

3D nodal method architectures for transient thermal modelling of an induction motor taking into account the variation of stator and rotor pole numbers

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Abstract

This paper is dealing with the transient thermal modelling of high-speed asynchronous machines for helicopter using nodal method. The main goal of this work is to choose a nodal network structure for a generalized numerical tool aiming to precisely predict the thermal behaviour of high speed asynchronous machines at steady state as well as in transient mode, taking into account geometry variations of the machine, particularly stator and rotor pole numbers variation.

In this paper the studied machine is a 29kW, 12000rpm high speed asynchronous motor including water cooling jacket.

1 Introduction

Nowadays, the electric propulsion system enters intensely in the aerospace world [1]. The machine technologies are compared in the context of their performances, dimensions and ability to satisfy the specific safety requirements. Once dimension and performance requirements are defined, the thermal design permits to identify the correspondence of the machine to the safety specifications.

In this article, thermal modelling using nodal method for high-speed asynchronous machines for helicopter use is discussed. This well-grounded method consists in 3D discretization of the induction motor into isothermal volumes linked together with thermal conductivities that represent different types of internal thermal transfers [2]. These thermal conductivities represent the conduction, convection and radiation phenomenon, as well as the mass flow in the cooling ducts. In this modelling of an asynchronous motor, the radiation phenomenon is neglected because of the relatively low level of reached temperature of such machines, particularly on their external surfaces.

While the variation of the values of the main dimensions does not influence on the calculation architecture, stator and rotor

tooth number variation requires a modification of the whole nodal network.

This work is aimed to compare different approaches of network architecture strategy, permitting to keep the same nodal network independently of the pole number variation. As a result, a symmetrical simplification stays valid, permitting to keep the minimal number of nodes without reducing the precision of the model with respect to the poles symmetries for rotor and stator.

2 Nodal network architectures

2.1 Context

The number of stator and rotor slots varies from one machine configuration to another, and usually it is not the same for rotor and stator as shown in Figure 1.

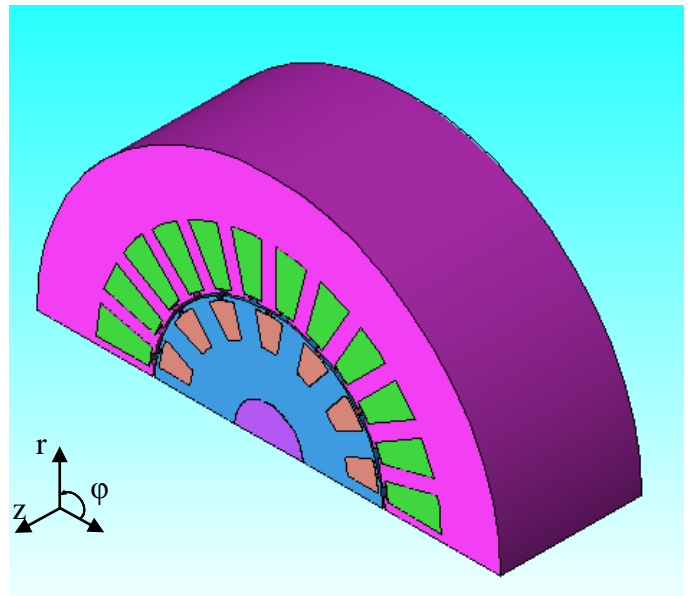


Figure 1: Machine halved geometry

Figure 2 shows that there are thermal resistances in ϕ -axis direction of cylindrical coordinate system, which doesn't

permit to reduce the thermal resistances network in the same way as if it was an electric circuit with parallel paths. So with the variation of number of slots, the number of ϕ -axis thermal resistances varies also, modifying the whole nodal network. Taking into account all the slot numbers leads to increase considerably the number of nodes, so modelling of each machine configuration separately leads to an important time cost.

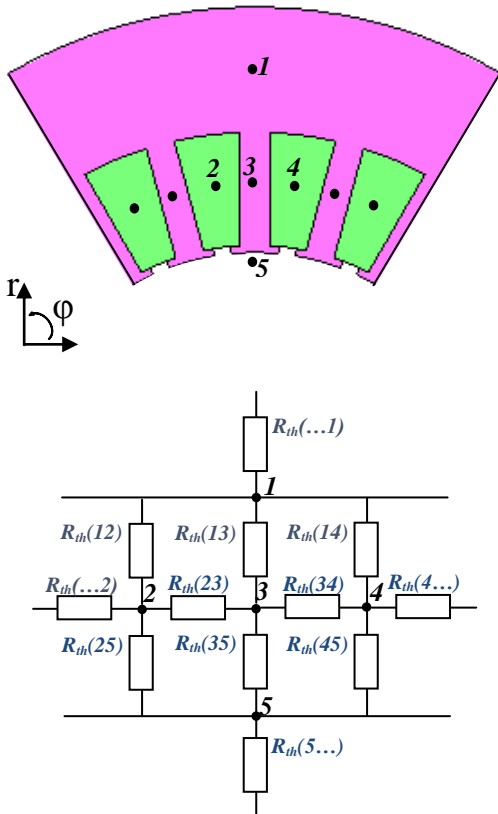


Figure 2: Thermal resistances network part

As a result, a generalized nodal network independent on slot number variation couldn't be developed without simplifications.

In this work three different nodal architecture strategies are studied. The results obtained with these architectures are compared to experimental test results from the literature in order to examine the accuracy of each one.

2.1 First architecture

Division of stator and rotor geometries by number of stator and rotor slots respectively may seem to be the most evident and feasible solution, because in that case the number of nodes is the same for no matter what motor geometry, and so the nodal network architecture remains constant.

However, as it could be seen in Figure 3 the pole angle of the stator is rarely the same as the pole angle of the rotor.

So the thermal flux generated in the stator does not correspond to that of the rotor, so the thermal model based on this theory is not accurate.

It seems to be interesting however to propose some simplifications in order to keep this architecture and to compare it with the other approaches.

As one of the proposed simplifications it could be suggested to introduce a coefficient depending on ratio of rotor and stator slot numbers permitting the adjustment of stator and rotor heat fluxes (along the radius) in accordance with chosen rotor or stator pole angle.

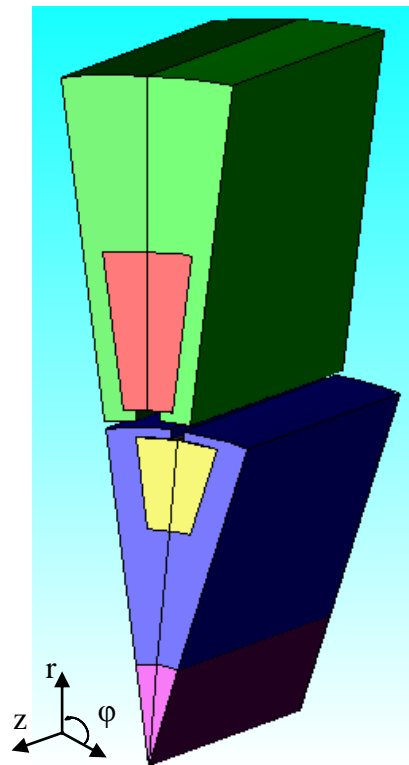


Figure 3: Stator and rotor geometry divided by number of stator and rotor slot numbers respectively

2.2 Second architecture

As the slots, and as a consequence electrical windings inside the slots, are thermally isolated in the radial and orthoradial directions, the ϕ -axis resistances between slots and teeth are high enough so that the heat exchanges in this direction could be neglected. The equivalent resistances taking into account stator and rotor slot numbers variation could be easily calculated without changing number of nodes as shown in Figure 4.

This simplification leads to introduce a coefficient permitting to adjust the contact surface among winding, tooth and yoke.

The advantage of this method is the fact that it permits to model the whole machine in such a way that thermal flux passing between stator and rotor is appropriate and the number of nodes remains constant.

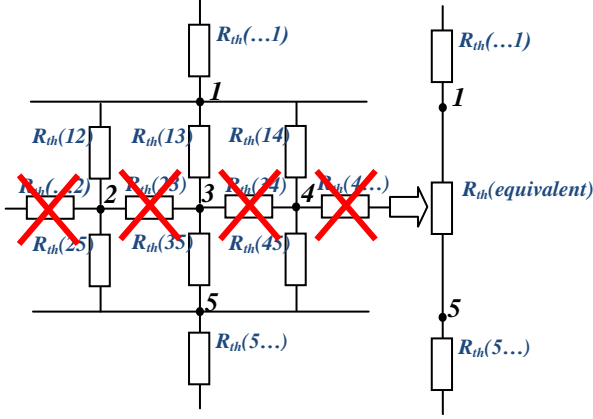


Figure 4: Equivalent resistance principle

2.3 Third architecture

The third method does not introduce any additional simplifications into the nodal method. In order to compare the two methods presented earlier, the nodal network taking into account all the resistances in all the directions is realized for a specific asynchronous machine.

The equivalent circuit for this method is the same as this of the second architecture, except that this time the ϕ -axis thermal resistances are taken into account as in Figure 2.

Taking into account of all the stator and rotor poles increases considerably the total number of nodes of the network. So with the variation of slot number the number of nodes varies also. The change of the number of nodes leads to the change of matrixes representing algebraic equations of the differential equation as one presented below. The creation of the matrixes with high number of elements is a time consuming process and could be inadmissible if a fast thermal analysis is needed.

$$\rho V c_p \cdot \frac{T_n^i - T_n^{i-1}}{\Delta t} + \sum \frac{T_n^i - T_m^i}{R_{th,m,n}} = \phi_n$$

with ρ – mass density of the considered volume [kg.m^{-3}], V – volume represented by its node n [m^3], c_p – heat capacity of the node n [$\text{J.kg}^{-1}.\text{K}^{-1}$], T – absolute temperature [K], Δt the time step [s], $R_{th,m,n}$ – thermal resistance between the node n and a surrounding node m [K.W^{-1}] and ϕ_n – internal heat generation in the volume n [W]. m and n are spatial parameters and i is a time parameter.

2.4 Experimental validation

Due to confidentiality reasons the results of comparison of the calculation values and experimental results couldn't be presented in this paper. However, the three architectures are compared to the results issued from the literature. The work of Pil-Wan Hab et al. [3] from the Korean Institute of Electrical Engineers has been chosen as the reference. The

authors consider a 29kW, 12000rpm high speed asynchronous motor including water cooling jacket.

The design characteristics and loss values in steady state given in the article [3] are presented in the Table 1 and in the Table 2 respectively.

Items	Values	Units
Outer stator diameter	135	mm
Inner stator diameter	88	mm
Stack length	150	mm
Stator slot number	36	
Rotor slot number	34	
Current density of stator	18	A/mm^2
Current density of rotor	20.7	A/mm^2
Flux density of airgap	0.76	T
Electrical steel thickness	0.35	mm
Core loss at 1.5T/834Hz	139	W/kg
Rotor cage conductor	copper	

Table 1: Design parameters of the machine

Items	Values	Units
Stator copper loss	622	W
Rotor copper loss	453	W
Iron loss	420	W
Mechanical loss	197	W
Stray load	863	W

Table 2: Loss values in steady state

3 Results and discussion

3.1 Measured results from the literature

The results of experimental tests provided by the authors in [3] are presented in Figure 5.

The temperatures of rear and front side end windings and of slot winding after 100 min of functioning of the machine are following: 80.4°C, 75.2°C and 65.5°C respectively.

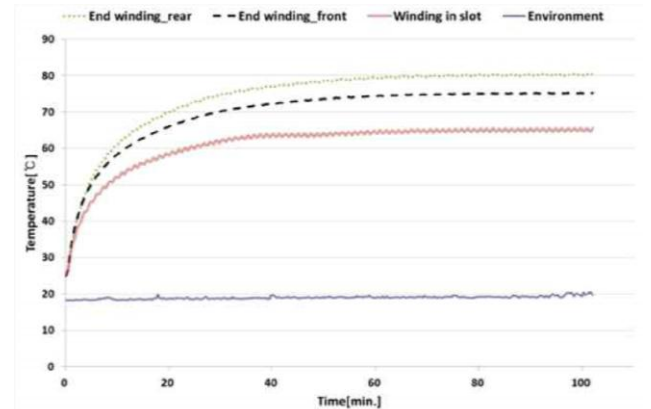


Figure 5: Measured temperature distribution

3.2 Results of the three architectures

Some values of losses, material properties and heat transfer coefficients presented in the article [4] were taken into account for the finite difference calculation.

The geometry details of the tested machine, such as insulation characteristics, winding parameters, slot type, cooling channel geometry etc., were not specified in the article [3]. So the geometry details for this machine were figured out basing on the design methodology from [4]. As the machine from [3] represents a totally enclosed machine all the missed loss values and heat transfer coefficients inside the machine were estimated basing on [5], [6], and [7].

Results for the first architecture:

The results of the thermal analysis using first method in transient mode are presented in Figure 6.

All the contact surfaces of the rotor are multiplied by the coefficient equal to the ratio of rotor and stator slot numbers.

All the losses for this method as well as all the dimensions and contact surfaces are multiplied by the adjustment coefficient.

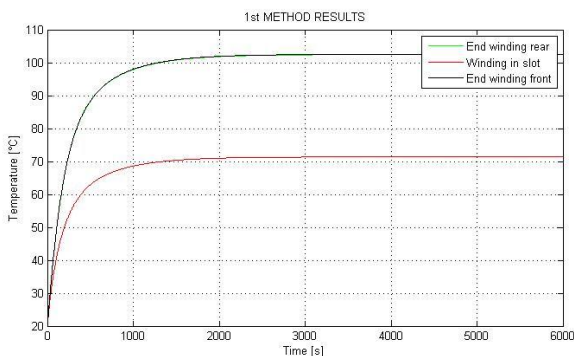


Figure 6 : Stator winding temperature distribution for the 1st nodal network architecture

As it is seen from the graph the temperature of the rear side stator enwinding is about 103 °C, of the front side –102°C and winding temperature inside the slots is about 71°C.

Results for the second architecture:

Nodal network of the second method takes into account the whole machine geometry. The principle simplification of this method is neglecting heat flux in orthoradial direction between slots winding and teeth. This simplification is justified by the fact of low heat conduction characteristics of slot insulation and the adaptation of surface contact between yoke and slot.

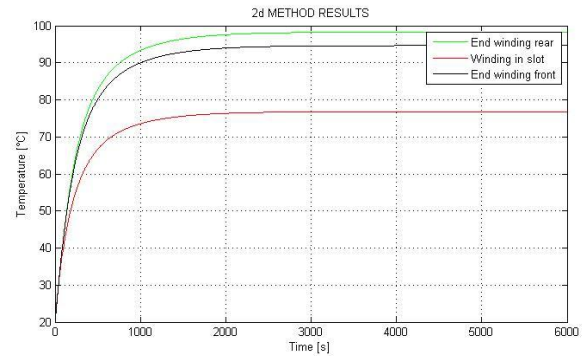


Figure 7: Stator winding temperature distribution for the 2nd nodal network architecture

The results using the second method are presented in Figure 7. The temperature of the stator rear side enwinding is equal to 98°C, of that one of the front side is equal 94°C. The winding temperature inside the slots is about 74°C.

Results for the third architecture:

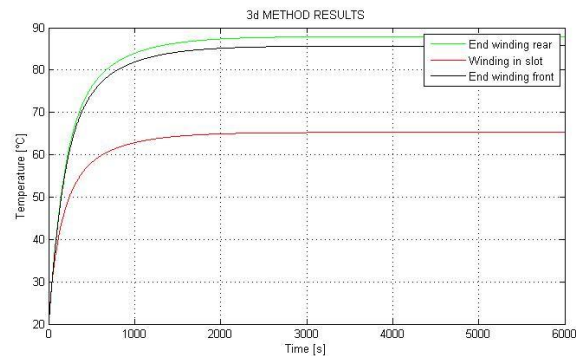


Figure 8: Stator winding temperature distribution for the 3rd nodal network architecture

The third method takes into account the thermal paths in all the directions, including those between slots and tooth.

This method has an important time cost and the developed nodal network for this specific machine is not acceptable for other electrical machine configurations with different numbers of stator and rotor slots.

Particularly this nodal network is composed of 204 nodes. Taking into account 2378 time steps the number of calculation points increases up to 485 000.

So it is evident that such a large number of nodes is not admissible if a generalized model, permitting to provide thermal analysis of whatever machine structure, is needed.

According to results of nodal method using third nodal structure the temperature of the stator rear side enwinding is equal to 88°C, of the front side - to 86°C and winding temperature inside the slots is about 65°C.

3.3 Results comparison

In the Table 2 the results of the three proposed calculation methods as well as the test results taken from the literature are presented.

As it was mentioned before, some geometry details and thermal parameters that were not presented in [3], have been estimated analytically to complete our calculation. So the difference between measured and calculated results could be easily explained by the inaccuracy of supposed values.

	Test results	1 st method	2 nd method	3 rd method
Stator end winding (rear)	80.4°C	102.6°C	98.3°C	87.9°C
Stator slot winding	65.5°C	71.4°C	73.8°C	65.3°C
Stator end winding (front)	75.2°C	102.4°C	94.6°C	85.7°C

Table 2: Results of thermal modelling and experimental test

The tendency of all the three methods to overestimate the temperatures is positive in point of view of the security requirements of the machine and its environment.

Nevertheless, the experimental results have to be treated carefully, knowing the high uncertainty of sensors and particularly their position sensibility in the perspective of consideration of the points with important temperature gradients.

This method permits to take into account the heat fluxes in all the directions, to keep low number of nodes, as a consequence to realize a fast thermal analysis. However, this method overestimates the temperature rise almost twice and doesn't give realistic temperatures.

It is clear that the third method taking into account all the heat flux paths and not requiring introducing of any adjustment coefficient is the most accurate. However as it was discussed earlier it is not admissible if a generalized model is needed.

The second method overestimates the temperature values for about 13%. It could be useful in case if fast calculation and moderate precision are required.

6 Conclusion

In this article, three nodal network architectures were compared to experimental test results from the literature. The study was carried out on a 29kW high speed asynchronous machine.

The difference between calculated values and experimental test results could be explained by the fact of lack of information about heat sources distribution inside the

machine, geometry details such as winding length, number of turns per phase, number of parallel path etc.

As a result, it appears that the nodal architecture neglecting the heat flux in orthoradial direction between slots and teeth could be a good compromise solution for a generalized thermal model of helicopter electric propulsion system. This method permits to keep a better time cost of the model as well as a moderate precision.

Acknowledgements

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