Prediction of Iron Losses in Doubly Salient Permanent Magnet Machine with Rectangular Current Waveform

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Abstract — The iron losses in doubly salient permanent magnet (DSPM) machine is difficult to predict, as the flux waveforms are complex and DC bias existed. This paper firstly measures iron losses at no load for different rotor speed and these measured core loss data are used to calibrate the calculation model of the DSPM machine. Then the iron losses at rated load are predicted by three phase rectangular currents exert on the armature windings. The results show that the percentage of iron losses in the rotor decreases which do benefit to the machine thermal dispersion design.

I. INTRODUCTION

In recent years, the doubly salient permanent magnet (DSPM) machine has been attracting more and more attention due to its advantages of high reliability, high efficiency and high power density [1-3]. The DSPM machine has stationary permanent magnets (PMs) on stator yoke combined with salient rotor. The DSPM machine owns high flux concentration effect and then homopolar stator has a high flux density (usually reach or over 1.5 Tesla). In usual the thermal dispersion of the DSPM machine is favored as the PMs and armature winding may be cooled at same time. However, the iron losses, especially in rotor side, would cause overheat if the iron losses prediction in DSPM machine at complex flux waveforms is under-estimated.

II. DSPM MACHINE TOPOLOGY

Fig. 1 shows the cross-section of a 6/4-pole DSPM machine which has two magnets inserted into the stator yoke. In order to keep the stator in a whole, iron bridges besides the PMs are retained. After the DSPM machine is assembled, the PMs are inserted into the slots on the yoke. It is also convenient to pull out the PM if necessary.

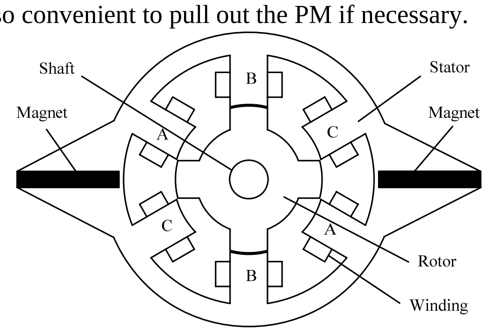

Fig. 1. Cross-section of a 6/4-pole DSPM machine

Fig. 2 shows the PM flux linked in one phase and the typical rectangular phase current waveform with reference to the rotor position. Here homopolar flux waveform is shown in Fig. 2(a).

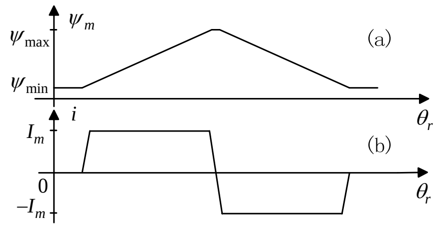

Fig. 2. Characteristics. (a) PM flux linkage, (b) Typical phase current wav.

III. FINITE ELEMENT ANALYSIS

The 2D finite element analysis (FEA) is used to analyze the magnetic field distribution of the DSPM machine. Fig. 3(a) shows the mesh model where the surrounding space around the stator circumference is taken into. Fig. 3(b) shows the flux line distributions at no load. The magnetic field distributions such as flux density versus rotor angle at no load and rated load may be calculated respectively.

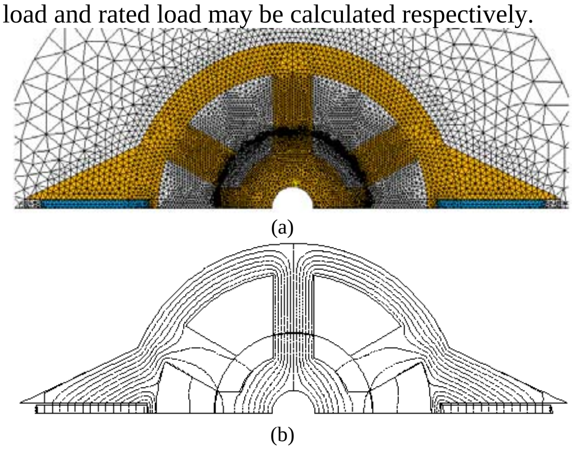

Fig. 3. Magnetic field distributions (0°). (a) Mesh model, (b) Flux line

IV. IRON LOSSES PREDICTIONS

A. Iron Losses Model

The loss separation method separates iron losses into three components

$$P_t = k_h f B_m^{\alpha} + k_e f^2 B_m^2 + k_{exc} f^{1.5} B_m^{1.5} \quad (1)$$

where k_h, k_e, k_{exc} are the factor of hysteresis loss, eddy-current loss and excess loss, respectively. The parameters α, k_h, k_e, k_{exc} may be calibrated from measured losses data.

B. No-load Situation

The flux density in the stator and rotor at no load is calculated by FEA, as shown in Fig. 4 and Fig. 5. It is shown that flux density in stator tooth is always in positive values. The waveform of flux density in rotor tooth is irregular where four minor loops occur in one cycle. Most of these flux density waveforms shown in Fig. 4 and Fig.5 have DC bias.

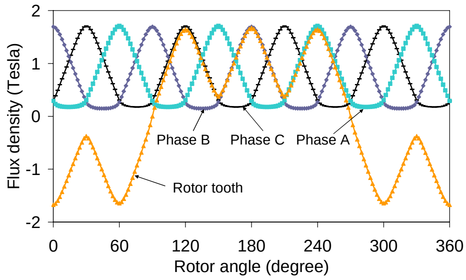

Fig. 4. Flux density in rotor tooth and stator tooth

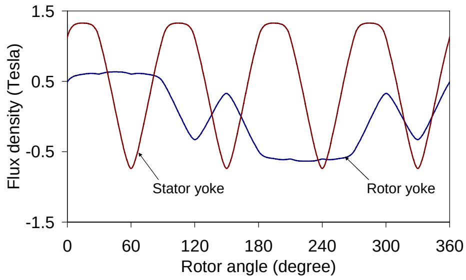

Fig. 5. Flux density in the yoke of stator and rotor

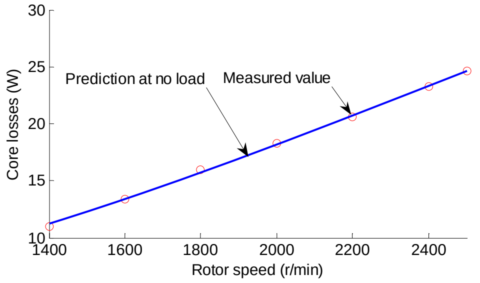

Fig. 6. Fitting results of the iron losses

In order to calibrate the iron losses at no load, firstly the PMs are pulled out and the mechanical power losses are carefully measured at different rotor speed. After that process, the PMs are put into the DSPM machine and the power consumptions are measured again at various rotor speed. The errors of the measured results in two cases represent the iron losses at no load.

By using eq. (1) and the flux density data at no load, the iron losses may be calculated [4]. The parameters are finally determined by curve fitting with the measured results.

TABLE I
PARAMETERS OF THE LOSS CALCULATION

Item	Value
k_h	0.0089
k_e	0.89e-5
k_{exc}	1.18e-3
α	1.314

C. *Rated Load Situation*

The calculation of the iron losses is carried out at rated load, where three phase rectangular current as shown in Fig. 2(b) is exerted on the armature windings. For simplicity, minor loops caused by the PWM in current are neglected. The iron losses at rated load are shown in Fig. 7, where most of the iron losses are located on the stator yoke and stator tooth. The percentage of rotor-side iron losses at no load and rated load are shown in Fig. 8. Due to the pulse magnetic field as the DSPM machine is loaded, the iron losses in rotor is increased not so much as the other parts of the machine. By considering the good thermal dissipation for salient rotor structure, the over-heat would no happen if appropriate electrical load is selected.

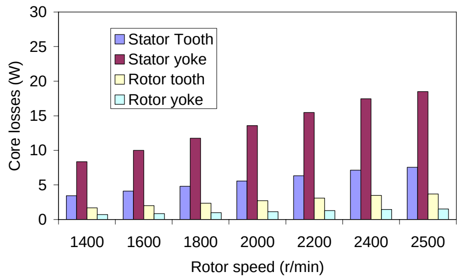

Fig. 7. Iron losses at rated load in DSPM machine

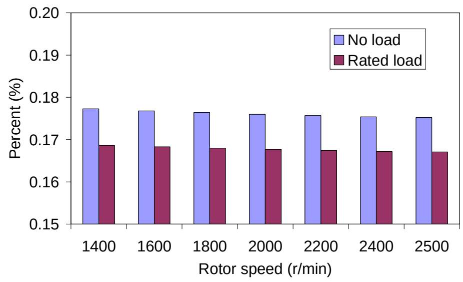

Fig. 8. Percentage of the rotor iron losses

V. CONCLUSIONS

The iron losses in DSPM machine are analyzed at no load and at rated load. The flux density in stator and rotor is calculated by FEA which shows DC bias in flux density waveforms. The iron losses in the rotor are not so high due to the pulse magnetic field in the DSPM machine when the machine is loaded with rectangular current waveform.

VI. ACKNOWLEDGMENT

This work was supported by a grant (Project No. 50977011) from the National Natural Science Foundation of China and Specialized Research Fund for the Doctoral Program of Higher Education of China (Project No. 20090092120042).

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