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An innovative natural air-cooling system technique for temperature-rise suppression on the permanent magnet synchronous machines

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ABSTRACT

This paper investigates a three-dimensional finite-element (3D-FEA) thermal analysis based on an embedded cooling system with various number of ducts for the outer-rotor permanent magnet synchronous machines (PMSMs). The segmented stator core due to closed-slot topology is the reason of a high temperature-rise at this core. The application-oriented study is aimed to reduce temperature-rise of the conventional model at the stator core via radial and circumferential airflow ducts. A temperature distribution, and heat transfer comparison among all FE models such as conventional, two and four ducts in-core natural cooling systems will be comprehensively presented through freezing the electromagnetic performance. The alternative models using FEA, and computational fluid dynamic (CFD) are experimentally verified the innovative technique, in which the generator is operated by a vertical axis twisted savonius type wind turbine (VAWT).

1. Introduction

1.1. Motivation

The PMSMs are subject to a high thermal stresses during their operation, if these stresses are observed, then that is possible to adapt the machine's control parameters such as current depending on the load and the supplying technique, in order to avoid overheating and a significant heat transfer problems. The conventional model observes with a considerable temperature-rise and related critical heat transfer at the stator core due to segmentation, in which closed-slot configuration is addressed for electromagnetic improvement. In fact, there are many type of cooling systems [1] to overcome this challenge. Although, they can be costly for a number of applications. We studied an innovative airflow coolant for an application-oriented case, in which the cooling system is exempt of employing any external resources to remove the heat in the stator core.

1.2. Literature review

The outer-rotor surface mounted PM synchronous machines (PMSMs), where two-layer fractional slot-concentrated stator winding is employed. The outer-rotor machines can reach a high torque at low speed, in which for the direct-drive small power generation applications with low-speed operation as [1].

Wrobel et al. [2] studied a thermal analysis of a segmented stator winding design. While the thermal performance played one of the major factors limiting a machine's output capability, a thermal test on a complete prototype machine is an essential part of the design process. The method was allowed for a rapid and inexpensive assessment of the thermal performance of the complete machine and early identification of design modifications needed. The research has been applied to the design of a highly efficient and compact permanent-magnet traction motor. A thermal model for a single-tooth was developed and supported by tests to identify key heat transfer coefficients.

Ref. [3], discussed the problem of temperature-rise that influencing the operation performance and also the life time of the PMSM. Based on double Fourier series decomposition, the research established a 3-D analytical model of PM eddy-current loss in the PMSM that considers the effect of time and space harmonics. By applying the thermal network model, the influence of different speed and load on temperature-rise has been analyzed, and

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Nomenclature

c	The specific heat (J/ kg K)
D_{sh}	Shaft diameter (mm)
D_r	Rotor diameter (mm)
J_c	Current density (A/mm^2)
$\{L\}$	The vector operator
l_s	Active stack stator length
m	Stator number of phases
N	Number of turns per phase
n_m	Minimum speed (rpm)
P_r	Rated power (W)
Q	The heat source rate per unit volume (W/m^3)
Q_s	Total number of the stator slots
S_d	Effective slot-depth (mm)
S_w	Slot-width (mm)
T	The temperature (^{o}C)
t	The time (s)
$\{v\}$	The velocity vector for mass transport of heat
α_p	Ratio of pole-arc to pole-pitch
δ_g	Air-gap length (mm)
ρ	The mass density (kg/m^3)
$2p$	Number of poles
$\%\eta$	Percentage of the efficiency

a steady-state thermal analysis of the motor has been performed using finite element analysis. The paper caters the theoretical basis for the design of ventilation and cooling system of the PMSM.

Polikarpova et al. [4] presented a direct liquid cooling system design for an 8 (MW) outer-rotor direct-drive permanent magnet synchronous motor (PMSG). The approach was novel for wind turbine generators, so its impact on the thermal behavior and reliability for the total electrical machine has been evaluated and reported. In addition, the article focused on a dramatic cost savings that can be realized with the development of a more effective stator windings cooling systems.

In Ref. [6], the authors discussed a thermal analysis and cooling system design of a dual mechanical port (DMP) using inner wound rotor is surrounded by the stator and the permanent magnet (PM) outer-rotor prototype machine are investigated. To predict the heat sources in actual operation, a transient co-simulation method has been presented. Thermal parameters and the flow distribution at the cooling ducts are calculated in detail. Finite-element analysis of the thermal field is carried out to obtain the temperature distribution and two typical thermal contacts are considered. A robust fully forced-air cooling system with inner rotor teeth ducts is proposed for the DMP machine and a 10-kW DMP machine is prototyped.

Tosetti et al. described a complete conjugate heat transfer analysis of a scaled-sized prototype of an integrated air-cooled surface-mounted permanent-magnet generator for the "more-electric engine" application. Additionally, to predict and prevent the critical working conditions of the prototype, the adopted cooling system has been investigated using a complete fluid–thermal analysis. Due to the capabilities of computational fluid dynamic software, it has been possible to analyze the temperature and flow fields inside the machine, giving an idea about the distribution of the thermal quantities both inside the solid materials and above the surfaces [21].

The finite-element analysis (FEA), CFD, and lumped-parameter-based methodologies are employed for the entire study [5–13,14–20,24–28].

1.3. Our contribution

In this paper, a speed-functional technique with radial and circumferential airflow ducts under 3-D thermal transient analysis of three FE models with two innovative structures are studied using an in-core circular natural cooling system, regardless of any external sources (liquid and/or air) at the stator yoke of an outer-rotor surface-mounted PM synchronous generator with closed-slot topology. Additionally, the proposed model is verified through its heat transfer calculation at each heat flux sensors, and along with experimental investigation. The CFD analysis is evaluated the heat transfer at a number of specific positions of heat flux sensors on the rotor and stator cores. Heat transfer coefficients are measured at 9 key positions in the stator and rotor cores, and accordingly a good performance of thermal analysis is also predicted. The natural airflow is assumed to vary over the range from 0 to 0.6 (m^3/s), and temperature between 18 to 35 (°C). Moreover, the rotor speed limited to 500 rpm due to malfunctioning in higher speeds of the data-loggers recording data from sensors on the machine. At last, the temperature-rise is suppressed by 11 °C without fail in the efficiency. Whereas, the electromagnetic performance of the FE models is also examined numerically and experimentally.

2. Design and problem statement

During the operation time, a high temperature-rise is experimentally measured in the stator core of the conventional FE model due to a high mechanical and thermal stresses. Under test bench, the temperature-rise of 83.8 (°C), in which the direction of heat transfer is from inner surface of the stator (with a higher temperature) to outer surface of rotor (with lower temperature), that is governed by the second law of thermodynamics.

Natural air cooling system based on the robustness of the FE results depends on the fitness of the generated mesh at the pre-calculation stage. Thermal FE modeling should be taken into account free of any following errors at this stage (1) improper geometric description (if an axial symmetry and/or rotational symmetry has been accounted without considering that an anti-symmetric load), (2) a poor definition of the used materials, for instance the limit of Poisson's ratio at isotropic materials, (3) improper definition of the load that is not recommended to simplify a complex load states or a number of loads with one load, (4) a wrong boundary expresses, (5) choosing a wrong kind of analysis (depends on the case), (6) singularity concept existing in the model which leads the points in the model where values tend toward an infinite value; FE model, where the infinite density and gravity are equivalent to an infinite stress in a sharp corner [22]. Therefore, a good mesh can be successfully generated for all three FE models.

The design solution alternatively resolves the problem using an innovative airflow path, in which the radial ducts are perpendicular to the shaft and pushes the air into the ducts due to rotation of the shaft and its path to out of housing, where we expect the natural airflow to vary over the range from 0 to 0.6 (m^3/s). Fig. 1 illustrates the main air-flow path, in which the innovative models consist of circumferentially (circular at the stator yoke) and axially (from the circular path to the inner face of the ducts). In continue, the heated air-flow goes out through the gap between the stator core and the shaft. Moreover, position of heat flux sensors is shown, in which positions 1, and 3 are on a pole-pair. Position 2, in the center of rotor yoke. Positions 4, and 5 on the stator centerlines of the coil front/and bottom faces. Positions 6, 7, 8, and 9 at the different points of the stator core.

Fig. 2 shows that ducts are introduced to separate the machine axial segments for enhance the thermal dissipation capability with relevant (r = 3.8 mm) dimensions. Table 2 represents the used