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

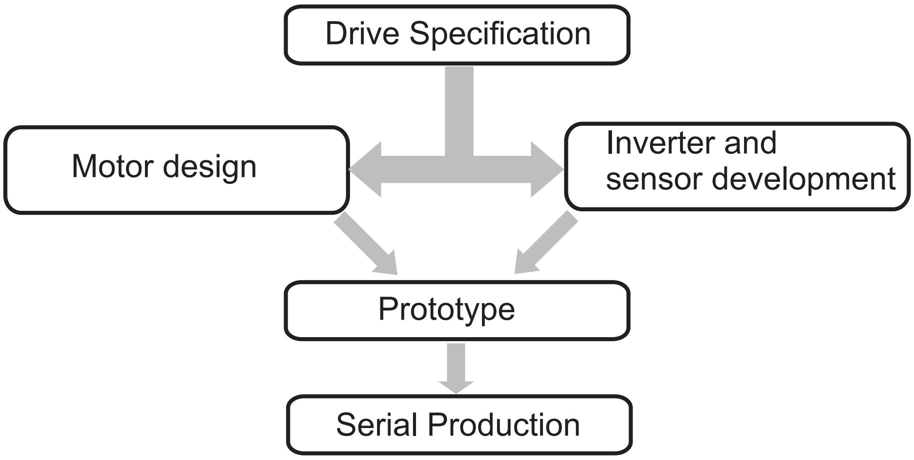

Figure 1.1.: Design of direct drive system.

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 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.

Figure 1.2.: Torque pulsation sense.

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 torque producing current component using closed control loop. In this control method, voltage reserve has to be taken in to account for the modulating current. Also, there is also maximum limit for switching frequency of the inverter. Further, during the field weakening, the speed and switching frequency are high which increases the inverter switching losses. Especially when minimizing torque ripple using control methods in field weakening operation, both switching frequency and voltage reserve should be thoroughly considered.

In the following section general rules based on the literature (geometry design ripple minimization method and active ripple minimization method)has been provided for the minimum torque pulsation.

1.4.1. Minimization Method - Design Parameters

Slot opening and pole coverage

The thesis of reference [8] discussed methods to reduce torque ripple by varying slot opening and pole coverage for three different rotor structures of permanent magnet motors with fractional slot winding ($q < 1$) arrangement. However the source of the torque pulsation are not provided. This analysis is also made by several authors in the past decades and it is not quoted in the work. The optimal pole coverage of the magnets are reported in reference [9].

Winding arrangements

Torque pulsation focussed on number of slots per pole per phase (q) is studied in paper [13]. The work from [14] for fractional slot winding investigates various winding arrangements to eliminate the sub-harmonics and harmonics. Magnussen [15] compared the integral slot winding with fractional slot winding.

Air gap field contour

Several methods are reported by influencing the air gap field distribution in order to reduce harmonics magnitude and thus minimizing the torque ripple. In [16] the force oscillations are reduced with shaped magnets. Paper [17] investigates the contour of magnet shape and teeth, curved magnet edge, unequal magnet thickness, introducing slot wedge with small relative permeability and asymmetry arrangement of magnets for an axially excited surface mounted PMSM. The other interesting techniques by using HALBACH type PM and pole shape variation are discussed in the paper [18]. Introducing auxiliary tooth and unequal tooth have reduced cogging torque [10]. In this work the investigation on air gap field closely differentiate the relation between reluctance effect (cogging) and force during load operation due to the super position of field harmonics in the machine.

Stator slot and rotor pole combinations

Significant effects of slot and pole combinations related to torque pulsation are studied in [10] and [8]. Most promising slot-pole combinations are provided. Salminen [8] made analysis for pull-out torque by varying either stator slot or rotor pole by keeping the other geometry parameters as constant. Approaches to find the reduced cogging torque with the help of least common multiple(LCM) are reported in [11] and [8]. Ackermann [12] in his paper also discusses the same (minimum cogging torque) based on the rate of change of surface area of magnets over armature teeth.

Manufacturing defects, Saturation and Eccentricities of the rotor

Additional cogging torque due to manufacturing imperfections are measured and calculated in [19]. Cogging torque effect on PM magnetization faults is explained in [20]. Due to saturation and eccentricity in the machine, the permeances of the magnetic circuit will modify. It generates additional harmonics in the air gap field accounting for pulsating torque and radial forces. The saturation effect and eccentricity effect are studied in [21] and the reparametrization of air gap field due to saturation in [22].

Skewing

Skewing is the common approach to reduce the parasitic torques. This method ideally eliminates the cogging torque but at the expense of the average torque, complication during manufacturing process and increased leakage inductance and stray losses. This approach is discussed in the papers [23], [17] and [24]. This method is not handled in this work.

1.4.2. Minimization Method - Active Control

Harmonic cancellation - Current profiling

Under load, torque ripple minimization can be minimized using additional control method. Optimal current profiling to influence the harmonics is discussed in papers from [18] and [25].

Torque-Position feedback to look-up table

This method is an on-line estimation. The torque versus rotor position information is entered in the look-up table and added to the torque controller to get ripple free reference torque current component as shown in Figure 1.3.

Adaptive instantaneous control

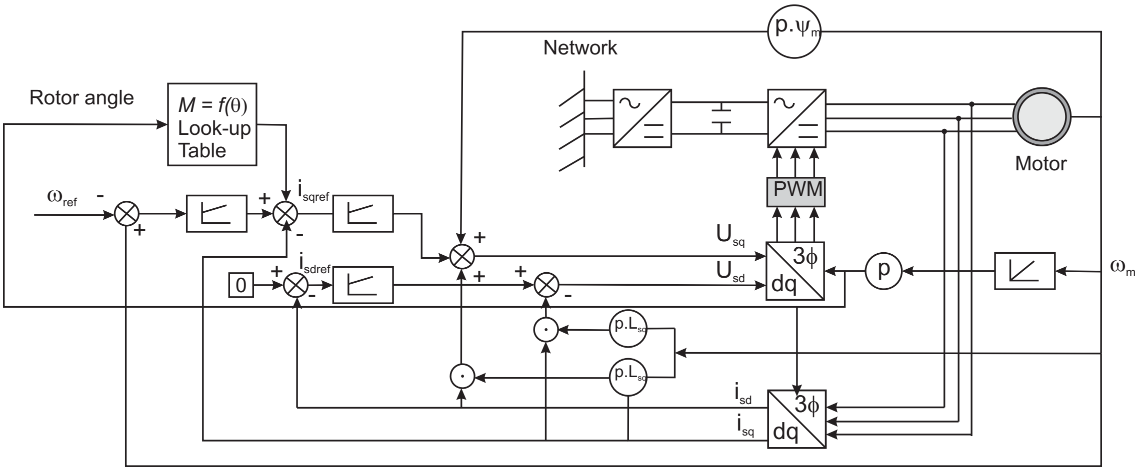

Figure 1.3.: PMSM Torque-Position control

The controller implementation and minimization of torque ripple with the help of adaptive control algorithm is discussed in the paper [26]. This paper also discusses about the experimental results for the controller implementation. The above mentioned solutions to reduce the torque ripple did not discuss about the other operating points. The other operating points are half the rated load and field weakening operation. For industry and automotive applications torque pulsations at these operating points are necessary. Torque pulsation during these operating points is also studied in this work.

Existing rules are summarized in Figure 1.4. In the design methods mentioned in the literature, it ss possible to reduce the cogging torque and torque ripple. But no certain methodological approach based on harmonic contents in the air gap field is provided for the geometries considered. In publications from [62], [63], [64], [65] and [66], the torque pulsation and the responsible harmonics based on 2D harmonic analysis are discussed. But the differences from the mentioned references in using the 2D harmonic analysis in this work is discussed in chapter 4.2.4. In this thesis a step by step approach by considering certain geometries and the influence of harmonics in air gap field for the generation of torque pulsation from these geometries are provided. Based on these analyses, a valid design rule is established for PMSM machines.

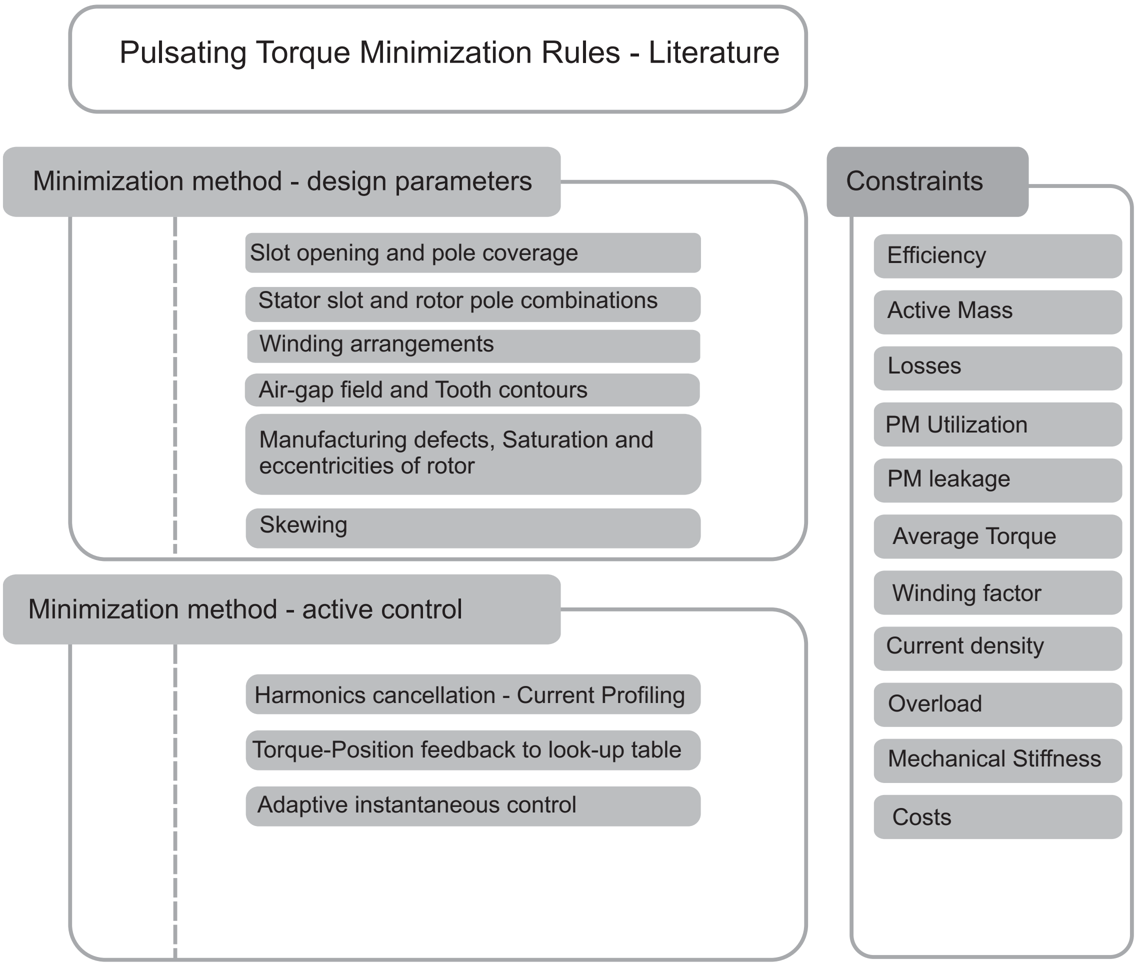

Figure 1.4.: Rules Summary