

AI-Based Design Optimization Environment for EV DWPT Chargers

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This paper presents a characterization and design optimization environment suitable for Electric Vehicle (EV) Dynamic Wireless Power Transfer charging systems. It utilizes a Particle Swarm Optimization search algorithm and Artificial Neural Networks. The system identifier employs electromagnetic 3D Finite Element and State Space models, and it is used in a case study of an EV Dynamic Wireless Power Transfer charging system with multi-ground transmitter coils and a receiver coil.

Index Terms—EV Wireless Power Transfer, 3D Finite Elements, State Space, Particle Swarm Optimization, Artificial Neural Networks.

I. INTRODUCTION

The growing interest in inductive Dynamic Wireless Power Transfer (DWPT) as a potential solution for charging Electric Vehicles (EVs) while in motion has prompted extensive research for developing and optimizing DWPT charging systems. This work presents a characterization and design optimization environment using Particle Swarm Optimization (PSO) search algorithm. As can be appreciated, design optimization problems necessitate evaluating numerous design points to reach an optimal design. Typically, computational electromagnetics is employed to predict performance characteristics, requiring extensive computational time [1]. To address this challenge, this paper presents an FE-SS based characterization environment to predict the performance characteristics in addition to a design optimization environment that utilizes a ANN-PSO search algorithm. It is implemented to optimize the design of a DWPT system in terms of output power, system efficiency, and electromagnetic field (EMF) leakage under a range of misalignment conditions.

II. DWPT SYSTEM CHARACTERIZATION AND DESIGN OPTIMIZATION ENVIRONMENT

The schematic of the design optimization environment is given in Fig. 1. It is implemented in a case study to optimize the design and improve the performance characteristics of a DWPT charging system. The DWPT system, shown in Fig. 2, includes multi-transmitter pads (ground-side coils) embedded in the road and a receiver pad (EV-side coil) located beneath the EV. The particulars of the transmitting and receiving pads or magnetic couplers are shown in Fig. 3. The proposed design optimization environment comprises three computational stages. Initially, a DWPT characterization module is developed, including a 3D FE-SS model to predict the performance characteristics of DWPT systems for a given design vector (I_{Design}). Next, the FE-SS model is used to train, offline, an ANN model, which is used as a system identifier. The input vector of the ANN model is the vector I_{Design} . The output is a set of performance indicators used online with the PSO algorithm to evaluate a design objective function (OF) corresponding to the design vector in a search space.

The DWPT system characterization environment model utilizes a 3D-FE analysis that accounts for the material nonlinearity to estimate the windings' self and mutual inductances as function of load conditions and position. These computed self and mutual

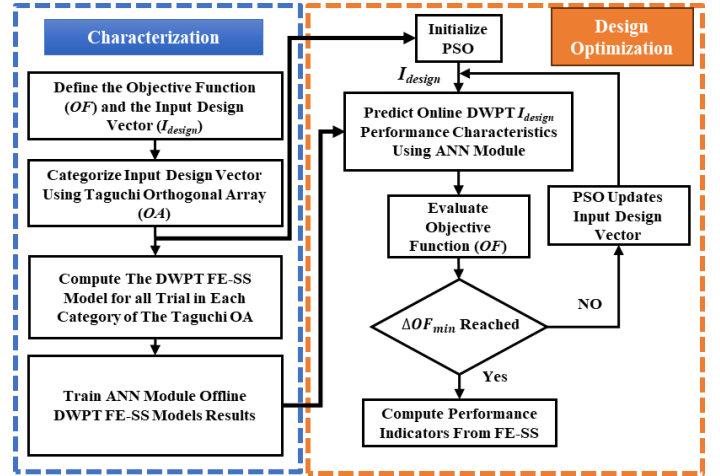


Fig. 1. Design Optimization Environment Schematic.

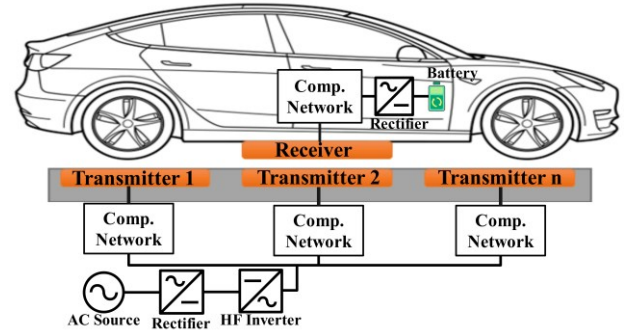


Fig. 2. DWPT system configuration.

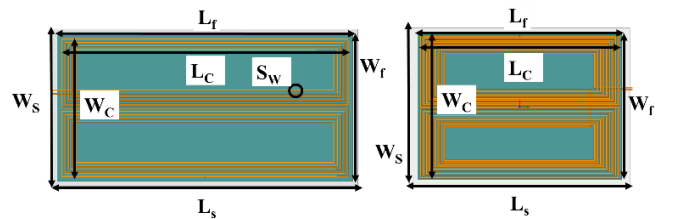


Fig. 3. Double-D transmitter/receiver charging pads top view.

inductances are subsequently used with the DWPT state space model, equation (1), to predict the system's performance characteristics for specific operating conditions [2]. The SS model is given in (1) and corresponds to a DWPT system with a receiver coil denoted as R and a transmitter coil designated as T . Also, v_R and v_T are the receiver and transmitter coil voltages, i_R and i_T are the receiver and transmitter coil currents. The coil resistances are

indicated by r , and the self and mutual inductances are denoted by L , using proper subscripts. Furthermore, the converters and compensating networks shown in Fig. 2 are interfaced to equation (1) through the voltage vector.

$$\begin{bmatrix} v_T \\ v_R \end{bmatrix} = \begin{bmatrix} r_T & 0 \\ 0 & r_R \end{bmatrix} \begin{bmatrix} i_T \\ i_R \end{bmatrix} + \begin{bmatrix} L_{TT} & L_{TR} \\ L_{TR} & L_{RR} \end{bmatrix} \frac{d}{dt} \left\{ \begin{bmatrix} i_T \\ i_R \end{bmatrix} \right\} + \frac{d}{dt} \left\{ \begin{bmatrix} L_{TT} & L_{TR} \\ L_{TR} & L_{RR} \end{bmatrix} \right\} \begin{bmatrix} i_T \\ i_R \end{bmatrix} \quad (1)$$

III. DESIGN OPTIMIZATION APPLICATION AND RESULTS

The proposed optimization environment utilizes a PSO search algorithm that emulates a flock of birds. The PSO starts with an initial swarm of random particles in the search space, where each particle is also assigned a randomized velocity. The velocity of each particle is dynamically updated based on the particle's best previous position reached and the best position reached among previous generations [3]. The PSO uses the ANN model to evaluate the objective function corresponding to any values of the design vector in the search space. As can be appreciated from the above, a large number of FE solutions and PSO iterations are required to find an optimum design. As such, a Taguchi algorithm (Fig. 1) is used to reduce the computational time needed to reach an optimum design. The Taguchi orthogonal array used in this work is of the three-level L27 orthogonal array type [4], which is used to determine the minimum number of input design parameter combinations required to cover the design optimization problem search space. The method assigns a range for each input design parameter and divides each range into equal intervals.

The design optimization environment was implemented in the case of a DWPT system with one receiver coil R and a transmitter coil T .

The optimization problem objective function, OF, used in this work is as follows:

$$OF = w_1 \frac{1}{\eta_E} + w_2 \frac{1}{E_{out}} + w_3 C_{total} + w_4 EMF \quad (2)$$

where w_1 , w_2 , w_3 , and w_4 are the optimization weights. The OF is used to maximize the transmitted energy efficiency (η_E) and transmitted energy (E_{out}) and to minimize total magnetic couplers material cost (C_{total}) and the electromagnetic field (EMF) leakage inside the EV.

The transmitted energy efficiency (η_E) is defined as the ratio of the output energy to the input energy, and the output transmitted energy (E_{out}) is calculated by integrating the output power over the operational time or distance:

$$E_{out} = \frac{1}{velocity} \int_{x(0)}^{x(end)} P_{out}(x) dx \quad (3)$$

where the *velocity* is the EV speed and x is the EV relative position to the transmitter.

Sample results are given in Table I, which shows the performance indicators of an optimized design using the proposed environment of Fig. 1, as compared to an initial design. An inspection of Table I reveals that the DWPT system energy efficiency (η_E) improved by 14.34%, and the transmitted energy (E_{out}) increased considerably by 89.32%. Moreover, the

total system cost (C_{total}) was reduced by 4.87%. In terms of electromagnetic field (EMF) leakage inside the EV, the optimized design reduced the maximum EMF leakage from 16.1 μT to 6.7 μT , thus complying with the safety standards for living humans and medical devices [4].

TABLE I
WPT INITIAL AND OPTIMIZED DESIGNS

Output	Initial Design	Optimized Design	Change (%)
η_E (%)	57.2	65.4	14.34
E_{out} (kJ)	0.88	1.666	89.32
C_{total} (\$)	6630	6307	-4.87
EMF (μT)	16.1	6.7	-58.39

In addition to the above, Table II summarizes each model's computational time, expressed in hours (h), under three different optimization frameworks. Implementing the optimization environment illustrated in Fig. 1 using the ANN-PSO-Taguchi method significantly reduced the computational cost compared to using the ANN-PSO and PSO-FE-SS directly for objective function (OF) evaluation. The proposed ANN-PSO-Taguchi approach required approximately 292 hours, indicating an estimated 99% decrease in computational time relative to directly using the FE-SS model as the system identifier during the optimization process.

TABLE II
COMPUTATIONAL TIME COMPARISON

Model	ANN-PSO-Taguchi (h)	ANN-PSO (h)	PSO-FE-SS (h)
FE-SS	292	66,682	153,368
ANN	4	13.74	-
PSO	4.1e-3	4.1e-3	4.1e-3
Total	297	66,696	153,368

IV. CONCLUSION

An AI-based design optimization environment is presented using 3D FE-SS models and a PSO search algorithm. It is successfully applied in a DWPT charging system case study with ground transmitter coils and an EV receiver coil to improve the system's performance characteristics. Employing this design optimization approach enhanced the system energy efficiency, increased the transmitted energy, lowered the overall system cost, and reduced EMF leakage inside the EV. Furthermore, integrating ANN-PSO with Taguchi reduced the total computational time by about 99% compared to directly using an FE-SS model, thus demonstrating the feasibility of the proposed method for large-scale design optimization studies.

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