

Thermal Modeling of PMSG Generator for Gas Turbine Applications

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Abstract

Objective: A customized high speed Permanent Magnet Synchronous Generator (PMSG) is designed for military applications. Thermal analysis is essential to improve the system utility during operating conditions, prevent overheating, insulation breakdown and demagnetization of magnets. **Method:** A thermal network model is proposed to analyze and estimate the temperature rise of the customized high speed, six phase PMSG for its design specifications. The detailed thermal model is analyzed and the thermal resistance values are obtained. The simplified model is obtained considering significant sections of the machine where the losses cause rise in temperature. **Results:** The thermal resistances in the thermal model are calculated based on the dimensions of the customized PMSG. The temperatures variations in the significant parts of the machine are calculated. **Conclusion:** The thermal values estimated are within the thermal limits for the selected class of insulation and design specifications.

Keywords: High Speed, Six Phase Permanent Magnet Synchronous Generator Nomenclature, Thermal Analysis

1. Introduction

PMSG is preferred because of self-excitation, lower weight, smaller size, less maintenance and high efficiency¹. The heat transfer behaviour model of PMSG is highly essential as it defines the cooling capability, power rating of the machine and temperature distribution required to analyse and avoid magnet saturation. Impact of direct cooling method, various loss minimization approaches for high speed PMSG are proposed in². Various models of thermal analysis are available to analyze the electrical machines³⁻⁶.

The lumped parameter thermal networks method is easy to construct, takes less time for computation with accuracy dependent on heat transfer co-efficient⁷. The heat transfer model can be obtained by using the analogy between electric and thermal circuits. Based on the analogy thermal resistance corresponds to electric resistance, heat flux corresponds to current, and temperature difference corresponds to power. Thermal network is constructed by first dividing the motor into separate geometrical sections, which are connected to

neighbouring sections through thermal resistances. The average temperature of the body and the power losses are assumed to be homogeneously distributed within the sections⁸.

The development stages of the thermal model are: Modeling the thermal network, calculating the thermal resistances in the thermal model, evaluating the losses based on the specifications and determining the temperature distribution based on the thermal resistances and losses. Various factors influence the results obtained from conventional lumped parameter method and the finite element method. The operating conditions determine the power losses, thermal characteristics of the materials, and the variation of thermal conductivity of the materials with the temperature⁹.

2. Detailed Thermal Model

A lumped-parameter thermal network model is used to represent the PMSG. The thermal model calculates the maximum temperature of the stator winding and the

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magnets. The model developed in the paper uses the principles arrived in⁸. The temperature differences in the circumferential direction of the generator are neglected.

Table 1. Machine Parameters

Parameter	Value	Parameter	Value
No: of Slots S	24	Current Density, J (A/mm ²)	6
Outer Diameter of Stator, Dy (mm)	150	Speed, N (rpm)	30000
Slot Height, hss (mm)	22	Inner Diameter of Rotor, Drc (mm)	70
Tooth Width, bts (mm)	4.5	Magnet Arc, α (degrees)	120
No: of Poles, P	4	Height of Magnet, hm (mm)	3

The detailed thermal model is shown in Figure 1. The model has thirty nine thermal resistances calculated using heat flow definitions in rectangular elements. The geometric parameters of the customized PMSG are given in Table 1. The values of the thermal constants used are given in Table 2. The calculated values of the thermal resistances in the detailed model are given in Table 3.

Table 3. Thermal Resistances of Detailed Model

Thermal Resistance	Value	Thermal Resistance	Value
$R0 = 1/(qvc*pc*ktkc)$	0.15	$R20 = -R13/3$	1.59
$R1 = 1/(3*I*bd*α1)$	9.83	$R21 = (hs1+hs2) / (lu*lfe*((0.5*tow) + (0.5*bd)))$	0.05
$R2 = 1/(3*I*bs*α1)$	19.49	$R22 = 1 / (I * α2 * (tow - bs))$	29.57
$R3 = (0.5*hys)/(lu*bd*λfe)$	0.17	$R23 = 1 / ((I*bm*α2) + (hm1 / (I*bm*λgrp)))$	144.74
$R4 = (0.5*hys)/(lu*bs*λfe)$	0.34	$R24 = (0.5*hm)/(I*bm*λm)$	1.17
$R5 = (0.5*bd) / (lu*hys*λfe)$	0.06	$R25 = -R24/3$	0.38
$R6 = (0.5*bs) / (lu*hys*λfe)$	0.03	$R26 = hm0/(I*bm*λglue)$	0.75
$R7 = -R5 / 3$	0.02	$R27 = hys / (I*tow*λfe)$	0.23
$R8 = -R6 / 3$	0.01	$R28 = 1 / (I*tow*α5)$	35.38
$R9 = -R3 / 3$	0.06	$R29 = 1 / (pi*α3*((0.5*d+hs+hys)* (0.5*d+hs+hys)))$	25.98
$R10 = -R4/3$	0.11	$R31 = (0.5*I) / (hcu*bcu*kcu*Icu)$	4.93
$R11 = hi / (I*bcu*λi)$	12.24	$R30 = -R31/ 3$	1.64
$R12 = (0.5* (hcu + 2*hi)) / (lu*bd*λfe)$	0.15	$R32 = (0.5*lb)/(hcu*bcu*kcu*λcu)$	7.37
$R13 = (0.5*hcu) / (I*bcu*λcoil)$	4.76	$R33 = -R32/3$	2.46
$R14 = (0.5*bd) / (lu*(hcu+2*hi).*λfe)$	0.07	$R36 = (0.5*hcu)/(lb*bcu*λcoil)$	3.18
$R15 = hi / (I*hcu*λi)$	7.52	$R34 = -R36/3$	1.06
$R16 = (0.5*bcu) / (I*hcu*λcoil)$	1.79	$R35 = 2/(lb*bcu*α4)$	131.02
$R17 = -R14/3$	0.02	$R39 = (0.5*bcu)/(lb*hcu*λcoil)$	1.20
$R18 = -R16 / 3$	0.60	$R37 = -R39/3$	0.40
$R19 = -R12/3$	0.05	$R38 = 2 / (lb*hcu*α4)$	80.48

Table 2. Thermal Constants

Heat transfer coefficients W/(K m ²)	Thermal conductivity W/(K m)		
Stator yoke back α1	60	Through the coil λ	1.8
Air gap α2	40	Coil λCu	400
End shields α3	25	Iron λFe	38
End windings α4	25	Insulation λi	0.2
Rotor yoke back α5	25	NdFeB magnets λm	9

3. Simplified Thermal Model

A simplified thermal model for the complete generator is derived from the detailed model by using the symmetry to reduce the number of thermal resistances in the yoke, teeth, coil sides, end windings and end shields. The generator cooling is symmetrical in the axial direction and, therefore, the two end windings of a coil are modeled as one.

The network is simplified to evaluate only those nodes that are necessary to model the temperature of the end windings and magnets. The losses in the thermal model

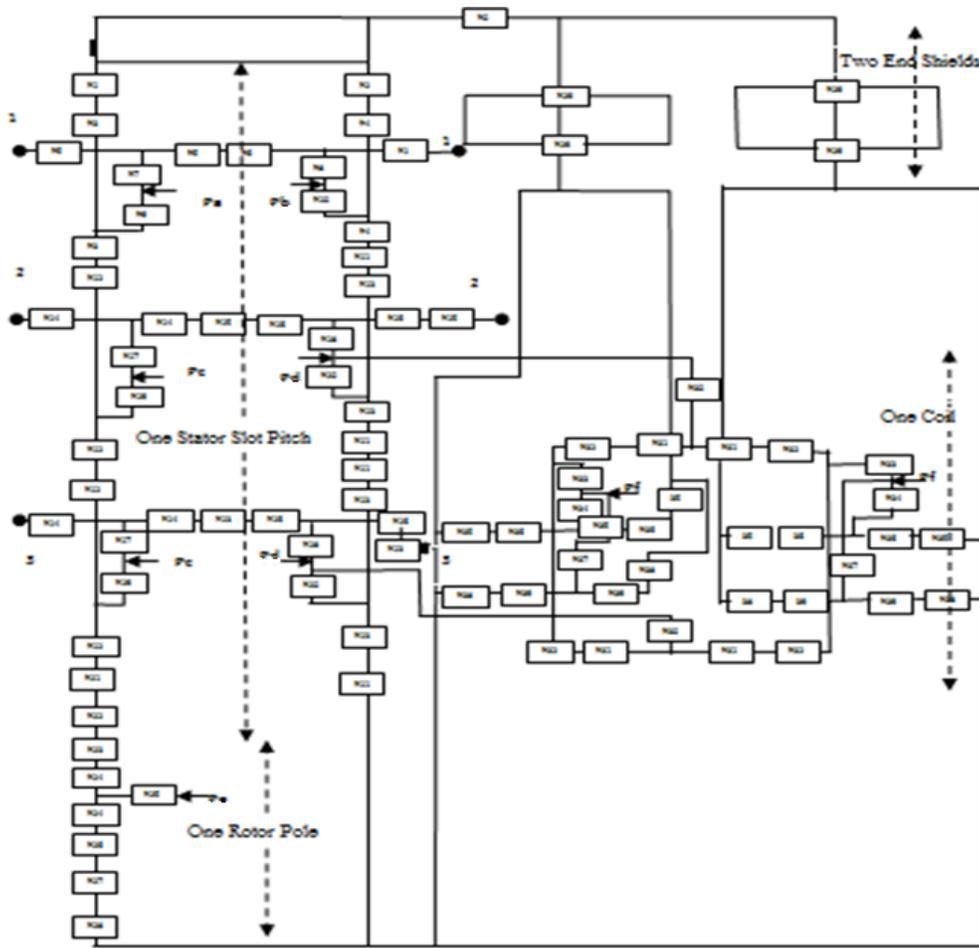


Figure 1. Detailed thermal model of high speed PMSG.

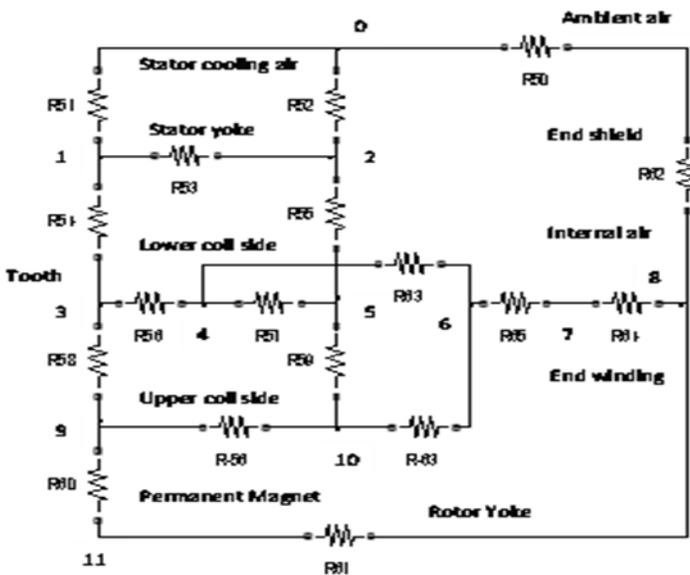


Figure 2. Simplified thermal model.

Table 4. Thermal resistances of Simplified Model

Thermal Resistance	Value	Thermal Resistance	Value
$R50=R0$	0.15	$R59=((2*R13)+(2*R11)+R20)/Q$	1.35
$R51=(R1+R3) / Q$	0.42	$R60=((R12+R21+R22)/Q) +((R23+R24)/(2*p))$	37.7
$R52=(R2+R4)/Q$	0.83	$R61=(R24+R26+R27+R28)/(2*p)$	1
$R53=(R7+R8+R9+R10+(0.5*(R5+R6))) /Q$	0.01	$R62=R29$	9.38
$R54=(R3+R12)/Q$	0.01	$R63=(R30+(0.5*(R31+R32)))/Q$	0.19
$R55=(R4+R11+R13)/Q$	0.72	$R64a= (0.5*R34 +(0.5*(R36+R35)))/Q$	2.77
$R56=((R19+R17+R18)/Q) +((0.5*(R14+R15+R16))/Q)$	0.17	$R64b=(0.5*R37+(0.5*(R39+R38)))/Q$	1.69
$R57=R20/Q$	0.07	$R64=(R64a*R64b)/(R64a+R64b)$	1.05
$R58=(2*R12)/Q$	0.01	$R65=(0.5*R33)/Q$	0.05

Table 5. Thermal resistances of Simplified Model

Nodes	Losses	Value
0: Stator cooling air (average temperature)	$P0=0$	0
1: Yoke above a tooth	$P1=(bd*(Phyys+Pftys))/tow$	338.19
2: Yoke above a slot	$P2=(bs*(Phyys+Pftys))/tow$	478.74
3: Tooth at the bottom coil side	$P3=0.5*(Phyd+Pftd)$	122.44
4 : Bottom coil in a slot	$P4=(0.5*l*Pcu)/(l+lb)$	12.63
5:Fictitious model node	$P5=0$	0
6: Fictitious model node	$P6=0$	0
7:An end winding	$P7= (lb*Pcu)/(l+lb)$	19.28
8: Internal air	$P8=0$	0
9: A tooth at the top coil side	$P9=P3+Pad$	182.9
10: A top coil side in a slot	$P10=P4$	12.63
11: Magnets	$P11=Ptm$	1.80

are copper losses in the stator winding, core losses in the stator teeth and yoke, eddy current losses in the magnets and additional losses. Friction and windage losses are neglected in this thermal model. The copper losses are divided into three basic sections:

- Losses in the end windings,
- Losses in the bottom-layer coil sides in the slots, and
- Losses in the top-layer coil sides. The magnet losses are assumed to be distributed homogenously in the magnets, while additional losses are assumed to be located in the tooth tip. The temperature rise of the cooling air in the outer surface of the stator yoke is included in the thermal model. The maximum winding temperature is of the end winding as the major part of the losses is cooled at the outer surface of the stator yoke⁸.

The simplified thermal model is shown in Figure 2. The thermal resistances of the simplified model are given in Table 4.

The losses used in various sections are given in Table

5. The thermal model has twelve nodes with reference node as the ambient temperature, and eighteen thermal resistances. The temperature rise problem is formulated as a matrix equation. The temperature drop ΔT across a given thermal resistance is calculated as $P*R$ from the loss at power node P and the corresponding resistance R. The vector of temperature rises is evaluated by multiplying the loss vector with the inverse of the thermal conductance matrix.

Table 6. Temperature in Machine Sections

Change in Temperature (Degrees)	
Ambient temperature	50
Lower teeth	35
Upper teeth	36
Lower coil side	41
Upper coil side	42
End winding	52
Magnets	49

The thermal model is obtained based on equivalent conductive and convective thermal resistances. They are in turn calculated based on geometry and thermal characteristics of the machine. A Matlab code is developed in this regard and the change in temperature values obtained are given in Table 6. The design accommodates the requirement within the average range of possible hotspot temperature for the application.

The hot spot occurs at the end winding and its temperature rise is 102 degrees. The design is found to be within the thermal limits for the given rating and selected class of insulation.

4. Conclusion

The thermal resistances in the thermal model are calculated based on the dimensions of the customized PMSG. The detailed thermal model is analyzed and the thermal resistance values are obtained. The simplified model is obtained considering significant sections of the machine where the losses cause rise in temperature. The temperatures variations in these significant parts of the machine are calculated. The hotspot is similar to result from other conventional lumped parameter and finite element analysis methods. The thermal values estimated are within the thermal limits for the selected class of insulation and design specifications.

5. References

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NOMENCLATURE

- bcu- conductor width
- bd- air gap flux density
- bm- magnet flux density
- bs-slot width
- kcu-copper fill factor
- kt- capacity factor
- l-active length
- lb-end winding length
- lu-useful length
- hi-insulation height
- hm-magnet height
- hs-stator slot height
- hs1-tooth tip height 1
- hs2-tooth tip height 2
- hyr-rotor yoke height
- hys-stator yoke height
- qvc-volumetric cooling
- Pad-additional losses
- Pcu-copper losses
- Pftd-eddy current loss in teeth
- Pftys-eddy current loss in stator yoke
- Phyys-hysteresis loss in stator yoke
- Phyd-hysteresis loss in teeth
- Q-slots