Determination of Thermal Model Parameters for Stator Slot Using Numerical Methods

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Abstract— The aim of the method detailed in this paper is to get the equivalent thermal model parameters for stator with complex slot geometries. The method is based on the discretization of the geometry using a Finite Integration Technique to calculate equivalent thermal parameters with a good accuracy.

1. INTRODUCTION

In the thermal modeling of electrical machines, one of the main problems concerns their winding where the temperature often rises to its maximum value. Temperature rise in stator windings decreases insulation system performances, can reduce life time of the motors and may even lead to the motor failure [1, 2]. Appropriate models for the windings are necessary to find the hot spot of the machine [3]. They can then be integrated in the overall thermal modeling of the machine to be more accurate. The usual approach is the application of lumped parameter which is used for a very long time [1, 2, 4, 5]. The demerit of this method concerns the determination of the model parameters with a good accuracy when complex geometries are considered [4, 6]. The objective of the present study is then to describe an accurate thermal model parameters with low calculation cost for stators with complex slot geometries, allowing the estimation of maximum and mean temperatures in the winding. The method proposed here is based on the discretization of the geometry using a Finite Integration Technique (FIT) in order to obtain a first order equivalent thermal model for the transient analysis of one desired temperature in the slot.

2. WINDING MODELING

The homogenization of the winding is first necessary to obtain thermal modeling of the stator slot that is a complex heterogeneous structure requiring careful modeling. The objective is then to replace the conductors and the resin by one homogenous material that reproduces a similar thermal behaviour. Several techniques can be used to determine the effective thermal conductivity λ_e of the composite material; its value can be obtained from experimentation, from average calculation using numerical tools considering random geometries or from an analytical approach [7]. Here Milton's estimation has been considered in order to obtain the equivalent thermal conductivity. It can be used for any composite made of two isotropic randomly distributed phases. Microstructural informations are included in Milton's homogenization such as the shape of inclusions that is considered

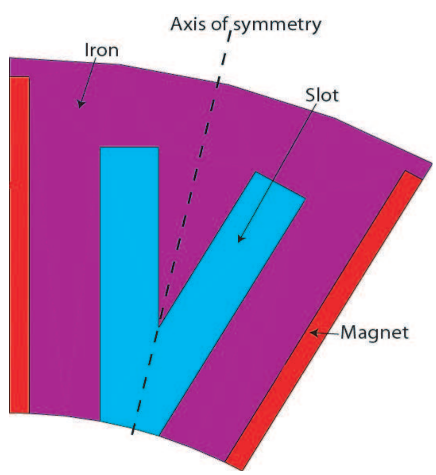


Figure 1: Stator slot of flux-switching machine.

cylindrical [8]. Considering a composite made of circular copper conductors and a resin matrix with thermal conductivity 401 and 0.25 W/m/K respectively, the application of this estimation gives an effective conductivity of the winding of 0.8469 W/m/K for a 50% filling rate. The study does not consider insulated conductors because of the enamel thermal property that is similar to the one of resin.

3. EQUIVALENT THERMAL MODEL OF THE SLOT

The aim of this part is to determine one thermal model for each node of the slot (Figure 1). Here two cases with hypothesis are considered: uniform or piecewise uniform temperature on the boundary of the slot.

3.1. Isothermal Slot Border

In this first case, the slot/iron interface is considered isothermal to be isothermal with temperature T_f. Splitting the temperature vector into two parts, the unknown temperatures T_i can be expressed as functions of temperature T_f:

Thermal equations:

$$\begin{cases} \mathrm{div}(\vec{\varphi}) + p = \rho C_p \dfrac{\partial T}{\partial t} \\ \vec{\varphi} = -\lambda \cdot \overrightarrow{grad}(T) \end{cases}$$

FIT ⇒ Matrix equations:

$$\begin{cases} -\tilde{S}\hat{\hat{\varphi}} + P = C \cdot \dfrac{dT}{dt} \\ \hat{\hat{\varphi}} = M_\lambda \hat{h} = M_\lambda \hat{S}^T T \end{cases} \Leftrightarrow \begin{pmatrix} T_1 \\ \vdots \\ T_n \end{pmatrix} + (\tau_{RC}) \frac{d}{dt} \begin{pmatrix} T_1 \\ \vdots \\ T_n \end{pmatrix} = \begin{pmatrix} R_1 \\ \vdots \\ R_n \end{pmatrix} P_0 + \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} T_f$$

Thermal resistances

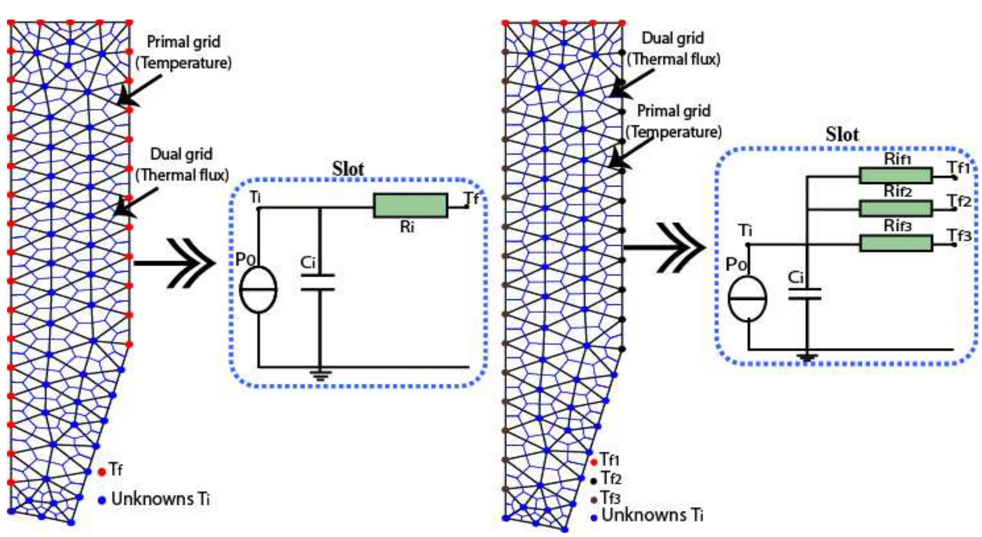
where R_i represents immediately the equivalent thermal resistances between the considered point i in the slot and the slot/iron boundary. (τ_{RC}) is a full matrix deduced from the inversion of the submatrix of $\tilde{S}M_\lambda\tilde{S}^t$ corresponding to the unknowns T_i multiplied by the corresponding thermal capacity matrix. A first order model could be deduced by choosing the highest eigen value $\tau_{\max}$ as time constant of the first order system, then the thermal capacities are deduced: $\tau_{\max} = R_i C_i$.

The Figure 2(a) shows the equivalent thermal model obtained with the first assumption.

Note that for symmetry reasons, the thermal study is focused only on one half of the geometry.

3.2. Non-isothermal Slot Border

In this second case, the slot/iron interface is non-isothermal but we can suppose that several parts of the border are isothermal at different temperatures (Figure 2(b)). Here for this example, three parts are isothermal at T_{f1}, T_{f2} and T_{f3}. As seen in the first case, the unknowns temperature T_i



(a) Isothermal slot border (b) Non-isothermal slot border

Figure 2: Equivalent thermal models of half of the slot.

can be expressed as functions of different temperatures T_{f1}, T_{f2} and T_{f3}:

$$\begin{pmatrix} T_1 \\ \vdots \\ T_n \end{pmatrix} + (\tau_{RC}) \frac{dT}{dt} \begin{pmatrix} T_1 \\ \vdots \\ T_n \end{pmatrix} = - \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} \cdot T_{f1} - \begin{pmatrix} y_1 \\ \vdots \\ y_n \end{pmatrix} \cdot T_{f2} - \begin{pmatrix} z_1 \\ \vdots \\ z_n \end{pmatrix} \cdot T_{f3} + \begin{pmatrix} R_1 \\ \vdots \\ R_n \end{pmatrix} \cdot P_0$$

The thermal resistances of the Figure 2(b) are calculated as following:

$$R_{if1} = \frac{R_i}{x_i}, \quad R_{if2} = \frac{R_i}{y_i} \quad \text{and } R_{if3} = \frac{R_i}{z_i}.$$

4. SIMULATION RESULTS

A stator slot of flux-switching machine is considered to validate the proposed equivalent thermal model. Figure 3 presents the simulation results obtained for the hot spot, including the comparison with the finite element method (FEM) implemented in the ANSYS software.

Using a FEM model taking into account the presence of the iron as a reference, the results obtained with the equivalent model in the static and transient analyses present a good accuracy in the case of the non-isothermal border. The isothermal-border hypothesis, giving the smallest thermal model, seems here to be inadequate, leading to a too low hot spot temperature.

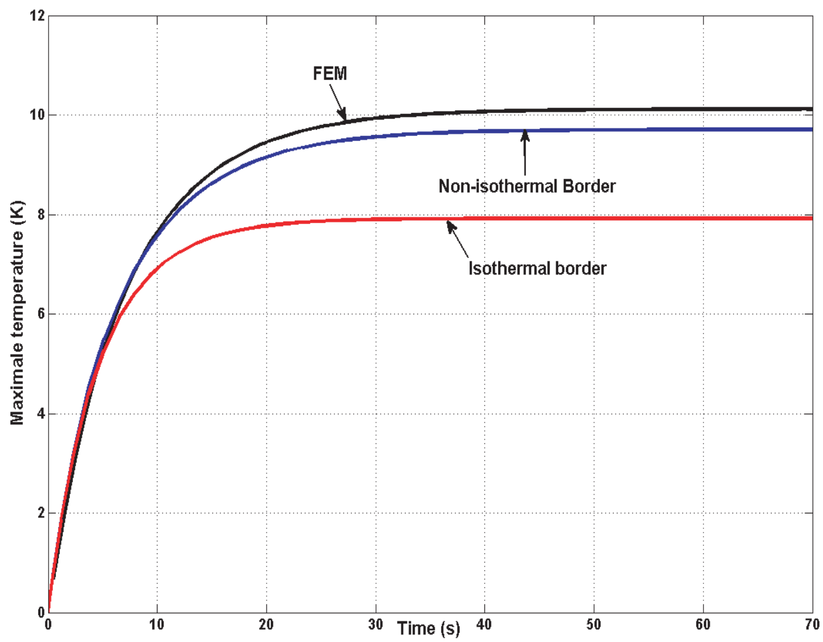


Figure 3: Simulations results.

5. CONCLUSION

A new methodology using a mesh-based numerical method (FIT) in order to obtain the model parameters has been presented with aim of evaluating quickly one particular temperature in the slot (hot spot). For more complex geometries, non-isothermal slot border should be taken into account in the equivalent thermal model in order to calculate the parameters of the model with a good accuracy.

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