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Thermal modeling of an AFPMSM: A review

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Abstract

This paper presents the axial-flux permanent-magnet synchronous motor (AFPMSM) and the history of axial-flux machines. Various machine structures, features of the AFPMSM over the conventional machines and disadvantages are clarified. AFPMSMs are being developed for many applications due to their attractive features; these applications are mentioned. It also reviews the studies of thermal modeling of AFPMSM and the various techniques to analyze the thermal behavior of it.

Keywords: Axial-flux permanent-magnet synchronous motor (AFPMSM); Thermal modeling; Finite-element analysis (FEA); Lumped parameter model (LPM); Computational fluid dynamics (CFD); Review

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1. Introduction

AFPMSM today is an important technology in many applications, since they are an alternative to radial-flux permanent-magnet machines (Mahmoudi et al., 2011), and they are being used in various applications in recent years (Acarnly et al., 1996). Axial-flux machines are different from conventional electrical machines in terms of the direction of the flux which runs parallel with the mechanical shaft of the machine. A prior knowledge of the magnitude of the temperature rises in various parts of the machine is important, especially in the case of a high-speed machine design. It is also important for the designer to know the magnitudes of the thermal parameters and to choose a suitable cooling strategy that will enhance the machine performance (Funda, 2001).

Whereas extensive research has been devoted to the thermal studies of conventional electrical machines, AFPMSM has received very little attention (Hrabovcová and Buršlica, 1990; Spooner and Chalmers, 1992; Wang et al., 2005). Analytical and experimental investigations of the temperature distribution in these types of AFPMSM, however, are lacking especially in recent literature. In case of AFPMSM, since the external diameter increases rather slowly with the increase of output power, the existing heat dissipation capacity may be insufficient to cope with excessive heat at

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certain power ratings, so that more effective means of cooling have to be enforced. Thus, quantitative studies of the heat dissipation potential of AFPMSM with vastly different topologies are important (Gieras et al., 2008). Analyzing the thermal behavior of AFPMSM by various techniques is reviewed in the paper.

2. History of axial-flux machines

The history of electrical machines shows that the axial-flux geometry is not new. After the invention of steam and combustion machines, Faraday built the first disk generator in 1831, this device is considered the first electric generator in history and it was an axial-flux machine. Tesla also patented a machine that used the axial-flux principle in 1889. Figs. 1 and 2 show Faraday's first axial-flux machine built in 1831 and Tesla's electromagnetic machine with a disk rotor built in 1889 respectively (Chen and Pillay, 2005; Patterson et al., 2009; Atherton, 1984). Radial-flux machines were invented later and were patented firstly by Davenport in 1937 (Chan, 1987; Challa, 2006; Parviainen, 2005). Since then radial-flux machines have dominated excessively the markets of the electrical machines (Challa, 2006; Parviainen, 2005).

After this the axial-flux machine was displaced and almost forgotten due to its high cost and the manufacturing difficulties in arranging the mechanical structure. This was primarily in because of accurately maintaining a necessarily small airgap in a relatively large disk shaped machine (Patterson et al., 2009). Nevertheless, the interest in axial-flux machines has increased in recent years due to special-application limited geometrical considerations and because of new materials and manufacturing technologies. A possibility to obtain a very neat axial length for the machine makes axial-flux machines very attractive in applications in which the axial length of the machine is a limiting design parameter (Challa, 2006; Parviainen, 2005).

The first work that focused on PM disk machines was performed in late 1970s and early 1980s (Chan, 1987; Campbell, 1974, 1981; Campbell et al., 1981; Henneberger et al., 1986; Weh, 1980; Weh et al., 1984; Leung and Chan, 1980; Kliman, 1983). Disk type axial-flux permanent-magnet (AFPM) machines have found growing interests in the last decade especially in the 1990s and have been increasingly used in both naval and domestic applications as an alternative to conventional radial-flux machines (Spooner and Chalmers, 1992; Kliman, 1983; Hanitsch and Park, 1990; Blenkinsop et al., 1980; Stiebler and Okla, 1992; Jensen et al., 1992; Dostal et al., 1993; Chalmers et al., 1997, 1999; Soderlund et al., 1997; Ficheux et al., 2001; Wu et al., 1995; Wallace et al., 1997; Lombard and Kamper, 1999; Caricchi et al., 1998; Aydin et al., 2001, 2004).

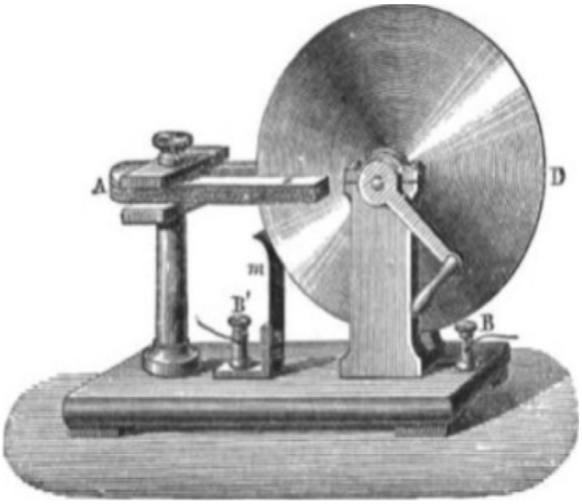

Fig. 1. Disk generator built by Faraday.

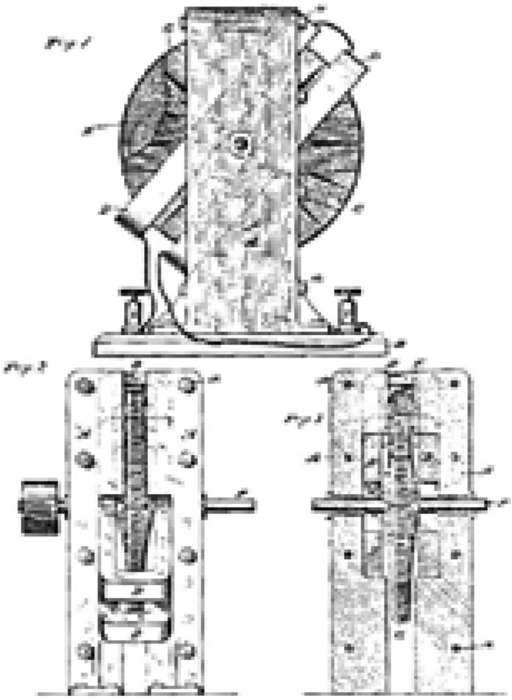

Fig. 2. Electromagnetic machine with a disk rotor built by Tesla.

3. Advantages and disadvantages

AFPMSM's today is an important technology in many applications, where they offer an alternative to radial-flux permanent-magnet machines (Mahmoudi et al., 2011). AFPMSM is being used in various applications in recent years (Acarnly et al., 1996). AFPMSM has many advantages over the conventional machines which includes that they can be designed – using permanent magnets – to possess a higher power-to-weight ratio resulting in less core material and higher efficiency, they have a larger diameter-to-length ratio; they have a planar and easily adjustable airgap, and their magnetic-circuit topology can be easily varied so that many different types of axial field machines may be designed (Aydin et al., 2004; Rizk and Nagrial, 1998; Huang et al., 2000, 2001; Cavagnino et al., 2002; Al-Badi et al., 2000; Sitapati and Krishnan, 2001). Owing to the fact that AFPM machines possess a relatively large air gap volume and quite often have multi-gaps, the general perception is that AFPMSM has better ventilation capacity than their radial field counterparts (Chan, 1982; Gieras and Wing, 2002).

AFPMSM's size and shape are important features in some applications such as electric vehicle where space is limited, so compatibility is crucial. AFPMSM has thin magnets, so are smaller in size than radial flux counterparts and have disk-shaped rotor and stator structures. The noise and vibration they produce are less than those of conventional machines (Mahmoudi et al., 2011). These benefits give AFPMSM advantages over conventional machines, in various applications (Wang et al., 2005; Rizk and Nagrial, 1998; Huang et al., 2000). The main disadvantages are relatively high manufacture cost. Furthermore, the winding inductance is small for large effective air gap, which limits the constant power-speed range (Xu et al., 2009).

4. AFPMSM topologies and applications

Axial-flux machines have a wide range of topologies and cover a broad range of various structures (Funda, 2001), depending on various rotor and stator configurations where they can be designed as double sided or single sided machines, with or without armature slots, with internal or external rotors and with surface mounted or interior type permanent magnets. Low-power AFPM machines are usually machines with slotless windings and the surface mounted permanent magnets (Challa, 2006). These different options may fit several applications. Chimento and Raciti did a deep study of the different topologies of axial-flux machines (Chimento and Raciti, 2004). The types of AFPMSM are Single-rotor single-stator, Double-rotor single-stator, Single-rotor double-stator and Multi-rotor multi-stator (Mahmoudi et al., 2011).

AFPM motors have found numerous applications due to their magnetic and geometric advantages, as opposed to conventional PM motors (Chan, 1987; Javadi and Mirsalim, 2008; Di Gerlando et al., 2011; Woolmer and McCulloch, 2006; Mahmoudi et al., 2013). They can be designed with high torque-to-weight ratio, power density, and low moment of inertia. These motors can be designed with high number of poles for various low-speed applications (Cavagnino et al., 2002; Di Gerlando et al., 2011; Bojoi et al., 2010). A possibility to obtain a very neat axial length for the machine makes axial-flux machines very attractive into applications in which the axial length of the machine is a limiting design parameter (Challa, 2006). Such applications are, for example, electrical vehicles wheel motors and elevator motors (Challa, 2006; Jensen et al., 1992; Lovatt et al., 1998; Mueller et al., 2005). Axial-flux machines have usually been used in integrated high-torque applications (Challa, 2006). Some additional applications are wind turbine generators (Chalmers et al., 1999; Wu et al., 1995), ship propulsion (Caricchi et al., 1999), Electric scooter drive, high-speed generator driven by a gas turbine and Adjustable-speed pump drive (Al-Badi et al., 2000).

5. Thermal modeling of AFPMSM

The temperature rise of electric motors under load can cause a problem in many applications. The thermal management of the motor is important because the electrical insulation has a temperature limit and also because the temperature of the motor affects its efficiency (Nordlund et al., 2005; Fakhfakh et al., 2008). During the operation of an electrical machine, a part of the energy is lost as heat. The electrical machine represents a very complex structure and consequently a very complex thermal system, with different materials and distributed heat (loss) sources. To ensure a long operational life for the machine, these losses must be removed as far as possible from the machine. The cooling is generally provided to increase the operating range of the machine without exceeding the temperature limits of the parts such as insulations, or magnets. Higher temperature levels are not desirable, to protect the insulation and bearings and to prevent excessive heating of the surroundings. Heating of the surrounding should especially be prevented if the machine is placed in the neighborhood of other temperature sensitive equipment. In addition to the consideration of the machine's operational life, a lower operating temperature reduces extra winding losses introduced by the temperature coefficient of the electric resistance (Funda, 2001; Gieras et al., 2008). The dependence of the safe operating conditions and overloading capabilities on the temperature rise makes a prior estimation of the thermal behavior of any electrical machine a very important issue. The temperature tolerance of the materials used in the machine such as the permanent magnets, the winding insulations, and the glue used to attach the magnets determines the safe operating limits of the machine. On the other hand, the temperature dependent characteristics of the winding resistances and consequently the losses, and the temperature dependent permanent magnet flux make the performance analysis of the machine thermally dependent (Funda, 2001).

There are various techniques to analyze the thermal behavior of an electrical machine which are experiment, lumped parameter thermal model (LPM), finite difference and finite elements (Cannistra and Labini, 1991; Cannistra et al., 1993), or alternative numerical techniques such as computational fluid dynamics (CFD) (Staton and So, 1998). Experiment method is appropriate for evaluation of cooling-strategy precise accuracy in designed and fabricated machines (Di-Gerlando et al., 2008; Marignetti et al., 2008; Sahin and Vandenput, 2003; Scowby et al., 2004; Sugimoto et al., 2007).

At present there are many general-purpose advanced CFD codes like FLUENT which are commercially available in the market and can be used for two- or three-dimension modeling of the thermal state of electrical machines. Such packages have extended capabilities to analyze heat and mass transfer processes in a physical system with arbitrary geometry (Lim et al., 2008). As well as there are many simulating programs that perform finite-element analysis like ANSYS (Amir, 2014). Nevertheless, the computation times and the loss of accuracy due to the 2D cross-section simplification make these methods undesirable. Therefore, LPM is used more (Funda, 2001). CFD modeling usually requires high performance multiprocessor computers and considerable computing time to obtain accurate numerical solutions and this makes it difficult to use the advanced CFD techniques for rapid design and optimization purposes. An alternative to CFD modeling of the thermal state of electrical machines is the application of the advanced LPM technique (Lim et al., 2008; Mellor et al., 1991).

Lumped-circuit analysis depicts thermal problem through a thermal network similar to an electrical circuit (Parviainen, 2005; Sahin and Vandenput, 2003). A thermal network in steady state comprises thermal resistance and heat sources connected between motor component nodes. For transient analysis, thermal capacitances are also used to consider change in body internal energy with time (Mahmoudi et al., 2011). The LPM works by splitting the electrical machines into a number of lumped components, which are connected to each other in the calculation scheme through thermal impedances, and representing them as thermal circuits. Both steady and transient temperatures of the AFPMSM components and the local air temperatures can be obtained by considering these equivalent thermal circuits (Lim et al., 2008). The features of LPM method are that the results from it always demonstrate a good agreement with both experimental and CFD data, and also in the LPM method, it is possible to use the corresponding thermal resistances in a dimensionless form and therefore results obtained can be scaled to a wide range of physical dimensions. One of the disadvantages of the LPM method is that the authors neglect the distributed energy flux between solid components of machines and adjacent air flow (Lim et al., 2008; Mellor et al., 1991). Numerical methods require calculation of different operating losses generated in various regions and form heat sources in the thermal analysis (Mahmoudi et al., 2011).

In the first paper we studied that the presented thermal model is a lumped-circuit model and it is developed to simulate the temperature during different loads of the machine. In this paper the thermal behavior and cooling system efficacy of an axial-flux stator have been modeled and investigated. A good agreement of the measured and simulated values has been proven for both the time dependent and steady state temperatures (Erik et al., 2005). Also a detailed lumped parameter thermal model is proposed by Scowby et al. (2004) for prediction of transient and of steady-state temperature rise at various AFPM machine parts.

In Parviainen (2005), the thermal analysis of a machine is based on the thermal resistance network. The computation model is developed for the steady-state analysis only and the thermal capacitances are thus omitted in the thermal model. A simplified thermal resistance network for an air-cooled structure is presented. The thesis discusses the thermal analysis of a high-speed axial-flux PM machine with one rotor – two stators configuration. This machine was designed for a flywheel application with water-cooling. In this study, the authors consider an internal forced air-cooling. Also heat pipe arrangements have been studied for the purpose of improving cooling. A study both on water-cooling and on air-cooling of an axial-flux machine with one rotor – two stators configuration has been reported in Parviainen et al. (2004). The temperature measurements were carried out with twenty Pt-100 temperature sensors. For the thermal modeling the thermal resistances of which were difficult to find accurately were adjusted according to the measurement result obtained at a rated 5 kW load. For the other power ranges in using the same values a good correspondence with respect to calculated efficiency and temperature rise is obtained. It must be noted that the values of the thermal resistances were adjusted according to the measurement results (Parviainen, 2005). Another paper presents the thermal analysis of an AFPMSM for EV traction application; the thermal design technique used is the analytical lumped circuit. Also two-cooling systems are applied to this model, cooling by air and water. The results show that water-cooling is the better solution for cooling the motor (Fakhfakh et al., 2008).

The work reported in Camilleri et al. (2012) was based on the LPM method. This paper shows a preliminary analysis of the thermal limitations for axial-flux internal-rotor (AFIR) and axial-flux internal stator (AFIS) machines. It looks into the thermal limitations of air-cooled axial flux electrical machines when applied to the urban mobility context, and develops a theory showing that when such machines are applied as in-wheel motors, they suffer from thermal limitations. LPM for the two geometries presented is different because the thermal resistance of the machine depends on the geometry of the machine. The paper presents the thermal resistance network for an AFIR type machine and an AFIS type machine. It also defines the heat transfer coefficients at each region in the motor (Camilleri et al., 2012).

A LPM is proposed by Lim et al. (2008) as an alternative to CFD simulations for thermal modeling of AFPM machines. The machine is a slotless Torus machine with three pole pairs. Cooling is achieved by means of the centrifugal airflow in the airgap generated by the PMs. The authors obtain the LPM from a simplified axi-symmetric model of the machine and they present results from lumped parameter thermal modeling of an axial-flux permanent-magnet generator based on the application of the 2D equivalent thermal circuit. A CFD axi-symmetric model is built and simulated to provide the LPM with local values of convective heat transfer coefficient and of mass flow rate. Two case studies have been performed to validate the accuracy of the 2D equivalent thermal-circuit model by comparison with CFD results. The results show good accordance between the two simulation methods (Lim et al., 2008).

Marignetti et al. (2008) investigate the thermal behavior of AFPMSM through a three-dimension thermal-magnetic FEA and to validate the model, the simulated surface temperature rise of the motor parts is compared by experimental data. The software package Comsol Multiphysics has been used to perform all simulations, as it is specifically aimed to couple FEM analysis (Marignetti et al., 2008). Also the paper presents the equivalent thermal network. The AFPMSM is of the single-stator single-rotor type with rated power of 2.2 kW and it is a small-scale prototype to be used in wind turbine application. The machine is air-cooled and in order to ease heat dissipation by forced convective air-flow, a system of channels in the stator coupled to fan-blade-shaped magnets generates a suitable air-flow from the back of the core that is centrifugally expelled from the air-gap. The authors perform three-dimension static electromagnetic FEA and calculate the iron losses in the stator. A three-dimension coupled thermal and fluid-dynamical analysis is performed, and it is assumed that the heat is generated in the stator and in the windings, but not in the rotor. The experimental results on a prototype show a good agreement for the predicted stator and winding temperatures but not for the rotor temperature (Marignetti et al., 2008). Marignetti and Colli (2009) studied exhaustively thermal characteristics of AFPM machine by 3D FEA, thermal-flux plot and thermal gradients in various rotor positions, and also developed a procedure to simulate steady state and transient thermal characteristics of AFPM machine.

Funda (2001) presents the transient thermal-circuit model with and without water cooling for double-stator single-rotor AFPMSM which called an axial-flux interior-rotor (AFIR) machine, constructed in slotted-stator structure with a flywheel used for electric vehicles. The author mentioned that he used the thermal-circuit model because this method is claimed to give very satisfactory results even for the simplified forms. The author assumed that the whole model is symmetric in both heat flow directions, thus the analysis were made for a quarter-thermal model. The thermal equivalent circuit is constructed with the calculated thermal parameters and the resultant temperature values for the machine parts were calculated by analyzing the circuit with ICAPS/PSpice. Throughout the calculations of the thermal parameters of the machine, related material properties and dimensional information of a manufactured machine prototype were used. Simulation results were presented and discussed for several critical machine operating conditions. Several thermocouples are placed in various parts of the prototype machine during manufacturing. A thermo-chip is also attached to a magnet and the cables are connected through slip rings to measure its temperature accurately. The measurements for different operating conditions were also recorded (Funda, 2001).

Finally, Amir (2014) also introduces an original thermal model for the same AFPMSM modeled in Funda (2001) and presents the implementation of the heat transfer through the AFPMSM and the temperature distribution inside an AFPMSM using finite-element technique to solve the three dimensional heat conduction equations to obtain the steady-state temperature distribution at any specified location through it. In spite of the difficulties of the AFPMSM structure. The thermal model was verified using ANSYS 13 finite-element analysis program, which is a general-purpose finite-element method based software package for heat transfer problems, and the results (nodal temperatures) are obtained from the thermal analysis. Due to symmetry, 1/16 of the 3D model is used to simplify the analysis and reduce the simulation time. The accuracy of computed results was verified by comparing the predicted temperature results with the measured values and the also computed temperature values of the previous thermal resistance model, both of which are reported in Funda (2001) and this shows that the developed FE model can perform the thermal analysis with reasonable accuracy. Simulation is performed for several conditions where the nodal temperatures are obtained from the thermal analysis for many different cases at different operating conditions of load, motor speed, cooling system and ambient temperatures and simulation results are proposed. 3D finite-element solution of steady-state heat conduction equation permits the calculation of the temperatures at any location within an AFPMSM, considering the variations in boundary conditions, and the contributions of the convective heat transfer. The analytical approach for evaluating temperature distribution followed in the present investigation seems to correspond adequately well with results of actual measurements. The 3D finite-element model has an important advantage than the thermal resistance model that is monitoring the heat distribution through the model indicating the temperature value at any point in the model making analyzation of the heat transfer easier (Amir, 2014).

6. Conclusion

This paper has presented a review of the research carried out in the thermal modeling and different techniques which were used in analyzing the thermal behavior of an AFPMSM in the past decade. Also it presents the history of AFPM machine, its topologies, and advantages over the conventional machines, disadvantages and applications. The paper then discusses the techniques used in thermal modeling of electric motors and finally, a complete list of references has been provided.

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