3–D FEM and Lumped–Parameter Network Transient Thermal Analysis of Induction and Permanent Magnet Motors for Aerospace Applications

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Abstract. Three dimensional (3–D), finite–element (FE) models and original lumped–parameter networks are developed for the transient thermal analysis of a permanent magnet motor (PMM) and an induction motor (IM) specifically designed and optimized for a demanding aerospace actuation application. A systematic comparison between the two different thermal modeling approaches is carried out using different loading conditions.

Introduction

Electric actuators used in aerospace applications, work in excessive environmental conditions due to reduced thermal dissipation and extreme changes of loading conditions [1]–[4]. This is a result of recent political, economical, and environmental trends that lead to the all electric aircraft concept and the corresponding elimination of high–pressure hydraulic lines [5].

This paper concerns the thermal analysis of two actuators, a permanent magnet motor (PMM) and an induction motor (IM), designed for inadequate convective heat transfer and short overload conditions, encountered in a demanding aerospace actuation application [6], [7].

The solution of the aforementioned problem requires a detailed three dimensional (3–D) finite–element (FE) transient thermal analysis due to the extreme loading conditions and the high integration of the actuators. For that purpose, a FE package for the 3–D transient thermal analysis was assembled, which incorporates a number of numerical techniques for the reduction of the computational cost.

The conventional approach for electric machine thermal analysis is based on lumped–parameter networks [8]. The popularity of the specific method stems from the fact that it is simple, easily applicable and computationally cheap. On the other hand, the FE analysis presents advantages over the lumped–parameter network analysis, such as geometry parameterization and detailed temperature gradient calculation [3].

Description of PMM and IM Actuators

Permanent Magnet Motor. A surface mounted PMM was designed for two different modes of operation encountered in a demanding aerospace application. Under normal mode of operation the torque and rotating speed are equal to 1.2 \(N\cdot m\) and 180 rpm respectively [6]. Under the extreme mode of operation, torque and rotating speed are equal to 6.0 \(N\cdot m\) and 6,000 rpm respectively. High temperature, samarium cobalt permanent magnets and non–overlapping, alternate–teeth–wound, fractional slot concentrated winding configuration were used [8]–[11].

Induction Motor. An IM was also designed for the aforementioned aerospace application. A non–overlapping winding was not the optimum choice for the IM. As a result, a conventional winding configuration was used. For the rotor bars the NEMA design class \(A\) was adopted due to the high torque capacity and efficiency at low slip frequencies [6].
3D FE Models of PMM and IM

Fig. 1 shows the 3D FE models of the PMM and IM actuators. Mesh sizes of $1.0 \cdot 10^6$ to $2.0 \cdot 10^7$ elements and a typical desktop PC were used for the analyses. Fig. 2 shows a cross section of the FE mesh and the regions comprising the two models. The regions of the stators of both actuators are the same and consist of the stator core, the windings, and the insulation material. Differences are located in the rotors of the two actuators. In the case of the PMM regions consist of the shaft, rotor core, permanent magnets and air–gap. In the case of the IM the respective regions are the shaft, rotor core, rotor bars, and air–gap.

3–D representation permits the modeling of complex electrical machines topologies such as skewed magnets, skewed rotor bar, and winding ends [12]–[14].

![Fig. 1. Geometry and FE mesh of the 3–D models of the two actuators. (a) PMM. (b) IM.](image)

![Fig. 2. Cross section of the 3–D FE mesh of the two actuators. (a) PMM. (b) IM.](image)
Lumped–Parameter Model for Thermal Transient Analysis

Fig. 3 shows the lumped–parameter networks developed for the thermal transient analysis of the two actuators. They are based on an original configuration that involves a minimum number of elements and therefore present a reduced computational cost in comparison with conventional lumped–parameter models.

The specific lumped–parameter networks were implemented using Matlab and the SimPowerSystems library of Simulink [8]. The values of the parameters of the elements of the two models were determined by analytical expressions taking into consideration the geometric and operational characteristics of the IM and PMSM. Finally, the loading characteristics of the lumped–parameter model were set by controlling the magnitude of the current sources. The difference between the two models consist in the introduction of one more current source in the case of the IM representing the rotor bars losses.

Fig. 3. Lumped–parameter network models. (a) PMM. (b) IM.

Results and Discussion

Lumped–Parameter Network Transient Analysis. A number of transient thermal analyses of the IM and PMSM were carried out using the lumped–parameter models for different load conditions. Fig. 4 show a comparison of the simulated 3–D FE and lumped–parameter network temperature variation of the stator winding and rotor of the actuators.

Fig. 4. Comparison of 3–D FE and lumped–parameter network simulated results. (a) Stator winding temperature variation. (b) Rotor temperature variation.
3D FE Thermal Transient Analysis of the PMM and IM. A number of transient and steady state, 3–D FE thermal analyses for different material attributes, ambient temperatures, and loading conditions of the PMM and IM were carried out using the FE package assembled by the authors [1], [3]. Mesh sizes of $1.0 \cdot 10^6$ to $2.0 \cdot 10^7$ first–order tetrahedral elements and a typical desktop PC were used for the analyses.

The temperature distribution results obtained from the transient analyses show that in both cases the winding of the stator is the critical temperature component. Also, the simulated results depict a notable difference between the temperature distribution of the rotor of the PMM and the cage rotor of the IM. This is due to the Joule losses of the rotor bars of the IM.

Fig. 5 shows the temperature distribution of the PMM for the extreme loading operation for six consecutive time–steps. It was obtained by a 10–step transient 3–D FE thermal 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.

![Fig. 5. Temperature distribution (°C) of PMM for extreme loading conditions. (a) 26.1 s. (b) 82.7 s. (c) 261 s. (d) 825 s. (e) 2606 s. (f) 8233 s.](image-url)

Fig. 6 shows the respective temperature distribution of the IM again for the extreme loading operation and for eight time–steps of the transient thermal. The same analysis procedure was used in this case as well.
Fig. 6. Temperature distribution (°C) of IM for extreme loading conditions. (a) 0.18 s. (b) 0.748 s. (c) 2.54 s. (d) 8.21 s. (e) 26.1 s. (f) 82.7 s. (g) 261 s. (h) 2606 s.

Summary

High efficiency actuators for demanding aerospace applications are complex devices that work under short overload conditions and harsh environmental conditions. In order to accurately predict the thermal performance of such electric machines a 3–D representation and a transient thermal analysis is used.
The main advantage of the 3–D FE thermal analysis over the lumped–parameter network analysis is the accurate computation of the conduction heat transfer mechanism of apparatus of complex geometry. Nevertheless, the use of the 3–D FE method by the aerospace industry is hindered by its high computational cost.

The present paper develops lumped–parameter networks and adopts FE techniques for the reduction of the computational cost of the 3–D FE transient thermal analysis. A FE package was assembled incorporating the numerical techniques. The specific package has task parallelism computing capabilities i.e., a desktop computer with a quad–core processor is capable of executing simultaneously four threads of the FE package.

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References