Power Loss Analysis of High Speed Permanent Magnet Machine

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Abstract—**Concerns about advantages such as high efficiency, high power density, small size, light weight, and fast dynamic response have contributed to the increasing industrial application of high speed permanent magnet machines (HSPMMs). Aiming at the complex power loss situations due to high operating speed and frequency, in this paper, the calculation models of HSPMM in terms of iron loss and copper loss are reviewed based on the thoroughly overview of previous research outcomes. Moreover, the research status and future directions about HSPMM power loss analysis are illustrated, which may provide a strong reference for the design and optimization of electrical drive systems with HSPMMs.**

Keywords-high speed permanent magnet machine* (*HSPMM*)*; iron loss*; *copper loss

I. INTRODUCTION

High speed permanent magnet machines (HSPMMs), compared with conventional electrical machines, possess many advantages such as: (i) the high speed machines are compact, light and highly efficient, (ii) they are able to be directly connected with a prime mover or a load device without additional transmission systems, by which the maintenance expenses, gear costs and losses as well as corresponding noises can all be reduced, and (iii) because of the small moment of inertia, high speed motors have a fast dynamic response characteristic [1]. However, HSPMMs are characterized by high speed, high operating frequency and low heat dissipation area, which mean that the power losses are relatively large and the motor efficiency is reduced. Additionally, the temperature rise and distribution inside the motor as well as the machine operating safety and stability can thus be affected [2]-[3].

Considering different motivation principles and calculation models, this paper aims to present an overall review about the stator power loss analysis technologies of HSPMM. The research status and developments of key loss calculation methods are discussed, which may help the future works in this area.

II. COPPER AND IRON LOSSES OF HSPMM

A. Copper Loss

The copper loss is the power dissipated in stator and rotor windings due to the resistance of copper wire. In consideration of skin effect, Dowell and Ferreira methods are verified to be effective for the calculation of winding losses, but the accuracy may not be satisfactory due to the structural assumptions as well as the ignorance of nonlinear factors [2-3]. To solve these problems, a simple calculation method of HSPMM copper loss was introduced based on the sum of power losses caused by DC resistance and skin effects, as (1) [4].

$$P_{Cu} = IR_{dc}^2 + P_{Cu\_Ad} \tag{1}$$

where I is the winding current, R_{dc} is the winding resistance, P_{Cu_Ad} ($P_{Cu\_Ad} = K_{skin}R_{\mathrm{dc}}$) is the additional loss due to the skin effect and proximity effect in alternating magnetic field, K_{skin} is the skin-effect coefficient that is related to the frequency ω and the wire radius r.

Then, Jang [5] and Zou [6] et al. proposed an improved calculation equation of copper loss, by which the proximity effect is taken into account, as (2).

$$P_{Cu} = \frac{\pi B^2 \omega^2 d^4 l}{128\rho} \tag{2}$$

where B is the magnetic flux density at the position of winding wires, d and l are the wire diameter and length, respectively, and ρ is the wire resistivity.

Finite element model (FEM) can also be utilized to not only accurately calculate the copper loss, but also analyze the magnetic field and internal current density distributions. By using FEM, in [7], the authors developed the optimization copper loss calculation models. The influencing factors mainly include the current frequency, conductor diameter, numbers of winding, slot size and winding arrangement.

Generally, although the analytical methods like Dowell and Ferreira models can be conveniently employed to calculate the AC copper loss coming from skin and proximity effects, they are always not able to guarantee the modelling accuracy for HSPMM due to the complex influencing factors and boundary conditions. FEM is more suitable to analyze the influences of HSPMM geometric/physical parameters on AC copper loss [7]. Based on the substantive research, researchers also gave some suggestions for relieving skin and proximity effects such as: (i) wounding the windings with some thin wires in parallel, (ii) making the wire radius smaller than the skin depth at the highest operation frequency, (iii) determining the optimal parallel wire numbers for a certain frequency, (iv) smoothening the current waveform to reduce the harmonics, and (v) designing the appropriate slot-openings.

B. Iron Loss

Since HSPMMs work at the conditions of high frequency of alternating magnetic field, high temperature rise and internal stress, its iron loss can be significantly higher than that in ordinary motors. However, the induction principle of iron loss is pretty complicated. As a result, researchers have been working on building accurate calculation models of iron loss for decades [8]-[12]. In the 1980s, Bertotti model, in which the iron loss is divided into three parts including hysteresis loss, classical eddy current loss and excessive loss, was proposed [8].

$$P_{Fe} = P_h + P_c + P_e = K_h B^{\beta} f + K_c (Bf)^2 + K_e \left(Bf\right)^{3/2} \tag{3}$$

where $P_i (i = Fe, h, c, e)$ are respectively the iron loss, hysteresis loss, classical eddy current loss and excessive loss, K_h, K_c and K_e are the coefficients of P_h, P_c and P_e, and β is also an empirical coefficient.

It should be noticed that K_h, K_c and K_e are all related to B and f. Hence, (3) are usually preferable to express with higher accuracy. Combined with the extra iron loss caused by the harmonics in winding current, the iron loss calculation model of an HSPMM can be improved as (4) [9].

$$
\begin{cases}
P_{Fe} = P_h + P_c + P_e \\
P_h = K_h \sum_{k=1}^{N} kf (B_{k1}^{\beta} + B_{k2}^{\beta}) \\
P_c = K_c \sum_{k=1}^{N} k^2 f^2 (B_{k1}^{\beta} + B_{k2}^{\beta}) \\
P_e = K_e \dfrac{1}{T} \int_0^T (\left| \dfrac{\mathrm{d}B_x(t)}{\mathrm{d}t} \right|^2 + \left| \dfrac{\mathrm{d}B_y(t)}{\mathrm{d}t} \right|^2)^{3/4} \mathrm{d}t
\end{cases} \tag{4}
$$

where k is the harmonics order, T is the period of magnetically density waveform, B_x and B_y are the flux density components in the radial and tangential directions, respectively, while the subscripts "1" and "2" stand for the maximum and minimum values of the flux density.

Multiplex magnetization mode of electric machines inspires the continuous exploration and revision of iron loss calculation model. In 1998, Zhu put forward an improved core loss calculation model based on considerations of both alternating and rotating magnetizations. The formulation for stator core losses in rotating electrical machines were achieved [10].

$$
\begin{cases}
P_{Fe} = P_{h\_total} + P_{cr\_total} + P_{er\_total} \\
P_{hr\_total} = \sum_{k=0}^{\infty} [P_{hr} R_{BK} + (1 - R_{BK})^2 P_{ha}] \\
P_{cr\_total} = K_{ca} \sum_{k=0}^{\infty} (kf)^2 (B_{ks}^2 + B_{kl}^2) \\
P_{er\_total} = \dfrac{K_{er}}{(2\pi)^{3/2}} \cdot \dfrac{1}{T} \int_0^T [(\dfrac{\mathrm{d}B_r(t)}{\mathrm{d}t})^2 + (\dfrac{\mathrm{d}B_{\theta}(t)}{\mathrm{d}t})^2]^{3/4}
\end{cases} \tag{5}
$$

where P_{hr_total}, P_{cr_total} and P_{er_total} are the total hysteresis loss, classical eddy current loss and excessive loss, B_{ks} and B_{kl} are respectively the minor axis and major axis of elliptical magnetic field with the k^{th} magnetic density harmonic, and $R_{BK} = B_{ks} / B_{kl}$, P_{hr} and P_{ha} are the hysteresis losses calculated based on the alternating and rotating magnetization, K_{ca} is the coefficient of classical eddy current loss in alternating magnetic field, K_{er} is the coefficient of excessive loss in elliptical magnetic field, $B_r(t)$ and $B_{\theta}(t)$ are respectively the radial and tangential components of elliptical magnetic field.

In spite of the high calculation accuracy of iron loss by using Zhu's model, the applications are still limited because the loss coefficients are difficult to be obtained. They need to be fitted by loss curves in both alternating and rotating magnetization conditions. In this case, a kind of orthogonal decomposition model was proposed by Hu and Huang et al. in which the rotating magnetization can be replaced by two orthogonal alternating magnetizations [11]-[12], namely, for an elliptical magnetic field with magnetic flux density $\vec{B}(t)$,

$$
\vec{B}(t) = \vec{B}_r(t) + \vec{B}_{\theta}(t) \tag{6}
$$

where $\vec{B}_r(t)$ and $\vec{B}_{\theta}(t)$ are respectively the radial and tangential components of elliptical rotating magnetic field.

Furthermore, the loss caused by $\vec{B}_r(t)$ and $\vec{B}_{\theta}(t)$ can be calculated via:

$$
\begin{aligned}
P_{Fe} &= K_h f (B_l^{\alpha} + B_s^{\alpha}) + K_c f^2 (B_l^2 + B_s^2) \\
&\quad + \frac{K_e}{8.763363} \cdot \frac{1}{T} \int_0^T \{ \left| \frac{\mathrm{d}B_r(t)}{\mathrm{d}t} \right|^{3/2} + \left| \frac{\mathrm{d}B_{\theta}(t)}{\mathrm{d}t} \right|^{3/2} \} \mathrm{d}t
\end{aligned} \tag{7}
$$

where B_s and B_l are the minor axis and major axis of elliptical magnetic field.

As far as the author's knowledge, due to the neglect of rotating magnetization, the classical iron loss Bertotti calculation model would definitely enhance the error for iron loss modelling in HSPMM. Zhu's model was verified to have satisfactory accuracy but needs dedicated measuring equipment to fit the loss coefficients. With the standardization of two-dimensional iron loss measuring equipment, the Zhu's model will inevitably be well-developed and widely-used. As for orthogonal decomposition model, the loss coefficient can be fitted by using the loss curve provided via manufacturer. In this case, it can be implemented in iron loss calculation more easily with good calculation accuracy. Future works should pay more attention on the compound interaction of not only the various magnetization modes but also the skin effect.

III. CONCLUSIONS

This paper presents a review for the development process of power loss calculation methods in HSPMM, including the copper loss due to skin and proximity effects and the significant iron loss owing to high magnetic density frequency. Both research status and suppression measures of the power loss are introduced. In addition, according to the literature discussions, we can get that the developments of HSPMM will soon be transited from feasibility analysis to optimized design and finally to widely industrial applications. In these processes, the parameter sensitivity and internal interaction mechanism of copper/iron losses due to skin effect as well as high operating frequency should be fully understood, such that the calculation or analysis algorithms of HSPMM power loss can be improved.

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