Field-Circuit Coupled T-S Finite Element Analysis of Core Losses for Induction Motor

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***Abstract*—A two-dimensional (2-D) field-circuit coupled finite element model of induction motor (IM) is built. The equivalent circuit of three-phase squirrel cage rotor is modeled. Based on time-stepping finite elements analysis (T-S FEA), core loss in the stator of a no-load IM under sinusoidal and Sinusoidal Pulse Width Modulation (SPWM) excitations is studied. The rotating flux density distributions with time variation at different locations of the stator are obtained. Meanwhile, the waveform and trajectory of magnetic flux density are analyzed. The areas where high-order harmonics mainly concentrated are simulated and the core losses in terms of the Bertotti's three-term separation model are calculated. All presented computations and models are verified through experiments.**

***Index Terms*—Core loss, induction motor, rotating flux density, time-stepping finite elements analysis.**

I. INTRODUCTION

In recent years, more and more electrical machines are applied to realize the various and complex control. The computational model about silicon steel laminations is studied by researchers, systematically, which is the material of the electrical machines. Whereas the magnetic properties of silicon steel laminations are changed in the process of manufacturing motors such as punching, heating and assembly. The core loss performance of the motor is rather different from that in silicon steel laminations. It is noted that the motors under SPWM power supply condition contain harmonics, which cause more core losses [1,2]. Therefore, more attentions must be paid to improve the efficiencies of electrical machines and accurate calculation method of core losses considering rotating flux density and harmonics is indispensable. However, the prediction of core losses in induction motor is limited, and the precision of the simulation results rarely reaches desired purpose for the electrical machine designers.

As is known to us, using SPWM inverter to supply the motor, a great deal of voltage harmonics produced by the converter exist a great influence on the core loss of the motor. Besides the fundamental voltage, the power supply voltage also contains a large number of higher harmonic voltage, which distort inevitably the magnetic density in the core of the motor. With the increasing demand of high design accuracy, it is necessary to consider the harmonics of the flux density and meaningful to apply FEM to the design of IMs [3]. Furthermore, accurate calculation of the flux densities distributions throughout the stator cores should be performed. Using field-circuit couple model in this paper, the magnetic properties of the stator are presented in detail by FEA [4].

Consequently, it is very crucial to obtain precise calculation and distribution of core losses in the stator to improve the efficiency of electrical machines.

II. MODELING AND SIMULATION

A. Calculation Model of Core Losses

Based on Bertotti's core loss separation model, the improved core loss model can be expressed:

$$P_{\mathrm{Fe}} = k_{\mathrm{h}} f (B_m)^{\alpha} + k_{\mathrm{c}} \frac{1}{T}\int_0^T \left(\frac{dB}{dt}\right)^2 dt + k_{\mathrm{e}} \frac{1}{T}\int_0^T \left(\frac{dB}{dt}\right)^{1.5} dt \tag{1}$$

where, P_{Fe} represents the total core losses by applying a sinusoidal alternating magnetic field, k_{h}, k_{c}, and k_{e} are alternating hysteresis, eddy current, and excess loss coefficients, respectively [5,6].

According to Eq. (1), the core losses of silicon steel laminations can be predicted directly and accurately, whereas the prediction in silicon steel laminations is very different from that in electrical machines, because of some specific factors related to motor ontology, such as rotating flux density and harmonics and uneven flux density distribution in the motor core. Therefore, the theory of core losses in IM should be further studied.

The eddy current loss and excess loss is obtained by calculating the fundamental frequency f and the peak value of the waveform of magnetic flux density, and magnetic flux density of certain point is divided into nth harmonic along the radial and tangential directions. The equations are expressed as:

$$P_{\mathrm{e}} = \sum_{n=1}^{\infty} k_{\mathrm{e}} (nf)^2 (B_{\mathrm{r,n}}^2 + B_{\mathrm{t,n}}^2) \tag{2}$$

$$P_{\mathrm{a}} = \sum_{n=1}^{\infty} k_{\mathrm{an}} (nf)^{1.5} (B_{\mathrm{r,n}}^{1.5} + B_{\mathrm{t,n}}^{1.5}) \tag{3}$$

where P_{e} and P_{a} are eddy current loss and excess loss, $B_{\mathrm{r,n}}$ and $B_{\mathrm{t,n}}$ are the amplitude of flux density along the radial and tangential directions in the motor core, respectively [7].

The hysteresis loss is determined by f and $\boldsymbol{B}$ and therefore have no high harmonic contributions. Due to consideration of

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minor hysteresis loops, a correction factor is needed in the process of calculating the hysteresis loss [8].

Considering the rotating field in the rotator core, the core loss separation model is computed by different methods. Based on Eq (1), correction factors can be used to make the total loss more accuracy. In addition, the total core loss is obtained by summing up the core loss along the radial and tangential directions of the motor, which is computed by the amplitude of magnetic flux densities along the two directions. After analyzing a large amount of computed core loss data and trying to manage the overall complexity of the model, the latter method is chosen for the total core loss model presented in this paper [9].

B. Experimental Data of Silicon Steel Laminations

In this paper, the core losses along the rolling and transverse directions of slicon steel laminations sample are measured with a novel 3-D magnetic properties testing system. The relationship of core loss with flux density ***B*** and excitation frequency *f* is obtained, which determine mainly the parameters of the motor. The core losses along the two directions present different upward trends with increasing of ***B*** and *f*, as shown in Fig. 1. According to the relationship, an optimal point which makes core losses lowest can be found in the design and optimization of the electromagnetic equipment [10].

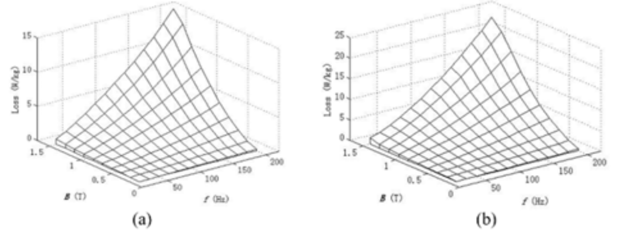


Fig.1 The relationship of core loss with flux density and excitation frequency: (a) rolling direction; (b) transverse direction

C. Field-Circuit Couple Model

The FEA involving control circuit and electromagnetic field is provided, and a moving air-gap boundary method combining motor motion equation is adopted to simulate the transient process of the motor.

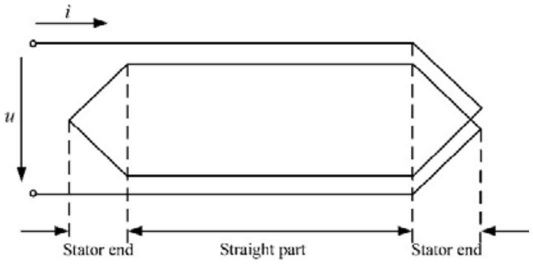


Fig. 2 Structure sketch of phase winding in motor stator

Using the finite element method, the straight line part is calculated by iterative algorithm, which takes the current and the vector magnetic field as the variables to realize the analysis about field-circuit coupled finite element method. The circuit equation of stator winding circuit is expressed by Eq. (4).

$$e + R_1 i_s + L_\sigma \frac{di}{dt} = v_s \tag{4}$$

where v_s is the impressed voltage; i_s is the phase current; R_1 is the stator resistance of each phase and L_σ is the end winding inductance.

According to Kirchhoff's law, the equivalent circuit of squirrel cage rotor can be modeled and analyzed including the rotor bar and end ring resistance and leakage inductance, as shown in Fig. 3. The inductances and resistances of the stator end windings and the rotor end rings are considered in the loop circuit equation.

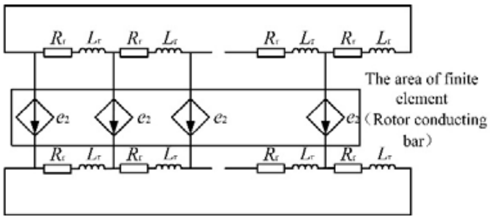


Fig. 3 Field-circuit coupled equivalent circuit of squirrel cage rotor

The main control circuit of the motor is three phase full bridge bipolar SPWM driving circuit, which is modeled by Maxwell circuit editor. In the FEA setup, the stator windings is specified to be connected with external circuit [11].

D. Establishment of Motor Core Model

By using the 2-D transient field solver FEA, the rotating core losses of three-phase squirrel cage IM are analyzed and calculated, with considering alternating and rotating flux densities. 2-D field-circuit coupled FEA model of an induction motor is established, and a Y2-132M-4 and 7.5 kW induction motor is chosen for 2-D FEA model, because a lot of time variation physical quantity changes in the process of solving problem. The silicon steel laminations used in the motor is non-oriented silicon steel 50WW800, whose thickness is 0.5 mm.

The finite element transient model of the motor is set in the rated speed 1450 rpm no-load operation. Ten testing points in the stator and rotor are selected and illustrated in Fig.3, where the flux density trajectory of each point is shown.

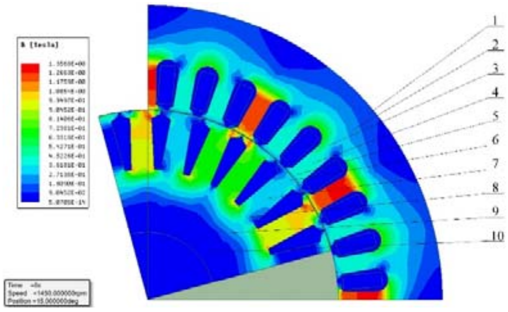


Fig. 4 Distribution of flux density in IM core and typical locations

III. SIMULATION RESULT AND EXPERIMENTAL VALIDATION

The 2-D field-circuit coupled FEA model of the motor is calculated by 2-D transient field solver. According to the magnetic field calculation and the flux density harmonic analysis results, the core losses distributions of the motor are shown in detail in this section.

A. Analysis of Rotating Flux Density

As is known to us, the core losses in stator and rotor are both contributed from both alternating and rotating flux densities. In order to express rotating field, flux densities are divided into tangential and radial components and the time variations of the flux density along two directions is calculated. Consequently, the total core losses consist of tangential and radial losses [12].

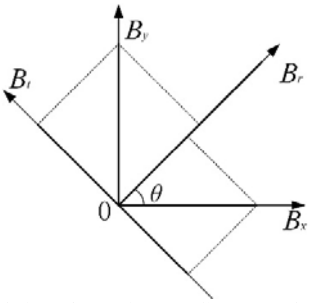


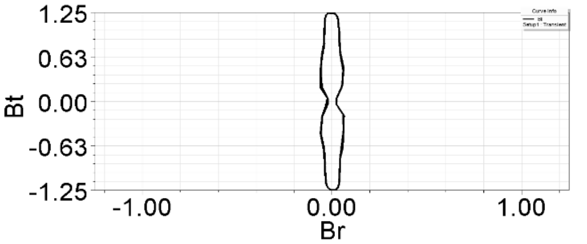
Fig. 5 Translation of cartesian coordinate to polar coordinate

The flux densities along the rolling and transverse directions in the polar coordinate is translated to that along the radial and tangential, as shown in Fig. 5. According to vector analysis method, the corresponding calculation formula of radial and tangential flux density is shown respectively, as following.

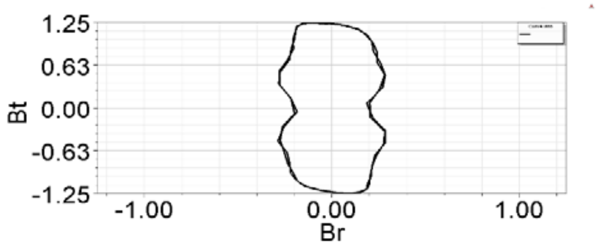
$$B_r = B_y \sin\theta + B_x \cos\theta \tag{5}$$

$$B_t = B_y \cos\theta - B_x \sin\theta \tag{6}$$

where θ is the φ direction in cylindrical coordinate system.



Point 1



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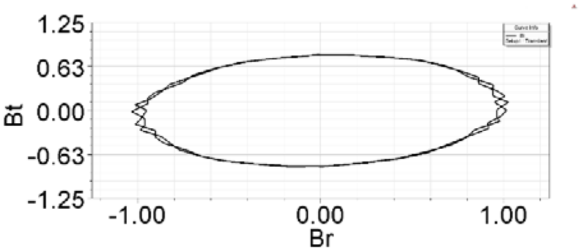

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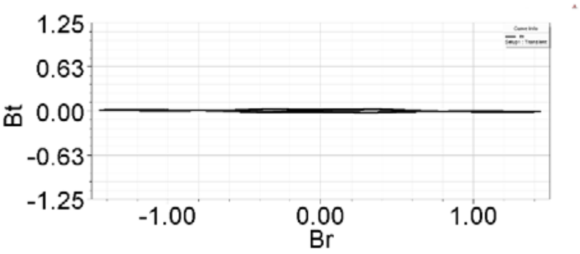

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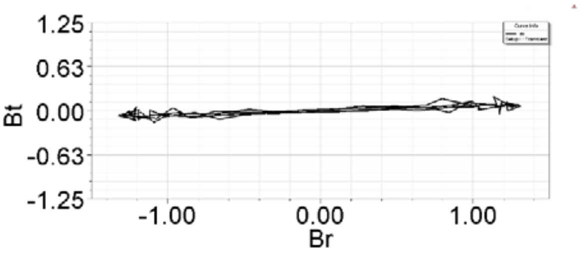


Point 5

Fig. 6 Trajectories of flux density in the stator

Fig. 6 shows the variation of the radial magnetic flux density B_r and the tangential magnetic flux density B_t in one cycle. The abscissa of the magnetic flux vector trajectory is B_r, and the ordinate is B_r. It can be found that there are two kinds of magnetization modes, which is alternating and rotating magnetization in the stator of the motor. In addition, the rotating magnetic flux is distributed near the edge of the stator, mainly. The flux density of point 3 is purely alternating in the teeth of stator.

From the distribution of core losses in stator, the core losses mainly distributed at the boundary between teeth and yoke, in yoke, as well as in tooth bodies; in rotor, the iron losses in the tooth top area contributes the most proportion due to harmonics.

Simulation result shows that the rotating flux density in the stator are concentrated at the bottoms and tips of the teeth, which can produce rotational core losses. Whereas, the middle parts of the teeth field present totally alternating flux density and are very low at the bottoms. The alternating core losses are concentrated in the middle parts of the teeth.

The total core loss of the motor can be calculated by the field calculator in the ANSYS maxwell.

TABLE 1
COMPARISON OF AMPLITUDE OF ***B*** IN STATOR
UNDER TWO POWER SUPPLY MODES

	Teeth (T)	Yoke (T)
SPWM	1.57	1.43
sinusoidal	1.51	1.39

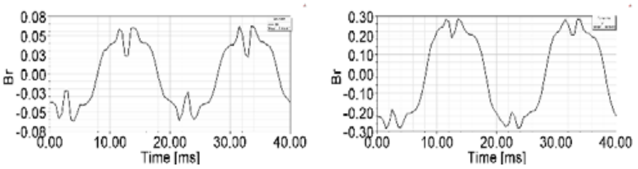
As shown in the Table 1, it can be seen that the former is larger, and the reason is that there are many times harmonic voltage generating magnetic flux density in the stator except the fundamental voltage. Therefore, the average total core loss of motor under the SPWM is 200.7525 W, which is larger than that under sinusoidal.

Comparing with core losses of sinusoidal input voltage, core losses of the PWM inverter voltage are increased in the analysis results.

The result of simulation shows that the magnetization of each region of the stator core depends on the structure, and the magnitude of the magnetization trajectory is influenced by the magnetic field strength on the magnetization mode, mainly.

B. Analysis of Harmonic

In order to consider the harmonic effect of the magnetic flux density waveforms on core losses, accurate prediction of the magnetic flux densities throughout the stator core need to be performed.



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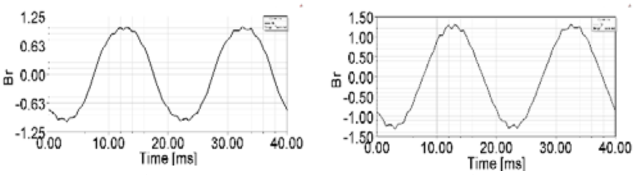
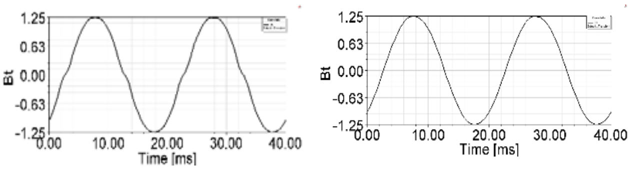


Point 3 Point 5

Fig. 7 The time variations of the radial flux density B_r



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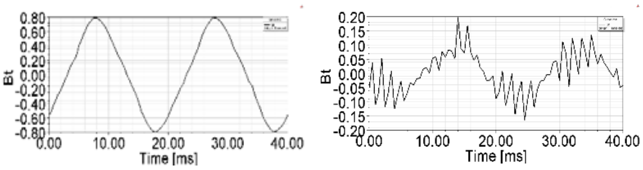

Point 3 Point 5

Fig. 8 The time variations of the tangential flux density B_t

The flux density in stator of IM is distorted in terms of harmonics. The sum of these harmonic components is nearly equal to the loss calculated by the proposed method.

The time variations of flux density along the radial and tangential directions are shown in Fig. 7 and Fig. 8. Comparing the figures, it can be seen that the waveform distortion along the radial direction decrease with the increase of radius, and the distortion become more and more serious along the radial direction.

With this method, the accuracy and reasonability of the model extensions for higher harmonics and minor loops in the IEM-Formula is studied. The presented resulting losses for different flux density waveforms, calculated as well as measured, emphasize the accuracy of the developed loss model.

C. Experimental Validation

The core losses in the Y2-132M-4 induction motor is measured by the testing prototype. By comparison, the computed losses show good agreement with the experimental results.

IV. CONCLUSION

A field-circuit coupled FEA is proposed considering the rotating core losses in a no-load induction motor. Three-phase full bridge bipolar SPWM driving circuit and the model of field-circuit are established. The time variation and loci of flux density are obtained, and the distributions of rotating core losses in different locations are analyzed. Core losses of IM is compared between sinusoidal and SPWM excitations. The waveforms of flux density in stator and rotor cores at different positions are simulated considering the harmonics. As a conclusion, it can be said that the evaluation of hysteresis losses has reached a good level of accuracy. The simulation results are verified by the experiment. The studies of core losses and harmonicswill play important rules in motor design.

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