Available online at www.sciencedirect.com
ScienceDirect
Mathematics and Computers in Simulation 130 (2016) 70–80
MATHEMATICS AND COMPUTERS IN SIMULATION
www.elsevier.com/locate/matcom

Original articles

Torque and torque components in high-speed permanent-magnet synchronous machines with a shielding cylinder

Bert Hannon[a,b,*], Peter Sergeant[a,b], Luc Dupré[b]

[a] *Department of Industrial Technology and Construction, Electrical Energy Research Group, Ghent University, V. Vaerwyckweg 1, 9000 Gent, Belgium*

[b] *Department of Electrical Energy, Systems and Automation, Electrical Energy Laboratory, Ghent University, Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium*

Received 25 September 2014; received in revised form 31 August 2015; accepted 16 September 2015
Available online 28 September 2015

Abstract

A demand for more efficient electrical machines with a high power density is driving the interest for high-speed permanent-magnet synchronous machines (PMSMs). However, the design of such machines is a challenging task. One of the problems is that the effect of the shielding cylinder, a conductive sleeve around the magnets, on the machine's performance has not been studied extensively. To cope with that problem the authors of this work introduce an analytical method to study the torque in high-speed PMSMs. The presented method implies dividing the torque into two components, depending on how they are produced. The method is successfully validated and an illustration of its advantages is provided.

Keywords: High-speed machines; Analytical modeling; Torque production; Shielding cylinder

1. Introduction

Two trends in modern society have sparked the interest in high-speed electrical machines. At the one hand an increasing ecological awareness has led to a demand for more efficient machines. At the other hand a trend towards more flexible applications pushes the demand for smaller machines. Since high-speed electrical machines, and more specifically high-speed permanent-magnet synchronous machines (PMSMs), combine a high efficiency with a great power density, the interest in such machines is on the rise. This is reflected in a large number of publications on high-speed machines. Some of these articles discuss specific aspects of the electrical machine, such as the shielding cylinder (SC) [12], while other articles present a more general view [1,2,10,15]. A great number of publications presents a specific application or design [8,7].

However, designing high-speed PMSMs is a challenging task. One of the reasons is that only little is known about the effects of the SC, which is commonly used in high-speed PMSMs. The SC is a conductive sleeve that is wrapped around the magnets. The reasons to implement a SC are twofold [13].

* Corresponding author at: Department of Industrial Technology and Construction, Electrical Energy Research Group, Ghent University, V. Vaerwyckweg 1, 9000 Gent, Belgium.
E-mail address: Bert.Hannon@UGent.be (B. Hannon).

http://dx.doi.org/10.1016/j.matcom.2015.09.006
0378-4754/

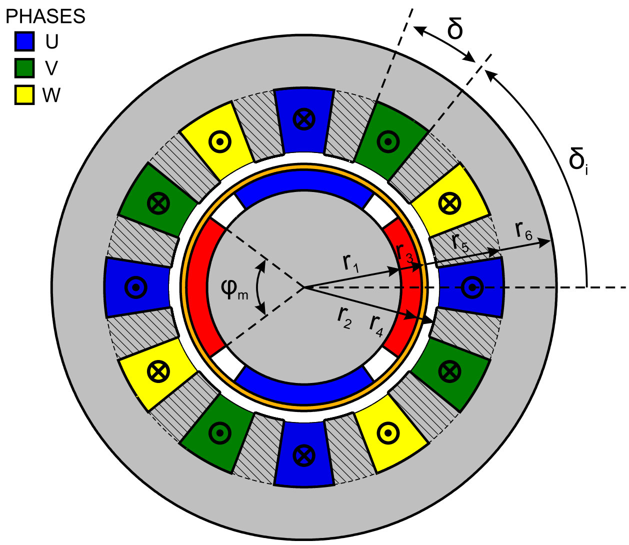

Fig. 1. Geometry of a 3-phase PMSM with 2 pole pairs and a SC.

Firstly, the magnets in high-speed machines experience high centrifugal forces. They are therefore kept in position with a retaining sleeve. Usually this sleeve has a relative magnetic permeability that is near to one. The electrical conductivity of such a retaining sleeve varies from very high, if for example inconel is used, to very low, if carbon fiber is used.

Secondly, operating PMSMs at high temperatures implies a risk of permanent demagnetization of the magnets. This is particularly true for high-speed PMSMs where cooling of the rotor is difficult. Therefore the rotor losses should be minimized. A commonly proposed technique to do so is the SC. Asynchronous harmonics in the machine's magnetic field will induce eddy-currents in the conductive sleeve. According to Lenz's Law, these eddy-currents will produce a magnetic field that counteracts their origin. The asynchronous harmonics in the magnetic field will thus be mitigated by the SC. This means that, when designed correctly, the SC reduces the overall rotor losses [6,13].

To get a better understanding of the effects of the shielding cylinder on the machine's performance, this work studies the torque in PMSMs that are equipped with a SC. The novelty of the work includes the separation of the torque in two components, as explained in Section 4. There are two major techniques to study the torque in electrical machines. One possibility is to build a finite-element model (FEM) of the studied machine. Such models are very accurate and relatively easy to construct. However, if the goal is to get a better understanding of the machine's physics, analytical models are better suited. Not only because of their low computational times and great flexibility but also because they intrinsically lend themselves to getting a better understanding of the impact of the chosen parameters. Therefore in this work an analytical model is used to study the torque.

To conclude this introduction an outline of the presented work is given in the following.

In Section 2 the studied machine topology is presented. Section 3 introduces the analytical model that was applied in the torque study. It also presents the assumptions that where adopted to enable the analytical approach. In Section 4 the torque production in high-speed PMSMs is discussed and the division of the torque in two components is presented. That section also discusses the calculation of the torque based on the model presented in Section 3. Before concluding the work in Section 6, Section 5 demonstrates the advantages of the proposed division in torque components.

2. Machine geometry

The machine type regarded in this study is a PMSM that is equipped with a SC. The cross section of such a machine, with 3 phases ($m = 3$), 2 pole pairs ($p = 2$) and 12 slots ($N_s = 12$), is shown in Fig. 1. The machine's geometrical parameters are r_1 (outer radius of the rotor yoke), r_2 (outer radius of the magnets), r_3 (outer radius of the SC), r_4 (inner radius of the stator windings), r_5 (outer radius of the stator windings) and r_6 (outer radius of the