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Magnetic Forces and Vibration in Wind Power Generators

Analysis of Fractional-Slot Low-Speed PM Machines with Concentrated Windings

Thesis for the degree of Philosophiae Doctor

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PREFACE

This thesis is submitted in partial fulfilment of the requirements for the degree of philosophiae doctor (PhD) at the Norwegian University of Science and Technology (NTNU) in Trondheim.

The PhD work has been carried out at the Department of Electric Power Engineering, between December 2010 and December 2014, with Prof. Arne Nysveen as main supervisor and Prof. Robert Nilssen as co-supervisor.

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ABSTRACT

The PhD research work presented in this thesis deals with radial magnetics forces and vibration in low-speed fractional-slot permanent magnet (PM) machines with concentrated windings. One of the applications of such machines is a direct-drive energy conversion system for wind turbines. Due to the presence of the low spatial harmonic orders in the radial forces distribution, fractional slot machines with concentrated windings can potentially have a higher vibration level than the traditional PM machines.

In order to investigate the magnetic vibration characteristics, flux density distribution is computed using finite element (FE) analysis. Then, the radial and tangential force densities are calculated using the Maxwell stress tensor. Spatial harmonic analysis of the radial force density distribution provides important information regarding the vibration behavior of the machine. The radial force distribution on the stator teeth are calculated and employed as input to a structural FE analysis. In this analysis, deformations in the stator bore due to the exciting magnetic forces are computed. Experimental work is performed on a prototype 120-slot/116-pole PM generator to validate the magnetic and structural simulations.

The influence of pole and slot combinations is investigated by comparing PM machines with 120 slots and 80, 112, 116 and 118 poles. Radial forces and vibration, the cogging torque and the torque ripple characteristics of these machines are studied. The effects of the slot harmonic are investigated in the prototype machine. It is discussed how the vibration behavior is changed in the case of different slot closures. The influence of loading is studied systematically; it is discussed how the *d*-axis and *q*-axis currents change the amplitude of the lowest spatial harmonic of the radial forces, and consequently the vibration level of the prototype machine.

CONTENTS

1

INTRODUCTION

Direct-driven permanent magnet (PM) generators are gaining popularity in the wind power industry, particularly for large offshore wind turbines with high power ratings. An example of such a direct-drive wind turbine is depicted in Fig. 1. In a direct-drive wind energy conversion system, the gearbox is eliminated. Elimination of the gearbox, which has a relatively high failure rate [1], improves the reliability of the conversion system and reduces the maintenance work considerably. This is a distinct advantage particularly in the growing number of offshore wind farms where maintenance operations are difficult, time consuming and expensive. On the other hand, direct-driven wind generators are normally larger and heavier than generators in geared systems. For operation at very low rotational speeds, direct-driven PM wind generators need to have a high number of poles to keep the frequency within a certain range. For a given number of slots per pole per phase (q), a high number of poles requires a large number of slots. As a result, having a high number of poles leads to a very large diameter for low-speed PM machines (e.g. direct-driven generators). In order to reduce the diameter of these machines, it can be beneficial to utilize non-overlapping concentrated windings. Since fractional-slot machines with concentrated windings have a low q, the number of slots can be kept relatively low. This is favorable in applications where a high number of poles is needed and the pole pitch is small.

In a variety of applications, fractional-slot PM machines with concentrated windings are becoming an attractive alternative due to several advantages (such as short end-windings, high fault-tolerant capability, low cogging torque) they have over traditional PM machines with distributed windings [2]. However, the main drawback of PM machines with concentrated windings is the high level of rotor losses and vibration. Rotor eddy current

Fig. 1. Siemens 6-MW direct drive offshore wind turbine. Source: Siemens D6 offshore brochure.

loss is high due to the rich spatial harmonic content of the magnetomotive force (MMF) produced by stator windings. The vibration level of these machines can be considerably higher than traditional PM machines, mainly due to the presence of the low spatial harmonic orders in the radial magnetic force distribution. Because of the high number of poles in low-speed PM machines, the diameter of the machine is large while stator yoke is relatively thin. As a result, low-speed PM machines normally have a moderate stator mechanical stiffness and therefore, magnetically induced vibration can be more critical. It is worth mentioning that having a higher vibration level requires stronger structural support for the generator and consequently increases the weight and the cost of the supporting structure. This is not favorable in large offshore wind turbines where weight reduction is important.

The above-mentioned introduction clarifies the motivation for the PhD research work presented in this thesis; magnetic vibration is a key issue in low-speed large PM generators with concentrated windings and needs to be studied. The prototype machine under investigation is a low-speed 120-slot/116-pole PM machine with single-layer concentrated windings. It was designed and prototyped as a down-scaled wind generator in a previous PhD project [3].

1.1 Objectives and Scope of the Work

The main objective of the PhD project is to investigate the radial magnetic forces and resulting vibration in low-speed PM wind generators. The work is focused on radial-flux iron-cored surface-mounted PM machines. The project is a part of a research program founded by Norwegian Research Centre for Offshore Wind Technology (NOWITECH). The main application is therefore offshore wind power. It should be noted, though, that the outcome of the research work is generally applicable to low-speed fractional-slot large PM machines with concentrated windings.

This research work aims to study what factors affect the magnetic vibration and how it is possible to reduce the vibration level. The main focus is on analysis of the radial magnetic forces while the link between the magnetic forces and vibration is well-described. It has not been within the scope of this PhD project to study the mechanical aspects in detail. In addition, the study of acoustic noise generated by the machine has not been within the scope of this research. In most cases, for the comparison of the vibration levels, the magnitude of the lowest spatial harmonic order in the radial force distribution is compared and no structural analysis is performed to estimate the vibration level. The presented three-dimensional structural finite element (FE) analysis is carried out in collaboration with a mechanical engineering expert.

While several types of electrical machines can be used as wind generators, only radial-flux iron-cored surface-mounted PM machines are investigated in this thesis. It has not been within the scope of work to investigate the vibration characteristics of other types of machines. The existing prototype PM generator has been the basis for simulations and analysis of the magnetic forces and vibration. Magnetic forces are calculated based on the Maxwell stress tensor method. In this method, radial and tangential forces are calculated using the radial and tangential components of magnetic flux density in the airgap. FE analysis is employed to obtain the magnetic field distribution in the airgap with a high accuracy, both in the orders of the spatial harmonics and in their amplitudes. It has not been within the scope of this research work to develop an analytical model to calculate the field distribution.

1.2 Background

Noise and vibration in rotating electrical machines can be of mechanical, aerodynamics and magnetic origin. Magnetic vibration is mainly generated by radial magnetic forces.

Radial force waves, which are functions of both time and space, cause deformations in the stator bore. The deformation amplitude is inversely proportional to the mode number (i.e. spatial harmonic order) in the radial force distribution [4]. This means that if radial force distribution contains low order spatial harmonics with considerable amplitude, the vibration level will be substantially higher.

It has been addressed in the previous research works that the vibration level of fractional-slot PM machines with concentrated windings can be considerably higher than the traditional machines with distributed windings. This is because the amplitude of the low spatial harmonic orders in radial force density can be relatively large in fractional-slot PM machines.

As previously mentioned, having low order harmonics in the radial force distribution leads to a high vibration level. The order of the lowest spatial harmonic is equal to the greatest common divisor (GCD) of the pole and slot numbers. Therefore, in PM machines where q is equal to 1 and 0.5, the lowest harmonic order is $2p$ and p, respectively (p denotes the number of pole pairs). In contrast, for fractional-slot PM machines with concentrated windings where q is lower than 0.5, the order of the lowest harmonic order can be considerably lower (e.g. 1 or 2) [5]. The difference between the above-mentioned PM machines from a vibration perspective is clearer in low-speed machines where the number of poles is high.

Previous research works regarding the vibration of PM machines with concentrated windings have mainly focused on relatively small machines, mostly 12-slot/10-pole machine. In these studies, the machines under investigation normally have semi-closed slots. As a result, the effects of the slot harmonic are not clear. In [6], an analytical model is developed for calculation of the radial forces in PM machines and the focus is on 12-slot/10-pole configuration. It is shown that the lowest spatial harmonic (i.e. 2 for 12-slot/10-pole machine) exists at no-load but its amplitude is relatively small and almost negligible. In the load condition, on the other hand, the amplitude of the 2nd harmonic is relatively high, due to the interaction between the PM field and MMF field. Moreover, it is concluded in [6] that the contribution from the tangential component of the flux density can be neglected in the calculation of the radial forces, because the tangential airgap flux density is usually small.

This PhD research work investigates the magnetic forces and vibration in low-speed large PM machines. It is common for these machines to have open slots. Hence, the effects of slotting are more significant. It is shown that the amplitude of the lowest spatial harmonic is considerable even at no-load, leading to a relatively high vibration level. It is found that the slot harmonic plays the major role in vibration behavior of the low-speed PM machines both in no-load and load conditions. Furthermore, the effects of loading are systematically studied, investigating the interaction between the PM and MMF fields. It is also addressed that due to a relatively large tangential flux component in large PM machines with open slots, its contribution should be neglected in the calculation of the radial forces. In this research work, the influence of pole and slot combination on the radial forces is also investigated. In low-speed PM machines with a high number of poles, there is more freedom to choose the right pole and slot combination in order to reduce the vibration level.

1.3 Outline of the Thesis

This PhD thesis is organized in two parts. The first part is an introduction to the concept and a summary of the scientific contributions. The second part consists of three papers, two published in *IEEE Transactions on Magnetics* and one published in *IEEE Transactions on Industry Applications*. The chapters in the first part of the thesis are kept brief, providing the key concepts, choices and a summary of the research results and major findings. The main scientific contributions, simulations and experimental results, detailed analysis and discussions are all presented in the appended papers.

The first part of the thesis is outlined as follows.

Chapter 2 presents an introduction to magnetic vibration of electrical machines. The vibration problem of the fractional-slot PM machines with concentrated windings is also highlighted in this chapter.

Chapter 3 briefly discusses the electromagnetic and structural simulations, as well as the experimental work. A summary of the research results and major findings is presented in this chapter.

Chapter 4 includes the concluding remarks and proposals for future research works.

1.4 Scientific Contributions

The main contributions presented in this thesis are listed as follows:

- [*Paper* I]: The influence of pole and slot combinations on radial forces and vibration in low-speed PM generators is discussed. Low-speed PM machines with 120 slots and 112, 116 (i.e. prototype generator) and 118 poles are studied.

Cogging torque waveforms and torque ripple characteristics are also compared. It is concluded that it is possible, in the design stage of the machine, to choose the right combination of the pole and slot numbers, in order to reduce the vibration level substantially. Meanwhile, the cogging torque, which is greatly influenced by the pole and slot combination, can be kept extremely low (practically zero). Among the machines under investigation, the 120-slot/112-pole machine has the lowest level of vibration while all three machines have almost the same level of torque ripple.

- [*Paper* I]: A three-dimensional structural FE analysis is employed to compute the resonance frequencies of the prototype PM generator, with and without structural support. The structural model is also used for computation of the maximum displacement amplitude in the stator, considering the structural support. In this case, the computed radial magnetic forces in the electromagnetic simulations act as the exciting forces in the structural simulation.

- [*Paper* I]: Experimental work is presented for the prototype generator at no-load. Accelerometers are mounted on the surface of the stator structural support. The main vibration frequency (i.e. twice the electrical frequency) is identified at different operational speeds, showing that the vibration is mainly due to the magnetic forces. The maximum deformation in the stator due to the vibration is measured, verifying that there is good agreement between the simulated and experimental results.

- [*Paper* I]: The lowest mode of vibration (i.e. 4th spatial harmonic for prototype generator) is observed experimentally at no-load. To visualize a quarter of the 4th mode shape, a waveform is drawn representing a rough approximation of the spatial distribution of the displacement amplitude.

- [*Paper* II]: The influence of the slot harmonic on radial forces and vibration is discussed. It is shown that in the prototype machine, the lowest spatial harmonic in radial forces exists even at no-load with considerable amplitude, leading to a relatively high vibration level. It is addressed that in large PM machines, where it is common to have open slots, the effect of slotting can be significant.

- [*Paper* II]: It is shown how the lowest mode of vibration is produced at no-load. The contribution of different flux density harmonics to produce the 4th spatial harmonic order in radial force distribution is analyzed. It is concluded that the interaction between the main harmonic of the flux density and the slot harmonic is the main factor in producing the lowest mode of vibration.

- [*Paper* II]: The effect of different slot closure on the radial forces is investigated. It is shown that in the case of semi-closed slots, the vibration level is much lower. However, the electromagnetic torque is also reduced considerably. It is shown that for large PM machines, the use of magnetic wedges can be beneficial to reduce the vibration level, by reducing the effect of slotting. Meanwhile, it is possible to maintain the torque level as high as the case of open slots.

- [*Paper* III]: The effects of loading on the radial forces and vibration are investigated for the prototype machine. A systematic approach is presented to study how the amplitude of the lowest mode of vibration changes with *d*-axis and *q*-axis currents.

- [*Paper* III]: It is found that the interaction between the main flux density harmonic and the slot harmonic is the main factor to produce the lowest mode of vibration in all loading cases. In addition, it is shown that the reason for changes in the vibration level is the changes in the amplitude of the slot harmonic which is heavily affected by loading.

- [*Paper* III]: Experimental tests are carried out in different loading conditions (i.e. resistive, capacitive and inductive). The measured vibration level is compared in different loading cases. It is shown that there is a good agreement between the simulation and experimental results.

- [*Papers* II & III]: It is concluded that the slot harmonic is the main factor in the vibration behavior of the low-speed open-slot PM machine, both in no-load and loading cases.

1.5 List of Publications

The following journal papers are included in the second part of this thesis.

- [*Paper* I] M. Valavi, A. Nysveen, R. Nilssen, R. D. Lorenz, and T. Rølvåg, "Influence of pole and slot combinations on magnetic forces and vibration in low-speed PM wind generators," *IEEE Transactions on Magnetics*, vol. 50, no. 5, p. 8700111, May 2014.

  In this paper, radial forces and torque ripple characteristics are investigated in permanent magnet machines (PM) having different pole and slot combinations. PM machines with concentrated windings having a large number of poles are compared to investigate the effect of pole and slot combinations on force and vibration characteristics in low-speed generators. Cogging torque waveforms and torque ripple are investigated using time-stepping finite-element analysis. Analysis of radial forces is presented including investigation on radial force density distribution, total forces on teeth and time-dependent force waveforms on a tooth. Structural analysis and experimental modal analysis are performed on the prototype generator. The main mode of vibration in the prototype machine is observed experimentally and results are in good agreements with the simulations.

- [*Paper* II] M. Valavi, A. Nysveen, R. Nilssen, and T. Rølvåg, "Slot harmonic effect on magnetic forces and vibration in low-speed permanent-magnet machine with concentrated windings," *IEEE Transactions on Industry Applications*, vol. 50, no. 5, pp. 3304–3313, Sept./Oct. 2014.

  In this paper, the influence of slot harmonics on magnetic forces and vibration is studied in a 120-slot/116-pole low-speed PM machine at no-load. It is shown how the lowest mode of vibration is produced at no-load due to the slotting. Comparing the cases of open slots, semi-closed slots and magnetic wedges, the effect of slot closure on radial forces and torque production capability is discussed. Magnetic flux distribution in the airgap is computed using finite element analysis. Spatial harmonics due to slotting are investigated in different cases. Maxwell's stress tensor is employed to calculate radial and tangential components of the force density in the airgap. Spatial distribution of the total forces on the teeth and also time-dependent force waveform on one tooth are analyzed and discussed for different cases. It is shown how the magnitude of the lowest mode of vibration is reduced in the case of using semi-closed slots and magnetic wedges. Tangential force density distribution and torque production capability are also discussed. Structural analysis is presented to compute the maximum amplitude of the stator deformations due to the radial forces. Experimental results of the prototype generator are presented verifying the existence of the lowest mode of vibration at no-load because of the slot harmonic.

- [*Paper* III] M. Valavi, A. Nysveen and R. Nilssen, "Effects of loading and slot harmonic on radial magnetic forces in low-speed permanent magnet machine with concentrated windings," *IEEE Transactions on Magnetics*, vol. 51, no. 6, p. 8105310, June 2015.

> *This paper investigates the effects of loading on radial magnetic forces and vibration in a low-speed permanent magnet machine with non-overlapping concentrated windings. Magnetic flux density distribution in the airgap of a 120-slot/116-pole machine is computed using finite element method. Maxwell's stress tensor method is then employed to calculate radial and tangential forces in the airgap. Flux density, radial and tangential force distributions are studied in different loading conditions and the effect of d-axis and q-axis currents are investigated. It is shown how the lowest mode of vibration is produced by different harmonic pairs in the flux density. It is found that d-axis current can significantly change the amplitude of the lowest spatial harmonic of radial force distribution and consequently the vibration behavior. The main reason is found to be the changes in the amplitude of the slot harmonic which is heavily affected by loading. Experimental tests are carried out to compare the vibration level of a PM generator supplying resistive, inductive and capacitive loads. There is a good agreement between simulations and experimental results.*

The following is a list of papers presented in IEEE sponsored conferences during the PhD research work. These papers are not appended to this thesis. Either because they are outside the scope of the thesis or their content is extended and included in the journal papers.

- [*Paper* IV] M. Valavi, A. Nysveen and R. Nilssen, "Magnetic forces and vibration in permanent magnet machines with concentrated windings: a review," in *Proc. IEEE ICIT*, Mar. 2012, pp. 977–984.

- [*Paper* V] M. Valavi, A. Nysveen and R. Nilssen, "Characterization of radial magnetic forces in low-speed permanent magnet wind generator with non-overlapping concentrated windings," in *Proc. ICEM*, Sep. 2012, pp. 2943–2948.

- [*Paper* VI] M. Valavi, A. Nysveen and R. Nilssen, "Analysis of a low-speed PM wind generator with concentrated windings in eccentricity conditions," in *Proc. ICEMS*, Oct. 2013, pp. 1266–1270.

- [*Paper* VII] M. Valavi, A. Nysveen and R. Nilssen, "Influence of slot harmonics on radial magnetic forces in low-speed PM machine with concentrated windings," in *Proc. ICEMS*, Oct. 2013, pp. 535–538.

- [*Paper* VIII] A. Matveev, M. Valavi, A. Nysveen and R. Nilssen, “Permanent magnet generator with three stators for renewable energy converters,” in *Proc. INTERMAG*, May 2014.

- [*Paper* IX] M. Valavi, A. Nysveen and R. Nilssen, “Effects of loading on magnetic forces in low-speed PM machine with concentrated windings,” in *Proc. ICEM*, Sep. 2014, pp. 1128–1132.

- [*Paper* X] M. Valavi, A. Matveev, A. Nysveen and R. Nilssen, “Multiple-airgap iron-cored direct-driven permanent magnet wind generators,” in *Proc. ICEM*, Sep. 2014, pp. 578–584.

2

Magnetic Vibration of Rotating Electrical Machines

There are three types of sources for noise and vibration in rotating electrical machines. Noise can be of mechanical, aerodynamics and electromagnetic origin. Mechanical noise is associated with the mechanical assembly of the machine, in particular bearings [4]. Aerodynamic noise is caused by the air flow, mainly due to the ventilation system [4]. Noise of magnetic origin in electrical machines is mainly caused by the magnetic forces. Radial force waves act on the stator, causing deformations and producing vibrations.

Due to the vibration of the stator frame, the surrounding air is also excited to vibrate and acoustic noise is generated. The frequency range of the sound waves which can be heard by human is approximately between 16 and 20,000 Hz [4]. At each frequency, the sound intensity should be sufficiently high to be heard by human. The minimum sound intensity is different at the various frequencies and is called the threshold of audibility. Humans are most sensitive to frequencies between 1000 and 5000 Hz (i.e. able to recognize at the lowest intensity) [7]. This clarifies an important difference between the analysis of vibration and the acoustic noise; a magnetic force wave can cause a substantial vibration, but not much acoustic noise because its frequency is not in the mentioned range of best heard frequencies by the human ear. As will be discussed later in this chapter, the frequency of the fundamental magnetic force waves is twice the electrical frequency, i.e. 100 Hz in the case of a 50 Hz machine. This frequency is considered low for the human ear and consequently a 100 Hz vibration does not generate considerable noise, even if the amplitude of the stator displacements is relatively high. On the other hand, force waves of higher frequencies can produce audible noise with much smaller amplitudes. In an example presented in [7], it is shown that a magnetic force wave with a frequency of approximately 3500 Hz produces much higher noise level than a 100 Hz force wave of the same spatial mode, even though its amplitude is 70 times lower.

Both mechanical and aerodynamic noises increase with the rotor speed. They are therefore more important at high rotor speeds. The magnetic noise is generally the most important source of noise at low rotational speeds [7].

In addition to the radial magnetic forces, magnetostrictive forces could also contribute to produce magnetic noise. Magnetostriction is a property of ferromagnetic materials so that their shape and dimensions change when exposed to a magnetic field. It is the major cause of the acoustic noise in transformers. In rotating electrical machines however, the magnetostrictive forces and resulting vibration are usually neglected [4, 7].

The focus of this research work is on the radial magnetic forces and the resulting vibration. It has not been within the scope of the work to study the acoustic noise. As mentioned before, there are some force waves which are most important from the vibration perspective, but are almost negligible in terms of acoustic noise.

2.1 Maxwell Stress Tensor

There are different methods for the calculation of the force and torque in rotating electrical machines. Virtual work method and Maxwell stress tensor are usually used to compute the magnetic forces [8].Maxwell stress tensor is often employed to calculate the radial vibration forces and estimate the noise and vibration characteristics of the machine [4, 7]. It has been used widely as the main method for the analysis of radial forces and vibration in different types of electrical machines, including induction [e.g. 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19] and PM machines [e.g. 5, 6, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31].

Using the Maxwell stress tensor, radial and tangential components of force density in the airgap of the electrical machine can be calculated as [6, 24]:

$$f_r = \frac{1}{2\mu_0}({B_r}^2 - {B_t}^2) \tag{1}$$

$$f_t = \frac{1}{\mu_0}(B_r B_t) \tag{2}$$

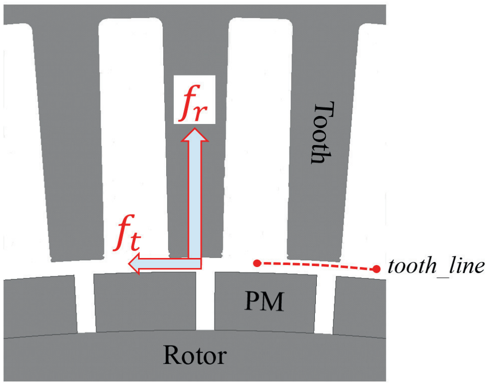

Fig. 2. Radial and tangential components of magnetic force.

where f_r and f_t denote the radial and tangential components of the force density (as depicted in Fig. 2) and B_r and B_t represent the radial and tangential components of the magnetic flux density in the airgap. All four quantities are functions of time and space. The tangential component of force creates useful electromagnetic torque, whereas the radial component may cause undesirable vibration. It is very common in the literature to neglect the contribution from tangential flux density in (1), assuming that the radial component is much larger than the tangential component of flux density [4, 7].

Using the radial force density distribution in the airgap, the following equation can be employed to calculate the total force acting on the stator teeth [20, 32, 33]:

$$F_{tooth} = L_s \int_{tooth\_line} f_r \, dl \tag{3}$$

where L_s is the stator stack length. The force on each tooth is calculated using the line integral over the tooth, as shown in Fig. 2.

2.2 Magnetic Field Distribution

As mentioned in the previous section, the Maxwell stress tensor method is used to calculate the radial forces. For analysis of the radial forces, according to (1), radial and tangential components of the flux density distribution in the airgap need to be computed first. Both analytical methods and FE analysis can be employed for field calculations.

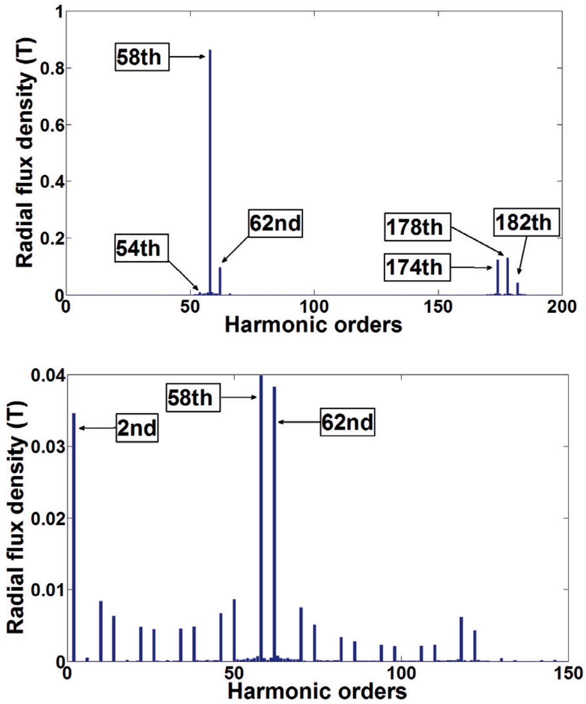

Fig. 3. Spatial harmonic content of flux density distribution for prototype 120-slot/116-pole machine due to the PM field (top) and MMF field at rated load (bottom).

However, FE analysis provides more precise results, specifically for the amplitude of the spatial flux harmonics. The accuracy of the field calculation method significantly affects the accuracy of the estimation of the radial forces and resulting vibration. Hence, in this PhD research work, FE analysis is used for precise computation of the field distribution in the machine.

In PM machines, the distribution of the flux density in the airgap is due to the permanent magnets (i.e. no-load field distribution) and stator currents (i.e. MMF). In surface-mounted PM machines with a relatively large airgap, the flux density is mainly produced by the permanent magnets and there is no substantial armature effect. This means that the field produced by the permanent magnets is much stronger than the field produced by MMF. This can be observed in Fig. 3.

Flux density harmonics produced by the permanent magnets are shown in Fig. 3 (top). The order of the main spatial harmonic at no-load is the pole pair number (i.e. 58th harmonic in 116-pole PM machine). The 62nd harmonic order (i.e. slot harmonic), which has a relatively large amplitude, is produced by slotting. The spatial order of this slot harmonic is the difference between the number of slots and the number of pole pairs. As discussed in *Paper II*, the slot harmonic has a significant impact on the radial force distribution in the prototype machine. Details regarding the flux density harmonics at no-load are presented in *Paper II.* Fig. 3 (bottom) shows the spatial harmonics produced by the MMF. As it is evident in the figure, the MMF field contains a high level of the spatial harmonics. In addition to the main harmonic (i.e. 58th), the lowest-order sub-harmonic (i.e. 2nd) and the slot harmonic (i.e. 62nd) have relatively large amplitudes. Details regarding the MMF harmonics and the interaction between MMF and PM fields are presented in *Paper III*.

2.3 Radial Magnetic Forces

The magnetic vibration of electrical machines is mainly caused by radial forces. The radial force density in the airgap can be expressed in the following general form:

$$f_r(\theta, t) = f_{rm} \cos(m\theta - k\omega t) \tag{4}$$

where θ and t denote the angular mechanical position and time, k is the time harmonic order, ω is the angular velocity and m represents the spatial harmonic order which is also called the mode number. As it will be discussed later in this chapter, the amplitude of the deformations in the stator bore, caused by the magnetic force waves, is inversely proportional to m^4; hence, the low modes of vibration can be more critical. In addition, if the low modes of vibration are excited by the magnetic forces, the natural frequencies can be in the range of the rotor speed and resonance is more likely to occur. Consequently, it can be concluded that the dominant vibration mode is generally the lowest mode.

In order to investigate the vibration characteristics of electrical machines, the most important parameter is the mode number (i.e. spatial order of the force wave) because it affects the mechanical response and deformation modes of the stator.

There are two special cases with respect to the mode number: If $m = 0$, there is uniform attraction between the stator and rotor along the airgap and if $m = 1$, it means that the force distribution along the airgap is not symmetric and there is a rotating point of

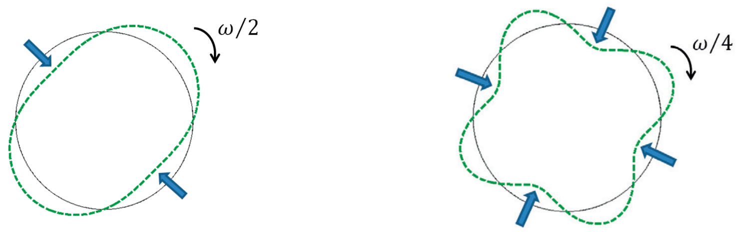

Fig. 4. Stator deformations for $m = 2$ (left) and $m = 4$ (right).

maximal attraction. In this case, unbalanced magnetic forces are generated which can be dangerous for the machine. This is also the case when eccentricity exists.

For $m \geq 2$, there are m points of maximal attraction between the rotor and stator and the force distribution is symmetric. Fig. 4 shows the mode shapes for $m = 2$ and $m = 4$ as well as their rotational speeds. The radial force waves rotate at angular speed of ω/m [4, 7].

As mentioned earlier, the lowest spatial harmonic order in radial force density distribution is the most important from a vibration perspective because it causes the largest displacement in the stator bore. The order of this spatial harmonic (i.e. lowest mode of vibration) can be recognized using the GCD (greatest common divisor) of the number of slots and number of poles. The lowest spatial harmonic in the magnetic flux density, h, is the GCD of the number of slots and the number of pole pairs. According to (1), the lowest spatial harmonic in the radial force density is $2 \times h$, i.e. the GCD of the number of slots and the number of poles. Therefore, PM machines with very low GCD could potentially have a high vibration level. PM machines with non-overlapping concentrated windings have a relatively low GCD because the number of poles and slots are close to each other.

The influence of the pole and slot combination on the lowest spatial harmonic order in radial force density can be seen in Fig. 5, where spatial harmonic orders depicted are for 120-slot/116-pole and 120-slot/118-pole PM machines. According to the figure, for the 120-slot/116-pole PM machine, the lowest mode is 4 (i.e. GCD of 120 and 116) and for the 120-slot/118-pole machine, the lowest spatial harmonic is 2 (i.e. GCD of 120 and 118). The largest harmonic order (116th for 116-pole and 118th for 118-pole machines) is the main harmonic order of the radial force density. According to (1), its order is twice the order of the main harmonic of flux density, i.e. the number of poles.

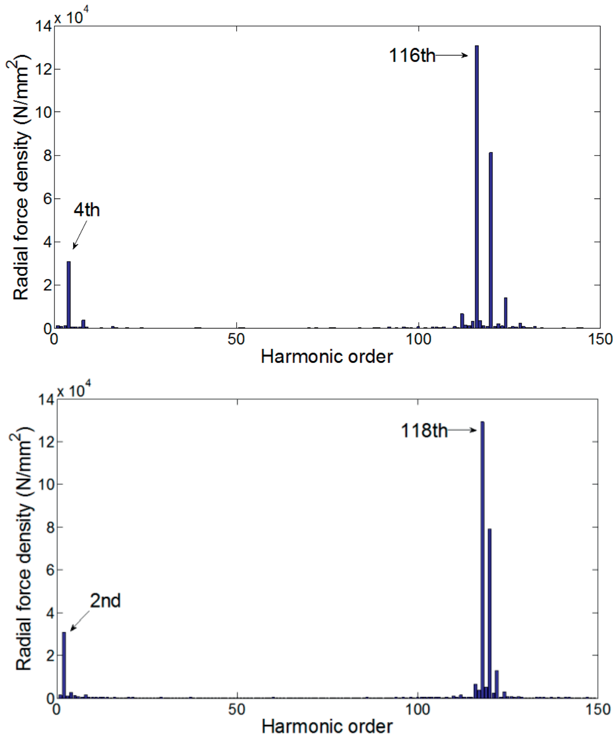

Fig. 5. Spatial harmonic content of radial force density distribution at no-load for 120-slot/116-pole (top) and 120-slot/118-pole (bottom) PM machines.

Fig. 6 presents the force distribution on all 120 teeth for both PM machines. This figure illustrates that the lowest spatial harmonic of the radial force density shapes the total force distribution on the teeth. The lowest mode of vibration shown in Fig. 5 can be clearly observed in the force distribution depicted in Fig. 6.

The magnetic vibration behavior of electrical machines is basically characterized by the spatial harmonic orders of radial force density distribution in the airgap. Different spatial harmonics of radial force are produced by the interaction between different spatial harmonics in the flux density distribution. The pole and slot combination, the MMF

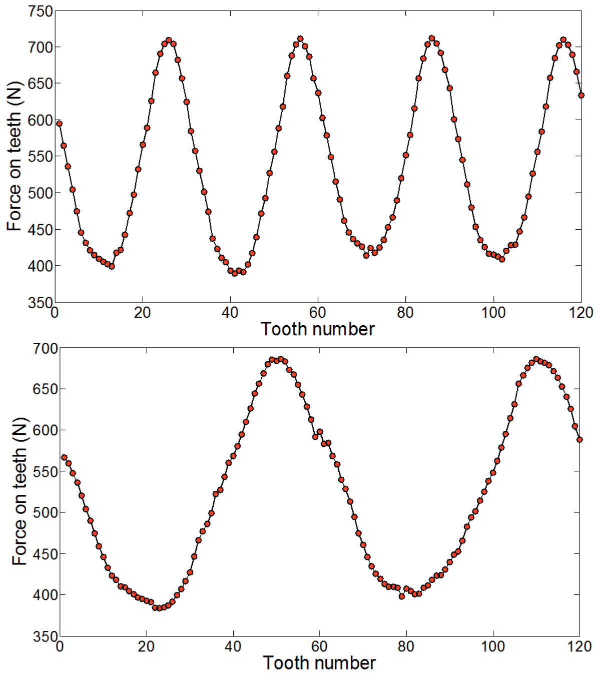

Fig. 6. Radial force spatial distribution on the teeth at no-load for 120-slot/116-pole (top) and 120-slot/118-pole (bottom) PM machines.

harmonic content, the slot openings, magnetic saturation and eccentricity can all affect the magnetic vibration [4].

2.4 Mechanical Considerations

In most cases, vibration calculation of electrical machines must be carried out using three-dimensional FE structural analysis. In order to estimate the vibration level of the machine, the structural support should also be considered. The structural support has substantial influence both on the resonance frequencies and the amplitude of the displacements in the stator. Therefore, a simple analytical model is not usually sufficient for the vibration calculation of the electrical machine. However, it is important to understand how different modes of radial forces produce displacement in the stator bore.

Mechanical considerations should be taken into account when investigating the radial magnetic forces. For this purpose, a few simple structural equations are presented in this section.

Assuming the sinusoidal distribution of the radial force waves according to (4), the relation between the mode number (m) and amplitude of static deformations of the stator bore for $m \geq 2$ can be expressed as [7]:

$$Y_{ms} = \frac{K_s\, f_{rm}}{(m^2 - 1)^2} \tag{5}$$

where Y_{ms} is the amplitude of the static deformation caused by mode m of radial force distribution, K_s is a coefficient determined by dimensions and structural properties of the stator bore and f_{rm} is the amplitude of mode m in radial force density distribution. In the calculation of static deformations, the influence of resonance is not considered.

According to (5), the amplitude of the deformations is heavily affected by the mode number. For the two PM machines mentioned previously in this chapter, the amplitude of the lowest mode (i.e. 4 for 120-slot/116-pole and 2 for 120-slot/118-pole machines) is almost the same. The stators in these two machines are identical. The displacement in the stator caused by the magnetic forces is very different though, because of the mode number. For the 116-pole machine, $Y_{4s} = 1.42 \times 10^8\, K_s$, and for the 118-pole machine $Y_{2s} = 3.55 \times 10^9\, K_s$. It means that the amplitude of the displacement caused by the 2nd mode is 25 times higher than the 4th mode. It clarifies the importance of the lowest mode of vibration. Higher the order of the lowest mode of vibration, lower the vibration level.

The parameter K_s which was introduced in (5), can be calculated as follows [7]:

$$K_s = \frac{12\, R\, R_y^3}{E\, T_y^3} \tag{6}$$

where R is the internal radius of the stator, R_y is the yoke average radius, T_y is the yoke radial thickness and E is the elasticity coefficient or Young’s modulus. Geometrical parameters introduced in this equation are shown in Fig. 7, where the stator of the prototype 120-slot/116-pole PM machine is depicted.

Looking into (6), it is possible to understand how the geometrical properties of stator affect the vibration level. A higher K_s means a larger Y_{ms} which means a higher vibration level. Based on (6), the amplitude of the stator deformations is proportional to the diameter of the machine and is inversely proportional to the yoke thickness. In low-speed PM

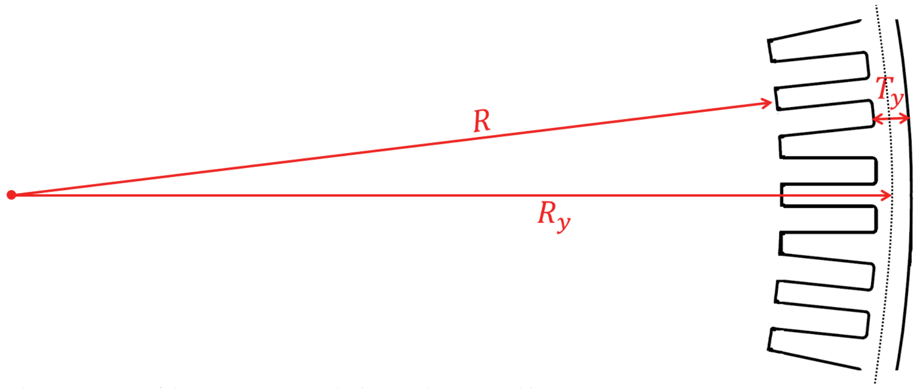

Fig. 7. Stator of the prototype 120-slot/116-pole PM machine.

machines with a high number of poles, the yoke thickness is normally relatively small and the diameter is relatively large. As a result, the same radial force wave can cause much larger deformations in such low-speed machines, compared to machines with a relatively low number of poles. This illustrates the importance of magnetic vibration for low-speed PM machines.

If an exciting force frequency is close to a resonance frequency of the machine structure, the amplitude of vibration could increase substantially. Values of resonance frequencies for each vibration mode must normally be computed using numerical methods and considering all structural details. Simple analytical approaches, however, can be used to understand the relation between the resonance frequencies and mode number. Based on the theory presented in [4, 7], the resonance frequency for mode m is proportional to the following term:

$$f_m^{res} \propto \frac{m\,(m^2-1)}{\sqrt{m^2+1}} \tag{7}$$

This means that the natural frequency increases with the mode number. As a result, if low modes of vibration are excited (this is the case for fractional slot machines with concentrated windings), the corresponding resonance frequencies could be sufficiently low to be in the range of the rotor speed and cause resonance vibration. This also explains the importance of the low modes of vibration.

2.5 Problem of Vibration in Fractional-Slot PM Machines with Concentrated Windings

This section briefly discusses the problem of vibration in PM machines with non-overlapping windings, addressing their higher vibration level compared to the traditional machines. Some previous research works regarding radial forces and vibrations in these machines are also reviewed in this section.

As discussed in the previous section, the lowest mode in the radial force spatial distribution is the most important factor to characterize the vibration behavior of the machine. If low modes of vibrations are excited, the vibration level would be relatively high because these low-order spatial force harmonics may cause much larger deformations in the stator, compared to high-order harmonics. As will be discussed later in this section, several research works have addressed that the vibration level of fractional-slot PM machines with concentrated windings can be substantially higher than traditional PM machines. This is mainly due to the fact that the radial force density distribution of these machines contains low-order spatial harmonics. As mentioned earlier, the order of the lowest mode of vibration is equal to the GCD of the pole and slot numbers. In fractional-slot machines with concentrated windings, since the number of poles and slots are close to each other, the GCD is relatively low.

In PM machines where q is equal to 1 and 0.5, the lowest harmonic order of radial forces is equal to the number of poles and the number of pole pairs, respectively. In contrast, for fractional-slot PM machines with concentrated windings where q is lower than 0.5, the order of the lowest harmonic order can be considerably lower (e.g. 1 or 2).

In [22], the mode orders of radial force distribution and vibration level are compared for 18-slot/6-pole ($q = 1$), 9-slot/6-pole ($q = 0.5$), 12-slot/8-pole ($q = 0.5$), 15-slot/10-pole ($q = 0.5$) and 12-slot/10-pole ($q = 0.4$). It is shown that for the traditional 18-slot/6-pole machine where q is equal to 1, the vibration level is substantially lower than other fractional-slot machines. Here the 12-slot/10-pole PM machine (lowest mode is 2) has the highest vibration level.

In [30], it is discussed that due to the presence of a large number of space harmonics in the MMF waveform, it is more likely that low modes of vibration are excited in the fractional-slot machines with concentrated windings, leading to a higher vibration level. Radial forces and vibration characteristics of a 24-slot/22-pole machine are investigated in detail. It is concluded that the vibration level at full-load can be significantly higher than no-load, due to interaction between MMF and PM field harmonics. Fig. 8 shows the radial

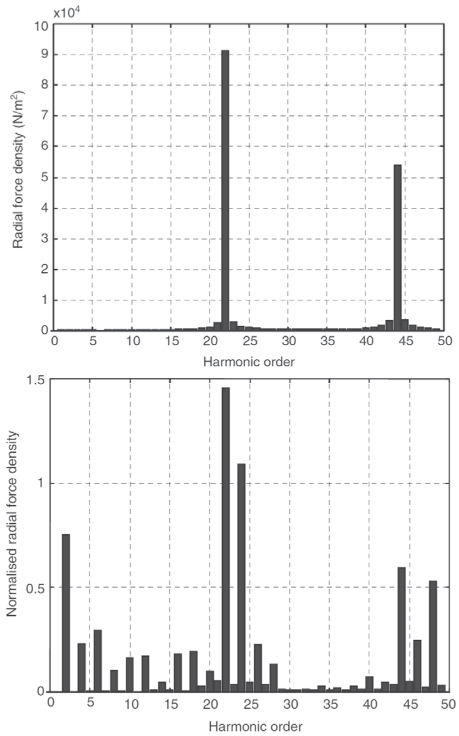

Fig. 8. Space harmonics in radial force distribution of a 24-slot/22-pole PM machine at no-load (top) and full-load (bottom) [30].

force density harmonics at no-load and full-load as presented in [30]. As can be seen in the figure, the 2nd harmonic in the radial force density has relatively large amplitude at full-load (and not at no-load), leading to a higher vibration level. It should be noted that the machine under investigation in [30] has semi-closed slots and as a result, the effect of slot harmonics is not considerable.

In [5], the influence of pole and slot combinations on radial forces and vibration modes is discussed. PM machines with different pole and slot combinations are studied. It is addressed that the dominant vibration mode in PM machines having $q = 1$ and $q = 0.5$ is equal to pole number and pole pair number, respectively. For fractional-slot machines having $q < 0.5$, it is shown that the lowest mode can be as low as 1 or 2 and consequently the vibration level can be significantly higher. It is also pointed out that the lowest mode of

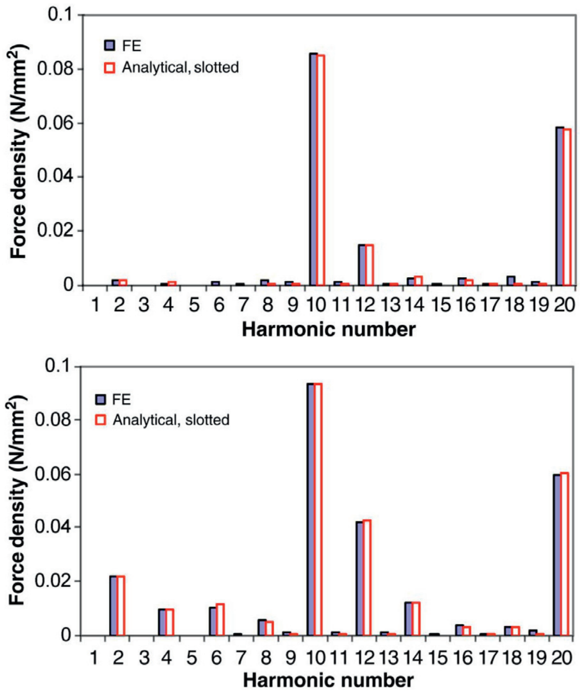

Fig. 9. Radial force density harmonics of 12-slot/10-pole machine at no-load (top) and full-load (bottom) [6].

vibration in 12-slot/10-pole machine (i.e. 2nd spatial harmonic) is produced at the load condition, as a result of the interaction between the MMF and PM field harmonics. It should be mentioned that the machines under investigation in [5] all have semi-closed slots and the effect of slotting is not substantial.

In [31], radial force density distribution is studied for a 12-slot/10-pole machine with concentrated windings. It is shown that the very strong 2nd force harmonic is excited in this machine, mainly due to interaction between the MMF and PM field harmonics, leading to a high vibration level.

In [6], an analytical model is developed for analyzing radial forces in fractional-slot PM machines and the focus is on 12-slot/10-pole configuration with semi-closed slots. It is shown that the lowest spatial harmonic (i.e. 2 for 12-slot/10-pole machine) exists at no-load but its amplitude is relatively small and almost negligible. In the load condition, on the other hand, the amplitude of the 2nd harmonic is relatively high, due to the interaction between the PM field and the MMF field. Fig. 9 compares the radial force density distribution presented in [6] in no-load and load conditions. Moreover, it is concluded in [6] that the contribution from tangential component of the flux density can be neglected in the calculation of the radial forces, because the tangential airgap flux density is usually small.

In [25], magnetic forces on the stator teeth and resulting displacement are calculated for four different PM machines (i.e. 12-slot/10-pole, 9-slot/6-pole, 27-slot/6-pole and 12-slot/8-pole). It is shown that 12-slot/10-pole machine has the highest vibration level. In addition, it is addressed the lowest mode of vibration in 12-slot/10-pole machine is amplified at full-load.

In the previous research works, the analysis of the magnetic forces and vibration is mostly presented for small PM machines with a low number of poles and semi-closed slots where the influence of slot harmonics is reduced significantly compared to large PM machines with open slots. Moreover, the effects of loading on radial forces have not been systematically investigated in the literature, specifically in the presence of a strong slot harmonic. In this thesis, radial forces and vibration are studied for a low-speed fractional-slot PM machine with open slots and influence of pole and slot combinations [*Paper* I], slot harmonic [*Paper* II] and loading [*Paper* III] on radial forces are investigated.

3

Summary of Simulations, Experimental Work and Research Results

This chapter presents a summary of the electromagnetic simulations, the structural analysis and experimental work. Major research results are listed. Detailed analysis, discussions and research results are presented in the appended three journal papers.

The prototype machine under investigation is a 120-slot/116-pole surface-mounted low-speed PM generator with single-layer concentrated windings. It was designed and prototyped in a previous PhD project [3]. The specifications of the prototype machine are presented in Table I. Fig. 10 shows the winding configuration of the prototype machine. A1, A2, A3 and A4 denote the windings of phase A which all are connected in series. Similarly, the windings of phase B and phase C are shown in the figure. Since a single-layer concentrated winding topology is utilized, the total number of coils is 60 in the prototype machine.

3.1 Electromagnetic Simulations

According to (1), in order to analyze the radial force distribution based on the Maxwell stress tensor, the flux density distribution in the airgap needs to be computed first. In this research work, FE analysis is employed to calculate the flux density with high accuracy. ANSYS MAXWELL [34] has been used as the FE software. Once the field distribution is computed, the analysis of the radial force density and total forces is performed using MATLAB [35].

Table I
PROTOTYPE GENERATOR SPECIFICATIONS

Rated power	30 kW	Stator slot depth	80 mm
Number of phases	3	Stator slot width	22.3 mm
Rated frequency	50 Hz	Stator stack length	100 mm
Rated speed	51.7 rpm	Number of coils	60
Number of poles	116	Number of turns	19
Number of stator slots	120	Airgap length	5 mm
Stator outer diameter	1777 mm	Magnet length	20 mm
Stator inner diameter	1557 mm	Magnet width	33 mm
Stator material	M250-50A	Permanent magnets	NdFeB N35

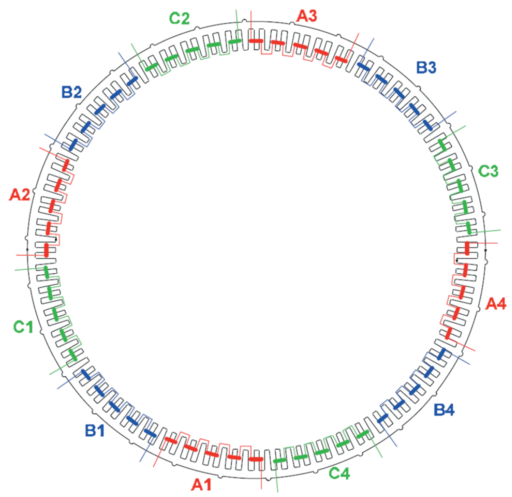

Fig. 10. Winding configuration of the prototype 120-slot/116-pole low-speed PM generator [3].

The stator of the prototype machine is made of laminated steel (M250-50A). The rotor back iron is made of structural steel. For both materials, magnetic saturation is considered in all electromagnetic FE simulations, using corresponding magnetization curves.

Flux lines at no-load are depicted for the prototype machine in Fig. 11. As can be seen in the figure, the machine has a large diameter, thin yoke and open slots.

Time-stepping FE simulations are employed to investigate the radial forces at no-load and load conditions based on the Maxwell stress tensor. To study the spatial distribution of the radial force density, the radial and tangential components of flux density are computed in a specific time instance (t_0). Further analysis then can be done to calculate the radial

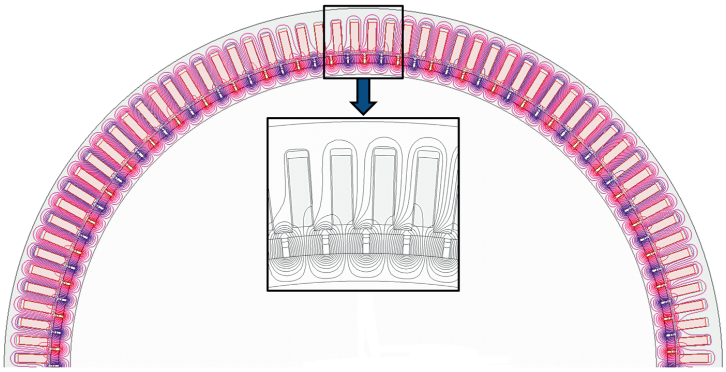

Fig. 11. Flux lines at no-load in prototype generator.

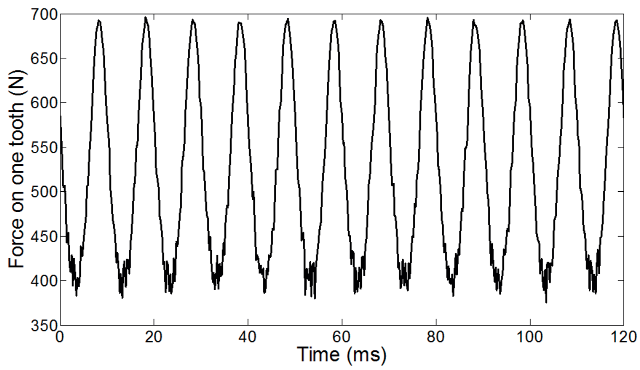

Fig. 12. Radial magnetic force acting on one tooth at no-load for prototype machine.

forces acting on each tooth at that time instant. The radial force distribution on stator teeth for the prototype machine is presented in Fig. 6. To investigate the time varying radial forces acting on one tooth, the values of radial and tangential flux density have to be stored in each time step in a time-stepping FE analysis. Radial force density and total radial force on a tooth can be computed afterward using the Maxwell stress tensor. In Fig. 12, the time varying radial force on one tooth is depicted at no-load for the prototype machine.

In order to study the load conditions, a coupled electrical circuit is used in FE simulations. Resistive, inductive and capacitive loading cases are analyzed.

Fig. Fig. 13 shows the circuit in the case of the resistive load. For capacitive and inductive loadings, capacitors and inductors are placed in parallel with the resistors shown in the figure, respectively.

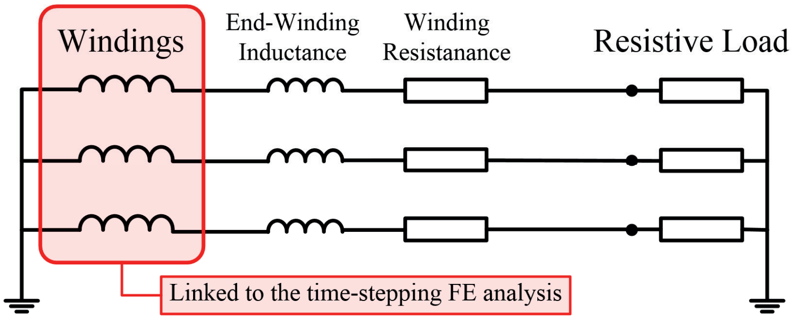

Fig. 13. Coupled electrical circuit in FE simulations (resistive load).

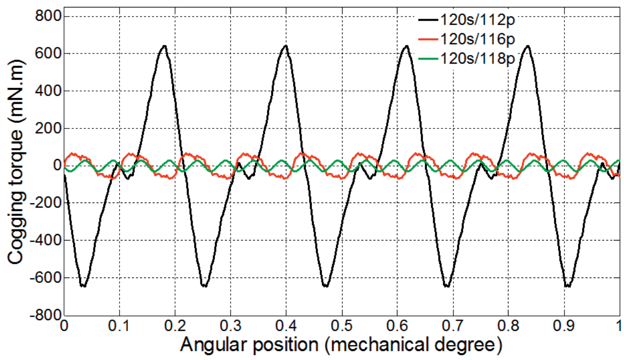

Fig. 14. Cogging torque waveforms.

A large number of magnetostatic FE simulations are performed to systematically analyze the effects of loading on the radial forces. The distribution of the flux density due to permanent magnets only (i.e. no-load), magnetomotive force (MMF) only and both of them simultaneously (i.e. load condition) are obtained. Several loading conditions have also been taken into account. The current is applied in *d*-axis, *q*-axis and a few intermediate modes with both *d*- and *q*-axis currents.

Fig. 14 shows the cogging torque waveforms computed by time-stepping FE analysis. The number of cogging torque periods per rotor revolution is equal to the LCM (least common multiple) of the number of poles and the number of stator slots. Higher cogging torque frequency leads to lower magnitude. Low-speed (high pole) PM machines with concentrated windings could have a very high LCM and as a result extremely low cogging

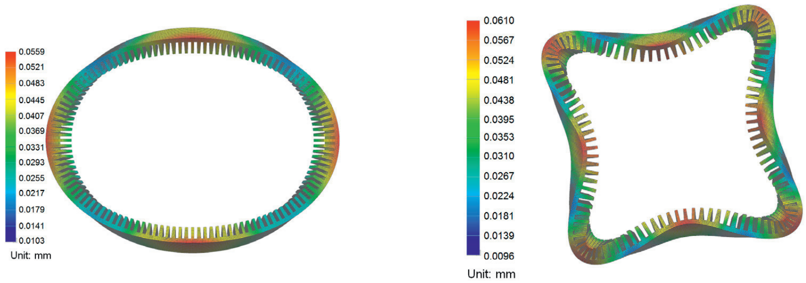

Fig. 15. Modal analysis of the prototype generator. 2nd mode (left) and 4th mode (right).

torque. When computing cogging torque waveforms with extremely low amplitude, the mesh density in the finite element analysis has to be significantly high. In the prototype 120-slot/116-pole machine, the number of cogging torque periods per revolution is 3480 which is extremely high. Time stepping finite element analysis is employed to compute such a high frequency cogging torque with very low amplitude. The rotor is rotated slowly and computation is done in an adequate number of time steps to be able to follow the high frequency changes in the cogging torque waveform.

3.2 *Structural Analysis*

The structural FE analysis is used for two purposes:

1) To compute the resonance frequencies for different modes of vibration.
2) To compute the deformation amplitude caused by the exciting radial magnetic forces.

To calculate resonant frequencies of the prototype 120-slot/116-pole generator, a three-dimensional modal analysis is performed in two cases; without and with structural support of the machine. In the modal analysis without structural support, only the stator ring and teeth are modeled. For accurate computation of the resonance frequencies, all structural details of the machine have to be considered. There will be a significant increase in the values of resonance frequencies when structural support is included. Such an analysis showing the mode shapes for $m = 2$ and $m = 4$ is presented in Fig. 15.

In static deformation analysis, computed radial forces on the teeth for the prototype generator are used as input for a three-dimensional static structural analysis including structural supports. It is then possible to compute the maximum deformation in the stator due to the radial force excitation. In this static analysis, the influence of the resonance frequencies is not considered. The resonance frequency for the dominant mode of vibration (4th mode) is not in the speed range of the prototype generator. So this is a reasonable assumption not to consider the case of the resonance vibration.

3.3 Experimental work

Experimental vibration measurement is carried out to:

1) Identify the magnetic vibration in the prototype machine.
2) Observe the lowest mode of vibration (4th spatial harmonic of radial force density).
3) Measure the vibration amplitude and compare it with simulated amplitude.
4) Investigate changing the vibration level in different loading conditions and compare it with the simulation results.

Fig. 16 shows the experimental setup for vibration measurement. An induction machine drive is used to rotate the shaft of the PM generator. Four piezoelectric charge accelerometers with charge amplifiers are used to measure vibration. The sensors are mounted on the supporting structure of the stator.

3.4 Major Research Results

This section presents a summary of major findings and research results from this PhD work. Detailed research results are further presented in the appended papers, i.e. the second part of the thesis.

The basis for the analysis of the forces and vibration is the flux density distribution in the airgap computed by FE analysis. The spatial harmonic orders of the radial flux density component produced by permanent magnets and MMF fields are shown in Fig. 3, for the prototype 120-slot/116-pole machine. The order of the main harmonic component is equal to the pole pair number (i.e. 58 for the prototype machine). The 62nd spatial harmonic is produced due to the slotting and is called the slot harmonic. It is shown in this thesis that the slot harmonic plays a significant role in the radial forces and vibration characteristics. It is worth mentioning that in large PM machine with concentrated windings, due to manufacturing advantages, it is common to use open slots. In this case, in contrast with small machines with semi-closed slots, the effects of slot harmonics are considerable.

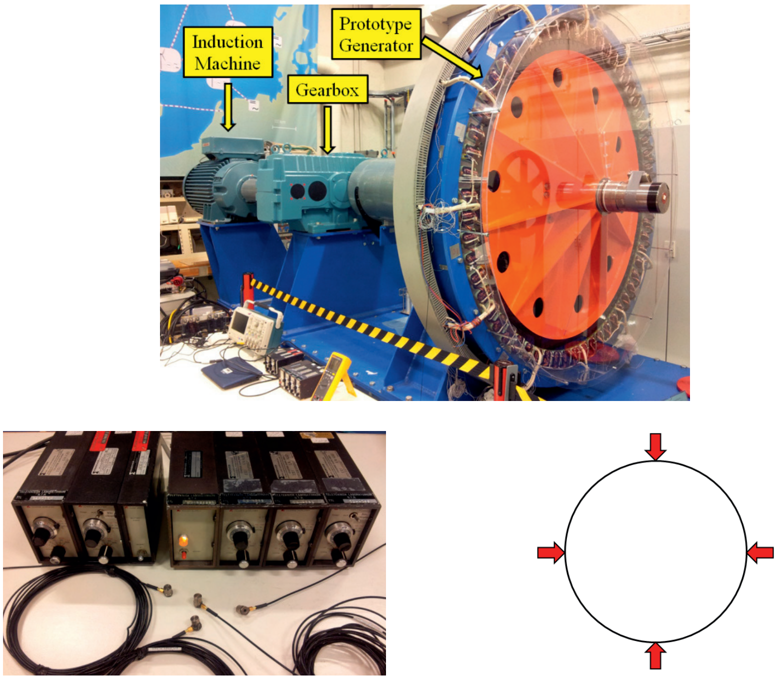

Fig. 16. Experimental setup with prototype generator, test rig (top), accelerometers and charge amplifiers (bottom left) and the position of the accelerometers on the stator (bottom right).

3.4.1 Influence of pole and slot combination [*Paper* I]

As mentioned before, the order of the lowest spatial harmonic in the radial force density distribution (i.e. lowest mode of vibration) is equal to the GCD of the number of slots and the number of poles. It is therefore possible to choose the right number of pole and slot combinations for the low-speed machines to avoid having an extremely low mode of vibration. TABLE II shows the order of the lowest mode of vibration for different pole and slot combinations. Three fractional-slot machines presented in the table have the same stator with 120 slots, but with 112, 116 (prototype machine) and 118 poles. A simple approximation of the amplitude of the static deformations in the stator is also presented based on (5). This simple structural approach does not provide enough accuracy of course, but it is a useful tool to simply compare the vibration level of the different pole and slot

Table II
SIMULATED AMPLITUDE OF STATIC DEFORMATION

Slot number/ pole number	Lowest mode of vibration (m)	Y_{ms}
120/112	8	$Y_{8s} = 8.82 \times 10^6\ K_s$
120/116	4	$Y_{4s} = 1.42 \times 10^8\ K_s$
120/118	2	$Y_{2s} = 3.55 \times 10^9\ K_s$

Table III
COGGING TORQUE AND TORQUE RIPPLE

Slot number/ pole number	LCM	Cogging torque	Torque ripple
120/112	1680	0.0215 %	0.6 %
120/116	3480	0.0023 %	0.6 %
120/118	7080	0.001 %	0.6 %

combinations. As can be seen in the table, the vibration level significantly decreases when the order of the lowest mode (i.e. the GCD of the number of slots and poles) increases. If instead of the prototype 120-slot/116-pole machine, the 120-slot/112-pole configuration is chosen, the magnetic vibration level would be 16 times lower.

In fractional-slot PM machines, normally the LCM of the number of slots and poles decreases when the GCD increases. This means that the cogging torque increases when the GCD is increased to have a lower vibration level. Reduction of the cogging torque is one of the design targets in the PM machines. Since the LCM of the numbers of slots and poles is usually high in PM machines with concentrated windings, they have a relatively low cogging torque. Table III shows that despite the fact that the cogging torque will be larger in the case of a higher LCM, it is practically zero for all three fractional-slot machines. Therefore, it is only the load-dependent component which causes torque ripple. As can be seen in the table, torque ripple level is almost the same for all three machines.

The conclusion is that it is possible to choose a proper pole and slot combination in initial design stage of the low-speed PM machines to have the magnetic vibration (i.e. the disadvantage of machines with non-overlapping concentrated windings) at a relatively low level while keeping the cogging torque and torque ripple (i.e. the advantage of machines with non-overlapping concentrated windings) extremely small without skewing.

3.4.2 *Estimation of the vibration level* [*Paper* I]

The spatial distribution of radial forces in the prototype machine (shown in Fig. 6) is used as an input for the three dimensional structural FE analysis. Structural support of the machine is also considered in this analysis. The simulated value of the maximum displacement in the stator as a result of magnetic forces is 0.0167 millimeters. The measured displacement of the prototype machine using the accelerometer is 0.014 millimeters. Good agreement between the simulation and experimental results indicates the accuracy of the electromagnetic and structural modeling and analysis.

3.4.3 *Experimental mode observation* [*Paper* I]

The lowest mode of vibration in the prototype generator is 4. This mode is observed experimentally using four accelerometers which are mounted 90 degrees apart on the stator. The acceleration waveforms of all four sensors must be in phase to prove the existence of a 4th mode of vibration. This can be clarified according to Fig. 6 where the radial force distribution on the teeth is shown for the prototype machine. Each of the four points, which are mechanically 90 degrees apart, experiences the same amplitude of magnetic forces at all times. The acceleration signals are depicted in Fig. 17 and as can be seen, they are all in phase.

3.4.4 *Slot harmonic effect* [*Paper* II]

The influence of the slot harmonics can be considerable in large low-speed machines with open slots. It is shown that the amplitude of the lowest mode of vibration is considerable even at no-load for the prototype machine, due to the slotting effect. This is illustrated in Fig. 5, where spatial harmonics of radial force density are shown for the prototype generator.

Fig. 18 shows the contribution of different flux density harmonics to produce the lowest mode of vibration at no-load for the prototype machine. As can be seen in the figure, the main factor is the interaction between the main harmonic (i.e. 58th) and the slot harmonic (i.e. 62nd).

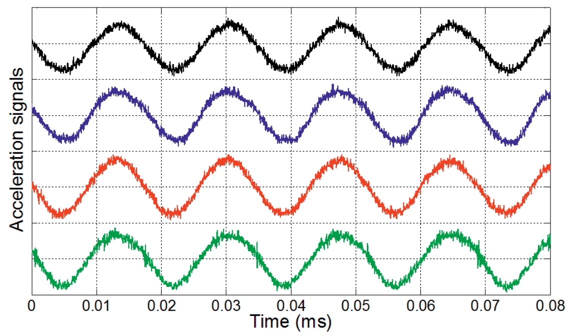

Fig. 17. Acceleration signals from four sensors placed 90 degrees apart.

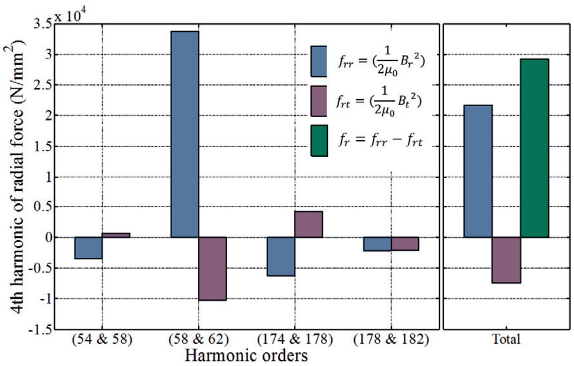

Fig. 18. Contribution of different flux density harmonics to produce 4th harmonic order in radial force distribution.

The effect of slot closure on the radial forces is studied. The amplitude of the lowest mode of vibration is investigated in the case of open slots (prototype machine), semi-closed slots and magnetic wedges in 120-slot/116-pole machine. Table IV shows how the amplitude of the lowest mode changes in the case of different slot closures. It should be noted that the electromagnetic torque is also greatly affected by the slot closure. It is found that in the case of magnetic wedge 1 ($\mu_r = 5$), the amplitude of the 4th spatial mode of radial force density and consequently vibration level is reduced compared to the case of open slots, while torque production capability is not affected negatively.

Table IV
RADIAL FORCE DENSITY (N/m^2)

	Open slot	Magnetic wedge 1 $(\mu_r = 5)$	Magnetic wedge 2 $(\mu_r = 10)$	Semi-closed slot
4th harmonic	3.08×10^4	2.25×10^4	1.94×10^4	0.89×10^4

3.4.5 *Consideration of tangential flux density contribution in radial force calculation* [*Paper* II]

According to (1), both radial and tangential components of flux density contribute to produce radial forces. However, the contribution of the tangential flux density is often neglected, because normally the radial component is much larger than the tangential one. It is shown in this research work though, that in PM machines with open slots this contribution has to be considered. This is due to the fact that the tangential flux density is relatively large in machines with open slots. As shown in Fig. 18, 25% of the amplitude of the lowest mode of vibration is produced by the tangential flux harmonics.

3.4.6 *Effects of loading* [*Paper* III]

The effects of loading on the radial forces and vibration in the prototype machine are systematically investigated in presence of a strong slot harmonic. A large number of magnetostatic simulations are performed to investigate how the amplitude of the lowest mode of vibration changes in different loading conditions. This is presented in Fig. 19.

The contribution from different harmonics in flux density to produce the lowest mode of vibration in different loading conditions is presented in Fig. 20. According to the figure, it can be observed that: 1) the contribution from the 2nd harmonic of flux density to produce the lowest mode of vibration is negligible, 2) the interaction between the main harmonic (58th) and the slot harmonic (62th) is the main factor to produce the lowest mode and the amplitude of the 4th mode is mainly determined by this harmonic pair, 3) The contributions of other harmonic pairs are almost unchanged for different loading conditions, 4) the contribution from tangential components is considerable.

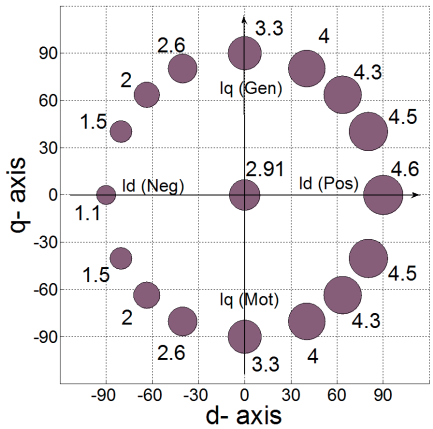

Fig. 19. Amplitude of the 4th spatial harmonic in radial force density in different loading conditions (unit: $10^4 \times N/m^2$).

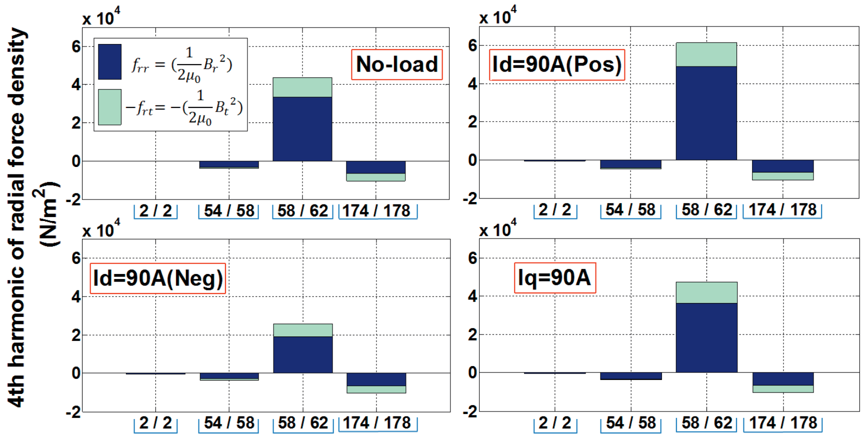

Fig. 20. Contribution of different harmonic pairs to produce the lowest mode of vibration in different loading conditions.

It is shown that positive and negative *d*-axis current increases and decreases the amplitude of the 4th harmonic by about 60%, respectively. The main reason for changing the vibration level due to loading is found to be the slot harmonic which is heavily affected by loading. It is concluded that the slot harmonic is the main factor in the vibration behavior of the prototype machine in the loading condition.

4

CONCLUSIONS

The PhD research work is summarized in this chapter. Concluding remarks are presented as well as recommendations for future work.

4.1 Concluding Remarks

In this thesis, magnetically induced vibration in low-speed PM machines with non-overlapping concentrated windings is studied. In fractional-slot PM machines with concentrated windings, low modes of vibration can be excited. As a result, these machines normally have a higher vibration level compared to the traditional PM machines with distributed windings. The prototype machine under investigation in this thesis is a 120-slot/116-pole surface-mounted PM generator.

Radial magnetic forces are the main cause of the magnetic vibration in electrical machines. In this research work, the magnetic flux distribution in the airgap is computed using FE analysis. The Maxwell stress tensor is then employed to calculate the radial force distribution. To compute the resonance frequencies of the stator and estimate the vibration level of the prototype machine, structural FE analysis is performed. Moreover, experimental work is carried out to measure the vibration of the prototype machine and to observe the lowest mode of vibration.

It is addressed that in low-speed PM machines, by choosing the right number of pole and slot combinations, it is possible to reduce the vibration level significantly. Meanwhile, the cogging torque can be kept extremely low.

Unlike small PM machines with semi-closed slots, it is found that for large low-speed PM machines with open slots, the amplitude of the lowest mode of vibration (lowest order spatial harmonic in the radial force distribution) is considerable at no-load due to the slotting effect.

In addition, it is found that in large PM machines with open slots, the contribution of the tangential flux density component cannot be neglected in the analysis of the radial forces and vibrations. In small PM machines with semi-closed slots, the contribution of the tangential flux density is often neglected.

Moreover, it is shown that magnetic wedges can be used to reduce the effect of slot harmonics and consequently the amplitude of the lowest mode of vibration. As a result, vibration level of the machine can be reduced. It is also shown that the torque production capability is not affected negatively in this case. If semi-closed slots are used, the vibration level is reduced even further, but the electromagnetic torque is also reduced substantially.

The effects of loading on radial forces and vibration are investigated systematically in the presence of a strong slot harmonic. It is concluded that the changes in the vibration level are due to the changes in the amplitude of the slot harmonic, which is heavily affected by loading. It is shown that the lowest mode of vibration is mainly produced by the interaction of the main harmonic and the slot harmonic in all loading cases. The contribution of the lowest spatial harmonic of flux density to produce the lowest mode is found to be negligible.

Furthermore, it is revealed that in large low-speed PM machines with concentrated windings, the slot harmonic is the main factor in the vibration behavior of the machine, both in no-load and load conditions.

4.2 Recommendations for Future Work

In this thesis, magnetic vibration due to radial forces is studied and magnetic noise is not investigated. It is possible that a magnetic force wave of higher frequencies, which is not that important from the vibration perspective (due to relatively low amplitude), generates much more noise than the main vibrational 100 Hz force wave. The reason is that in the noise analysis, the frequency of the force waves becomes very important. Magnetic noise can be studied for low-speed PM machines. When speed is low, magnetic noise is the most important source of the noise in electrical machines. Since time harmonics are important in such an analysis, the noise can be studied in the machines connected to the power electronic converters.

In the presented research work, radial forces and vibration are studied for healthy low-speed PM machines. Vibration characteristics of the low-speed machines could be investigated in faulty conditions, e.g. in the case of eccentricity and demagnetization faults. A fault diagnostic method could then be developed based on vibration monitoring of the machine.

A major drawback of PM machines with concentrated windings is the high rotor losses. This could be investigated thoroughly for the low-speed PM machines. Special attention should be given to the influence of the slot harmonic.

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Paper I

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Paper II

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Paper III

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