Temperature rise calculation of a flux-switching permanent-magnet double-rotor machine using electromagnetic-thermal coupling analysis

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The flux switching permanent magnet double rotor machine (FSPM-DRM) used for hybrid electric vehicles (HEVs) has attracted considerable attention due to the compact structure and high torque density. Compared with conventional machine, the FSPM-DRM suffers from more severe thermal problems in its inner rotor. This paper aims to make an accurate prediction of the performances and temperature distributions in the FSPM-DRM. First, the ac copper loss with an improved analytical method is discussed and the results are validated by those from a 2-D finite element (FE) model. With the obtained power losses, a 3-D FE electromagnetic-thermal coupling model is built to predict the temperature in each part of the FSPM-DRM at various operation mode. The maximum temperatures of different parts at the rated load and 160% load under various operational modes are simulated. Finally, the cooling system of the FSPM-DRM is designed. The results show that the temperature rises can be effectively reduced by using the designed cooling system. Some experimental results are reported, validating the numerical and simulated results.

***Index Terms*—Flux switching permanent magnet machine, double-rotor machine, ac copper loss, temperature rise, finite element method**

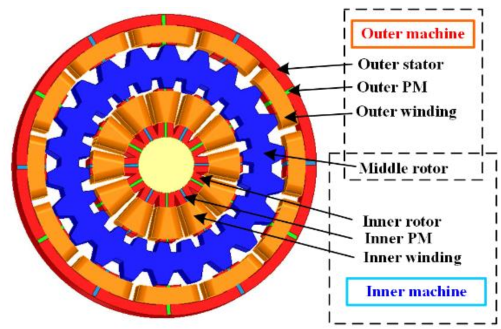
I. Introduction

Double rotor machine (DRM) used for hybrid electric vehicles (HEVs) can offer multi-operational modes and enables the internal combustion engine (ICE) to operate at optimum efficiency independent of road conditions, thus decreasing the emissions and fuel consumption. To achieve high torque density and little torque ripple, recently, a flux-switching permanent-magnet double-rotor machine (FSPM-DRM) has been proposed (see Fig.1(a)) [1][2]. The FSPM-DRM's inner rotor suffers from more severe thermal problem due to the fact that the wound and PM located inner rotor is surrounded by the outer stator and the middle rotor and rotates with the ICE, which brings difficulty for its heat dissipation and the cooling duct design. Compared with other DRMs, such as the 4QT, the interaction of PMs and windings in the FSPM-DRM is greater for that they are both located on the outer stator and the inner rotor. The working point of the PMs can influence the flux density and subsequently affect the loss and temperature rise of the windings. Conversely, the temperature rise of the windings can change the PMs' working point, especially at short circuit fault conditions, it may cause irreversible PM demagnetization and insulation breakdown. So, an improved electromagnetic-thermal coupling analysis scheme is adopted for accurate temperature rise evaluation of the FSPM-DRM.

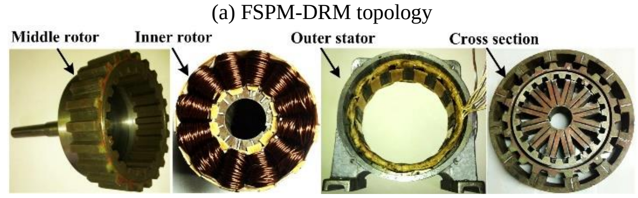
II. Analysis scheme

A. Machine topologies

In the HEV system, the inner rotor of the FSPM-DRM (Fig.1(a)) is connected with ICE and rotates with it. The middle rotor is connected with the shaft of the final driveline. The FSPM-DRM can be seen as the integration of two radial-flux FSPM machines, in which the outer stator and the middle rotor can operate as the outer machine, while the inner rotor and the middle rotor operate as the inner machine.



(a) FSPM-DRM topology



(b) Prototype photo

Fig.1. FSPM-DRM topology and prototype photo.

B. Thermal analysis scheme

In the traditional temperature analysis method, the conductor eddy current loss, as a part of heat source, is usually ignored. While for the FSPM-DRM, it exhibits higher electromagnetic torque density than that of most doubly salient machine, and the slot opening is larger, this may cause higher conductor eddy current loss. Besides, the frequencies of the inner and the outer machines are relatively high for large middle rotor pole number, and the narrow slots also result in high slot leakage across the coils, which also increase the conductor eddy current loss. Moreover, although the eddy current loss of armature winding in the FSPM-DRM is smaller than the iron loss at rated load, it increases much faster with the frequency and current density than the iron loss, and has great influence on the performances and temperature rises of the inner and the outer machines, especially on large load and high speed operations.

It should be mentioned that the FSPM-DRM used for HEV system can work at several operational modes, such as the full-electric mode, the high-speed cruise mode, and the hybrid driving mode, etc. The temperature rises in the FSPM-DRM differ very much at various operational modes, which is different with the thermal analysis of conventional doubly salient machine. So, an improved electromagnetic-thermal coupling analysis scheme considering conductor eddy current loss and various operational modes is adopted for accurate temperature rise evaluation of the FSPM-DRM [3].

III. Loss analysis

The power losses of the FSPM-DRM are input as the heat sources for temperature calculation and properly allotted to the corresponding nodes in the thermal model. The power losses within the FSPM-DRM is composed of four parts: the DC copper loss, the eddy current loss in windings, the iron loss, PM eddy current loss, and the mechanical loss. An improved analytical scheme for eddy current loss in windings is proposed, in which the relatively large width of the outer slot and the variation of the flux density with tangential direction are considered. The calculated results show a good agreement with those from a 2-D FE simulation, in which the eddy current losses of winding increase faster than the iron loss and the PM eddy current loss with the loads, which means that the eddy current losses of winding in the FSPM-DRM cannot be ignored for thermal analysis(Fig.2).

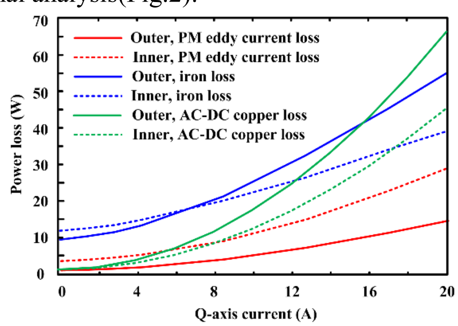


Fig.2. Power losses in FSPM-DRM at 750rpm.

IV. Thermal analysis

A. 3D FE thermal analysis

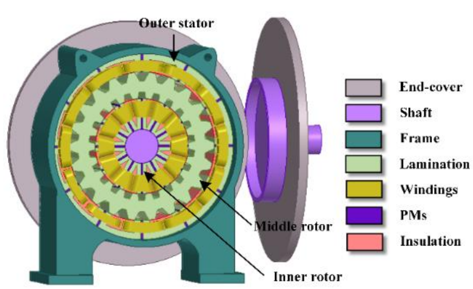
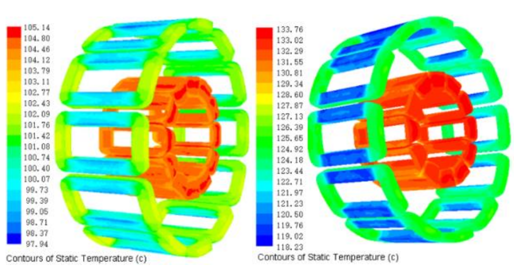


Fig.3. 3-D FE thermal model of the FSPM-DRM.



（a）Rated load （b）160% rated load

Fig.4. Temperature distributions in windings at hybrid mode.

ANSYS/FLUENT software permits us to elaborate the 3-D FE electromagnetic-thermal model (Fig.3) and predict the maximum temperatures of different parts. Several simulations are made to calculate the temperature distributions of the FSPM-DRM on different loads at different operational modes. The temperature distributions of the inner and the outer windings at hybrid driving mode are shown in Fig.4. The maximum values of different parts in FSPM-DRM at hybrid driving mode, high-speed cruise mode (Table I), and full-electric mode are investigated in detail. Table I displays that the highest hot spot in the FSPM-DRM is located in the inner winding (158.6 ºC on rated load and high-speed cruise mode).

TABLE I
SIMULATED MAXIMUM TEMPERATURE AT FULL ELECTRIC MODE AND HIGH-SPEED CRUISE MODE.

Operation mode	Full electric	High-speed cruise
Speed	750rpm	3000rpm
T_{max} in windings	62.8 ºC(outer)	158.6 ºC(inner)
T_{max} in PMs	61.6 ºC (outer)	151 ºC (inner)
Frame	45.4 ºC	90.1 ºC
Shaft	43 ºC	85.1 ºC

B. Cooling system design

Considering the relatively high temperatures in the inner winding, especially at heavy load and high speed, two cooling systems (a forced-air cooling system with double-fan and a water-cooling system) are designed and analyzed. The influences of the forced-air cooling, water cooling, and the distribution of the cooling channels on the cooling performance are discussed, respectively. The speed impacts of air flow and water flow are discussed and provide a parameter reference for choosing the forced-air cooling fan and water pump properly.

V. ELECTROMAGNETIC-THERMAL TWO-WAY COUPLING ANALYSIS

The no-load electromotive forces (EMF) of FSPM-DRM are calculated by the electromagnetic-thermal two-way coupling FEM and validated by the experimental tests. Furthermore, the predicted and tested mechanical torques of the FSPM-DRM are analyzed for various operational modes and loads. Some thermocouples are implemented to measure the temperatures of windings. For all these results, the ac copper loss and temperature rise are considered. A good agreement is observed between the tested results and the simulated results.

References

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