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Conjugate heat transfer analysis of an energy conversion device with an updated numerical model obtained through inverse identification

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ABSTRACT

Energy conversion devices undergo thermal loading during their operation as a result of inefficiencies in the energy conversion process. This will eventually lead to degradation and possible failure of the device if the heat generated is not properly managed. The ability to accurately predict the thermal behavior of such a device during the initial developmental stage is an important requirement. However, accurate predictions of critical temperature is challenging due to the variation of heat transfer parameters from one device to another. The ability to determine the model parameters is key to accurately representing the heat transfer in such a device. This paper presents the use of an inverse identification technique to estimate the model parameters of an energy conversion device designed for vehicular applications. To simulate the imperfect contact and the presence of insulating materials in the permanent magnet electric machine, thin material are introduced at the component interface of the numerical model. The proposed inverse identification method is used to estimate the equivalent thermal conductance of the thin material. In addition, the electromagnetic losses generated in the permanent magnet is also derived indirectly from the temperature measurement using the same method. With the thermal properties and input parameters of the numerical model obtained from the inverse identification method, the critical temperature of the device can be predicted more accurately. The deviation between the maximum measured and predicted winding temperature is less than 2.4%.

1. Introduction

Permanent magnet electric machines have been used in a variety of energy conversion applications ranging from wind energy conversion [1] to vehicular traction [2]. Accurate representation of the thermal behavior of such a machine during the developmental stage is critical to ensure its eventual safe and reliable operation. For instance, magnet over temperature can cause permanent demagnetization and adversely affect the performance of the machine [3]. Prototype development and full scale testing of such a machine is not always economical and can be time consuming [4]. Alternatively, mathematical models can be used to predict the critical temperatures but the accuracy of such predictions is limited by inadequacies of the models in representing the actual heat transfer processes. For instance, the discontinuity between components such as the stator and winding is a physical barrier to heat transfer while the internal fluid dynamics also affects the heat transfer between components [5]. The thermal behavior of an electric machine depends not only on the operating point but also the construction method and material which affects the interface heat transfer [6]. In addition, knowledge of the electromagnetic losses generated during operation is also required in order to obtain an accurate representation of the final machine temperature. Comprehensive thermal analysis of an electric machine would therefore require estimates of the effective interface thermal conductance and amount of electromagnetic heating in the components as well as knowledge of the convective cooling caused by the rotating flow.

Numerical models such as those used in a Computational Fluid Dynamics (CFD) analysis are preferred to study the effects of convective cooling in electric machines [7]. On the other hand, lumped parameter models have proven to be useful for on-line temperature monitoring in electric machines but are insufficient in predicting the internal convection heat transfer accurately [8]. However, such models are shown to be useful to estimate the interface thermal conductances of electric machines through the

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Nomenclature

Greek

ε	prediction error
κ	interface thermal conductance (W/(m^2 K))
v	stator core volume (m^3)
ω	rotation speed (rad/s)
φ	input–output data
τ	torque (N m)
θ	model parameters
υ	kinematic viscosity (kg/(m s))

Subscripts

cu	copper
e	eddy current
h	hysteresis
mg	magnet
wd	winding
B	magnetic flux density
C	thermal capacitance (J/kg)
f	fundamental frequency (Hz)
h	heat transfer coefficient (W/(m^2 K))
I	current (A)
K	thermal conductance (W/K)
P	heat generation rate (W)
R	resistance (Ω)
Re	Reynolds number
T	temperature (°C)
y	response data

implementation of inverse methods [9]. Attempts have been made to couple inverse modeling methods with numerical analysis for the design of electric machines [2]. In this paper, a method combining a reduced order lumped parameter model and high fidelity numerical model is explored with the aim of achieving more accurate temperature prediction in a permanent magnet electric machine which is illustrated in Fig. 1. The introduction of thin material at the component interface of a numerical model of the machine is better able to simulate the imperfect contact and the presence of insulating material. An inverse identification technique is proposed to estimate the equivalent thermal conductance of the thin material as well as the electromagnetic losses generated in the permanent magnet. A constraint least square algorithm coupled to an analytical solution of the one step ahead predictor of temperature is used for parameter estimation. The current parameter estimation method gives a weighted average value of the parameters by using the transient input–output data measured through a series of experiments. The method is a practical approach towards improving the modeling accuracy of electric machines to achieve more reliable temperature predictions.

2. Electromagnetic losses

The electromagnetic losses generated in a permanent magnet electric machine are caused by the resistive heating of the stator winding, eddy current heating and hysteresis behavior of the stator core while the permanent magnets are also subjected to eddy current heating. In this analysis, the components of electromagnetic losses are calculated analytically, measured directly or determined from a parameter estimation process which will be presented in Section 4.1.

2.1. Copper loss

Copper loss is caused by the resistive heating of the stator winding which is commonly constructed from copper wires. In an alternating current (AC) machine, the copper loss (P_{cu}) per phase is calculated from the RMS phase current (I) and the winding resistance (R) which is shown in (1) to be temperature dependent. T_{wd} is the winding temperature while $R_0 = 0.015\ \Omega$ is the winding resistance at a temperature of 20 °C and α is a material dependent constant which is equal to 0.00393 for copper.

$$P_{cu}(T_{wd}) = I^2 R_0[1 + \alpha(T_{wd} - 20)] \tag{1}$$

2.2. Core loss

The core loss is caused by eddy current and hysteresis loss generated in the stator core due to the fluctuating magnetic flux. The magnetic flux is assumed to vary sinusoidally with time in an AC machine. This allows the core loss to be expressed as functions of the peak flux density (B) in the core and the frequency (f) of the fluctuations. Components of the core loss are described by the following relationship

$$P_e = k_e v f^2 B^2 \quad \text{and} \quad P_h = k_h v f B^{\beta} \tag{2}$$

where P_e and P_h is the eddy current and hysteresis loss component respectively. The volumed of the core material is denoted by v while k_e and k_h are the eddy current and hysteresis loss constants respectively which are material and geometry dependent. For example, k_e is dependent on thickness of the laminate used for constructing the core as well as the conductivity of the laminate material. Similarly, β, known as the Steinmetz constant is dependent on the hysteresis behavior of the core material. These constants are typically provided by the material manufacturers. In this analysis, the total core loss is determined directly from measurements taken from an open load test which will be described in Section 3.

2.3. Magnet loss

The magnetic flux density in the air gap varies sinusoidally with time as a result of the interaction between the field set up by the permanent magnet and the stator winding. On top of the main flux variation, there are also small ripples in the air gap flux which

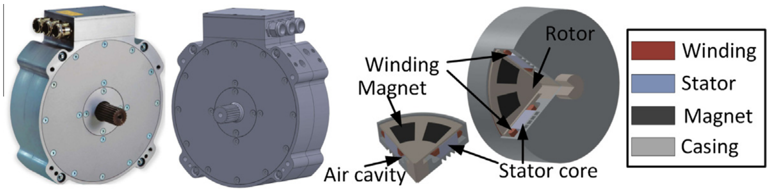

Fig. 1. Illustration of the test device: a permanent magnet electric machine.