Core Loss Modeling for Permanent Magnet Motor Based on Flux Variation Locus and Finite Element Method

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Abstract — Core loss prediction is an important issue in both design and analysis of permanent magnet motor. Because of their diverse structure, flux distribution, and rotational variation of flux, it is difficult to predict the core loss in a machine exactly. A core loss model for PM motor is introduced in which flux variation locus in different parts of the motor are predicted by carrying out a finite-element transient analysis. Since the flux variation pattern is complicated, the improved equation based on the conventional three-term expression is used for core loss calculation. The core loss model is developed totally in ANSYS parametric design language as a parametric model and it can be used easily for different types of PM motor. Calculation and experiments on a high speed permanent magnet motor have verified that the model produce results that agree with the experimental ones.

I. INTRODUCTION

It has been shown that the permanent magnet (PM) motors have many advantages over other kinds of machines, such as higher efficiencies, smaller size, lower weight and simpler control. They are replacing the monopoly of induction machines in pumps, fans, and compressor, and have more widely used in electrical vehicles, traction drives and new energy generation.

Core loss in PM motors constitutes a larger portion of the total loss, than in case of induction machines, due to near elimination of rotor loss and non-sinusoidal flux density waveforms. Therefore, the analysis technique to predict the core loss generated in PM motor by magnetic field before trial manufacturing becomes very important in motor development and design. A number of authors have presented models basically based on three-term core loss model [1] for calculating core loss in PM motors [2]-[6]. The flux density waveforms in the tooth and yoke can be deduced based on a number of approximations, and the analytical expressions for hysteresis loss, eddy-current loss and excess loss are developed [2]-[4]. These approaches are useful when used in the many iterations needed in the initial design. The finite element method (FEM) is used in [5], the harmonic flux densities in the radial and tangential direction are obtained from the post-processing of FEM. The total core loss of each element is equal to the sum of hysteresis loss, eddy-current loss and excess loss of every harmonic flux density at two directions. The above models are with reference to core losses associated with an alternating magnetic field. Practical electrical machines generally exhibit rotational fields. It had been reported that core loss occurring in a rotational field has a much larger value than that in an alternating field, and ignoring such additional loss caused by the rotational field will result in an excessively large value of error [6]. A core loss prediction model with rotational loss included was presented for PM motor in [6]. The excess loss was neglected in the model, and a correction factor was used. In the present paper, a more complete model of core loss which includes rotational loss will be provided, and the excess loss is also included. It will be shown that this new model is in good agreement with the experiment one without the use of any correction factor.

II. CORE LOSS SEPARATELY MODEL

This paper considers three basic loss components, which occur in a magnetic material when it is excited by a variable magnetic field [1]. These losses are hysteresis loss, eddy-current loss, and the excess or anomalous loss. The division of loss in these components is due to the presence of different scales of magnetization. For a periodically varying flux density, they can be written as

$$P_h = k_h f B_m{}^{\alpha} \tag{1}$$

$$P_e = \frac{d^2}{3\pi\rho\rho_e}\frac{1}{T}\int_0^T (\frac{d\mathbf{B}}{dt})^2 dt \tag{2}$$

$$P_a = \sqrt{\frac{A\beta n_0}{\rho}}\frac{1}{T}\int_0^T (\frac{d\mathbf{B}}{dt})^{3/2} dt \tag{3}$$

The total core loss P_{fe} is the sum of hysteresis loss, eddy-current loss and excess loss. Each coefficient appearing in (1), (2) and (3) can be deduced using the least square method by comparing calculation result with the standard 25cm Epstein test data as show in (4)

$$\sum_{f=f_1}^{f_n}\sum_{B=B_1}^{B_m}[\frac{P_{fe\_cal} - P_{fe\_\exp}}{P_{fe\_cal}}]^2 = \min \tag{4}$$

III. CORE LOSS DUE TO ROTATION FLUX

The elliptical $\boldsymbol{B}$ locus can be expressed as:

$$\vec{B} = e_{maj} B_{maj}\cos(wt) + e_{\min} B_{\min}\sin(wt) \tag{5}$$

where e_{maj} and e_{min} are the unit vectors along the major and minor axes of the elliptical locus, respectively. B_{maj} is the major axis component and B_{min} is the minor axis component. According to the three term model, the eddy current loss under the elliptical B locus is

$$\begin{aligned} P_{e\_ell} &= \frac{d^2}{3\pi\rho\rho_e}\frac{1}{T}\int_0^T (\frac{d\vec{B}}{dt})^2 dt \\ &= \frac{d^2}{3\pi\rho\rho_e}\frac{1}{T}\int_0^T [(\frac{dB_{maj}(t)}{dt})^2 + (\frac{dB_{\min}(t)}{dt})^2]dt \\ &= K_e(fB_{maj})^2 + K_e(fB_{\min})^2 \end{aligned} \tag{6}$$

The anomalous loss under the elliptical B locus is

$$P_{a\_ell} = \sqrt{\frac{A\beta n_0}{\rho}}\frac{1}{T}\int_0^T\left|\frac{d\mathbf{B}}{dt}\right|^{3/2}dt$$
$$= \sqrt{\frac{A\beta n_0}{\rho}}\frac{1}{T}\int_0^T[(\frac{dB_{maj}(t)}{dt})^2+(\frac{dB_{\min}(t)}{dt})^2]^{3/4}dt \quad (7)$$
$$= \frac{K_a}{15.74}\frac{1}{T}\int_0^T[(\frac{dB_{maj}(t)}{dt})^2+(\frac{dB_{\min}(t)}{dt})^2]^{3/4}dt$$

Brailsford [7] reported that the rotational hysteresis loss behaves very differently from its alternating counterpart. A rotational filed causes nearly twice the loss, compared to the loss produced by an alternating field with the same peak value at mid-range flux density. However, at saturation the loss caused by a rotational field drops rapidly and approaches zero. Therefore, the hysteresis loss under the elliptical B locus can be expressed as:

$$P_{h\_ell} = K_h f(B_{maj})^h + \alpha_h K_h f(B_{\min})^h \quad (8)$$

Where α_h=1~1.2 when $B_{maj}<B_s$, and α_h=-1 when $B_{maj}>=B_s$, B_s is the saturation value of flux density.

In a PM motor, the magnetic field distribution can be analyzed by the finite element method at various rotor positions and then the B locus in any element can be deduced. A series of elliptical loci can be obtained, when an arbitrary rotating flux density vector is expanded into a Fourier series. After determining the major and minor axes, B_{kmaj} and B_{kmin}, of the elliptical locus of the k-th harmonic flux density vector, the total loss in each element can be obtained by summing up the contributions from these harmonics, and the total core loss of the machine can then be obtained by summing up the core loss of each element as the following:

$$P_{fe} = \sum_{j=1}^{N_e}\sum_{k=0}^{\infty}[P_{h\_ell\_kj} + P_{e\_ell\_kj} + P_{a\_ell\_kj}] \quad (9)$$

where $P_{h\_ell\_kj}$, $P_{e\_ell\_kj}$ and $P_{a\_ell\_kj}$ are the hysteresis, eddy current and anomalous losses of the k-th harmonic in the j-th element, and N_e is the total number of elements of stator core in the finite element model.

IV. EXPERIMENTAL VALIDATION

A concentrated winding high speed PM motor is studied in this paper and the main specification is given in Table I. A test bench is set up to measure the core loss of high speed PM motor. The core loss at no-load is measured by separating the core loss from the mechanical loss using the dummy rotor method. The calculation and measurement results of core loss are compared in Fig. 1. Below 12krpm, the error is less than 10%, but the maximum error is about 15% when the rotate speed is over 12krpm. The possible reasons are: (1) loss coefficients derived from the rotational core loss data at low frequency may cause some errors when they are used in high frequency, (2) rotor loss cannot be distinguished from the measurement results.

TABLE I
SPECIFICATION OF THE HIGH SPEED PM MOTOR

Item	Value	Item	Value
Number of phases	3	Rotor inner diameter	18mm
Rated power	2kW	Permanent magnets	N35
Rated frequency	666.7Hz	Magnet arc	75°
Rated speed	20krpm	Magnet radial length	2mm
Number of pole	4	Air gap radial length	1mm
Stator outer diameter	78mm	Motor axial length	48mm
Rotor outer diameter	29mm	Number of slot	6

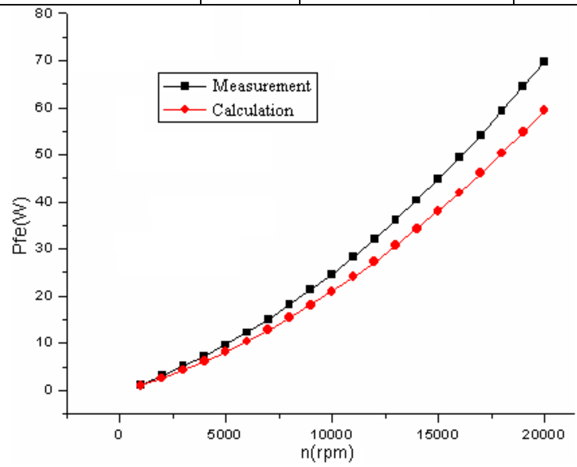

Fig. 1 Core loss of the high speed PM motor

V. CONCLUSION

A complete model is proposed to calculate core loss of PM motor, which is based on flux variation locus and FEM. The major and minor axes of flux elliptical locus at each harmonic frequency in every element are utilized to calculate core loss due to rational field in the core of PM motor. The proposed method is carried out on a high speed PM motor. By comparing the calculated results with the experimental results, it shows the good accuracy without the use of any correction factor.

VI. REFERENCES

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