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ORIGINAL ARTICLE

An experimental study of rotational pressure loss in rotor-stator gap

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Abstract The annular gap between rotor and stator is an inevitable flow path of a throughflow ventilated electrical machine, but the flow entering the rotor-stator gap is subjected to the effects of rotation. The pressure loss and volumetric flow rate across the rotor-stator gap were measured and compared between rotating and stationary conditions. The experimental measurements found that the flow entering the rotor-stator gap is affected by an additional pressure loss. In the present study, the rotational pressure loss at the entrance of rotor-stator gap is characterised. Based upon dimensional analysis, the coefficient of entrance loss can be correlated with a dimensionless parameter, i.e. rotation ratio. The investigation leads to an original correlation for the entrance loss coefficient of rotor-stator gap arisen from the Coriolis and centrifugal effects in rotating reference frame.

1. Introduction

To prevent insulation breakdown and demagnetization due to excess heat in the electrical machines, cooling medium is commonly passed into an electrical machine to enhance the cooling performance nowadays and the fluid motion is driven by differential pressure. Consequently, advanced fluid flow modelling must be integrated into traditional thermal modelling of electrical machine in order to increase the accuracy of the thermal calculation. The lumped-circuit thermal network is commonly used to perform thermal analysis of electrical machines because of its good accuracy and solutions (steady state and also transient)

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can be done in seconds. The integration of equivalent thermal network and flow network has been demonstrated for open self-ventilated induction machine [1], axial flux permanent magnet (AFPM) machines [2,3], dual mechanical port machine [4], water-hydrogen-hydrogen-cooled turbogenerator [5] and synchronous machine [6].

In thermal network, the heat transfer at convective boundaries is predicted using heat transfer correlations. The topic of Taylor vortex flow in rotor-stator annular gap formed between two concentric cylinders was first introduced by Taylor [7]. The annular gap flow convective heat transfer is then followed by more studies especially those involve the case with superimposed axial flow which can be found in Refs. [8–13]. The rotor-stator gap heat transfer correlations due to the mixed axial and rotational flow were proposed and they can be used in thermal modelling of throughflow ventilated machines. For the correlations, besides the Taylor number or rotational Reynolds number which is normally used to characterise the effects of rotation, the annular gap heat transfer also strongly depends on the Reynolds number of the axial flow. In fact, the amount of cooling medium passing into a throughflow ventilated machine is limited by the system flow resistance and fan performance. In Ref. [14], the impact of ventilation on the temperature rise of a throughflow ventilated AFPM machine has been investigated.

In Refs. [15–17], the studies have showed that the rotor-stator gap flow suffers additional pressure loss due to rotation. Rotation increases the flow resistance and reduces the flow rate through the rotor-stator gap. Therefore, this must be taken into account in the flow network analysis. However, the review of existing literature reveals that the correlation of describing the effect of how rotation increases the pressure losses in rotor-stator gap is very limited.

The objective of this paper is to characterise the pressure loss at the entrance of rotor-stator gap. A dimensional analysis is performed to identify the important parameters that affect the entrance loss. An experimental test rig is built for the present study. For stationary condition, the experimental measurements are verified by comparing with the theoretical results. Then, the test rig is used to investigate the rotational pressure losses. This investigation leads to an original set of correlations for the entrance loss of rotor-stator gap arisen from the Coriolis effect and centrifugal effect in rotating reference frame. The experimental results are also compared with the results obtained using computational fluid dynamic (CFD) method [18,19].

2. Effect of rotation

The operation of electrical machines involving rotation complicates the fluid flow and heat transfer problem in cooling paths. The effects of rotation introduce additional forces to the system due to Coriolis and centrifugal accelerations.

2.1. *Coriolis effect*

In electrical machine, the fluid motion is influenced by the Coriolis force from a rotating reference frame. The Coriolis force is directly proportional to the mass of the fluid particle (m), the angular velocity vector of the rotating frame (ω_m) and also the velocity vector of the fluid particle (V) with respect to the rotating frame. The vector equation of the Coriolis force ($F_{Coriolis}$) can be expressed as follows:

$$F_{Coriolis} = -2m(\omega_m \times V) \quad (1)$$

The cross product operator (i.e. $\times$) in the Eq. (1). multiplies only the ω_m and V vectors that are orthogonal. The ω_m vector is directed along the axis of the rotating reference frame. It is important to note that the resulting Coriolis force is also orthogonal to both ω_m and V. The fluid around a rotor-stator gap is subjected to pressure gradient force and tends to flow towards the gap. At the same time, the fluid adjacent to the rotor is dragged by the rotor due to the no-slip condition. Therefore, in rotating reference frame the flow entering rotor-stator gap is deflected from its initial direction due to the Coriolis effect which is represented by red arrows in Figure 1.

2.2. *Centrifugal effect*

Besides Coriolis effect, the fluid motion is also affected by the centrifugal force in a rotating reference frame. The centrifugal force acts outwards in the radial direction. The centrifugal force ($F_{centrifugal}$) is directly proportional to the square of angular velocity (ω_m), the mass of the fluid particle (m) and the distance of the fluid particle from the axis of the rotating reference frame (r) which can be written as:

$$F_{centrifugal} = m{\omega_m}^2 r \quad (2)$$

Consequently, Coriolis and centrifugal effects increase the pressure loss of fluid entering the rotor-stator gap. The additional pressure losses due to rotation need to be characterised before the convective heat transfer can be estimated accurately.

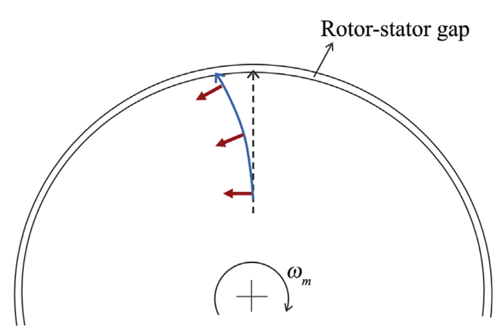

Figure 1 The flow pattern at the entrance of rotor-stator gap in rotating reference frame is represented by blue arrows. The dashed arrows represent the flow direction due to the pressure gradient force. The red arrows indicate the direction of Coriolis force acting on the fluid particles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)