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Lumped Parameter Analysis of SMPM Synchronous Electric Motor used for Hybrid Electric Vehicle Traction Drive

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ABSTRACT: *A key component in any Hybrid Electric Vehicle (HEV) is the electric motor. Permanent Magnet (PM) motors are popular choices for HEV traction drive applications due to their high efficiency, power density and torque-to-inertia ratio. The prediction of the temperature profile inside an operating electric motor is one of the most important challenges while designing. The paper focuses on thermal analysis of Surface Mounted Permanent Magnet (SMPM) synchronous electric motor used for HEV traction drive. In this paper, a lumped parameter thermal network is developed to predict the motor temperatures. The network is composed of 23 interconnected nodes and 38 thermal resistances representing the heat processes within motor for steady state analysis and thermal capacitances of main components are added for transient analysis. The thermal network is then solved in MS-Excel/MATLAB through a system of linear equations. The results of analytical model are confirmed with results obtained from Motor-CAD software. Both steady state and transient results obtained using this approach showed good agreement with existing available experimental results for same motor. This thermal network is accurate enough to predict the thermal behavior of the critical components in the electric motor as well as provides information necessary for component material selection, lubricants, cooling methods, insulation, etc.*

Keywords: *Hybrid Electric Vehicle, Lumped Parameter, Surface Mounted Permanent Magnet, Temperature Profile, Thermal Network*

I. INTRODUCTION

As the demand for more environmental-friendly cars continues to grow, originating from both individual customers, as well as driven by governmental means, the hybrid electric vehicles (HEV) are come into focus. The main purpose of the use of HEV's is to decrease the urban air contamination especially caused by black smoke, hydrocarbons, and nitrogen oxides of diesel engine used in buses and trucks. A key component in any HEV is the electric motor. Induction motors and permanent magnet motors are the most common types that are suitable for HEVs. Permanent Magnet (PM) motors are popular choices for hybrid electric vehicle traction drive applications due to their high efficiency, power density and torque-to-inertia ratio. Such electric motors must operate at varying loads and speeds which require a careful selection of motor parameters by the designer, in order to minimize losses. In particular, the effects of excessive heat in the magnets can degrade the performance of these motors if not dealt properly. It is therefore critical to develop a complete and representative model of the heat processes in the electric motors.

Traditionally electric motor manufacturers have concentrated on improvement of the electromagnetic design and dealt with the thermal design aspects superficially. However the increasing requirement for miniaturization, energy efficiency, cost reduction and need to fully exploit new topologies and materials, showed the importance of thermal analysis to the same extent as the electromagnetic design. Mellor and Turner [1] firstly described a lumped-parameter thermal model which provides both steady-state and transient solution to the temperatures within an electrical motor of the TEFC design. Refaie *et al*. [2] presented a lumped-parameter thermal model with 9 nodes and 12 thermal resistances for a multi-barrier interior PM synchronous machine. Fakhfakh *et al*. [3] developed a lumped circuit thermal model using two cooling systems for thermal analysis of PMSM used for electric vehicles traction application. Fan *et al*. [4] presented a lumped parameter thermal analysis of permanent magnet motor by considering real driving duty cycle along with set up of test bench to measure the temperature distribution in the driving motor. Ding *et al*. [5] developed a simplified analytical model as a thermal circuit with a network of interconnected nodes and thermal resistances representing the heat processes within the SPMSM. This model studies the effect of excessive heat inside the magnets caused by eddy current loss.

II. SMPM SYNCHRONOUS ELECTRIC MOTOR

The paper focuses on the study of Interior Rotor Surface Mounted Permanent Magnet (SMPM) Synchronous Electric Motor. This type of motor is increasingly being employed in electric vehicles (EV) and hybrid electric vehicles (HEV), due to their high efficiency, high power density and minimal maintenance. The thermal analysis is done for a SMPM synchronous motor having power ratings above 40KW. This motor is considered of totally enclosed non ventilated (TENV) type. That means the dissipation from the outside of the motor is assumed to be a combination of natural convection, radiation and conduction. The inside and outside fluid is considered as only air and hence named as air-cooled SMPM synchronous motor. A typical axial and radial geometry for air-cooled SMPM motor is shown in Fig.1. The motor is covered by round housing. The geometry shows shaft, rotor, stator, winding, housing, end cap and bearings. The motor has horizontal orientation.

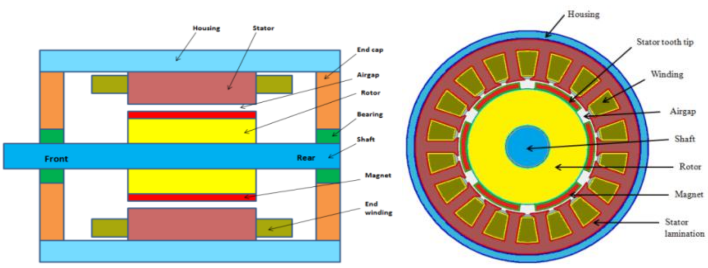

Fig.1 Typical Axial and Radial Geometry for Air-cooled SMPM Motor

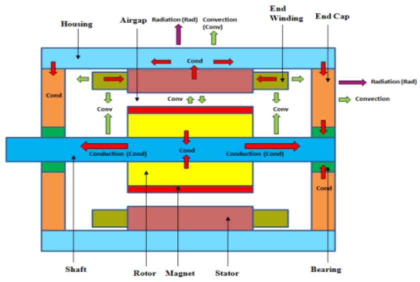

Fig.2 Different Heat Flow Processes within the Motor

2.1 Heat Flow Processes within the Motor

Whenever there is a temperature difference between two elements heat transfer takes place. This heat is transferred by three different modes viz. conduction, convection and radiation. Different heat transfer processes taken place in an electric motor are shown in Fig.2. Here heat transfer due to radiation from internal surface is neglected.

2.2 Thermal Models

In electric motor, thermal model parameters are nothing but the analytical model used to calculate thermal resistances offered by various motor components such as housing, stator, rotor, magnet, winding, shaft and bearing. Most of these electric motor parts are of cylindrical shape. For such motor parts conduction, convection and radiation thermal resistance are calculated by following relations:

$R_{conduction} = \frac{ln(r_o/r_i)}{2\pi Lk}$, $R_{convection} = \frac{1}{h_c A}$ and $R_{radiation} = \frac{1}{h_r A}$

where
r_o = Outer diameter
r_i = Inner diameter
L = Axial length
K =Thermal conductivity
h_c = Convective heat transfer coefficient
h_r = Radiative heat transfer coefficient
A = Surface area

III. THERMAL NETWORK MODELING

In thermal network modeling, the object is divided into basic thermal elements, which are represented by a special node configuration. The elements are linked together, forming a network of nodes and thermal resistances. The thermal network is similar to an electrical network consisting of current sources and resistances. Heat transfer analysis is the thermal counterpart to electrical-network analysis with the equivalences such as: temperature to voltage, power to current and thermal resistances to electrical resistance. In the heat transfer network, a thermal resistance circuit describes the main paths for power flow, enabling the temperatures of the main components within the motor to be predicted for a given loss distribution.

In the present work, conventional lumped parameter calculation method with centric nodes and concentrated loss model is used for thermal analysis. The principle of lumped-circuit or lumped-parameter thermal analysis is to develop an electrical equivalent circuit for thermal analysis. Thermal lumped-circuit analysis can be used in the design and optimization of electrical machines. Each node of the circuit represents a part of the machine. Each node is connected to other nodes via thermal resistances through which heat can flow.

3.1 Lumped Parameter Method

During the thermal analysis, the electrical system here motor is divided geometrically into a number of lumped components, each component having a bulk thermal storage as well as heat generation and interconnected to neighboring components through a linear mesh of thermal impedances. The lumped parameters are derived from entirely dimensional information, the thermal properties of the materials used in the design and constant heat transfer coefficients. The thermal circuit in steady-state condition consists of thermal resistances and heat sources connected between the component nodes. For transient analysis, the thermal capacitances are used additionally to take into account the change in internal energy of the component with the time.

Fig.3 shows the equivalent thermal network of one simple thermal system for steady-state case. In this equivalent thermal network, all the heat generation in the component is concentrated in its midpoint. This point represents the mean temperature of the component. The power generation in the volume '1' is denoted with P_1 and it is marked with a big black dot. A thermal capacity C_1 is added at node T_1 and ambient to be taken into account the energy stored by the materials.

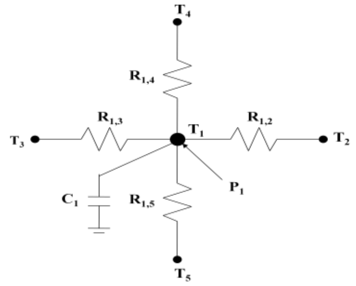

Fig.3 Equivalent Thermal Network

3.2 Node Configuration

A node configuration should be understood as the way a particular element is modeled by nodes and by thermal resistances to the surroundings. For calculating temperature T_1 from Fig.3 following node configuration is used.

$$\frac{(T_1 - T_2)}{R_{1,2}} + \frac{(T_1 - T_3)}{R_{1,3}} + \frac{(T_1 - T_4)}{R_{1,4}} + \frac{(T_1 - T_5)}{R_{1,5}} + C_1 \frac{dT_1}{dt} = P_1$$

$$\left[\frac{1}{R_{1,2}} + \frac{1}{R_{1,3}} + \frac{1}{R_{1,4}} + \frac{1}{R_{1,5}}\right] T_1 - \left[\frac{T_2}{R_{1,2}}\right] - \left[\frac{T_3}{R_{1,3}}\right] - \left[\frac{T_4}{R_{1,4}}\right] - \left[\frac{T_5}{R_{1,5}}\right] + C_1 \frac{dT_1}{dt} = P_1$$

The resulting system matrix equation is:

$$C\frac{\partial T}{\partial t} = P - GT$$

Or

$$\frac{\partial T}{\partial t} = C^{-1}.(P - GT)$$

Where G is the conductance square matrix, T is the column matrix of temperatures as variables, P is the column matrix of power losses as constants and C is a thermal capacity square matrix signifying heat stored in motor. The above equation is applicable to transient analysis, only when the ambient temperature is assumed to be constant. For steady state analysis neglecting thermal capacitances, the resulting system matrix equation can be written as:

$$T = G^{-1}.P$$

3.3 Detailed 1D Thermal Network

The locations for nodes in any circuit are usually chosen to have a clear physical significance. For a detailed 1D thermal network, different node locations are chosen as shown in Fig.4. As the motor components are symmetrical about its axis, only motor cut section is shown in that figure which gives a clear idea of all node locations. A large single component is divided into more than a single node for prediction of temperature changes in that single component due to different heat transfer capacities.

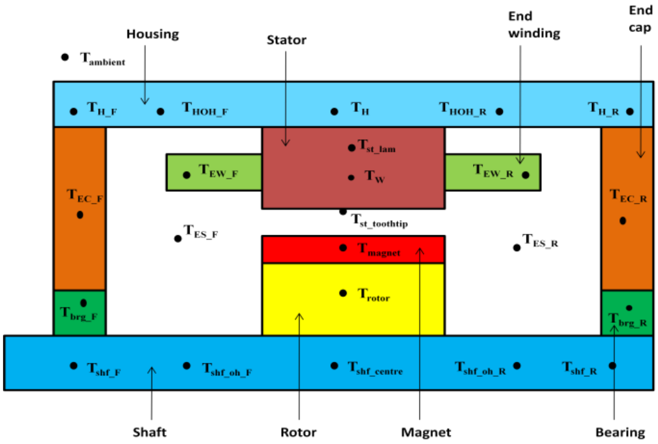

Fig.4 Motor Cut Section Showing Different Node Locations

A detailed 1D thermal network for air-cooled SMPM synchronous motor is shown in Fig.5. The suggested thermal network is primarily intended for design purposes. It is large and little complicated than previously suggested simplified network. The network is constructed using 23 nodes and 38 resistances. The symmetry makes it possible to divide different components into elements that are concentric around the shaft. These elements are modeled radially and axial temperature variation is considered uniform. There is no peripheral temperature gradient present in the geometry. The shaft under rotor cover, rotor, magnet, stator and housing portion covering stator are modeled as infinitely long hollow cylinders. The radial heat transfer is considered for rotor, magnet, airgap, stator and active windings. Both radial and axial heat transfers are considered in case of shaft, end winding, end cap and housing. The convection resistances between end space fluid and front as well as rear parts of shaft, end winding, bearing and end cap are taken into consideration. The heat transfer from end cap and housing to ambient is considered by both convection and radiation mode whereas radiation heat transfers from any internal surface is neglected. The heat transfer from extended shaft portion to ambient is also neglected here because of its less significance. The iron losses, eddy current losses and friction losses are assigned to stator tooth tip, magnet and front as well as rear parts of shaft respectively. The copper losses are distributed among active winding, front end winding and rear end winding according to their respective volumes.

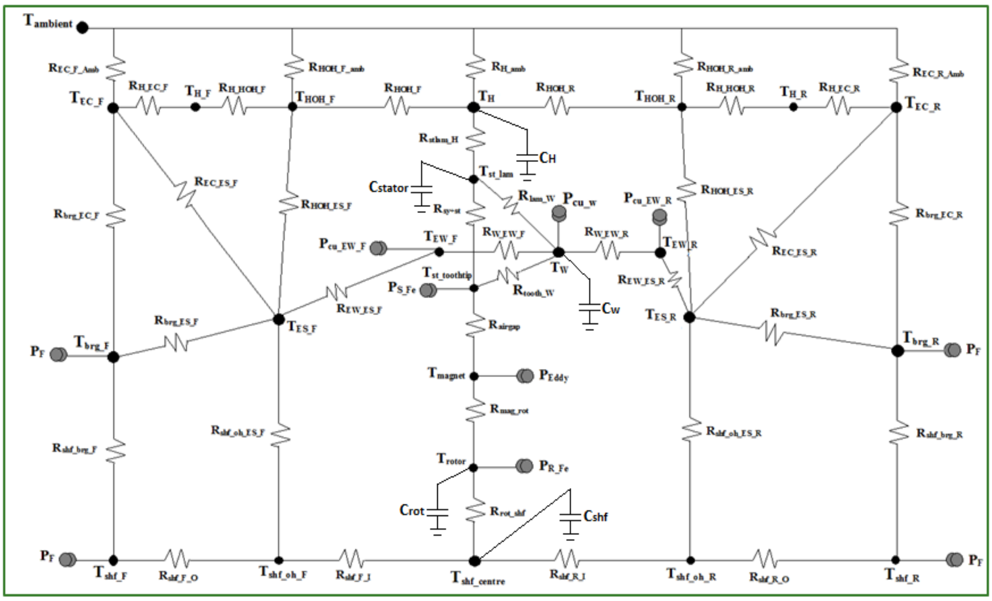

Fig.5 Detailed 1D Thermal Network for Air-cooled SMPM Synchronous Motor

IV. RESULTS

Thermal analysis is done for a SMPM motor with stationary rotor. Losses induced in winding of test motor by supplying defined current to generate 33W heat due to Joule losses are directly given as input to the circuit. For steady state results, thermal capacitances are neglected while ambient temperature is considered as fixed temperature and is taken as 45^{0}C. Table 1 shows comparison between analytically calculated temperatures of different motor components with those obtained by using Motor-CAD simulation software.

Table 1 Analytical and Simulated Temperature for Detailed 1D Thermal Network

Electric Motor Components	**Temperature Nodes**	**Temperatures in ^{0}C**		**% Error**
		Analytical	**Simulated**	
Active housing	T_H	95.55	95.80	-0.26
Front housing overhang	T_{HOH_F}	95.24	95.40	-0.17
Rear housing overhang	T_{HOH_R}	94.81	95.00	-0.20
Front housing	T_{H_F}	95.17	95.30	-0.14
Rear housing	T_{H_R}	94.67	94.90	-0.24
Stator lamination	T_{st_lam}	102.64	102.60	0.04
Stator tooth tip	$T_{st\_toothtip}$	105.17	105.70	-0.50
Active winding	$\mathbf{T_W}$	**107.82**	**110.50**	**-2.42**
Front end winding	T_{EW_F}	108.39	108.70	-0.28
Rear end winding	T_{EW_R}	108.39	108.70	-0.29
Front end space	T_{ES_F}	99.38	100.00	-0.62
Rear end space	T_{ES_R}	99.73	100.00	-0.27
Magnet	T_{magnet}	99.06	99.70	-0.64
Rotor	T_{rotor}	98.61	99.20	-0.59
Shaft centre	T_{shf_centre}	97.44	98.10	-0.67
Front shaft overhang	$T_{shf\_oh\_F}$	96.00	96.80	-0.82
Rear shaft overhang	$T_{shf\_oh\_R}$	96.50	97.00	-0.52
Front shaft	T_{shf_F}	94.56	95.50	-0.98
Rear shaft	T_{shf_R}	95.54	96.00	-0.47
Front bearing	T_{brg_F}	93.82	94.80	-1.04
Rear bearing	T_{brg_R}	95.19	95.60	-0.43
Front end cap	T_{EC_F}	92.04	93.30	-1.35
Rear end cap	T_{EC_R}	94.27	94.70	-0.45

For getting transient temperature profile based on detailed 1D thermal network model, respective thermal masses are assigned additionally to the main motor components like housing (C_H), stator (C_{stator}), rotor (C_{rot}), shaft (C_{shf}) and active windings (C_w). Simulated and experimental transient temperature profiles are shown in Fig.6 and 7 respectively.

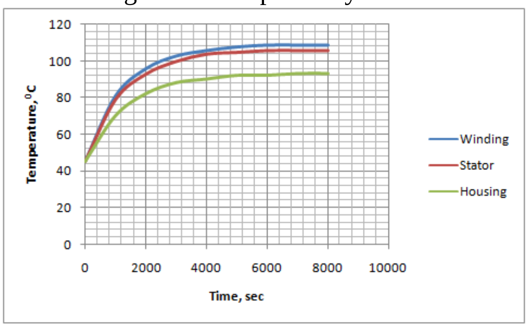

Fig.6 Simulated Temperature Profile

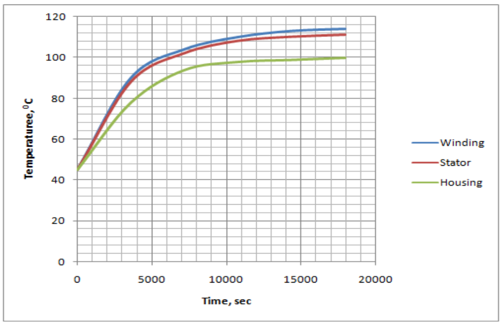

Fig.7 Experimental Temperature Profile

V. CONCLUSION

In this paper lumped parameter approach is proposed to design a detailed 1D thermal network that can be used as a tool for determining temperature profile inside the SMPM synchronous motor. The lumped parameter approach showed fast and accurate response for thermal analysis of this motor. Steady state temperatures of different motor components obtained by analyzing the network showed good agreement with those obtained from network solver software Motor-CAD. Also the simulated temperature profile is validated with available experimental temperature profile. Due to complexity in motor geometry and heat transfer phenomena, this approach is used to predict only mean temperature of each motor component. By 3D FEA simulation as well as CFD analysis, temperature variation along its cross section within motor can be obtained. This approach can be modified for different cooling methods like fan cooling, spray cooling, water jackets, etc. Also, the proposed thermal analysis method can be extended for different motor configurations, rotor speeds, airgap lengths, rotor geometries and corresponding magnet arrangements, etc.

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