

Coil Design Multi-Objective Optimization of Power Pad in IPT System for Electric Vehicle Applications

Ahmed A. S. Mohamed, Siguang An, A. A. Marim, *Members IEEE* and Osama Mohammed, *Fellow, IEEE*

Energy Systems Research Laboratory, Department of Electrical and Computer Engineering, Florida International University, Miami, FL 33174 USA

The proper magnetic design is one of the most difficult and critical phases in developing inductive power transfer system (IPTS), especially in electric vehicle (EV) charging. In this paper, a fast and an efficient improved Tabu search (ITS) algorithm coupled with 2D finite element analysis (FEA) was used to determine the optimum design parameters of power pads. A multi-objective optimization was achieved considering several objective function such as magnetic coupling, misalignment (horizontal, vertical and rotational) as well as the cost. The double-D pad structure was considered as a case of study and the most effective design parameters were obtained. The 2D-FEA was used to calculate the coupling factor at different misalignment conditions and the electromagnetic field emission (EMF), which must comply with standard limits. For verification purposes, an 8 kW IPTS for EV applications was developed in a simulation environment. A laboratory scale prototype was built for experimental verification as well. The optimization results were verified by means of simulation and experimentally. The results proved the validity and advantages of the proposed method.

Index Terms—Coil design, electric vehicle (EV), Tabu optimization, inductive power transfer (IPT).

I. INTRODUCTION

INDUCTIVE power transfer is a technology which could set the human free from the inconveniences of wires. It is capable of moving the electric power through relatively large air gap without physical connection. It is very attractive for EV charging since it provides safe, flexible, reliable energy transfer especially in harsh environment [1]. IPTS consists of two electrically isolated sides. Each one consists of the power pad, compensation topology and power converters, as indicated in Fig. 1. The power transfer between the two sides is achieved by magnetic induction. Different planar pad configurations are presented in literature such as circular, double-D (DD), bi-polar and double-D Q [2]. In these works the coil turns were modeled as rectangular block of copper (one turn and one layer), which is acceptable as long as the turns are close enough to each other (the separation is less than the coil diameter). But if the separation exceeds the coil diameter, this approximation will be incorrect. Moreover, in these studies there is no automatic optimization was used, however, the IPTS design is very complex problem with different related variables which are challenging with manual studies. Some automatic optimization for IPTS design were presented in literature using Pareto multi-objective optimization which was solved based on genetic algorithm and particle swarm [3]. These techniques are time consuming especially when FEA is involved in the optimization. Moreover, the simplified coil model was considered as well.

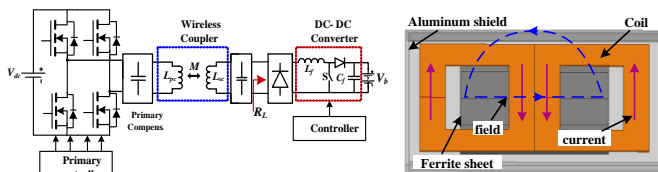


Fig. 1. Structure of double-D wireless pad. Fig. 2. Structure of DD pad.

This paper presents a multi-objective optimization algorithm for the coil design of IPTS's power pad. The procedure is based on an improved Tabu search (ITS) algorithm. Detailed 2D-FEM was developed for the power pads and linked with the search algorithm for optimization purposes. The DD pad structure was considered in this paper as a case of study.

II. FINITE ELEMENT MODELING OF DD PAD

Due to the advantages of better coupling, greater tolerance, greater charging zone, and cost effectiveness, DD structure was chosen in this paper for performing the optimization. Each power pad consists of one or more coils, which are wound in a way to construct closed magnetic field path, as depicted in Fig. 2. It contains ferrite sheet or bars under the coils to direct the magnetic field and achieve a single sided flux operation. It also, reduces the flux path reluctance and enhances the magnetic coupling between the two sides. In addition, the pad is shielded by Aluminum frame which is essential to reduce the EMF around the charger to comply with the acceptable limits defined by the international standards such as International Commission on Non-Ionizing Radiation Protection (ICNIRP).

The estimation of different parameters related to IPTS is essential for design optimization purposes. Due to complex structures of such systems, finding accurate analytical solutions for electromagnetic field distribution may not be conceivable. However, distinctive numerical analysis techniques can be utilized for electromagnetic field analysis. In this study, the FEA was done using ANSYS software for electromagnetic field calculation and magnetic parameters estimation. Two detailed 2D quasi-static electromagnetic FEMs were built and used in this study. The coil turns are exactly modeled to accurately investigate the effect of the separation between them, as shown in Fig. 3. Each turn was modeled as a stranded coil domain to emulate the litz wire performance. In Fig. 3(a) (Model I), the outer coil sides are single-layer, however, in Fig. 3(b) (Model II), the outer coil sides are double-layer.

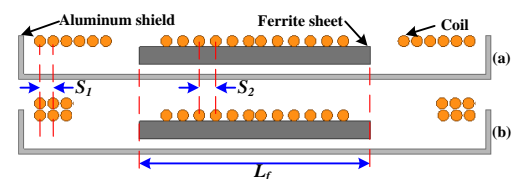


Fig. 3. 2D-FEM of double-D wireless pad (a) model I, (b) model II.

The two models I and II were analyzed based on the 2D FEA for solving the static problem using the static magnetic vector potential partial differential equation given in (1).

$$\nabla \times (v(\nabla \times \bar{A})) = \bar{J}_e \quad (1)$$

where, v is the magnetic reluctivity (m/H), A is the magnetic vector potential (V.s/m), and J_e is the current density vector.

III. OPTIMIZATION PROBLEM

IPTS's output power can be calculated from (2) without regard to the tuning circuit topology (series or parallel).

$$P_o = \omega I_1^2 (M^2/L_2) Q_2 \quad (2)$$

where, ω is the frequency of the primary current I_1 , M is the mutual inductance, L_2 is the secondary pad self-inductance, and Q_2 is the secondary circuit quality factor. For parallel compensation at the secondary, fixed resonant frequency in both the primary and secondary circuits, and identical pads ($L_1=L_2=L$) (which is the case in this work), $Q_2 = R_L/\omega L$ and $M=kL$, where k is the coupling factor. Hence the output power in (2) will be as in (3).

$$P_o = I_1^2 k^2 R_L \quad (3)$$

From (3), it can be noted that the power can be increased by increasing power supply current (I_1^2), the load equivalent resistance (R_L) or the magnetic coupling (k^2). The term $I_1^2 R_L$ is limited by the power electronic converters and the system losses, while the coupling factor is related to IPTS structure and alignment. To achieve higher efficiency, it is important to accomplish a high k . Generally, by increasing the dimensions and amount of materials, higher k can be attained, but the cost will be high. Therefore, in this work both the coupling coefficient and system cost are considered as objectives in the optimization problem. These objectives are function of the geometry parameters given in Fig. 3. In this optimization problem the main concerns are to investigate the effect of the separation between turns (S_1 and S_2) and the ferrite material length (L_f). Thus the pad size and number of turns are fixed.

The improved Tabu search algorithm is considered in this paper. It is based on the universal Tabu search (UTS) algorithm for global optimization with continuous variables in electromagnetics [4]. There are two searching phases in the UTS; diversification and intensification. The diversification phase is to search the objective space widely and the intensification phase is to locate the global optimal solution precisely. ITS generates the sampling points with Latin Hypercube Sampling method [5], which provides more uniform sampling in the objective space than the random sampling used in UTS. The advantages of ITS method are; 1) the ability to jump out of the local optimal solutions, 2) high convergence speed, 3) simple implement and realization. The mathematic formula of the multi-objective function (MOF) is given in (3) and the optimization constraints are indicated in (4).

$$\text{Min MOF}(S_1, S_2, L_f) = w_1 C_t + w_2 (1 - k_{ave}) \quad (3)$$

$$\text{Constraints} = \begin{cases} S_{1min} < S_1 < S_{1max} \\ S_{2min} < S_2 < S_{2max} \\ L_{fmin} < L_f < L_{fmax} \\ EMF < EMF_{max} \end{cases} \quad (4)$$

where, w_1 and w_2 are the weighting factors, C_t is the total pad cost, k_{ave} is the average coupling factor which is evaluated at the perfect alignment (k_a), worst horizontal (k_h), worst vertical (k_v) and worst rotational (k_r) misalignment ($k_{ave}=(k_a+k_h+k_v+k_r)/4$), and EMF_{max} is the EMF ICNIRP standard limit. The setting for the performed optimization are described in Table I.

TABLE I OPTIMIZATION SETTINGS AND RESULTS

Param.	Value	Param.	Value	Param.	Value
S_{1min}	2.6 mm	EMF_{max}	27 μ T	Iterations	700
S_{1max}	20 mm	L_{fmin}	93 mm	S_{1opt}	2.8 mm
S_{2min}	2.6 mm	L_{fmax}	558 mm	S_{2opt}	10.3 mm
S_{2max}	20 mm	Population	10	L_{fopt}	372 mm

IV. RESULTS

The proposed optimization algorithm was achieved for DD pad design. The optimum parameters were obtained and introduced to the FEM to obtain the final magnetic parameters. These parameters are inserted into the Simulink model for 8 kW LCL WPT system. Moreover, based on the optimization results, two identical pads were built and tested in a small scale IPTS prototype as shown in Fig. 4. The flux distribution of the 2D-FEM is depicted in Fig. 5. A comparison between the simulation and experimental system waveforms is shown in Fig. 6.

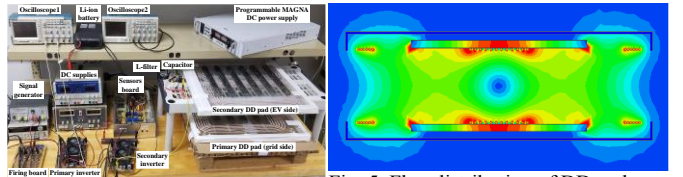


Fig. 4. LCL WPT system setup.

Fig. 5. Flux distribution of DD pad.

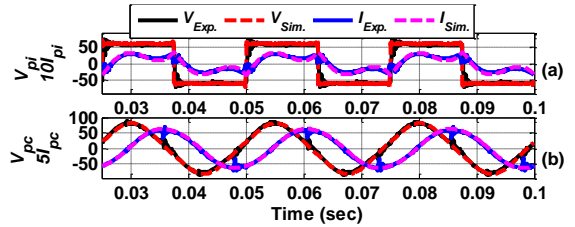


Fig. 6. Measured and simulated results of LCL IPT system. (a) Primary inverter variables. (b) Primary coil variables.

V. CONCLUSION

This paper presented a fast and an efficient multi-objective optimization technique for the magnetic design of power pads in IPTS for EV applications. The algorithm is based on the improved Tabu search technique. The results show that, increasing the middle turns separation and decreasing the outer ones results in greater magnetic coupling and power transfer capability. The optimization results were verified by both of simulation and experimental data.

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