Design of the Forced Water Cooling System for a Claw Pole Transverse Flux Permanent Magnet Synchronous Motor

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***Abstract*— This paper presents a detailed finite element analysis-based design procedure of the forced water cooling system for a low voltage claw pole transverse flux permanent magnet motor (TFPM), which is used in marine propulsion systems. Iron and copper losses density distributions are obtained using commercial finite element method software JMAG 10.5. Surface water cooling system, with spiral cooling ducts passing through the aluminum hosing of the stator, is chosen as the proper cooling system. To prevent any thermal and electrical unbalanced situation, for each phase separate water input and output are considered. Dimensions of the cooling ducts, as well as the velocity of water flowing through these ducts are calculated in a way that makes the water flow completely turbulent, having the right speed for cooling purposes. Number of required cooling ducts for an acceptable temperature distribution, below the thermal limits of motor, is determined by finite element thermal analysis. To consider the worst case scenario, a number of assumptions are made in the thermal analysis of the motor.**

Keywords—Finite Element Analysis, Losses Distribution, Thermal Analysis, Transverse Flux Permanent Magnet Motor, Water Cooling System.

I. Introduction

Transverse flux permanent magnet motors (TFPM) are widely used in electric propulsion systems, thanks to their great efficiencies and high power and torque densities [1]. The power density of some TFPM topologies could reach values more than three times greater than those provided by conventional machines [2]. These high power densities are achieved by increasing the number of pole pairs, which is not the case in conventional machines.

Several topologies have been proposed for TFPMs which can be classified into two major categories: 1) the double-sided topologies with high power production capabilities, but complicated structures and 2) the single-sided topologies with lower power production capabilities, but simpler structures [2]. Compared to other TFPM topologies, the claw pole TFPM benefits from the simplicity of the single-sided TFPMs, while its performance is comparable with double-sided ones [3]. Therefore, the claw pole TFPM is the chosen topology for electric propulsion systems by many researchers around the world.

The more compact a motor is, the more difficult is heat dissipation from it. Any temperature increase above the thermal limits of the motor may lead to insulation system failure or demagnetization of the permanent magnets. Therefore, design of an effective cooling system is of great importance for compact motors. Choosing the proper cooling system depends on several factors, such as the rated power of the machine, its application, losses distribution inside the machine, degree of protection, etc. In this paper, considering its application, forced water cooling system is selected for heat dissipation from the claw pole TFPM.

Thermal analysis of the motor is necessary to design an effective cooling system. In the past, it was believed that the electromagnetic analysis of electric machines is more important than their thermal analysis. Considering the new trends in compact and efficient motors as well as the usage of new materials and topologies, it is now necessary to give equal importance to both electromagnetic and thermal analysis. Thermal analysis methods for electric machines can be divided into two basic groups: 1) analytical (lumped circuit) methods and 2) numerical methods [4]. Although the analytical method is very fast to calculate, it is difficult to use this approach for motors with a complex geometry, like claw pole TFPM. The advantage of numerical methods, on the other hand, is that motors with complex geometries can be modeled. Numerical methods classified into two types: computational fluid dynamics (CFD) and finite element analysis (FEA). One of the advantages of CFD over the FEA is that it is able to calculate the flow of fluid in complex regions [4]. Unfortunately using CFD is difficult and time consuming. FEA is something more familiar to electrical engineers, but it can only be used to model conduction heat transfer in solid components. For convection heat transfer, just like the analytical approach, convection correlations should be used.

Since in the surface forced water cooling system the flow of water isn't too complicated, it is possible to use the FEA for thermal analysis of Claw Pole TFPM motor. So, in this paper both the thermal analysis and electromagnetic analysis of the claw pole TFPM are carried out using commercial finite element method software JMAG 10.5.

II. Case Study

Based on the sizing equations of [1] and [3], and with some changes, a 500 KW transverse flux motor is designed. Fig. 1 shows one pole pair of one phase of the designed TFPM. 60 pole pairs around the axis of motor form one phase, which is illustrated by Fig. 2. Multiphase structure is achieved by stacking shifted phases along the machine axis direction. The six phase motor is depicted in Fig. 3.

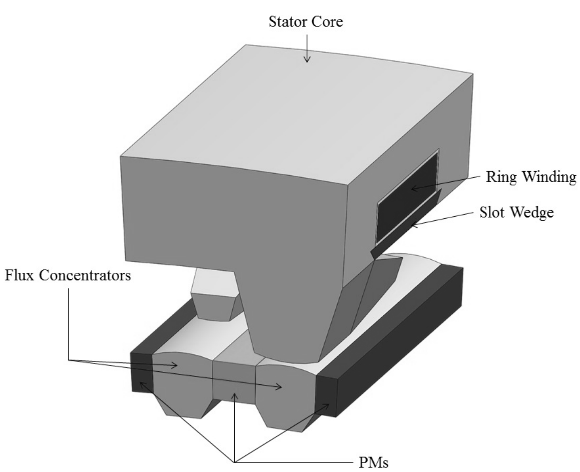

Figure 1. One pole pair of the designed claw pole TFPM.

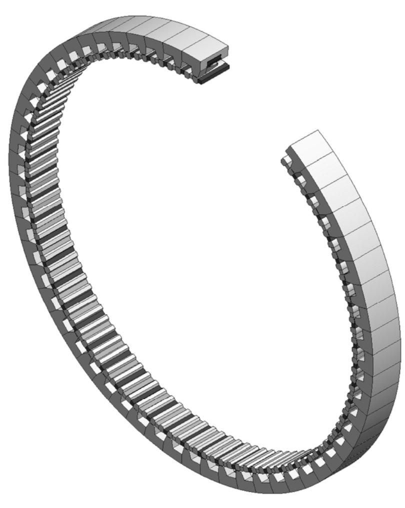

Figure 2. One phase of the designed claw pole TFPM.

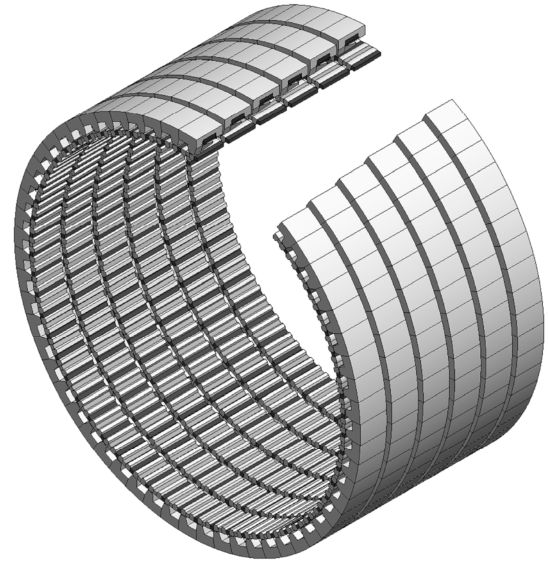

Figure 3. The six phase designed claw pole TFPM.

The machine parameters are listed in TABLE I. Materials which have been used in structure of motor are given in TABLE II.

III. Losses Distribution inside the Motor

According to IEEE 115-2009, loss components of a synchronous machine are friction and windage loss, core loss, stray load loss, armature copper loss and field copper loss [5]. For a permanent magnet synchronous machine there is no field copper loss. Also, for a low speed machine, friction and windage loss can be neglected. Calculation of stray load loss is difficult, so it is considered as a certain percent reduction of full load efficiency. However, its effect on thermal analysis of machine, compared to other loss components, can be neglected. In a PM machine, because of armature current harmonics, while rotation, magnets will experience changing flux density. This changing flux density will induce eddy currents inside magnets, which, in turn, results in eddy current loss. So, for thermal analysis heat sources are core loss, armature copper loss and magnets eddy current loss.

Core loss of electric machines is comprised of hysteresis and eddy current losses. There are several methods, with different accuracies and applications, for calculating these losses. Taking into account the simplicity of the design procedure of this paper, losses density distribution is obtained by using commercial finite element method software JMAG 10.5. Iron loss calculation method of JMAG is based on Steinmetz equation, which its required coefficients are obtained from the loss data provided by the core material manufacturer [6]. Armature copper loss and magnets eddy current loss are calculated based on the famous Ohm's Law.

Due to special construction of the multiphase TFPM, each phase is electromagnetically independent from other phases. So, the losses of each phase can be calculated separately. Fig. 4 shows losses density distribution inside one pole pair of one phase of machine. Numerical values of losses for each phase are given in TABLE III.

TABLE I. DESIGNED MACHINE RATINGS AND PARAMETERS

Rated Power	500 kW
Rated Speed	300 rpm
Rated Frequency	300 Hz
Maximum phase voltage (Amplitude)	105 V
Number of phases	6
Outer diameter	1377 mm
Air gap surface diameter	1312 mm
Stator slot depth	44 mm
Stator core back depth	14.5 mm
Height of PMs in radial direction	12 mm
Stack Length per phase	105 mm
Slot axial length	51.5 mm

TABLE II. MATERIALS IN MOTOR STRUCTURE

Stator core	Somaloy500+0.5%Kenolube_800MPa
Rotor flux concentrators	Somaloy500+0.5%Kenolube_800MPa
Permanent magnets	NEOMAX-32EH
Winding	Copper

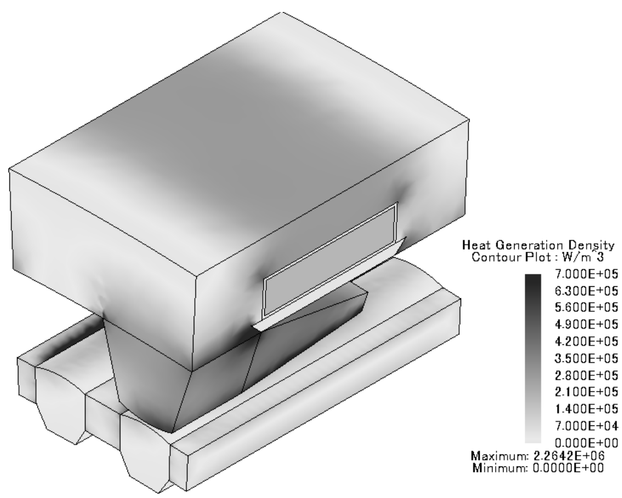

Figure 4. Losses density distribution inside one pole pair of one phase of machine.

TABLE III. NUMERICAL VALUES OF LOSSES FOR EACH PHASE

Stator core iron loss	3532 W
Rotor flux concentrators iron loss	350 W
Permanent magnets eddy current loss	200 W

IV. WATER COOLING SYSTEM DESIGN

A. Choosing the Structure of Cooling System

Since the major loss component is the stator core loss, the cooling system structure should be in a way that could dissipate the stator core heat loss easily. Cooling ducts inside the stator core may increase the losses. So, for this motor cooling ducts will pass through the aluminum housing that holds stator cores together. Spiral cooling ducts with circular cross section are selected to conduct water inside the motor. Fig. 5 shows the proposed cooling system for one phase of motor.

As mentioned earlier, each phase of motor is electromagnetically independent from other phases. Because the temperature has a serious effect on the electromagnetic solution inside the motor, the cooling process of each phase should be independent from other phases. Otherwise, an unbalanced situation will occur. So, for each phase separate water input and separate water output is considered.

B. Calculation of the Flow Rate

The required minimum flow rate is calculated by

$$Q = \frac{P_{loss}}{\rho \cdot C_p \cdot \Delta T}, \qquad (1)$$

where P_{loss} is the total loss per phase. ρ and C_p are the mass density and the specific heat capacity of the water respectively. ΔT is the maximum temperature rise of the water. Taking into account the effects of drive system on losses, also the mechanical and stray load losses, total loss is considered to be 6 kW. In the designed cooling system, the allowed temperature rise of water is around $10^\circ C$. Using (1) results in a minimum flow rate of $Q = 1.4446 \times 10^{-4} m^3/s$.

C. Selection of the Cooling Tube Diameter

For piping applications, the diameter of the pipe or tube is selected based on the pressure drop limit inside the tube. However, for cooling purposes, it's better to use small diameter tubes for two reasons. First, the smaller the diameter of tube is, the higher is the convection heat transfer coefficient. Second, smaller diameter tubes are more flexible. So, the standard 1/2 inch annealed type L copper tube is selected for conducting water through the aluminum housing. Pressure drop per 100 feet of this tube is about 5.5 PSI.

The speed of water inside the tubes is calculated by

$$V = \frac{Q}{A}, \qquad (2)$$

where A is the tube cross section area. With $Q = 1.4446 \times 10^{-4} m^3/s$ and $A = \pi(0.013843/2)^2 m^2$, the speed of water will be $0.958 m/s$. Cooling water velocity in pipes and tubes should not exceed 1.5-2.5 m/s.

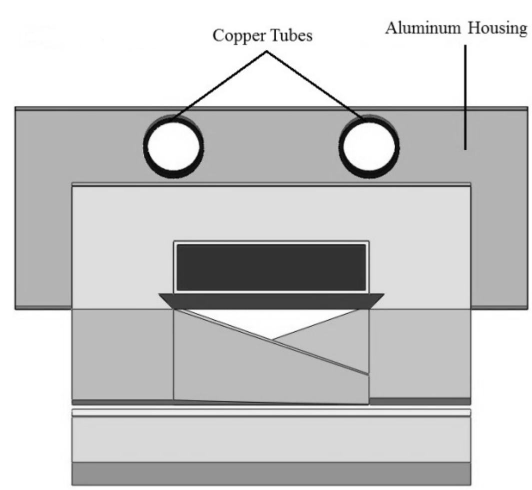

Figure 5. The proposed cooling system structure for one phase of motor.

D. Calculation of the Tube Wall Heat Transfer Coefficient

Empirical correlations are available to estimate heat transfer coefficients for a variety of natural convections and forced convections heat transfer configurations. These correlations are typically expressed in terms of dimensionless numbers. The dimensionless numbers used for forced convection heat transfer coefficients are the Nusselt number (Nu), Prandtl number (Pr), and Reynolds Number (Re). The heat transfer coefficient, h, appears in the Nusselt number, so the correlations are typically in the form of an equation for Nu in terms of Re and Pr. The definition of Nu, Pr, and Re are given by following equations [7]

$$Nu = \frac{hD}{k}, \tag{3}$$

$$\Pr = \frac{\mu C_p}{K}, \tag{4}$$

$$\mathrm{Re} = \frac{DV\rho}{\mu}, \tag{5}$$

where K is the thermal conductivity of the fluid in $W/m^{\circ}C$, D is the hydraulic diameter of the duct or tube in m and μ is the viscosity of the fluid in Ns/m^2. Other parameters have been introduced before. It should be noted that the fluid properties, specially the viscosity of the fluid, is dependent to temperature, which, in turn, makes the heat transfer coefficient to be temperature dependent.

There are several correlations available for calculation of the convective heat transfer coefficient for turbulent flow through a fluid in a pipe or duct. The most accurate one is [7]

$$Nu = \frac{(\frac{f}{8})(\mathrm{Re}-1000)\Pr}{1+12.7(\frac{f}{8})(\Pr^{2/3}-1)}. \tag{6}$$

The f in (6) is the Moody friction factor, which is given by [7]

$$f = (0.79\ln(\mathrm{Re})+1.64)^{-2}. \tag{7}$$

Equation (6) is valid for $0.5 \le \Pr \le 2000$ and $3000 \le \mathrm{Re} \le 5\times10^6$ [7].

Cooling system convective heat transfer related parameters are given in TABLE IV. These parameters are calculated for both input and output water temperatures.

TABLE IV. COOLING SYSTEM CONVECTIVE HEAT TRANSFER RELATED PARAMETERS

	Water at 30 degree centigrade	**Water at 40 degree centigrade**
Reynolds Number	1.6561×10^4	2.0169×10^4
Prandtl number	5.3997	4.3165
Nusselt number	113.2777	122.8188
Heat transfer coefficient	5.0484×10^3	5.603×10^3

E. Determination of the Number of Cooling Ducts per Phase Using FEA

Based on the Newton's law of cooling, temperature distribution inside the cooled body, for a specific heat source and a constant convective heat transfer coefficient, only depends on the heat transfer surface area [7]. Therefore, number of cooling ducts per phase should be determined in a way that ensures the temperature distribution inside the motor would not lead to failure of the machine.

There are two limits on the maximum temperature inside the machine. First one is the thermal endurance of insulation material, which is related to thermal class of insulation system. The thermal class of this motor is 130. Second limit is the maximum temperature of the magnets. High temperatures for magnets results in irreversible thermal demagnetization of magnets. This limit, for the selected magnets is $140^{\circ}C$. So, the limiting temperature is considered to be $130^{\circ}C$.

Evaluating the temperature distribution inside the machine is done by using finite element analysis. In this analysis, both natural convection and forced convection are considered. There are many papers dedicated to thermal analysis of electric machines using finite element method. In this paper, thermal analysis has been conducted based on the [6], [8].

For cooling system design it's better to consider the worst case scenario. For this purpose a number of assumptions are made:

- The air inside the cover of machine is completely trapped, i.e., there's no way for the trapped air inside the cover to exchange with the surrounding air.
- Natural convection heat transfer coefficient is set to $10\,W/m^2\cdot^{\circ}C$ for all surfaces of the machine (This coefficient is between 10 and $25\,W/m^2\cdot^{\circ}C$).
- An interface gap of 0.05 mm is considered between components. This interface gap is due to imperfections in the touching surfaces and is a complex function of material hardness, interface pressure, smoothness of the surfaces and air pressure [8].
- Thermal conductivity of the winding area is set to $0.2\,W/m\cdot^{\circ}C$, due to presence of the air and insulation materials in this part of the motor.
- Temperature distribution of the pole pair adjacent to the water output ($40^{\circ}C$ water) will be the criterion for the selection of number of cooling ducts.

One duct is the natural first selection for the number of spiral cooling ducts per phase. The temperature distribution inside the machine with one cooling duct per phase is depicted in Fig. 6. Since the maximum temperature in the machine is higher than $130^{\circ}C$, the number of ducts should be increased to reach the desired temperature distribution.

Fig. 7 shows the temperature distribution when two series ducts are considered for cooling the motor. In this case, the maximum temperature of the motor is less than $117^{\circ}C$. Therefore, the number of cooling ducts per phase is set to 2. The designed cooling system parameters and properties are given in TABLE V.

V. CONCLUSION

In this paper, we have developed a procedure for design of forced water cooling system for a low voltage high power transverse flux permanent magnet synchronous motor. Heat losses have been estimated based on the Steinmetz equation using the commercial finite element method software JMAG 10.5. Surface water cooling, using spiral cooling ducts with circular cross section passing through the aluminum housing of the stator cores, has been chosen as the proper structure. Also, to prevent an unbalanced situation, separate water inputs and outputs for each phase have been considered. The diameter of the cooling ducts has been determined in way that makes the water flow completely turbulent, having the right speed for cooling systems. Results of thermal analysis conducted by finite element method software JMAG 10.5, shows that the number of cooling ducts has to be 2 per each phase in order to lower the maximum temperature inside the motor below the thermal limit of insulation materials and permanent magnets. A number of assumptions have been made to consider the worst case scenario, for both natural and forced convection, in thermal analysis of the motor.

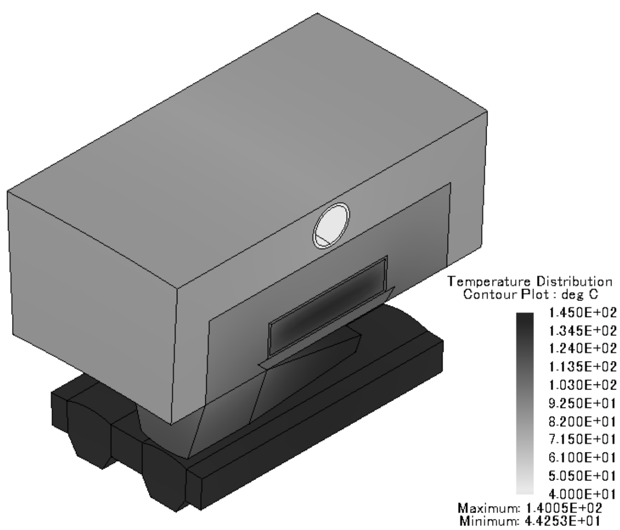

Figure 6. Temperature distribution inside the machine with one cooling duct per phase.

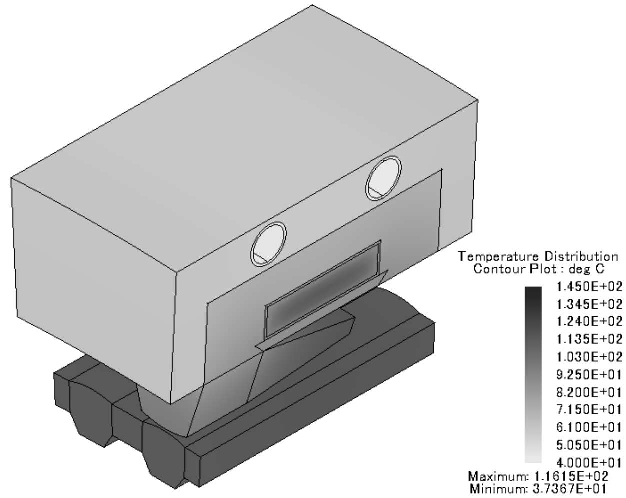

Figure 7. Temperature distribution inside the machine with two cooling duct per phase.

TABLE V. THE DESIGNED COOLING SYSTEM PARAMETERS AND PROPERTIES

Number of cooling ducts per phase	2
Number of parallel ducts for six phases	6
The speed of water inside the cooling ducts	0.958 m/s
Water flow rate for each duct	2.3 $g.p.m$
Pump flow rate	13.8 $g.p.m$
Pump head	735 mm H_2O

REFERENCES

[1] A. Masmoudi and A. Elantably, “An approach to sizing high power density TFPM intended for hybrid bus electric propulsion,” Elect. Mach. Power Syst., vol. 28, no. 4, pp. 341–354, 2000.

[2] A. Masmoudi, A. Njeh, and A. Elantably, “On the analysis and reduction of the cogging torque of a claw pole transverse flux permanent magnet machine,” Euro. Trans. Electr. Power, vol. 15, no. 6, pp. 513–526, 2005.

[3] A. Masmoudi, A. Njeh, A. Mansouri, H. Trabelsi, and A. Elantably, “Optimizing the overlap between the stator teeth of a claw pole transverse-flux permanent-magnet machine,” IEEE Transactions on Magnetics, vol. 40, no. 3, pp. 1573–1578, 2004.

[4] A. Boglietti, A. Cavagnino, D. Staton, M. Shanel, M. Mueller, and C. Mejuto, “Evolution and Modern Approaches for Thermal Analysis of Electrical Machines,” IEEE Transactions on Industrial Electronics, vol. 56, no. 3, pp. 871–882, 2009.

[5] IEEE Guide: Test Procedures for Synchronous Machines Part I--Acceptance and Performance Testing Part II-Test Procedures and Parameter Determination for Dynamic Analysis, IEEE Std 115-2009.

[6] JMAG designer online help, ver. 10.5, 2011.

[7] J. H. Lienhard IV, and J. H. Lienhard V, A Heat Transfer Textbook, 4th ed., Phlogiston Press, 2012, pp. 343-396.

[8] D. Staton, A. Boglietti, A. Cavagnino, “Solving the More Difficult Aspects of Electric Motor Thermal Analysis in Small and Medium Size Industrial Induction Motors,” IEEE Transactions on Energy Conversion, vol. 20, no. 3, pp. 620–628, 2005.