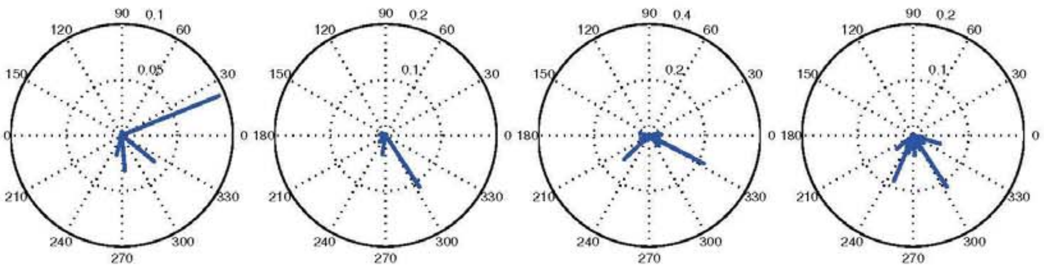
Ahamed Bilal Asaf Ali

Design Rules for Permanent Magnet Synchronous Machine with Tooth Coil Winding Arrangement



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Design Rules for Permanent Magnet

Synchronous Machine with Tooth Coil Winding Arrangement

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Von der Fakultät für Elektrotechnik, Informationstechnik, Physik
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Abstract

This thesis presents the generic rules for permanent magnet synchronous machine with tooth coil winding arrangement. The generic rules concentrates on minimized cogging torque and torque ripple. In this dissertation work, paper-mill is selected as an application. Initially, literature research is provided about the existing design rules. Moreover, rough comparison of direct drive and drive with gears is explained using simplified approach. The geometries considered in this thesis are two different tooth coil winding arrangements and three different rotor types.

The armature flux density and the permanent magnet flux density are derived analytically. The permeance function which is also the source for cogging torque and torque ripple is discussed. The cogging torque and torque ripple are derived analytically using the stator field, rotor field and the permeance functions. The detailed torque analysis of all the considered geometries are performed in Finite Element Method (FEM) for different slot opening and magnet pole coverage. The 2D harmonics analysis approach is used to predict the sources of the harmonics from the numerical calculation. The harmonic sources are reconstructed and validated with the pulsating torque obtained directly from the FEM. The results from the reconstructed curve and the curve which directly obtained from the FEM are in good agreement.

The harmonic sources of pulsating torque are also validated with prototype for a geometry. The investigations on pulsating torque are extended to other operating points such as field weakening and half load condition. Alternative field weakening method is also examined for pulsating torque. Moreover, optimization tool is also used in this thesis to find the minimum cogging torque. In all the cases, the corresponding sources of harmonics for pulsating torque are discussed.

Finally, a generic design rule is suggested for permanent magnet synchronous machine (PMSM). In addition, simplified design rules are suggested to have quick design approach for PMSM. Since manufacturing plays an vital role for a product, this thesis also shows design guidelines from manufacturing view point.

Kurzfassung

In dieser Arbeit wird die generische Gestaltung von dreisträngigen, permanent-magneterregten Synchronmaschinen mit Zahnspulenwicklungsanordnung diskutiert. Dabei liegt der Fokus auf denjenigen generischen Regeln, die zur Minimierung des Rastmomentenverlaufs und der Drehmomentwelligkeit genutzt werden können. Es werden beispielhaft Antriebe in einer Papiermühle-Anwendung betrachtet.

Zuerst wird eine Literaturrecherche über die bestehenden Entwurfsregeln durchgeführt. Außerdem wird ein grober Vergleich zwischen einem Direktantrieb und einem Antrieb mit Getriebe dargestellt. Die Untersuchungen in dieser Arbeit beschränken sich auf zwei verschiedene Zahnspulenwicklungsanordnungen und drei unterschiedliche Rotortypen.

Sowohl die Anker- als auch die Erregerfeldverteilung werden mit Hilfe eines zweidimensionalen , analytischen Ansatzes beschrieben. Unter Berücksichtigung der magnetischen Leitwertfunktion des Luftspaltbereichs lassen sich daraus Werte für das Rastmoment und die Drehmomentwelligkeit ableiten. Die vergleichenden, detaillierten Drehmomentberechnungen der betrachteten Geometrien werden mittels FE-Analysen für verschiedene Nutöffnungen und Polbedeckungen durchgeführt. Der analytisch harmonische Ansatz wird verwendet, um die harmonischen Quellen der numerischen Berechnung zu identifizieren. Diese Quellen werden rekonstruiert und mit dem pulsierenden Drehmoment der FE-Analyse verglichen. Die Ergebnisse zeigen eine gute Übereinstimmung zwischen der rekonstruierten Kurven und den Kurven aus den FE-Analysen.

Die ausführliche Drehmomentanalyse der betrachteten Geometrie werden im FEM für verschiedene Nutöffnung und Polbedeckung durchgeführt . Jedoch werden einige Parameter konstant gehalten für das Drehmoment Analyse. 2D Harmonischen Analyse Ansatz wird verwendet, um die harmonischen Quellen aus der numerischen Berechnung vorherzusagen. Die harmonischen Quellen werden rekonstruiert und mit dem pulsierenden Drehmoment direkt von FEM-Analyse

validiert. Die Ergebnisse zeigen eine gute Übereinstimmung zwischen der rekonstruierten Kurve und der Kurve aus der FEM-Analyse.

Die harmonischen Quellen des pulsierendes Drehmoments wurden mit einem Prototyp entsprechend einer Geometrie validiert. Weiterhin lassen sich die Untersuchungen zum pulsierenden Drehmoment auch auf andere Arbeitspunkte, wie Feldschwächung oder Teillast, erweitern. Eine alternative Methode zur Feldschwächung wird ebenfalls hinsichtlich des Rastmomentenverlaufes untersucht. Ferner wird das in dieser Arbeit präsentierte Optimierungs-Tool zum Auffinden des minimalen Rastmoments verwendet, wobei in allen Fällen die entsprechenden Quellen von Harmonischen des pulsierenden Drehmomentes zur Verfügung gestellt werden.

Abschließend wird eine generische Entwurfsregel für permanentmagneterregte Synchron-maschinen empfohlen, die zusätzlich auch in vereinfachter Form dargeboten wird, um möglichst schnell ein geeignetes Maschinendesign zu erhalten. Da die Herstellungsverfahren eine wichtige Rolle beim Maschinendesign spielen, werden in dieser Arbeit die Entwurfs-regeln auch von diesem Standpunkt aus betrachtet.

Contents

1. Introduction and Literature

Generally there are various low-speed drive systems available in the industry. Existing components are replaced with modern technology to have high power density, reduced losses, improved power electronics control, computer based monitoring of the drive and to have reliable and continuous operation of the drive system. Additionally, direct drive allow high acceleration and higher dynamics in production machines e.g. milling industries. The modern drive system can save energy by reducing the energy consumption costs as well as global emission [1]. Thus modernization of industries are necessary due to the economical and environmental aspects. Typical applications of low-speed drives include paper and pulp industry, ship propulsion, wind turbine, etc.

Enormous amount of papers, which is one of the basic necessities in day to day life, is used in different forms by us. These papers are manufactured in bulk volumes by the paper industries during the process of paper making, thus consuming 30 % of the produced renewable and non-renewable energy sources in countries like Germany [2]. There are more than 150 paper manufacturers present in Germany [3]. Therefore, improvements of efficient drive systems for the paper industries are a challenging task which leads to save energy. The current trend in paper industry is to have direct drive solution by reducing the mechanical components and compact high torque direct drive to have more surrounding space. Asynchronous Machine (ASM) drives have been widely used in the paper industry and it still exists commercially. However proper selection of machine will have best choice when chosen in terms of better efficiency, high power density, high control dynamics and reduced space.

The alternative solution to the ASM is permanent magnet synchronous machine (PMSM). PMSM have high dynamics and precise control and ASM has complicated field oriented control strategies. In direct drive the motor is directly coupled to the load and therefore reduction in the mechanical components which is a problem for the drive with gears. The reliability of the transmission in the drive system with gears is less and hence the replacement of the gearbox is earlier than expected [4]. There are different types of PMSM. The rotor can be arranged either inner or outer; the permanent magnets can be placed on the surface or inserted in to the rotor; the stator winding types are either distributed arrangement or fractional slot arrangement. The disadvantage of PMSM is that it is subjected to demagnetization under load and short circuit conditions. The other disadvantages are, it has magnet losses under no-load operation and Joules losses during field weakening which is not the case in ASM. Nevertheless, PMSM with fractional-slot arrangement is a good choice of candidate for low-speed direct drive application due to reduced copper volume which reduces the joules loss and increases the efficiency. It also has reduced production costs and has high power density.

1.1. Design Process of Drive System

The details of the direct-drive are discussed in Chapter 2. The approach from design specification to the prototype development and mass production is shown in the Figure 1.1. The goal

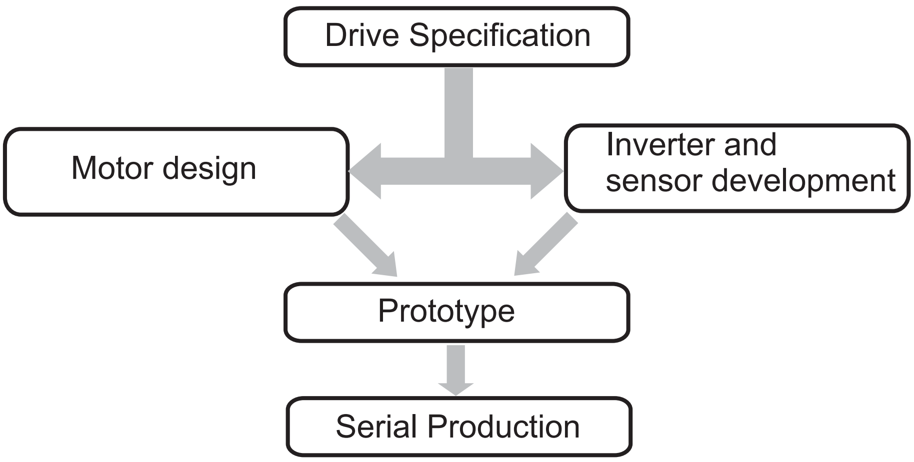

Figure 1.1.: Design of direct drive system.

of drive configuration is to reduce the overall drive dimensions and to improve efficiency.

The typical design specifications for paper-mill application are mentioned below.

- A rated torque of 3 $kN.m$ at a rated speed of 200 min^{-1}.
- Range of speed in the constant power region (field weakening) from 200 min^{-1} to 400...500 min^{-1}.

- The DC Link voltage is 690 V.
- The motor outer dimension is restricted to a diameter of 750 mm.

The key component in the electromechanical energy conversion is the electrical machine. There are certain analytical approaches to calculate the geometry dimension parameters of the electrical machines. These approaches are discussed in publications [5] and [6]. Basic design is done analytically with initial selection of force density, magnetic flux density in the magnetic circuit such as air gap, stator and rotor and current density of the stator coil, etc. The dimension of the geometry can be obtained together with the electrical parameters and the power balance of the energy conversion. This geometry is further optimized with the help of finite element method program (FEM). The FEM calculation details are described in detail in the literature [7]. A routine process using software program is done by varying the initial design parameters until the geometry fulfills the given requirement. Next step is to prepare a prototype model and validating the results with FEM results. Usually in prototype the machine is tested for synchronous generated voltage, torque for the given current, mechanical power, efficiency, overload capability, thermal and mechanical durability, short circuit behavior, etc. Once the prototype gives most promising results then the machine is ready for the mass production.

1.2. Objective

When PMSM is selected as a drive motor for low-speed application the next question that arises is about its pulsating torque. Pulsating torque is of two kinds; Cogging torque under no-load operation and Torque ripple under load operation. The methods to reduce the pulsating torque are described in many publications. Few publications are discussed at the end of this chapter. Based on the literature, torque pulsations are minimized either using control methods or by design parameters. If there is negligible pulsation in the PMSM, one can easily turn its rotating part with a free hand. As shown in Figure 1.2, the motor was a prototype with increased torque pulsation and a lever is required for the person to overcome the pulsating torque.

The objective of this dissertation is to develop the generic design rules for permanent magnet synchronous machine for reduced torque pulsation. However, other factors in the existing rules such as losses, average torque, efficiency, machine utilization, mechanical stiffness and economical aspects are also considered to some extent. The work focuses on detailed analysis of pulsation torque of two fractional slot winding arrangements and three permanent magnet rotor arrangements. The basic design parameters are slot opening, ratio of pole arc to pole

Figure 1.2.: Torque pulsation sense.

pitch (pole coverage). These design parameters are further analyzed by considering different stator winding arrangements and rotor geometries. It should be noted that the skewing method is not taken as a measure to reduce the torque ripple although it is used. In this work, the input current for the analysis of the torque pulsation is considered as sinusoidal. Harmonics due to inverters are not considered because it is not possible to eliminate pulsating torque from design side due to the presence of these harmonic contents. Finally the design rules gives information to design the geometry of a machine. Although in this work, two winding types and three rotor types are considered as examples, these rules should be valid in general because the rules are formed based on the waves in the fields, for example, the selection of geometrical parameters for minimum cogging torque.

1.3. Structure of the Work

Chapter 2 gives an introduction of PMSM in high torque application. This chapter provides information about the drive systems arrangement, difference between drive with gears and without gears and design and working principle of PMSM. Finally, this chapter discusses about considered geometry in this dissertation work.

Chapter 3 gives an introduction to the general derivation of force in PMSM based on Lorentz force and Maxwell's stress tensor. This chapter begins with the study of parasitic torque and permeances in PMSM. The mathematical formulation of the torque pulsation is also explained in this chapter. Analytically derived results are compared with the FEM results in this chapter.

Chapter 4 discusses about detailed analysis of the torque pulsation for the considered geometries. The harmonics which are responsible for the pulsating torque are tabulated. The reconstruction of the torque curve using two dimensional Fast Fourier Transform (2D FFT) is discussed in this chapter.

Chapter 5 describes the measured results and torque pulsation special study. This study includes torque minimization using optimization algorithm and influence of torque pulsation during other operating points. For example torque pulsation is increased during field weakening [4]. This section also discusses about preserving the minimized torque pulsation using alternative field weakening method and torque pulsation during other operating points.

Chapter 6 explains to derive design rules of PMSM for reduced torque pulsation. Finally, the thesis is concluded with the remarks on PMSM rules and future developments. The losses and short circuit analysis are not considered in this work. Basic details of Schwartz-Christoffel transformation, field solutions of current sheet, model analysis of rotor and flux lines and flux density of geometry are provided in the appendix.

1.4. Pulsating Torque Minimization Rules- Literature Discussion

The method to minimize torque pulsations can be classified in to two categories. Design parameters such as slot opening and pole coverage (ratio of pole arc to pole pitch), stator slot and rotor pole combinations, eccentricities of the rotor, permanent magnet magnetization, stator slot shape, permanent magnet shape, auxiliary teeth slots, lamination materials, saturation, number of slots per pole per phase in winding arrangements, manufacturing tolerances and skewing have influence on torque pulsation from the design side. However, optimal design solution is somewhere in the above mentioned design parameters. Alternatively torque pulsation is reduced using control methods (Active torque ripple minimization method). However, there are limitations using control methods. For example, torque ripple in PMSM is a function of rotor angular position. The compensation of torque ripple can be done by modulating the