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Research Paper

Porous metal model for calculating slot thermal conductivity coefficient of electric machines

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HIGHLIGHTS

- Proposing a Porous Metal Model (PMM) for calculating the equivalent thermal conduction coefficient (TCC) of Motor's Slot.
- Verifying PMM with a 2-layer flat thermal conduction model.
- TCC precision is improved by 10%.
- 3 TCC models are compared and discussed.

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ABSTRACT

The calculation accuracy of Slot Thermal Conductivity Coefficient (TCC) is related to the estimation of temperature rise of electric machines, which is important in the process of improving motor's efficiency and working capacity. In this article, the Porous Metal Model (PMM) with a variety of filling materials considered is proposed to improve the accuracy of TCC. A simplified structure model and thermal resistance network of slots are established to investigate the equivalent TCC of a slot. The calculated result is verified by a 2-layer flat thermal conduction model, which is based on experiments and electromagnetic simulations. Moreover, TCC obtained through the PMM method is compared with the Parallel Method (PM) and Classical Estimate Method (CEM). The results show that the calculation method of TCC based on PMM is more accurate; besides, the formula only includes one variable usually fixed for a certain motor, so the proposed method is more suitable for the practical application.

1. Introduction

There is an increasing requirement for miniaturization, energy efficiency, cost reduction, as well as the exploitation of new topologies and materials of the electric machines. For such demands, more accurate thermal models integrating thermal material properties (electric insulates and magnetic materials) are necessary to present the system behavior. In the thermal study, one of the main problems of electric machines is their slot section, which is the most vulnerable component, as the insulation materials surrounding the windings can be damaged or reduce the lifetime if the thermal limit for the material is surpassed [1]. However, as slots are filled with composite materials, the actual slots model is difficult to establish. The prediction of Thermal Conductivity Coefficient (TCC) by numerical computational tools, like the Finite Element Method (FEM) will lead to excessive simulation time.

At present, due to the TCC of copper is large, the temperature gradient along the direction of copper wire is small, temperature can be considered equal everywhere along the copper wire. The vertical TCC of silicon steel is far greater than that of the horizontal (along the laminated direction) TCC, so heat can be considered to transmit primarily along the vertical orientation, and then conduct into air. Therefore, the model of motor temperature field simplified from 3D to 2D is reasonable [2].

In the 2D thermal calculation field, the main idea for calculating the TCC currently is to use a homogeneous equivalent material to replace the composite material-that is to say, to establish the equivalent model and to calculate the equivalent TCC. Milton's homogenization including additional micro-structural information are studied in [1]. Thermal conductivity bounds for internal and external porosity materials are described in [3]. The equivalent heat transfer coefficient of lotus-type porous copper is obtained through a homogenization [4,5]. Besides, three models or methods are mainly applied in this type of research in the existing methods. They are equivalent square thermal conductor model [6], parallel

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Nomenclature

Letters	
L_P	quadrangle length of the cell unit
D	length of the copper equivalent tetrahedron
T	temperature
L	length of heat transfer path
A	cross-sectional area perpendicular to the path
V_α	total volume of the porous
V_p	the volume of the hole in the porous
V_s	volume of the mental in the porous
A_s	slot-sectional area
N	the number of turns in the slot
A_{wb}	bare wire cross-sectional area
d'	diameter of enameled wire
d	diameter of copper conductor
ε'	varnish fill factor
λ^m	TCC of an inclusion embedded in an infinite medium
q	heat flux of one slot
ρ	heat source density (W/m^3)
P	loss
N_s	slot number
V	volume of one slot
t_1, t_2	temperature of the center point of slot and tooth
i	phase current
R	phase resistance
T_0	base ambient temperature
α	the change coefficient that resistance changing with temperature
$\emptyset$	the whole heat dissipating capacity of the up surface
λ	thermal conductivity (W/(m K))
Δt	temperature variation
v	the point velocity on the outer surface
ν	the viscosity of air
P_r	the Prandtl constant
φ	the porosity of the porous
ε	bare wire slot fill factor

Sub-indexes	
ex	insulating materials
cu	copper conductor
eq	equivalent materials
silicon	silicon steel or tooth

model [7–9] or area weighted average approach [10] and the classical estimate method [11]. A simplified equivalent thermal conductivity formula obtained by a 2-D simplified equivalent slot model is presented in [2], but the thickness of different heat conductors in the formula is difficult to estimate precisely. A parameter estimation formula is proposed in [7], but the error is relatively large. Lu calculates the TCC by the equivalent thermal resistances, which need to calculate the resistances of epoxy, insulation magnet and sheet. Although the calculation accuracy is relatively higher, the calculation of thermal-conduction resistances is complex [12]. A classical estimate formula is applied in a flux-switching permanent magnet motor [11], and it may be a relatively precise method for the TCC calculation at present.

The excitation windings side of electric machines usually is closed as an enclosed area by epoxy resin (mainly in special linear motors) or impregnating varnish (mainly in rotary motors), copper conductors are insulated from each other. What's more, the wire enamel outside the copper conductor, slot wedge and insulation paper are filled to increase the insulation. Owing to the TCC of epoxy resin, impregnating varnish, wire enamel, slot wedge and insulation paper are very small and nearly equal, they can be replaced by an equivalent TCC according to the existing Maxwell-Eucken model, the slot section can be described into a container only contains equivalent insulation and copper conductors, and the filler can be regarded as a porous structure. However, differing from the porous mental materials, the component of metal and gas in porous mental materials are replaced by equivalent insulation and copper conductors respectively. Besides, there is no any fluid thermal transfer between them, the porosity can be replaced by bare wire slot fill factor [4].

Porous mental material can be arranged with regular directional pores of micrometer or millimeter scales with Gasar technology [13]. In this paper, assuming the slot sections are made up with numbers of regular pores, so the TCC calculation of slot section can be simplified to calculate the TCC of one pores unite, and considering the definition of bare wire slot fill factor, the TCC of one slot can be obtained.

The main process for applying the PMM is shown in Fig. 1 and the remainder of this paper is organized as follows. In Section 2, the PMM and its mathematical model, the existing traditional method of PM and CEM are introduced. In order to verify the TCC calculation method based on PMM, a 2-LFM is built, the heat source and temperature are obtained and verified by electromagnetic-thermal analysis and experiment in Section 3. Finally, the TCC calculation results with PM, CEM and the methods based on PMM are compared, and the method proposed in this paper is verified accurately.

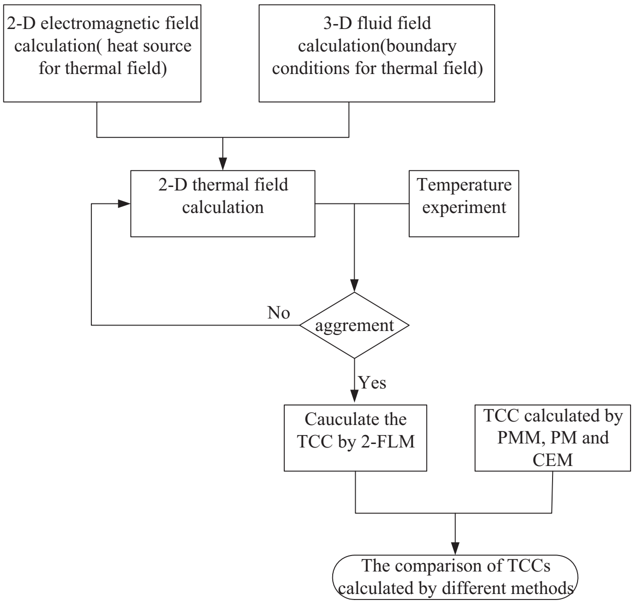

Fig. 1. The main process for applying the PMM.

2. Porous metal model

2.1. Principle of PMM

A permanent magnet linear motor (PMLM) is applied in this paper. The structure of porous copper is shown in Fig. 2(a) [13], the porous copper is composed of copper and gas, and gas is filled