# Thermal Optimization of a High Speed Permanent Magnet Motor


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***Abstract*—This paper investigates the losses of a high speed permanent magnet (HSPM) motor, predicts the temperature distribution of the motor and optimizes its structure for better rotor cooling. Firstly, losses of the HSPM motor, particularly stator iron loss and rotor eddy current loss, are estimated by 3D time-stepping electromagnetic finite element analysis (FEA). By involving the measured current waveforms, pulse width modulation (PWM) harmonics brought by the voltage source inverter are considered in loss calculation. Then temperature distribution of the motor is predicted by using the conjugate heat transfer analysis based on the calculated losses and the CFD model. Finally, based on the CFD results, the motor structure is optimized. Both CFD analysis and experimental results show that the optimized structure can reduce the rotor temperature significantly compared with the original design.**

***Index Terms*—Finite element method, fluid dynamics, permanent magnet machines, thermal analysis**


## I. INTRODUCTION

Recently, high speed permanent magnet motors (HSPMs) are extensively studied. They are considered as good replacements for geared electric drives in many applications due to their high power density, high reliability and small size [1].

High fundamental frequency of the HSPM can produce a significantly higher iron loss in the stator, while asynchronous magneto-motive force (MMF) harmonics caused by stator slotting and non-sinusoidal stator current waveforms may induce significant eddy-current losses in the rotor [2]. Losses in both cases will be exaggerated by the pulse width modulation (PWM) current harmonics brought by the inverter. In addition, large losses appear in the air space of the HSPM caused by the rotor rotation and gas-flow [3]. Meanwhile, smaller size of the HSPM results in a high loss density and limited heat dissipation surface, which make the cooling of the HSPM more difficult. Overheating of the machine can cause irreversible demagnetization of the permanent magnets (PMs). Therefore, in order to ensure the safe operation, losses and corresponding temperature distributions of the HSPM should be analyzed in depth.

The structure of the HSPM investigated in this paper is shown in Fig. 1. The rotor assembly is formed by a diametrically magnetized PM cylinder and two shafts retained by a sleeve made of high strength steel. The rotor is supported by active magnetic bearings, which require high rotor stiffness. To improve the rotor stiffness, rotor axial length should be reduced, so the Gramme ring winding with shorter coil ending length is used instead of conventional distributed windings [4].

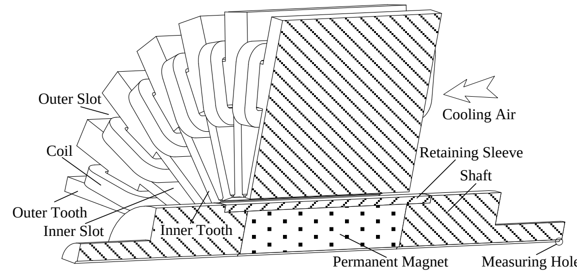


Fig. 1. Structure of the investigated HSPM.

In the full paper, loss components of the presented HSPM are calculated in detail. Then temperature rises of the motor are analyzed by using computational fluid dynamic (CFD) [5] modeling based on the loss results. By investing the thermal analysis results, the motor structure is optimized to reduce the rotor temperature. The optimization is verified by both CFD analysis and experiments.

## II. LOSS ANALYSIS

Losses are calculated first as heat sources in the thermal model. Stator iron loss and rotor eddy current loss are calculated by using the finite element analysis (FEA) [6] and presented in Table I. The actual phase current waveforms (see Fig. 2) are used in the analysis to consider additional harmonics brought by the voltage source inverter (VSI) [7]. Mechanical losses, including the air-friction loss and gas-flow loss are considered directly in the CFD model.

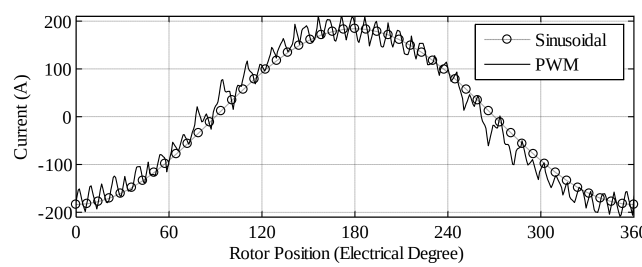


Fig. 2. Measured phase current and the fundamental component of the HSPM under the rated condition: 36,000 rpm, 75 kW.

TABLE I ELECTROMAGNETIC LOSSES IN THE HSPM (IN WATTS)

| | Stator iron loss | | | | Rotor eddy current loss | |
|---|---|---|---|---|---|---|
| | Hysteresis loss | | Eddy current loss | | | |
| | Tooth | Yoke | Tooth | Yoke | Sleeve | PM |
| Sinusoidal | 126.1 | 212.0 | 110.7 | 180.0 | 86.1 | 5.1 |
| PWM | 140.1 | 229.2 | 472.0 | 621.2 | 327.2 | 16.3 |

## III. THERMAL ANALYSIS USING CFD

The motor is forced air cooled. The processed air is blown into the motor through a cooling duct in one end of the motor frame. After passing through passages in the inner and outer slots separately, the hot air is taken out from the other end of the motor. Fig. 3 depicts the CFD thermal model.

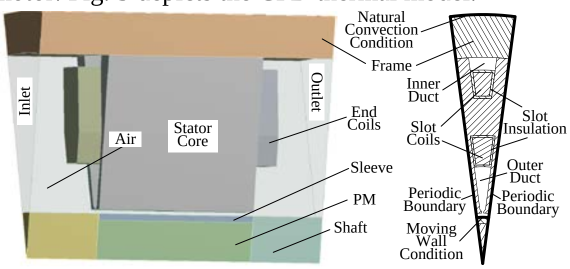


Fig. 3. CFD model of the HSPM.

To include the influences of working temperatures on motor losses, a series of iterative calculations are carried. Firstly, losses are calculated and mapped to the CFD model under the assumed average working temperature of each part in the model. Then a new estimation $T_i$ is obtained based on the last estimation $T_{i-1}$ and calculated average temperature $T_{i-1(calc)}$:

$$T_i = T_{i-1} + \kappa_a (T_{i-1(calc)} - T_{i-1}) \quad (1)$$

here $\kappa_a$ is an acceleration factor. The iteration stops when the difference between the estimated and calculated average temperature of each part is less than a preset requirement.

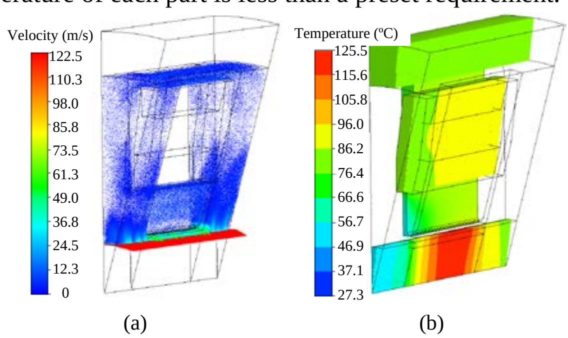


Fig. 4. CFD calculation results of the HSPM under the rated condition: (a) Velocity vector distribution. (b) Temperature distribution (half model).

Calculated velocity vector and temperature distribution of the HSPM is shown in Fig. 4. The highest temperature calculated in the winding and the rotor is approximately 96.0 ºC and 125.5 ºC, respectively. The measured values under the same working condition by using RTDs are 97.4 ºC and 123.0 ºC, respectively.

## IV. THERMAL OPTIMIZATION

It can be seen from Section III that the rotor temperature is significantly high, which decreases the motor output and increases the risk of demagnetization. In order to reduce the rotor temperature, several modifications are applied to the structure of the HSPM. As is shown in Fig. 5 and Fig. 6, the outer duct is closed, the inner and outer teeth widths are increased, and additional heat dissipation fins [8] are planted on the motor frame in the modified motor.

Losses and the temperature distribution of the modified HSPM are calculated by using the same method. Calculated hottest spot in the winding is 97.0 ºC, which is only 1.0 ºC higher than that of the original structure; while the highest rotor temperature is 118.9 ºC. Measured values of the highest temperature in the winding and the rotor are 98.0 ºC and 116.2 ºC, respectively. Detailed results will be presented in the full paper.

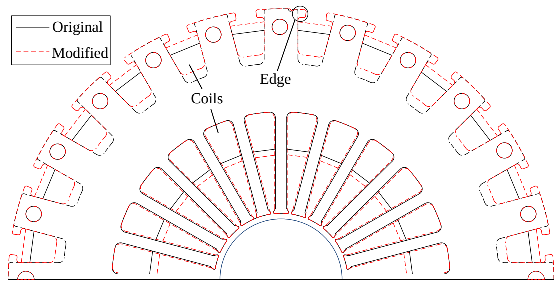


Fig. 5. Stator lamination of the original and modified HSPM.

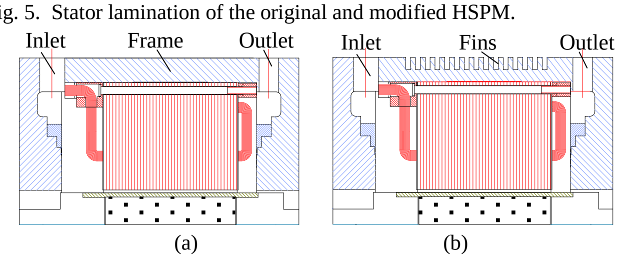


Fig. 6. (a) Sectional view of the original structure. (b) Sectional view of the modified structure.

## V. CONCLUSION

The losses and temperature rises of a HSPM are calculated by using the numerical methods. Then the motor structure is optimized for better rotor cooling based on the thermal analysis results. The calculated results and optimization are verified by experiments. Detailed methods and implementation will be described in the full paper.

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