

New Optimization Process of a Magnetic Coupler with Three Resonant Solenoid Coils for Wireless Power Transfer

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The growing use of wireless power transfer technology demands the development of fast and optimized computational strategies for executing complex designs. In recent years, full-wave methods have gained prominence for their ability to provide accurate results in optimizing electrical parameters and coil geometries. However, these methods often face challenges due to the high computational cost associated with handling large matrices. In this context, this work proposes a novel optimization methodology based on circuit theory for a new wireless power transfer system utilizing three solenoidal resonant coils. This system stands out by the inclusion of an intermediate coil that directs the magnetic field from the transmitter to the receiver. The results demonstrate that the proposed optimization significantly reduces computational time without compromising accuracy in input impedance and scattering parameters. The proposed methodology thus offers a precise and computationally efficient solution, with the new coil geometry achieving a high energy transfer rate.

Index Terms—Wireless power transfer, optimization, coils, solenoid, resonance.

I. INTRODUCTION

WIRELESS Power Transfer (WPT) is a widely recognized research field that has gained popularity due to its diverse applications. Recent technological advancements include powering implantable biomedical devices, charging batteries for electric vehicles and drones, and supplying energy to Internet of Things (IoT) devices in hard-to-reach locations [1]-[2]. The standard configuration consists of a transmitter coil and a receiver coil, both tuned to the same resonant frequency and magnetically coupled, with external capacitors added to each coil to ensure resonance [3].

Several methods have been proposed to optimize WPT systems, enabling the design of systems with specific characteristics, such as ideal impedance matching and high efficiency [4]. Traditional methods often rely on numerical solutions to Maxwell Equations, achieving high accuracy at the expense of significant time and computational effort. Alternatively, new formulations are being explored to reduce computational effort and support customized geometric designs [1].

This study introduces a novel optimization process that combines high precision, rapid execution, and minimal computational resource usage, offering performance comparable to commercial software and enabling the complete design of a resonant magnetic WPT system. The optimization is applied to an innovative configuration comprising three coils: a transmitter (1), an intermediate guiding coil (2), and a receiver coil (3). The inclusion of an intermediate solenoid-shaped coil establishes a magnetic pathway between the transmitter and receiver coils, enhancing energy transfer efficiency.

II. MODELING AND OPTIMIZATION

The mathematical modeling of the resonant magnetic WPT system is carried out using circuit theory, where each coil is

modeled in series by its resistance (R) and self-inductance (L), associated with an external capacitance (C) in series. The magnetic coupling between the coils is characterized by mutual inductance (M). The flowchart in Fig. 1 illustrates the proposed new optimization process (NOP) that is implemented in Julia Programming Language. This process operates on the individual reactance of each coil comprising the circuit model and subsequently on the input resistance to determine the ideal input impedance (Z_i) as defined by Equation (1), where V_s is a input voltage, $Z_{m=n} = R_m + j\omega L_m + \frac{1}{j\omega C_m}$ is the impedance of each coil and $Z_{m \neq n} = j\omega M_{mn}$, where m and n represent it coils. The scattering parameters S_{11} and S_{21} are calculated with Equation (2), where Z_p is a standard impedance of 50Ω [5].

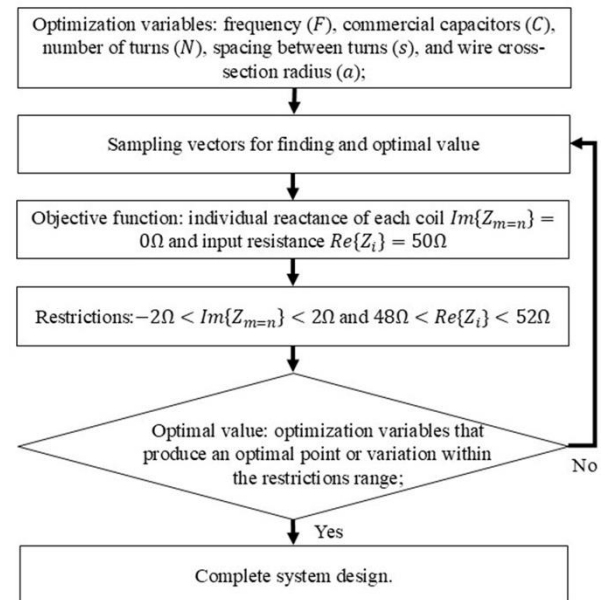


Fig. 1 – New optimization process.

$$Z_i = \frac{Z_{11}Z_{22}Z_{33} + 2(Z_{12}Z_{23}Z_{31}) - Z_{11}Z_{23}^2 - Z_{22}Z_{13}^2 - Z_{33}Z_{12}^2}{(Z_{22}Z_{33} - Z_{23}^2)} \quad (1)$$

$$S = \begin{bmatrix} 1/(2\sqrt{Z_p}) & 0 \\ 0 & 1/(2\sqrt{Z_p}) \end{bmatrix} \left(\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} - \begin{bmatrix} Z_p & 0 \\ 0 & Z_p \end{bmatrix}^* \right) \times \left(\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} + \begin{bmatrix} Z_p & 0 \\ 0 & Z_p \end{bmatrix} \right)^{-1} \begin{bmatrix} 1/(2\sqrt{Z_p}) & 0 \\ 0 & 1/(2\sqrt{Z_p}) \end{bmatrix}^{-1} \quad (2)$$

III. RESULTS

The results obtained through the NOP are presented in Fig. 2, along with the geometric design of the system coils. The obtained input impedance was $Z_i = 50.73 + j0.17 \Omega$, and the scattering parameters S_{11} and S_{21} were -37.99 dB and -0.41 dB at the resonant frequency $f = 423 \text{ kHz}$. The validation of the optimized system is carried out using the commercial software Studio Suite (CST ®), where the input impedance, scattering parameters, execution time, RAM consumption, and processor usage are compared.

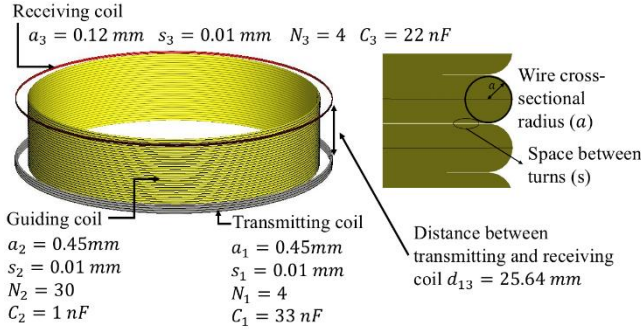


Fig. 2 - System design after optimization.

The input impedance and scattering parameter results are presented in Fig. 3 and 4, respectively. It is observed that the results obtained through the NOP show overlap with the CST results across the analyzed frequency range. This characteristic demonstrates that the circuit theory modeling was effective when compared to the Finite Element Method executed in CST. Furthermore, in Fig. 4, the high S_{21} value indicates a high-energy transfer rate, highlighting the strategic use of the guiding coil.

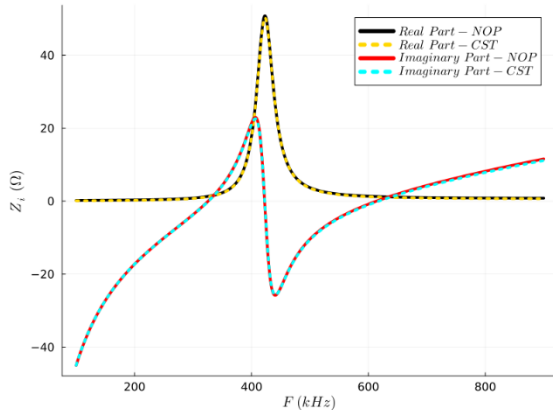


Fig. 3 - Input impedance

Regarding computational performance, the NOP and graph generation were executed in 638 seconds, while CST software required 1973 seconds just to analyze the pre-configured system and produce the graphical results, which is three times longer. The processor and RAM usage for the Julia implementation were 36% and 10.9%, respectively. CST showed 61.8% processor usage and 33.9% RAM consumption. These numbers indicate a low computational resource usage for the NOP with circuit-based modeling, compared to the CST software that employs the Finite Element Method.

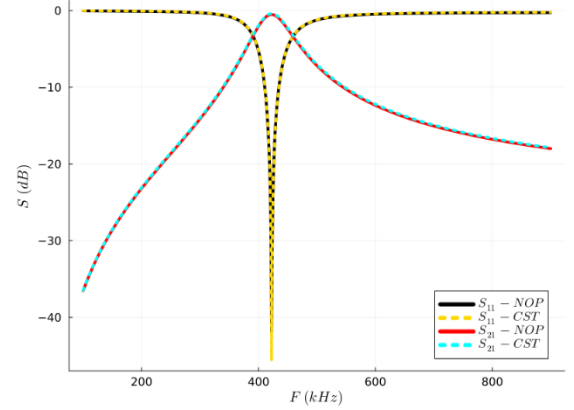


Fig. 4 - S parameters.

The comparison of input impedance results and scattering parameters reveals the fidelity and physical consistency of the circuit model in relation to the numerical method applied by CST. Furthermore, the versatility of the new optimization process, combined with its low computational resource consumption and reduced execution time, allows it to be used as an effective tool in the design of resonant magnetic WPT systems. The guiding coil performs as expected, providing a path for the magnetic coupling between the transmitter and receiver coils, thereby increasing the energy transfer rate.

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