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Experimentally validated numerical model of thermal and flow processes within the permanent magnet brushless direct current motor

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ABSTRACT

In this paper, a numerical model describing the heat transfer and air flow inside and outside the casing of the permanent magnet brushless direct current (PM BLDC) motor is presented. In the model, a conjugate heat transfer including the heat conduction with heat sources in windings, magnets, bearings, natural and forced convection and radiation phenomena within internal and external air domain were analysed. The complex geometrical model included windings, a magnet circuit, a rotor with neodymium magnets, a PCB electronic plate, plastic covers, internal air between solid parts as well as a portion of the external air. The validation process of the developed model was realised on the basis of the velocity and temperature fields. The experimental data were recorded by 7 constant temperature anemometers at 4 levels above the motor housing, Laser Doppler Anemometry sensors in two axes inside the rear portion of the motor and 25 thermocouples fixed inside and outside the motor. The experimental and numerical tests were performed for 4 motor loadings and 3 rotational speeds. The average temperature error for the internal point was of 9 K, while that of the external points was of 2 K. The velocity field was very well predicted close to the housing wall in terms of horizontal and vertical components. A slightly worse agreement was found for the vertical component, especially in the vicinity of the shaft. The results were consistent for all the considered motor loadings and rotational speeds.

1. Introduction

Environmental, political and industrial tendencies have directed a reduction of non-renewable sources of energy consumption [1]. One way to achieve this goal is to increase the use of electrical power drives in vehicles and other machines to replace internal combustion engines of lower efficiency. Hence, a direct current electric motor is expected have wider application as a direct source of drive [2]. Today, the problem with implementing this concept, on the large scale, is the limitation of electric power storage in vehicles and small systems. Nevertheless, the prospective for electric power storage technology and its improved maintenance is promising [3–6]. An additional challenge to solve with increased electric vehicle usage is the integration of charging stations into the electric grid. Nevertheless, many studies and proposed solutions can be found [7,8]. Therefore, in the near future, increased use of small power electric motors powered by direct currents can be expected.

The most popular technologies for motors powered by direct current are brush or brushless solutions. Brush motors are cheaper to produce and their construction is simpler [9]. Nevertheless, the brush solution with a mechanical commutator requires a special maintenance monitor and requires systematic brush replacements. Moreover, the efficiency of brush motors decreases with additional losses of the mechanical commutation and higher electrical contact resistance [10]. The brushless solution is free of the above-mentioned disadvantages [11]. A permanent magnet brushless motor powered by direct current (PM BLDC motor) is characterised by high-efficiency, high-power density and lack of mechanical commutation [12]. The main disadvantages of this machine are the high market price of the motor with an electronic commutator and the electronic commutation complexity. Nonetheless, they are becoming ever more popular due to the mentioned advantages. Therefore, this paper focuses on this type of motor.

In electric motor design, thermal analysis plays an important role [13]. It helps estimate the value and location of the maximum temperature in the machine. The specific material and components of the motor should be protected from exceeding the maximum safe working temperature. Hence, proper estimation of the maximum temperatures occurring during exploitation could help reduce the risk of overheating and failure of the machine [14]. A precise thermal analysis allows for decreasing the machine size by reducing the safety margin and,

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consequently, decreasing the material costs. The optimisation of the thermal motor behaviour could also minimise the copper losses of the machine by decreasing the electrical resistivity of the windings depending on the temperature. Due to these facts, thermal analysis should always be included in the electric motor design process.

One of the simplest and the most popular models to predict the temperature distribution in electric machines is the lumped parameter model (LPM) [15]. LPM in the thermal analysis of electric machines is also known as the thermal network [16]. Complex thermal networks contain dozens of the elements - nodes [17]. Usually, LPM allows the temperature of the entire element to be calculated, e.g., one temperature for winding, when it is based on the zero-dimensional model without spatial resolution. Moreover, it does not contain precise information about the coolant flow. The essential parameters used in the thermal networks, e.g., convective heat transfer coefficients, are assumed or calculated usually from the empirical equations, which are presented in the literature for the general simplified shapes and geometries. These equations were derived from the heat transfer field analysis, e.g., in Ref. [18]. The main advantage of thermal networks is their sufficient accuracy with short computational times. Even simple thermal networks produce reasonable temperature response for short-time thermal transient [19]. It is possible, especially for the machines with high thermal inertia, while the thermal capacitance of applied materials was correctly assumed. The temperature prediction in the electric motors with permanent magnets can also be realised by means of numerical simulation and on-line measurements together [20].

A more complex and accurate method for estimation of the temperature distribution is Computational Fluid Dynamics (CFD). In this method, many characteristic parameters, such as the heat transfer coefficient, can be calculated directly and locally within a selected computational domain. This is possible by extending the model geometry to space outside the machine and, consequently, by considering the heat generated inside the motor and then dissipated directly to the ambient air [21,22]. As a result, a more detailed analysis leads to more accurate heat dissipation predictions. In the literature, there are many studies that compare CFD and LPM with respect to experimental data [23]. One of the most important works about thermal modelling of the electric motor operation describes the CFD model formulation and the usage of the CFD field results in the LPM analysis [24]. In the literature, there are also studies based on the Finite Element Method, which is usually applied when researchers focus only on the thermal conduction in solids. One of the studies with thermal conduction analysis in the motor housing is the study of [25]. In the cited work, the authors assumed heat flux from the internal surface of the housing frame and analytically calculated the heat transfer coefficient. Consequently, the estimated temperature field of the finned housing was compared with the experimental study conducted. Zhang et al. [26] presented a coupled analysis between the electromagnetic and thermal solvers. However, the external heat transfer coefficient was calculated analytically, while radiation between internal elements was assumed to be negligible. An interesting work was presented by Jungreuthmayer et al. [27], where thermal analysis was conducted for a water-cooled electric motor. Oil spray cooling of internal parts of electric motor was investigated experimentally in Ref. [28] and also numerically in Ref. [29]. Heat storage mechanism allowing cooling intensification of the transient mode of electric motor using phase change material was investigated in Ref. [30]. The multi-physics simulation connecting thermal analysis with mechanical analysis was presented for case of aircraft actuator in Ref. [31].

Nevertheless, studies showing the flow field inside and outside the motor casing are not prevalent in the literature. The velocity measurements were made in a water-filled axial machine in the work of Aubert et al. [32]. Preliminary results of the air velocity validation were also described in our previous work [33]. Moreover, the velocity validation caused by natural convection from a small heat source using Particle Image Velocimetry technique in the closed cavity was presented in Ref. [34]. The authors obtained satisfactory agreement between the model and experimental results. They suggested the RNG $k-\varepsilon$ model for turbulence modelling in the heat dissipation process via natural convection.

The main aim of the presented paper was to determine the hot-spot temperature and flow fields in terms of a safe and long-term operation of the analysed low-power PM BLDC motor. To achieve this goal, the temperature and the velocity fields were determined within and around the machine housing under various loadings and rotational speeds. The fields were computed on the basis of the developed thermal model that included the computational domain of a very complex internal structure of the considered motor. In addition, the block of the surrounding ambient air was formulated.

To validate the model, a test rig was built to measure temperature and velocity fields at specified locations inside and outside the motor housing. A set of calibrated thermocouples was used to record the values at the stator magnetic core, housing and in the vicinity of the windings. Moreover, the temperatures were also captured at a number of locations above the machine housing. The velocity field was measured by means of the Laser Doppler Anemometry (LDA) technique in the rear part of the motor. The velocity validation inside the motor housing and around the motor is a challenging task. Therefore, this problem is rarely presented in the literature. In the presented study, the LDA technique was used showing its strengths and weaknesses in this application. In addition, the anemometers were used to find the velocity fields above the motor at four levels. All the mentioned parameters were measured for the motor working at four loading conditions at various rotational speeds reaching the maximum value of 3500 rpm. Namely, the considered PM BLDC motor was experimentally tested at 11 operating conditions.

A temperature comparison of the solid motor parts shows very good agreement between the numerical and experimental results. Similarly, the velocity profile inside and the field outside the housing was predicted accurately for most measurement points. The study also shows some problems in the velocity predictions at some near-wall locations.

2. Test rig

2.1. Motor description and test rig components

The studied machine was a low-power electric motor with permanent magnets on the rotor. The motor was supplied by the electronic commutator transforming direct current. The hall effect sensor was used to control the rotor position in the control process. The rated parameters of the rotor were as follows: the output power of 431 W, the input voltage of 24 V and the current of 21 A.

The test rig consisted of two PM BLDC motors connected to each other by a universal coupling. The first motor worked in the motor mode, while the second one worked in the generator mode. The machines were mounted with aluminium brackets and the natural rubber distances to the aluminium base. The distances were used to reduce heat conduction towards the base. The test rig was covered by an acrylic glass cover. The cover was applied to reduce velocity fluctuations caused by the laboratory space. The cover was a square-shaped channel open from the bottom and closed at the top. In addition, an 8 mm hole was drilled through the top wall for natural air flow around both motors. The above-mentioned elements were the main parts of the test rig and all of them were taken into consideration for the formulated CFD model. The picture of the test rig is presented in Fig. 1 with schematically marked boundary conditions set in the model. The motor construction with measuring probes positions were schematically presented in Fig. 2.

The remaining elements used in the test rig but not included in the model were the main power supply unit, an electronic commutator consisting of mosfet transistors, a control system for the PM BLDC motor, and system of resistors used to dissipate electric power produced