A Computational Approach for a Wireless Power Transfer Link Design Optimization Considering Electromagnetic Compatibility

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This work proposes an electromagnetic-artificial intelligence design optimization approach of a Wireless Power Transfer link (WPTL), while utilizing the electromagnetic solutions to minimize the magnetic field density of each design attained in the optimization search space and thus allowing for attaining an optimized design electromagnetically compatible with international standards. Besides, because this design optimization requires the use of large number of iterations utilizing 3D Finite Element (3DFE) analysis, Artificial Neural Networks (ANN) are used to significantly reduce the electromagnetic computational time.

***Index Terms*—Finite Element Analysis, Electromagnetic Compatibility, Neural Networks, Genetic Algorithm, Optimization**

I. INTRODUCTION

PUBLIC perception in real-world applications is moving towards using WPT in the context of electromagnetic resonance. Several applications have been presented in literature, such as charging of batteries in consumer electronics and electric vehicles. In the initial design phase of any application, the undesirable effects on the human body caused by the interaction with the magnetic fields must be considered. Since shielding of low frequency signals for human body protection is difficult, the WPTL should be designed with low electromagnetic emissions [1], meeting the ICNIRP 2010 [2] and IEEE Std. C95.1-2005 standard. Compared with the IEEE Std. C95.1-2005 whose maximum permissible exposure of head and torso for general public is 205 μT, the ICNIRP 2010 standard is still more conservative, where the reference level for general public is 27 μT. For demonstrating compliance of the WPT system with EMC standard requirements, mathematical modeling using 3D software is needed to predict the magnetic field densities around the device.

Several approaches for the analysis of wireless power transfer systems have been presented in literature. An example of the analytical approach was presented in [3], where the authors treat the WPT scheme as a two-port network and analyze the model using the coupled mode theory. In addition to this analytical approach, there are many other applications including experimental and numerical approaches. Electromagnetic emissions of the WPTL is a point of interest in this paper. A numerical approach of coupled 3DFE analysis and circuit theory will be combined to provide a simple and accurate solution for both efficiency calculations and minimizing the field density around the WPTL to achieve the ultimate objective of complying with EMC standards at the design stages. In addition, because this design optimization requires the use of large number of iterations utilizing 3D Finite Element (3DFE) analysis, Artificial Neural Networks (ANN) are used to significantly reduce the electromagnetic computational time. The AI portion involves Neural Networks and Genetic Algorithms (GA). The objective is to maximize the efficiency and minimize the field density around the WPTL with the constraint applied on the power obtained as output in the circuit after the compensation network that imposes resonance.

II. CO-SIMULATION OF 3DFE DESIGN AND LUMPED CIRCUIT MODEL

Through the 3DFE model, a virtual WPT experiment via resonant magnetic field for parameter extraction can be performed. The geometry used for the investigation is a practical transmission system setup consisting of two stranded circular loop coils, resonating at the same frequency and lumped in an equivalent circuit of a magnetic resonant coupling wireless power transfer setup. It should be noted that the modeled coil in the FE domain is an excellent approximation of a stranded coil (Litz coils) [4]. This allows significant decrease of the undesirable ac resistance caused by the skin effect which is a usual consequence of frequency level in the application at hand.

Since the power system under study is smaller than 1/10th of the dimension of the wavelength, it can be represented as a lumped-parameter system in which circuit theory can be used to analyze its behavior [5]. The NN training data, obtained from 3DFE simulation, were verified using a lumped-circuit model.

The circuit, with the parallel-parallel compensation network, is shown in figure 1 as used in the FE software, where the coils CoilT and CoilR represent the circuit parameters of the 3DFE modeled coils. The current source and the capacitors are modeled as ideal components in this electric circuit simulation. Figure 2 shows the Electromagnetic Model of the WPTL in the 3DFE.

In addition, with the resonance frequency and the equivalent series resistance (ESR) of the coils being key design parameters [1], the two variables taken into account in this optimization are the resonance frequency and the number of turns, which directly affects the ESR.

III. AUTOMATED MATLAB-FE ROUTINE

At each combination of the 2 parameters, a series of steps linking MATLAB and the FE model are automated. By applying a small current to one of the coils and then performing static analysis, the flux linking the coil, and thus the self-inductance L of each of the two coils is obtained since they are identically modeled.

A time harmonic analysis is performed and the mutual inductance M obtained by taking the ratio of the magnetic flux through the second coil generated by the first current-carrying coil and the magnitude of the current applied to the first coil. Also, the total power loss of the single coil is obtained from the solver results, thus obtaining the parasitic resistance R of the coil, respectively. In addition, the magnetic field density at a 3 critical points is obtained. Biot-Savart law and the inversely proportional rule can be utilized to obtain the magnetic field density at the distances required, even if it is out of the boundary of the solution generated. After the circuit parameters are obtained, the value of the resonant capacitors C are calculated according to equation (1) to achieve the set resonant frequency. The efficiency is calculated based on (2).

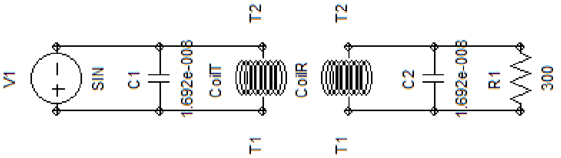

Fig.1. Electric Circuit Model of the WPTL in the 3D FE software

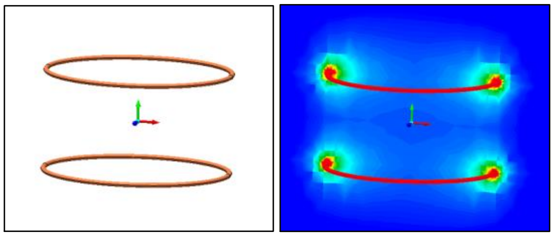

Fig.2. EM Model and Magnetic Field Distribution of the WPTL in 3DFE

$$C = C_1 = C_2 = \frac{1}{L\,{\omega_0}^2} \tag{1}$$

$$\eta = \frac{P_{R_L}}{P_{in}} \times 100\% \tag{2}$$

IV. THE EM-AI OPTIMIZATION APPROACH

In this paper, the ANNs are used to determine the efficiency of a WPTL, the output power, and the values of the magnetic field density of the design at different locations in the model. The ANN approach is selected due to its ability to capture the nonlinear patterns observed in the data sets and re-estimate the outputs at different inputs. The used ANN are based on feed-forward architecture with back propagation training algorithm [7]. The smallest possible size of the ANN will be attained to reduce the computational burden. The effectiveness of using the ANN in the proposed EM-AI design optimization in this work is demonstrated in Table I, which shows an 89% decrease in the computational time needed. The 6.56 hours are mainly the time needed for preparing the training data set of the ANN, using the FE-MATLAB routine presented in section III. The flowchart of figure 3 describes the full optimization process. The optimum design reached is verified using the FE-MATLAB routine.

TABLE I
COMPARISON OF COMPUTATIONAL TIME FOR THE EM-AI DESIGN OPTIMIZATION APPROACH WITH AND WITHOUT NN UTILIZATION

Number of Iterations	Time Without NN	Time With NN
800	60 hours	6.56 hours

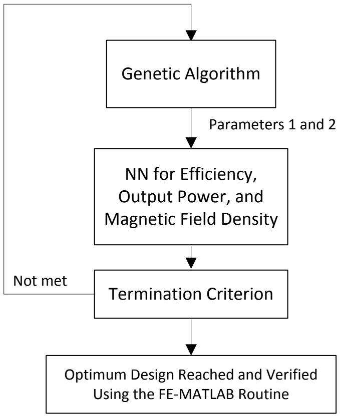

Fig.3. Optimization Procedure

TABLE II
OPTIMUM POINT FROM GA

Number of Turns	Freq (kHz)	Eff (%)	B1 (μT)	B2 (μT)	B3 (μT)	Pout (W)
4	136	96.2	9.36	2.53	5.76	177

V. CONCLUSION

An EM-AI design optimization environment was developed and applied in a case-study to maximize the efficiency of a WPTL and minimize the field density around the WPTL with the constraint applied on the power obtained as output in the circuit. In addition, with the use of ANN, the computational time required for the EM-AI optimization of the WPTL was reduced by 89% for a GA search space with 40 generations, 20 individuals.

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