter and the receiver; indeed, not perfectly aligned coils share a drastically reduced inductive mutual coupling, leading to a degradation of the global WPT performance. In this contribution, a study on a metasurface, in which each resonator is passive, is performed, with the goal of addressing the misalignment recovering purpose.

II. WORKING PRINCIPLE

The WPT configuration object of this study is a commonly used magnetic resonance-based system resonant at a specific working frequency. Instead of adopting additional repeater coils, a metasurface is specifically designed. Typically, all the metasurface unitcells are tuned at the same operating frequency of the two main coils: driver (Tx) and receiver (Rx); the metasurface is usually positioned in between them. The authors in [5] performed an analysis on the geometrical characteristics of the metasurface, identifying, with the purpose of shielding the field, the optimal number of elements.

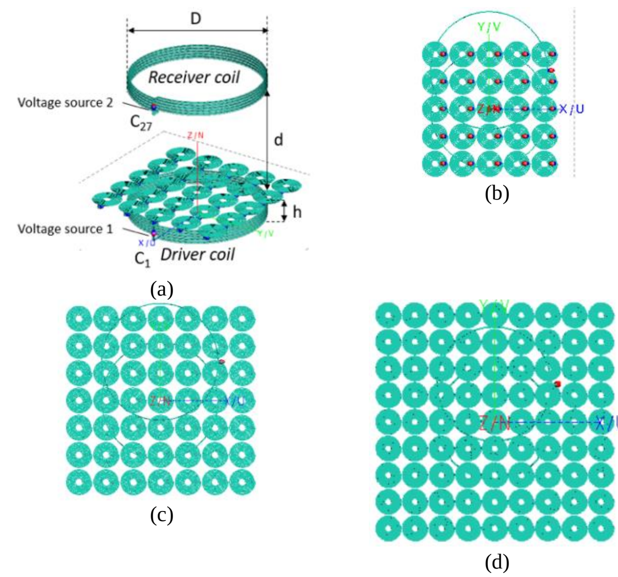

Fig. 1. Geometry of the proposed WPT system: (a) Aligned case. WPT system with 5×5 (b), 7×7 (c), 9×9 (d) metasurfaces and the receiver in misaligned position.

Figure 1 shows the complete system after the design process, leading to an optimal configuration of the metasurface, i.e. a 5×5 matrix of resonators. The geometrical parameters are following described: Tx and Rx diameter, D = 18 cm; metasurface slab thickness, 5 mm; operating frequency, $f_0 = 6$ MHz; slab distance from the transmitter, 1.4cm; distance $d = 16cm$; unit cell average diameter, $d_{cell} = 40mm$. The performance of metasurfaces of different dimensions are compared (system#1: 5×5 elements, system #2: 7×7 elements, system #3: 9×9 elements), and a procedure for the optimization of the loading capacitors value is performed. The analyzed configurations with the presence of a misalignment along y axis direction between the transmitting and receiving coils equal to $D_y = 6cm$, are shown in Fig. 1(b)-Fig.1(d).

III. Methods and Results

The CAD model of the system, as shown in Fig. 1, has been created with a commercial electromagnetic software (Feko suite, Altair, Troy, MI, USA). In the full wave model, each coil of the WPT system (including the unit cells of the metasurface) terminates in a lumped port. The ports of the metasurface elements are, in turn, closed on a lumped capacitor; the port of the driver coil (transmitter) is terminated with a series connection between the generator and the proper resonant capacitor, while the port of the receiver is terminated with the resonant capacitor and resistive load. A single full-wave simulation (for a given operation frequency) allows the characterization of the system as an N-port entity, represented by using the S or Z parameters matrix. The efficiency of the system is calculated as:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{|\dot{I}_2|^2 R_L}{\Re\{\dot{E}\dot{I}_1^*\}} \quad (1)$$

Equation (1) applies to the N-port circuit represented in [5], with $\dot{E} = 1V$ and both the generator and the load resistances R_s and R_L equal to 50Ω. The calculations on the N-port circuit have been carried out by using the Keysight Advanced Design System (ADS) software, according to the following steps: a) evaluation of the performance in case of perfect alignment between transmitter and receiver, with the capacitance value optimized to a specific single nominal value C_{nom} ; b) evaluation of the performances in case of misalignment, with the capacitances C_{nom} set to the nominal value; c) optimization the capacitances, with the goal of maximizing the efficiency level of the system in presence of misalignment.

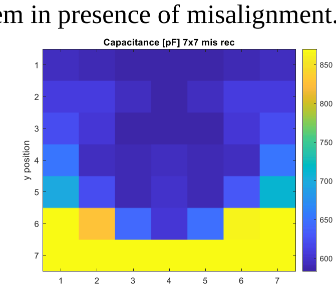

Fig. 2. Values of the tuning capacitors in the metasurface with 7×7 elements.

In all the studied cases, the optimal value of the capacitances that leads to the higher efficiency level is evaluated. Furthermore, for all the reported steps, simulations have been carried out to obtain the efficiency (1) and the power delivered to the load. Finally, the optimization procedure has been set to optimize each single capacitance (Fig. 2 is an axample of capacitance values map in the metasurface). It can be easily noted that in areas of the metasurface not covered by the misaligned receiver, the capacitance assumes a higher value, i.e., the single resonator is characterized by a higher inductive behavior. All the obtained results are summarized in Table I. As it is evident from the values, the optimized capacitances allow a partial recovery both efficiency and the power delivery level.

TABLE I. Efficiency and Power Results

Metasurface size	Step	C_{nom} [pF]	η	P_L [mW]
5×5	a)	585	0.57	0.37
	b)	585	0.49	0.27
	c)	---	0.52	0.36
7×7	a)	598	0.57	0.77
	b)	598	0.52	0.61
	c)	---	0.56	0.59
9×9	a)	607	0.52	1.3
	b)	607	0.48	1.13
	c)	---	0.51	0.59

IV. Conclusions

In this work the authors investigated the use of passive metasurfaces as a tool for the compensation of misalignment in wireless power transfer systems. Starting from a system implemented in the lab, the authors have simulated metasurfaces of different dimensions and verified that, when they are properly designed, the use of passive metasurfaces for misalignment compensation is possible, and constitutes a basis for the designers, evidencing how the size of the metasurface affects the performance of the system.

References

[1] A. K. RamRakhyani, S. Mirabbasi, and M. Chiao, "Design and optimization of resonance-based efficient wireless power delivery systems for biomedical implants," IEEE Trans. Biomed. Circuits Syst., vol. 5, no. 1, pp. 48–63, Feb. 2011.

[2] M. Mohammad, E. T. Wodajo, S. Choi, and M. E. Elbuluk, "Modeling and design of passive shield to limit EMF emission and to minimize shield loss in unipolar wireless charging system for EV," IEEE Trans. Power Electron., vol. 34, no. 12, pp. 12235–12245, Dec. 2019.

[3] S. Barmada, N. Fontana, L. Sandrolini and M. Simonazzi, "Optimal Terminations of 2D Meta-Surfaces for Uniform Magnetic Field Applications," in IEEE Trans. on Magn., doi: 10.1109/TMAG.2022.3231354.

[4] Y. Cho et al., "Thin hybrid metamaterial slab with negative and zero permeability for high efficiency and low electromagnetic field in wireless power transfer systems," IEEE Trans. Electromagn. Compat., vol. 60, no. 4, pp. 1001–1009, Aug. 2018.

[5] D. Brizi, N. Fontana, M. Tucci, S. Barmada and A. Monorchio, "A Spiral Resonators Passive Array for Inductive Wireless Power Transfer Applications With Low Exposure to Near Electric Field," in IEEE Trans. on Electromagn. Compat., vol. 62, no. 4, pp. 1312-1322, Aug. 2020.

[6] T. Liang, S. Barmada, N. Fontana, Y. Xie, D. Brizi, A. Monorchio, "Electromagnetic interferences susceptibility analysis for a metasurface-modified wireless power transfer system", Int. J. Numer. Model. 2022; e3084, doi:10.1002/jnm.3084.