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Thermal Sensitivity Analysis of a High Power Density Electric Motor for Aeronautical Application

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Abstract—This paper studies the sensitivity of the thermal behavior of a high power density electric motor to some parameters. The machine is conceived for aeronautical application. It is of Permanent Magnet Synchronous type totally enclosed, configured with a double cooling system around the stator and in the shaft. A Lumped Parameter Thermal Model of the motor is primarily elaborated to explore hot spot points. Then, the thermal parameters, related to the heat evacuation from the critical zones, are investigated. Windings' thermal conductivity as well as laminations' one appear to influence the most the hottest regions of the machine.

Keywords—sensitivity analysis, thermal design, LPTM, electric motor, aircraft propulsion

I. INTRODUCTION

The development and design of compact electrical machines with high power densities (generally used in transportation propulsion) require specific heat evacuation techniques to prevent temperature increase. Consequently, during the design process, it is essential to predict accurately the temperature of the motor. Indeed, limited by thermal constraints, electromagnetic components are subject to troubles in their operation when reaching some high temperature. In some cases, this can lead to a complete failure of the machine. Conceiving electric motors with super high power density, high efficiency, and enough reliability is a genuine challenge, in particular when considering the constraints in the transportation domain such as compactness. Electric motors are currently applied in ground vehicle propulsion and are simultaneously under investigation in the aeronautical sector for electric propulsion of aircraft [1].

Numerous authors have evoked the thermal analysis of electric machines in their studies ([2]–[10]) and have highlighted the importance of some thermal considerations in many of their works. Based on these facts, improving the performance of electrical machines requires an investigation of the influence of each parameter participating in temperature determination. This is particularly important to allow machine designers to opt out appropriate materials, and to define the adequate cooling technology. Besides, sensitivity studies are being used in this area to evaluate the influence of some important parameters, assumed to be the control factors in the thermal management process of electric machines for terrestrial application [11], [12]. From these factors, one can cite heat transfer coefficients, cooling locations, material orthotropic thermal properties, heat distribution, mass flow rate of coolant and stator geometry shape. Other authors used the sensitivity analysis to reduce previously developed thermal models [13], [14].

These studies were conducted on low to average power densities electrical machines whose application will remain far from that for electrified aircraft propulsion requiring high and super high power densities motors. Compared to classical existing electric machines, in motors with high to super high power densities, the produced heat inside is much harder to extract since the thermal obstacles, and then the preponderant parameters, could be very different. For instance, increasing the external heat transfer coefficient may not be enough for specific parts of the motor. Indeed, it has been proved that the same cooling topologies would not be adequate to decrease temperatures when applied to machines of this type. This paper deals with the study of several parameters for a super high power density electric motor, by 1) developing analytically a Lumped Parameter Thermal Model (LPTM) and solving it, 2) identifying hot spot temperature locations and 3) simulating the model under different scenarios using MATLAB software. Herein, the case study motor is a permanent magnet synchronous machine of around 0.9 MW of power with around 98.5% efficiency. It is a TENV (totally enclosed non-ventilated) machine with a double liquid cooling system with water jackets around the frame and an axial flow in the shaft. Based on conduction and convection heat transfers, the elaborated nodal model is defined based on the composition of machine parts, the aerodynamics in the end-space region of the motor, as well as the characteristics of liquid cooling flows around the motor outer case and in the shaft.

II. LUMPED PARAMETER THERMAL MODEL

A. Analytical Model Presentation

To understand the importance of each component in the analytical model, a brief description of the (LPTM) technique is provided in this section. Basically, it is a modeling method that consists in discretizing a distributed system to apprehend its behavior. Based on certain assumptions reducing the system, it is often used in electrical problems as well as in thermal and heat transfer problems due to the analogy between electrical and thermal quantities.

In a solid configuration, the thermal energy balance at a point of an elementary volume ‘ $-V_i$ ’ (m^3) of the machine

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represented by the node ' i ' having a temperature T_i (K), is written as follows:

$$\rho c \frac{\partial T}{\partial t} - \text{div}(\vec{\phi}) - \dot{q} = 0 \quad (1)$$

where ρ (kg/m³) and c (J/kg K) are respectively the density and heat capacity of V_i . $\vec{\phi}$ (W/m²) and \dot{q} (W/m³) are respectively the heat flux density and produced heat.

Integrating over V_i , assumed homogeneous and isothermal, (1) can be rewritten as follows:

$$\rho_i c_i V_i \frac{dT_i}{dt} = \sum_{j,i \neq j} G_{ji} (T_j - T_i) + \dot{Q}_i \quad (2)$$

Considering the homogenization of the volume, characteristics of the elementary volume are indexed accordingly. G_{ji} (W/K) are thermal conductances connecting nodes in each heat transfer mode, defined as the ratio of the heat flux (W) Φ_{ij} (from i to j) in that mode, to the temperature difference (K) ΔT_{ij} (between i and j) inducing this heat flow: $G_{ij} = \Phi_{ij} / \Delta T_{ij}$. \dot{Q}_i (W) is the total heat production of volume V_i : $\dot{Q}_i = \dot{q} V_i$.

It is worth to mention that for heterogeneous components, conductances are calculated based on equivalent properties.

B. Thermal Coefficients

Newton's law of cooling characterizes the convection heat transfer, expressed as follows:

$$\Phi_{conv} = h S_{conv} (T_{ref} - T) \quad (3)$$

Φ_{conv} is the heat flux in convection mode, h (W/m² K), S_{conv} (m²) and T_{ref} (K) respectively denote the heat transfer coefficient, the surface of convection heat transfer and the reference temperature of the surrounding fluid (which is often equal to the ambient temperature or the fluid temperature far from the wall).

Nusselt number is the dimensionless form of the heat transfer coefficient h ($Nu = \frac{h L_{ref}}{\lambda_{fluid}}$ where L_{ref} is the characteristic length of the surface and λ_{fluid} (W/m K) is the fluid thermal conductivity).

Convection conductances are expressed by:

$$G_{j,i}^{conv} = 1 / h S \quad (4)$$

Conduction heat transfer takes place in a solid medium and its thermal model follows Fourier's law:

$$\vec{\phi}_{cond} = -\lambda_m \vec{\nabla} T \quad (5)$$

In this expression, $\vec{\phi}_{cond}$ is the heat flux density in conduction mode, λ_m is the thermal conductivity of the medium and $\vec{\nabla} T$ is the temperature gradient.

Conductance expressions for Cartesian and cylindrical geometries are expressed respectively by:

$$G_{j,i}^{cond,car} = \lambda_m s / L_{ij} \quad (6)$$

$$G_{j,i}^{cond,cyl} = 2\pi \lambda_m H / \ln(r_j - r_i) \quad (7)$$

where s is the cross section of the geometry, $L_{ij} = \|\vec{L}_{ij}\|$ (m) is the distance that separates nodes i and j , H (m) is the height of the cylindrical object, r_i and r_j (m) are the radii of the consecutive surfaces separating the adjacent nodes ($r_j > r_i$)

Radiation heat transfer is neglected in the present work.

C. Nodal network of the electric motor

The analytical modeling technique of the electric motor based on the LPTM is a platform to simulate the machine thermal behavior with respect to power losses and to perform sensitivity analysis. It has already been used many times in different works to predict motor temperatures and in particular for the Lexus 2008 [15], a motor similar to the present one.

As set forth, the motor is synchronous with permanent magnets of 20000 rpm rotational speed. Windings are made of copper wires impregnated in an epoxy resin and wrapped with a polyimide film insulator. Motor stator has 24 slots, each of 2.18×10^{-4} m² surface, wound with distributed windings. Rotor and stator laminations are made of a soft magnetic material: cobalt iron alloy, having a radial thermal conductivity of 46 W/m K, while permanent magnets are samarium-cobalt rare earth magnets of 10 W/m K thermal conductivity (Table I). Convection coefficients are determined based on [16]–[19]. Different types of losses produce heat in the motor and break out with temperature rise: Iron losses in stator and rotor laminations, Joule losses in windings and end-windings, aerothermal losses in air-gap and mechanical losses at the bearings. The estimation of these losses assumes a heat dissipation production of around 14 kW, with around 71% in windings and end-windings, 20% in stator lamination and the rest is distributed in rotor laminations, air-gap, and bearings.

Parameter Type	Characteristics		
	Machine zone	Value Source	Value
Convection Coefficient (W/m ² K)	Air-gap	$Nu = 0.409[\omega^2(e_{ag}/2)^3 r_{rot}/\nu_{fluid}^2]^{0.241}$ * [16]	200
	End-windings	[17]	100
	Stator	[18], [19]	2500
	Shaft		4000
Thermal Conductivity (W/m K)	Windings	[20]	1.5
	Laminations (radial direction)	Aperam Company; Soft Co-Fe magnetic alloy	46
	Frame	Aluminum	200
	Shaft	Steel	45
	Magnets	Sm2Co17	10

* ω is rotor speed in (rad/s), r_{rot} is the rotor radius (m) and ν_{fluid} (m²/s) is the air kinematic viscosity, e_{ag} (m) is the airgap thickness

TABLE I. Thermal Parameters Characteristics

Due to axial and angular symmetries, 1/(slot number*2) of the total motor design is considered in the modeling which simplifies the nodal network modeling of the motor to 1/48 and reduces considerably the calculation and simulation time. The temperatures in the machine are obtained for component nodes 1 to 15 depicted in Fig. 1 representing the axial and angular sections.

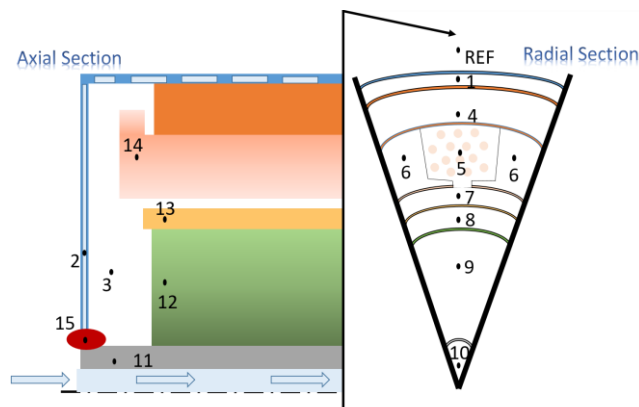


Fig. 1. Motor Nodes locations in axial and radial sections

The modeling radial section is taken at the exact middle plane of the machine since this is supposed to be the hottest region inside the machine (most distant from external heat exchange medium). Nodes 5 and 14 represent the windings and end-windings respectively, while stator lamination nodes are the 4th and 6th. Magnets and rotor laminations are represented by nodes 8 and 9 at their respective centers and by nodes 13 and 12 at their extremities. Air nodes 3 and 7 correspond to the end-space

cavities and air-gap region respectively. Two nodes are located in the frame: for the radial part, it is node 1 and for the lateral part, it is node 2. Bearings are represented by node 15. Finally, nodes 10 and 11 represent the rotor center and its end respectively. The cooling system around the motor and in the shaft is outlined in the sketch and corresponds to the reference node REF.

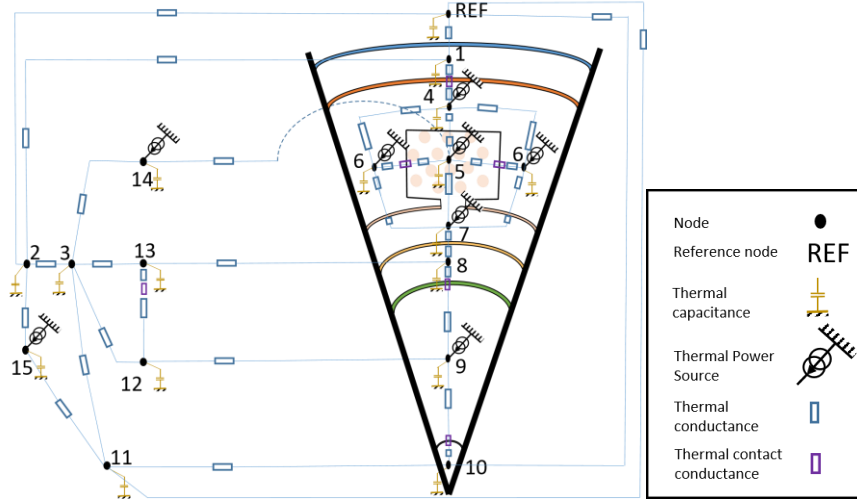


Fig. 2. Motor nodal network

The nodal network is developed analytically as shown in Fig. 2. Nodes are connected through thermal conductances as presented in Table II.

Conductance Type	Conductances $G_{i,j}$ between nodes i and j
Radial Conduction Conductance (7)	$G_{1-4} G_{4-5} G_{4-6} G_{8-9} G_{9-10} G_{12-13} G_{15-2}$
Cartesian Conduction Conductance (6)	$G_{1-2} G_{5-14} G_{8-13} G_{9-12} G_{10-11} G_{15-11} G_{5-14}$
Convection Conductance (4)	$G_{3-2} G_{3-11} G_{3-12} G_{3-13} G_{3-14} G_{5-7} G_{6-7} G_{7-8}$ $G_{ref-1} G_{ref-2} G_{ref-10} G_{ref-11}$

TABLE II. Conductances Types and notations

Thermal conductivities are defined for each homogeneous material according to its characteristics. For heterogeneous parts such as windings, stator and rotor laminations, some information is found in the literature based on experimental or numerical results. The particularity of windings according to machine type makes it difficult to find a general thermal conductivity approximation for all types. Therefore the initial thermal conductivity used in this study as well as the range of values were extracted from the numerical finite element study carried out on the same machine [20]. It is expressed in (8) with constants grouped in Table III where τ is the winding fill factor.

$$\lambda_{eq} = A + B\lambda_{imp} + C\tau + D\tau\lambda_{imp} + E\tau^2 \quad (8)$$

It leads to an overall equivalent thermal conductivity of around 1.5 W/m K.

Constants	A	B	C	D	E
Angular	2.05	0	-12.14	4.39	17.4
Radial	0.23	1.17	0.94	0.56	-0.57

TABLE III. Constants of correlation (8)

Convection coefficients are integrated into the model as given inputs calculated from empirical correlations or obtained from experimental data.

The considered cooling system consists of water jackets around the motor and an axial flow inside the shaft. The reference node stands for external liquid medium offering a coolant temperature and thermal characteristics. This liquid is supposed to exchange with external air thanks to an efficient heat exchanger not modeled here allowing to maintain the liquid temperature

equal to the external air one. The highest external air temperature is reached during taxiing phases at ground level and is supposed to be equal to 40°C.

The cooling fluid is water-glycol with 1065 kg/m³ density, 2.2567×10⁻³ Pa s dynamic viscosity, 3361 J/kg K specific heat capacity and 0.3937 W/m K thermal conductivity. The dimensionless Prandtl number Pr correlates between fluid properties: specific heat capacity (c_{fluid}), dynamic viscosity (μ_{fluid}) in (Pa s) and λ_{fluid} as in (9):

$$Pr = c_{fluid} \mu_{fluid} / \lambda_{fluid} \quad (9)$$

Stator channel is parallel to the shaft with 2.9 mm height and the liquid flows at a rate of 3.2×10⁻³ m³/s. Shaft channel has a circular section of 5 mm radius and 6×10⁻⁶ m³/s liquid flow rate. Liquid velocity is related to flow rate \dot{v} by:

$$\dot{v} = S_{ch} u \quad (10)$$

where \dot{v} is in m³/s, S_{ch} is the channel section in m² and u is the mean liquid velocity in m/s.

Convection coefficients for channel flows is calculated based on Nusselt number expression (cf. II.B) determined according to [18], [19] as follows:

$$Nu = \frac{\frac{f}{8} (Re-1000) Pr}{1 + 12.7 \left(\frac{f}{8}\right)^{1/2} (Pr^{2/3} - 1)} \quad (11)$$

In their correlation, Re is the Reynolds number characterizing the fluid flow of density ρ_{fluid} ($Re = \rho_{fluid} u L_{ref} / \mu_{fluid}$) and f is the friction coefficient depending on Re . This correlation is applied to get G_{ref-1} , G_{ref-2} , G_{ref-10} , and G_{ref-11} .

Heat sources are injected where losses occur. A capacitance is designated for each node but in the current work, only steady state thermal regime temperatures are investigated and the matrix of capacitances does not take part in this model. The reference node stands for external liquid medium offering a coolant temperature and thermal characteristics.

Resulting temperatures are presented in Fig. 3. The highest temperatures are in the windings and particularly in the end windings. This is due to the very high heat dissipation rates in these parts and to the relatively small value of thermal conductance between windings center and stator laminations. Permanent magnet temperature is also high, considering their thermal specificity. This is due to heat path length until reaching the shaft cooling and to the heat exchanged with the windings through the air gap.

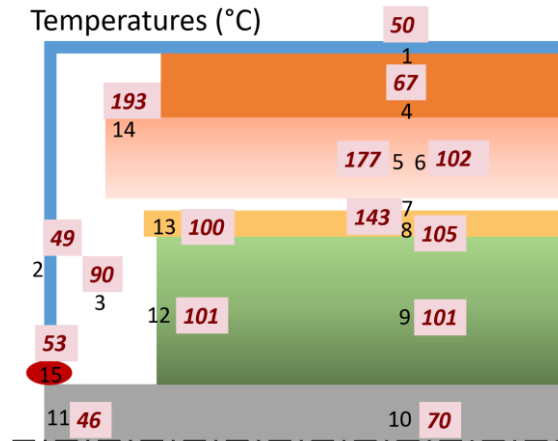


Fig. 3. Resulting temperatures in different locations of the motor

III. SENSITIVITY STUDY

In this study, three types of parameters are considered: the convection heat transfer coefficients, the thermal conductivities and the number of slots in the stator. The slot number in the machine stator is a physical variable usually set in the electric design phase; though, it can be modified respecting some constraints if it could eventually influence the temperature rise in the

slots and at the end-windings. The sensitivity study consists in simulating the model with different realistic values of some variables from these 3 sets. The parameters and the values are grouped in Table IV.

Parameter Type	Characteristics			
	Machine zone	Name	Range	Variation
Convection Coefficient (W/m ² K)	Air-gap	h airgap	200-300	+50%
	End-windings	h end-windings	100-150	
	Stator	h stator	2500-3750	
Thermal Conductivity (W/m K)	Windings	λ windings	1.5-2	+33%
	Laminations	λ laminations	46-61.33	
	Frame	λ frame	200-267	
Slots number	-		20-40	-

TABLE IV. Parameters Characteristics

A. Temperature Sensitivity to Thermal Coefficients

The results of the sensitivity study are depicted in Fig. 4-7 .

Changing frame conductivity or air-gap convection coefficient has no significant effect on temperature decrease neither in stator nor in rotor. It is quite consistent to obtain such results since the resistance between the frame and the stator is usually far lower than the other resistances in the heat evacuation path (in this case it is less than 4 % of the total resistance from the slot to the frame). While for air-gap convection coefficient, the fact that it links two high-temperature areas could explain its low influence.

Improving the convection heat transfer on end-windings does not influence but this targeted area, since it is the hottest point where there is a high heat production in a relatively small zone of the motor then no heat extraction from other areas can pass through end-windings. Thus, proceeding with end-windings cooling is recommended only when the rest of the stator parts are already below their maximum operating temperatures. In the other side, increasing the winding conductivity by 33% results in reducing considerably all of the winding temperature range but not that of the stator laminations. The results show that the heat extraction there depends on the lamination conductivity, which also indirectly influences slot temperature and less significantly the end-windings. The main heat production of the machine is in the windings and the heat flux conduction occurs mainly through the teeth side (ortho-radially) to the outside due to the much lower resistance in this way rather than directly from the slot radially to the laminations and since the laminations resistances between those two points is 33% of the total resistance.

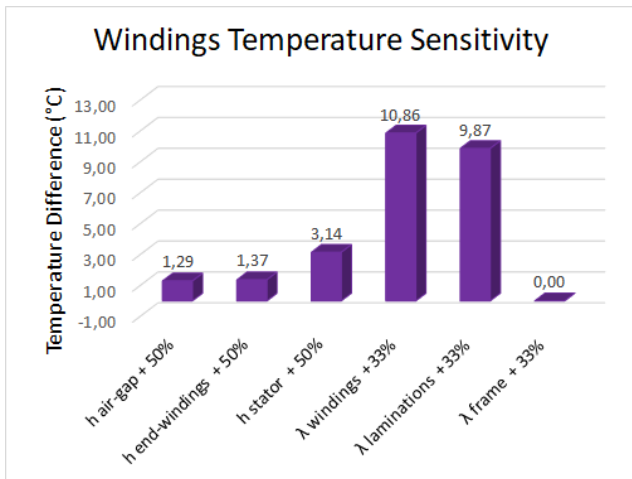


Fig. 4. Windings temperature sensitivity to parameters

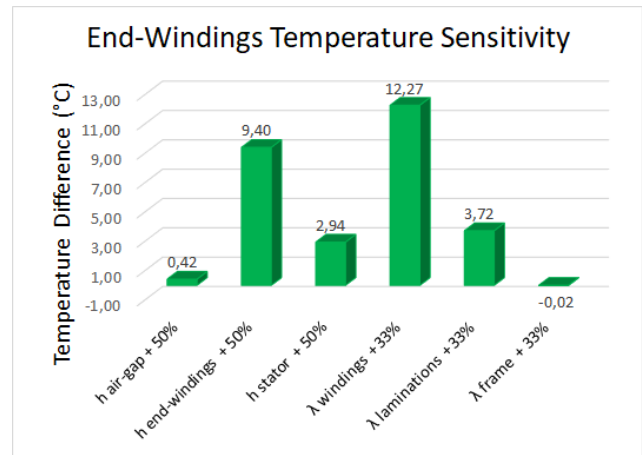


Fig. 5. End-windings temperature sensitivity to parameters

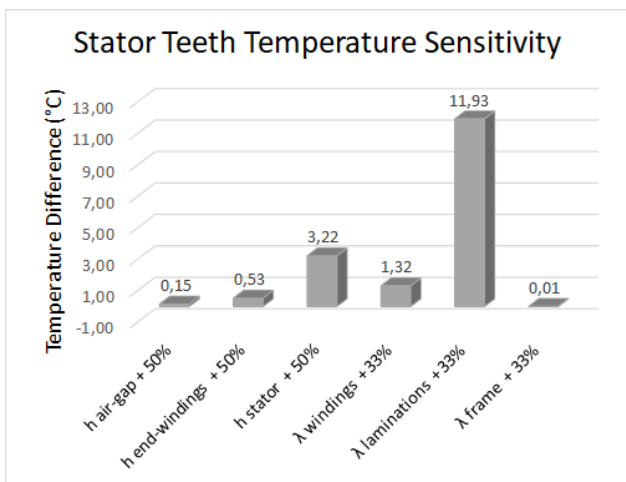


Fig. 6. Stator teeth temperature sensitivity to parameters

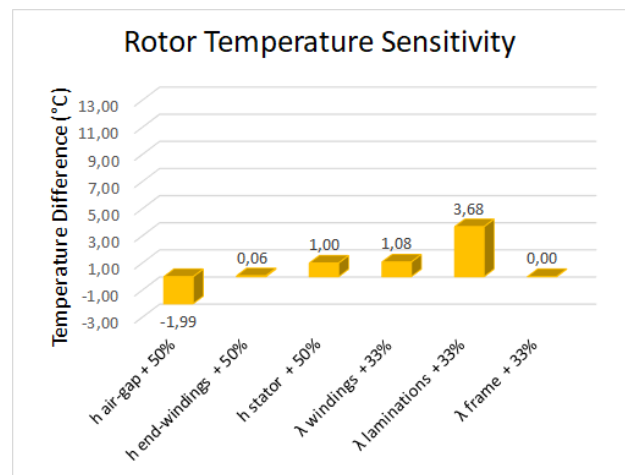


Fig. 7. Rotor temperature sensitivity to parameters

It is evident to notice that the heat transfer phenomenon in the rotor is also improved by few degrees with the increase of the lamination conductivity.

Finally, concerning the liquid convection coefficient around the motor, 50 % improvement has a low impact on the stator temperatures (laminations, windings, and end-windings). Having a 20 times higher convection coefficient than that with air cooling (air conductivity is around 0.026 W/m K), the liquid cooling allows a great reduction in temperature to some level. However, at this level, improving this coefficient by acting on the coolant or its hydraulics will not make the thermal results get relatively any better.

B. End-Windings Liquid Cooling Case

Liquid Cooling of End-windings allows obtaining a convection coefficient up to hundred times greater. This is particularly interesting for a machine with hot spot temperature in the end-windings, which is the focus of the current study. It is actually true and proved by the variation of this coefficient between its initial value 200 and 10 000 W/m² K resulting in a reduction of temperature at the end-windings level of around 30°C.

C. Temperature Sensitivity to Slots Number

In addition to being a significant parameter in the electromagnetic design, the number of slots defines also the distribution of heat dissipation, due to Joule losses, in the windings and end-windings zones. This is especially important in the process of heat evacuation since it becomes easier to drive the heat flux out of the windings through the lateral sides of a narrower slot that provides a smaller thermal resistance. That being said, the simulations show that a variation of the slot number from 20 to 40 results in reducing the temperature from 205 to 174 °C in the end-windings and from 188 to 166 °C in the slots, which means between 22 and 31 °C of temperature drop.

IV. CONCLUSION

Lumped Parameter Thermal Modeling was applied to a permanent magnet synchronous machine with high power density to evaluate its thermal behavior. The increase in temperature specifically in the stator windings in such machines raises the interest in identifying the parameters influencing the most the heat transfers from machine components to the outside. The results confirm some hypotheses and elaborate others compared to machines of the same power range. The frame conductivity, as well as air-gap convection coefficient, are of negligible effect on the temperature. The winding conductivity appears to be the most important factor on temperature rise in the stator. Lamination conductivity affects quite significantly the stator and rotor temperatures, which are less sensitive to convection around the stator when applying liquid cooling.

REFERENCES

- [1] B. Lukasik, "Turboelectric Distributed Propulsion System As a Future Replacement for Turbofan Engines," p. V001T01A017, Jun. 2017.
- [2] D. Staton, S. Pickering, and D. Lampard, "Recent Advancement in the Thermal Design of Electric Motors." 2001.
- [3] V. T. Buyukdegirmenci, S. Nategh, M. P. Magill, and P. T. Krein, "A fast and flexible analytical approach for thermal modeling of a linear stator structure," in 2013 International Electric Machines Drives Conference, 2013, pp. 793–800.
- [4] P. H. Mellor, D. Roberts, and D. R. Turner, "Lumped parameter thermal model for electrical machines of TEFC design," IEE Proceedings B Electric Power Applications, vol. 138, no. 5, p. 205, 1991.
- [5] S. Nategh, Z. Huang, A. Krings, O. Wallmark, and M. Leksell, "Thermal Modeling of Directly Cooled Electric Machines Using Lumped Parameter and Limited CFD Analysis," IEEE Transactions on Energy Conversion, vol. 28, no. 4, pp. 979–990, Dec. 2013.
- [6] S. Nategh, O. Wallmark, M. Leksell, and S. Zhao, "Thermal Analysis of a PMaSRM Using Partial FEA and Lumped Parameter Modeling," IEEE Transactions on Energy Conversion, vol. 27, no. 2, pp. 477–488, Jun. 2012.
- [7] V. T. Buyukdegirmenci, M. P. Magill, S. Nategh, and P. T. Krein, "Development of closed-form solutions for fast thermal modeling of rotating electric machinery," in 2013 International Electric Machines Drives Conference, 2013, pp. 832–838.
- [8] S. Y. Goh, J. Wale, and D. Greenwood, "Thermal analysis for stator slot of permanent magnet machine," in 2016 XXII International Conference on Electrical Machines (ICEM), 2016, pp. 2093–2098.
- [9] G. D. Demetriades, H. Z. d l Parra, E. Andersson, and H. Olsson, "A Real-Time Thermal Model of a Permanent-Magnet Synchronous Motor," IEEE Transactions on Power Electronics, vol. 25, no. 2, pp. 463–474, Feb. 2010.
- [10] M. L. Hosain and R. B. Fdhila, "Air-Gap Heat Transfer in Rotating Electrical Machines: A Parametric Study," Energy Procedia, vol. 142, pp. 4176–4181, Dec. 2017.
- [11] K. Bennion and J. Cousineau, "Sensitivity analysis of traction drive motor cooling," in 2012 IEEE Transportation Electrification Conference and Expo (ITEC), 2012, pp. 1–6.
- [12] A. Gudi, A. Singh, and B. Agarwal, "Electric machine stator thermal sensitivity analysis using CFD," in 2017 IEEE Transportation Electrification Conference (ITEC-India), 2017, pp. 1–6.
- [13] B. Assaad, K. E. kadri Benkara, G. Friedrich, S. Vivier, and A. Michon, "Reducing the complexity of thermal models for electric machines via sensitivity analyses," in 2017 IEEE Energy Conversion Congress and Exposition (ECCE), 2017, pp. 4658–4665.
- [14] B. Assaad, K. E. kadri Benkara, S. Vivier, G. Friedrich, and A. Michon, "Thermal Design Optimization of Electric Machines Using a Global Sensitivity Analysis," IEEE Transactions on Industry Applications, vol. 53, no. 6, pp. 5365–5372, Nov. 2017.
- [15] S. Touhami, Y. Bertin, Y. Lefèvre, J. F. Llibre, C. Hénaux, and M. Fénot, "Lumped Parameter Thermal Model of Permanent Magnet Synchronous Machines," in ELECTRIMACS 2017, 2017.
- [16] G. I. Taylor, "Statistical Theory of Turbulence," Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, vol. 151, no. 873, pp. 421–444, 1935.
- [17] C. Micallef, "End winding cooling in electric machines," 2006. [Online]. Available: <http://eprints.nottingham.ac.uk/10260/>. [Accessed: 05-Jun-2018].
- [18] Incropera and De Witt, Fundamentals of heat and mass transfer. Johny Wiley Sons, 1985.
- [19] A. F. Mills, Heat Transfer. Englewood Cliffs, NJ: Prentice-Hall, 1999.
- [20] A. Zeaiter, M. Fénot, and D. Saury, "Numerical Approach to Determining Windings' Thermal Conductivity," in 2018 XXIII International Conference on Electrical Machines (ICEM), 2018.

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