An Effective Method for Optimal Design of Electric Machines Based on Finite Element Analysis

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Abstract— This paper presents an effective method for optimal design of electric machines. In this method, three key techniques are employed to save computational time related to the time-stepping finite element method (T-S FEM). The first technique involves using the field-circuit coupling steady state FEM to calculate initial values for the time-stepping finite element analysis. The steady state method uses a simpler, faster model to estimate the initial values reasonably close to the actual ones. The second technique is an adaptive meshing adjustment for minor shape modifications in which minor geometric changes can be made without re-meshing. The third technique encompasses using state variables from the previous design iteration as the initial conditions for the next iteration. Together these 3 techniques can reduce the total simulation time required to optimally design an electric machine. An example a 5.5kW induction motor is discussed and the results demonstrate a significant reduction in simulation time.

I. INTRODUCTION

The Time Stepping Finite Element Method (T-S FEM) is widely used in the study of magnetic fields during the design of electric machines, and it is also used to predict a machine's operational performance and to optimize its design. [1-2]. In general the T-S FEM has the following unique advantages. Phenomena such as uneven flux density distribution and its effect on rotational flux harmonic content can be effectively computed. Additionally losses arising from flux density and/or current harmonics and minor slot shape modifications are naturally part of the solution.

The disadvantage of the T-S FEM is the significant amount of computing resources and time that it consumes. When the T-S FEM is used for design optimization, including transient performance simulation the amount of computing resources required may easily exceed the reasonable capabilities of all but the largest computers. Some measures have been studied in [3-5], however they all have difficulty in reducing the simulation time significantly.

This paper presents a method for optimal design of electric machines. Three key technologies are adopted to reduce the simulation time. An example of stator slot shape optimization for a 5.5kW induction motor confirmed that significant amount of simulation time can be saved by use of the proposed method..

II. THREE KEY TECHNOLOGIES FOR OPTIMAL DESIGN

A. Initial value determination for time-stepping FEM

In this step, the field-circuit coupling steady state FEM is used to calculate the initial values. The function of the FEM in two dimensions can be expressed as in [6]:

$$F(\mathbf{A}, I_S, \delta_r, E_{bm}) = \iint_G \frac{\nu}{2}[(\frac{\partial \mathbf{A}}{\partial x})^2 + (\frac{\partial \mathbf{A}}{\partial y})^2]dxdy - \iint_G J(I_S, \delta_r, E_{bm})\mathbf{A}dxdy \qquad (1)$$

Where, **A** is the nodal vector magnetic potential, δ_r is the electrical angle between the rotor field amplitude and A-phase axis, E_{bm} is EMF of the rotor bars and ν is the reluctivity. It is well known that the unique stable operational state of the machine can be confirmed if the power supply and load are given. In such a case, the non-linear equation of the field-circuit coupling for the steady state FEM can be expressed as [7]:

$$\begin{cases} \frac{\partial F}{\partial \mathbf{A}} = 0 \\ L_a^T \mathbf{A} - \frac{\sqrt{2}E\cos\delta}{\omega} = 0 \\ L_b^T \mathbf{A} - \frac{\sqrt{2}E\cos(\delta+2\pi/3)}{\omega} = 0 \\ \mathbf{A}^T \mathbf{H}\mathbf{A} - T_m = 0 \\ E^2 + I_s^2(r^2 + x_s^2) + 2EI_s(r\sin\delta + x_s\cos\delta) - U^2 = 0 \\ sL_{b1}^T \mathbf{A} - \frac{E_{bm}\sin(\delta_r+\theta_{b1})}{\omega} = 0 \\ sL_{b2}^T \mathbf{A} - \frac{E_{bm}\sin(\delta_r+\theta_{b2})}{\omega} = 0 \end{cases} \qquad (2)$$

The meaning of the state variables above can be found in [7]. The non-linear equations (2) can be solved by Newton-Raphson iteration and the initial values relative to the starting point can be determined. This solution will contain the nodal vector magnetic potential **A**, stator current $\boldsymbol{I}_s$, bar current and the slip **s**. Furthermore, the time stepping computation can now use those steady state values as the initial conditions to perform a complete time stepping simulation.

B. Adaptive mesh adjustment for minor shape modification

In this step, the adaptive meshing method is adopted for minor shape modifications typically during design optimization. A simple minor shape modification is given in Fig.1, and it can be seen that even though the point A is changed to A', the meshing topology remains unchanged. Due to content limits the details of the batch solving process will be presented in the full paper.

C. Initial value selection of optimal design

In this step, the state variables from the previous design iteration are used as the initial conditions for the next design iteration. In doing so, the machine's optimal geometric variables are computed continuously. Fig. 2 shows that, with this technique, the phase A current of the 5.5kW example motor when the slot width and radius increase by 1mm and 0.3mm, respectively, is accurately computed. The transition occurs at 0.3s and can be seen to be smooth and continuous.

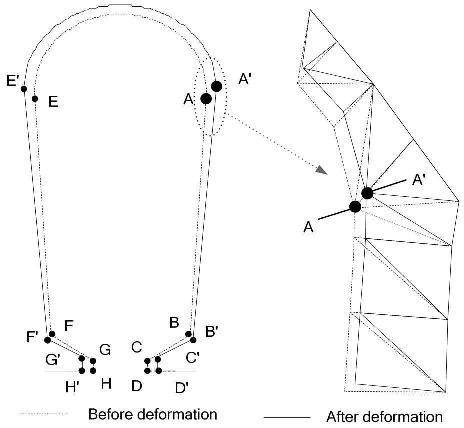

Fig.1. Adaptive re-meshing application on the key points

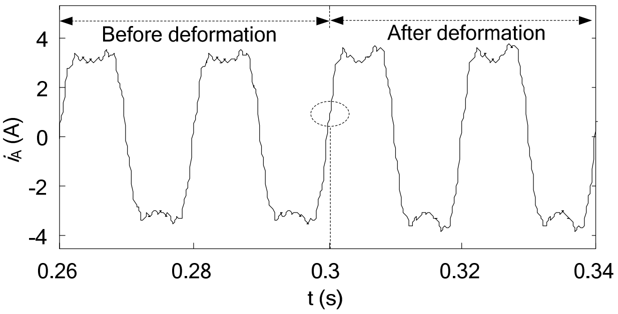

Fig.2. T-S FEM numerical example taking steady-state values before element deformation as initial values

III. OPTIMAL DESIGN EXAMPLE

A. *Comparison of simulation time consumption*

Applying the above method to a 5.5kW induction motor will result in a significant reduction of simulation time. For this example a simulation computer with an Intel i7-920 Core CPU and 6GB of RAM was used. A 5-slice multi-slice FEM method is employed to account for rotor skew. The total number of elements is 63205 and the time step is set to 0.0001s. Simulating the motor's starting transient consumes 15 hours when using a traditional T-S FEM while only ½ hour when the method in this paper is adopted.

B. *Optimal example*

During a series of continuous simulations of the example 5.5 kW motor, two optimal results for stator slot size are obtained and shown in Fig.3 and Fig.4. The loss comparison, between old slot and new-1, are given in Table I, and it can be noticed that the loss computation method is as [8-9]. Additional details such as improved slot size and the loss comparison will be present in the full paper.

TABLE I Loss comparison between old and new-1 with no-load condition

	Total loss (W)	Stator loss (W)	Stator loss (W)	Rotor loss (W)	Rotor loss (W)
		copper	iron	copper	iron
old	179	58	93	4	24
new-1	163	56	90	3	14

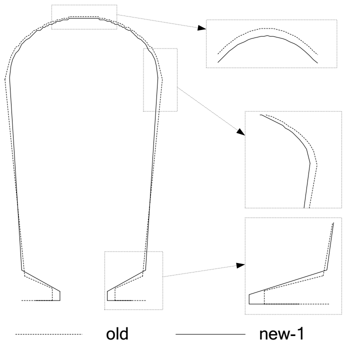

Fig.3 Comparison of stator slot between old slot and new-1

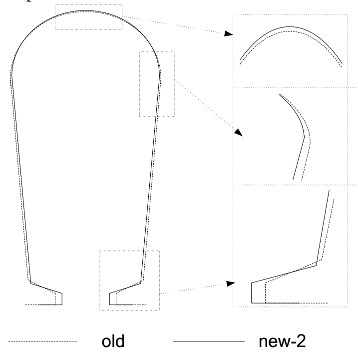

Fig.4 Comparison of stator slot between old slot and new-2

IV. CONCLUSIONS

An effective method for optimal design of slot sizes in electric machines has been presented in this paper. This method employs three key techniques to help reducing computer simulation time and resources. The method has been applied to a 5.5kW induction motor to demonstrate its capabilities and validity.

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