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Thermal Modeling of a TEFC Synchronous Reluctance Motor

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***Abstract*— This paper presents an analytical thermal model of a synchronous reluctance motor to predict the temperature of its different parts using Motor-CAD. This software is commercial software, which develops the 3-D lumped parameter thermal network. The synchronous reluctance machine is used to validate the proposed approach. A test rig using a TEFC synchronous reluctance motor (SynRM) was constructed, and the collected experimental data was used to validate the proposed analytical method successfully.**

Keywords—AC machine, Synchronous reluctance motor, temperature measurement, thermal model.

I. Introduction

The design of the electrical machine is an interdisciplinary process and multiphasic problem, which consists of electromagnetic, thermal, mechanical design, and materials science. The thermal analysis of the electrical machine is one of the most critical sections in the design process of the electrical machine, which plays a vital role in the performance, torque, power density, and energy efficiency of the electrical machine.

The modern thermal design of an electrical machine is divided into two main categories: analytical and numerical methods [1], [2], and [3]. In the analytical approach, the temperature of critical parameters of electrical machines is evaluated using an equivalent thermal circuit called lumped parameter thermal network (LPTN). However, the numerical analysis approach consists of finite element analysis (FEA) and computational fluid dynamic (CFD) methods [4], [5]. FEA models the heat transfer in the solid materials, and the heat transfer among the different media is modeled by the CFD method [6].

According to the advantages of LPTN, e.g., fast computation time, cost-effectiveness, and familiarity for electrical engineers make it more attractive for machine designers. In this method, the main thermal paths are modeled by resistances representing the three main heat transfer

phenomena conduction, convection, and radiation. However, in this method, thermal resistances are calculated using semi-empirical correlations prepared by some simplification assumptions or experiments that may lead to uncertainty results [7].

One of the common commercial software for thermal analysis of electrical machines is Motor-CAD, which can model the heat transfer of various electrical machines using an analytical LPTN approach. Therefore, the paper's main objective is to develop the analytical thermal model of TEFC SynRM using this commercial software and consider the thermal performance and model's accuracy.

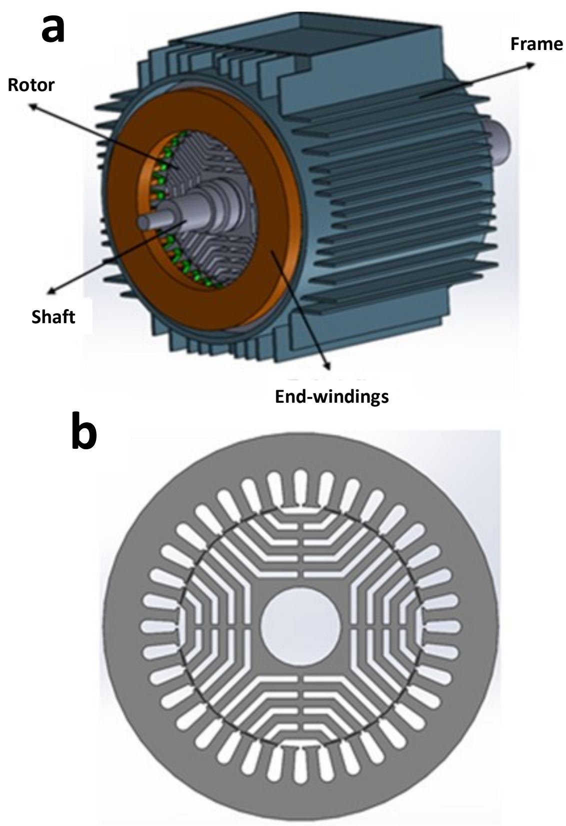

Fig. 1. Structure and topology of the transverse-laminated SynRM [6], [8].

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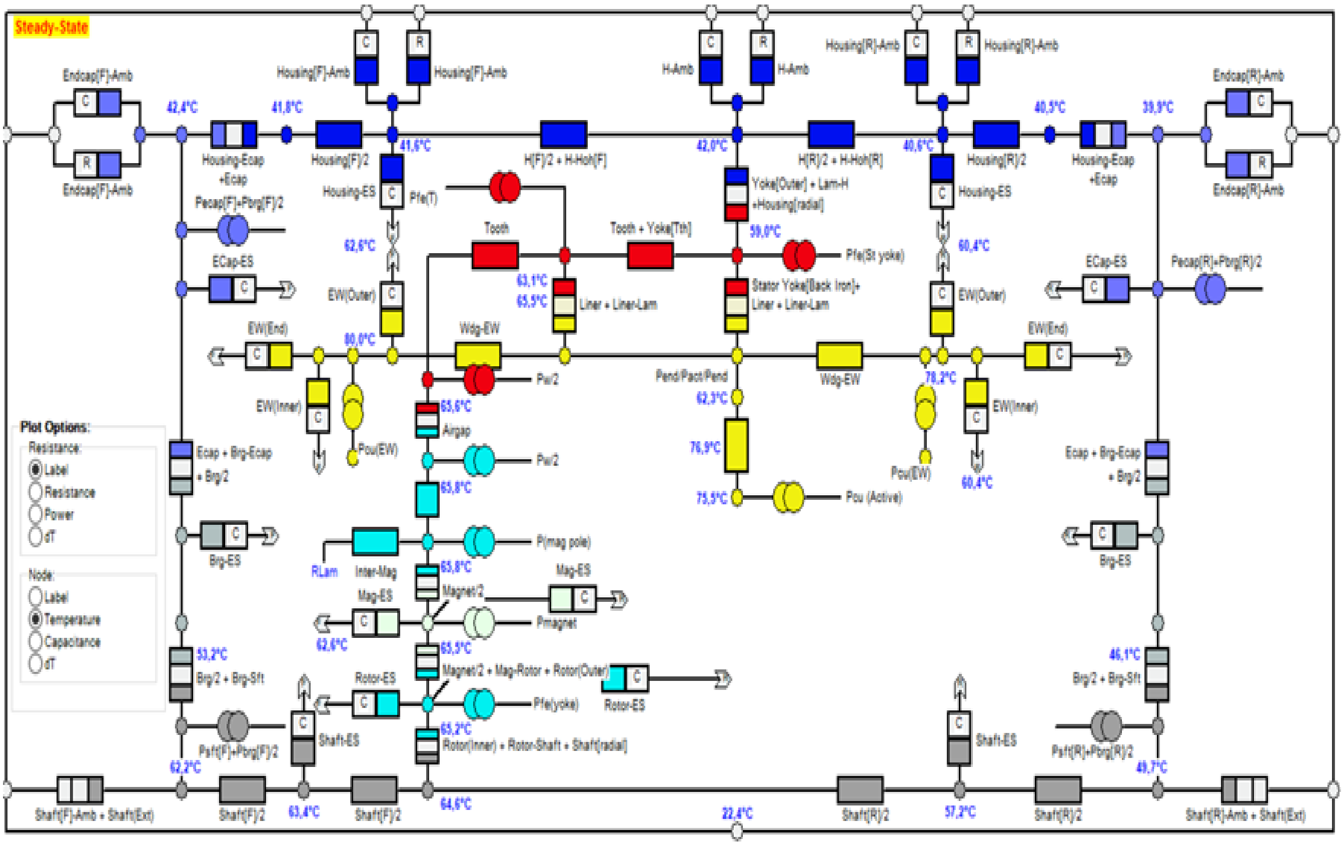

Fig. 2. Analytical Thermal model of SynRM using Motor-CAD

For the research purposes, the thermal models described in this study are applied to four poles 10 kW, 400 V, 50 Hz, transverse-laminated radial flux SynRM with 'F' insulation class. Figure 1 shows a CAD drawing of the machine and its cross-section. This machine is a totally enclosed fan-cooled (TEFC) machine, and it uses the air forced cooling method. Firstly, the analytical thermal model for evaluating the temperature of the machine's various sections is described. Next, a test bench is set up, and measurements are conducted. Then, the experimental data are compared to the corresponding results obtained through the proposed analytical method to validate the analytical model.

Detailed information on the geometrical data of the motor is given in Table I, and the material properties of the machine are presented in Table II.

TABLE I. GEOMETRICAL DATA OF THE TRANSVERSE-LAMINATED SYNRM

Name	Symbol	Unit	Value
Stator core length	L_s	mm	156
Stator inner diameter	D_{is}	mm	136
Stator outer diameter	D_{os}	mm	219
Number of slots	N_s	-	36
Air-gap height	H_{ag}	mm	0.4
Rotor inner diameter	D_{ir}	mm	45
Rotor outer diameter	D_{or}	mm	135.2
Slot height	H_{slot}	mm	21
Slot filling factor	k_f	-	0.6
Slot area	S_{lots}	mm^2	130.1

TABLE II. MATERIAL DATA OF THE TRANSVERSE- LAMINATED SYNRM

Machine part	Material	Thermal conductivity symbols	Thermal conductivity [W/(mK)]
Frame	Aluminum	k_{al}	230
Laminations	M-350-50A	k_{ir}	28
Winding	Copper	k_{cu}	387
Impregnation	Resin	k_{res}	0.2
Air gap	Air	k_{air}	0.0257
Shaft	Steel	k_{sh}	41

II. ANALYTICAL THERMAL MODEL

Motor-CAD is commercial software for the design and analysis of electrical machines. This software uses the analytical approach to develop the 3-D LPTN for modeling the heat transfer of electrical machines. Figure 2 shows the 3-D LPTN, which is modeled main heat transfer paths in the SynRM. This LPTN is equivalent to the electrical circuit [9]. Therefore, the nodal temperature is akin to voltage, the power loss is similar to the current source, and the thermal resistances are identical to electrical resistances [9]. In this software, the conductive resistance is calculated based on the material's thermal conductivity and the dimension of the appropriate section. While, for the convection resistances, the convection coefficients are evaluated by the well-known empirical correlations based on the dimensionless analysis presented in [10]. Finally, the thermal radiation resistances also is calculated based on the emissivity and simplify assumption for view factor, which is presented in [8], [11], and [12].

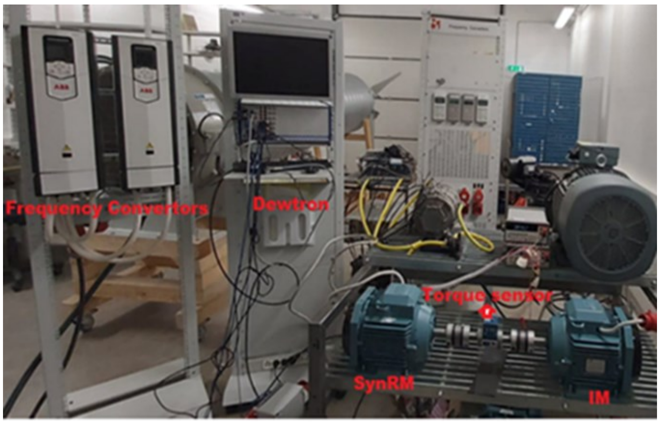

Fig. 3. Experimental setup.

In the first step of modeling, the machine type should be selected. Then, input parameters, e.g., the machine dimensions, housing type, and fan, are set in the geometry section. Next, the data related to the windings and their positions are defined. Next, cooling system characteristics, losses, materials, the value of interface gap, radiation, and convection data are set in the input data. Finally, the solving method, whether steady-state or transient, shaft speed, and model option are selected in the calculation sections. After solving the model, the temperatures of various parts of the machine axially and radially are available in the temperature tool box and output data section.

III. Experimental Methodology

An experimental verification stage was carried out to effectively validate and evaluate the SynRM's thermal model's performance and gain details about the accuracy of the method in predicting temperature distribution across the machine's most relevant sections. The experiments conducted for the validation of the model are described hereafter.

For the experimental work, the SynRM is operated under load conditions. For this purpose, the SynRM is coupled to the induction motor (Fig. 3). In this condition, the induction machine is acting as a load. Both machines were controlled by frequency converters. The SynRM has been equipped with six PT100 thermal sensors. Three sensors have been located in each phase's end winding section, and three others have been installed inside the slots. An infrared laser digital thermometer has measured the motor surface temperature. During the test, in addition to temperature, the injected power, output power, rotor rotational speed, current, voltage, and power factor of each phase were measured with a data acquisition system (Dewetron).

The SynRM was run at a rated speed (1500 r/min) under the load of 41 N.m. The power losses in the SynRM consist of resistive losses, iron losses, and mechanical losses. Table III shows the value of losses for the load test that were determined experimentally in the rated voltage and frequency. Besides, these values were applied in the machine's thermal model.

TABLE III. Losses of the SynRM under Load

Name	Symbol	Value (W)
Stator winding losses	P_{cu}	477.4
Iron losses	P_{Fe}	206.2
Mechanical losses	P_m	36.6

IV. Results & Discussion

To verify the developed thermal model, the steady-state temperature results are compared with the experimental results. As described, the machine was loaded with 70 % of rated torque. During the experiment, the ambient temperature was 22.4 °C, and the mean value of the inlet airflow rate into the semi-open fin channels was 9.7 m/s. Figure 4 a and b shows the thermal model of machine under study radially and axially.

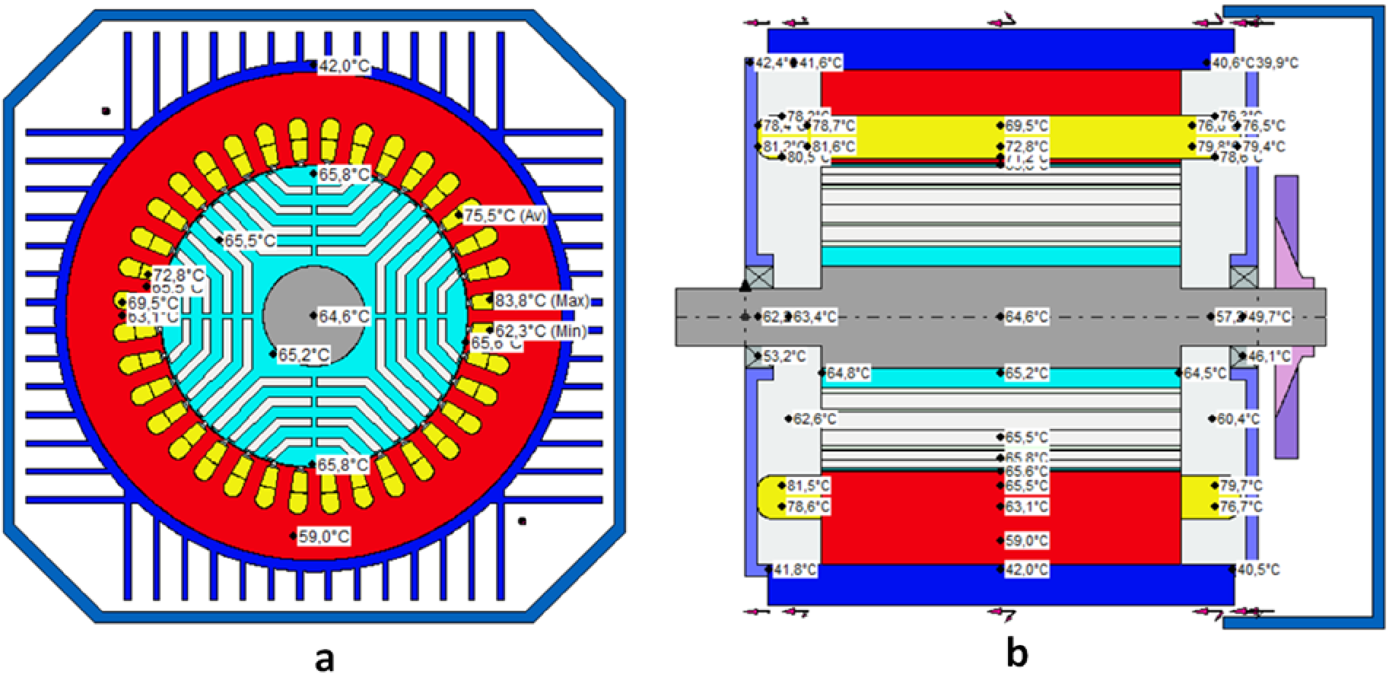

Fig. 4. The temperature of various SynRM's sections a) radially, b) axially.

For better comparison, the measured and estimated results of the different parts of the SynRM for 70% of the nominal torque are presented in Tables IV.

TABLE IV. RESULTS FOR 41 N.M

Machine Parts	Thermal model (°C)	Test Results (°C)
Housing surface	42	45.5
Stator Yoke	59	--
Stator Teeth	64.3	--
Active winding	71.2	71.8
End winding	79.1	82.8
Rotor	65.8	--

Comparing the mean temperature results of the thermal model and measurement for 41 N.m shows around 1% deviation for active winding, about 4.5 % for end winding, and 7.5 % for housing. Accordingly, the thermal model can predict the machine's temperature, especially temperature distribution inside the slot and end winding, as the most challenging parameters of SynRM.

V. CONCLUSION

This study has illustrated the analytical approach to predicting temperatures of various sections of a TEFC of SynRM using Motor-CAD software. This software provides the 3-D LPTN of the machine.

Finally, the proposed thermal models were validated experimentally. The comparison shows close agreement between the thermal model and the measurements data. According to the initial results, the analytical approach can successfully predict the heat transfer coefficient with a low mean relative difference of around 1% deviation for active winding, about 4.5 % for end winding, and 7.5 % for housing.

REFERENCES

[1] A. Boglietti, A. Cavagnino, D. Staton, M. Shanel, M. Mueller, and C. Mejuto, "Evolution and Modern Approaches for Thermal Analysis of Electrical Machines," IEEE Trans. Ind. Electron., vol. 56, no. 3, pp. 871–882, Mar. 2009, doi: 10.1109/TIE.2008.2011622.

[2] C. Mejuto, "Improved lumped parameter thermal modelling of synchronous generators," The University of Edinburgh, 2010.

[3] C. Micallef, "End winding cooling in electric machines," 2006.

[4] 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 Trans. Energy Convers., vol. 28, no. 4, pp. 979–990, Dec. 2013, doi: 10.1109/TEC.2013.2283089.

[5] P. Shams Ghahfarokhi, A. Kallaste, A. Belahcen, T. Vaimann, and A. Rassõlkin, "Hybrid thermal model of a synchronous reluctance machine," Case Stud. Therm. Eng., vol. 12, pp. 381–389, 2018, doi: 10.1016/j.csite.2018.05.007.

[6] P. Shams Ghahfarokhi, "Development of Thermal Analysis Tools for Synchronous Reluctance Motors - TalTech raamatukogu digikogu," Tallinn University of Technology, 2019.

[7] S. LIPIŃSKI, K. Grunt, and J. Zawilak, "2D steady-state thermal analysis of a line-start, permanent magnet synchronous motor," PRZEGLĄD ELEKTROTECHNICZNY, vol. 1, no. 3, pp. 183–186, Mar. 2017, doi: 10.15199/48.2017.03.42.

[8] P. Shams Ghahfarokhi et al., "Determination of Heat Transfer Coefficient from Housing Surface of a Totally Enclosed Fan-Cooled Machine during Passive Cooling," Machines, vol. 9, no. 6, p. 120, Jun. 2021, doi: 10.3390/machines9060120.

[9] M. Rosu et al., Multiphysics simulation by design for electrical machines, power electronics and drives, 1st ed. Wiley-IEEE Press, 2017.

[10] D. A. Staton and A. Cavagnino, "Convection Heat Transfer and Flow Calculations Suitable for Electric Machines Thermal Models," IEEE Trans. Ind. Electron., vol. 55, no. 10, pp. 3509–3516, Oct. 2008, doi: 10.1109/TIE.2008.922604.

[11] "Motor-CAD Software by Motor Design - EMag, Therm and Lab." https://www.motor-design.com/motor-cad-software/.

[12] P. Shams Ghahfarokhi, A. Kallaste, T. Vaimann, and A. Belahcen, "Thermal Analysis of Totally Enclosed Fan Cooled Synchronous Reluctance Motor-state of art - IEEE Conference Publication," in IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society, 2019, pp. 1–5, Accessed: Dec. 12, 2019. [Online]. Available: https://ieeexplore.ieee.org/document/8927706.

BIOGRAPHY OF PRESENTING AUTHOR

Payam Shams Ghahfarokhi (Member, IEEE) was born in Iran in 1986. He received a B.Sc. degree in electrical power engineering from IAUN, Iran, in 2010, an M.Sc. degree in electrical power engineering from Newcastle University, UK, in 2011, and the Ph.D. degree in electrical engineering and machines from Tallinn University of Technology, Estonia, 2019. He is currently senior researcher and postdoc research with the Department of Electrical Machines and Devices, Riga Technical University, Latvia. His main interest is the electromagnetic design and thermal management of PM and Synchronous Reluctance electrical machines.