Development of Thermal Equivalent Circuit of Surface Mounted Permanent Magnet BLDC Machine

M.R. Pasumarthi, P.R.J. Lakshmi, T. Narasimhulu*
Andhra University, Visakhapatnam, India

Abstract

Permanent magnet (PM) motors are popular choice for Industrial uses due to their great efficiency, power density and torque-to-weight ratio. The prediction of the temperature profile inside an operating electric motor is one of the most important challenges while designing. This paper focuses on thermal analysis of surface mounted permanent magnet (SMPM) Brushless direct current (BLDC) electric motor. In this paper, a lumped parameter thermal network is developed to predict the motor heat flow and temperatures. The network is composed of interconnected nodes and thermal resistances representing the heat process within motor for steady state analysis. Steady state results are obtained using this approach. This thermal network is accurately sufficient to predict the thermal behaviour of the critical parts in the electric motor as well as provides information necessary for component material selection, lubricants, cooling methods, insulation, etc.

Keywords: permanent magnet, surface mounted, temperature profile, thermal network

****Corresponding Author***
E-mail: electricalprofessor@gmail.com

INTRODUCTION

Earlier, thermal analysis was not considered as important as electric and magnetic analysis. Only thermal limits were calculated by the designers. But with the increasing requirements of miniaturization, efficiency, cost and material needed. Thermal analysis has become basic and essential in designing an electrical machine. In any electrical machine the internal temperatures that will be reached at given operating point must be predicted during design to ensure that the cooling provision is sufficient to avoid overheating sufficient. All electrical machines create losses which evident themselves in the manufacture of heat, which increases the temperature of the materials within the machine. The temperature that is reached in steady state is ruled by the equilibrium amid heat input and heat elimination.

These materials, especially permanent magnets and insulation polymers, can simply endure moderately low temperatures, characteristically. Major sources of loss are Joule losses in the windings, core losses due to eddy currents, hysteresis, and mechanical losses electric-motor thermal analysis.[1]

Analysis can be classified into two basic types: analytical lumped-circuit and numerical methods. Numerical analysis is of two types: finite element analysis (FEA) and computational fluid dynamics (CFD).

The analytical approach has the advantage of being very fast in computation. Thermal-network analysis can be subdivided into two main types: heat-transfer and flow-network analyses. Flow-network analysis is the fluid mechanics counterpart to electrical-network analysis with equivalences: pressure to voltage, volume flow rate to current, and flow resistance to electrical resistance. Heat transfer analysis is the thermal counterpart to electrical network analysis with equivalences: temperature to voltage, power to current and thermal resistance to electrical resistance. In the heat-transfer network, a thermal resistance circuit describes the main paths of power flow, enabling the temperatures of the main components of the machine to be predicted for a given loss distribution.[1,2]

The thermal management of the motor is important since the electrical insulation has a temperature limit and affects its efficiency. The designers must know the thermal performance of the equipment to choose suitable cooling strategy. The rise in the temperature of electric motors under load can cause a problem in many applications. Earlier approximation of the thermal behaviour develops a thoughtful substance owing to the necessity of the harmless operating conditions and overloading capabilities on the temperature rise.[3–5] The temperature characteristics are contingent on the winding resistances, therefore the losses and permanent magnet flux. Consequently, the performance analysis of the machine is thermally dependent.

LUMPED THERMAL MODEL

The lumped thermal models include heat storage components as well as conduction, contact and convection thermal resistances and translate to a set of linear deferential equations which can easily and quickly be solved by a computer, or even in real time by a microprocessor (for condition monitoring). Surface parameters such as radiate and convective heat transfer coefficients are calculated based on geometry, view factors and empirical correlations from the literature.[6–9] However, the convection coefficients typically require the local air flow speed as an input, and therefore a simple flow model is also included which treats the flow as a network and calculates pressure drops from pipes, bends, contractions and expansions using empirical correlations (Figure 1).

In a thermal network, it is possible to lump together components that have uniform temperatures and to signify each as a single node in the network. Nodes are separated by thermal resistances that represent heat transfer between components.[10–15] Inside the machine, a set of conduction thermal resistances represents the main heat- transfer paths, such as from winding copper to the stator tooth and back iron (in this case, the heat transfer is through the winding insulation consisting of a combination of enamel, impregnation, and slot liner materials), from tooth and stator back iron nodes to stator bore and housing interface, etc.

In addition,[16] internal convection and radiation resistances are used for heat transfer across the air gap and from end windings to the end caps and housing. External convection and radiation resistances are used for heat transfer from the outside of the machine to ambient[1] (Figure 2).

Thermal Resistance

The thermal resistance 'R' models the flow of heat 'Q' between parts (nodes) of the machine as being proportional to the temperature difference T between the two nodes.[17]

$$P_\phi = \frac{\Delta T}{\Theta} = \frac{t}{\kappa A}$$

where t is the material thickness, K the thermal conductivity and A is the effective area for heat transfer.(Figure 3)

Thermal Resistance Between External Frame and Ambient Due to Natural Convection[17]

When the total area A of the external

frame is known, and taking into account both convection and radiation effect,

$$P_0 = 0.167\ A^{1.039}$$

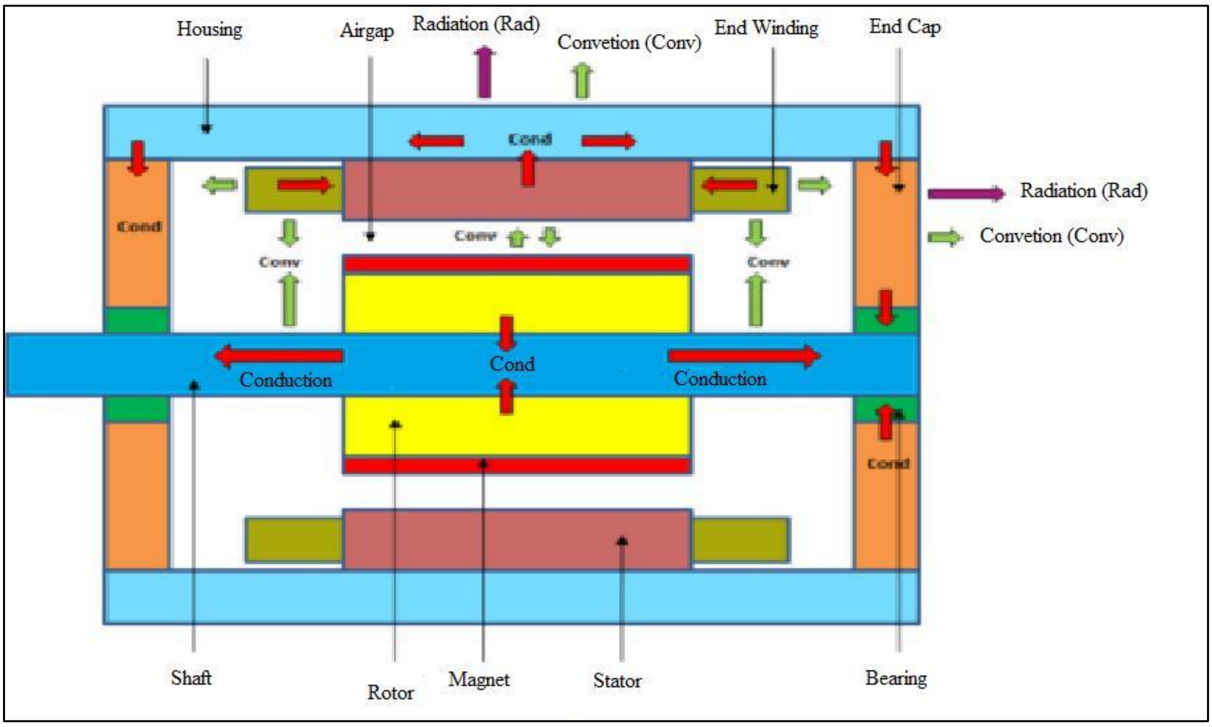

Fig. 1. *Different Heat Flow Processes within the Motor.*

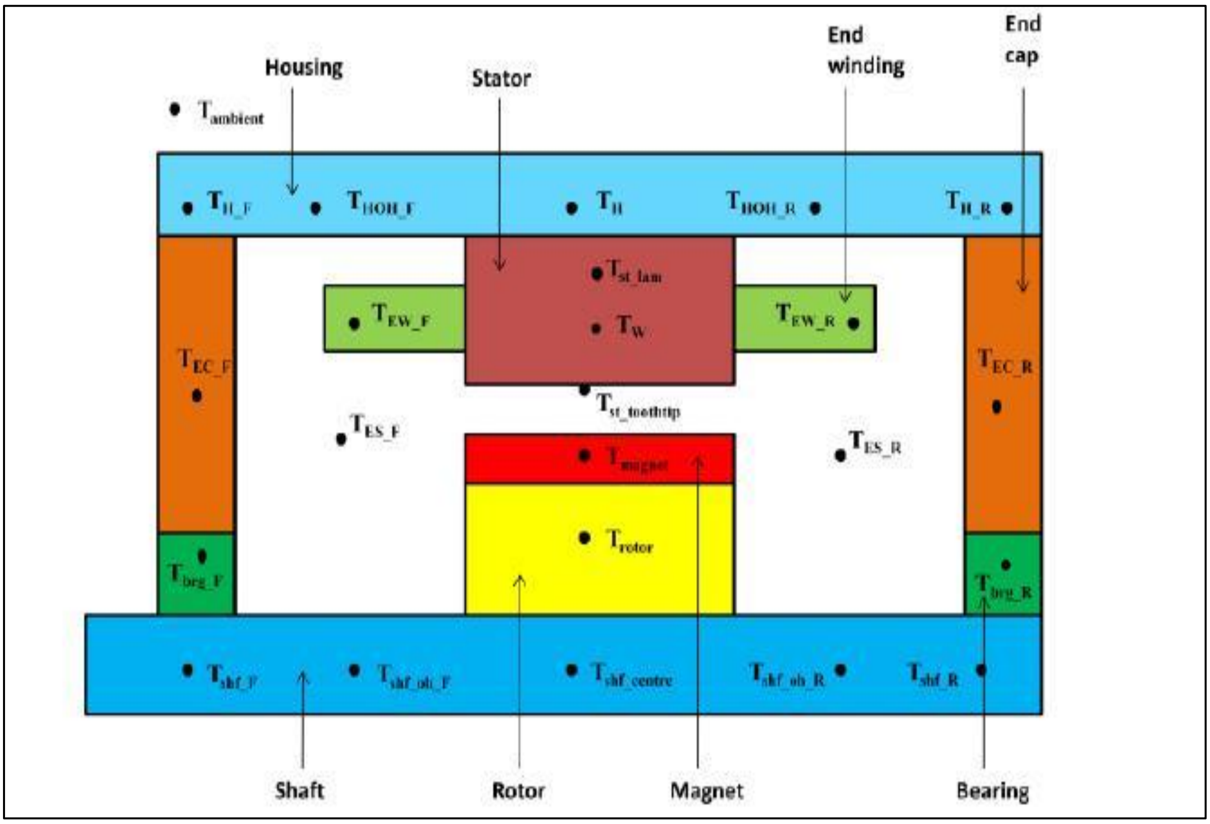

Fig. 2. *Motor Cut Section Showing Different Node Locations.*

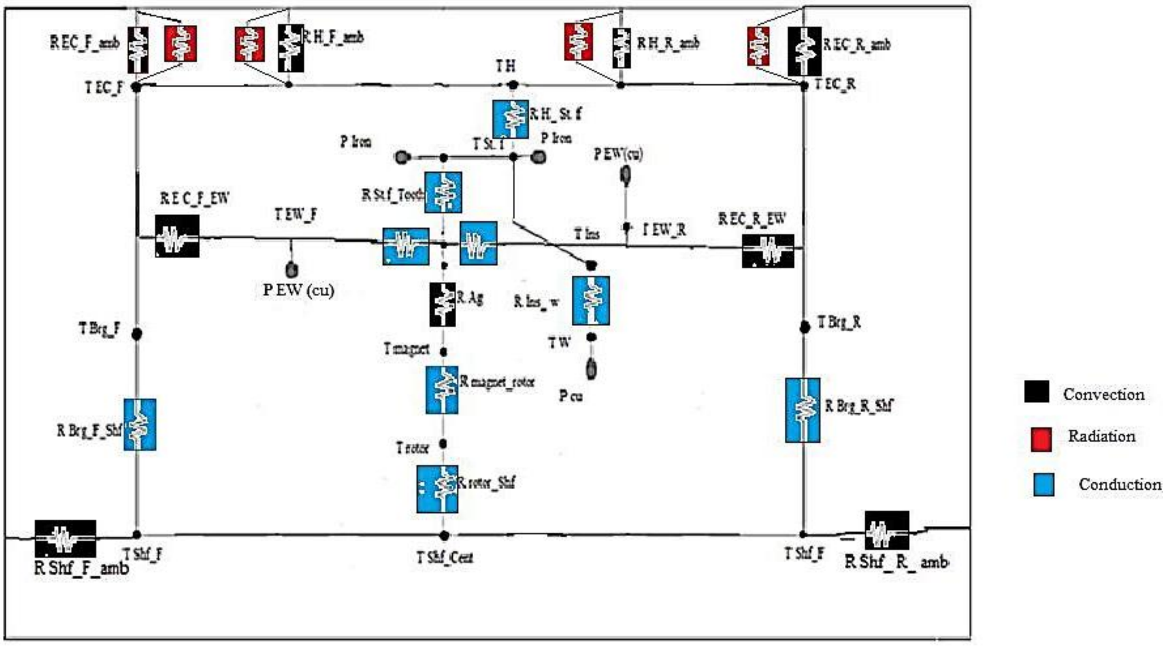

Fig. 3 *Thermal Resistance Equivalent Network.*

Thermal Conductivity Between Winding and Lamination[18]

An equivalent thermal conductivity of the system winding impregnation and insulation is used instead of thermal conductivity K. This equivalent thermal conductivity be governed by numerous features, such as material and quality of the impregnation, residual air quantity after the impregnation process, and so on.

When the slot fill factor K_f, the slot area A_{slot}, and the axial core length L_{core}.

$K_{\chi\upsilon,\iota\rho} = 0.2749[(1-\kappa_{\phi})\, A_{\sigma\lambda o\tau}\, \Lambda_{\chi o\rho\epsilon}]^{(-0.4471)}$

So thermal resistance will be,

$$R_{ws} = \frac{t_{eq}}{k_{cu}A_{slot}}$$

where S_{slot} is stator slot surface, S_{cu} the copper surface area and I_{sp} is the stator slot perimeter

$$t_{eq} = \frac{(S_{slot} - S_{cu})}{I_{sp}}$$

Heat-Transfer Coefficient Between End Winding and End Caps[17]

The thermal resistance between winding and end caps due to force convection can be evaluated. For totally enclosed machines, the value of h_C can be evaluated as a function of the air speed inside the motor end caps

$h_C = 6.22\, v$

To account for combined natural and forced convection

$H = 41.4 + 6.22v$

Radiation-Heat-Transfer Coefficient [17]

The thermal resistance for radiation can be evaluated, when h_R is available. Inside and outside the motor, several parts exchange heat by radiation. In some cases, such as aerospace applications, all the heat transfer is due to radiation.

The subsequent values of the radiation-heat-transfer coefficients can be initially used:[17]

8.5 W/(m^{2}C) between copper–iron lamination;

6.9 W/(m^{2}C) between end winding–external cages;

5.7 W/(m^{2}C) between external cage–ambient.

Radial Conduction Thermal Resistances of Stator Tooth ($R_{St.}$ Tooth)[19]

$$R_{st.y} = \frac{\ln(r_{ms}/r_{is})}{2 * pi * k_{iro} * L_s * p}$$

where r_{is} is the inner stator radius, r_{ms} the inner stator yoke radius, k_{iro} the thermal conductivity of stator and p is the percentage of the teeth section respect to the total teeth plus all slot section (Figure 4).

Radial Conduction Thermal Resistance of Stator Tooth ($R_{st.y}$)[18]

$$R_{st.y} = \frac{\ln(r_{os} - r_{ms})}{2 * pi * k_{iro} * L_s}$$

where r_{os} is the outer stator radius and Ls is the axial length of the stator.

Thermal Resistance Between Bearings to Shaft at front end (R_{Shf})[19]

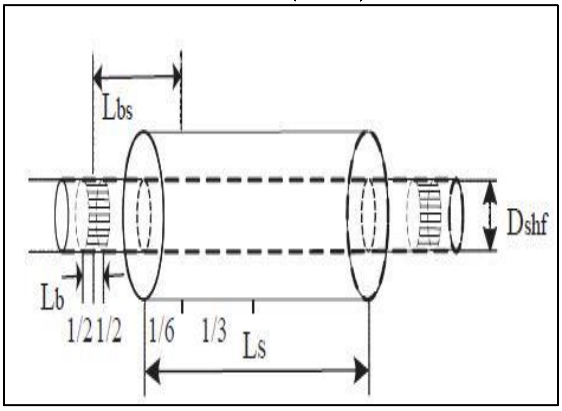

Fig. 4. *Axial Dimensions of the Shaft.*

$R_{shf}=(R_a+R_b)/2$

$$R_a = \frac{1}{2\Pi k_{shf} L_s} + \frac{L_{bs}}{2\Pi k_{shf} (D_{shf}/2)^2}$$

$$R_a = \frac{1}{4\Pi k_{shf} L_b} + \frac{L_{bs}}{2\Pi k_{shf} (D_{shf}/2)^2}$$

where L_{bs} is the distance of bearing centre to rotor mean, L_b the thickness of bearing and D_{shf} is the radius of shaft.

Thermal resistance between magnets to rotor (R_{Mag_Rot}):[19]

$$R_{conduction} = \frac{\ln(r_{magnet}/r_{rotor})}{n\theta L_s K_m}$$

Thermal resistance between rotor to shaft($R_{Rot\_ Shf}$):[19]

$$R_{conduction} = \frac{\ln(r_{rotor}/r_{shaft})}{2 * pi * L_s K_{rotor}}$$

Thermal resistance of air gap(R_{Ag}):[19]

$$R_{ag} = \frac{l_g}{Nnuk_{air} A_{ag}}$$

Consider, N_{nu} = 2, for constant air, L_g= air gap length.

Heat Sources:[18]

The heat generation due to losses in various machine works was controlled with current generator parallel associated to the thermal components of the machine portions that create these losses.[20] The losses of an electric machine encompass of stator iron losses, stator copper losses, rotor losses and frictional losses. The power losses can be calculated analytically or using FE procedures. For every operating circumstance, the calculated losses of the electric machine have to be used as the thermal model inputs. As the parameters of the electrical machines are temperature dependent parameters, there is a robust interaction among the electromagnetic and thermal analysis, i. e. the losses are analytically dependent on the temperature and vice versa.

THERMAL ANALYSIS OF 73.8 KW BLDC MOTOR

For 73.8 KW motor, the equivalent circuit is shown in Figure 5.

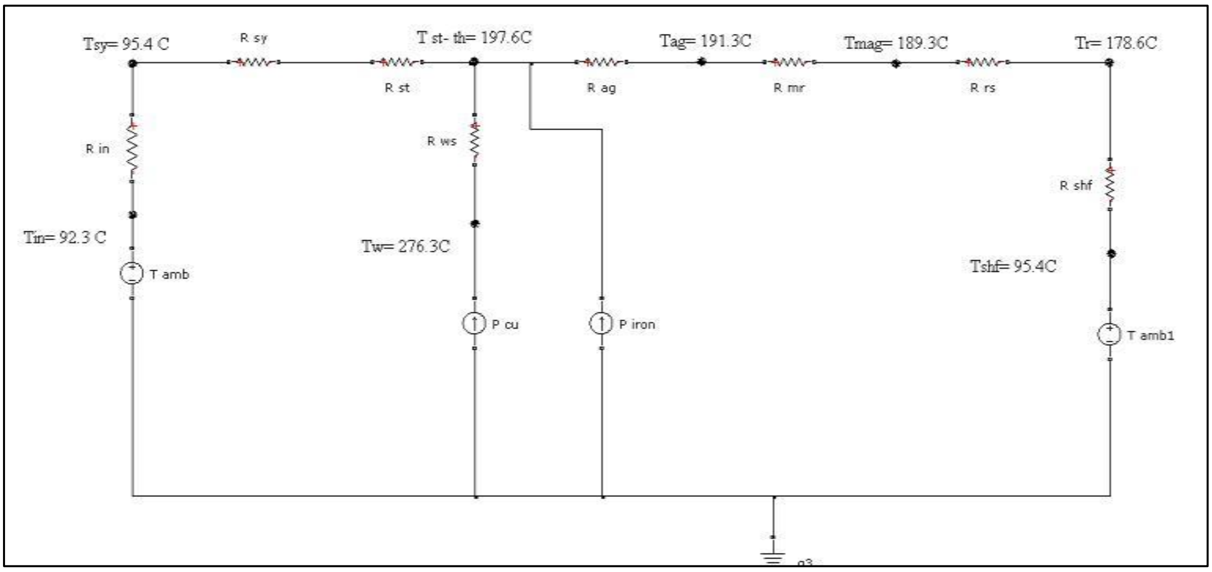

Fig. 5. *Thermal Equivalent Network with Node Temperatures.*

The effect of Temperature on motor surface is shown in Figure 6. Figures 7 and 8 show effect of temperature at winding and at magnet.

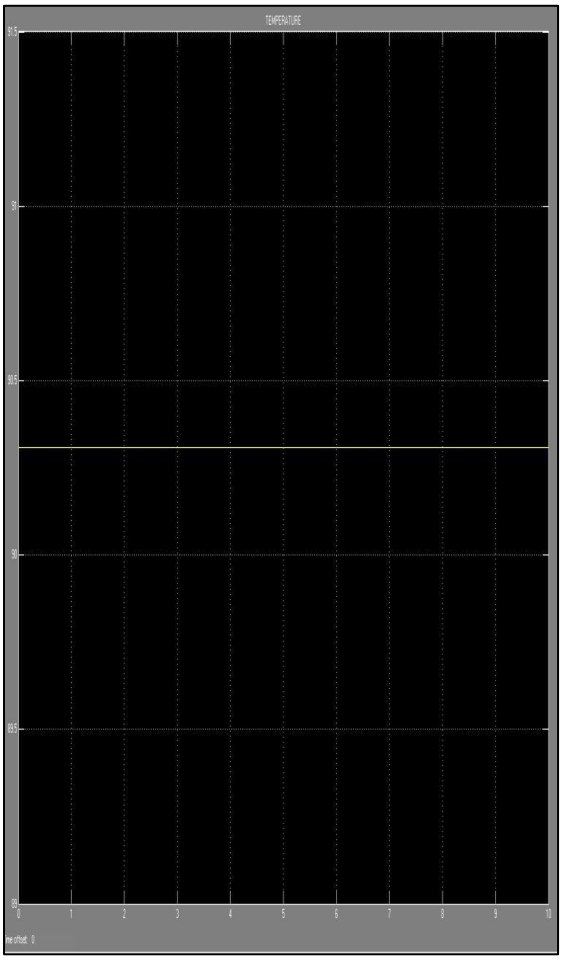

Fig. 6. *Temperature on the Motor Surface.*

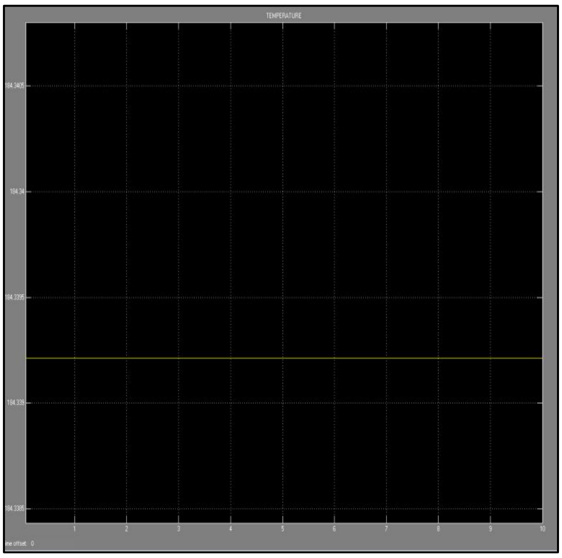

Fig. 7. *Temperature at the Winding Lam.*

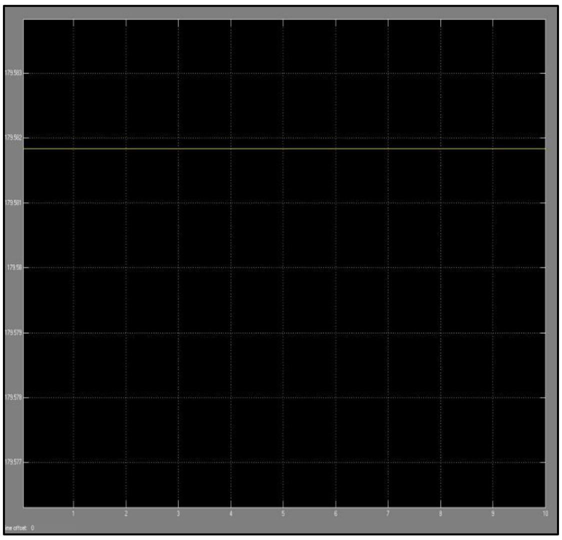

Fig. 8. *Temperature at the Magnet.*

CONCLUSION

In this paper lumped-parameter thermal model was presented. Thermal calculations are performed based on motor operational parameters. Node temperatures have to be calculated from the lumped-parameter thermal network. Steady state analysis of the lumped parameter model is considered for surface mounted PMBLDC motor. The network is analysed for temperatures at surface of the motor, winding lam and magnet surface are shown. This paper presents a complete reference about heat flow and node temperatures for motor.

APPENDIX

When a system shows temperature gradient, heat transfer occurs. Three types of heat transfer are:

- Conductive heat transfer
- Convective heat transfer
- Radiative heat transfer

These heat transfers are ruled by first principle of thermodynamics which emphasizes that nothing is created, nothing is lost, and the energy is transferred from one form to another.

 Conduction heat transfer:

The conduction resistance is equal to the path length divided by the product of the area and the materials thermal conductivity. Conduction thermal resistance can be simply calculated using the following:

$$R = \frac{L}{kA}$$

Where L (in meters) is path length, A (in square meters) is the path area, and k (in watt per meter degree Celsius) is the thermal conductivity of the material.

- Radiation Heat transfer:

The radiation resistance is equal to one divided by the product of the surface area and the heat-transfer coefficient. Radiation thermal resistances for a given surface can be simply calculated using:

$$R = \frac{1}{h_R A}$$

Where, A (in square meters) is the surface area and h_R (in watt per square meter degree Celsius) is the radiation heat-transfer coefficient. The surface area is easily calculated from the surface geometry. The radiation-heat-transfer coefficient can be calculated using the following:

Where, $\sigma = 5.669108$ W/ (m^2. K^4),

Ɛ is the emissivity of the surface,
F_{1-2} is the view factor for dissipating surface 1 to the absorbing surface 2 (ambient temperature for external radiation), and T1 and T2 are, respectively, the temperatures of surfaces 1 and 2, in units of kelvin. The emissivity is a function of the surface material.

- Convection Heat transfer:

Convection is the transfer process due to fluid motion. In natural convection, the fluid motion is due entirely to buoyancy forces arising from density variations in fluid. In a forced convection system, movement of fluid is by an external force, e.g., fan, blower, or pump. If the fluid velocity is high, then turbulence is induced. In such cases, mixing of hot and cold air is more efficient; and there is an increase in heat transfer. Convection thermal resistances for a given surface can be simply calculated using:

$$h_c = \sigma \varepsilon F_{1-2} \left(\frac{T_1^4 - T_2^4}{T_1 - T_2} \right)$$

Where, h_c is convection-heat-transfer coefficient.

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