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Modeling and analysis of eddy current losses in permanent magnet machines with multi-stranded bundle conductors

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Abstract

This paper investigates the influence of eddy current losses in multi-stranded bundle conductors employed in out-runner permanent magnet machines, by adopting an analytical model. The analytical model is based on a sub-domain field model that solves the two-dimensional magnetostatic problem using the separation of variables technique for each of the non-magnetically permeable machine sub-domains: PM, airgap and slots. The validity and accuracy of the proposed model is verified using finite element analysis and then used to investigate the eddy current losses. The machine considered for the analysis has 36 slots and 42-poles previously designed for aircraft taxiing. The influence of the number of turns and the conductor cross-sectional area are investigated. It is shown that efficiency can be improved considerably by the choice of multi-stranded bundle conductors.

Keywords: AC losses; Analytical; Proximity losses; Permanent magnet; Sub-domain field model

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1. Introduction

Permanent magnet (PM) machines are being used extensively in diverse transportation applications due to the high torque density and subsequently high power density that they can achieve. Although such machines are designed to have high power density, the resultant losses including winding losses, iron losses and magnets' eddy current losses are inevitable. To diminish these losses and thus improve the overall efficiency, several actions can be taken at the design stage, namely:

1. Laminated material and segmented magnets are used to reduce eddy current losses in the iron and the magnets, respectively;
2. Materials that have a better magnetic properties are preferred to avoid magnetic losses;
3. Magnetic material with high resistivity to reduce iron losses;
4. Litz conductor or multi-stranded bundle conductors are used to diminish winding eddy current losses.

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Here, it is worth highlighting that although the application of Litz wire/multi-stranded bundle conductor significantly limits the effects of eddy current losses due to skin effect [1,2], the winding eddy losses due to the proximity effect still persists. In addition direct current (DC) winding losses also increase due to the poor fill factor of the Litz wire/multi-stranded bundle conductors. However, considering that these losses can be minimized, and then, there is still much to gain by implementing a Litz wire/multi-stranded bundle conductor.

In literature, proximity losses are researched thoroughly and methods for reducing them are presented where it has been reported that these losses can be reduced by an appropriate winding arrangement in the slot [6]. Alternative analytical methods [1,3,5,7] are also proposed to predict proximity losses within acceptable accuracy and less computation time. But, the influence of the number of strands and the strand cross-sectional area of the Litz/multi-stranded conductor is not reported. This all indicates that the choice of the conductors' number/cross-sectional area of Litz wire becomes an important factor to consider during the design stage, in order to balance the alternating current (AC) losses and their DC counterpart.

In this paper, the influence of eddy current losses in multi-strand bundle conductors employed in an out-runner, PM machine used for aircraft taxing [4] is investigated adopting an analytical model. The machine considered for the analysis is a 36-slot/42-pole with an outer rotor. The analytical model is based on a sub-domain field model that solves the two-dimensional problem using the separation variables technique for each of the non-magnetically permeable machine sub-domains: PM, airgap and slots. The validity and accuracy of the proposed model is verified using finite element (FE) analysis and then used to investigate proximity losses. The influence of the number of turns and conductor cross-sectional area is then investigated. It is shown that the efficiency can be improved considerably at the design stage by an appropriate choice of conductors.

2. Analytical model

It is well known that the use of FE method in the prediction of the eddy current losses in slot's conductors requires a significantly large mesh. Indeed, creating the FE model consists of individual conductors and solving are highly time-consuming. Analytical models which provide the complementary solution can be an alternative for analyzing the eddy current losses. The analytical methods are not only faster than FE, but also provide insight into the field computations. Herein, analytical model is therefore considered to analyze the eddy current losses. The adopted analytical method is based on field model which divide the field domain into several simple sub-domain and solve the potential expression in each sub-domain.

To compute the field in each sub-domain, the cross-sectional area of the machine which is the field domain, is therefore divided into three sub-domains: rotor PM sub-domain (A_I—region I), air gap sub-domain (A_{II}—region II), and slot sub-domain (A_i—region III) as shown in Fig. 1(b) where, A represents the Z-component of the magnetic vector potential.

The machine considered for the study has Q number of open slots and each slot is represented with subscripts i. The angular position of the ith slot is defined as

$$\theta_i = -\frac{\beta}{2} + \frac{2\pi i}{Q} \quad \text{with } 1 \le i \le Q \tag{2.1}$$

where β is the slot angle and the other geometric parameters are represented in Fig. 1. The modeling paradigm assumes the following:

1. the machine has a radial geometry as shown in Fig. 1;
2. the stator and rotor cores have an infinite permeability and zero conductivity;
3. the magnets are magnetized in the radial direction and their relative recoil permeability is unity ($\mu_r = 1$);
4. the end-effects are neglected and thus the magnetic vector potential has only one component along the z direction and it only depends on the polar coordinates r and θ;
5. the walls of the slot are finely laminated so that the effect of eddy currents within the iron can be neglected.

The magnetostatic partial differential equations governing in the different sub-domains derived from Maxwell's equations and formulated in terms of vector potential are