FEA ESTIMATION AND EXPERIMENTAL VALIDATION OF SOLID ROTOR AND MAGNET EDDY CURRENT LOSS IN SINGLE-SIDED AXIAL FLUX PERMANENT MAGNET MACHINES

by

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The rotor and magnet loss in single-sided axial flux permanent magnet (AFPM) machines with non-overlapped windings is studied in this dissertation. Finite element analysis (FEA) estimations of the loss are carried out using both 2D and 3D modeling. The rotor and magnet losses are determined separately for stator slot passing and MMF space harmonics from currents in the stator. The segregation of loss between the solid rotor plate and the magnet is addressed. The eddy current loss reduction by magnet segmentation is discussed as well. Two prototype 24 slot/22 pole single-sided AFPMs, fabricated with both single layer (SL) and double layer (DL) windings are assembled. Methods of loss segregation are illustrated in order to separate the eddy current loss. Finally, an optimal design approach to axial flux permanent magnet machines is presented.

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Chapter 1

Introduction

1.1 Motivation

The development and design of electrical machines has changed over the last few decades due to materials and technology improvements. Axial flux permanent magnet (AFPM) machines have gained much attention because of their disc-shaped structure, which is suitable for traction systems such as in hybrid vehicles, and for use in wind power generation [1, 2, 3, 4, 5, 6, 7].

Fractional slot concentrated winding (FSCW) machines, with nonoverlapped windings (NOW), have also become attractive due to the short end-windings and consequently less copper loss, as well as their fault tolerance and flux weakening ability [8, 9, 10, 11, 12]. However, the rotor eddy current losses, which occur both in solid rotor and in magnets may increase dramatically, because of stator MMF space harmonics, and stator open slotting which is commonly used with form wound coils in AFPM machines.

A newly burgeoning research area - computer aided optimisation in machine design has been investigated during the last two decades coinciding with the increasing in

computing power to evaluate the performance of thousands of machine designs by 2D or 3D finite element analysis (FEA) models to minimize the losses or other design objectives.

This dissertation focuses mainly on the eddy current loss analysis in the rotor and magnets in single-side axial flux permanent machines. In the last, an optimal machine design approach is presented.

1.2 Literature Review

1.2.1 Literature Review of Eddy Current Loss Analysis in Rotor and Magnets

The estimation of rotor and magnet eddy current loss has been studied a lot recently [13]. There are basically two approaches to calculate the eddy current loss: using analytical methods and using finite element method in 2D or 3D modelling.

Bianchi (2007, 2010) [14, 15] provided a rapid estimation of rotor losses for choosing different combinations of slots and poles in the early stage of design. In [16, 17], the impact of MMF space harmonics is analysed based on a non slotted straight line model. In [3, 4, 18], the rotor losses are measured in an AFPM machine.

Polinder (2006, 2007) [19, 20] presents an analytical method to calculate the eddy current loss in rotor back iron. First, the flux density in the air gap due to stator current is determined. A Fourier series is then used to obtain the magnitudes of space harmonics of the flux density. The relative motion of the flux density harmonics is calculated. Based on the expressions derived by [21], the eddy current loss is calculated based on two-dimensional fields. Their later work that compares of the analytical method and the finite element calculation shows that analytical calculation

are overestimated or underestimated due to a number of assumptions [22, 23, 24]. The non-linear material properties and slot opening, which is not included in the calculation, have a major impact.

Extensive research has been conducted on the analytical calculation of the eddy current loss in magnets as in [25, 26, 27, 28],etc. Analytical 2-D modelling for predicting the eddy current loss in the permanent magnets due to the armature reaction field was proposed in Zhu (2001) [29], and later improved in [30, 31]. In [32], analytical estimation of the slotting effect on magnet loss is studied. In [33], a precise analytical calculation of rotor eddy current loss is developed. Different rotor layer material and dimensions are studied to reduce the eddy current loss. However, most of the analytical models are two-dimensional with simplifying assumptions. Complex equations are derived based on Maxwell equations.

A finite element model is preferred because its simulation is based on exact physical geometry, although it is time consuming. Two dimensional FEA is a common approach. Reference Ugalde (2010, 2011) [34, 35] analysed the eddy current loss in the solid rotor back iron and magnets in 2D time stepping FEA. It shows in general that single layer windings have higher losses than double layer winding and the loss in the solid back iron is higher than in magnets. In [36], the impact of rotor back iron resistivity on eddy current loss in rotor and in magnets is studied, which shows that the rotor back iron eddy current impact on the permanent magnet (PM) loss. In [16, 15], the impact of MMF harmonics of various orders on rotor loss is analyzed. They concluded that single layer windings have more rotor loss due the richer subharmonics than double layer windings. However, the use of a 2D model leads to an approximate result due to the limited radial extension of actual magnets and rotor in AFPM machines [6]. In [37], a hybrid calculation method, referred to as the finite-element aided analytical method, is presented to accurately predict the eddy loss in

AFPM machines. In [38],a hybrid approach using analytically 2D current sheet and 3D FEA is proposed for determining the eddy current loss in high speed PM rotors. In [39], a 3D finite element method that considered the harmonics of inverters is used to calculate loss in each part of the motor separately. It is proved that eddy current loss in permanent magnets from concentrated or NOW windings is larger than that from distributed windings.

1.2.2 Literature Review of Stator Core Loss Analysis

Core loss prediction and measurement has always been a concern for electrical machine design engineers especially because of the difficulty of quantifying increased core loss associated with increasing frequency. Steel manufacturers usually only provide 50/60 Hz core loss data, which is not sufficient for accurate core loss prediction at higher frequencies. The American Society of Testing and Materials (ASTM) and the International Electrotechnical Commission (IEC) set several standards for core loss measurements. Generally, there are three test fixtures used in industry: an Epstein frame, a toroid tester and a single sheet tester. In [40, 41, 42], the authors compare the results from these three testers. It is shown that higher core losses are obtained in a toroid tester compared to an Epstein frame, which is caused by the magnetic damage produced by shearing stresses in a toroid. The drawback of the single sheet tester is that the flux is only measured at the center of strips, which is the same defect as in the Epstein frame. The single sheet tester is the least popular and is mainly used for quality control. Thus the toroid tester, which approximates the machine's geometry is preferred by machine design engineers.

With the measured core loss data, a core loss model could be set up to estimate the stator core loss in a fabricated machine. Various core loss models have been

developed. Steinmetz did the early work since 1891 [43]. In classical equations, the core losses are separated into two parts: hysteresis and eddy current loss.

$$P = P_h + P_e = K_h f B_m^n + K_e f^2 B_m^2 \tag{1.1}$$

where, P_h is the hysteresis loss, P_e is the eddy current loss, K_h is the hysteresis loss coefficient,K_e is the eddy current loss coefficient, n is an empirically determined constant varying from 1.5 and 2.5, often taken as being equal to 1.6, f is the excitation frequency and B_m is the peak flux density.

Later research has added a third component called excess loss [44, 45], which explains the difference between experiment results and the two components above, shown as:

$$P = P_h + P_e + P_{ex} = K_h f B_m^2 + K_e f^2 B_m^2 + K_{ex} f^{1.5} B^{1.5} \tag{1.2}$$

where P_{ex} is the excess loss and K_{ex} is the excess loss coefficient. To summarize, hysteresis loss is the loss within the structure of the magnetic material at the domain level. Eddy current loss is the resistive loss due to induced electric current produced by the changing flux density. It is found that K_h is linked to material intrinsic properties and behaviour measured through permeability [42]. K_e is assumed constant at lower frequencies .

$$K_e = \frac{Kt^2}{\rho} \tag{1.3}$$

K is the material determined constant, t is the material thickness, and ρ is the resistivity. However, at higher frequencies, (1.2) needs to be modified to take the skin effect into consideration. K_{ex} is found to vary with both frequency and flux density. In [46], the iron loss distribution is shown by a thermographic camera. It can be seen that at a lower speed, hysteresis loss is the main loss contributor, while at a higher

speed eddy current loss is responsible for the main loss.

Recent work, in Domeki (2004) [47], employs a step-wise approximation for core loss coefficients based on (2.1). K_h and n are different in certain peak flux density ranges. In Ionel (2006,2007) [48, 49] focuses on curve fitting of the Epstein data by variable coefficients. The model proposed based on (2.2) uses hysteresis loss coefficients, which are variable with frequency and induction, and eddy-current and excess loss coefficients, which are variable with induction only. These models are more accurate compared with the typical conventional core loss model with constant coefficients.

However, there is another concern that the measured core loss data produced by a toroid tester or by an Epstein frame are different from the actual fabricated stator core loss. The properties of steel in the fabricated stator will be changed during the manufacturing process Clerc(2012) [50]. Sprague(2012) [51] analyzes potential variations in the performance of the machine caused by the allowable variations of the magnetic properties of steel, such as eddy current loss differences due to thickness variation etc. Boglietti(2003) [52] shows that core loss increases due to the punching process, but that an annealing process allows removal of this increased core loss. Different lamination cutting techniques cause variations in losses and in permeability as presented by Arshad(2007), [53]. The electrical design engineer usually bypasses these problems by using corrective coefficients, known as "building or fabrication factors" based on the designers experience.

1.2.3 Literature Review of Machine Design Optimization

The implementation of an optimization algorithm with analytical or FEA modelling in electrical machine design optimization has been studied recently. Genetic algorithm,

particle swarm optimization, and differential evolutions are generally used.
In [54, 55], the authors propose an analytical procedure for the design of a surface mounted PM machine with binary genetic algorithm in order to optimize a single objective function of material cost. In [56, 57], a multi-objective optimization of a 48 slot/4 pole interior permanent magnet (IPM) motor with three barriers per pole is presented. In [58], the optimization design of an IPM motor is presented by means of an FEA-based multi-objective genetic algorithm (MOGA). Three objectives are maximum torque, maximum constant power speed range and minimum torque ripple. In [59], the author includes rotor losses in the optimization process with an additional cost function.

There are some papers using particle swarm optimization in the machine design as in [60, 61, 62, 63, 64, 65]. In [60],a method of comparing three different machine types in terms of efficiency and weight using multi-objective PSO and 2D static FEA is presented. In [63] a transverse flux machine, in [62, 64] a switched reluctance machine and in [65] a surface mounted PM motor are discussed.

The implementation of a differential evolution in electrical machine design optimization has been studied recently. In [66, 67, 68, 69, 70, 71, 72, 73]. In [66], a multi-objective optimization for the design of an IPM motor based on the differential evolution and finite element model is presented. The objective is to minimize active volume and while maximizing the power output in the flux weakening area. In [67], an optimal design practice of an IPM machine with modular stator structure based on FEA and a different evolution is discussed. Single and multi-objectives of maximum torque and minimum total harmonic distortion (THD) of back electromotive force (EMF) is implemented. In [68], an automated machine design process with differential evolution techniques is proposed to maximize the torque and efficiency. In [69, 70], a bi-objective optimization of a PM machine with 11 parameter variables