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Fast iron losses model of stator taking into account the flux weakening mode for the optimal sizing of high speed permanent internal magnet synchronous machine

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Abstract

The optimal design of electrical machines is an important issue in automotive industry in order to reduce cost and volume of the actuator and improve its performances. In this context, the use of compact machines with high power density is preferred and consequently high speed machines where field weakening is required. In addition, a really optimal design requires to dispose sufficiently accurate models of main physical phenomena involved in electromechanical conversion. This models need to be sufficiently fast in order to be suitable with optimization process. An important limitation in the use of internal permanent magnet synchronous machine with distributed windings is temperatures insides the machine especially in the windings and thus the internal losses. At high speed with field weakening operation, iron losses, sensitive to flux densities variation in iron, could be really high because of the high electrical frequency linked to rotor speed and sharp variation of flux density waveforms inside the iron in stator due to the field weakening operation. This study, for the electric machine design, is based on the first harmonic hypothesis, i.e., without harmonic currents. An original and mathematical model has been developed and provides fast and accurate estimation of iron losses particularly in field weakening operation even with machine supplied by sinusoidal currents as described in this paper. It uses a polynomial form of iron losses in function of fundamental electrical frequency and take into account the flux density waveforms in yoke and teeth by use of nonlinear iron coefficients linked to i_d–i_q currents. This paper will present the complete method calculating the iron coefficients from a nonlinear magnetic nodal network of the machine. A detailed study of local flux density waveform and harmonic content in yoke and teeth will be provided for two particular operating points: at maximal power without field weakening and at maximal power at maximal speed. These two points require accurate estimation in an optimal design of electrical machine. In addition, the local iron coefficients in teeth and yoke per volume unit will be provided in order to study the local evolution of iron losses in field weakening operation. It will show that iron losses do not follow the same evolution in the yoke and the teeth by the fact that the flux density distribution in teeth is more sensitive to the field weakening. An application of

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this model will be provided for the calculation of iron losses on whole operating space for a specific machine. A comparison will be provided between the fast model and finite elements approach.

Keywords: Iron losses; High speed application; Control laws; Fast model

1. Introduction

In the context of embedded applications like hybrid vehicles, the specifications of electrical machines are particularly tight in terms of space and energetic performances. The electrical machine needs to operate on a wide speed range. In addition, the machine could be coupled with a coaxial mechanical reduction gear in order to reduce its size by operating only at low torque and high speed up to 20 000 rpm. Consequently, high speed operating and field weakening are required. So iron losses may be comparable to the copper losses and could have a real impact on the machine performances and the sizing machine. Consequently, in an optimization process of sizing machine, a fast and accurate iron losses model is required. In [5], Internal Permanent Magnet Synchronous Machines (IPMSM) appear to be the most suitable actuators for these applications because of their high power density and their high efficiency. This machine type that will be studied in this paper with the geometry is given in Fig. 1 with dimensions and parameters given in Table 1.

Firstly, this paper will introduce the state of art of models calculating the iron losses in materials. As the field weakening influences the Flux Densities Waveforms (FDW) especially in the teeth and in the yoke, the proposed model calculates the FDW from a semi-analytical approach, i.e. a nonlinear nodal network with magnetic saturation [10]. The phenomena linked to the rotor speed and the control laws, i.e. FDW, are decoupled in a polynomial formulation of the iron losses in function of the fundamental frequency and non-constant coefficient depending on the control laws. The principle of coefficient mappings in function of pair of currents i_d–i_q is applied as in [6] making this model easily integrated with the electrical machine multiphysics model and the control laws optimization. It provides an accurate and fast estimation of the iron losses for the whole operating space. The coefficient mappings derive from the generalized Bertotti formula. Previous works used mapping principle as [12] for iron losses computation but from the FDW in air-gap with time-dependency.

Secondly, an analysis of the flux density distribution in teeth and yoke and the impact on the iron losses will be presented for two operating points, i.e. without and with field weakening operation at similar phase current and power rating and the study will be extended with an analysis of iron losses coefficients per volume unit in d–q space.

Thirdly, a comparison of this method with finite elements method in terms of calculation time and accuracy will be done.

Finally, a conclusion about the new approach in terms of computation time and accuracy will be discussed together with the level and the localization of iron losses in high speed machine.

2. State of art: iron losses in the stator of electrical machine

2.1. Calculation of iron losses in materials

We can distinguish two main types of iron losses models, i.e. local models and global models. Local models use hysteresis curves in order to establish mappings of magnetic field in function of the flux density and the time derivation of the flux density. There are several approaches to calculate the magnetic losses in materials as the Preisach model [14] and the work initiated by Cester [4] called Loss Surface model (LS model). The calculation of iron losses uses the fundamental equation of power density dissipated in the material. In [3], it has been shown that this model is more accurate than a global model but requires a good knowledge of the material. Improvements have been carried out in [8]. Global models are much older than the LS model and early work carried out by Steinmetz [15] led to a polynomial formulation of iron losses in function of the frequency. However this model gathers in one formula several magnetic phenomena and it does not separate the different losses and the FDW in the material. This model was suitable for electric transformer. Therefore Jordan [9] proposes to improve this model by separating the losses linked to hysteresis phenomenon and Eddy current phenomenon. Yet this model does not take into account other