Equivalent Thermal Model of Stator Slots using FEA

Adolfo Dannier
DIETI
University of Napoli Federico II
via Claudio 21, 80125 Naples
(Italy)
adolfo.dannier@unina.it

Andrea Del Pizzo
DIETI
University of Napoli Federico II
via Claudio 21, 80125 Naples
(Italy)
andrea.delpizzo@unina.it

Luigi Pio Di Noia
DIETI
University of Napoli Federico II
via Claudio 21, 80125 Naples
(Italy)
luigipio.dinoia@unina.it

Renato Rizzo
DIETI
University of Napoli Federico II
via Claudio 21, 80125 Naples
(Italy)
renato.rizzo@unina.it

***Abstract*— The rapid evolution of electric propulsion requires the design of high-performance electric motor. During the operations, the electric power train can operate in critical ambient condition, with high mechanical and thermal stresses. Therefore, several accurate analyses/simulations must be done during the design procedure, with an increase of simulation time. The paper proposes a method to obtain an equivalent thermal model of the slots of a PMS M using the finite element analysis. The equivalent model is calculated solving an optimization procedure by means of heuristic method. Some numerical simulations are reported in order to show the goodness of the proposed solution.**

Keywords—Electric Aircraft propulsion, High Power Density Electric Motor, Permanent magnet, Thermal analysis,

NOMENCLATURE

$c_{p,v}$	[J/kg/K] Volumetric heat capacitance
h_a	[m] Equivalent conductor height
h_b	[m] Equivalent conductor width
h_c	[m] Slot height
h_s	[m] Spacer thickness
l_w	[m] Slot opening
k	[W/m/K] Thermal conductivity of the materials
q	[W/m^3] Volumetric heat generation
T_i	[K] Maximum temperature in a conductor
$T_{e,h}$	[K] Maximum temperature in a conductors of equivalent slot
$\mathbf{E}$	[V/m] Electric field in the conductors
$\mathbf{H}$	[A/m] Magnetic field in the conductors
$\mathbf{J}$	[A/m^2] Current density distribution in the conductors
μ	[H/m] Magnetic permeability of the conductor materials
σ	[S] Conductivity of the conductor materials
τ_1	[m] Right and left lateral thickness of the insulation in the equivalent slot
τ_2	[m] Top and bottom thickness of the insulation in the equivalent slot

I. INTRODUCTION

Due to the high power per weight and the high value of efficiency, the permanent magnet synchronous machines are widely used in propulsion and in traction applications. Recently, there is a large interest in the hybridization/electrification of aircraft propulsion [1,2]. The application is characterized by different problems and difficulties, such as: the necessity to reduce the weight of the electric powertrain, the high reliability requested and the extreme environmental conditions. Therefore, the optimum design of an electric motor for aerospace applications is based on the knowledge of the required performances and on the use of good models for the simulations before the prototype realization.

The greatest part of the PMSM used in traction and propulsion are fed by inverter and the machine are made with a pole pairs number usually greater than the induction machine adopted in the same applications. This determines the necessity to supply the machine with a high value of fundamental frequency and the skin effects and iron losses become important sources of losses. Besides, the necessity to reduce the sizes of the motor makes difficult the heat dissipation. Therefore, the thermal analysis plays an important role for the choice of the cooling system during the design procedure.

The topic of thermal management of high-power density electric motor is widely treated in literature. For example, a new cooling method for the end-windings is proposed in [3], where is analyzed and modelled the behavior of a noninvasive cooling system that provides a uniform cooling of machine's winding through a direct cooling method. Instead in [4] an optimization of machine housing based on evolutionary algorithm is performed for a totally enclosed fan cooled electric motor (TEFC). Often the propulsion motors are used in overload for a short duty ratio, determining some difficulties in thermal management. About that, the paper [5] analyzes the correlation between the quality of slot impregnation and the thermal behavior of the machine during short transient. Using a sensitive analysis of a lumped parameters models, the results show that the temperature behavior is affected by the quality of slots manufacture.

Focusing the attention on the hybrid distributed propulsion for aircraft, it is plausible to consider that most of the operating time of electric motors occurs during the take-off and the climb phase. Usually, the durations of this stage are a few hundred second and this allows the possibility to further reduced the weight of electric motors taking the advantages from the overload capacity. Another important improvement which can be obtained exploiting the overload capacity, is the elimination or the undersize of the liquid cooling system. The aspect related to the type of adopted cooling system plays an important role in

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aerospace applications. In fact, a liquid cooling system reduces the reliability and increases the weight, while a natural cooling system avoids the use of a complex system composed of many parts. Obviously, this choice can be made only by means of an accurate thermal analysis able to provide accurate results of the motor thermal behavior.

A good thermal analysis can be carried out using large lumped parameters models which can be affected by errors/approximations. The use of multi-physics finite element software can improve the precision in the analysis but introduces also a high computational cost, mostly when different scenario must be simulated.

The aim of the paper regarding the development of a simplified thermal procedure based on finite element analysis and related to the study of temperature rise in a multi-layer slots with flat conductor. The method proposes the design of an equivalent “thermal slot” able to reduce the computational effort for the determination of transient temperature rise in a PMSM in overload condition. The equivalent thermal slot is obtained starting from a detailed magnetic and thermal finite element analysis and using a random walk optimization procedure. The proposed method is applied through some numerical simulations using the data of a 120 kW PMSM.

II. ANALYSIS PROCEDURE FOR LOSSES CALCULATION IN THE CONDUCTORS

As it is previous mentioned, the actual trend in the design of high-power density electric motor is based on the use of high frequency fed machine. This determine an increase of skin effect losses which must be correctly calculated.

It is well known from the literature [6], that the description of the skin effect model can be obtained starting from the Maxwell equations (1)-(3):

$$\nabla \times \mathbf{E} = -\mu \frac{d\,\mathbf{H}}{dt} \tag{1}$$

$$\nabla \times \mathbf{H} = \mathbf{J} \tag{2}$$

$$\nabla \cdot \mathbf{H} = 0 \tag{3}$$

And considering the Ohm’s law:

$$\mathbf{J} = \sigma \mathbf{E} \tag{4}$$

Applying the rotor to equation (2) is possible to obtain:

$$\nabla \times \nabla \times \mathbf{H} = \nabla\left(\nabla \cdot \mathbf{H}\right) - \nabla^2 \mathbf{H} = \nabla \times \mathbf{J} \tag{5}$$

Substituting eq.s (3) and (4) and considering constant both the permeability and the conductivity, the following equations is calculated:

$$\nabla^2 \mathbf{H} = \sigma\mu \frac{d\,\mathbf{H}}{dt} \tag{6}$$

In the same manner, the relation (7) can be formulated for the electric field:

$$\nabla^2 \mathbf{E} = \sigma\mu \frac{d\,\mathbf{E}}{dt} \tag{7}$$

The solution of the two relations (6) and (7) gives the results of the skin effect problem. Usually the (6) and (7) are particularized in a quasi-stationary state, where the magnetic and electric field solutions are $\mathbf{H} = H\,e^{j\omega t}$ and $\mathbf{E} = E\,e^{j\omega t}$, obtaining:

$$\nabla^2 \mathbf{H} = j\omega\sigma\mu\,\mathbf{H} = \kappa^2 \mathbf{H} \tag{8}$$

$$\nabla^2 \mathbf{E} = j\omega\sigma\mu\,\mathbf{E} = \kappa^2 \mathbf{E} \tag{9}$$

The analytical solution of the skin effect problem for a generic geometry is quite difficult. The most famous analytical solution for a transformer winding is proposed by Dowell in [7]; the obtained results are also applied for the winding with flat conductors utilized in rotating electrical machine. The use of semi-analytical elements is often used for rotating electrical machines, as it is shown in [8]. In order to reduce the computation cost of the skin effect with finite element, some equivalent circuit are used, as it is shown in [9].

A precise calculation of the skin effect losses in the windings of rotating electrical machine is necessary for an accurate thermal analysis and the calculation of motor efficiency. The finite element method allows the possibility to solve equations (6)-(7) using a detailed geometry of the motor, but a high computational cost is required. The presented approach is based on calculation of conductor losses using a high accuracy geometry. In this way it is possible to find a precise location of losses inside the windings and improve the calculation of motor efficiency. The overall reduction of time simulation and computational cost is reserved only to the thermal analysis of windings.

III. WINDING THERMAL ANALYSIS

The thermal analysis of the electrical machine winding is affected by many difficulties, like the presence of material with different thermal characteristics, difficult in the evaluation of airgap heat exchange coefficients, inhomogeneous materials around the windings (e.g. inside the slot and along the end-windings).

The most critical temperature values which must be checked are inherent the insulation system inserted in a slot. In fact, the conductor materials must be isolated by the iron parts using different insulation layers and the presence of a wedge and a spacer for multilayer windings aggravates the difficulty in containing temperatures. Usually the insulation is made with a good thermal performance which permits a rapid exchange of the heat generated in the motor, but an overload of the electric motor could cause a rapid degradation of the insulations.

The evaluation of the heat exchange coefficients of the many parts of electrical machine (es. airgap, stator frame etc…) can be solved using experimental tests [10,11] and the variation during the simulation could be considered by means of mathematical procedure [12]. The difference in thermal behavior of the different part of a winding introduces some simulation difficult if a 2D thermal analysis is used. Some modifications in the model are required or the necessity to use a 3D thermal analysis is necessary [13]. The presented paper is focused on the thermal analysis of a slots of a radial PMSM, therefore a 2D analysis is enough. The thermal analysis with finite element is based on the solution of the following thermal equations:

$$c_{p,v} \frac{dT}{dt} - \nabla \cdot \left(k \nabla T\right) = q \tag{10}$$

where "$c_{p,v}$" is the the volumetric heat capacitance [J/kg/K] , "k" is the thermal conductivity [W/m/K] and "q" is the volumetric heat generation. The solution of (10) in the considered domain with opportune boundary conditions, gives the thermal state of the motor.

- *Accurate thermal analysis of windings in the slot*

The accurate thermal analysis procedure for the slots starts with the calculation of skin effect losses in the conductors and the iron losses in the iron around the slots. After the determination of current density distribution as explained in section II, the losses are calculated for each conductor in the slots using the well-known integral relation (11):

$$p_{c,loss}(t) = \frac{1}{\sigma}\int_V J^2 \, dV \qquad (11)$$

Due to the main sizes of the conductor, insulation and slots, an accurate mesh must be utilized, determining a reduction of mesh size and an increase of computational costs.

The other terms of losses are due to the iron losses, magnet losses and mechanical losses. In the carried-out analysis, the magnet and mechanical losses are neglected because it is assumed that their effect on the slot temperature is negligible. The iron losses are evaluated through the five parameters formula [14]. The accurate method here described allows the possibility to check the temperature of the single conductors during a thermal simulation, giving a high accuracy in the results. Many times, this accuracy is not useful when a large transient simulation is required or when several thermal analyses must be done, how it happens for the overload in traction and propulsion applications. Then a simplified thermal analysis must be implemented.

- *Simplified thermal analysis based on finite element*

The simplified thermal analysis based on finite element reduces the detailed of geometry, creating an equivalent geometry of the slot. Starting from the results of the detailed geometry simulation and using the calculated Joule losses and iron losses, the flat conductors for each layer are commuted into one conductor with a Joule loss equals to the average value of losses per layer, Fig.1:

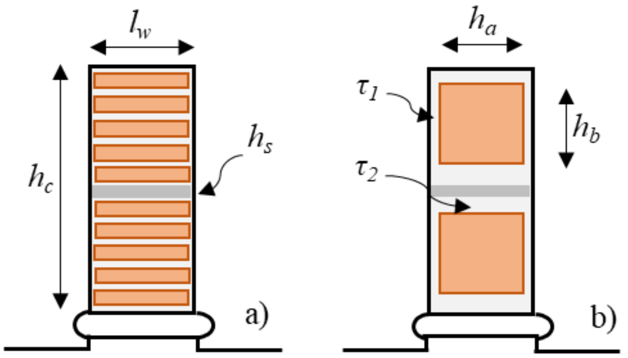

Fig. 1 a) Detailed slot with flat conductors; b) equivalent thermal slots

As it is highlighted in Fig.1 b), the geometry of the slot is the same, and only the main dimensions of the conductor are modified in order to obtain a thermal equivalent. The advantages of the transformation are related to the reduction of the complexity of the geometry and of the number of mesh nodes. As previous mentioned, the Joule losses are calculated from the detailed geometry considering the skin effect in each conductor. The average value of the obtained losses for each layer is fixed in the single conductor of the equivalent thermal slot. The main dimensions of the conductors in the equivalent slots and the equivalent thickness of the insulation is obtained by means of an optimization procedure. The objective function to minimize is the sum of the squared error defined as:

$$\min(SSE) = \sum_{h=1}^{m\cdot Q}\sum_{i=1}^{N_{c,h}}\left(T_i - T_{e,h}\right)^2 \qquad (12)$$

where the temperature $T_{e,h}$ depends by the thermal parameters of the slots and therefore from the geometric variable h_a, h_b, τ_1, τ_2. The constraints of the problem are:

$$\begin{cases} 2\tau_1 + h_b = l_w \\ 2\tau_2 + h_s + h_b = h_c \\ T_{e,h} \geq \min\left(T_i\right) \\ T_{e,h} \leq \max\left(T_i\right) \end{cases} \qquad (13)$$

The optimization problem is completely solved through finite element analysis and using a heuristic method based on random walk. The flow chart of procedure is shown in Fig.2.

IV. NUMERICAL SIMULATIONS

In order to verify the goodness of the proposal solutions, some numerical simulations are carried out. In particular, the analyzed motor is a PMSM with two layers distributed windings. The conductors are made with flat copper and each layer is insulated with an internal coat of Kapton® and an external coat of Nomex®. With the aim to study the behavior of the motor for a short duty, the length of simulation is fixed to 5 s. During the simulation it is supposed that the initial temperature of the machine is 40 °C and the temperature on the external boundary is kept to the initial value [3]. No convective and irradiation boundary conditions are defined and the airgap is considered as insulator [1]. The finite element analysis is carried out with FEMM 4.2 [15] coupled with Matlab ©.

TABLE I. MOTOR PARAMETERS

Rated Power	120 kW
Rated Angular speed	1500 rpm
Rated Current	290 A
Number of slots	48
Number of pole pairs	4
Number of layers	2
Number of conductors per layer	8
Type of Permanent magnet	Samarium-Cobalt
Thermal class	>200 °C
Cooling	TEFC

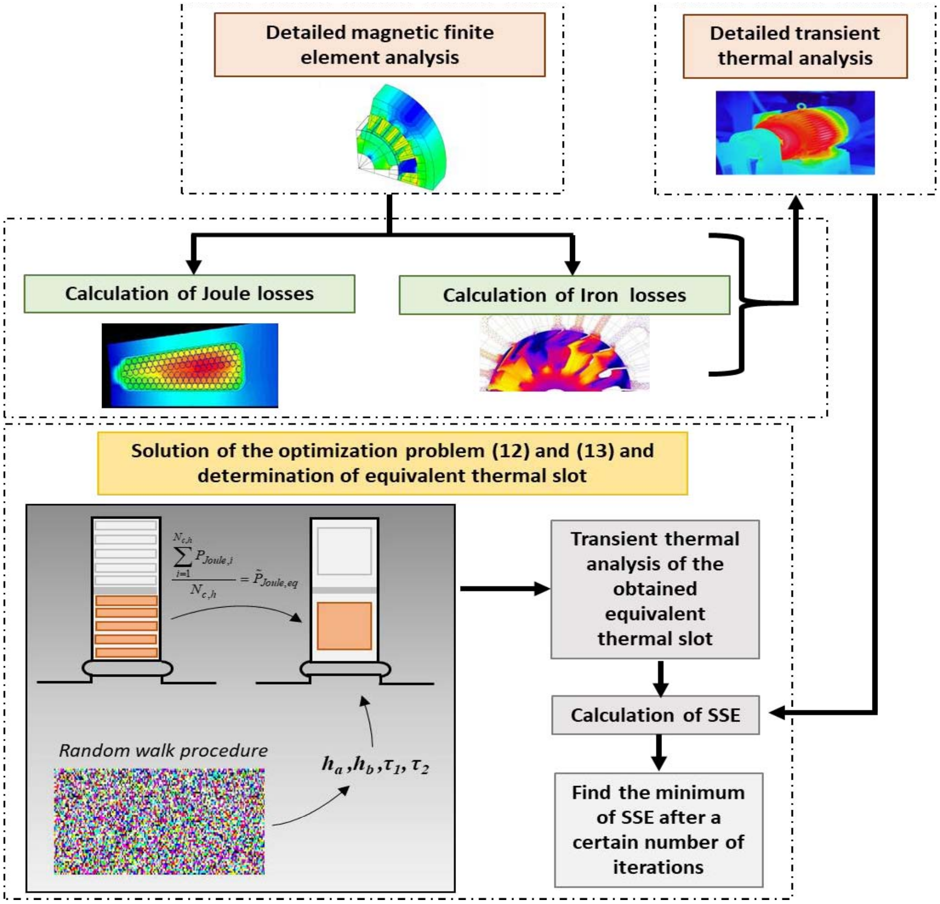

Fig.2 Flow chart of the equivalent thermal slot determination

As shown in Fig.2, the first step is the FEM analysis of the detailed geometry of the motor, with the calculation of the Joule losses considering the skin effect and the determination of the iron losses. The results of current density distribution in the conductors is reported in Fig.3.

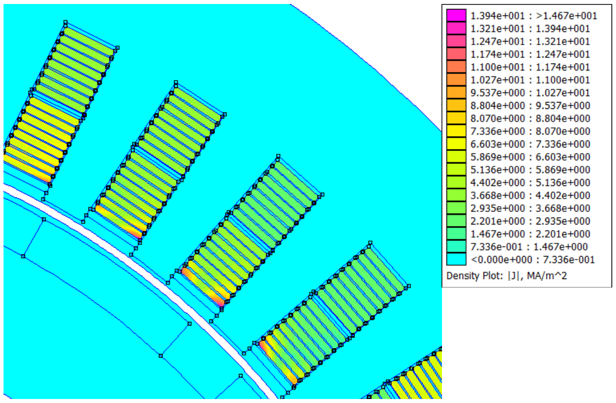

Fig.3 Current density [MA/m^2] distribution in the considered motor for 100 Hz fundamental frequency

The variation trends of the maximum temperature in the conductors of a selected slot and of a single layer are depicted in Fig. 4.

The differences of temperature are due to the skin effect and the different position of the conductor in the slots. In fact, the higher value of the temperature is reached in the conductor close to the airgap.

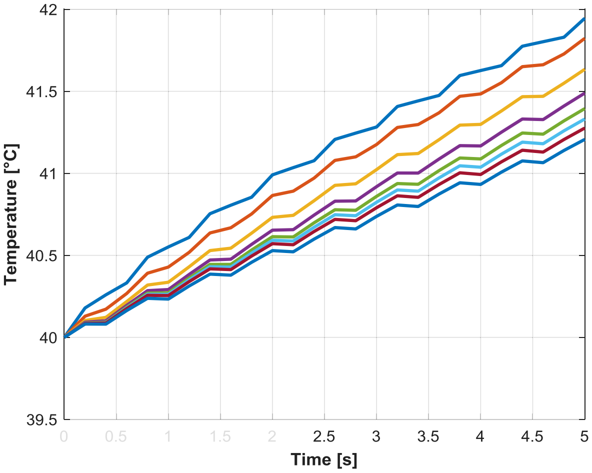

Fig. 4 Temperature rise in each conductors of one layers of the reference motor phase

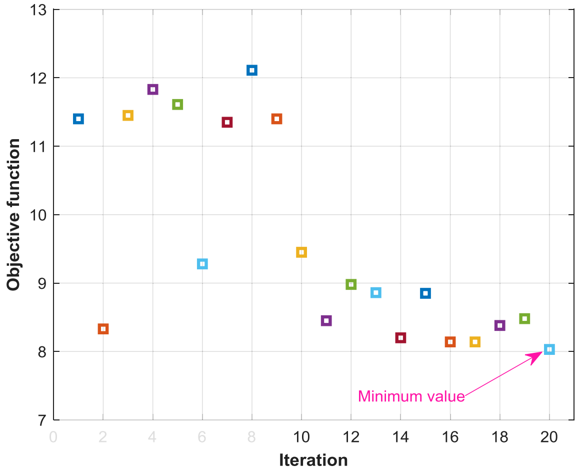

Fig. 5 Objective function variation during the optimization process

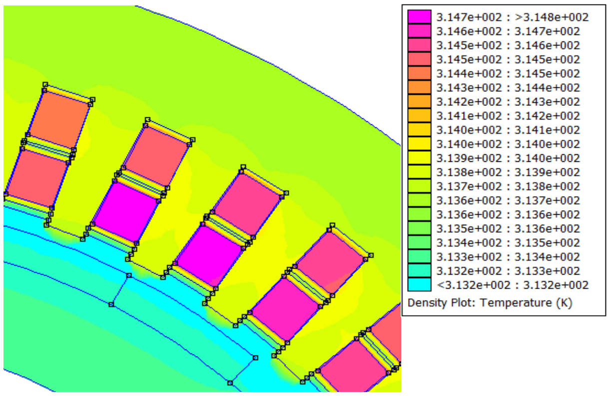

Fig. 6 Thermal finite elements analysis of the equivalent thermal slot

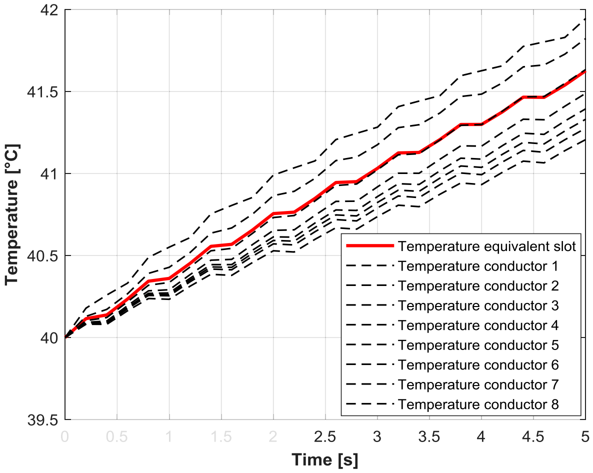

Fig. 7 Trend of temperature variation in a layer of equivalent slot and temperatures in the different slot conductors

Through the detection of the motor losses, it is possible to solve the optimization problem referred to eq.s (12) and (13). A total of 20 iterations are performed and the values obtained for the objective function (12) are shown in Fig. 5. The temperature map of the equivalent slot obtained with the minimum value of SSE after 5 s is depicted in Fig.6. The comparison of maximum temperature trends between the conductor and the equivalent thermal slot is shown in Fig. 7. As it is possible to note, the proposed model reproduces in a good manner the overall behavior of the maximum temperature in each conductor, with a maximum error of about 0.4 °C. Regarding the complexity of the simulation, the elapsed time for a thermal simulation decreases 452.5 s to 69.5 s.

V. CONCLUSIONS

The necessity to design high power density electric motors requires the development of simulation models capable of accurately analyzing the behavior of the motor during the performance. A critical aspect for electric motors concerns the thermal behavior. In the presented paper, a methodology to simplify the thermal analysis of the slot conductors during the transients was proposed. The numerical results carried out shows a good agreement between the classical FEM analysis and the proposed. Future works will be able to integrate the analysis in a sizing procedure and to verify the results with experimental tests.

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