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Lumped Parameter Thermal Model for Axial flux Surface Mounted Permanent Magnet BLDC Machine

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Abstract

Axial flux surface mounted permanent magnet BLDC machines are of particular interest for power generation in typical and confined conditions. Due to their compactness & high power density, the ventilation and cooling inside axial flux permanent magnet BLDC machine have become increasingly important for further performance improvement. This paper describes a lumped parameter thermal model of Axial flux Surface Mounted Permanent Magnet BLDC Machine. The transient thermal characteristics and steady state temperature of the motor are estimated from a lumped parameter thermal model. The transient characteristic has been also simulated mathematically, developments of a lumped parameter, thermal modelling technique for axial flux permanent magnet generators. Lumped parameter thermal network is developed to predict the motor heat flow and nodal temperatures. The network is composed of 29 interconnected nodes, 63 thermal resistances and 29 capacitors representing the heat process within motor for steady state and transient analysis.

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Keywords: Axial flux; Surface mounted permanent magnet; Temperature profile; Thermal network.

1. Introduction

An axial flux permanent magnet (AFPM) motors with pancake shape have been widely used in recent years due to their high torque density, modular and compact construction, high efficiency, reliability and easy integration with other mechanical components. The advent of modern high energy permanent magnet (PM) materials, such as NdFeB, has resulted in the rapid development of these types of machines.

Thermal analysis of the electric motor has attracted Scientists attention in recent years. Vilar [1] proposed a lumped parameter thermal network model for the stationary single sided axial-flux permanent magnet motor in

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2005. Huang [2] presented the thermal analysis of a high-speed motor with soft magnetic composite (SMC) in 2009. Mezani [3] presented a model for coupling electromagnetic and thermal phenomena in an induction motor. Gilson [4] set up a design strategy which is capable of optimizing both the electromagnetic as well as the thermal design of permanent magnet synchronous machines (PMSM) for aerospace actuation system in 2010. Staton [5] dealt with the formulation used to predict convection cooling and flow in electric machines. For motor temperature rise prediction, Yabiku [6] outlined a set of useful calculations and design guidelines. Popescu [7] built a thermal model for a duplex three-phase induction machine for fault-tolerant applications in 2013. Kefalas [8] conducted a thermal investigation of a surface-mounted permanent-magnet synchronous motor designed for high-temperature aerospace actuation applications. In computational dynamics Wang [9] developed a thermo-fluid model combining a lumped parameter heat transfer model and an air-flow model of a typical axial-field permanent-magnet (AFPM) machine. Jungreuthmayer [10] presented a comprehensive computational fluid dynamics (CFD) model of a radial flux permanent magnet synchronous machine with interior magnets. Boglietti [11] proposed an extended survey on the evolution and the modern approaches in the thermal analysis of electrical machines in 2009. In addition, the water cooling of the AFPM machine has been studied in [12-14].

The use of rare earth permanent magnet material, such as Samarium Cobalt (SmCo5) and recently introduced Neodymium-Iron-Boron (NdFeB) further improved the power generation capability at higher ambient temperature. Several axial flux machine configurations have been proposed, regarding the stator(s) position with respect to the rotor(s) position and also regarding the winding arrangements, giving freedom to select the most suitable machine structure for particular applications. From the construction point of view, AFPM machines can be designed as single-sided or double sided, with or without armature slots or armature cores, with surface mounted permanent magnets or surface embedded permanent magnets, and as single or multistage machines. The axial flux permanent magnet (AFPM) BLDC machine is defined as an electrical machine in which the magnetic fluxes are parallel to the rotating axes. In general, AFPM BLDC machine have disc type rotors with permanent magnets attached to them, and disc type stators, which include the windings.

In the success of radial flux permanent magnet machines, axial flux permanent magnet machines continue to be of interest, particularly for industrial applications in harsh and volume confined working environments. Unlike the radial flux machines, axial flux machines have high flexibility operating at a variety of rotational speeds. By changing the number of magnets on the rotating disks and varying its diameter, the AFPM BLDC machine is capable of accommodating different rotational speeds applications [2-8]. The large diameter axial flux machines with a high number of poles are ideal for low rotational speed, high torque applications. Conversely, small diameter axial flux machines with fewer poles are suitable for high speed low torque applications. The slim and light-weight AFPM machines have higher power density compared with the conventional radial flux generators. Therefore, AFPM generators are suitable for electrical vehicles (e.g. Traction cars), wind turbines, robot arms etc. [15-17]

The paper distinguished the construction of a generic thermal equivalent circuit, which comprises of conductive and convective circuits to model the conduction and convection heat transfers and temperature distributions in axial directions within these machines. The conduction heat transfer between the solid components of these electrical machines is modelled by an annulus conductive thermal circuit derived from previous researchers; whereas, for convection heat transfer between the working fluid (air) and solids. Since all the thermal resistances and capacitances used in the thermal circuits are in dimensionless form, the developed generic thermal equivalent circuit is capable of performing thermal simulations for axial flux BLD machines of different sizes and topologies.

2. Thermal modeling of surface mounted permanent magnet BLDC machines

Extensive research has been devoted to thermal studies of conventional radial flux electrical machines, but AFPM machines have received very little attention. Depending on the sizes of the machine and the types of enclosure, different cooling mechanism arrangements have been introduced for AFPM machines. Generally, they can be classified into two configuration categories, which are self-ventilated and externally ventilated configurations. For self-ventilated configurations, the disk type AFPM BLDC machine use their inherently advantageous feature of the rotor disks (with attached magnets), which act like pump impellers, drawing the ambient air flow through the inlet and subsequently into the gaps between the stator and rotor disks, to cool the stator core and windings. Most self-ventilated machines are air-cooled [18-20]. By knowing the thermal and physical properties of the machine components, these thermal resistances and capacitances of each component can be evaluated by well-known analogies. Subsequently, by connecting these collections of thermal resistances and capacitances, based on the heat flow paths in the electrical machine, the thermal equivalent circuit is constructed. Hereby, the temperature and surface heat flux can be predicted by solving the thermal equivalent circuit [21-26].

Fundamentally, the thermal equivalent circuit is analogous to an electrical circuit. The heat flowing in each path of the thermal circuit is analogous to the current in the electrical circuit. The heat flow is driven and determined by the temperature differences, in which it is analogous to the voltage difference in the electrical circuit and the thermal resistances and capacitances in the machine thermal equivalent circuits are analogous to the resistances and capacitances in the electrical circuit. Thermal predictions from the equivalent thermal circuit obtained from previous research demonstrate good agreements with both experimental and CFD results. In addition, the LPM demonstrates the advantage of using the corresponding thermal resistances and capacitances in the dimensionless form, to perform thermal analysis for a wide range of machine dimensions. The aim of this paper is modelling the conduction and convection heat transfer in the axial direction, within AFPM BLDC machine.

Table1: Motor Parameters

Number of poles	N	16
Low speed torque	To	45 Nm
RMS torque	T rms	34 Nm
Rated speed	N	3600 rpm
Speed at RMS torque	N rms	1440 rpm
Current at To	I	28.6 A
Resistance at 20C per phase	R	0.223 ohm
Nominal winding indutane per phase	L	1.5 mH

Table2: Motor Dimensions

Geometry parameters	Dimensions in [mm]
Diameter of external frame	80
Axial length of the cylinder	77
External casing length	78
Axial length of stator	48
Inner stator radius	8
Diameter of rotor frame	30
Thickness of magnet	9
Axial length of the shaft	76
Inner stator radius	8
Inner stator yoke radius	23
Outer stator radius	25
Distance of bearing center to rotor mean	24.3
Thickness of bearing	15
Radius of shaft	15
Air gap	5
Stator slot surface	104
Copper section in stator slot	42
Stator slot perimeter	36

3. Thermal analysis of 16 kw BLDC motor

A case study of 16 kW PMBLDC motor has been taken up whose specification and design data is given in the table1, 2. For 16 kW PMBLDC motor, the equivalent circuit is in figure 1,

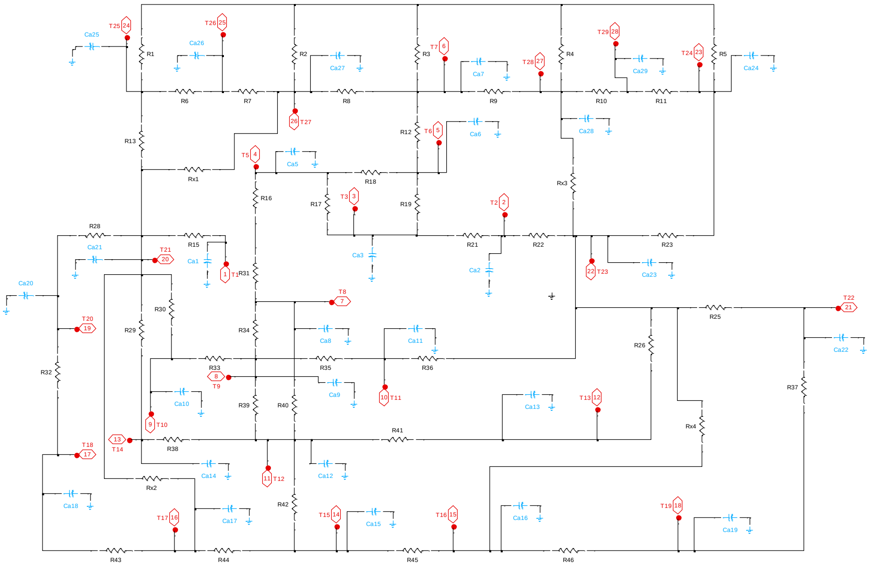

Fig 1: Thermal network

Temperatures at different surfaces of the motor are presented ion table3; the highest temperature that is observed at end windings and active winding.

Table: 3 Temperature Nodes

Electric Motor Components	Temperature Nodes	Values (0C)
ACTIVE HOUSING	T_{H}	153.9
FRONT HOUSING	T_{H_F}	130.3
REAR HOUSING	T_{H_R}	131.5
STATOR YOKE	$T_{St\_ fr}$	187
STATOR TOOTH	$T_{St\_ Tooth}$	195.2
WINDING (slot Wall)	T_{W1}	203.3
WINDING (Active Hot Spot)	T w2	209.5
FRONT END WINDING	T_{EW_F}	212.1
REAR END WINDING	T_{EW_R}	212.1
MAGNET	T_{Magnet}	158.8
ROTOR	T_{Rotor}	159.7

SHAFT CENTRE	T_{Shf_Centre}	150.7
FRONT SHAFT	T_{Shf_F}	128.8
REAR SHAFT	T_{Shf_R}	128.6
FRONT BEARING	T_{Brg_F}	114.1
REAR BEARING	T_{Brg_R}	113.4
ROTOR LAM	$T_{Rot\text{-}lam}$	155.1
STATOR BORE	$T_{St\text{-}bore}$	195
INSULATION	T_{Ins}	203.3

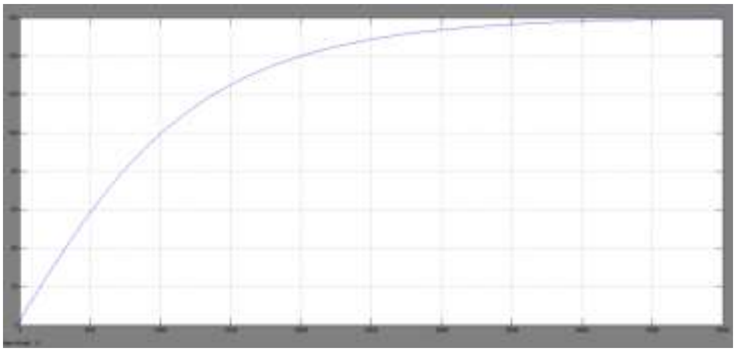

Fig2: Transient temperature distribution on Rotor surface

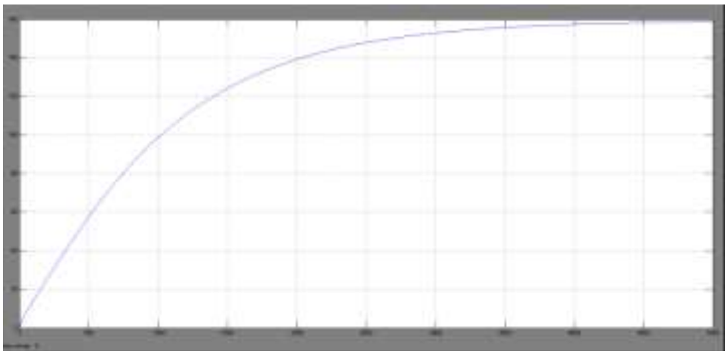

Fig3: Transient temperature distribution on magnet surface

Figure 2, shows the transient characteristics of temperature distribution on rotor surface. As seen from the plot the temperature rise and finally reaches its study state on the rotor surface of PMBLDC motor. The transient response of temperature distribution on the magnet surface, Similar to figure 2 the temperature rise and gets steady state on the magnet surface of the PMBLDC machine as shown in fig 3.

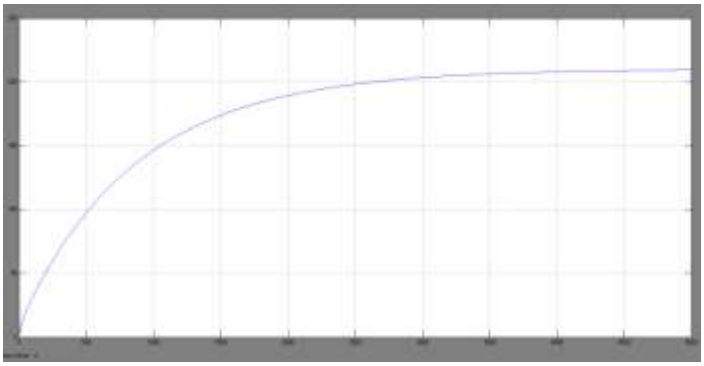

Fig 4: Transient temperature distribution on Active Winding surface

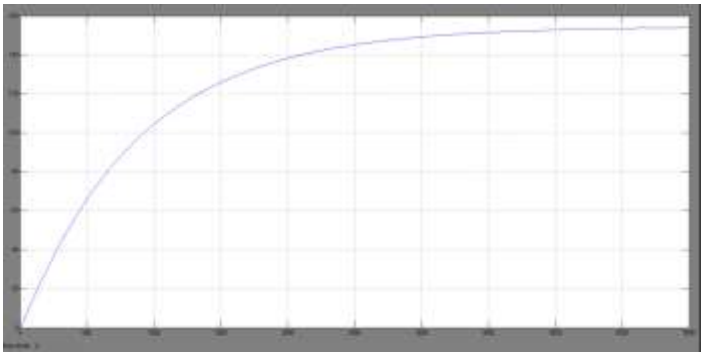

Fig 5: Transient temperature distribution on Active Housing surface

As depicted from figure 4 and figure 5 the transient temperature distribution on the active winding and active housing surface rise for some time and reaches its steady state respectively.

Conclusion

In this paper lumped-parameter axial flux BLDC 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 and transient analysis of the lumped parameter model is considered for surface mounted PMBLDC motor. The network is analysed for temperatures at different surfaces of the motor, such like winding lam and magnet surface are shown. This paper presents a complete reference about heat flow and node temperatures for motor.

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