Double-Circulatory Thermal Analyses of a Water-Cooled Permanent Magnet Motor Based on a Modified Finite Formulation Model

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This paper presents a modified finite formulation method (FFM) based double-loop circulation technique in the thermal analyses of permanent magnet synchronous machines (PMSM). The inner loop of the circulation procedure is employed to guarantee the energy balance of the air enclosed in the end-caps, while the outer loop is used to correct the heat transfer coefficients that change with temperatures. The thermal model based on FFM is modified to simplify the outer loop process. The temperature estimation techniques are then applied to analyze the temperature distribution of a PM motor with a spirally-mounted water-cooling system. A ventilation system is established to maintain the temperature rise. The analyses based on the proposed methodologies are validated by experiments.

***Index Terms*—Finite Formulation Method, Modified Thermal Model, Double-Circulatory System, Thermal Analysis, Permanent Magnet Traction Machine.**

I. INTRODUCTION

PERMANENT magnet (PM) motors have attracted extensive research attentions in the field of electric vehicles (EV) due to their superior characteristics such as high efficiency, high torque density, and fast dynamics. Since the loading conditions are mostly strict, it is of vital importance to predict accurately the temperature in design process. However, during calculation, the interactions between material parameters and temperatures should not be neglected since the latter ones can be greatly affected by the former and vice-versa [1]. Indeed, the choice of input parameters with both conciseness and the complex dependence on the output data is a key point in thermal analyses.

The finite formulation method (FFM), also known as the cell method (CM), is a new numerical method based on the reconstruction of physical laws on a set of cell complexes [2]. Since its proposal, CM has been used extensively in the field of magnetic fields in both static and transient forms [3]-[4]. Considering its governing equations with definite physical meanings [5] and the general form of integral conservation, CM could be a reliable and effective means for the computation of temperature distribution in electrical machines.

This paper proposes a modified CM thermal model with the two-way coupling of physical parameters and the temperature distribution inside a PM traction motor. A double-circulatory procedure is presented with the iteration of fluid temperatures as the inner loop and the recalculation of heat conductivity coefficients based on the body temperatures as the outer loop.

II. CIRCULATION SYSTEM

The double-circulatory procedure consists of two loops, as shown in Fig.1. The inner loop is used to verify the fluid temperature for compliance of the energy conservation law. The heat convection coefficients are then modified by the air temperature [6]. The outer loop is used to judge the veracity of heat conductivity coefficients. When the iteration reaches its end, there are one-to-one correspondences between temperatures and physical property parameters through the outer loop and right air temperature inside the machine by the inner loop.

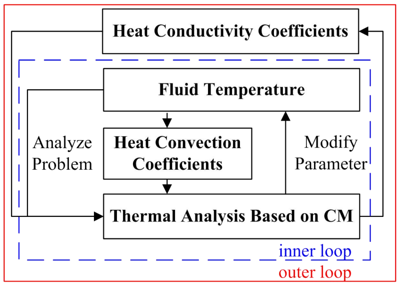

Fig. 1. Flow chat of the double-circulatory procedure.

III. MODIFIED THERMAL MODEL

According to the fundamental principle of CM, the governing equations of heat transfer can be formulated as [7]:

$$\boldsymbol{G}^T \boldsymbol{M}_\lambda \boldsymbol{G} \boldsymbol{T} = \boldsymbol{q} \qquad (1)$$

where $\boldsymbol{T}$ stands for the discrete vector of temperature rise, $\boldsymbol{G}$ is the primal topological edge-node matrix, $\boldsymbol{M}_\lambda$ the constitutive matrix connecting primal lines and dual faces, and $\boldsymbol{q}$ the generated heat vector based on dual volumes.

It is worth noting that in the finite formulation form, the heat conductivity coefficients are loaded in the constitutive matrix. In order to take into account the influence of temperature distribution on the heat conductivity coefficients, $\boldsymbol{M}_\lambda$ should be reconstructed, resulting in a great computational burden in generating the global stiffness matrix.

To simplify the computational procedure and reduce significantly the computational burden, the product of temperature rise and conductivity coefficient instead of the temperature rise alone is chosen as the solution quantity. This new established variable physically stands for a kind of temperature potential which is noted as $\boldsymbol{\varphi}_T$. In this form, equation (1) could be modified as

$$\boldsymbol{G}^T \boldsymbol{M}_s \boldsymbol{G} \boldsymbol{\varphi}_T = \boldsymbol{q} \tag{2}$$

where $\boldsymbol{M}_s$ is the new constitutive matrix, which depends only on the dimensions of the cells.

Equation (2) is only applicable to the pure regions where adjacent nodes in these regions share the same material properties. For nodes located at the interface(s) of two or more materials, (2) cannot be directly applied since a node is related to two or more conductivity coefficients.

In this paper, we propose a method to handle this problem by dividing the solution domain into several parts, and each part only stand for one kind of material. Since that, equation (2) is applicable to each region of single material. However, a range of nodes on the interfaces are added into the cell complexes by the previous process, making the equations unclosed and cutting off the heat transferred through the interfaces. In order to remedy this problem, extra equations should be employed and filled into equation (2) describing the continuity as

$$\Gamma_{n-m} : \boldsymbol{G}_n{}^T \boldsymbol{M}_{snb} \boldsymbol{G}_n \boldsymbol{\varphi}_{T_{nb}} + \boldsymbol{G}_m{}^T \boldsymbol{M}_{smb} \boldsymbol{G}_m \boldsymbol{\varphi}_{T_{mb}} = \boldsymbol{q}_{nb} + \boldsymbol{q}_{mb} \tag{3}$$

$$\Gamma_{n-m} : \boldsymbol{\varphi}_{T_{nb}} / \lambda_{nb} = \boldsymbol{\varphi}_{T_{mb}} / \lambda_{mb} \tag{4}$$

where n_b and m_b are the dual points on the interface of the contiguous bodies, which means the $\Gamma_{n\text{-}m}$.

Equation (3) stands for the continuity of heat transferred through the interfaces and (4) the continuity of temperature. As can be seen, the rewind process is greatly simplified as:

1. The heat conductivity coefficients only have an influence on (4). Other equations are non-rewound implicit functions.

2. In the circulation of (1), matrix multiplications in large scales are needed. By using this modification model, computing complexity can be greatly reduced.

Motor temperature vector $\boldsymbol{T}$ can be obtained by dividing $\boldsymbol{\varphi}_T$ by λ. During computation, λ calculated by the previous iteration step can be used. When the iteration converges, the norm of the difference between the consecutive $\boldsymbol{T}$ vectors of two steps should be smaller than a pre-specified error.

For the PM motors, the magnetic properties of the PMs are evidently effected by the temperatures. Since that, the thermal and electromagnetic analyses can hardly be separated. The co-simulated program can be illustrated as the loops in Fig.2.

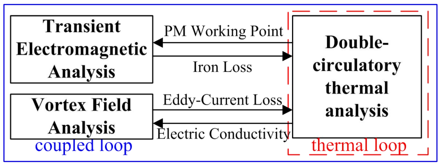

Fig. 2. Co-simulating process of the electromagnetic and temperature fields.

IV. PRELIMINARY RESULTS AND EXPERIMENTS

The modified CM thermal model embedded with the doubly circulatory system is employed in computing 3-D temperature distribution of a 10kW, 2250rpm PM traction motor. The temperature on the broadside of the PMs is measured by a wireless thermal sensitive resistor buried inside the rotor core adjoin the PMs while the signals are transmitted by an antenna tied to the shaft. Table I compares the calculated and measured temperature rise under water flow rate 17.78 liter/min. The proposed methodology is validated by the close agreement between the computed and measured temperature rise.

TABLE I
TEMPERATURE RISES TESTED AND CALCULATED

Position	Tested	Computed	Error
End-winding	111.4K	106.7K	4.22%
PM	149.5K	142.0K	5.02%

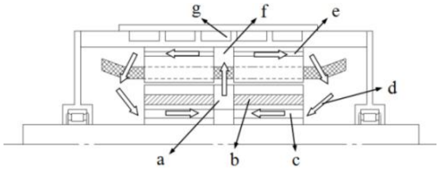

Fig. 3. Cooling structure of the radial-axial mixed ventilation system, which are (a) clapboard, (b) PM, (c) axial rotor vent, (d) cooling air, (e) axial stator vent, (f) radial vent, (g) coolant gallery.

TABLE II
TEMPERATURE RISES WITH AND WITHOUT VENTILATION SYSTEM

Position	Non-ventilated	Ventilated	Reduction
End-winding	106.7K	99.2K	7.5K
PM	142.0K	118.0K	24.0K

Since the PMs are over-heated during full-load operation, a radial-axial mixed ventilation system is employed to maintain the temperature rise of the rotor parts. As shown in Fig.3, the cooling air is driven by the clapboards mounting in the radial vent as the centrifugal fan. The PM temperature rise is thus reduced by 24.0 K, as shown in Table II. The temperature rises with different load sustained rates are also calculated.

V. CONCLUSION

This paper presents a modified 3-D CM thermal model for the simplification of the adjustments of heat conductivity coefficients during calculation. The model is numerically implemented with a double-circulation procedure in which the temperature of air enclosed in the end-caps is rewound as the inner loop and heat conductivity coefficients as the outer loop. The proposed methodology is applied for thermal analyses of a water-cooled PM traction motor and the calculation results are validated by experiments. A new ventilation structure is proposed to maintain the rotor temperature rise.

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