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DESAFIOS DAS ENGENHARIAS:

ENGENHARIA ELÉTRICA 2

JOÃO DALLAMUTA
HENRIQUE AJUZ HOLZMANN
(ORGANIZADORES)

Atena Editora
Ano 2021

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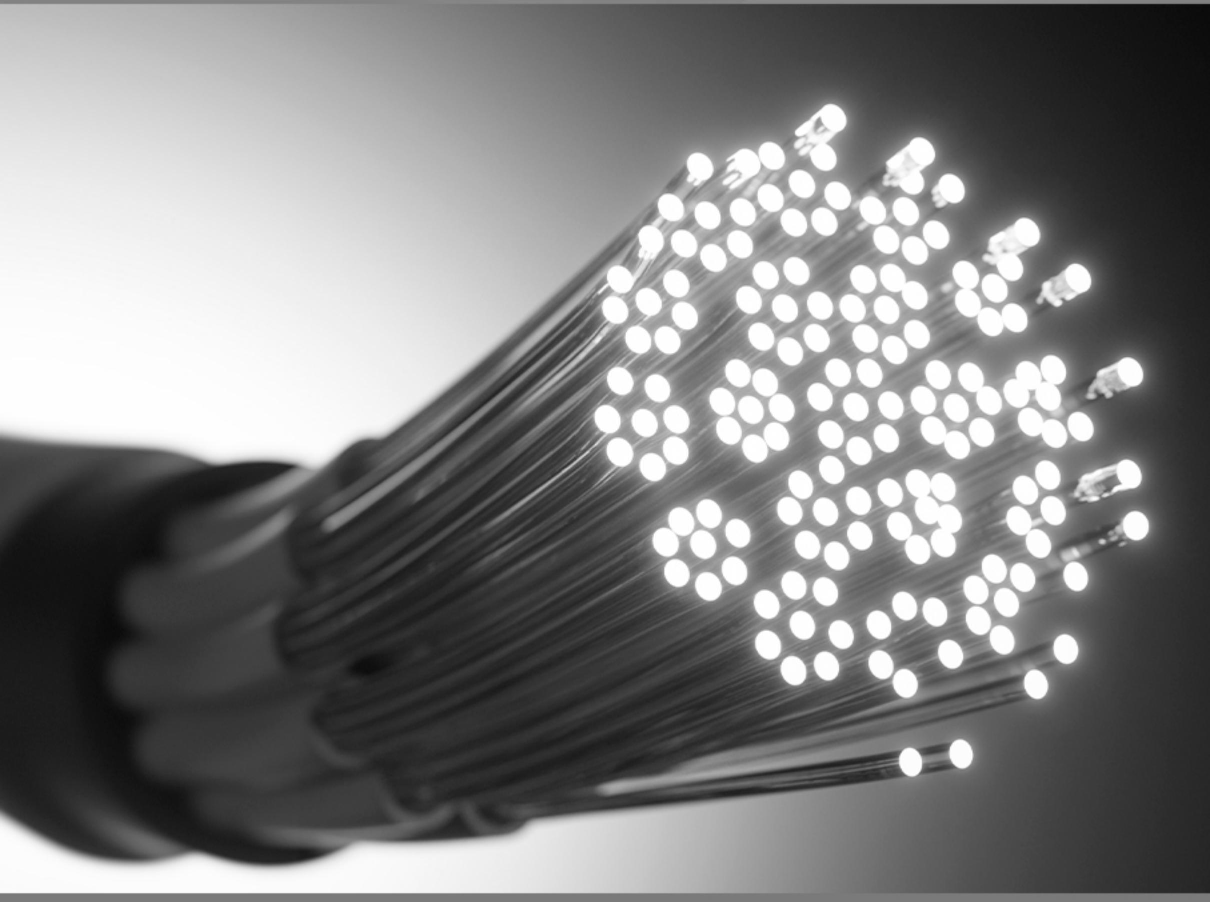

JOÃO DALLAMUTA
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APRESENTAÇÃO

A engenharia elétrica tornou-se uma profissão há cerca de 130 anos, com o início da distribuição de eletricidade em caráter comercial e com a difusão acelerada do telégrafo em escala global no final do século XIX.

Na primeira metade do século XX a difusão da telefonia e da radiodifusão além do crescimento vigoroso dos sistemas elétricos de produção, transmissão e distribuição de eletricidade, deu os contornos definitivos para a carreira de engenheiro eletricista que na segunda metade do século, com a difusão dos semicondutores e da computação gerou variações de ênfase de formação como engenheiros eletrônicos, de telecomunicações, de controle e automação ou de computação.

Produzir conhecimento em engenharia elétrica é portando pesquisar em uma gama enorme de áreas, subáreas e abordagens de uma engenharia que é onipresente em praticamente todos os campos da ciência e tecnologia.

Neste livro temos uma diversidade de temas, níveis de profundidade e abordagens de pesquisa, envolvendo aspectos técnicos e científicos. Aos autores e editores, agradecemos pela confiança e espirito de parceria.

João Dallamuta

Henrique Ajuz Holzmann

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TRANSMISSÃO DE ENERGIA SEM FIO POR MEIO DE ACOPLAMENTO MAGNÉTICO RESSONANTE COM METAMATERIAIS CONVENCIONAIS E SUPERCONDUTORES

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RESUMO: Transmissão de energia sem fio (*Wireless Power Transfer*, WPT) é uma opção de ganho em mobilidade e conveniência enquanto dispositivos elétricos são carregados. Metamateriais são usados para aumentar a eficiência de transmissão da energia por meio de acoplamento magnético ressonante. Um sistema WPT foi implementado em um software capaz de solucionar problemas eletromagnéticos em 3D, onde três configurações foram simuladas: inicialmente sem Metamateriais, com Split Ring Resonators, e com uma linha espiral supercondutora (Metamateriais supercondutores) que foi desenvolvida neste trabalho. Uma investigação da potência e da eficiência destes sistemas foi realizada por meio de simulações. A distância entre as bobinas foi aumentada desde 4 cm até 10 cm, e com desalinhamento horizontal que variou até 3 cm. Os Metamateriais mostraram-se eficientes conforme se pode ver nos resultados.

PALAVRAS-CHAVE: Transmissão de Energia Sem Fio; Acoplamento Magnético Ressonante Forte; Metamateriais; Supercondutividade.

WIRELESS POWER TRANSFER THROUGH COUPLED MAGNETIC RESONANCE WITH CONVENTIONAL AND SUPERCONDUCTING METAMATERIALS

ABSTRACT: Wireless Power Transfer (WPT) is an option to gain mobility and convenience while charging electrical devices. Metamaterials are used to increase the energy transmission efficiency by coupled magnetic resonance. A WPT system was implemented in a 3D electromagnetic solver, where three configurations were simulated: initially without Metamaterials, with Split Ring Resonators, and with a superconductor spiral line (superconducting Metamaterials) that was designed in this work. An investigation of the power and efficiency of these systems was carried out through simulations. The distance between the coils was increased from 4 until 10 cm, and the horizontal misalignment varied up to 3 cm. The metamaterials showed themselves efficient as can be seen in the results.

KEYWORDS: Wireless Power Transfer; Strongly Coupled Magnetic Resonance; Metamaterials; Superconductivity.

1 I INTRODUCTION

MMs are artificial structures effectively homogeneous, that is, their average cell size is much smaller than the wavelength. Because of it, the refractive phenomenon overlaps to the scattering and diffraction in the propagation of the wave [4].

MMs are also called Left-handed materials (LHM) because they do not obey the “right-hand rule”. Furthermore, these elements can present a negative refractive index (NRI), and for that, they can change the behavior of the wave according to the reversal of Snell’s law. In order to obtain an NRI, a metamaterial must have at least the electric permittivity or the magnetic permeability negative in the same frequency range.

The Wireless Power Transfer (WPT) is a technology able to transmit electromagnetic energy from a source to an electrical charge between a gap in the air. It can offer energy to small devices [1], biomedical implants, portable devices, networks sensors, Internet of Things (IoT), robots and electrical vehicles [2].

This technology is an option to replace the traditional methods of transmission by cables. It features advantages over security in low frequency, mobility, and convenience. Furthermore, it increases flexibility on devices whose battery replacement is expensive or dangerous [3].

There are many techniques for WPT, among them the strongly coupled magnetic resonance (SCMR) that was used in this work. This technique works over the magnetic field oscillation between two coupled coils that operate in resonance.

However, the WPT has some problems regarding the cost of implementation and the power decay with distance. The efficiency decay comes from the increase of the distance between the source and load, misalignment between the transmitter and receiver, and inherent problems like radial propagation and reflection.

In order to mitigate losses in WPT, and consequently increase the transmission distance and efficiency, the application of metamaterials (MMs) has been studied. MMs are made by natural elements and can present unnatural properties. When properly arranged and submitted to electromagnetic fields, they work like perfect absorbers.

There are two types of MMs. The “conventional metamaterials”, such as the Split Ring Resonators (SRRs) and the thin wires (TWs), and currently “superconducting metamaterials” have been developed. In these two forms, the MMs have been employed to increase the electromagnetic waves absorptivity capturing the magnetic flux dispersed in the air.

In this work, an investigation of the applicability of metamaterials is made. The behavior of conventional and superconducting MMs in wireless power transfer by strongly coupled magnetic resonance SCMR is evaluated when there are load variation and misalignment. A spiral line of superconducting MM was projected. The system is simulated without MM and with conventional MM. An investigation of the power and efficiency behavior according to the increase in the distance between the transmitter and receiver coils and to the horizontal misalignment between them, for all system configurations, is also made.

Section II presents the theory of conventional and the called superconducting MMs. Section III presents the simulated systems and the design of the superconducting MM unit cell. Section IV presents the results and the Conclusion is in Section V.

2 I METAMATERIALS

MMs are artificial structures effectively homogeneous, that is, their average cell size is much smaller than the wavelength. Because of it, the refractive phenomenon overlaps to the scattering and diffraction in the propagation of the wave [4].

MMs are also called Left-handed materials (LHM) because they do not obey the “right-hand rule”. Furthermore, these elements can present a negative refractive index (NRI), and for that, they can change the behavior of the wave according to the reversal of Snell’s law. In order to obtain an NRI, a metamaterial must have at least the electric permittivity or the magnetic permeability negative in the same frequency range.

A. Conventional metamaterials

Among the so-called conventional metamaterials, there are two very used models: Thin Wires and Split Ring Resonators. The TWs models have a negative electric permittivity, and the SRRs have a negative magnetic permeability. In this work, it is used SRR in simulations because of the SCMR technique, where the magnetic part of the evanescent fields prevails.

The ring resonators have a cut to operate at a resonance frequency in which the wavelength is significantly greater than its diameter.

B. Superconducting metamaterials

The superconducting MMs are different in their constructive characteristics comparing to the conventional ones. To exhibit superconducting behavior, the material must be below the critical temperature (), when the MM can present the Meissner effect and have its resistivity considerably reduced and no magnetic flow inside the conductor.

Low losses are achieved in superconducting MMs, higher quality factor, and smaller wavelength when compared with the conventional MMs [5]. Furthermore, superconducting MMs can be miniaturized, and then they can be applied in small and medium-sized devices.

In this paper, the two types of metamaterials and their respective behaviors in the simulated system of WPT are investigated.

3 I SIMULATED SYSTEMS

This section are presented the general data for the three system configurations simulated. In this work, a superconducting metamaterial unit cell was also projected.

A. General data

The system was simulated on CST® Studio software using the Finite Integration Technique (FIT) in time domain. The transmitter and receiver copper coils are flat and have 7 loops, width of 2.49 mm, spacing of 1.0 mm, inner radius of 22 mm, outer radius of 47 mm. Furthermore, this system has an inductance of 4.73 μH, relative electrical permittivity () of 4.3, tangent loss (δ) of 0.015, as shown in Fig. 1. These data and geometry were obtained in [6]. These coils are in an Flame Retardant 4 (FR4) substrate with dimensions of 100 mm x 100 mm x 1.5 mm.

In the transmitter coil was used a discret port of voltage, defined by a starting point and an endpoint. These two points were connected by a perfectly conducting wire (visualized by a thick blue line) and the respective port source (indicated by a red cone) in the center of this wire, as shown in Figures 1 and 2. This port type realizes an ideal voltage source, exciting with constant voltage amplitude. This discret port is used in all simulations, c.a., with a peak voltage of . In the receiver coil, a resistor of 100 Ω is used (in the without misalignment simulations between the coils).

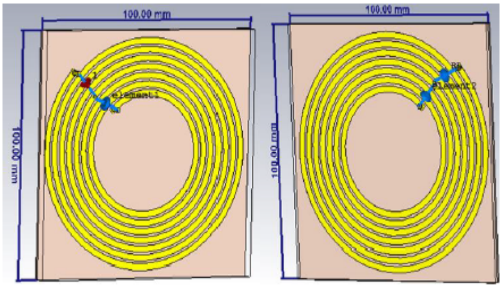

Fig. 1. (a) Transmitter coil (b) Receiver coil.

The operating frequency in which the system was projected is 1 MHz. In this frequency, there are many applications in WPT such as self-resonant structures [7] and biomedical implants [8].

The percentage efficiency (η %) can be calculated through the relation between the load power ($\mathcal{P}_L$) and source power ($\mathcal{P}_s$), both in watts:

$$\eta\ (\%) = \frac{P_L}{P_s} \cdot 100\% \tag{1}$$

B. SCMR without any Metamaterial

Initially, the system was simulated with the transmitter and receiver coils with only air between them, as shown in Fig. 2.

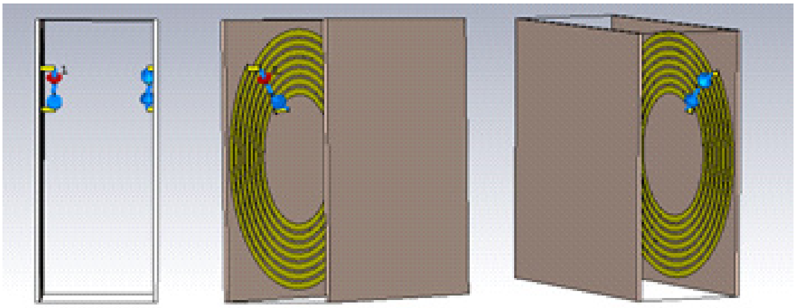

Fig. 2. SCMR system without metamaterial: (a) Complete system. Lateral view showing details of transmitter coil (b) and receiver coil (c).

C. SCMR with conventional metamaterial

The SRR model simulated in this work is based on the prototype of [4]. The metamaterial slab has 12 unit cells arranged in 3 columns and 4 lines, 300 cm² in total and it is placed at halfway between the coils, as shown in Fig. 3.

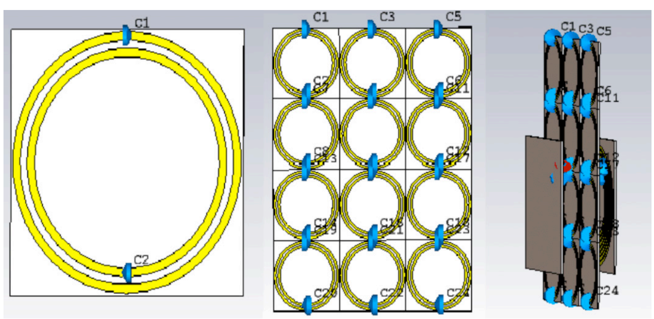

Fig. 3. SCMR system without metamaterial: (a) Complete system. Lateral view showing details of transmitter coil (b) and receiver coil (c).

Every unit cell of the slab has two copper rings presenting width of 1.63 mm, spacing of 1.47 mm, height of 0.02 mm, inner radius of 19.87 mm, with overall of 50 mm x 50 mm x 1.5 mm and one capacitor of 47 nF in each ring.

D. Design of the Superconducting Metamaterial Unit Cell

A superconductor unit cell was designed in this work. Its dimensions were reduced when compared with conventional MM. The substrate of has dielectric constant of 25, tangent losses (δ) of 0.0005, and critical current density of in 77 K. Furthermore, its dimensions were defined with an average size much smaller than the wavelength to respect the effective homogeneity principle [4]. The dimensions for every cell are 40 mm x 40 mm x 0.5 mm, and the area of the whole slab is 144 cm² (9 unit cells in 3 lines and 3 columns, 52% lower the conventional slab simulated), as shown in Fig. 4.

The superconductor metamaterial has a spiral line geometry of YBCO, a superconductor material that generally is used in a critical temperature of 90 K. After the definition of the unit cell, the dimensions of the spiral line were defined after computer simulations and analysis: an outer radius of 38 mm and an inner radius of 2 mm.

The equivalent circuit of a superconducting MM is an RLC circuit and it is necessary to place capacitors to achieve the resonance. From [9] we have:

$$C(pF) = 0.035D_o(mm) + 0.06 \quad (2)$$

where C is the capacitance in pF, with a value of 1.39 pF in this case.

After that, the geometric inductance ($\mathcal{L}_g$) was defined from:

$$f = \frac{1}{2\pi\sqrt{L_g C}} \quad (3)$$

obtaining $\mathcal{L}_g$ = 0.0182 H, where f is the resonance frequency.

The number of loops ($\mathcal{N}$) of the spiral conductor is determined by:

$$N = \sqrt{\frac{2L_g\left[\left(\frac{2.46}{a} + 0{,}2a^2\right)\right]}{D_{avg}\mu_0}} \quad (4)$$

where the factor a is:

$$a = \frac{(D_o - D_i)}{(D_o + D_i)} \quad (5)$$

In (5) $\mathcal{D}_o$ is the outer diameter, $\mathcal{D}_i$ is the inner diameter and the average diameter is calculated as:

$$D_{avg} = \frac{(D_o - D_i)}{2} \quad (6)$$

It was obtained N = 43.37, which was considered N=43. The designed unit cell is shown in Fig. 4 (a) and the complete system in Fig. 4 (b).

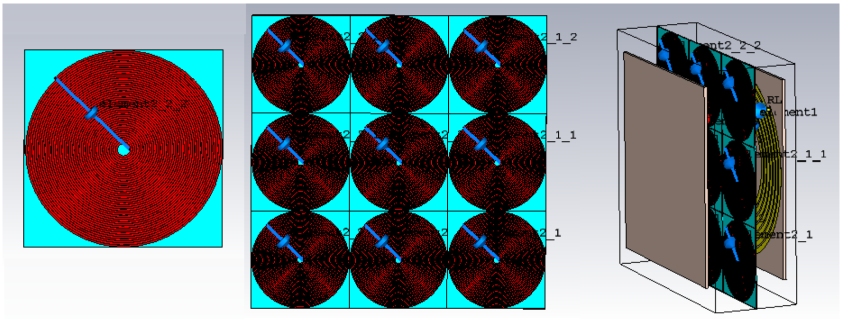

Fig. 4. Unit Superconducting MM: (a) Unit cell (b) Slab of superconducting metamaterial (c) Complete System.

4 I RESULTS

In this work, a transmission-line (TL) network periodically loaded using

The results of the simulations and the comparison between them are presented in this Section. The system was simulated without MM, with Conventional and Superconducting MM.

A. Comparison of the configurations without misalignment

The distance between the coils varied from 4 cm to 10 cm. The system was simulated without MM, and with conventional and superconducting MM. The comparison can be seen in Fig. 5.

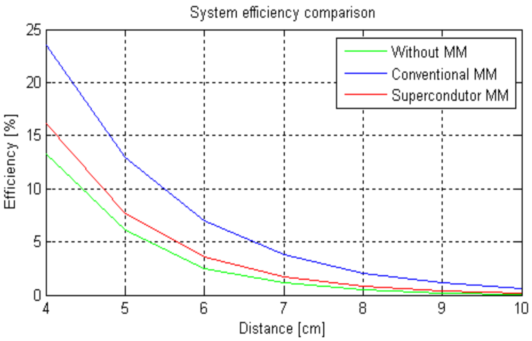

Fig. 5. Efficiency comparison.

The best results were at 4 cm of distance between the transmitter and receiver coil. Without the MM, the power in the load resistor was 45.14 W, and the efficiency of 13.23%.

With the conventional metamaterial, the power in the load was 69.59 W and efficiency of 23.46% in the transmission, as shown in Table I. There was an increase of 77.32% in the efficiency and 54.16% in the power after inserting the conventional MM.

In the presence of the superconducting metamaterial, the efficiency was 16.11% (an increase of 21.76%) and the power was 49.34 W (an increase of 9.30%) when compared to the simulations without metamaterial.

The MMs were responsible to direct the disperse magnetic flux. Both types of MM were able to increase the power flux and transmission efficiency.

1 MHz	**Without MM**		**Conventional MM**		**Superconduct. MM**	
Distance (cm)	P (W)	η (%)	P (W)	η (%)	P (W)	η (%)
4	45.14	13.23	69.59	23.46	49.34	16.11
5	21.03	6.12	48.00	18.64	23.10	7.65
6	8.86	2.52	24.15	14.62	10.71	3.63
7	3.99	1.13	13.61	10.75	4.97	1.73
8	1.66	0.47	7.21	7.44	2.32	0.82
9	0.64	0.18	4.07	5.54	1.09	0.39
10	0.26	0.07	2.34	4.17	0.51	0.19

Table 1 - Efficiency and power comparison.

B. Comparison of the configurations with misalignment

An investigation was carried out on the horizontal misalignment between the transmitter and receiver coils. It is important in cases where there is no absolute certainty about the position of the recipient (biomedical implants, for example). The coils were initially with their centers 4 cm apart and then there was a horizontal displacement from 1 to 3 cm, as shown in Fig. 6. The simulations, again, occurred without MM, with the conventional and superconducting MM and there was a comparison between them.

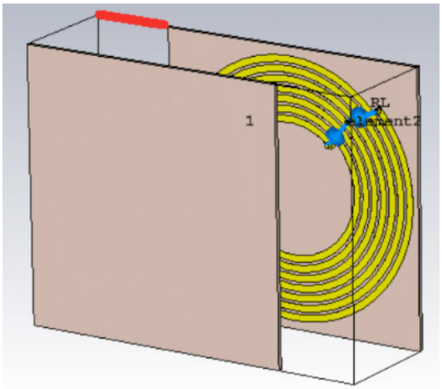

Fig. 6. Displacement of the receiver unit.

The system efficiency shows an increase after the insertion of the metamaterial as can be seen in Fig. 7.

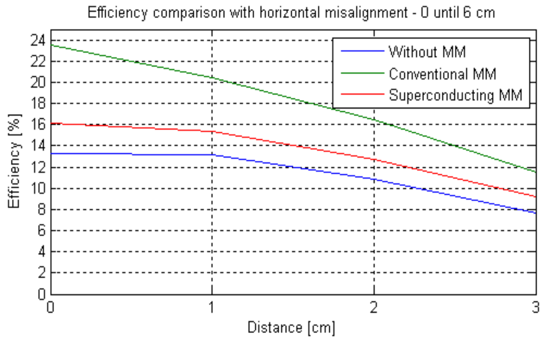

Fig. 7. Efficiency comparison with misalignment between coils.

Even with 3 cm of displacement, the efficiency was increased with metamaterials: 49.41%, from 7.67 to 11.46% with the conventional and 20.33%, from 7.67 to 9.23% with the superconductor, as shown in Table II.

1 MHz	Without MM	Conventional MM	Superconduct. MM
Misalignment (cm)	η (%)	η (%)	η (%)
0	13.23	23.52	16.11
1	13.14	20.45	15.33
2	10.81	16.51	12.69
3	7.67	11.46	9.23

Table 2 - Efficiency and power comparison with misalignment.

Although the system is very sensitive to the misalignment, it still presents a better efficiency compared to no MM setup. Thus, the MM was able to increase efficiency in wireless power transfer even with horizontal misalignment between coils.

5 I CONCLUSION

After inserting the two configurations of MMs and comparing their results with the simulations without MM, it was verified an increase of 77.32% and 21.76% in the efficiency with conventional and superconducting respectively. Even with a horizontal misalignment of 3 cm between the transmitter and receiver coils the efficiency was also increased after inserting the MM.

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