Multi-Applicable Electromagnetic Field Design Method Based on Zero-One Programing

Tianqi Hong[1,2], Lei Huang[1], Haitao Yu[1], Minqiang Hu[1], Kun Dong[1]

[1]Engineering Research Center for Motion Control of MOE, School of Electrical Engineering, Southeast University, Nanjing 210096, China
[2]Polytechnic School of Engineering, New York University, Brooklyn, NY 11201, USA, th1275@nyu.edu

This paper proposes a method for developing the electromagnetic field under certain requirements. In this paper, the electromagnetic field design is considered as an optimization problem. Instead of solving this optimization problem directly, we rewrite the problem into zero-one programming form. By applying the proposed algorithm to solve the zero-one programming problem, design requirements can be achieved and optimization time can be dramatically saved compared with using other intelligent searching algorithm. Two practical applications are proposed to validate this novel method. All design results are compared with FEM calculation results.

***Index Terms*—Electromagnetic fields, design optimization, superconducting devices, wireless power transfer.**

I. INTRODUCTION

ELECTROMAGNETIC field design is necessary in various applications [1]-[3]. To satisfy certain requirements, designing a particular electromagnetic field is the common objective. Numerous algorithms are developed in the past decades to reach those requirements in diverse ways.

This paper intends to solve a set of electromagnetic field design problems with identical process. A general algorithm will be presented focus on field design under different applications.

II. PROBLEM DESCRIPTION

This paper is aiming to solve a type of design problems that the electromagnetic field is created by power wire with identical current $i(t)$ (say design the air-gap electromagnetic field of synchronous machine).

According to practical application, the magnetic field in particular position needs to be precisely designed to achieve better characteristics. For clear illustrate the problem, a generalized example is plotted in Fig. 1.

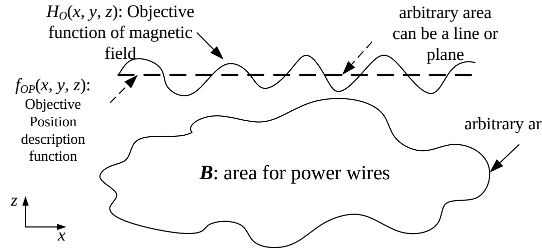

Fig. 1. A generalized example of the electromagnetic field design.

Based on the Fig. 1, several functions are defined in 3-D coordinate (x, y, z) as follows:

Objective Position function $f_{OP}(x, y, z)$: the certain position of expecting electromagnetic field. $\boldsymbol{O}$ is the set of the discrete points which are satisfied with $f_{OP}(x, y, z)$.

Objective Function of Electromagnetic Field $\vec{H}_O(x,y,z)$: the expecting electromagnetic field at the determined position described by $f_{OP}(x, y, z)$.

Placement function $f_{CF}(x, y, z)$: describes the area of power wires placement information. Since the power wires cannot be placed continuously, the matrix $\boldsymbol{B}$ is defined as the discretized placement matrix. All elements in $\boldsymbol{B}$ are satisfied with Placement Function $f_{CF}(x, y, z)$.

Optimal Position Matrix $\boldsymbol{P}^*$: describes the optimal distribution of power wires to achieve the objective electromagnetic field.

Apart from the definitions above, the electromagnetic field density function of single power wire is defined as $\vec{H}_i(x,y,z,p_i)$, where p_i is the position parameter of i^{th} power wire and $p_i \in \boldsymbol{B}$. For linear problem, Biot-Savart Law can be applied to calculate $\vec{H}_i(x,y,z,p_i)$. In nonlinear cases, finite element method can be applied to obtain the discrete function of $\vec{H}_i[x_k,y_k,z_k,p_i]$.

Based on the definition above, the electromagnetic field design problem can be equivalent into an optimization problem which is:

$$\begin{gathered} \boldsymbol{P}^* = \underset{p_i\ for\ i=1,2,\ldots,N}{\operatorname{argmin}} \left\|\vec{H}_O - \vec{H}_\Sigma\right\|_2 \\ s.t.\ \begin{matrix} p_i \in \boldsymbol{B} \\ (x,y,z) \in \boldsymbol{O} \end{matrix} \\ \vec{H}_\Sigma = \sum_{i=1}^{N} \vec{H}_i(x,y,z,p_i) \end{gathered} \tag{1}$$

where $\vec{H}_\Sigma$ is the summation of electromagnetic field generated by each power wire and N is the number of power wires which is a variable in this optimization problem.

The error between the optimization result and objective result is defined as:

$$e = \left\|\vec{H}_O - \vec{H}_\Sigma\right\|_2$$

III. MODEL SIMPLIFICATION AND NUMERICAL ALGORITHM

Due to the nonlinearity of the problem described in Section II, the analytical solution is difficult to obtain. Instead of computing the $\boldsymbol{P}^*$ directly, we can rewrite the Optimal Position Matrix as:

$$\boldsymbol{P}^* = \boldsymbol{A}_{n\times m} \cdot \boldsymbol{B}_{n\times m} \tag{2}$$

where $\boldsymbol{A}_{n\times m}$ is the a "0/1 matrix" which describes the existence of power wire. Matrix $\boldsymbol{B}$ is assumed to be a $n \times m$ matrix.

According to (2), the existence of power wire is presented by $\boldsymbol{A}$. Any element a_{ij} in $\boldsymbol{A}$ equals to one means the power wire exists at position b_{ij}, vice versa. Hence, problem (1) is equivalent into a zero-one programing problem.

Instead of obtain the global optimal solution, the practical solution (most the elements in B are expected to be "1", and the "1" elements are expected to be in group) for large scale matrix $\boldsymbol{B}$ is more appreciate. Hence, the "inverse searching" (IS) algorithm is applied. Different with other intelligent searching algorithm, the initial matrix $\boldsymbol{A}^0$ is set as "all-one" matrix (a_{ij} = 1 for all i, j). The IS algorithm process is represented in Fig. 2.

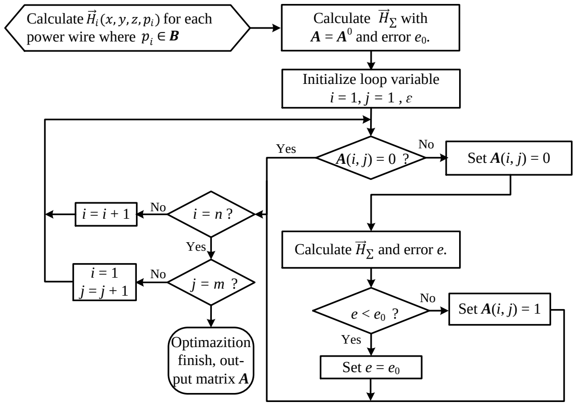

Fig. 2. Flow chart of the IS algorithm.

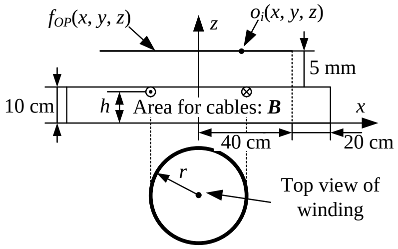

Fig. 3. The graphical model of wireless charging lot for cellphones.

IV. APPLICATION EXAMPLES

A. Wireless Charging lot of cellphones

To obtain uniform charging efficiency of wireless charging lot (one transmitter with N receivers), a uniform electromagnetic field along z-axis direction is expected.

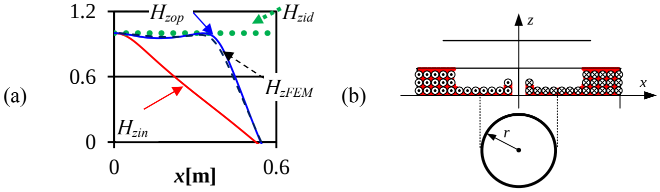

Fig. 4. Optimization results of wireless charging lot; (a) The comparison between ideal objective H_{zid} and optimization result H_{zop} and initial H_{zin}, and FEM result $H_{zFEM,}$ magnetic field intensities are normalized; (b) The cable distribution computed by optimization algorithm and FEM model based on optimal cable distribution.

According to the assumption that all cellphones have similar dimensions, the graphical model of magnetic field design problem is drawn in Fig. 3. The Objective Position Function $f_{OP}(x, y, z)$ describes a plane which is 5 mm higher than the power wire (thickness of cellphones).

By applying the proposed algorithm to wireless charging design problem, the cable distribution can be obtained; see red area in Fig. 4(b). The comparison between objective electromagnetic field and optimization results are plotted in Fig. 4(a).

B. Superconducting synchronous generator (SSG)

Due to high current density of superconductor, the normal superconducting synchronous generators with large capacity are designed as ironless or half ironless structure. With symmetrical ferromagnetic shielding or ferromagnetic stator, the nonlinear electromagnetic field design problems can be equivalent into linear design problems. One quarter of a four poles example rotor is shown in Fig. 5.

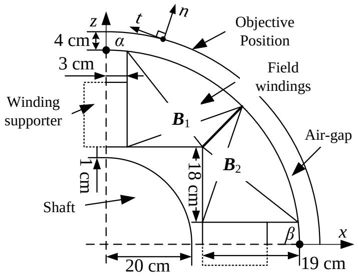

Fig. 5. One quarter of the example rotor model.

The sinusoidal magnetic field is expected along normal direction ($\vec{n}$) of air-gap. According to this requirement, the optimizing results are shown in Fig. 6.

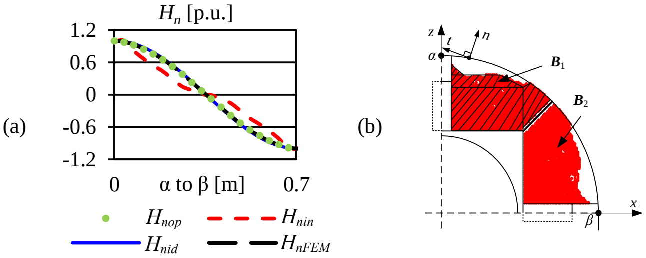

Fig. 6. Optimization result of SSG. (a) The per unit value of H_n along arc α to β; blue line is ideal air-gap H_{nid}; red line is initial H_{nin}, green dots are the optimization result of H_{nop} obtained from proposed method, black line is the FEM result of H_{nFEM} with magnetic shielding which is overlap with H_{nid}; (b) The distribution of power wires, power wire, the hatched area is FEM model approximated from red area.

According to the results shown in Fig. 6, an applicable result of the power wires distribution can be obtained by proposed the novel algorithm, which creates the magnetic field in the position we expect.

V. REFERENCES

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