Effect of Rotor Speed on the Thermal Model of AFIR Permanent Magnet Synchronous Motor

S. Wahsh *, A. Yassin*[‡], J. Shazly**

*Department of Power Electronics and Energy Conversion, Electronics Research Institute, Giza, Egypt

**Department of Electrical Engineering, Fayoum University, Faculty of Engineering, Fayoum, Egypt

(wahsh@eri.sci.eg, amir@eri.sci.eg, J_shazly2001@yahoo.com)

[‡] Corresponding Author; A. Yassin, Giza, Egypt, Tel: +201223094893, amir@eri.sci.eg

Received: 25.07.2016 Accepted:22.09.2016

Abstract- Thermal modeling for electrical machines at different operating conditions is very important to estimate its temperature limits. This paper studies the influence of varying the rotor speed at full load on a three dimension finite element (FE) thermal model of an axial flux interior rotor (AFIR) permanent magnet synchronous motor. The study includes analyzing at rotor speeds of 1000 rpm and 7000 rpm and a comparison of the resulted temperature values of both cases.

Keywords Thermal model, finite-element method, rotor speed, AFPMSM, AFIR, convection, heat conduction.

1. Introduction

During electrical machines operation, portion of the energy is lost as heat. Electrical machines are represented by a very complex structure and consequently, more complicated thermal system, containing multi various materials and allotted heat sources. Damage can occur due to temperature rise of the machine under load [1]. Estimation of the thermal performance helps in determining the safe operating limits which depend on the temperature. Tolerance of the temperature depends on the utilized materials in the machine [2].

We don't prefer increased temperature levels to protect the insulation and bearings and to ensure a long operational life for the electrical machine [3], [4]. In many applications nowadays, axial flux permanent magnet synchronous motors (AFPMSM) are preferable as they are the surrogate of radial flux type of permanent magnet synchronous machines [5], [6].It receives a few concern although a broad research has been consecrated to traditional electrical machines thermal studies [7], [9].

Studying the heat generated and its dissipation in various topologies of AFPMSM is the major where the capacity of heat dissipation may be inadequate to face the excessive heat at high power ratings [4]. The machine thermal behavior can be analyzed by FE which gives satisfactory results [10], [11].

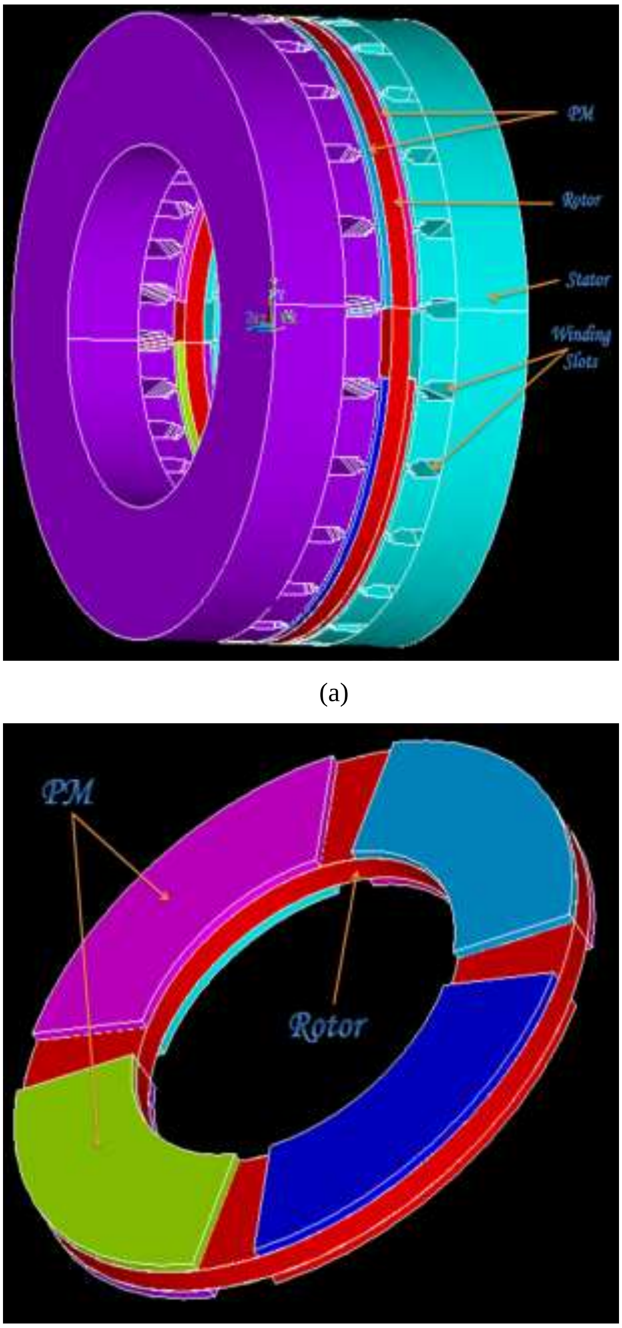
Axial flux interior rotor (AFIR) is one of the AFPMSM topologies constructed of double-stator single-rotor [12],[13]. It has very high power-to-inertia ratio so it is recommended for applications like electric vehicles [5]. For good estimating of the thermal behavior of this machine, all losses must be considered. Sources of heat inside it are copper, core, and mechanical losses [2], [11].

It is observed that many losses inside the motor depend on the speed so the rotor speed becomes an influential factor that affect the temperature of the motor components and it should be studied.

2. Geometry Studied and Model Analyzing

The motor modeled in this paper is AFIR type which constructed in slotted stator structure as shown in Fig 1. Figure2 illustrates the thermal model showing each part inside the motor with taking into account that the 3D thermal model is reduced to a section equals 1/16 of the full motor model to simplify the analysis and this is applicable due to symmetry of the motor. This assumption is done due to the complexity of the 3D model and to reduce the simulation time for each trail. Cooling ducts are represented by two tubes submitted behind the stator. Also, windings are modeled as solid objects to simplify the geometry and the end windings epoxy is ignored due to difficulty to be simulated.

The developed model is bounded by other assumptions to simplify it such as the generated heat per unit volume is distributed uniformly in the iron core also in the copper. Temperatures of AFIR's parts are set to ambient temperature initially. Properties of air and different materials used in the machine are assumed to be temperature dependent and the insulation of windings is ignored because the dielectric loss in it is very small compared to copper losses in conductors [11], [14]. Motor parameters and geometrical data used in the analysis are presented as in [11], [14].

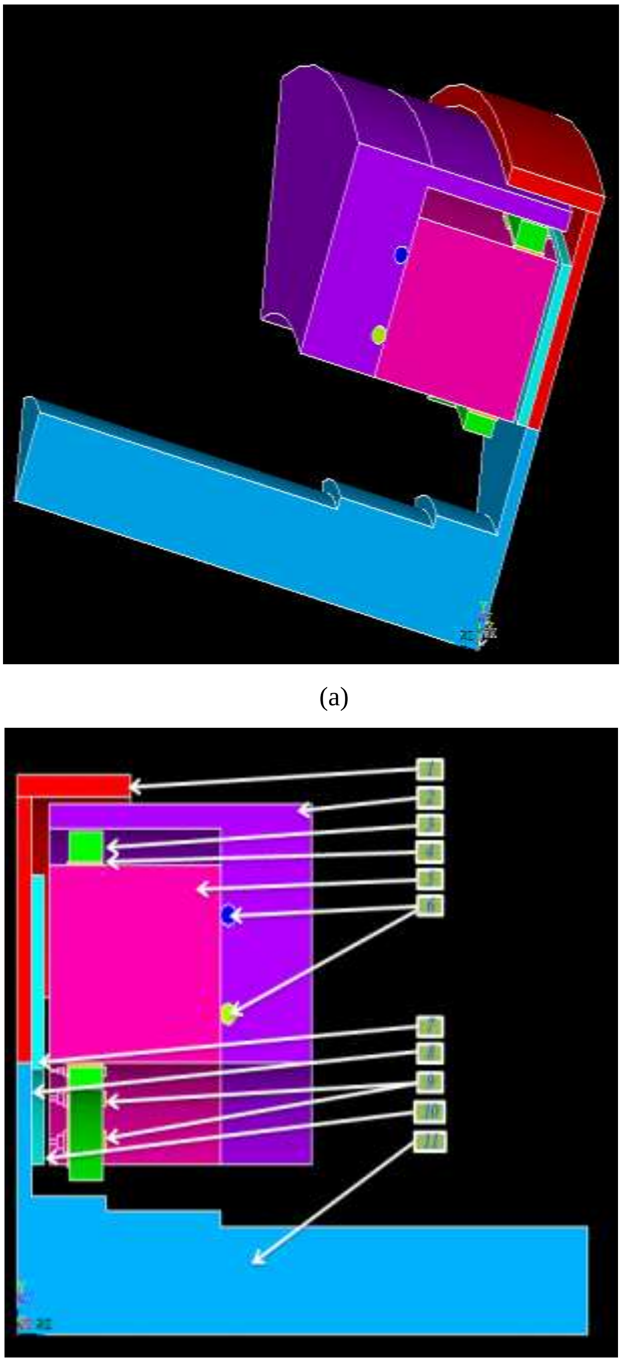


(a)

(b)

Fig. 1. 3D view of an AFIR. (a) Motor model, (b) Rotor and permanent magnet (PM) Configuration.

In [14], thermal model was verified to study the temperature distribution inside an AFIR using FE technique to solve the three dimensional heat conduction equations by using ANSYS FE analysis program and the nodal temperature distribution are achieved through the thermal analysis. Model accuracy is investigated by the comparison of the theoretically calculated results with the computed temperature values of the thermal resistance model and with the actual measured values. This shows that the developed FE model can perform the thermal analysis with reasonable accuracy [11], [14].



(a)

(b)

Fig. 2. Model of one sixteenth of the AFIR. (a) 3D, (b) 2D. 1 rotor, 2 casing, 3 copper windings, 4 pressboard, 5 stator, 6 cooling pipes, 7 PM, 8 glue, 9 slots, 10 air gab and 11 shaft.

Losses are transformed into heat which is transferred by conduction in the solid parts of the machine, and by convection in any fluids contained in it. Transferred heat by means of radiation is commonly insignificant in electrical machines thus can be neglected [15].

Heat conduction for the steady state heat transfer of the AFIR 3D model is governed by this differential equation [16].

$$\frac{d}{dx}\left(K\frac{dT}{dx}\right)+\frac{d}{dy}\left(K\frac{dT}{dy}\right)+\frac{d}{dz}\left(K\frac{dT}{dz}\right)+q^{o}=0 \qquad (1)$$

Where T is temperature in (K), x, y and z are spatial variables in (m), K is the thermal conductivity in (W/m.K), q^{o} is the heat transfer rate in (W/m3).

A valuable part of the losses inside the AFIR depends on its speed. Here in the paper, a 3D finite element thermal model for AFIR is solved at different rotor speeds at full load using ANSYS software package, for heat transfer problems in order to take into account the effect of varying the speed on the temperature of each part of the AFIR.

Losses inside the AFIR are computed as in [11] for each case of rotor speed then the heat generated of every component of the motor is calculated per unit volume as:

$$q^{o}=\frac{q\ (W)}{\text{volume of each component}\ (m^{3})} \qquad (2)$$

Where q is the loss in every component of the motor in (W).

Convection boundary condition can be attained by considering the energy balance at the stated surface as:

$$-k\frac{dT}{dx}-k\frac{dT}{dy}-k\frac{dT}{dz}=h(T-T_{B}) \qquad (3)$$

Where T_B is the bulk temperature in (K).

The convective heat transfer coefficients used in analyzing the model is calculated as in [3, 14].

3. FE Results and Discussion

To consider the effect of changing the rotor speed on the AFIR component temperatures, the thermal model has been tested at two different speed at 1000 rpm, and 7000 rpm at rated current, no water cooling, with air natural cooling system and at ambient temperature of 30 ^{o}C.

3.1. At rotor speed of 1000 rpm

When solving the 3D model using the FE package, we get the temperatures range inside the motor. The contour plot for a nodal temperature distributions at 1000 rpm through all the magnet, stator yoke and windings, which resulted from solving are shown in Figs. 3, 4 and. 5.

Table 1 gives results of the predicted temperature values for the 3D FE motor model using ANSYS and corresponding average temperatures of each model component at rotor speed of 1000 rpm.

Table 1. Predicted temperatures for the 3D FE model and their corresponding average temperatures values at 1000 rpm

Material	**Temperature Values of 3D FE Motor Model Using ANSYS (°c)**	
	Range	**Average**
Windings	83.16 to83.92	83.54
Stator	51.83 to 62.05	56.94
Magnet	48.78 to 50.64	49.71

3.2. At rotor speed of 7000 rpm

The estimated results of a nodal temperature distribution at 7000 rpm through all the magnet, stator yoke and windings are demonstrated in Figs. 6, 7 and 8 respectively. It can be observed that, the winding temperature varies between 103.39 ^{o}C and 104.13 ^{o}C with average temperature equals 103.76 ^{o}C, the stator temperature varies between 68.86 ^{o}C and 82.46 ^{o}C with average temperature equals 75.66 ^{o}C, and the magnet temperature varies between 101.23 ^{o}C and 109.45 ^{o}C with average temperature equals 105.34^{o}C.

Table 2 presents the results of the predicted temperature values for 3D Finite Element model using ANSYS and average temperature of each element in the model at rotor speed of 7000 rpm.

Table 2. Predicted temperatures for the 3D FE model and their corresponding average temperatures values at 7000 rpm.

Material	**Temperature Values of 3D FE Motor Model Using ANSYS (°c)**	
	Range	**Average**
Windings	103.39 to 104.13	103.76
Stator	68.86 to 82.46	75.66
Magnet	101.23 to 109.45	105.34

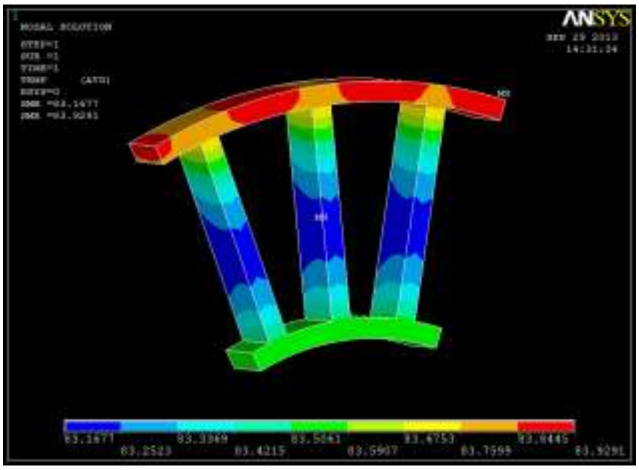


Fig. 3. Windings temperature distribution at 1000 rpm

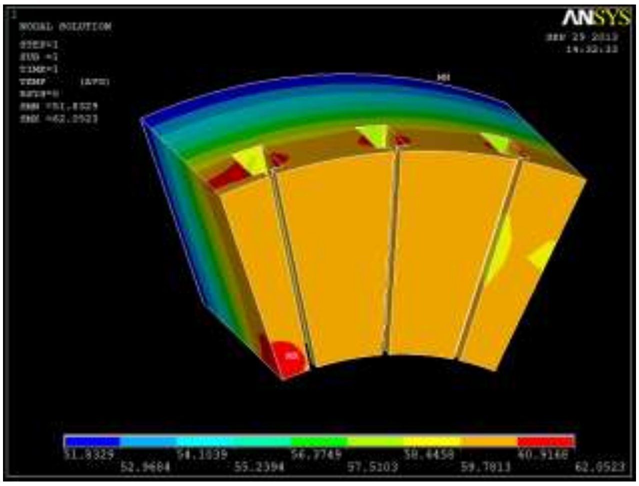


Fig. 4. Stator temperature distribution at 1000 rpm

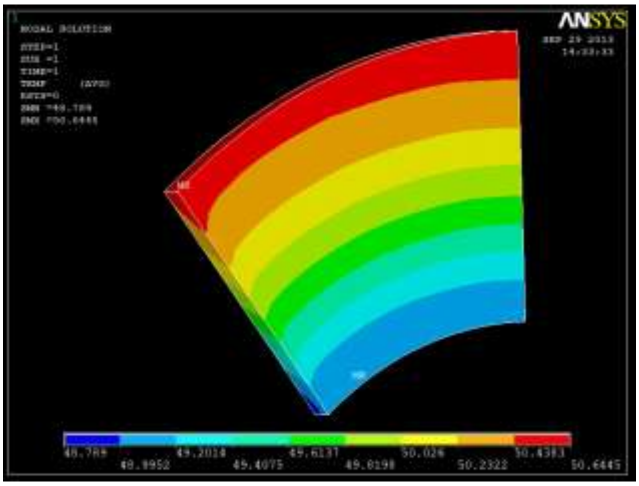


Fig. 5. PM temperature distribution at 1000 rpm

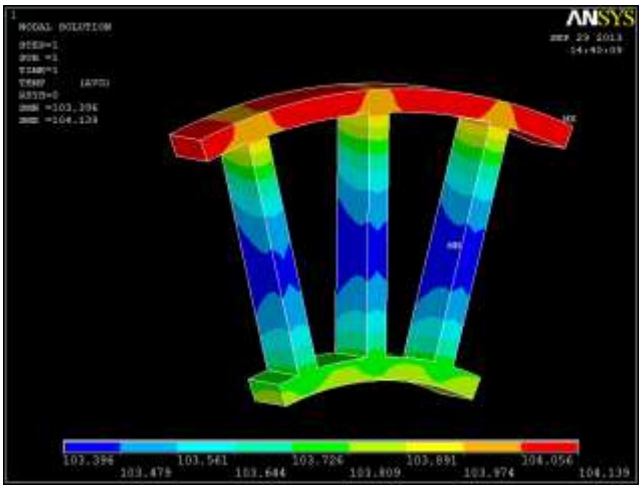


Fig. 6. Windings temperature distribution at 7000 rpm

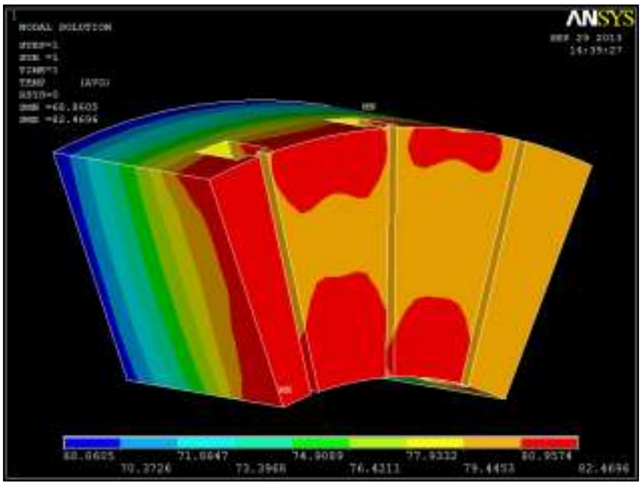


Fig. 7. stator temperature distribution at 7000 rpm

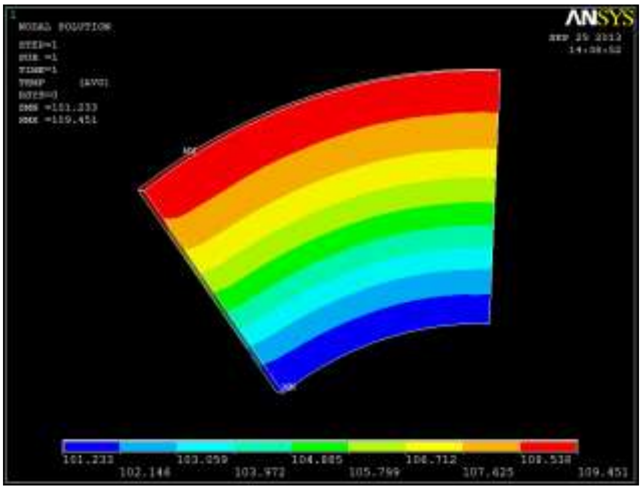


Fig. 8. PM temperature distribution at 7000 rpm

Table 3 shows the increases of the predicted average temperature values for 3D Finite Element model using ANSYS at 7000 rpm than 1000 rpm at the same conditions of load, cooling strategy and ambient temperature. It can be noticed that, the increase of rotor speed from 1000 rpm to 7000 rpm causes an increase of the temperatures distributed inside the AFIR. The influence of increasing the speed is greatest on the PM temperatures about 55.63 ºC in average while the windings temperature increase of about 20.22 ºC, in average and the stator temperatures increase of 18.72 ºC in average.

Thus the increase of PM temperature is high compared to the increase of the temperature of both the stator and the windings and this seems logical because the losses of the motor increases with increasing the speed of the rotor, especially the mechanical losses, and rotor losses. PMs are glued on the rotor surface, therefore their temperatures increase largely with increasing the rotor rotational speed.

Table 3. The difference of the predicted average temperature values at 1000 rpm and 7000 rpm

Material	Average Temperature (ºC) at 1000 rpm	Average Temperature (ºC) at 7000 rpm	The change in the Temperature (ºC)
Windings	83.54	103.76	20.22↑
Stator	56.94	75.66	18.72↑
Magnet	49.71	105.34	55.63 ↑↑↑

4. Conclusion

The thermal model of the AFIR was simulated considering the variations in boundary conditions, and the contributions of the convective heat transfer using ANSYS finite-element analysis program and the nodal temperatures are obtained at full load at two different operating conditions of motor speed. The comparison between the two cases shows that the machine's overall temperature is dependent directly on the speed of the rotor. It observed that with increasing the rotor speed from 1000 rpm to 7000 rpm, the temperature of the PM is increasing more than the windings and the stator.

References

[1] http://www.rosner-tdl.de/english/ROSNER-TDL_TR-02.pdf . "Thermal Analysis of Electric Motors Necessity – Model – Conclusions".

[2] M.A. Fakhfakh , M.H. Kasem M, S.Tounsi and R. Neji , "Thermal Analysis of a Permanent Magnet Synchronous Motor for Electric Vehicles", Journal of Asian Electric Vehicles 2008; 6.

[3] S. Funda, "Design and Development of a High-Speed Axial-Flux Permanent Magnet Machine", Technische Universite it Eindhoven, 2001. Proefschrift. - ISBN 90-386-1380-1

[4] J.F.Gieras ,R. Wang and M.J. Kamper , "Axial Flux Permanent Magnet Brushless Machines", Book, Second Edition, ISBN 978-1-4020-6993-2.

[5] A.Mahmoudi ,N.A. Rahim and W.P. Hew , "Axial-Flux Permanent-Magnet Machine Modeling, Design, Simulation and Analysis", Scientific Research and Essays 2011; 6,pp:2525-2549.

[6] J. Shazly, S. Wahsh and A. Yassin, " Thermal Modeling of an AFPMSM: a Review ", Journal of Electrical Systems and Information Technology (*JESIT*), May 2015, vol 2, pp 18-26.

[7] V.Hrabovcov´a and V. Brˇslica, "Disk Synchronous Machines with Permanent Magnets – Electric and Thermal Equivalent Circuits", Electr. Drives Symp., Capri, Italy,1990, pp. 163–169.

[8] E.Spooner and B.J. Chalmers ., "Torus: a Slotless, Toroidal-Stator, Permanent-Magnet Generator", Proc. of IEE, Pt. B EPA 1992; 139: pp 497–506.

[9] R.J.Wang , M.J.Kamper and R.T. Dobson , "Development of a Thermo Fluid Model for Axial Field Permanent Magnet Machines", IEEE Trans EC-2005;20(1) pp:80–87.

[10] G. Cannistra and M.S. Labini, "Thermal Analysis in an Induction Machine Using Thermal Network and Finite Element Method," Fifth International Conference on Electrical Machines and Drives, London, UK,1991, pp. 300-304.

[11] J. Shazly, S. Wahsh, and A. Yassin. "Thermal Analysis of Axial Flux Permanent Magnet Synchronous Motor using 3D Finite Elements.", International Journal of Thermal Technologies, Vol.4, No.4, December, 2014, pp. 313-319,

[12] D. Platt, "Permanent Magnet Synchronous Motor with Axial Flux Geometry," IEEE Trans. Magnet, vol.25,1989, pp.3076-3079.

[13] A. Parviainen and M.N.J. Pyrhönen, "Design of Axial-flux Permanent Magnet Machines: Thermal Analysis," Proc. Conf. International Conference on Electrical Machines (ICEM), Cracow, Poland, 2004.

[14] A. Yassin , "Thermal Model of Electric Motor in Hybrid Electric Bus", Master Thesis, Faculty of Engineering, Fayoum University, Fayoum, Egypy, 2014.

[15] E.S.Hamdi, "Design of Small Electrical Machines", John Wiley and Sons, 1994.

[16] M. N. Ozisik, "Heat Transfer: a Basic Approach," NewYOrk: McGrawHill, 1985.