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Lumped-Parameter Network Thermal Analysis of Permanent Magnet Synchronous Motor

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Abstract. This paper develops a model based on an original lumped-parameter network configuration for the thermal transient analysis of a permanent magnet synchronous motor (PMSM). The specific PMSM was designed and optimized for a demanding aerospace application. The validity of the proposed lumped-parameter model is verified by measurements carried out in a thermal chamber.

Introduction

Political, economical, and environmental trends, lead to the all electric aircraft concept and to the corresponding elimination of hydraulic power sources [1]-[4]. Due to the absence of hydraulic fluid, heat will not be dissipated from electric actuators used in demanding aerospace applications. As a result, actuators work under a severe thermodynamic environment and rapid load conditions where localized heat effects and the absence of forced cooling affect the motor performance [5]-[9].

This paper concerns the thermal analysis of an actuator designed for high ambient temperatures, inadequate convective heat transfer, and short overload conditions. The thermal analysis is carried out by developing a model based on an original lumped-parameter network configuration.

Prototype Permanent Magnet Synchronous Motor

A surface mounted permanent magnet synchronous motor (PMSM) was designed and optimized for extremely high ambient temperature environmental conditions encountered in aerospace applications. High temperature, samarium cobalt (SmCo), permanent magnets and a non-overlapping, all-teeth-wound, fractional slot concentrated winding configuration were used for the specific PMSM. Fig. 1 shows the stator of one of the prototypes and Fig. 2 shows an assembled prototype PMSM on the test rig.

The proposed PMSM topology presents maximum torque per copper loss square root ratio, minimum torque ripple, and minimum back-EMF harmonic content comparing to full pitch concentrated winding (FPCW), and non-overlapping, alternate-teeth-wound, fractional slot concentrated winding (FSCW2) configurations [1].

The drawback of the proposed PMSM topology is its high cost due to the use of double layer windings involving increased fill factors. However, manufacturing costs is not an issue in this type of aerospace application.

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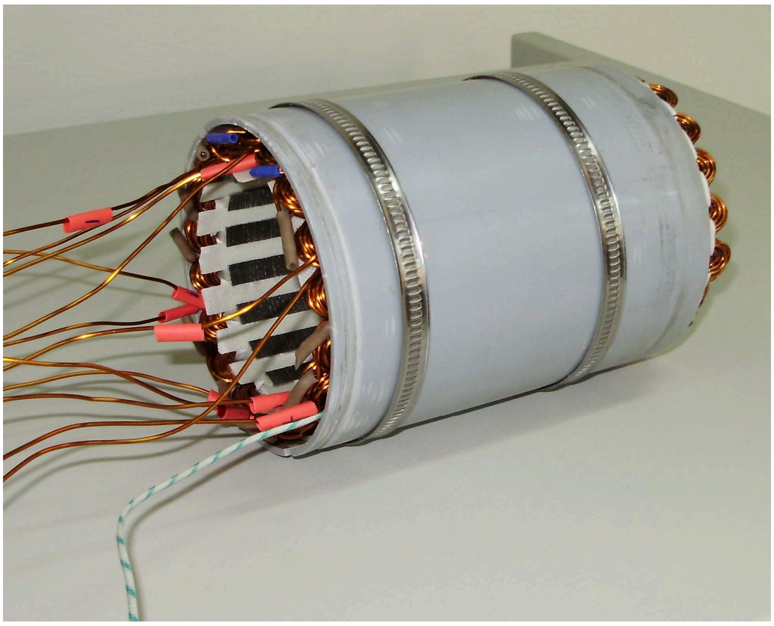

Fig. 1. Prototype PMSM stator core and winding.

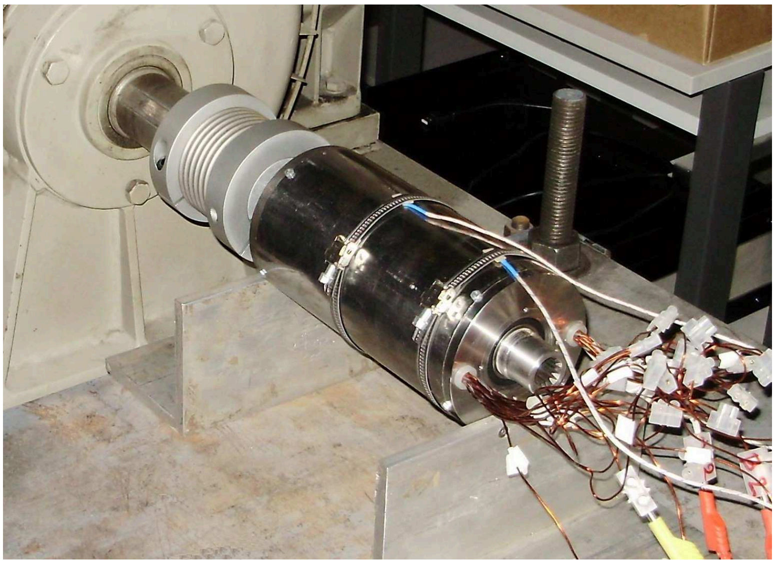

Fig. 2. Assembled prototype PMSM on the test rig.

Lumped-Parameter Model for Thermal Transient Analysis

Fig 3. shows the lumped-parameter network developed for the thermal transient analysis of the PMSM. It is based on an original configuration that involves a minimum number of elements and therefore it presents a reduced computational cost in comparison with conventional lumped-parameter models.

The specific configuration was implemented using Matlab and the SimPowerSystems library of Simulink. The values of the parameters of the elements of the specific model were determined by analytical expressions taking into consideration the geometric and operational characteristics of the PMSM, as well as the physical properties of the materials of the PMSM i.e., the stator laminated steel, the permanent magnets, the winding copper, and the winding insulation material. Finally, the loading characteristics of the lumped-parameter model were set by controlling the magnitude of the current sources. The current sources in the specific model represent the winding losses and the iron losses of the stator and rotor.

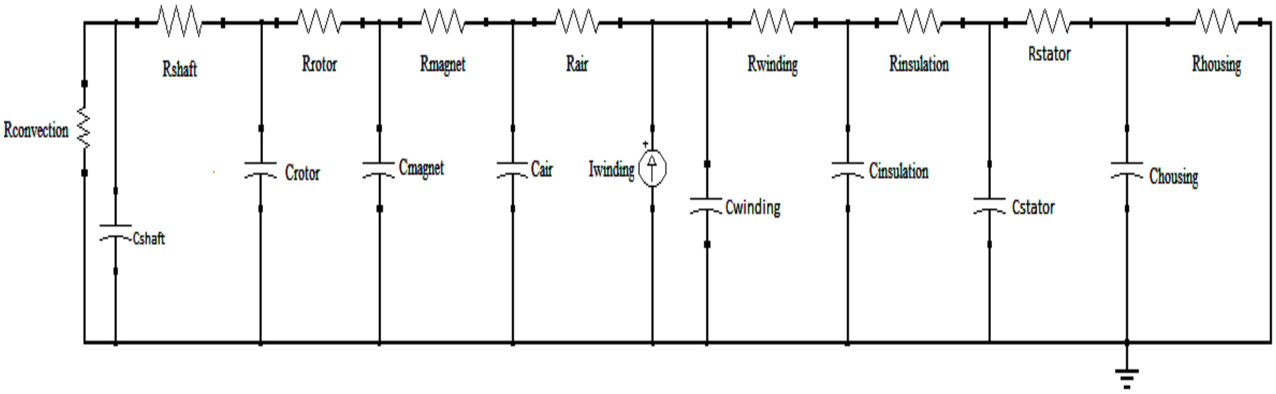

Fig. 3. Lumped-parameter model for the thermal analysis of the PMSM.

Finite Element 3D Thermal Transient Analysis

In order to validate the lumped parameter thermal model a finite element (FE) thermal transient analysis package was used [5]-[7]. The specific FE package has been assembled for the 3D FE transient and steady state analysis of actuators. It consists of seven codes and integrates numerical techniques for the minimization of the computational cost [10]-[13].

A number of steady state and transient 3D FE thermal analyses for different material attributes and load characteristics of the PMSM, were carried out using the FE package.

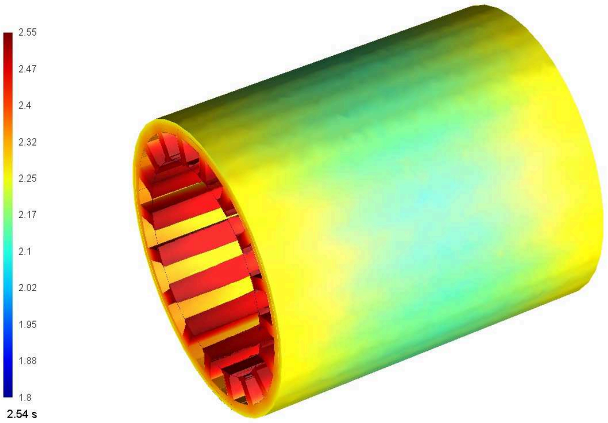

Fig. 4. PMSM temperature distribution at 2.54 s (stator core).

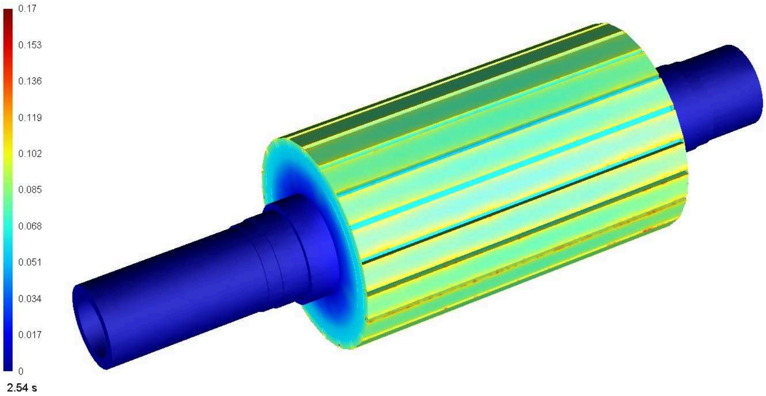

Fig. 5. PMSM temperature distribution at 2.54 s (rotor).

Figs. 4 to 7 show the temperature distribution of the PMSM running under maximum load. It was obtained by a 10-step transient analysis. Analysis time ranges from 0.18 s to 8,233 s and the time-step ranges from 0.18 s for the first step to 5,626 s for the last step. More specifically, Figs. 4, 5 show the temperature distribution of the stator core and the rotor at the third time-step of the analysis. Figs. 6, 7 shows the temperature distribution for two steps of the transient analysis. Figs. 6, 7 show that the windings are the critical temperature component of the PMSM.

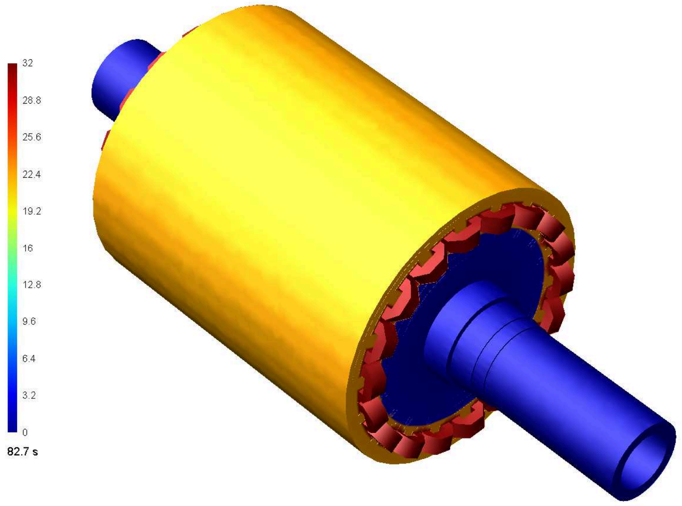

Fig. 6. PMSM temperature distribution, 82.7 s.

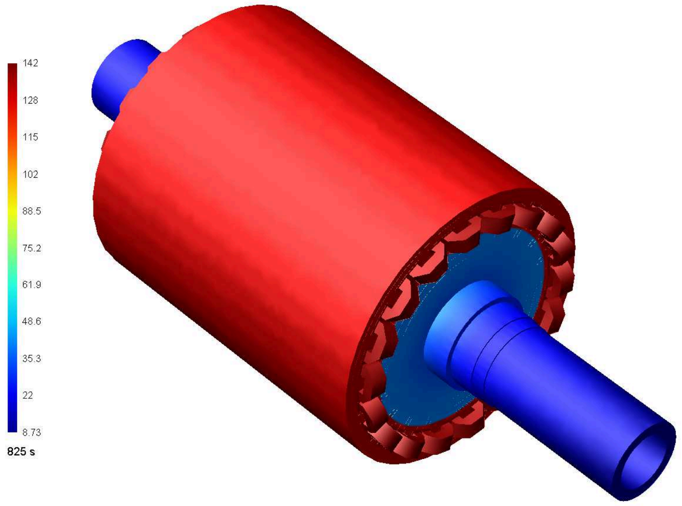

Fig. 7. PMSM temperature distribution, 825 s.

Description of the Experimental Setup

In order to control the ambient temperature, the PMSM was mounted onto two metal plates and placed in a thermal chamber as shown in Fig. 8. The specific environmental chamber uses a PID controller to keep the temperature constant. Thermal insulation material was placed between the motor housing and the two plates so that the dissipation was minimized. Five type-K thermocouples were attached to the PMSM, Fig. 9. Thermocouples 1 to 3 were attached to the center and to the two ends of the motor housing respectively. Thermocouple 4 was attached to the center of a tooth and thermocouple 5 was placed on one of the winding ends. A sixth thermocouple was used to measure the temperature of the shaft when the rotor was stationary [14].

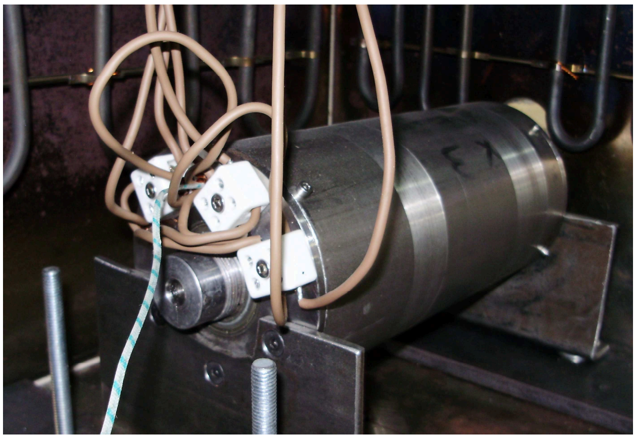

Fig. 8. Prototype PMSM inside the thermal chamber.

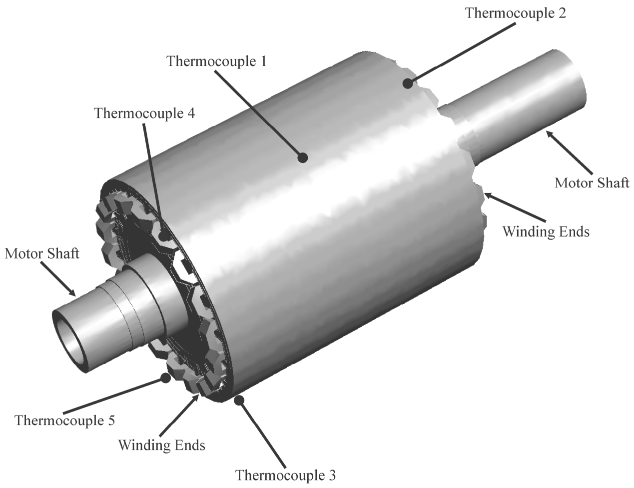

Fig. 9. Thermocouple arrangement for temperature measurement.

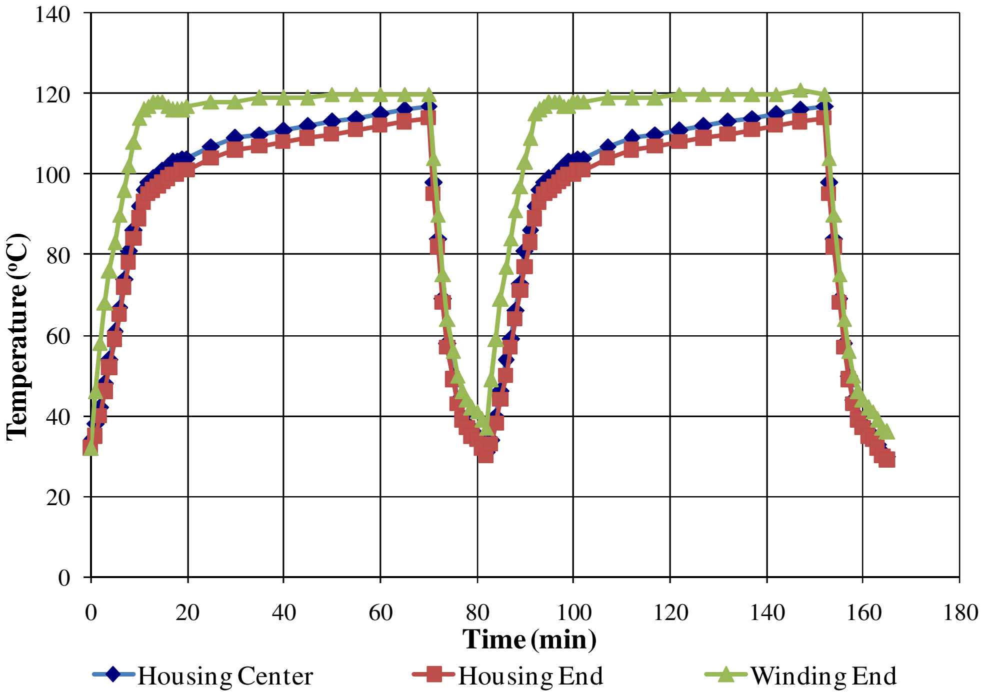

Fig. 10. Temperature variation of the PMSM for a mixed cycle.

Results and Discussion

In order to evaluate the thermal impact on the PMSM of rapid load conditions a mixed cycle was employed using variable loads and high air forced cooling conditions. The first sub-cycle was obtained for constant loads that resulted in a winding end temperature rise of 10 °C/min. The second sub-cycle was obtained by regulating the loads over 60 min, in order to maintain the winding end temperature constant. Finally the third sub-cycle was obtained by using the air forced cooling apparatus in order to achieve a winding end temperature decrease of 10 °C/min. Fig. 10 shows the respective temperature distribution at three locations of the PMSM for two consecutive duty cycles.

Thermal transient analyses were carried out using the developed lumped-parameter model, for different ambient temperatures and load conditions of the PMSM. In all cases the respective error is within 5% and 15%. Figs. 11, 12 show respectively a comparison of the simulated and experimental temperature variation of the housing and stator of the PMSM.

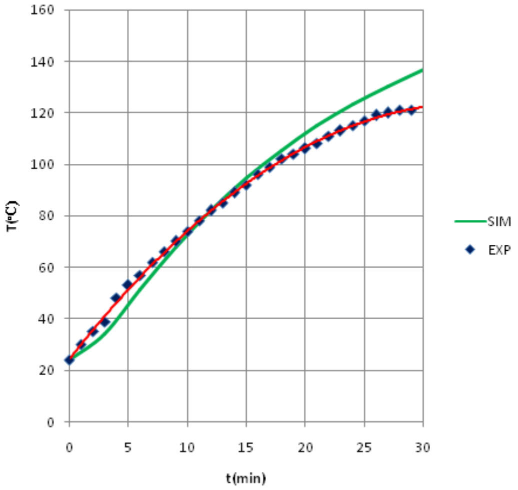

Fig. 11. Temperature variation of the housing.

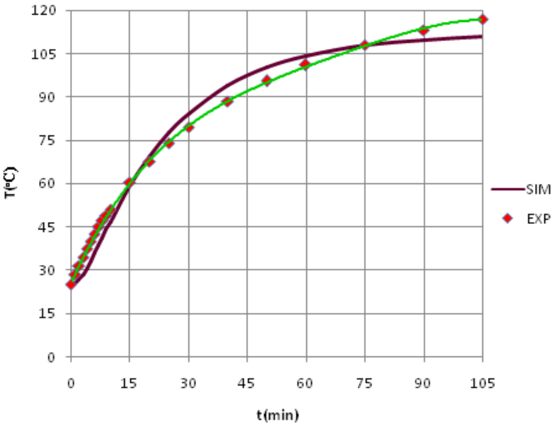

Fig. 12. Temperature variation of the stator.

Conclusion

High efficiency actuators for aerospace applications work under short overload conditions and harsh environmental conditions. In order to accurately predict the thermal performance of such electric machines a transient analysis is needed. For that purpose a lumped-parameter network employing an original configuration and low computational cost has been developed.

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