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Steady State Thermal Analysis and Design of a Cooling System in an AFPM Motor

K. Sarrafan, and A. Darabi

Abstract—In this paper, the steady-state temperature of a sample 500 KW two rotor one stator Non-slotted axial flux permanent magnet motor is calculated using the finite element simulator software package. Due to the high temperature in various parts of the machine, especially at stator winding, a cooling system is designed for the motor and the temperature is recalculated. The results show that the temperature obtained for the parts is within the permissible range.

Keywords**—**Axial Flux, Cooling System, Permanent Magnet, Thermal Analysis.

I. INTRODUCTION

IN designing electrical machines thermal analysis and cooling of machine is of high rank. Distribution of thermal sources i.e. losses in various parts of the machine should be considered greatly since the temperature of a machine is assessable when we have a clear understanding of the temperature distribution for the parts of the machine and how to remove it. In machines taking high power density, the direct cooling method (forced convection) is utilized. In this method the coolant is directly used to remove the temperature of the element within the machine. In [4] the total description of the cooling system is given according to the power range of electrical machines.

In permanent magnet machines, the excess temperature increase is harmful for the machine because of the following three reasons:

1. The destruction of the insulator covering the copper windings.
2. The jeopardy of demagnetization for the permanent magnets since the demagnetized curves depend highly on temperature and hence, flux of the permanent magnet reduces with respect to temperature.
3. Losses increase due to the increase in windings resistance.

Thus, in two parts of AFPM machine i.e. the stator windings and also the permanent magnets temperature has considerable effect in machine performance and in total operation cycle of the motor the temperature should remain in these two points in permissible range. Permanent magnets and insulators have the capacity of tolerating maximum continuous temperature of 150°C. [1]

There exist various methods to thermally analyze AFPM machines. For instance, lumped parameter models, CFD models and the finite element analysis are of the so-called methods. Lumped-parameter method is one of the most prominent methods to estimate the temperature increase in electrical systems. This method is based upon the thermal resistance, thermal sources and power of losses.

In [9] the lumped-parameter is applied by Nerg to thermally analyze the high speed 430 KW inductive machine. In [10] Maynes investigated the air flow and heat transfer in a radial flux car alternator using the CFD and finite element analysis. Although there are numerous methods and approaches deduced to the thermal analysis of AFPM machines, few articles are written on cooling systems design as in these machines the air gap volume is relatively great and the majority of these machines are self-ventilated or cooled by air. [3] Proposes various cooling methods for AFPM machines, in which the best method for high power machines is to use heat pipes and water or air as fluids going through. In [2] thermal analysis is presented in a sample AFPM machine in which the stator is fixed by bolts to the bearings body. By placing water pipes on body of bearings the stator cools and the bolts maintaining the stator inside cooling channel act as a mixer for heat transfer. This method is highly suited for slotted AFPM machines.

In the section III, the steady state temperature of the machine and the temperature distribution are presented for various parts of the machine using the finite element simulator software package and in section I, cooling system used in the studied motor is introduced and the steady-state temperature after cooling is presented.

II. CALCULATION OF LOSSES

As the main factor for heat creation in electrical machines is losses, one should identify and calculate them correctly especially in AFPM machines. In AFPM machines the losses include stator core iron losses, Eddy current losses in rotor and permanent magnets, mechanical losses and additional losses. In this paper, mechanical losses are omitted since the motor is low speeded. Values for losses in full load situation and during rotor rotation are given in Table I.

Rotor losses are created due to the pulsatile flow generated by rapid changes in air gap reluctance when rotor passes stator teeth [5]. These losses are negligible in the studied machine, since it is non-slotted. The value obtained by the software exhibits this reality.

F. K. Sarrafan is Faculty of Electrical & Robotic Engineering, Shahrood University of Technology, Iran (e-mail: sarrafan123@gmail.com).

S. A. Darabi is with Faculty of Electrical & Robotic Engineering, Shahrood University of Technology, Iran (e-mail: darabi_Ahmad@hotmail.com).

TABLE I
IRON LOSSES OF STATOR AND ROTOR AT FULL LOAD CONDITION

Rotor iron loss			Stator iron loss		
$P_h(W)$	$P_f(W)$	$P_c(W)$	$P_h(W)$	$P_f(W)$	$P_c(W)$
0.43198	1.7492	2.1812	452.96	205.26	658.28

Copper losses in stator windings and also Eddy current losses in permanent magnets are 13.24 KW and 173 W, respectively.

III. HEAT DISTRIBUTION IN STEADY-STATE BY FINITE ELEMENT METHOD

The heat transfer fundamental mechanisms in these machines are conduction in solid elements and convection in the surface contacting the fluid. Often the radiation heat transfer is little valued and hence, can be ignored. The importance of every mechanism is dependent on machine design and the corresponding topology. For example, in the studied machine the main path for heat transfer is through stator to rotor in air gap. Thus, the accurate prediction of heat transfer coefficient in stator-rotor system in air gap has a considerable influence on thermal analysis and its precision.

Table II presents the thermal properties of the used materials in the studied AFPM machine.

TABLE II
THERMAL PROPERTIES OF MATERIALS IN THE AFPM MACHINE [3]

Material	$\rho(\frac{kg}{m^3})$	$C_p(\frac{J}{kg}{}^\circ C)$	$K(\frac{W}{m^\circ C})$
Mica	3000	813	0.33
Plastic resin	140	1700	0.5
Copper	8954	380	386
50JN400	7650	450	30
Nd-Fe-B[1]	7500	501.6	8.95
Aluminum	2700	903	237
Water	1000	4184	0.63
ASTM 40 (Cast Iron)	7060	490	53.3

In various references, there are numerous methods and heuristic formulas to estimate heat transfer coefficient in AFPM machine.

Data used in convection heat transfer coefficient calculation such as rotational Reynolds ($R_{e\theta}$) and Nusselt numbers often have no dimension. Hence, the results can be generalized for various machines with different sizes. The equations to calculate the convection heat transfer coefficient are as follows:

$$N_u = \frac{hR}{k} \tag{1}$$

$$R_{e\theta} = \frac{\Omega R^2}{\upsilon} \tag{2}$$

$$G = \frac{g}{R} \tag{3}$$

In these equations R represents the rotor disk diameter in meter, Ω rotational speed in (rad/s), υ fluid kinematic viscosity (often in reference temperature) in (m^2/s), h convection heat transfer coefficient in $(W/m^2{}^\circ c)$, k fluid conductivity (often in reference temperature) in $(W/m^\circ c)$, g the air gap between rotor and stator in meter, μ dynamic viscosity of the fluid in $(kg/m.s)$.

In [6] Daily and Nece, observed four distinct flow regimes in a totally enclosed stator-rotor with no air flow path, which were highly dependent on G and $R_{e\theta}$.

For the studied motor $R_{e\theta}$ is 6.85118×10^5 and G is 0.0075. So, the third flow regime is considered. [6]

In [1] heuristic formulas are given to calculate the convection coefficient of rotor in air gap. But these calculations are considered on the basis of a special air gap.

Taking $G \approx 0.01$ (4) is given as follows:

$$Nu = 0.044 R_{e\theta}^{\;0.75} \tag{4}$$

According to (4) convection heat transfer coefficient in the rotor of the studied machine is $46.44\, {}^{W}\!/_{m^2{}^\circ C}$.

In [38] the heat transfer coefficient from stator in a stator-rotor system is dependent on (5):

$$Nu = 0.044 R_{e\theta}^{\;0.75} \tag{5}$$

Values for A and B for $G \approx 0.01$ are 0.079 and 0.64, respectively.

These are desired for turbulent flow regime i.e. ($R_{e\theta} \rangle 5.19e5$).

According to (5) the calculated convection heat transfer coefficient from stator to air gap is $19.016\, {}^{W}\!/_{m^2{}^\circ C}$.

As can be seen, heat transfer coefficient in stator side is less than that of the rotor, since tangential and radial velocity gradient in stator is lower in comparison with rotor. This is proven in [7] by Boutafa and Harmand.

The equations to calculate convection heat transfer coefficient on peripheral edge of the rotor disk and also free rotation disk in laminar and turbulence flow regimes are given in [3] and [8]. After calculating the convection heat transfer coefficients for various parts of the machine and applying it to the software and also coupling the electromagnetic analysis with thermal analysis the steady-state temperature in various parts of the motor is given in Table III considering heat sources generated from losses in motor parts.

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[1] Neodymium-Iron-Boron

TABLE III
STEADY STATE TEMPERATURE OF VARIOUS PARTS OF THE AFPM MOTOR IN FINITE ELEMENT SOFTWARE

Name of the part	Average temperature (centigrade)
winding	285.56
Stator core	278.23
Rotor core	94.08
magnet	95.74
mica	281.15
Plastic resin	98.91

Heat transfer pattern in stator and rotor cores with magnets are depicted in Fig. 1 and Fig. 2, respectively. Due to the symmetric geometry, a pair of pole from studied motor with half stator is used for analysis.

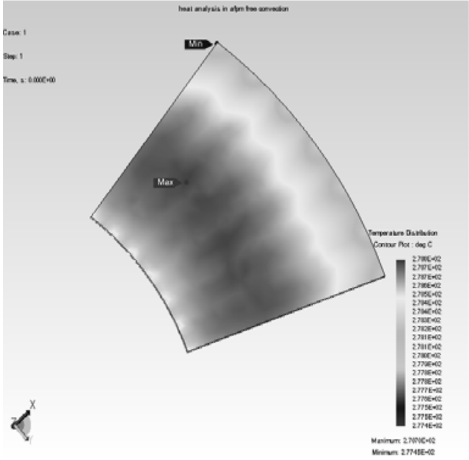

Fig. 1 Steady state temperature distribution in stator core

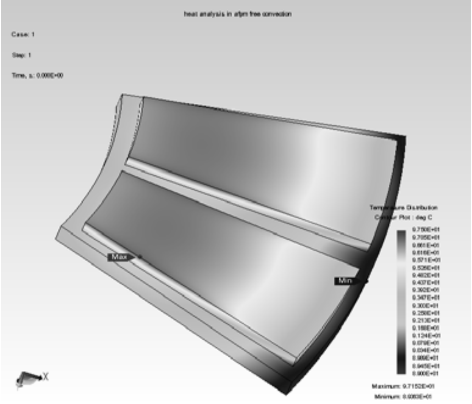

Fig. 2 Steady state temperature distribution in Rotor with two magnets

IV. DESIGN OF COOLING SYSTEM AND CALCULATION OF STEADY STATE TEMPERATURE AFTER COOLING

Due to the high temperature in stator winding and also the topology of the machine the best cooling system is to use heat pipes. What seems to be important here in this type of cooling is to determine pipe material, the kind of connection, the place located and its dimensions. In addition, the fluid speed inside the pipe and its temperature is of value.

In this cooling design, two heat pipes made of Iron are placed beside each other on stator edge. A 5 millimeter space is devoted to fix stator to body between the two pipes. Water is utilized as a fluid for cooling. The temperature considered is $30^{\circ C}$ and the flow path in each pipe is against the other. Water speed in the pipe is $0.2\,(m/s)$ and each pipe diameter is 35.55^{m}.

Fig. 3 depicts the complete schematic of the machine followed by the embedded cooling system.

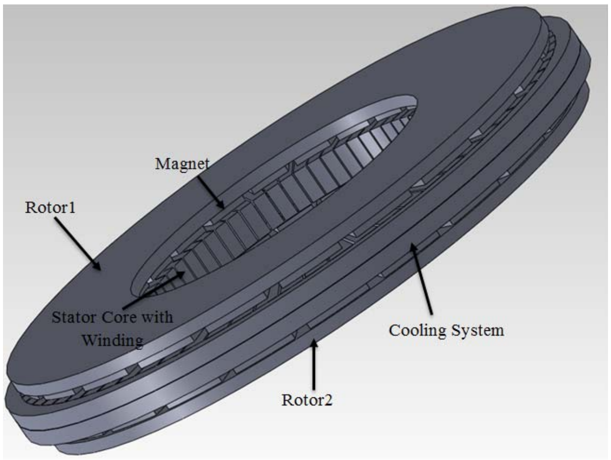

Fig. 3 The complete schematic of the AFPM machine followed by the cooling system

Convection heat transfer coefficient dependent on the calculated Reynolds number from the surface of the pipes to the fluid water that representing the fluid flow regime inside the pipe. Because of this, the Reynolds number is calculated from (6). [3]

$$R_{ed} = \frac{\rho v d}{\mu} \tag{6}$$

In which, d is the diameter of the pipe in meter, v the fluid speed inside the pipe in (m/s). If the calculated Reynolds number is greater than 2000 the flow regime type is turbulent otherwise laminar. The calculated Reynolds number for water with $0.2\,(m/s)$ speed is 9102.607. Therefore, Nusselt number is calculated according to the equations available in turbulent mode. [3]

$$N_u = 0.023 R_e^{0.8} P_r^{\,n} \tag{7}$$

In which, P_r is the prandtl number related to the fluid in special temperature and n is 0.4 for hot region, 0.3 for cold region.

According to the Nusselt number being obtained convection heat transfer coefficients is calculated from (8). [3]

$$h = \frac{kN_u}{d} \tag{8}$$

In the studied motor Nusselt number and also convection heat transfer coefficient from the surface of the pipe to the fluid water are 64.91 and 1130.9, respectively. For a better robustness and also better heat transfer, the pipe is placed inside aluminum to ensure maximum conductive heat transfer with winding. Of course, the space between winding and the aluminum is filled with mica that not only it protects the windings, but also the high electrical conductivity of aluminum brings about no effect on magnetic analysis of the machine.

Fig. 4 depicts a schematic of a pair of the poles for the machine followed by the cooling system.

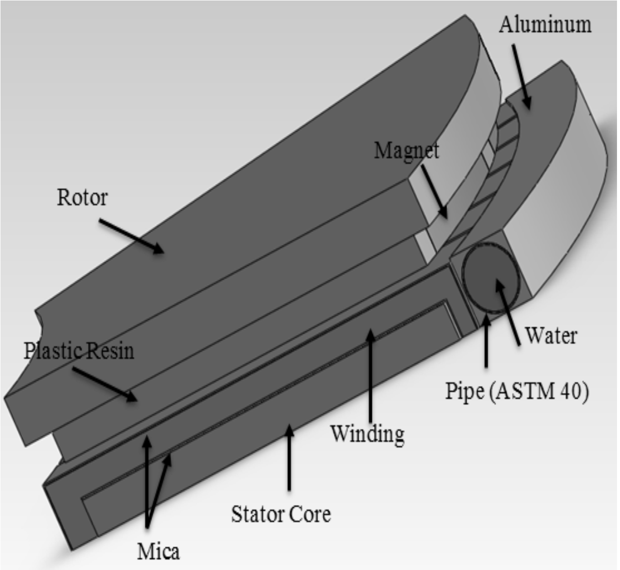

Fig. 4 3D schematic view of a pair of poles for an AFPM machine followed by cooling system

In Table IV the steady-state temperature is shown after the simulation in the software. As can be seen, the temperature at stator side is reduced by 142.69 degrees and the temperature of all parts is in permissible range. Heat distribution is also depicted in Figs. 5 and 6, respectively.

TABLE IV
STEADY STATE TEMPERATURE OF VARIOUS PARTS OF THE AFPM MOTOR IN FINITE ELEMENT SOFTWARE WITH COOLING SYSTEM

Name of the part	Average temperature (centigrade)
winding	142.87
Stator core	134.06
Rotor core	80 / 57
magnet	81.34
mica	137.32
Plastic resin	82.245

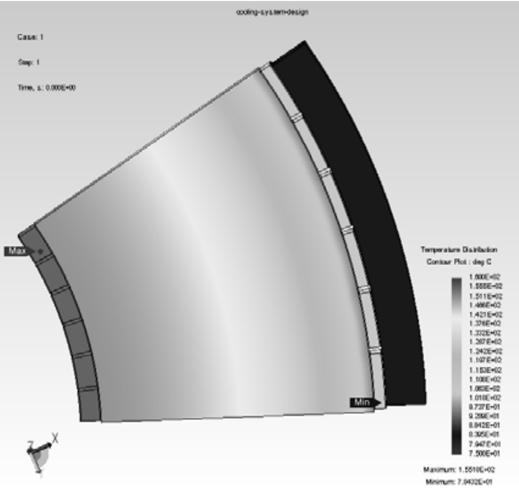

Fig. 5 Steady-state temperature distribution in stator core after cooling

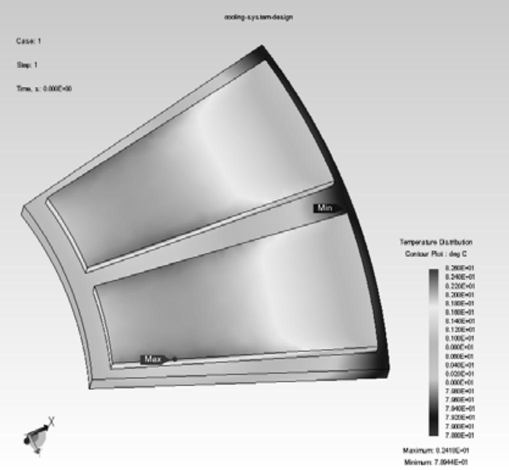

Fig. 6 Steady-state temperature distribution in rotor with two magnets after cooling

V. CONCLUSION

In this paper, steady-state temperature in a sample500 KW TORUS Non-slotted axial flux permanent magnet motor was calculated using the finite element simulation software. We utilized heat pipes with water as a fluid for cooling stator windings. After cooling, temperature was calculated at windings and the magnets sides taking the values $142.78^{\circ C}$ and $81.34^{\circ C}$, respectively. This shows that they are less than $150^{\circ C}$ i.e. in a permissible range. It is possible to keep the machine temperature at lower values by increasing the speed of water flow in the pipe. As a next study, we can analyze the influence of cooling system in transient-state.

REFERENCES

[1] D.A Howey, P.R.N. Childs, and A.S. Holmes, “Air-gap convection in rotating electrical machines,” IEEE Transactions on Industrial Electronics, vol. 59, pp. 1367–1375, 2012.

[2] Parviainen, Design of Axial-Flux Permanent-Magnet Low-speed Machines and Performance Comparison between Radial-flux and Axial-

flux Machines, Thesis for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the auditorium 1382 at Lappeenranta University of Technology, Lappeenranta, Finland on the 19th of April, 2005.

[3] J. Gieras, R.J Wang, and M.J. Kamper, Axial Flux Permanent Magnet Brushless Machine. Print ©2004 Kluwer Academic Publishers Dordrecht.

[4] Prof. A. Binder, "Large Generators and High Power Drives," part 2.

[5] J. F. Gieras, and M. Wing, Permanent Magnet Motor Technology, Design and Applications, Second edition, Marcel Dekker, Inc., 2002.

[6] J. Daily and R. Nece, “Chamber dimension effects on induced flow and frictional resistance of enclosed rotating disks,” ASME J. Basic Eng, vol. 82, pp. 217–232, 1960.

[7] R. Boutarfa and S. Harmand, “Local convective heat transfer for laminar and turbulent flow in a rotor-stator system,” Experiments in Fluids, vol. 38, pp. 209–221, 2005.

[8] R. Wang,R.T. Dobson, and M.J. Kamper, “thermo fluid analysis of an Axial Flux Permanent Magnet (AFPM) generator,” R & D journal, vol. 17, 2001.

[9] J. Nerg, M. Rilla, and J. Pyrhonen, “Thermal analysis of radial-flux electrical machines with a high power density,” IEEE Transactions on Industrial Electronics, 55(10):3543–3554, 2008.

[10] C.E. Tindall B.D.J. Maynes, R.J. Kee and R.G. Kenny, “Simulation of airflow and heat transfer in small alternators using CFD,” IEE Proceedings on Electric Power Applications, 150(2):146–152, 2003.

K. Sarrafan was born in Tehran Iran in 1987. He received the B.Sc. degree from Sadjad Institute of Higher Education in 2009 (Mashad/Iran), He is currently pursuing the M.Sc. degree at the Shahrood University of Technology Shahrood-Iran. His interested areas are permanent magnet machines design, loss calculation and heat transfer analysis in electrical machines.

A. Darabi received the B.Sc. degree in electrical engineering from Tehran University, Tehran, Iran in 1989 and the M.Sc. degree in the same field from Ferdowsi University, Mashhad, Iran, in 1992. He obtained the Ph.D. degree with the electrical machine group, Queen’s University, Belfast, UK, in 2002. He is now an associate professor and has been with Faculty of Electrical and Robotic Engineering, Shahrood University of Technology, Iran from 1993. His research activities are mostly on design, modelling and manufacturing of miniature electrical machines and generating sets. Dr. Darabi is a member of IAENG.