TYPES AND DESIGN OF SYNCHRONOUS MACHINES FOR LOW SPEED APPLICATIONS

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The rotor of a typical wind turbine rotates at a speed of 20-200 rpm. In conventional wind power plants the generator is coupled to the turbine via a gear so that it can typically rotate at a speed of 1000 or 1500 rpm. The wind power plant can be simplified by eliminating the gear and by using a low-speed generator. The rotor of which rotates at the same speed as the rotor of the turbine. The hypothesis in this work is that the typical generator-gear solution in the wind power plant can be replaced by a low speed Pm synchronous generator.

This thesis deals with the electromagnetic design and the optimisation of two types of low speed generators for gearless wind turbines. The generators designed are radial-flux permanent magnet synchronous machines excited by NdFeB magnets. The machines have different kinds of stator windings. The first machine has a conventional three-phase, diamond winding. The second machine has a three-phase, unconventional single coil winding consisting of coils which are placed in slots around every second tooth. The electromagnetic optimisation of the machine is done by the finite element method and by a genetic algorithm combined with the finite element method. The rated powers of the machines optimised are 500kW, 10kW and 5.5 kW. Two prototypes machines were built and tested.

The optimisation of the machines shows that the cost of active materials is smaller and the pull out torque per the cost of active materials higher in the conventional machines than in the single coil winding machines. The torque ripple can be reduced to a low level by choosing a suitable magnet and stator slot shape in both the designs. The demagnetisation of permanent magnets is easier to avoid in the single-coil winding machines than in the conventional designs. The investigation of various rotor designs shows that the rotor equipped with curved surface-mounted magnets has various advantages compared with the other rotor designs, for the instance pole shoe versions. The analysis of the machines also that the load capacity of the machine is lower than that when connected directly to a sinusoidal grid.
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<thead>
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<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>(a_I)</td>
<td>Experimental coefficient</td>
</tr>
<tr>
<td>(A_s)</td>
<td>Area of the conductive region in a stator slot</td>
</tr>
<tr>
<td>(b)</td>
<td>Magnet width per pole pitch</td>
</tr>
<tr>
<td>(b_m)</td>
<td>Magnet width</td>
</tr>
<tr>
<td>(b_s)</td>
<td>Stator slot width</td>
</tr>
<tr>
<td>(B_{\text{min}})</td>
<td>Minimum flux density in permanent magnets</td>
</tr>
<tr>
<td>(B_r)</td>
<td>Remanence of the magnets</td>
</tr>
<tr>
<td>(B_{\phi})</td>
<td>Tangential component of the air-gap flux density</td>
</tr>
<tr>
<td>(C)</td>
<td>Machine constant</td>
</tr>
<tr>
<td>(\text{Cost})</td>
<td>Cost of active material</td>
</tr>
<tr>
<td>(d)</td>
<td>Air-gap material</td>
</tr>
<tr>
<td>(E)</td>
<td>Induced voltage</td>
</tr>
<tr>
<td>(H_c)</td>
<td>Coercivity voltage</td>
</tr>
<tr>
<td>(l)</td>
<td>Length of the stator and rotor cores</td>
</tr>
<tr>
<td>(l_b)</td>
<td>Length of the winding overhang</td>
</tr>
<tr>
<td>(n)</td>
<td>Rated speed</td>
</tr>
<tr>
<td>(N_c)</td>
<td>Number of conductors in series in a stator slot</td>
</tr>
<tr>
<td>(p)</td>
<td>Number of pole pairs</td>
</tr>
<tr>
<td>(q)</td>
<td>Number of slot per pole and phase</td>
</tr>
<tr>
<td>(r_r)</td>
<td>Inner radii of the air gap</td>
</tr>
<tr>
<td>(r_s)</td>
<td>Outer radii of the air gap</td>
</tr>
<tr>
<td>(R_s, R_k)</td>
<td>Stator resistance</td>
</tr>
<tr>
<td>(R_L, R_{L1}, R_{L2})</td>
<td>Load resistance</td>
</tr>
<tr>
<td>(S_{\text{ag}})</td>
<td>Cross-Sectional area of the air gap</td>
</tr>
<tr>
<td>(T)</td>
<td>Torque</td>
</tr>
<tr>
<td>(T_{\text{cog}})</td>
<td>Cogging Torque</td>
</tr>
<tr>
<td>(T_{\text{max}}, T_m)</td>
<td>Pull-out Torque</td>
</tr>
<tr>
<td>(T_n)</td>
<td>Rated air-gap torque</td>
</tr>
<tr>
<td>(U)</td>
<td>Line to Line voltage</td>
</tr>
<tr>
<td>(U_{\text{ind}})</td>
<td>Induced voltage</td>
</tr>
</tbody>
</table>
\( U_{1f}, U_{2f}, U_{3f} \)  \hspace{0.5cm} \text{Phase voltage}
\( x_d \)  \hspace{0.5cm} \text{Per unit synchronous machine}
\( x_b \)  \hspace{0.5cm} \text{End-winding reactance}
\( \tau_m \)  \hspace{0.5cm} \text{Magnet width per pole pitch}
\( \tau_p, \tau \)  \hspace{0.5cm} \text{Pole pitch}
\( \tau_r \)  \hspace{0.5cm} \text{Pole pitch of the rotor}
\( \mu_0 \)  \hspace{0.5cm} \text{Vacuum permeability}
\( \omega \)  \hspace{0.5cm} \text{Electrical angular frequency}
\( \omega_m \)  \hspace{0.5cm} \text{Mechanical angular frequency}
\( \psi_m \)  \hspace{0.5cm} \text{Peak flux linkage of the phase winding}
## LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite element method</td>
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<tr>
<td>HTF</td>
<td>Harmonic voltage factor [IEC-34-1]</td>
</tr>
<tr>
<td>NdFeB</td>
<td>Neodymium-Iron-Boron permanent magnets</td>
</tr>
<tr>
<td>PM</td>
<td>Permanent magnet</td>
</tr>
<tr>
<td>PS-1</td>
<td>Machine with rectangular magnets equipped with pole shoes, constant air-gap length</td>
</tr>
<tr>
<td>PS-2</td>
<td>Machine with rectangular magnets equipped with pole shoes, air-gap length varies</td>
</tr>
<tr>
<td>RM-1</td>
<td>Machine with rectangular surface-mounted magnets, one magnet per pole</td>
</tr>
<tr>
<td>RM-3</td>
<td>Machine with rectangular surface-mounted magnets, three parallel magnets per pole</td>
</tr>
<tr>
<td>SM</td>
<td>Machine with curved surface-mounted magnets</td>
</tr>
<tr>
<td>UC</td>
<td>Machine with unconventional single-coil winding</td>
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CHAPTER 1

1. INTRODUCTION

A synchronous machine is an AC rotating machine whose speed under steady state condition is proportional to the frequency of the current in its transformer. The magnetic field created by the armature currents rotates at the same speed as that created by the field current on the rotor, which is rotating at the synchronous speed, and a steady torque results.

Synchronous machines are commonly used as generators especially for large power systems, such as turbine generators and hydroelectric generators in the grid power supply. Because the rotor speed is proportional to the frequency of excitation, synchronous motors can be used in situations where constant speed drive is required. Since the reactive power generated by a synchronous machine can be adjusted by controlling the magnitude of the rotor field current, unloaded synchronous machines are also often installed in power systems solely for power factor correction or for control of reactive kVA flow. Such machines, known as synchronous condensers, may be more economical in the large sizes that static capacitors.

With power electronic variable voltage variable frequency (VVVF) power suppliers, synchronous motors, especially those with permanent magnet rotors, are widely used for variable speed drives. If the stator excitation of permanent magnet motor is controlled by its rotor position such that the stator field is always $90^0$ (electrical) ahead of the rotor, the motor performance can are very close to the conventional brushed dc motors, which is very much favoured for variable speed drives. The rotor position can be either detected by using rotor position sensors or deduced from the induced emf in the stator windings. Since this type of motors does not need brushes, they are known as brushless dc motors.

1.1. Synchronous Machine Structures

Stator and Rotor

The armature winding of a conventional synchronous machine is almost invariably on the stator and is usually a three phase winding. The field winding is usually on the rotor and excited by dc current, or permanent magnets. The dc power supply required for excitation usually is supplied through a dc generator known as exciter, which is often mounted on the same shaft as the synchronous machine. Various excitation systems using ac exciter and solid state rectifiers are used with large turbine generators.

There are two types of rotor structures: round or cylindrical rotor and salient pole rotor as illustrated schematically in the diagram below. Generally, round structure is used for high speed synchronous machines, such as steam turbine generators, while salient pole structure is used for low speed applications, such as hydroelectric generators. The pictures below show the stator and rotor of a hydroelectric generator and the rotor of a turbine generator.
Fig. 1.1 (a) Round or cylindrical rotor

(b) Salient rotor structures

Fig. 1.2: Stator of a 190-MVA three-phase 12-kv 375-r/min hydroelectric generator.

Stator of a 190-MVA three-phase 12-kv 375-r/min hydroelectric generator. The conductors have hollow passages through which cooling water is circulated. (Brown Boveri Corporation.)
Fig. 1.3: Water-cooled rotor of the 190-MVA hydroelectric generator.

Fig. 1.4: Rotor of a two pole 3600 rpm turbine generator
Angle in Electrical and Mechanical Units

Consider a synchronous machine with two magnetic poles. The idealized radial distributions of the air gap flux density are sinusoidal along the air gap. When the rotor rotates for one revolution, the induced emf, which is also sinusoidal, varies for one cycle as illustrated by the waveforms in the diagram below. If we measure the rotor position by physical or mechanical degrees or radians and the phase angles of the flux density and emf by electrical degrees or radians, in this case, it is ready to see that angle measured in mechanical degrees or radians is equal to that measured in electrical degrees or radians, i.e.

$$\theta = \theta_m$$

Where $\theta$ is the angle in electrical degrees or radians and $\theta_m$ the mechanical angle.
A great many synchronous machines have more than two poles. As a specific example, we consider a four pole machine. As the rotor rotates for one revolution ($\theta_m = 2\pi$), the induced emf varies for two cycles ($\theta = 4\pi$), and hence

$$\theta = 2\theta_m$$

For a general case, if a machine has $P$ poles, the relationship between the electrical and mechanical units of an angle can be readily deduced as

$$\theta = \frac{p}{2} \theta_m$$

Taking derivatives on both sides of the above equation, we obtain

$$\omega = \frac{p}{2} \omega_m$$

Where $\omega$ is the angular frequency of emf in electrical radians per second and $\omega_m$ the angular speed of the rotor in mechanical radians per second. When $\omega$ and $\omega_m$ are converted into cycles per second or Hz and revolutions per minute respectively, we have

$$f = \frac{p}{2} \frac{n}{60} \quad \text{Or} \quad n = \frac{120f}{p}$$
Where $\omega = 2\pi f$, $\omega_m = \frac{2\pi n}{60}$, and $n$ is the rotor speed in rev/min. It can be seen that the frequency of the induced emf is proportional to the rotor speed.

**Distributed Three Phase Windings**

The stator of a synchronous machine consists of a laminated electrical steel core and a three phase winding. Fig (1.7) below shows a stator lamination of a synchronous machine that has a number of uniformly distributed slots. Coils are to be laid in these slots and connected in such a way that the current in each phase winding would produce a magnetic field in the air gap around the stator periphery as closely as possible the ideal sinusoidal distribution. Fig (1.8) is a picture of a coil.

![Stator lamination](image)

**Fig. 1.7: Stator lamination**

![Coil of a synchronous machine](image)

**Fig. 1.8: Coil of a synchronous machine**

As illustrated below, these coils are connected to form a three phase winding. Each phase is able to produce a specified number of magnetic poles (in the diagram below, four magnetic poles are generated by a phase winding). The windings of the
three phase are arranged uniformly around the stator periphery and are labelled in the sequence that phase a is $120^\circ$ (electrical) ahead of phase b and $240^\circ$ (electrical) ahead of phase c. It is noted that in the diagrams above, two coils sides are laid in each slot. This type of winding is known as the double layer winding. In the case that there is only one coil side in each slot, the winding is known as the single layer winding.

Fig. 1.9: Single phase, whole-coil distributed winding.
1.2. Rotating Magnetic Fields

Magnetic Field of a Distributed Phase Winding

The magnetic field distribution of a distributed phase winding can be obtained by adding the fields generated by all the coils of the winding. The diagram below plots the profiles of mmf and field strength of a single coil in a uniform air gap. If the permeability of the iron is assumed to be infinite, by Ampere’s law, the mmf across each air gap would be $N_i a 2$, where $N$ is the number of turns of the coil and $i_a$ the current in the coil. The mmf distribution along the air gap is a square wave. Because of the uniform air gap, the spatial distribution of magnetic field strength is the same as that of mmf.

It can be shown analytically that the fundamental component is the major component when the square wave mmf is expanded into a Fourier series, and it can written as

$$F_{a1} = \frac{4 N i_a}{\pi} \cos \theta$$

Where $\theta$ is the angular displacement from the magnetic axis of the coil.

When the field distributions of a number of distributed coils are combined, the resultant field distribution is close to a sine wave, as shown in the diagram in the next page. The fundamental component of the resultant mmf can be obtained by adding the fundamental components of these individual coils, and it can expressed as
Fig. 1.11: The mmf of a concentrated full-pitch coil.
Fig. 1.12: The mmf of one phase of a distributed two-pole three-phase winding with full pitch coils.

\[ F_{a1} = \frac{4N_{ph}}{\pi} i_a \cos \theta \]

Where \( N_{ph} \) is the total number of turns of the phase winding, which is formed by these coils, \( k_p \) is known as the distribution factor of the winding, which is defined by

\[ k_p = \frac{\text{fundamental mmf of a distributed winding}}{\text{fundamental mmf of a concentrated winding}} \]

And \( P \) is the number of poles.

In some windings, short pitched coils (the distance between two sides of coil is smaller than that between two adjacent magnetic poles) are used to eliminate a certain harmonic, and the fundamental component of the resultant mmf is then expressed as

\[ F_{a1} = \frac{4k_wN_{ph}}{\pi} i_a \cos \theta \]

Where \( k_w = k_d k_p \) is the winding factor, \( k_d \) is known as the pitching factor, which is defined by

\[ k_d = \frac{\text{fundamental mmf of a short pitch winding}}{\text{fundamental mmf of a full pitch winding}} \]

And \( k_wN_{ph} \) is known as the effective number of turns of the phase winding.

Let \( i_a = I_m \cos \omega t \), and we have

\[ F_{a1} = \frac{4N_{ph}}{\pi} I_m \cos \omega t \cos \theta \]

\[ = F_m \cos \omega t \cos \theta \]

Where

\[ F_m = \frac{4k_wN_{ph}}{\pi} I_m \]
The mmf of a distributed phase winding is a function of both space time. When plotted at different time instants as shown below, we can see that it is a pulsating sine wave. We call this type of mmf as a pulsating mmf.

Because \( \cos \alpha \cos \beta = \frac{\cos(\alpha - \beta) + \cos(\alpha + \beta)}{2} \), the above expression of the mmf fundamental component can be further written as

\[
F_{a1} = \frac{F_m}{2} \cos(\theta - \omega t) + \frac{F_m}{2} \cos(\theta + \omega t)
\]

\[
= F_+ + F_-
\]

Fig. 1.13: Single-phase winding fundamental mmf: (a) mmf distribution of a single-phase winding at various times; (b) total mmf \( F_{a1} \) decomposed into two travelling waves \( F_+ \) and \( F_- \); (c) phasor decomposition of \( F_{a1} \).

It can be shown that the first term in the above equation stands for a rotating mmf in the +\( \theta \) direction and the second a rotating mmf in the –\( \theta \) direction. That is a pulsating mmf can be resolved into two rotating mmf’s with the same magnitudes and opposite rotating directions, as shown above. For a machine with uniform air gap, the above analysis is also applicable to the magnitude field strength and flux density in the air gap.
Magnetic Field of Three Phase Windings

Once we get the expression of mmf for a single phase winding, it is not difficult to write the expressions of mmf’s for three single phase windings placed 120° (electrical) apart and excited by balanced three phase currents:

\[ F_{a1} = F_m \cos \omega t \cos \theta = \frac{F_m}{2} \cos(\theta - \omega t) + \frac{F_m}{2} \cos(\theta + \omega t) \]

\[ F_{b1} = F_m \cos(\omega t - 120^\circ) \cos(\theta - 120^\circ) = \frac{F_m}{2} \cos(\theta - \omega t) + \frac{F_m}{2} \cos(\theta + \omega t - 240^\circ) \]

\[ F_{c1} = F_m \cos(\omega t - 240^\circ) \cos(\theta - 240^\circ) \]

And

\[ = \frac{F_m}{2} \cos(\theta - \omega t) + \frac{F_m}{2} \cos(\theta + \omega t - 480^\circ) \]

Therefore, the resultant mmf generated by a three phase winding is

\[ F_1 = F_{a1} + F_{b1} + F_{c1} = 3F_m \frac{\cos(\theta - \omega t)}{2} \]

Note that \( \cos(\theta + \omega t) + \cos(\theta + \omega t - 240^\circ) + \cos(\theta + \omega t - 480^\circ) = 0 \)

![Diagram](image)

**Fig. 1.14: Rotating mmf in +θ direction.**

The above diagram plots the resultant mmf \( F_1 \) at two specific time instants: \( t=0 \) and \( t=\frac{\pi}{2\omega} \). It can be readily observed that \( F_1 \) is a rotating mmf in the +θ direction with a constant magnitude \( 3F_m/2 \). The speed of this rotating mmf can be calculated as
\[ \omega_f = \frac{d\theta}{dt} = \frac{\pi/2}{\pi/2\omega} = \omega \text{ rad/s (electrical)} \]

When expressed in mechanical radians per second and revolutions per minute, the speed of the rotating mmf can be expressed as
\[ \omega_f = \frac{\omega}{P/2} \text{ rad/s (mechanical)} \]

And
\[ n_f = \frac{60\omega_f}{2\pi} = \frac{120f}{p} \text{ rev/min} \]

Respectively. Again, for a machine with uniform air gap, the above analysis for mmf is also valid for the magnetic field strength and the flux density in the air gap. Therefore, the speed of a rotating magnetic field is proportional to the frequency of the three phase excitation currents, which generate the field.

Comparing with the relationship between the rotor speed and the frequency of the induced emf in a three phase winding derived earlier, we can find that the rotor speed equals the rotating field speed for a given frequency. In other words, the rotor and the rotating at same speed. We call this speed synchronous speed, And use specific symbols \( \omega_{syn} \text{(mechanical rad/s)} \) and \( n_{syn} \text{(rev/min)} \) to indicate it.

The above analytical derivation can also be done graphically by using adding the mmf vectors of three phases, as illustrated in the diagrams below. When \( \omega t = 0 \), phase a current is maximum and the mmf vector with a magnitude \( F_m \) of phase a is the magnetic axis of phase a, while the mmf's of phases b and c are both of magnitude \( F_m/2 \) and in the opposite directions of their magnetic axes since the currents of these two phases are both \(-I_m/2\). Therefore, the resultant mmf \( F_1 = 3F_m/2 \) is on the magnetic axis of phase a. when \( \omega t = \pi/3 \), \( i_c = -I_m \) and \( i_a = i_b = I_m/2 \). The resultant mmf \( F_1 = 3F_m/2 \) is on the axis of phase c but in the opposite direction. Similarly, when \( \omega t = 2\pi/3 \), \( i_b = I_m \) and \( i_c = i_a = -I_m/2 \). Hence the resultant mmf \( F_1 = 3F_m/2 \) is in the positive direction of the magnetic axis of phase b. In general, the resultant mmf is of a constant magnitude \( 3F_m/2 \) and will be in the positive direction of the magnetic axis of a phase winding when the current in that phase winding reaches positive maximum. The rotating mmf equals the angular frequency in electrical rad/s.
Fig. 1.15: The production of a rotating magnetic field by means of three-phase currents

In the case of synchronous generator, three balanced emf's of frequency \( f = Pn/120 \) Hz are induced in the three phase windings when the rotor is driven by a prime mover rotating at a speed \( n \). If the three phase stator circuit is closed by three phase electrical load, balanced three phase currents of frequency \( f \) will flow in the stator circuit, and these currents will generate a rotating magnetic field of a speed \( n_f = 120f/P = n \).

When the stator winding of three phase synchronous motor is supplied by a balanced three phase power supply of frequency \( f \), the balanced three phase currents in the winding
will generate a rotating magnetic field of speed \( n_f = 120f/P \). This rotating magnetic field will drag the magnetized rotor, which is essential a magnet, to rotate at the same speed \( n = n_f \). On the other hand, this rotating rotor will also generate balanced three phas emf’s of frequency \( f \) in the stator winding, which would balance with the applied terminal volatage.

**Rotor Magnetic Field**

Using the method of superposition on the mmf’s of the coils which form the rotor winding, we can derive that the distribution of the mmf and hence the flux density in the gap are close to sine wave for a round rotor synchronous machine with uniform air gap, as illustrated below.

![Fig. 1.16: The mmf of a distributed winding on the rotor of a round-rotor generator.](image)

In the case of salient pole rotor, the rotor poles are shaped so that the resultant mmf and flux density would distribute sinusoidally in the air gap, and thus the induced emf in the stator windings linking this flux will also be sinusoidal.
The field excitation of a synchronous machine may be provided by means of permanent magnets, which eliminate the need for a DC source for excitation. This can not only save energy for magnetic excitation but also dramatically simplify the machine structures, which is especially favorable for small synchronous machines, since this offers more flexibility on machine topologies. The diagram below illustrate the cross sections of two permanent magnet synchronous machines.

Fig. 1.17: (a) Cylindrical-rotor, permanent magnet machine  
(b) Sailent-pole, permanent magnet machine

1.3. Per Phase Equivalent Electrical Circuit Model

The diagram below illustrates schematically the cross section of a three phase, two pole cylindrical rotor synchronous machine. Coils \(aa', bb'\) and \(cc'\) represent the distributed stator windings producing sinusoidal mmf and flux density waves rotating in the air gap. The reference directions for the currents are shown by dots ad crosses. The field winding \(ff'\) on the rotor also represents a distributed winding which produces sinusoidal mmf and flux density waves centered on its magnetic axis and rotating with the rotor.

The electrical circuit equations for the three stator phase windings can be written by the kirchpf’s law as

\[
v_a = R_a i_a + \frac{d\lambda_a}{dt}
\]
Fig. 1.18: Schematic diagram of a three phase cylindrical rotor synchronous machine

\[ v_b = R_b i_b + \frac{d \lambda_b}{dt} \]
\[ v_c = R_c i_c + \frac{d \lambda_c}{dt} \]

Where \( v_a, v_b \) and \( v_c \) are the voltages across the windings \( R_a, R_b \) and \( R_c \) are the winding resistances and \( \lambda_a, \lambda_b \) and \( \lambda_c \) are the total flux linkages of the windings of phases \( a, b \) and \( c \) respectively. For a symmetric three phase stator winding, we have
\[ R_a = R_b = R_c \]

The flux linkages of phase windings \( a, b \) and \( c \) can be expressed in terms of the self and mutual inducances as the following
\[ \lambda_a = \lambda_{aa} + \lambda_{ab} + \lambda_{ac} + \lambda_{af} = L_{aa} i_a + L_{ab} i_b + L_{ac} i_c + L_{af} i_f \]
\[ \lambda_b = \lambda_{ba} + \lambda_{bb} + \lambda_{bc} + \lambda_{bf} = L_{ba} i_a + L_{bb} i_b + L_{bc} i_c + L_{bf} i_f \]
\[ \lambda_c = \lambda_{ca} + \lambda_{cb} + \lambda_{cc} + \lambda_{cf} = L_{ca} i_a + L_{cb} i_b + L_{cc} i_c + L_{cf} i_f \]

Where \( L_{aa} = L_{bb} = L_{cc} = L_{aa0} + L_{al} \)
\[ L_{ab} = L_{ba} = L_{ac} = L_{ca} = -L_{aa0}/2 \]
\[ L_{af} = L_{afm} \cos \theta \]
\[ L_{bf} = L_{afm} \cos(\theta - 120^0) \]
\[ L_{cf} = L_{afm} \cos(\theta - 240^0) \]

For a balanced three phase machine, \( L_{aa0} = \phi_{aa0}/i_a \), \( L_{al} = \phi_{al}/i_a \), \( \phi_{aa0} \) is the flux that links all three phase winding, \( \phi_{al} \) the flux that links only phase \( a \) winding and \( \theta = \omega t + \theta_0 \).
When the stator windings are excited by balanced three phase currents, we have

\[ i_a + i_b + i_c = 0 \]

The total flux linkage of phase a winding can be written as

\[ \lambda_a = (L_{aa_0} + L_{al})i_a - L_{aa_0}(i_b + i_c)/2 + L_{afm}i_f \cos(\omega t + \theta_o) \]

\[ = (L_{aa_0} + L_{al})i_a - L_{aa_0}i_b/2 + L_{afm}i_f \cos(\omega t + \theta_o) \]

\[ = (3L_{aa_0}/2 + L_{at})i_a + L_{afm}i_f \cos(\omega t + \theta_o) \]

Similarly, we can write

\[ \lambda_b = L_s i_b + L_{afm}i_f \cos(\omega t + \theta_o - 120^\circ) \]

And

\[ \lambda_c = L_s i_c + L_{afm}i_f \cos(\omega t + \theta_o - 240^\circ) \]

Where \( L_s = 3L_{aa_0}/2 + L_{at} \) is known as the synchronous inductance.

In this way, the three phase windings are mathematically de-coupled, and hence for a balanced three phase synchronous machine, we just need to solve the circuit equation of one phase. Substituting the above expression of flux linkage into the circuit equation of phase \( a \), we obtain

\[ v_a = R_a i_a + L_s \frac{di_a}{dt} + \frac{d\lambda_{af}}{dt} \]

In steady state, the above equation can be expressed in terms of voltage and current phasors as

\[ v_a = E_a + (R_a + j\omega L_s)I_a = E_a + (R_a + jX_s)I_a \]

Where \( X_s = \omega L_s \) is known as the synchronous reactance and

\[ E_a = j\frac{\omega L_{afm}f}{\sqrt{2}} = j\frac{2\pi}{\sqrt{2}} f k_w N_{ph} \Phi_f = j4.44f k_w N_{ph} \Phi_f \]

is the induced emf phasor, noting that \( L_{afm}I_f = \lambda_{afm} = k_w N_{ph} \Phi_f \). \( I_f \) is the DC current in the rotor winding and \( \Phi_f \) the rotor magnetic flux in the air gap.

It should be noticed that the above circuit equation was derived under the assumption that the phase current flows into the positive terminal. The reference direction of the phase current was chosen assuming the machine is a motor. In the case of a generator, where the phase current is assumed to flow out of the positive terminal, the circuit equation becomes

\[ V_a = E_a - (R_a + jX_s)I_a \]

The following circuit diagrams illustrate the per phase equivalent circuit of a round rotor synchronous machine in the motor and generator mode respectively.
Experimental Determination of Circuit Parameters:

In the per phase equivalent circuit model illustrated above, there are three parameters need to be determined. Winding resistance $R_a$, synchronous reactance $X_s$, and induced emf in the phase winding $E_a$. The phase winding resistance $R_a$ can be determined by measuring DC resistance of the winding using volt-ampere method, while the synchronous reactance and the induced emf can be determined by the open circuit and short circuit tests.

Open Circuit Test:

Drive the synchronous machine at the synchronous speed using a prime mover when the stator windings are open circuited. Vary the rotor winding current, and measure stator winding terminal voltage. The relationship between the stator winding terminal voltage and the rotor field current obtained by the open circuit test is known as the open circuit characteristic of the synchronous machine.

Short Circuit Test:

Reduce the field current to a minimum, using the field rheostat, and then open the field supply circuit breaker. Short the stator terminals of the machine together through three ammeters; close the field circuit breaker; and raise the field current to the value noted in the open circuit test at which the open circuit terminal voltage equals and rated voltage, while maintain the synchronous speed. Record the three stator currents. (This test should be carried out quickly since stator currents may be greater than the rated value).
Fig. 1.20: (a) Connections for short circuit test  
(b) Open-and short circuit characteristics

Under the assumptions that the synchronous reactance $X_s$ and the induced emf $E_a$ have the same values in both the open and short circuit tests, and that $X_s \gg R_a$, we have

$$X_s = \frac{\text{open circuit per phase voltage}}{\text{short circuit per phase current}}$$

For some machines, the short circuit current is too high if the machine is driven at the synchronous speed. In this case, short circuit test can be performed at a reduced speed say half synchronous speed $n_{syn}/2$ or $f_{rated}/2$. Since $E_a f$, the induced emf in the short circuit test is halved. Thus

$$X_s \bigg|_{f_{rated}/2} = \frac{\frac{1}{2}V_a |f_{rated}}{I_{sc} \bigg|_{f_{rated}/2}}$$

1.4. Synchronous Machine Operated as a Generator

**Electromagnetic power and Torque**

When a synchronous machine is operated as a generator, a prime mover is required to drive the generator. In steady state, the mechanical torque of the prime mover should balance with the electromagnetic torque produced by the generator and the mechanical loss torque due to friction and windage, or

$$T_{pm} = T + T_{loss}$$

Multiplying the synchronous speed to both sides of the torque equation, we have the power balance equation as

$$P_{pm} = P_{em} + P_{loss}$$
Where $P_{pm} = T_{pm}\omega_{syn}$ is the mechanical power supplied by the prime mover, $P_{em} = T\omega_{syn}$ the mechanical power loss of the system. The electromagnetic power is the power being converted into the electrical power in the three phase stator windings, that is

$$P_{em} = T\omega_{syn} = 3E_a I_a \cos \phi_{E_aI_a}$$

where $\phi_{E_aI_a}$ is the angle between phasors $E_a$ and $I_a$.

**Fig. 1.21:** A synchronous machine operated as a Generator

For larger synchronous generators, the winding resistance is generally much smaller than the synchronous reactance, and thus the per phase circuit equation can be approximately written as

$$V_a = E_a - jX_s I_a$$

The corresponding phasor diagram is shown on the right hand side. From the phasor diagram, we can readily obtain

$$E_a \sin \delta = X_s I_a \cos \phi$$

When the phase winding resistance is ignored, the output electrical power equals the electromagnetic power, or

$$P_{em} = P_{out} = 3V_a I_a \cos \phi$$

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Therefore,

\[ P_{em} = \frac{3E_a V_a}{X_s} \sin \delta \]

And

\[ T = \frac{P_{em}}{\omega_{syn}} = \frac{3E_a V_a}{\omega_{syn} X_s} \sin \delta \]

Where \( \delta \) is the angle between the phasors of the voltage and the emf, known as the load angle. When the stator resistance is ignored, \( \delta \) can also be regarded as the angle between the rotor and the stator rotating magnetic fields. The electromagnetic torque of a synchronous machine is proportional to the sine function of the load angle, as plotted in the diagram above, where the curve in the third quadrant is for the situation when the machine is operated as a motor, where the electromagnetic torque is negative because the armature current direction is reversed.

**Voltage Regulation**

The terminal voltage at constant field current varies with the armature current, or load current; that is the generator has regulation that becomes more marked as the load circuit becomes more inductive and the operating power factor falls. This regulation is defined as

\[ VR = \frac{V_{a(NL)} - V_{a(rated)}}{V_{a(rated)}} \]

Where \( V_{a(NL)} \) is the magnitude of the no load terminal voltage, and \( V_{a(rated)} \) the magnitude of the rated terminal voltage. When a generator is supplying a full load, the required terminal must be the rated voltage. The normalized difference between the
magnitudes of the no load voltage and the full load voltage by the rated voltage is defined as
the voltage regulation.

This value may be readily determined from the phasor diagram for full load operation. If the regulation is excessive, automatic control of field current may be employed to maintain a nearly constant terminal voltage as load varies.

1.5. Synchronous Machine Operated as a Motor

Electromagnetic power and Torque

When a synchronous machine is operated as a motor to drive a mechanical load, in steady state, the mechanical torque of the motor should balance the load torque and the mechanical loss torque due to friction and windage, that is

\[ T = T_{\text{load}} + T_{\text{loss}} \]

Multiplying the synchronous speed to both sides of the torque equations, we have the power balance equation as

\[ P_{\text{em}} = P_{\text{load}} + P_{\text{loss}} \]

Where \( P_{\text{em}} = T\omega_{\text{syn}} \) the electromagnetic power of the motor, \( P_{\text{load}} = T_{\text{load}}\omega_{\text{syn}} \) is the mechanical power delivered to the mechanical load, and \( P_{\text{loss}} = T_{\text{loss}}\omega_{\text{syn}} \) the mechanical power loss of the system. Similar to the case of a generator, the electromagnetic power is the amount of power being converted from the electrical into the mechanical power. That is

\[ P_{\text{em}} = 3E_{a}I_{a} \cos \phi_{E_{a}I_{a}} = T\omega_{\text{syn}} \]

Where \( \phi_{E_{a}I_{a}} \) is the angle between phasors \( E_{a} \) and \( I_{a} \).

![Fig. 1.24: A synchronous machine operated as a motor](image)
When the stator winding resistance is ignored, the per phase circuit equation can be approximately written as

\[ V_a = E_a + jX_s I_a \]

The corresponding phasor diagram is shown on the right hand side. From the phasor diagram, we can readily obtain

\[ V_a \sin \delta = X_s I_a \cos \phi \mid_{E_{al}} \]

Where,

\[ \phi_{E_{al}} = \phi - \delta \]

Therefore,

\[ P_{em} = \frac{3E_a I_a}{X_s} \sin \delta \]

And

\[ T = \frac{P_{em}}{\omega_{syn}} = \frac{3E_a V_a}{\omega_{syn} X_s} \sin \delta \]

Where \( \delta \) is the load angle. When the stator winding resistance is ignored, \( \delta \) can also be regarded as the angle between the rotor and stator rotating magnetic fields. In motor mode, the stator field is ahead of the rotor. The electromagnetic torque of a synchronous machine is
proportional to the sine function of the load angle, as plotted in the diagram above, where
the curve in the third quadrant is for the situation when the machine is operated as a
generator, where the electromagnetic torque is negative because the armature current
direction is reversed.

**Synchronous Motor power Factor**

Assume that a synchronous motor is driving a constant torque load. The active power
converted by the machine is constant, no matter what the value of the field current is, since
the motor speed is a constant. Thus,

\[
T = \frac{3V_aE_a}{\omega_{syn}x_s}\sin\delta = \text{constant}
\]

or

\[
E_a\sin\delta = \text{constant}
\]

And

\[
P_{em} = 3V_aI_a\cos\phi = \text{constant}
\]

or

\[
I_a\cos\phi = \text{constant}
\]

Using the phasor diagram below, we analyze the variation of the power factor angle
of a synchronous motor when the rotor field excitation is varied. For a small rotor field
current the induced emf in the stator winding is also small, as shown by the phasor \(E_{a1}\). This
yields a lagging power factor angle \(\phi_1 > 0\). As the excitation current increases, the lagging
power factor angle is reduced. At a certain rotor current, the induced emf phasor \(E_{a2}\) is
perpendicular to the terminal voltage phasor, and hence the stator current phasor is aligned
with the terminal voltage, that is a zero power factor angle \(\phi_2 = 0\). When the rotor current
further increases, the stator current leads the terminal voltage, or a leading power factor angle
\(\phi_3 < 0\). In the phasor diagram, the above two conditions on \(E_a\) and \(I_a\) mean that they will
only be able to vary along the horizontal and the vertical dotted lines, respectively, as shown
below.
Fig. 1.27: Phasor diagram of a synchronous motor in under excitation, unit power factor, and over excitation mode.

For conversion of a certain amount of active electrical power into mechanical power, a certain amount of magnetic flux is required. In the case of a lagging power factor, the rotor field current is so small that some reactive power is required from the stator power supply, and hence the stator current lags the terminal voltage. This state is known as under excitation. When the rotor field current is just enough to produce the required magnetic flux, a unit power factor is obtained. If the rotor field current is more than required the spurious reactive power is to be exported to the power lines of the power supply. This state is known as over excitation.

In practice, because of this feature, synchronous motors are often run at no active load as synchronous condensers for the purpose of power factor correction. The diagram underneath the phasor diagram illustrates schematically the power factor compensation for an inductive load, which is common for factories using large induction motor drives, using a synchronous condenser draws a line current of leading phase angle, whose imaginary component cancels that of the load current, the total line current would have a minimum imaginary component. Therefore, the overall power factor of the inductive load and the synchronous condenser would be close to one and the magnitude of the overall line current would be minimum.

It can also be seen that only when the power factor is unit or the stator current is aligned with the terminal voltage, the magnitude of the stator current is minimum. By plotting the magnitude of the stator current against the rotor excitation current, a family of “v” curves can be obtained. It is shown that a larger rotor field current is required for a large active load to operate at unit power factor.
Synchronous Motor Drives

A synchronous motor cannot start in synchronous mode since the inertia and the mechanical load prevent the rotor to catch up with the rotating magnetic field at the synchronous speed. A common practice is to embed a few copper or aluminium bars short circuited by end rings in the rotor and to start the motor as an induction motor. When the rotor speed is close to the synchronous speed, the rotor is energized with a DC power supply and it will catch up for synchronize with the rotating magnetic field. This, however, is not a problem for power factor electronic inverter controlled synchronous motors because the inverter can ramp up the excitation frequency.

Since the rotor speed is proportional to the stator excitation frequency, the speed of a synchronous motor can only be controlled by varying the stator frequency. A common speed
control strategy is the **variable voltage variable frequency (VVVF)** speed control, in which the ratio between the stator voltage and frequency is kept a constant. Below is the block diagram of an open loop synchronous motor drive. For rotor speeds below the rated speed, VVVF strategy is employed, and the maximum torque that the motor can produce is a constant. When the rotor speed required is higher than the rated speed, the stator voltage is capped to the rated voltage while the frequency is increased. The maximum torque is then reduced as the speed increases. As illustrated by the torque-speed curves in the diagram below, the motor drive is suitable for a constant torque load when the speed is below the rated speed, and would be suitable for a constant power load when the speed is higher than the rated speed.

**Fig. 1.30: Stedy-state model of an open-loop synchronous motor drive**
In the closed loop control, the stator excitation can be controlled according to the rotor position such that stator magnetic field is perpendicular to the rotor field and hence the electromagnetic torque the motor produces is always maximum under any load conditions. The torque speed curve of the motor in this case is essentially same as that of a DC motor. This type of motor drive is known as the brushless DC motors. The diagrams below illustartes an optic position sensor and the block diagram of the closed loop synchronous motor drive.
Fig. 1.33: Rotor position sensor

Fig. 1.34: Steady-state model of a closed-loop synchronous motor drive
CHAPTER 2

2. Low Speed Direct Drives

In this chapter is a review of the state of the art in low-speed direct drives. For each application, its specific advantages are mentioned followed by examples of the required power and speed of the electrical machine. Various direct-drive solutions which are already commercialized or under investigation are then shortly described along with the machine topology. Finally, some features specific to low-speed electrical machines for direct-drive applications are presented.

2.1. Advantages of Direct Drives

Many applications require a low rotating speed and a high torque. Usually, conventional machines with speeds from 1000 to 3000 rpm are connected to gearboxes, in order to achieve the required low speed and high torque. The emergence of a PM machine technology offers today another alternative. PM machines can rotate directly at low speed and high torque, making it possible to eliminate the gearbox in the drive.

Fig. 2.1: (a) Geared drive (b) Direct drive

Direct drives have many advantages over geared drives, mostly coming from the simplification of the transmission system. These advantages include [2,3]:

- Reduced maintenance – A gearbox requires maintenance. Indeed, it needs to be regularly lubricated in order to minimize friction.
- Higher reliability – without gearbox, important sources of failures are eliminated and the drive can have a longer lifetime.
- Reduced noise - A gearbox and other mechanical parts of the transmission system such as belts or pulleys are sources of noise. With fewer mechanical parts, the direct drives may thus be less noisy.
- Higher efficiency- Removing the gearbox means also removing a potential source of losses. The losses in the gearbox are mostly generated by friction between the gears.
- Reduced weight – A direct drive can be made lighter than geared drive.
Direct drives can procure other advantages specific to the application, as will be seen in the examples.

2.2. Examples of Low-Speed Direct-Drive Applications

2.2.1. Wind Turbines

The number of wind turbine installations has increased greatly during the past years. Most of the installed wind turbines have a gearbox enabling a generator rotating at high speeds. In [4], case of wind turbines, the main benefit of a direct drive is the reduction of failures and maintenance. A survey of statical data of wind power turbine failures and downtime shows that the gearbox is the most troublesome component in a typical turbine: The gearbox is responsible for 20% of the total downtime and requires in average 256 hours of reparation time per failure.

Depending on the turbine size, the power of the generator can be from a few kilowatts to several megawatts. The shaft of large turbines rotates at a speed of approximately 15rpm when the wind is optimum.

Direct drive wind turbines are widely studied and some are already manufactured. Different generator types can be used in a direct drive. Some manufacturers utilize induction or synchronous machines. An example is Enercon that uses a direct-drive doubly-fed induction generator (DFIG) in a 2MW turbine. However, PM machines enable a significant weight reduction compared to DFIGs, which is of importance when the generator has to be lifted into the nacelle. Some examples of direct-drive wind turbine projects with PM geneartors are listed below sorted by machine topology:

- Radial-flux PM (RFPM)- RFPM generators are quite common in direct-drive wind turbines. Harakosan commercializes one of the largest direct-drive wind turbines with its 2MW Z72. Details on the design of this wind turbine along with its RFPM generator can be found in [5]. In another interesting project, VG Power proposes a RFPM generator with a reduced weight obtained by placing the bearing in the airgap. A 3MW prototype is intended to be constructed, following the successful testing of a down scaled prototype [6].
- Axial-flux PM (AFPM)- AFPM generators are also widely investigated [7-9] and manufactured by some wind- turbine producers such as Jeumont Industry.
- Transverse-flux PM (TFPM)- TFPM are intending because of their high torque density [10]. No large wind turbines equipped with TFPM generators are currently installed. However, Eocycle technologies commercializes TFPM generators with a power of up to 10KW and intends with claw poles partly in soft magnetic composites (SMC) is described in [11]. Another original TFPM topology is investigated in [12].
2.2.2. Marine Propulsion

Most of the cruise ships manufactured today have an electric propulsion. Among other advantages, the electric propulsion offers a better passenger comfort and is more reliable than conventional drives with diesel engines or gas turbines [15]. Direct-drive PM motors also tend to replace synchronous machines connected to gearboxes. For this application, the main advantage of the direct drive is its lower weight and the gain in maneuverability for the ship. The PM motor can be placed in a rotatable pod directly connected to the propeller which makes it possible to change the position of the propeller (and thus of the ship) very easily and smoothly.

The largest ships require motors with a rated power over 10MW. The speed of the propeller is then lower than 200 rpm [3,14].

The most famous solution for Direct-drive ship propulsion in ABB’s azimuthing podded propulsor named Azipod [16]. RFPM motors are used in Azipods. Depending on the size of the pod, the motors have a rated power between 400kW and 5MW, run between 150 to 500 rpm and have 10 to 16 poles [3]. Other solutions have also been investigated, such as AFPM motors [15] or TFPM motors [17].
2.2.3. Elevators

Different solutions exist to lift an elevator cabin depending on the building size and architecture. Traditionally, induction machines have been used together with an hydraulic system or a gear. Another solution for large elevators is to utilize direct-drive DC or Induction machines [18].

Elevators driven by gearless PM machines have recently gained popularity for medium-sized buildings, i.e., buildings with less than 20 floors. In addition to the common advantages of a direct drive such as an oil free system, less noise, and a higher drive efficiency, the gearless elevators do not need any machine room. Therefore, space is saved in the building. However, the drive is not exactly direct since cables or belts are used to move the cabin.

A typical passenger’s elevator for medium-sized buildings carries loads from 500kg to 2500kg at a speed of approximately 1m/s. 5 to 20kw motors are required with a shaft speed lower than 300rpm. Larger elevators can require motor ratings of up to 500kW.

All of the four largest elevator manufactures propose gearless elevators using PM machines. Otis with its Gen2 proposes a RFPM motor driving the elevator with a system of belts that replace the conventional steel cables. Kone adopted the solution of a flat AFPM machine. As can be seen in the below figure 2.4. the AFPM machine can be placed inside the space needed for the counter weight, between the elevator’s cabin and the wall [19]. Another similar solution with details on the design of a slotless AFPM machine is described in [20].

Solutions with linear motors are being investigated for lifting elevators of large buildings, such as in [21] with linear switched reluctance motors.

Fig. 2.4: (a) KONE Eco Disc AFPM machine [22]; (b) Kone Mono space elevator [19].
2.2.4. Washing Machines

In a conventional washing machine, a DC or an induction motor drives the drum via a belt and pulleys. The main advantage of a direct-drive washing machine comes from the suppression of the belt, pulley and eventual brushes of the DC motor. Indeed, these elements are the weak parts of the washing machine and are often the cause of failures.

A washing machine motor for home appliance rates usually less than one kilowatt. The drum of the machine rotates approximately at 50rpm during the washing process, up to approximately 1500rpm or higher during the drain [23]. Therefore, the direct-drive motor of the washing machine should run over a large speed range which is achieved by operating under field-weakening.

LG Produces the most famous commercialized direct-drive washing machine for home appliances. The motor, directly-connected to the drum, is a brushless DC (BLDC) PM motor. BLDC PM motors have trapezoidal back-EMF waveforms and are supplied with rectangular currents.

Fig. 2.5: (a) conventional washing machine (b) LG’s Direct-Drive washing machine [24].

2.2.5. Pulp and Paper Industry

Low speed drives with gearboxes are widely used in the pulp and paper industry. However, a direct drive without gearbox allows, among other advantages, a gain of space and an easier installation.

Paper machine have rotational speeds between 200 and 600rpm. Motor powers range from 30kW to 1800kW [25]. Direct drives with induction motors can compete with geared drives in some cases [26]. PMSM are also successfully used in direct drives for pulp and paper applications [3, 25]. These machines are RFPM motors with usually 12 poles [3]. Different designs of RFPM machines with non-overlapping concentrated windings are investigated in [27] and a 45kW, 600rpm prototype motor with V-shaped buried PMs has been built.
2.2.6. Others

Direct drives area also becoming more common in applications requiring precise speed and position controls. Such applications include machine tools, turning tables, radar, telescopes, etc. The motors used in these applications are the so-called torque motors which are brushless DC servomotors with surface mounted PMs on the rotor. The torque motor can have sizes from 100mm to more than 2m [28]. In order to provide large torques, the torque motors have a large airgap diameter and, therefore, they look like a ring.
CHAPTER 3

3. Design of Low-Speed Radial-Flux Permanent-Magnet Synchronous Machines

A summary of the main results of the research is presented in this chapter. First, the background of the design and the optimisation are presented briefly. Then the two types of the radial-flux PM synchronous machines designed are presented separately. First, the machine topologies are presented briefly and then the main results of the analysis and the optimisation are summarised. The experimental machines are also presented.

3.1. Background of The Design

The purpose of this study is to design a generator for gearless wind turbines. The study focuses on the electromagnetic design and optimisation of two types of multipole, radial-flux PM synchronous machines. The machines have different kinds of stator windings. The first machine has a conventional three-phase, diamond winding. The second machine has an unconventional three phase, single-coil winding. The rated powers of the machines analysed are 500kW, 10kW and 5.5KW. The rated speed is 40 rpm for the high power and 175 rpm for the low-power machines.

Several features should be taken into account when designing a low-speed generator. The characteristics of the machine should be sufficient, for example, the efficiency high and the torque ripple low. Furthermore, the dimensions of the machine should not be too large and the weight and the cost too high.

The diameter of a low-speed machine may be rather large and the length small. There may be a great number of poles in a low-speed machine and the pole pitch and slot pitch should not be allowed become too small. For mechanical reasons, a generator with a large air-gap diameter should have a rather large air-gap. Furthermore, the surface-mounted magnets should be mechanically protected by a band surrounding the rotor. Therefore, the air-gap length should be at least 1% of the air-gap diameter of the low-speed machine. The output frequency is usually lower than 50HZ and a frequency converter is needed in the low-speed machines. The converter makes it possible to use the machines in variable speed operation.

Usually, most of the losses in PM machines are concentrated in the stator winding but there can be high losses in the rotor. The losses should not be too high in the PM machine. Especially in the rotor side, because the heating can cause the polarisation of the magnets to disappear.

When the rotor rotates and the flux from the magnets jumps sharply from one stator tooth to another, the force caused by the magnetic field changes its direction rapidly. The result is a torque ripple around the average torque. The torque ripple is also partly caused by the higher harmonics in the supply voltage. The stator winding is not sinusoidally distributed along the air gap surface but embedded in the stator slots. This induces higher harmonics in
the flux distribution, which affects the torque. The torque ripple can cause problems of noise and vibration and especially cogging torque can make the machine difficult to start.

The torque ripple of the machine analysed is reduced by changing the shape of the magnets and the stator slots. The torque ripple can also be reduced by skewing the stator slots or magnets. However, the skewed design is more complex than the unskewed one. The skewing also causes leakage flux between parallel magnets and increases losses of the machine. The analysis method used in this work is based on the assumption of a two-dimensional magnetic field. It is not suitable for analysing the three-dimensional effects associated with skewing. Therefore, the skewed design is not analysed in this study.

The properties of the permanent-magnet materials used in the calculations are shown in the below table. High-energy sintered NdFeB magnets are chosen to be used. The magnets give a sufficient air-gap flux density with a low volume of the magnet material. Furthermore, these magnets tolerate demagnetising forces quite well. The temperature of magnet material A is chosen to be 60°C in the calculations, because the risk of demagnetisation of the magnets increases very strongly when the temperature increases. The characteristics of magnet material B are better at high temperature than those of magnet material A and, therefore, it is possible to use a higher temperature, 100°C, with a lower risk of demagnetisation. The magnets lose their properties completely at a Curie temperature of 310°C.

<table>
<thead>
<tr>
<th>Magnet</th>
<th>A at 60°C</th>
<th>B at 100°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet type</td>
<td>NdFeB</td>
<td>NdFeB</td>
</tr>
<tr>
<td>Remanence [T]</td>
<td>1.14</td>
<td>1.0</td>
</tr>
<tr>
<td>Coercivity [kA/m]</td>
<td>850</td>
<td>760</td>
</tr>
<tr>
<td>Conductivity [kS/m]</td>
<td>461</td>
<td>715</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>7600</td>
<td>7600</td>
</tr>
<tr>
<td>Curie temperature [°C]</td>
<td>310</td>
<td>310</td>
</tr>
</tbody>
</table>

The demagnetisation curves of magnet type B at different temperatures are shown in fig 3.1. The curves in the second quadrant are linear. The working point of the magnet moves on the curve depending on the loading of the machine. When the working point is on the linear part of the curve, the polarisation of the magnet is not changed. If the working point moves beyond the knee of the curve, the permanent-magnet material starts to lose its polarisation, i.e., the magnets operate in the irreversible demagnetisation region and will not be able to recoil back to their original operation point. Therefore, the maximum loading of the machine must be limited by the largest allowable demagnetisation current specified by the demagnetisation characteristics. The place of the knee of the demagnetisation curve depends on the properties of the material and the temperature of the magnets. The limit of the minimum flux density in the permanent magnets as a function of the temperature is shown in fig. 3.2 if the minimum flux density in permanent magnets is beyond the curve, the magnets are in danger of being damaged. The characteristics of the permanent magnet material are
improving and, therefore, fig. 3.1 has two curves for magnet material A: A old(year 1995) and A new (year 1999).

One of the most critical situations for the magnet material demagnetisation is a short circuit at the machine terminals. A sudden three-phase, and also in some cases a two-phase, short circuit at the machine terminals at rated load is analysed in this study. The machine should be designed so that the demagnetisation problem can be avoided, or a certain percentage of demagnetisation at a possible maximum current and temperature is allowed.

The corrosion of the magnet material can be a problem, especially in offshore wind turbines. The corrosion can be avoided by coating the magnets, for example with Nickel or Aluminium chromate coatings. The magnets of the experimental machines are protected from corrosion by using impregnation.

The high energy magnets must be magnetised before they can be assembled on to the rotor. It is not possible to get high enough flux density in the rotor core for magnetising the magnets because of the saturated rotor iron. The mounting of the magnetised magnets on the rotor are usually complicated and special tools must be used.

### 3.2. Background of The Optimisation

The machine are optimised using a genetic algorithm combined with the finite element method. For optimising an electrical machine, several features need to be considered. The operational characteristics of the machine should be sufficient and the cost of the machine low. The optimisation problem is to find a design which fulfills all the requirements. However, there are many possibilities for choosing an objective function. The objective function can, for instance, be the cost, the pull-out torque, the efficiency or a combination of these.
The first optimisation problem considered is finding a design which is as cheap as possible. The objective function is the cost of active materials (cost). The cost of active parts of the machines is based on the assumption that the cost of the materials and the manufacturing can roughly be estimated as a cost per active weight of the different materials. The costs of the materials used in the optimisation are given in below table 4. The cost of the copper includes the manufacturing cost of the winding. The punching and the waste parts of the sheet are taken into account in the iron cost. The magnets have been divided into sufficient pieces, phosphorated and magnetised. However, the material and manufacturing costs change continually and, therefore, the cost ratio between the materials is more important than the real cost of each material in the comparison of the machines.

<table>
<thead>
<tr>
<th>Material</th>
<th>Cost [EUR/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NdFeB magnets</td>
<td>100</td>
</tr>
<tr>
<td>Copper</td>
<td>6</td>
</tr>
<tr>
<td>Iron</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3.2: Cost of materials

The second optimisation problem considered is finding a design which has a high pull-out torque. If the objective function is the pull-out torque, the optimisation leads to a very expensive design. Therefore, the objective function is chosen to be the pull-out torque per the cost of active materials ($T_{max}/Cost$), which is reasonable in the comparison of different designs.

The third optimisation problem considered is finding a design which has high efficiency. The objective function is the electromagnetic losses.

The summary of the main data of the optimisation is given in table 5. Twenty-eight different designs of the PM machines are optimised in this study. The optimisation have 5-8 free parameters and some constant parameters. The other dimensions are calculated from the given parameters.

In the structural optimisation especially, the unconstrained optimisation easily leads to designs that could hardly be realised. The minimum pull-out torque, the minimum efficiency, the minimum power factor and in some cases the maximum cogging torque are used as constraints in the optimisation.

Some dimensions of the machines are chosen before the optimisation process. In this way, the number of free variables can also be reduced. The maximum size of the machine usually depends on the applications. The outer diameter of the machines is chosen to be constant in most of the optimisations, because the diameter should not be too large in wind power plants. The manufacturing process and the strength of the design should also be taken into account when designing an electrical machine. The stator and rotor yoke heights have lower limits so that the design is rigid enough. The yoke heights are chosen to be constant in most of the optimisations, although electromagnetically the yoke heights would not have to be so large.
The genetic algorithm combined with the finite element method was successfully used for optimisations of low-speed PM machines for gearless wind turbines. The finite element method gives detailed information of the electrical characteristics of the machines and various machine designs can reliably be compared with each other. However, the genetic algorithm combined with the finite element method used consumes plenty of computer time.

Table 5. Data on the optimisations of PM machines. F means free variable, C constant parameter, $b_s$ stator slot width and * coupling between the diameter and the length (machine constant is equal).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>5</th>
<th>5</th>
<th>600</th>
<th>55</th>
<th>55</th>
<th>10</th>
<th>500</th>
<th>10</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power [kW]</td>
<td>5</td>
<td>5</td>
<td>600</td>
<td>55</td>
<td>55</td>
<td>10</td>
<td>500</td>
<td>10</td>
<td>500</td>
</tr>
<tr>
<td>Machine type</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Diamond winding</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>- Single-coil winding</td>
<td>-</td>
<td>-</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Objective function</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Efficiency</td>
<td>-</td>
<td>-</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- Cost</td>
<td>x</td>
<td>-</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>x</td>
</tr>
<tr>
<td>- Pull-out torque / Cost</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Constraints</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Pull-out torque</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>- Efficiency</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>- Power factor</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>- cogging torque</td>
<td>-</td>
<td>-</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Different constructions</td>
<td>10</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Free parameters</td>
<td>6/8</td>
<td>5/7</td>
<td>7</td>
<td>8</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3.3: Data on the Optimisations of PM machines. F means free variable, C constant parameter, $b_s$ stator slot width and * coupling between the diameter and the length.

3.3. Conventional PM Synchronous Machines[30-34]

3.3.1. Machine Topology

The cross-sectional geometry of the conventional PM synchronous machine is shown in figure and the phase belts of the winding in table 6. The main data of the machines
analysed are shown in table 7. The machines have a three-phase, two-layer, round-wire diamond winding. Different stator and rotor designs of the machine have been compared in this study. The machine shave NdFeB permanent magnets and they are mounted on the surface of the rotor yoke or below the pole shoes. The rotor core is made of solid iron and also in some cases of electrical sheets. The machines chosen for further analysis have fractional-slot windings and the number of stator slots per pole and phase is $q=1.5$.

![Cross-sectional geometry of the PM machine](image)

**Fig. 3.3: Cross-sectional geometry of the PM machine**

<table>
<thead>
<tr>
<th>Slot number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom layer</td>
<td>A</td>
<td>A</td>
<td>-C</td>
<td>B</td>
<td>B</td>
<td>-A</td>
<td>C</td>
<td>C</td>
<td>-B</td>
</tr>
<tr>
<td>Top layer</td>
<td>A</td>
<td>-C</td>
<td>-C</td>
<td>B</td>
<td>-A</td>
<td>-A</td>
<td>C</td>
<td>-B</td>
<td>-B</td>
</tr>
</tbody>
</table>

**Table 3.4: Phase belts of the three-phase two-layer winding of the PM machine.**

<table>
<thead>
<tr>
<th></th>
<th>5.5kW</th>
<th>10kW</th>
<th>500kW</th>
<th>500kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated output</td>
<td>5.5</td>
<td>10</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Rated Frequency</td>
<td>17.5</td>
<td>17.5</td>
<td>26.7</td>
<td>50</td>
</tr>
<tr>
<td>Rated speed</td>
<td>175</td>
<td>175</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>No. of poles</td>
<td>12</td>
<td>12</td>
<td>80</td>
<td>152</td>
</tr>
<tr>
<td>No. of phases</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>No. of stator slots</td>
<td>54</td>
<td>54</td>
<td>360</td>
<td>684</td>
</tr>
<tr>
<td>Connection</td>
<td>Wye</td>
<td>Wye</td>
<td>Wye</td>
<td>wye</td>
</tr>
</tbody>
</table>

**Table 3.5: Main data of the PM machines analysed.**

3.3.2. Design of The Machines[30]
The main results of the design and the analysis of a 500kW, 80 pole PM machine are presented in this section. An example of a 152 pole machine is also presented in detail [30]. The aim of the work is to find a suitable electromagnetic design for the directly driven low-speed generator.

Several features should be taken into account when designing an electrical machine. The magnet height affects, for instance, the air-gap flux density of the machine. According to the analysis, the need for magnet material increases rapidly when the peak air-gap flux density exceeds 0.8T. The magnet width also affects the voltage wave form, the air-gap torque and torque ripple of the machine.

The torque ripple can cause problems of noise and vibration and the cogging torque especially can make the starting of the machine difficult. The torque ripple depends, for instance, on the magnet, stator slot width and the number of stator slots per pole and phase \( q \). By using different values of \( q \), the analysis shows that one minimum point is almost at the same magnet width, \( 2/3 \) times the pole pitch. By using a fractional slot winding the torque ripple is smaller than with an integral slot winding. The torque ripple can also be decreased if the width of the slot opening is as small as possible.

Usually, most of the losses in PM machines are concentrated in the stator winding but there can also be high losses in the rotor. The eddy-current losses in rotor iron (solid steel) and magnets are very high, 0.5-1.1% of the output power at rated load, when the number of slots per pole and phase, \( q \), is 1 or 1.25. With so few slots per pole and phase, the stator magneto motive force contains a lot of harmonics. When \( q \) is more than 1.5, the rotor eddy-current losses are low, less than 0.1% of the output power at rated load. The electromagnetic losses also depend on the magnet width. The analysis also shows that the pull-out torque versus magnet weight is highest when the width of the magnet is 65-80% of the pole pitch.

As summary of the design, the electromagnetic properties of the PM machine are highly dependent on the number of stator slots per pole and phase as well as the shape of the magnets, the stator slots and the slot opening. Very much magnet material would have to be used in the machine designed if the peak air-gap flux density should exceed 0.8T. The pull-out torque versus magnet weight is highest when the width of the magnets is 65-80% of the pole pitch. The torque ripple can be made low by using fractional slot winding, suitable magnet width and small slot opening width. The good compromise of the magnet width is \( 2/3 \) times the pole pitch. If the torque ripple and voltage waveform are also taken into account.

3.3.3. Machine With a Diode Rectifier [31-33]

The main results of the electromagnetic analysis of a 500kW, 80 pole PM machine connected to a frequency converter are presented in this section [31-33]. The aim of this work [31] is to compare the characteristics of the PM machine with a diode rectifier and a resistive load [32]. The losses of the machine are analysed in a diode rectifier load[33].

A synchronous machine can be directly connected to a simple diode rectifier. The price of a diode rectifier is low and control electronics are not needed. The electrical
characteristics of the machine with a diode rectifier load are calculated with a circuit simulator combined with two dimensional finite element modelling of electrical machines. The electric circuit of the simulation is presented in figure 5. The frequency converter consists of a rectifier, an intermediate circuit and an inverter unit. A rectifier with a current source type intermediate circuit (L) is used. The inverter unit, which makes active power from the intermediate circuit, is replaced by a resistor ($R_L$).

Fig. 3.4: A PM generator feeding a conventional and a special six-pulse diode rectifier.

First, the characteristics of the machine with a resistive and two different diode rectifier loads are compared [31]. The first circuit is a conventional and the second one a special six-pulse diode rectifier. The leading time of the diodes of one phase is longer in the special diode rectifier than in the conventional one and, therefore, it may be possible to use the stator winding effectively. A diode rectifier causes harmonics in the phase currents and is not able to deliver reactive power to the machine. The maximum electrical output of the machine is lower in the diode rectifier load than the output when connected directly to the sinusoidal grid. The terminal voltage of the machine decreases when the load increases. Furthermore, the high load affects the voltage drop. The load capacity of the machine in the rectifier load is less than 81% of the load capacity in the resistive load, when the total electromagnetic losses of the machine are equal under different load conditions. The stator resistive and rotor eddy-current losses are high with the rectifier loads. The load capacity and the maximum output power of the machine with the special rectifier load are lower than those of the conventional rectifier load and in the resistive load. The reason is that the low order harmonic contents is higher and the power factor and the terminal voltage lower in the special rectifier load than those in the other cases.

According to the calculation the maximum output power [32] and the efficiency of the machine can be improved by increasing the volume of the magnet material, and they can be improved more as a function of the magnet weight by increasing the magnet height than by increasing the magnet width. The pull-out torque per magnet weight is highest when the width of the magnets is 65-80% of the pole pitch.

The stator losses are higher in the rectifier load than in the resistive one [33]. The rotor core is made of conducting material (solid steel) and most of the rotor losses are eddy current losses caused by high frequency flux variations. On the other hand, rotor core and permanent magnets have very low losses in resistive load. Thus, the rotor losses are much
higher in the rectifier load than in the resistive load. A high efficiency is obtained when the width of the magnets is 65-80% of the pole pitch. If the magnet width is less than 60% of the pole pitch, the machine has high efficiency only at low load.

As a summary of the analysis, the efficiency, the load capacity and the maximum output power of the machine are lower in diode rectifier loads than that when connected directly to a sinusoidal grid. The maximum output power and the efficiency of the machine can be improved by increasing the volume of the magnet material and they improved more as a function of the magnet weight by increasing the magnet height than the magnet width. The efficiency of the machine is high when the magnet width is 65-80% of the pole pitch. If the magnet width is less than 60% of the pole pitch, the machine has high efficiency only at low speed.

3.3.4. Comparison of Different Rotor Designs[34]

Various Rotor designs of a 5.5kW and a 10kW PM machine are optimised and compared in their section[34]. The aim of the comparison is to find a suitable rotor design for the low-speed PM machine.

Five different rotor designs are investigated. The cross-sectional geometries of the machines are shown in below figure6. The following abbreviations are used for the rotor designs:

- SM: Curved surface-mounted magnets
- RM-1: Rectangular surface-mounted magnets, one magnet per pole.
- RM-3: Rectangular surface-mounted magnets, three parallel magnets per pole
- PS-1: Rectangular magnets equipped with pole shoes, constant air-gap length
- PS-2: Rectangular magnets equipped with pole shoes, air-gap length varies

The first rotor(SM) has curved surface-mounted magnets. The air-gap length between the magnets and the stator core is constant. The surface-mounted magnets should be mechanically protected by a band surrounding the rotor and, therefore, the air-gap length should be large enough. The shape of curved magnets depends on the rotor diameter. The manufacturing of curved magnets is more complex than that of reactangular magnets. The cost of curved magnets is about 3-6% higher than the cost of reactangular magnets depending of the shape of the magnets.

The second and thrid rotors(RM-1,RM-3) have rectangular magnets. One size of the magnets can be used in different by varying the number of parallel magnets. If only one magnet per pole(RM-1) is used, the air-gap will be some millimetres larger in the middle of the magnet(pole) than at the edge of the magnet when the rotor diameter is small. The rotor
The construction of rectangular magnets is more complex than that of the curved magnets and the assembly of many parallel rectangular magnets may be difficult.

The fourth and fifth rotors (PS-1, PS-2) have pole shoes. The air-gap length is constant in the PS-1 machine. In the PS-2 machine, the air-gap length varies; at 60 electrical degrees the air-gap length has twice the value of the pole centre. A binding is not needed to be used and the air-gap length can be small. The pole shoes protect the magnets mechanically and magnetically from demagnetisation. A disadvantage of the pole-shoe machines is the complex design.

Fig. 3.5: Cross sectional geometries of the PM machines.

The machines compared are first optimised by using equal constraints and after that compared with each other. The first optimisation problem considered to find a design which is as cheap as possible. The objective function is the cost of active materials (Cost). The second optimisation problem considered to find a design which has a high pull-out torque. The objective function is the pull-out torque per the cost of active materials \( T_{\text{max}}/\text{Cost} \). The main data of the optimisation are shown in the above table 5. The optimisation of the surface-magnet machines includes six free variables and the pole-shoe versions eight free variables, because of the more complex design.
The optimisation results are shown in figs 7 and 8. The best rotor design has curved surface mounted magnets (SM). The cost of active materials is the lowest and the pull-out torque per the cost of active materials the highest in this design. The machine is also shortest, when the length of the machine can vary in the optimisation. The second best rotor design has three parallel rectangular surface-mounted magnets in each pole (RM-3). If the machine has only one rectangular magnet per pole (RM-1). The pull-out torque the cost of active materials is the lowest in the optimisation. In this design, the average air-gap length between the magnets and the stator surface increases and this affects to the air-gap flux density negatively. The results of the pole-shoe machine with a constant air gap between the stator and pole shoe (PS-1) and the machine with more curved pole shoe (PS-2) are almost similar. The voltage waveform can be made sinusoidal by using the curved pole shoe, but then the average air-gap length also increases.

The analysis of the torque ripple and the minimum flux density in permanent magnets are not included in the optimisation, but the phenomena are studied separately. The torque ripple analysis shows that there are three different torque ripple minima within the magnet width of 60-100% of the pole pitch. The cogging torque can be reduced to less than 1% of the rated torque in all the designs analysed by choosing a suitable magnet width. On the other hand, for the pole-shoe machine with unconstant air gap (PS-2), the cogging torque at any pole shoe width is under 1% of the rated torque. The torque ripple depends on the distance between two magnets in the three rectangular-magnet machine (RM-3). Thus, the torque ripple contents of the machines are highly dependent on the relative movement of the stator slots and the magnets and also the form of the air gap flux density, i.e., is it a sinusoidal or a rectangular form having a lot of low order harmonics.

The minimum flux density in permanent magnets is analysed during a sudden three-phase short circuit. The analysis shows that the minimum flux density of the surface-magnet machine is lower than that in the pole-shoe versions. The minimum flux density in the permanent magnets is the highest, when the stator slot and tooth widths are narrow, i.e., the
number of poles is large. The risk of demagnetisation can be decreased by increasing the magnet height, i.e., by increasing the magnetic flux density in the air gap. An advantage of the pole shoes is that magnets can reliably be protected against demagnetisation. In this case, the stator demagnetising flux does not penetrate significantly into the magnets. However, the eddy-current losses in the solid pole-shoe rotor are rather high, more than 1.5% of the output power at rated load. The risk of demagnetisation can be reduced in a surface-magnet machine by using advanced magnet materials and sufficient magnet thickness.

The investigation of various rotor designs shows that the rotor equipped with curved surface mounted magnets has various advantages. The cost of active materials is the lowest and the pull-out torque per the cost of active materials the highest in this design. The second best rotor design has three parallel rectangular surface-mounted magnets in each pole. The pull-out torque per the cost of the active material of the rotor design of one rectangular magnet per pole is the lowest in the optimisations. The magnets can reliably be protected mechanically and magnetically by using advanced magnet materials and sufficient magnet thickness. The cogging torque can be reduced to less than 1% of the rated torque in all the designs compared by choosing a suitable magnet width.

3.3.5. Experimental Machine [34]

A picture of the machine is shown in Fig 9 [34]. The number of poles is 12 and the number of stator slots per pole and phase 1.5. the outer diameter of the machine is 400mm and the stator and rotor core lengths are 200mm. the machine has three parallel rectangular magnets in each pole(RM-3). The magnets are divided into four parts in the axial direction and mechanically protected by a glass fibre ban surrounding the rotor.

The laboratory set-up used for testing the PM machine and the equipments used in the experiments are presented. The prototype machine was first tested by rotating the machine as a generator. The measured open-circuit voltage is 376V and the calculated one 380V. the phase-to-voltages of the machine are almost sinusoidal. The measured harmonic voltage factor(HVF) [IEC 34-1] in each phase is lower than 4.5% and in line-to-line voltage 0.6%. the HVF is computed by using the following formula:

$$HVF = \sqrt{\frac{\sum u_n^2}{n}}$$

Where $u_n$ is the per unit value of the harmonic voltage and $n$ is the order of harmonic. The measured and the calculated cogging torque is 5Nm, i.e., 1% of the rated torque. The calculated synchronous reactance of the machine is $4.8\Omega$ ($x_d = 0.33$) and the measured stator resistance $1.3\Omega$. the calculated minimum flux density in permanent magnets during a sudden three-phase short circuit is 0.03T.

The prototype machine was tested as motor, too. In this case the machine is fed by a PWM frequency converter. The terminal voltage of the machine is 411V and the frequency
18HZ in the load test. The torque-current characteristics and the efficiency of the machine are shown in below fig 10 and 11. The measured pull-out torque is 1330Nm in converter supply and the calculated one 1400Nm in sinusoidal supply. The measured total efficiency at rated load is 90.09%. The measured no load losses are 23W. The calculated efficiency is 90.8% in sinusoidal supply without the cooling and the bearing losses and 90.6% with them. The efficiency of the machine is also high at partial load. The calculated torque ripple at rated load is 29Nm, i.e., 5%.

The prototype machine has moderate torque ripple and high efficiency, furthermore, the voltage waveform is almost sinusoidal. The computed results agree well with the measured ones. The machine type can be used, for example, as a wind power generator or as a machine in other low-speed applications.

Fig. 3.8: The prototype PM Machine.
3.4. Single-Coil WINDING PM Synchronous Machines[35-37]

3.4.1. Machine Topology

The single coil winding PM machines have a special type of stator winding. The cross-sectional geometry of the machine is shown in below figure 12 and the phase belts of the winding table number 8. The coil design of the winding is shown in figure 13. The main data of the machines are shown in table number 9. The machines have a three-phase winding consisting of coils which are placed in slots around every second tooth. The stator winding can be assembled from the same types of coils used in a small transformer. The stator slots can be open or semi-close. The length of the overhang winding is as short as possible. Furthermore, the coils of two phases are not close to each other in the winding overhangs and the phase insulation is not needed. The coils of each phase can be connected in parallel or in series. The stator core can be wound directly from the tape of the electricity sheets. The number of stator slots per pole is small, only 1.5. It means the value of $q$ is 0.5, and therefore, the pole pitch can be very small. The design of the machine is very simple and it is easy to manufacture.

![Cross sectional geometry of the single coil winding PM machine](image)

<table>
<thead>
<tr>
<th>Slot Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>A</td>
<td>-A</td>
<td>C</td>
<td>-C</td>
<td>B</td>
<td>-B</td>
</tr>
</tbody>
</table>

Table 3.6: Phase belts of the three-phase winding of the PM machine
Fig. 3.12: Winding design of the single-coil winding PM machine.

<table>
<thead>
<tr>
<th></th>
<th>5.5kW</th>
<th>10kW</th>
<th>500kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated output power [kW]</td>
<td>5.5</td>
<td>10</td>
<td>500</td>
</tr>
<tr>
<td>Rated Frequency [HZ]</td>
<td>46.7</td>
<td>46.7</td>
<td>50</td>
</tr>
<tr>
<td>Rated speed [rpm]</td>
<td>175</td>
<td>175</td>
<td>40</td>
</tr>
<tr>
<td>Number of poles</td>
<td>32</td>
<td>32</td>
<td>152</td>
</tr>
<tr>
<td>Number of phases</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Number of stator slots</td>
<td>48</td>
<td>48</td>
<td>228</td>
</tr>
<tr>
<td>Connection</td>
<td>Wye</td>
<td>Wye</td>
<td>wye</td>
</tr>
</tbody>
</table>

Table 3.7: Main parameters of the Single-Coil winding machine analysed.

3.4.2. Design of The Machines [35-36]

The main results of the design and optimisation of a single-coil winding 500kW and 5.5kW PM machine are presented in this section. The results are presented in more detailed[35-36]. The aim is to find a suitable electromagnetic design for the directly driven low drive generator. The electromagnetic design and optimisation of the 500kw are presented [35].

The torque ripple of the machine depends, for instance, on the stator slot and slot opening width and the magnet width. The analysis of the machine shows that there is one torque ripple minimum between the magnet width of 60-100% of the pole pitch. The minimum is obtained at the magnet width of 74-80% of the pole pitch. When the slot width is 30-70% of the slot pitch. The torque ripple is minimum when the slot opening is as small as
possible. Even with open slots the cogging torque is under 7% of the rated torque. The torque ripple can also be reduced by skewing the stator slots or permanent magnets.

The minimum flux density in permanent magnets is analysed during a sudden three-phase short circuit at machine terminals. The minimum flux density in the permanent magnet during the short circuit is positive, in the analysed case over 0.2T. Although the machine has surface mounted permanent magnets or open stator slots, the demagnetisation can be avoided during a three-phase short circuit.

An optimisation of a 500 kW machine is presented [35]. The objective function the efficiency at rated load. The main data of the optimisation are shown in table 5. The optimisation has seven parameters. The design have the same machine constant, i.e., the rotor volume is constant. If the height were a free parameter, it would lead to a very expensive design.

The rotor yoke height decreased from the initial value of 20mm to 8.5 mm during optimisation so that the iron of the yoke saturated. Therefore, the eddy-current losses in permanent magnets reduced by 30% from the initial values. The total electromagnetic losses of the machine optimised decreased by 10% from the initial values. Most of the changes in the machine dimensions are rather small in the optimised machine compared to the initial machine. This is caused by the constraints of the pull-out torque and the torque ripple.

An electromagnetic design and optimisation of a 5.5kW machine with two magnet designs is presented [36]. The first variant has one magnet per pole and the second variant two magnets per pole. The objective function is the cost of active materials. The main data of the optimisation are shown in table 5, the optimisation has 8 free parameters. The dimension of the machine is larger if we divide the magnet in the axial direction and leave a rather larger span between two magnets. There are local minima in the air-gap flux density above the magnet span. The length of the machine is 11% longer, air gap length 8% and magnet height 45% higher in the two-magnet machine than in the one-magnet machine. Furthermore, the total weight is 13% higher and active materials 43% more expensive. The span between the two magnets affects the machine characteristics considerably and it increases the volume of the machine and the cost of active materials.

As a summary of the design, the torque ripple minimum of the single-coil winding machine is obtained at a magnet width of about 75% of the pole pitch when the slot width is half of the slot pitch. The torque ripple can also be reduced by decreasing the slot opening width and it is rather low even with open slots. Although the machine has surface-mounted permanent magnets or open stator slots, the demagnetisation can be avoided during a three-phase short circuit. If two parallel magnets per pole instead of one magnet are used. The span between the two magnets affects the machine considerably. The optimisation shows that the volume of the machine and the cost of active materials increase in this case.
3.4.3. Experimental Machine [37]

A Design and analysis of a prototype machine are detailed in [37]. A Picture of the machien is shown in figure 14. The machine was designed for sinusoidal supply. The line voltage of the machine is 400V, the frequency 50Hz and the synchronous rotation speed 150 rpm. The stator is assembled from overlapped U-sheets used in small transformer cores. The machine has a three-phase winding (30 coils) which creates 20 pole pairs. The stator has an outer diameter of 600mm and the length of the core is 66mm. The rotor has 40 surface-mounted NDFeN permanent magnets, and they create a flux density of 0.9 T in the air gap. The rotor is divided in the axial direction into three slices, which have been rotated with respect to each other. As a result of this splitting, the magnets have been with respect to the stator slots.

The measured open-circuit voltage is 391 V and the calculated one 396V. The voltage waveform of the machine is almost sinusoidal. The measured harmonic voltage factor (HVF) in each phase is lower than 0.8% and in line to line voltage 0.3%. The third harmonic has the highest value, i.e., 1.2%. The reason for the low harmonic content is the three slice PM rotor, which at the same time damps the cogging torque and gives an almost sinusoidal flux linkage distribution. The measured maximum value of cogging torque do not exceed 6Nm, i.e., 1% of the rated torque. The torque ripples are calculated without skewing and the cogging torque is 17Nm, i.e., 4% of the rated torque.

The loading properties of the machines are measured and calculated in generator use. The terminal voltage is 400V and the frequency 50Hz. The synchronous reactance of the machine is $9.8\Omega (x_d = 0.42)$ and the stator resistance $1.7\Omega$. The torque-current characteristics and the efficiency of the machine are shown in figures 15 and 16. The pull-out torque of the machine is 1380Nm. The measured efficiency at rated load is 91.3% and the calculated one 90.9%. The efficiency of the machine is also high at partial load. The measured no-load losses of the machine are 66W. The torque ripples are calculated without skewing and the torque ripple at rated load is 23Nm, i.e., 5%.

In spite of the simple construction of the prototype machine, moderate torque ripple and high efficiency are achieved and the voltage waveform is almost sinusoidal. The dimensions of the machine built are not exactly the same as those of the designed one for constructional reasons. The stator is assembled from many small ordinary transformer laminations and, therefore, the airgap length is not constant. Furthermore, the rotor is skewed. However, the computed results agree rather well with the measured ones. The machine can be used [Tellinenen at 1996].
Fig. 3.13: The prototype PM machine

Fig. 3.14: Torque-current characteristics of the prototype machine

Fig. 3.15: Efficiency of the prototype machine
3.5. Comparison of The PM Machines [38-39]

The main results of the optimisation and the comparison of two types of PM machines with different kinds of stator windings are mentioned in this section. The aim of the optimisation is to find a design with a high pull-out torque and with a low active material cost. The optimisation and the comparison of the two types of 5.5 kW, 10 kW and 500 kW machines are presented [38]. The optimisation of a 500kW conventional machine with two different pole numbers also presented [39].

First, two types of the 5.5 kW, 10 kW and 500kW machines are optimised and compared. The optimisation results are shown in figs 17 and 18. The characteristics and main of the machines are shown in table 10. The objective functions are the cost of active materials and the pull-out torque per the cost of active materials. The optimisation of the machines shows that the pull-out torque per the cost of active materials is higher and the cost of active materials smaller in the conventional machines (SM) than in the single-coil winding machines (UC). The materials and the volumes of the conventional machines can be used more effectively than those of the single-coil winding machines. Although the specifications of the optimisation of the 5.5 kW, 10 kW and 500kW machines are different, the optimisation results are similar.

The optimisation of a 500kW conventional machine with two different pole numbers. The objective function of the optimisation is the cost of active materials. The first machine has 80 poles, i.e., the frequency is 26.7 Hz, and the second one 152 Poles, i.e., 50Hz. The main data of the optimisation are shown in table 5. The optimisation has five free parameters. The outer volume of the machines is constant in the optimisation. The outer diameter is chosen to be 3 meters in the 80 pole machine and 3.5 metres in the 152 pole machine and, therefore, the slot pitch is 38% smaller in the 80 pole machine. The optimisation results are an example of the multipole design. The 152 pole machine has the lowest cost of active materials, and it is 16% smaller than in the 80 pole machine. The torque ripple and eddy current losses in the rotor are small in both the machines. The minimum flux density in permanent magnets of the 152 pole machine is higher during a three-phase short circuit and at a maximum load than that in the 80 pole machine. Both conventional 500 kW machines are cheaper than the single-coil winding machines.

![Cost of active materials. 80 pole P(80) and 152 pole P(152) machine. Open stator slots (OS).](image-url)
Fig. 3.17: Pull-out Torque per the cost of active materials. Solid (S) and laminated (L) rotor core.

![Graph showing pull-out torque vs cost for different configurations](image)

Table 3.8: Characteristics and main data of the PM machines optimised. Objective functions, $T_{\text{max}} / \text{Cost}$, in blod face, Open statro slots (OS).

<table>
<thead>
<tr>
<th>Objective function</th>
<th>$T_{\text{max}} / \text{Cost}$</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Machine type</strong></td>
<td>SM</td>
<td>UC</td>
</tr>
<tr>
<td>Rotor (solid / laminated)</td>
<td>S</td>
<td>L</td>
</tr>
<tr>
<td>Output power [kW]</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Poles</td>
<td>12</td>
<td>32</td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td>90.0</td>
<td>90.0</td>
</tr>
<tr>
<td>Losses [kW]</td>
<td>- Resistive losses, stator</td>
<td>0.514</td>
</tr>
<tr>
<td></td>
<td>- Iron losses</td>
<td>0.093</td>
</tr>
<tr>
<td></td>
<td>- Eddy-current losses, rt.</td>
<td>0.003</td>
</tr>
<tr>
<td>Power factor</td>
<td>0.82</td>
<td>0.80</td>
</tr>
<tr>
<td>$T_{\text{max}} / T_n$</td>
<td>3.4</td>
<td>3.7</td>
</tr>
<tr>
<td>$T_{\text{max}} / \text{Cost}$ [Nm/EUR]</td>
<td>1.61</td>
<td>1.30</td>
</tr>
<tr>
<td>$b_{\text{min}} [T]$ 3-p. short circuit</td>
<td>-0.4</td>
<td>-0.1</td>
</tr>
<tr>
<td>$b_{\text{min}} [T]$ 2-p. short circuit</td>
<td>-0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Outer diameter [mm]</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Air-gap diameter [mm]</td>
<td>291</td>
<td>295</td>
</tr>
<tr>
<td>Core length [mm]</td>
<td>128</td>
<td>179</td>
</tr>
<tr>
<td>Weight [kg]</td>
<td>- Iron</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>- Copper</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>- Magnets (NdFeB)</td>
<td>3.5</td>
</tr>
<tr>
<td>-Total weight (active mat.)</td>
<td>75</td>
<td>92</td>
</tr>
<tr>
<td>Cost [EUR] (active mat.)</td>
<td>628</td>
<td>862</td>
</tr>
</tbody>
</table>

The single-coil winding machines have higher harmonics and, therefore, higher eddy-current losses in the rotor than the conventional machines. On the other hand, the design of
the single-coil winding machine is very simple and the machine is easy to manufacture. The number of stator slots per pole and phase is small and, therefore, the pole pitch of the machine can be small. The width of the stator slots and the teeth has a lower constructive limit. For these reasons, the diameter of the single-coil winding machine can be smaller than that of conventional machines with equal output frequency. The length of the overhang winding is as short as possible in the single-coil winding machine. Furthermore, there is no overlap in the overhang winding, i.e., the conductors of different coils are not close to each other. Therefore, the machine has a more reliable insulation system than the conventional machine. The demagnetisation of permanent magnets is easier to avoid in the single-coil winding machines than in the conventional designs analysed. The cogging torque can be reduced to less than 2% of the rated torque by choosing a suitable magnet width and stator slot opening width in both the designs.
4. Design of a PM Motor For a Low-Speed Direct-Drive Mixer

A Design study is conducted to find the most appropriate design of a PMSM for the direct-drive mixer. The reasons behind the selections of the winding type, rotor configuration, PM placement, and PM material are revealed. After showing how the chosen PMSM may be manufactured, the direct-drive and geared mixers are compared and conclusions are drawn.

4.1. Design Study

4.1.1. Design and Optimisation Procedures

The design of a PMSM for the direct-drive mixer is conducted by solving an optimisation problem, using an own-developed numerical design tool in matlab. The models used in the design tool, based on the assumption of a linear magnetic circuit, are described and verified with FE simulations. Various optimized designs with different number of poles, rotor or winding types can then be calculated and compared. The optimization procedure is shown in below figure 4.1. The goal of the optimization is to minimize the active weight of the motor while fulfilling the motors specifications given in table 4.1. The constraints that guarantee the required mechanical, thermal and magnetic behaviors of the machine given in table 4.2 should also be fulfilled. Thus, all the designs are calculated for the same nominal torque (840Nm) and nominal speed (50rpm). The exterior diameter is limited to 500mm and a limit of 5.5kg is set on the PM weight (for the NDFeB magnets) because of the relatively high cost of the PM material. Some constraints on the teeth and stator yoke dimensions are defined in order to guarantee a mechanically rigid structure. The magnetic flux density in the teeth and stator and rotor yokes are limited at open-circuit condition in order to prevent from saturation and thus too inaccurate results due to the assumptions made in the analytical models. The copper losses can not exceed 700W in order to avoid a low efficiency and high temperature in the windings. All the calculated motors have the same square slot shape with a tooth width constant along the tooth.

The influence of different parameters on the design can be seen in torque equation.

\[ T = \frac{4}{\pi} S_1 \hat{B}_s \delta k_{\text{uv1}} (D - \delta)^2 L \sin \beta \]

- PM size
- limited by fixed external diameter
- saliency
- fixed slot area (limited copper losses)
- winding type
- influences greatly the active weight
Where,

\[ T \] Torque

\[ S_1 \] Maximum of the fundamental current loading

\[ B_\delta \] Maximum of the fundamental open-circuit airgap flux density

\[ k_{w1} \] Fundamental winding factor

\[ D \] Inner stator diameter

\[ \delta \] Airgap length

\[ L \] Active length

\[ \beta \] Angle between the d-axis and the current vector

The torque \( T \) is constant and equal to its rated value. The fundamental current loading \( s_1 \) is directly related to the slot area, if the copper losses and external diameter are fixed and equal to their maximum allowable values (which is almost always the case). The slots size influences in turn the dimensions of the air gap diameter \( D - \delta \). The fundamental winding factor \( k_{w1} \) varies depending on the winding type; a lower fundamental winding factor should be composed by a higher current loading, open-circuit airgap flux density or a larger active length. The fundamental open-circuit airgap flux density \( B_\delta \) is limited by the constraint on the PM weight, and the PM weight depends on the active length. The active length influence greatly the active weight, if the external diameter is constant.
Vary the parameters; number of poles, length, air gap length, slot and magnet dimensions

Express stator parameters as a function of the variables

Open-circuit air gap flux density

Flux density in: stator yoke and stator teeth

Current loading

Current density

Conductor Number

Copper losses

Active weight

Optimal Result?

Verification with FEM

Subject to constraint on:

Outer dimensions

Rigidity of the

Magnetic saturation

Torque

Thermal Behaviour

Efficiency

Fig. 4.1: Optimization procedures.
<table>
<thead>
<tr>
<th>Objective of the constraints</th>
<th>Description of the constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guarantee the rigidity of the mechanical structure</td>
<td>Stator yoke height at least half the slot height slot width between 0.15 and 0.5 times . The slot height tooth width at least 30% of the slot pitch Slot opening width at least 2mm Slot opening height at least 2mm</td>
</tr>
<tr>
<td>Avoid magnetic saturation</td>
<td>Flux density in stator teeth under 1.6T Flux density in stator yoke under 1.4T Flux density in rotor yoke under 1.4T Fundamental air gap flux density under 1.1T</td>
</tr>
<tr>
<td>Prevent high temperature and guarantee a minimum efficiency</td>
<td>Winding temperature set to 80°C copper losses under 700W</td>
</tr>
<tr>
<td>Limit the price limit the machine weight</td>
<td>Magnet weight under 5.5 kg Machine weight under 150 kg</td>
</tr>
</tbody>
</table>

Table 4.1: Design specifications of the direct-drive mixer motor.

Table 4.2: Constraints

4.1.2. Distributed Versus Non-Overlapping Concentrated Windings

**Distributed Windings**

When the number of poles is high, the number of slot per pole per phase q is chosen equal to 1 in order to limit the number of slots. The fundamental winding factor $k_{w1}$ is equal to 1. So do also the odd harmonics of the winding factor. Therefore the torque ripple of the machines with q=1 is usually high, if there is no skew. The windings are overlapping giving rather long end-windings compared to the machine length, as the machines for low-speed application are often with a large diameter.

Several designs of inner rotor surface-mounted PM (SMPM) machines with distributed windings, q=1 and NDFeB magnets are calculated following the optimization procedure. The number of poles is varied from 20 to 70.figure 4.2 shows how the active weight decreases for an increasing number of poles. For pole numbers over 50, it decreases slower due to the constraints on the rigidity of the structure. A possible design with 70-pole is presented in figure 4.3a. The external diameter of the machine is as large as possible and the active length as short as possible in order to minimize the active weight. As in addition the
copper losses cannot exceed 700W, the slots should have a minimum area and therefore they are thin and long. The torque ripple of these machines with distributed windings is approximately 10%. The length of the end-windings is approximately 15% of the machine’s active length.

Fig. 4.2: Active motor weight as a function of the pole number for SMPM motors with concentrated and distributed windings.

Non-Overlapping Concentrated Windings

The commonly mentioned advantages of the non-overlapping concentrated windings are the short end-windings, low cogging torque and torque ripple, easy assembling of the stator and cheaper manufacturing as there are fewer slots. On the other hand, the fundamental winding factor is lower and the MMF has a large harmonic content which causes losses in the rotor PMs and Iron.

In the case of the mixer application, double-layer concentrated windings are the most appropriate. Indeed, with the lower harmonic content in the MMF, the losses and torque ripple are lower than with a single-layer winding. Furthermore, there are no requirement on a wide speed range of constant power operation and no constraints on fault tolerance for the mixer.

The combinations of pole and slot numbers selected for the study give high fundamental winding factors. Moreover, the corresponding winding layouts present much symmetry to avoid an unbalanced magnetic force. They are the combinations with the number of slots per pole per phase q equal to 2/5 and 2/7 giving a fundamental winding factor $k_{w1}$ equal to 0.933, q=3/8 and 3/10 with $k_{w1} = 0.945$ and q = 5/14 and 5/16 with $k_{w1} = 0.951$.

Figure 4.2 shows the active weight as a function of the pole number for values of q. the trend for SMPM motors with concentrated windings is that the active weight decreases with an increasing pole number. Some points do not follow this tend due to the fact that the
active weight also varies with the number of slots. Thus, the motors with \( q = \frac{2}{5} \) or \( \frac{2}{7} \) are slightly heavier than the others, because of their lower fundamental winding factor. Figure 4.2 reveals also that the motors with concentrated windings are approximately 15kg lighter than those with distributed windings (\( q = 1 \)). Since there are fewer teeth in designs with concentrated windings, both the slots and teeth can be wider, as figure 4.3b shows. As in addition the end-windings are shorter, the current loading \( S_1 \) can be higher for given copper losses. Furthermore, the PMs are allowed to be thicker and the open-circuit air gap flux density \( B_\delta \) to be higher without saturating the teeth. This allows the motors with concentrated windings to be shorter and thus lighter even though the fundamental winding factor is lower and air gap diameter smaller than for machines with distributed windings. Another interesting characteristic is the reduction of the torque ripple from 10% for machines with distributed windings to fewer than 3% with concentrated windings.

The advantages of the machines with concentrated windings are substantial with their lower active weight and lower torque ripple. Therefore, these machines are a good choice for the mixer.

**Fig. 4.3: Geometries of two 70-pole SMPM motors:**
- a) With distributed windings (\( q = 1 \));
- b) With concentrated windings (\( q = \frac{3}{10} \)).

### 4.1.3. Inner Versus Outer Rotor

The outer rotor structure is often chosen because of its suitability in the mechanical drive. For example, this structure is well adapted for in-wheel motors [41, 42] or wind turbines [45], as the wheel’s or turbine’s had can be fixed directly to the outer rotor, which makes the system more compact.

In the case of the mixer, fixing the propellers blades on an outer rotor does not bring any decisive advantage [40]. Therefore, other aspects than the mechanical design should be taken into account for the choice of the rotor configuration:
• Thermal design- when running, the submersed mixer makes the waste-water circulate around the motor. This circulating water should be sufficient to dissipate the motor losses. The main source of losses, the windings, is located in the stator. Therefore, in the case of an outer rotor, the cooling would be less efficient as the stator windings are further away from the water.

• Magnetic design- A SMPM motor with an outer rotor has usually a larger air gap diameter than a SMPM motor with inner rotor having the same external diameter, as illustrated in figure 4.4. The torque being proportional to the square of the air gap diameter, the length and thus the weight of the machine can be decreased for a machine with an outer rotor. Therefore, the designs of outer-rotor SMPM motors obtained by following the optimization procedure are approximately 15% lighter than the motors with an inner rotor, if only the active weight is considered.

![Fig. 4.4: Inner-and outer rotor PMSMs with same external diameter.](image)

• Winding type- in the case of non-overlapping concentrated windings, PMSMs with outer rotors are slightly easier to wind since the teeth point outward, especially if the slots are open.

• PM placement- if the PMs are surface-mounted, they are subject to centrifugal forces during the operation. The centrifugal forces are proportional to the radius and to the square of the speed. If the rotor is internal, the centrifugal forces tend to detach the PMs and a bandage or other protection is often necessary. However in the case of an external rotor, the PMs are pressed on the rotor iron by the centrifugal forces, making their detachment more improbable.

Outer rotors with buried PMs are rare. The mechanical design is difficult and it is not guaranteed that the air gap diameter is larger with an outer rotor with buried PM than with an inner rotor.

Considering these different aspects, the solution of an inner rotor is chosen for the mixer’s moor. The better cooling and the possible use of a buried PMs structure are the main arguments for this solution.
4.1.4. Surface-Mounted Versus Buried PMs

Radial-flux PMSMs can be classified in three categories: SMPM machines, inset PM machines and buried or interior PM machines. The main advantage of the SMPM machine is its simplicity and consequently a lower construction cost compared to other PM machines. The main drawback is the exposition of the permanent magnets to demagnetization fields.

The inset PM machines have surface-mounted PMs with iron inter poles that give a salient structure. Therefore, inset PM machines combine the advantages of the SMPM machines, with the possibility to have a reluctance torque due to the salient structure.

An advantage of the buried PM machine configuration is the possibility to concentrate the flux generated by the PMs in the rotor and thus achieve a high open-circuit air gap flux density. Moreover, machines with buried PM are salient and thus a reluctance torque is produced in addition to the alignment torque from the PM. They can also achieve wide speed range of constant power operation [44]. Finally, the buried PMs are well protected against demagnetization and mechanical stress.

There are many ways to place the buried PMs in the rotor. The most attractive solution for the application, as the number of poles is high, is to have tangentially-magnetized PMs, as illustrated in figure 4.5a. as for the SMPM configuration, optimized designs with different number of poles and concentrated windings are calculated.

Figure 4.5 shows two 70-poles, 63-slot motors with tangentially-magnetized and surface-mounted PMs respectively. When the PMs are buried, the PM flux concentrates in the rotor iron which allows a higher open-circuit air gap flux density than with surface-mounted PMs. The current loading is then lower for the motor with buried PMs leading to smaller slots and a larger air gap diameter (4.1). The machine can then shorter. Therefore, the motor with tangentially-magnetized PMs has an active weight that is approximately 20kg lower than the SMPM motor, as can be seen in table 4.3. Furthermore, the weight of the PM material is substantially lower. The advantages of the concentrated windings over distributed windings (q=1) can also be noticed in this table: Besides the 20kg lower active weight, the torque ripple is consequently decreased, especially in the case of tangentially-magnetized PMs. The torque ripple is obtained from 2D-FE simulations.

The configuration with tangentially-magnetized PMs is chosen for the mixer application as it gives a substantially lower motor active weight and especially the PM weight is decreased, which may give a lower cost. This configuration opens also for the use of cheaper PMs.
Fig. 4.5: Geometries of two 70-pole, 63 slot motors:

a) With tangentially-magnetized PMs

b) With surface-mounted PMs.

<table>
<thead>
<tr>
<th>Motor Configuration</th>
<th>Design q, pole/slot</th>
<th>Active Weight [kg]</th>
<th>PM Weight [kg]</th>
<th>Torque Ripple[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface-mounted PMs</td>
<td>q=3/10, 70/63</td>
<td>76.1</td>
<td>5</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>q=1, 70/210</td>
<td>91.4</td>
<td>5.5</td>
<td>9.3</td>
</tr>
<tr>
<td>Tangentially magnetized PMs</td>
<td>q=3/10, 70/63</td>
<td>55.9</td>
<td>3.4</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>q=1, 70/210</td>
<td>76.4</td>
<td>5.5</td>
<td>41.7</td>
</tr>
</tbody>
</table>

Table 4.3: Results for 70-pole SMPM and tangentially-magnetized PM designs.

4.1.5. Magnet Material

Ferrite Magnets

For the tangentially-magnetized PM motor designs, the NDFeB magnets may be replaced with ferrite magnets. Indeed, the flux concentration in the rotor allows reaching high open-circuit air gap flux density with a low weight of NDFeB magnets. Furthermore, the designs with NDFeB magnets are light thanks to the use of concentrated windings. With ferrite magnets, the designs, through heavier, may still be lighter than the induction motor and its gear box. The ferrite magnets have poorer magnetic properties than the NDFeB magnets but they are much cheaper. The solution with ferrite magnets can then be a better compromise between the machine’s weight and the machine’s cost.
The advantages of ferrite magnets are listed below [43]:

- Ferrite magnets are very cheap compared to NdFeB magnets. In 2005, their cost was approximately 5.5Euro/kg. Whereas the NdFeB magnets costed approximately 50Euro/kg [40]. Since 2005, the political and economic situation in China has led to a strong increase in the price of NdFeB magnets. The price for ferrite magnets has been stable until 2008 but it is also starting to change. In 2008, the price for NdFeB magnets is estimated around 120Euro/kg while the ferrite magnets cost around 7Euro/kg [46].
- Demagnetization can occur below $-40^\circC$ and over $200^\circC$ [47]. These temperatures will never be reached for the considered application: the mixer is submerged and the temperature in the windings is estimated around $80^\circC$.
- Ferrite magnets are electrically none conducting. This means that there is no problem of eddy currents in these magnets.
- No corrosion.
- They are easy to manipulate compared to NdFeB magnets, as they are not as strong.
- They are easy to magnetize.

Their drawbacks are:

- Ferrite magnets have poorer magnetic properties i.e. a low remanence flux density (0.3-0.4T against 1.1-1.3T for NdFeB magnets) and a low energy density (20-35 $kJ/m^3$ against 250-350$kJ/m^3$)[48]. Therefore, PMSMs with surface-mounted magnets will have low open-circuit air gap flux densities. When the PMs are buried, it is possible with the flux concentration to reach the same open-circuit air gap flux density as in the NdFeB magnet machines, but the quantity of ferrite material is much more important. The weight of the rotor is therefore much higher. However, it can be noticed that the ferrite magnets have a lower density than the NdFeB magnets (5000$kg/m^3$ against 7500$kg/m^3$).
- Since the rotor is larger with ferrite magnets, an outer-rotor structure has no longer a larger air gap diameter.
- The remanence flux density varies consequently with the temperature (-0.2%/K)[48].

**Design With Ferrite Magnets**

The possibility to replace NdFeB magnets with ferrite magnets is investigated for a 56-pole, 63-slot tangentially-magnetized PM motor. This combination of pole and slot numbers is chosen because it gives a high fundamental winding factor(0.945) and no unbalanced magnetic pull. The number of poles is chosen as a compromise between the achieve weight that is low for a high slot number, and the manufacturing that is easier and cheaper with fewer PMs and teeth [40].

The machine with NdFeB magnets, shown in figure 4.6a has a PM width $w_m$ of 10mm. At open-circuit conditions, its fundamental air gap flux density is high, equal to 1.6T.
Since the ferrite magnets have a remanence flux density much lower than the NdFeB magnets (0.4T against 1.08T), they have to be wider in order to achieve a comparable air gap flux density. The influence of the ferrite magnet width $w_m$ on the open-circuit air gap flux density is shown in figure 4.7a and figure 4.7b. As can be seen, the air gap flux density produced by the PMs increasing with a reduced rate the wider the PMs. Therefore, it would be efficient to try to reach a very high air gap flux density with ferrite magnets. Figure 4.8 shows how efficient the PMs are utilized in the machine. The operating points of PMs with a width over 30mm get further away the maximum energy product operating point when the magnet width increases. The magnet is best utilized when its width is between 30mm and 40mm, giving a open-circuit air gap flux density of approximately 0.9T.

![Fig. 4.6: Geometries of two 56-pole tangentially-magnetized PM motors:
   a) With NdFeB magnets;
   b) With ferrite magnets.](image)

![Fig. 4.7: open-circuit air gap flux densities for different ferrite PMs Width $w_m$.](image)

The PM thickness $l_m$ should also be adjusted in order to avoid saturation in the rotor iron. Furthermore, the PM thickness influences also the active rotor weight. Figure 4.9 shows how the open-circuit air gap flux density varies as a function of the PM thickness, the PM.
width being set to 30mm. as can be seen, the fundamental open-circuit air gap flux density increases to a certain point with an increasing PM thickness. Over \( l_m = 14\, \text{mm} \), it decreases very rapidly, due to the saturation in the rotor iron. With \( w_m = 30\, \text{mm} \) and \( l_m = 14\, \text{mm} \), the open-circuit air gap flux density is maximized. The flux density in the PMs is of approximately 0.2T, which gives an operating point in the magnet close to the one giving the maximum energy product, as can be seen in figure 4.8. The cross-section of the design with \( w_m = 30\, \text{mm} \) and \( l_m = 14\, \text{mm} \) is represented in figure 4.6b.

![Figure 4.8: magnetization curve of the ferrite magnet material with operating points of designs with different PM widths and same PM thickness.](image)

![Figure 4.9: Open-circuit air gap flux densities for different magnet thickness \( l_m \).](image)
Comparison:

The 56-pole, 63-slot designs with NdFeB or ferrite magnets can be compared using figure 4.6 and table 4.4. Both machines have the same torque, copper losses and active length. The machine with ferrite magnets has larger slots and a higher current loading in order to compensate for the lower open-circuit air gap flux density $B_\delta$. As can be seen in figure 4.6, the rotor of the machine with ferrite magnets is much wider. This results in a heavier rotor in the case of ferrite magnets and a higher total active weight (~50%). Both machines have the same torque ripple at load conditions. The iron losses at load conditions, calculated with FE simulations, are slightly higher for the machine with ferrite magnets, since there is more iron both in the stator and rotor. However, the losses in the PM are expected to be much lower with ferrite magnets. The machine with ferrite is much heavier, but its cost is substantially lower (~30%).

![Comparison table](image)

Table 4.4: Some characteristics of the designs with NdFeB and ferrite magnets.

![Material price table](image)

Table 4.5: Material price in 2005.

The prices for the material used for the cost calculations are given in table 4.5 and dated from 2005. They were not updated with more recent prices. If the prices from 2008 were taken into account, the difference in cost between the NdFeB magnets motor and the ferrites magnet motor would be about the same or even greater. Indeed, the NdFeB magnets (instead of 10 times more) while the price of copper has almost double at the same time.
4.2. Method To Manufacture The Machine With Buried PM’s

4.2.1. Rotor

A motor with ferrite magnets fulfills the specifications for the direct-drive mixer. However, the originality of the rotor demands further investigations on how to manufacture it [40]. The mechanical design of an optimized motor with ferrite magnets presented. In order to keep the PMs in place, the iron pieces and the PMs are profiled as illustrated in figure 4.10a. The iron pieces and PMs are fixed to the aluminum hub by molding the gap between them and the hub with a plastic filter material [40]. The whole rotor is illustrated in figure 4.10b. With the new PM shape, the fundamental open-circuit air gap flux density is slightly decreased, reducing the torque by few percent’s. There is also some flux leakage at the bottom of the PM.

![Fig. 4.10: a) two ferrite magnets and an iron piece b) Assembled rotor proposed by Hallberg [40].](image)

4.2.2. Non Active Components

The non-active components are those components that do not participate to the torque production, such as the bearings, housing and seals. The motor being sub-mersed, the housing of the machine should be carefully designed to avoid any water leakage. Figure 4.11a shows a drawing proposed by Hallberg of the motor with its inactive components.

![Fig. 4.11: a) Hallberg’s direct-driver mixer deigns [40] b) Geared mixer.](image)
4.3 Comparison Of Direct-Drive And Geared Mixers
4.3.1 Final Design

Taking into account the modifications for the manufacturing of the rotor, a final design with ferrite magnets and concentrated windings is calculated. Table 4.6 shows some characteristics of this design, while its geometry with flux lines at open-circuit conditions is given in figure 4.12.

The motor losses are estimated in order to obtain a value for the efficiency. The iron losses are calculated from a FE-simulation at load conditions. Since the rotational speed is very low, the friction losses are also low. The value of 20W is actually over estimated in comparison with measurements on an available prototype. The efficiency of the converter is defined as 98%. The efficiency of the drive (converter+motor) is then approximately 80%.

4.3.3. Comparison

Figure 4.11 shows the proposed direct-drive mixer and the geared mixer at approximately the same scale. As can be seen, the direct-drive mixer has a volume that is slightly bigger than the geared mixer. The estimated weight of the whole machine exceeds the specified limit by 50%. However, the size and weight of the non-active components, such as the housing and seals, have not been optimized and therefore, could most probably be decreased.

<table>
<thead>
<tr>
<th>Active component</th>
<th>Weight [kg]</th>
<th>Cost [euro]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrite magnets</td>
<td>12.8</td>
<td>70.4 (27%)</td>
</tr>
<tr>
<td>Stator iron</td>
<td>22.6</td>
<td>37.4(14%)</td>
</tr>
<tr>
<td>Rotor iron</td>
<td>44.4</td>
<td>73(27%)</td>
</tr>
<tr>
<td>Conductors</td>
<td>26.9</td>
<td>83(31%)</td>
</tr>
<tr>
<td>Total</td>
<td>106.6</td>
<td>264</td>
</tr>
</tbody>
</table>

Table 4.6: Characteristics and performance of the final motor design.

<table>
<thead>
<tr>
<th>Total torque</th>
<th>850Nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reluctance torque</td>
<td>35Nm</td>
</tr>
<tr>
<td>Cogging torque</td>
<td>0.6%</td>
</tr>
<tr>
<td>Torque ripple</td>
<td>3.7%</td>
</tr>
</tbody>
</table>

Table 4.7: Torque.

<table>
<thead>
<tr>
<th>Stator iron</th>
<th>55</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor iron</td>
<td>5.5</td>
</tr>
<tr>
<td>Copper</td>
<td>690</td>
</tr>
<tr>
<td>Friction losses</td>
<td>20</td>
</tr>
<tr>
<td>Converter losses</td>
<td>105</td>
</tr>
<tr>
<td>Efficiency</td>
<td>80%</td>
</tr>
<tr>
<td>Motors power factor</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 4.8: Losses [W]
Hallberg estimated in [40] the cost to manufacture the considered motor, giving a range of possible prices for each component. The results presented below are the average values of the estimated costs for each component, for the prices in 2005. The propeller being the same for both mixers, it is not included in the total costs of the mixtures. Figure 4.13.a shows that the cost of the direct-drive mixer exceeds the geared mixer cost by 50%. This higher cost is due to several reasons:

- **Size of the non-active components** – the shaft, seals, bearings, and housing are larger and thus more costly since the PM motor has a large diameter. Figure 4.13.b shows the relative cost of each component of the direct-drive mixer without propeller. As can be seen, the seals, fixing plates and stator housing, which are components specific to the submersed application, represent almost half of the cost. The PM motor without its housing is then only approximately one third of the total cost.

- **Converter** - unlike the induction motor of the geared drive, the PM motor needs a variable frequency converter in order to be able to start. The variable frequency converter is estimated to 10% of the cost of the direct drive.

- **Stator core** - as can be seen in figure 4.13.c, which shows the relative cost for the manufacturing of the PM motor’s active components, the stator core
Fig. 4.13: a) Costs of the direct and geared drives (with our propeller)

b) Relative costs of the direct-drive mixer components without propeller.

c) Relative costs of the active components of the PM motor.

Accounts for 49% of the motor cost. The cost of the stator core manufacturing is much higher than the cost of the required iron material only, which is 14% of the active material cost. This is mostly due to the waste of iron during the manufacturing of the stator core.

- Stator windings- the stator windings represent 31% of the cost of the motor’s active components. The stator windings cost approximately 3 times the conductor’s material because they are considered hand-made [40]. Unexpectedly, the cost of the of the PMs is low, only 9% of the total motor cost.

The direct-drive mixer costs more than the geared mixer. However, it has a better efficiency. The geared mixer’s drive has an efficiency of 73% against 80% for the direct drive. Figure 4, 14 shows the initial and operating costs of both mixers in p.u. as a function of the number of years. The initial cost of the geared mixer is 1p.u. the operating costs of the mixers are calculated for different electricity prices. An example of electricity price in Sweden for a medium-size industry is 0.53 h/kWh without the taxes, which are 0.27h/kWh. The mixers are considered operating 50 weeks out of 52 in a year. The pay-off time of the direct-drive mixer is in this case.
4.4 Conclusions

The proposed direct-drive mixer is larger and heavier than the geared mixer and has a higher initial cost. Although the efficiency is higher, leading to a lower operating cost, convincing the customers to buy the direct-drive mixer may be a difficult task, especially since the geared mixer has a lifetime of 5 years and the pay-off time is already 3 years. Therefore, no prototype motor has been built and the project of the direct-drive mixer was put on hold.

A prototype motor would have been required to confirm the study. In particular, many questions remain concerning the manufacturing of the rotor and the cost of the direct drive. The design was based on the assumption of a winding temperature equal to 80\(^\circ\)C, which could have been verified with a prototype. Furthermore, the influence of the temperature dependency of the magnet remanence flux density on the motor’s performance could have been more deeply investigated. The FE-simulations could have been validated as well. The construction and evaluation of the prototype may have confirmed, or not, the decision of freezing the project.

The Ph.D. project went further on by evaluating another prototype with non-overlapping concentrated windings built by Danaher motion. One issue revealed by the study on the direct-drive mixer, concerns the manufacturing of the stator for PMSM with concentrated windings, which was not as easy and inexpensive as expected.
CHAPTER 5

5. WIND POWER PLANTS

5.1. Overview of Wind Power Plants

Wind turbines are widely used as a pollution free and renewable source to supplement other electricity generation. Wind power technology has been developed remarkably during the latest decade. The real cost of energy from wind turbines is falling dramatically. Nowadays more than 10000 MW wind power capacity has been installed world-wide. The installed capacity will be 37 MW including 63 wind turbines in Finland at the end of 1999. The machines now entering the market generate 300–1500 kW per turbine rather than the 100 kW average of the late eightie models. This up scaling is foreseen to continue at least one step more to a 4–6 MW offshore turbines.

A present day typical and a new directly driven wind power plant are illustrated in Fig. 1. The electromechanical system of a wind power plant usually consists of three main parts: turbine, gearbox and generator. The rotor of a typical wind turbine rotates at a speed of 20–200 rpm. In conventional wind power plants, the generator rotational speed is usually 1000 or 1500 rpm. This means that a gear is needed between the turbine and the generator. A standard asynchronous generator can be used in conventional wind power plants. The constant speed operation is commonly used in this type of the wind turbine. The generator can be connected directly to the grid, which results in a simple electrical system. However, the gearbox adds to the weight, generates noise, demands regular maintenance and increases losses. The maintenance of the gearbox-generator system may be difficult, because the nacelle is located at the top of the tower. Furthermore, there may also be problems with materials, lubrication and bearing seals in cold climates.

![Diagram of wind power plants](image)

Fig. 5.1: Typical and directly driven wind power plants.

The wind power plant can be simplified by eliminating the gear and by using a low-speed generator the rotor of which rotates at the same speed as the rotor of the turbine. Many disadvantages can also be avoided in gearless wind turbines. The noise caused mainly by a
high rotational speed can be reduced. The advantages are also high overall efficiency and reliability, reduced weight and diminished need for maintenance. However, the diameter of a low-speed generator may be rather large because a great number of poles is needed in a low-speed machine. Due to the multipole structure, the total length of the magnetic path is short. The winding overhangs can also be shorter and stator resistive losses lower than those in a long pole pitch machine. The output frequency is usually lower than 50 Hz, and a frequency converter is usually needed in low-speed applications. The converter makes it possible to use the machines in variable speed operation. The speed can be variable over a relatively wide range depending on the wind conditions, and the wind turbines can extract maximum power at different wind speeds. The advantages of the variable speed operation are, for instance, the reduction of the drive train, mechanical stresses, the improved output power quality and the increased energy capture.

The main data of the commercial gearless and geared 500 kW wind turbines are given in Table-1. The gearless turbine has variable-speed operation and the geared turbines have constant speed operation. The average price for large, modern wind turbines is around 1000 EUR per kilowatt electrical power installed. The annual energy production is higher and the total weight of the rotor and nacelle lower in the gearless turbine than the average values in the geared turbines. The data of a typical 500 kW generator-gear solution are shown in Table-2. The generator is a four pole induction machine. The gear is a combined planetary and parallel stage design planetary in the first stage and parallel in the second and third stages. The gear contains the main shaft bearing and the gear ratio is 50.

<table>
<thead>
<tr>
<th>Wind turbine</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>Average</th>
<th>Diff. [%] B-F/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output [kW]</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>150/500</td>
<td>500</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Speed [rpm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotor</td>
<td>18-38</td>
<td>32</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30.4</td>
<td></td>
</tr>
<tr>
<td>Generator</td>
<td>18-38</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
<td>1000/1500</td>
<td>1500</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>Energy prod. at mean wind speed [kWh/a]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 m/s</td>
<td>615</td>
<td>588</td>
<td>505</td>
<td>543</td>
<td>513</td>
<td>491</td>
<td>528</td>
<td>-14</td>
</tr>
<tr>
<td>10 m/s</td>
<td>2350</td>
<td>2120</td>
<td>2196</td>
<td>2281</td>
<td>2203</td>
<td>2145</td>
<td>2189</td>
<td>-7</td>
</tr>
<tr>
<td>Tower height [m]</td>
<td>42</td>
<td>39</td>
<td>33.8</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>38.6</td>
<td>-8</td>
</tr>
<tr>
<td>Rotor diameter [m]</td>
<td>40.3</td>
<td>40.8</td>
<td>37</td>
<td>39</td>
<td>37</td>
<td>37</td>
<td>38.2</td>
<td>-5</td>
</tr>
<tr>
<td>Weight [1000 kg]</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotor, incl. hub</td>
<td>20.5</td>
<td>12.0</td>
<td>8.8</td>
<td>6.7</td>
<td>8.5</td>
<td>9.8</td>
<td>9.2</td>
<td>-55</td>
</tr>
<tr>
<td>Nacelle</td>
<td>5.6</td>
<td>22.0</td>
<td>18.0</td>
<td>17.3</td>
<td>20.5</td>
<td>21.5</td>
<td>19.9</td>
<td>+225</td>
</tr>
<tr>
<td>Rotor + nacelle</td>
<td>26.1</td>
<td>34.0</td>
<td>26.8</td>
<td>24.0</td>
<td>29.0</td>
<td>31.3</td>
<td>29.0</td>
<td>+11</td>
</tr>
<tr>
<td>Tower</td>
<td>34.0</td>
<td>30.5</td>
<td>23.2</td>
<td>28.5</td>
<td>30.0</td>
<td>27.0</td>
<td>27.8</td>
<td>-18</td>
</tr>
<tr>
<td>Total</td>
<td>60.1</td>
<td>64.5</td>
<td>50.0</td>
<td>52.5</td>
<td>59.0</td>
<td>58.3</td>
<td>56.9</td>
<td>-5</td>
</tr>
</tbody>
</table>

Table 5.1: Main data of the commercial 500-kW wind turbines [51].
Table 5.2: Main data of a typical 500-kW generator-gear solution [50].

<table>
<thead>
<tr>
<th></th>
<th>Weight [kg]</th>
<th>Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gear</td>
<td>5100</td>
<td>98.0</td>
</tr>
<tr>
<td>Induction generator</td>
<td>2900</td>
<td>95.6</td>
</tr>
<tr>
<td>Total</td>
<td>8000</td>
<td>93.7</td>
</tr>
</tbody>
</table>

The developments of wind turbines are moving in the direction of larger and well optimised units. The gearless design with a low-speed generator is a promising concept for wind turbines. The number of moving components can be reduced by using a directly driven generator.

5.2. Overview of Directly Driven Wind Generator

There are different alternatives for the design of a directly driven generator. It can be, for example, an asynchronous machine, a permanent-magnet synchronous machine or a synchronous machine excited by a traditional field winding. Furthermore, the machine can be a radial, an axial or a transverse-flux machine. The stator core can be slotted or slotless, and there can, for example, be a toroidal stator winding in an axial-flux machine. Many different generators have been proposed in the literature as directly driven wind-turbine generators.

5.2.1. Radial-Flux Generators With Field Winding

A radial-flux synchronous machine excited by a traditional field winding is one alternative for making a directly driven wind generator. The diameter of the machine in a large wind power plant will be large and the length small. The pole pitch must be large enough in order to arrange space for the excitation windings and pole shoes. The frequency must usually be lower than 50 Hz, typically 10–20 Hz, and a frequency converter is needed. The generator can be directly connected to a simple and cheap diode rectifier. However, the machine demands regular maintenance.

The first commercial directly driven generator in the power range of some hundreds of kilowatts is a synchronous machine excited by a traditional field winding [51]. The first prototype was built in 1992. The outer diameter of the 500 kW generators is about 5 metres and the length 0.6 metre. The wind power plant is designed to be used with a frequency converter and the roto rotational speed varies between 18–38 rpm. Nowadays, this type of 200 kW – 1.5 MW gear turbine is on the market [52,53]. However, the designs of the generators have not been presented in detail.

5.2.2. Axial-Flux Permanent-Magnet Generators

Today, most of the low-speed wind-turbine generators presented are permanent-magnet (PM) machines. The characteristics of permanent-magnet materials are improving and the material prices are decreasing. PM generators are usually axial- or radial-flux machines. The axial-flux machines usually have slotless air-gap windings. A design without slots simplifies the winding design. The magnets used can be of a flat shape, which is easy to manufacture. The length of the axial-flux machine is short compared to the radial-flux
Many axial-flux machines can easily be connected directly to the same shaft. The machine may have high axial force between the stator and rotor discs. Practical problems may arise in maintaining a small air gap in a large diameter machine and the structural stability of the large diameter discs.

Many papers have been written on axial-flux PM generators. An axial-flux slot less machine with a toroidal air-gap winding. More magnet material is needed in a slotless machine than in a slotted machine, because the total air gap (air gap + winding thickness) is large. On the other hand, the increased air-gap length reduces the effect of demagnetising field. In the slotless machine the cogging torque can be completely avoided, that also decreases noise. A skewed construction of the stator or rotor is unnecessary in this type of a machine. However, eddy-currents are induced in the winding by the main air-gap flux. A 1.5 kW, 24 poles as well as a larger 5 kW experimental machine have been built. The machines are for use in small-scale stand-alone generating systems in remote areas. The reduction of the cost of high energy permanent-magnet materials is expected to open up applications for the axial-flux machines.

NdFeB permanent magnets are mounted on two rotor discs on both sides of the stator. A 5 kW and a 10 kW experimental machine have been built and tested. The machines have 14 poles. Special attention must be paid to the choice of structural materials. If the casing is too close to the rotating magnets, the leakage flux will induce eddy currents causing extra losses and heating. A 100 kW, 90 pole experimental machine is under construction. Stiebler and Okla [1992] have presented design aspects for an axial-flux machine with toroidal air-gap winding. A 2.7 kW, 18 pole experimental machines has been built and tested. The measured results have indicated a good agreement with the predicted results.

A 16 pole experimental machine of 1.3 kW has been built and tested. A 5 kW, 24 pole generators to be installed in the extremely cold climate in Antarctica has also been proposed by Caricchi. The field test includes monitoring of generator and power converter significant quantities as well as tuning of the control algorithm for optimisation of the wind generator power-speed characteristic. An example of a 1 MW, 60 pole machine has been presented by Honorati. However, the rated speed is 100 rpm, which is rather high in such a large wind turbine.

Muljadi have proposed a modular axial-flux PM generator. The machine has two stators - one on each side of the rotor. The machine has a toroidal stator winding located in open stator slots. The modular concept was designed for the commercial production of the machines with different sizes and output requirements. A small 18 pole single-phase machine has been built. The efficiency of the machine is only 75% because of high leakage and core losses. The geometry of the machine was not optimised, because the project focuses on the proof of the concept.

An axial-flux generator, in which two stators are sandwiched between three rotor discs, has been presented by Alatalo and Svensson [1993]. The rated power of the generator
designed is 235 Kw and the number of poles 100. A 4.7 kW, 12 pole double-stator axial-flux experimental machine has been built. The machines have air-gap windings.

Most of the axial-flux machines presented have an air-gap winding and surface-mounted magnets. The advantages of the axial-flux machine are low cogging torque and noise, small length of the machine and the fact that many machines can be mechanically connected with each other.

The disadvantages are the need for a large outer diameter of the machine, structural instability of the large diameter discs, and large amount of magnet material in the slotless design. The output of the experimental machines is in most cases rather low, only some kilowatts, but a 100 kW machine is also under construction.

5.2.3. Radial-Flux Permanent-Magnet Generators

Radial-flux PM generators may be divided into two main types, surface-magnet and buried magnet machines. The simple way to construct a rotor having a great number of poles is to mount the magnets onto the surface of a rotor core. However, it is necessary to use high-energy magnets such as NdFeB magnets to provide an acceptable flux density in the air gap. The high-energy magnets are very expensive and the magnet material should be used effectively. Furthermore, the surface-mounted magnets should be mechanically protected by a band surrounding the rotor. Cheaper ferrite magnet material can be used in a buried-magnet machine. The cost of the magnet material is relatively low but the assembly is complicated and costly. More magnet material is needed in a machine with ferrite magnets than in a machine with rare-earth magnets and, therefore, the weight of the rotor becomes rather high.

Many papers have been written on radial-flux PM generators. Spooner and Williamson [1996] have proposed generators excited by buried ferrite magnets and surface-mounted NdFeB magnets. The machines have a fractional slot winding and the number of stator slots per pole and phase, \(q\), is less than one. The machines can be designed with a small pole pitch and diameter, if permanent magnet excitation is used. Two experimental machines of a few kilowatts have been built. The machines have 16 poles and the number of stator slots per pole and phase, \(q\) is 3/4. The machines generated an almost sinusoidal terminal voltage, whilst the voltage induced in individual coils contained significant harmonics components. The larger experimental machine of surface-mounted magnets has 26 poles and \(q\) is 5/13. With so few slots, the sub harmonic field was prominent and it may lead to additional losses. A 400 kW, 166 pole machine has also been designed. The efficiency was maintained at a high value over a very wide range of operating power.

Grauers has optimised analytically a surface-mounted PM generator with a simplified cost function, which includes the cost of active parts, structure and average losses. The generator type from 30 kW up to 3 MW is investigated, and it is more efficient than a convention induction generator with a gear. The active weight per rated output and total cost
per rated output are about the same for all the generator sizes. The outer diameters of the
directly driven generators are only slightly larger than the width of conventional wind turbine
nacelles. Compared with other directly driven generators, the proposed generator type is
small. It is much smaller than the electrically excited generator, the axial-flux generator and
the direct grid-connected radial-flux generator. It is of about the same size as the transverse-
flux generator with a diode rectifier. The reason for the small size is mainly that a high pull-
out torque is not required, because the generator is connected to a forced commutated
rectifier. The efficiency at rated load is similar for all the alternatives in the comparison.
Furthermore, Grauers have built a 20 kW, 66 pole surface-magnet machine excited by NdFeB
magnets. The system of a PM generator and a frequency converter had a good performance
and high efficiency.

Kladas and Papathanassiou have proposed a generator excited by buried and surface-
mounted magnets. 20 kW, 50 pole machines with \( q=1 \) have been designed. The machines
were first designed analytically and then by the finite element method in order to investigate
the optimal shape of the permanent magnets. According to the results, the torque ripple of the
surface-magnet machine was lower than that of the buried-magnet machine. A thin magnet
configuration with sufficient magnet width provides high torque per magnet volume.
However, this magnet geometry involves a risk of demagnetisation of the magnets.

Yildirim have presented test results of a drive system of a directly driven wind power
plant. The 20 kW, 12 pole generator used has surface-mounted NdFeB magnets and the
number of stator slots per pole and phase is two. The harmonic content of the line current of
the machine is over 10%. The characteristics and the design of the generator have not been
presented in detail.

Lampola [54, 55] have proposed surface-magnet generators excited by NdFeB
magnets. 500 kW, 10 kW and 5.5 kW machines have been optimised using a genetic
algorithm combined with the finite element method. A 10 kW prototype machine has 12
poles and \( q \) is 1.5. The results of the research are presented in more detail in this thesis.

Chen has proposed an outer rotor generator, where the position of the stator and the
rotor are exchanged. The machine has surface-mounted NdFeB magnets. While the generator
is running, the centrifugal force of the magnets applies pressure to the outer rotor core. Thus,
the reliability of the glued joints becomes higher. On the other hand, the stator winding may
be difficult to locate in the inner stator with a small diameter, because the slot pitch and pole
pitch should be large enough. A simple magnetic equivalent circuit approach was designed
for the outer rotor design. The design principles were used for initial design iteration and
FEM was applied to analyse the detailed characteristics. A 20 kW, 48 pole machine with \( q=1 \)
has been built. It is verified that a PM generator made in such a simple construction can
operate with good and reliable performance over a wide range of speeds. The design of the
generator was not presented in detail.

Rasmussen has proposed an outer rotor generator having buried ferrite magnets. The
rotor has salient poles with pole shoes and permanent magnets placed in between the poles

81
instead of the traditional DC excitation coils. According to the results, the pole pitch is nearly constant independent of the generator size. In practice, it is between 30 mm and 50 mm for the power range from 1 kW to 500 kW. The numbers of stator slots used are 3 to 4 per pole pitch. 20 kW, 90 pole and a 100 kW, 130 pole machine have been built.

Radial-flux PM generators with special stator design have been proposed by Spooner. The machines have a winding consisting of coils which are placed in slots around every second tooth, i.e. a single-coil winding. The machine design is modular. The stator modules consist of an E-core with a single coil producing a single phase AC output. The module outputs are to be rectified separately and combined at a common DC link. The rotor modules use standard ferrite magnet blocks. The modules can be used for a wide range of machine designs. A small 26 pole prototype machine consisting of 26 rotor and 15 stator modules has been built. Designs for a 400 kW, 166 Pole and 1 MW, 150 pole machines have been presented. The outer diameter of the 1 MW machine is about 4 m and the length 0.6 m. Addition loss mechanisms peculiar to the modular arrangements have been identified. For example, the rotor eddy-current losses were the dominant parasitic losses and required the redesign of the rotor modules based on laminated flux concentrators.

Carlson has presented test results of a 40 kW, 48 pole experimental machine of the above mentioned design. The machine is a pilot scale test unit of a 500 kW machine. They showed that a wind turbine system with a directly driven, low-speed PM generator and a frequency converter is well suited for up-scaling today’s commercial sized wind turbines.

The single-coil winding machine has also been presented by Tellinen and Jokinen, Lampola and Tellinen and Lampola. The machine has a three-phase winding and the excitation of the machine is made by surface mounted NdFeB magnets. The number of stator slots per pole and phase is low and, therefore, the diameter of the machine can be small. A 6 kW, 40 pole prototype machine has been presented. The rotor is divided in the axial direction into three slices, which have been rotated with respect to each other. As a result of this splitting, the magnets have been skewed with respect to the stator slots. The proper choice of permanent magnet width and a three-slice rotor structure reduced noticeably the torque ripple of the machine. The analysis of this type of a machine is presented in more detail in this thesis.

Many radial-flux PM generators are used in small commercial gearless wind turbines. However, the output of the machines is usually rather low, less than 30 kW. Very little information is available on these generators.

Many different radial-flux PM generators have been proposed in the literature as directly driven wind-turbine generators. Most of the machines have a conventional inner rotor design but some outer rotor designs have also been presented. In a modular design the similar modules can be used for a wide range of machine designs. The machines are excited by surface-mounted NdFeB magnets or by buried ferrite magnets. The design of the radial-flux machine is simple and widely used. The pole pitch of the PM machine can be small. The
structural stability of the radial-flux machine is easy to make sufficient. The directly driven PM generators can operate with good and reliable performance over a wide range of speeds. Most of the low-speed wind-turbine generators presented are radial-flux PM machines and this type of a machine seems to be the most interesting machine type for gearless wind turbines.

5.2.4. Special Generators

Some special directly driven generators have also been proposed, for example, a linear induction machine, transverse-flux machines, reluctance machines and a split-pole machine.

Gripnau and Kursten and Deleroi have presented a linear induction generator for direct grid connection. This machine is a double-sided axial-flux generator. The two stator sides form a segment of the circumference and the stator is fixed to the turbine tower. The rotor is a disc which is directly coupled in or parallel to the turbine rotor. The construction of the machine is relatively simple and light compared with the conventional design. Due to the fact that the rotor diameter may be large, the air gap in the discrete stator sector will be large. The generator has a great slip, 10 to 15% and the efficiency will not exceed 80–85%. A 150 kW prototype machine has been made and its efficiency is over 65%. The diameter of a 500 kW machine designed is about 9 m. The machine is still in a developing stage.

Weh [57] have presented a transverse-flux machine. The construction of the machine is very different from the construction of a conventional machine. The transverse flux principle means that the path of the magnetic flux is perpendicular to the direction of the rotor rotation. The non-active part of the copper winding is to a considerable extent smaller than the corresponding parts in a conventional generator. The weight of a low speed transverse-flux machine is about half of the total weight of an asynchronous machine with a gearbox. The machine can be built for a single-phase and also for multiple-phase connection. A 5.8 kW experimental machine has been built and a 55 kW machine has been designed. The outer diameter of the 55 kW, 78 rpm machine is 1.2 m and the length 0.35 m.

Zweygbergk has also designed a transverse-flux machine, Z-machine. The machine has a special type of stator core elements. The output of the Z machine is twice as big as the output of an ordinary transverse-flux machine of the same volume. Copper losses are equal in both types of transverse-flux machine. Iron losses are twice as high in a Z-machine as in an ordinary transverse-flux machine. No test results of this Z-machine are available since the machine is still in a developing stage.

A variable-reluctance generator has been proposed by Torrey and Hassanin. The reluctance machine has a simple cheap structure. The specific interest of the design is in reducing the torque ripple, weight and losses. The torque ripple could be reduced through shaping of the stator and rotor poles. A 20 kW, 60 pole machine has been designed. The outer diameter of the machine is 0.6 m and the length 0.7 m.
5.2.5. **Comparison of Directly Driven Generators**

Comparison of the machines presented is very difficult. The generators are designed for different specifications using different methods. For example, the total cost of the machines depends on the price of materials and on the complexity of construction. Also, the total design of a wind power plant depends on the weight and the size of the generator. Furthermore, the design and the requirements are not presented in detail in most of the cases. However, the design principles of the directly driven generators do not differ much from the ordinary one. They can be built in the same way as other electrical machines. Some comparisons of different machine topologies have been presented in literature.

Bindn er and Søndergaard and Bindner have investigated different kinds of directly driven wind generators and conventional generators with a gear. Directly driven generators have a much larger diameter, about the same total weight and a slightly higher price than the conventional generators with a gear. Low-speed switched reluctance generators need a large frequency converter (low excitation penalty). Multipole induction generators have a low power factor and they are also heavy. Therefore, the above-mentioned machines are not so suitable for low-speed wind generators as synchronous generators. Electrically-excited synchronous generators are larger and less efficient than PM synchronous generators. Consequently, the PM generator was found to be the most suitable machine for gearless wind turbines.

Soderlund and Perala have compared a toroidal, slotless axial-flux machine with a slotted surface-magnet radial-flux machine. The aim of the optimisation was to find the economically optimal electromagnetic design. The total cost of the machines includes active part material costs, structural costs and lifetime energy loss costs. The radial-flux machine is a better choice for gearless wind turbines than the axial-flux machine, if the machine output is more than 100 kW. In a smaller machine, there is no significant difference between the two types of machines.

A 750 kW and a 1.5 MW radial-flux synchronous machine with NdFeB permanent magnets and with direct current excitation have been analysed by Jockel and by Hartkopf. They showed that the wind energy converters using a synchronous generator should be built without a gearbox. The energy cost and the active material weight of the PM machines are lower than those of the DC excited machines. The optimum rectifier concept, diode or forced-commutated rectifier, is strongly dependent on the assumed prices. The diode rectifier is cheaper, the forced commutated rectifier leads to compact generators, with respect to both the active part and the structure.

Veltman have compared five different directly driven wind generators: an electrically excited and a PM synchronous machine, a radial and an axial-flux induction machine and a switched reluctance machine. The paper describes mainly the design method, and there are only a few results of the comparison. The efficient switched reluctance generator has a large
outer diameter. Due to the relatively large air-gap length the machine will not be very suitable for directly driven applications.

Lampola [54, 55] has compared 500 kW directly driven, low-speed PM and asynchronous generators as well as a conventional normal-speed asynchronous generator with a gear. The diameters of the low-speed generators are rather large. The total weight of the low-speed PM generator is twice as large as the weight of the normal-speed asynchronous generator without a gear, but 40% smaller than with a gear. The material costs of the low speed PM generator and the normal-speed asynchronous generator with a gear are almost equal. The efficiency of the low-speed PM generator is higher and the outer dimensions are smaller than those of the normal-speed asynchronous generator with a gear and the low-speed asynchronous generator. The studies showed that the multipole low-speed generator should be a PM synchronous machine. The permanent magnet excitation is necessary in order to construct a machine of the requisite pole number with a reasonable outer diameter. Lampola [54, 55] has also presented a review of existing directly driven wind generators.

Different machine topologies have not been compared very much with each other in the literature. However, the comparison shows that the conventional asynchronous machine and the switched reluctance machine will not be very suitable designs for a large directly driven generator. The PM synchronous machine is smaller, lighter and more efficient than the electrically-excited synchronous machine. The radial-flux machine is economically a better choice for large-scale gearless wind turbines than the axial-flux machine.

5.2.6. Summary of Directly Driven Generators

Many different generator designs for gearless wind turbines have been presented, i.e. electrically-excited synchronous machines, surface-magnet and buried-magnet radial-flux PM machines, axial-flux PM machines, transverse-flux PM machines, switched reluctance machines and a linear induction machine. Some directly driven generators are used in low power commercial gearless wind turbines. The first commercial directly driven generator in the power range of some hundred kilowatts is a synchronous machine excited by a traditional field winding. Many low-speed experimental machines have been built and tested.

The conventional asynchronous machine and the switched reluctance machine are large and heavy and they will not be very suitable designs for a large directly driven generator compared to the other designs. The transverse-flux machine is small, efficient and light compared to the other designs, but the mechanical design is very complicated. The electrically-excited synchronous machine is larger, heavier and less efficient than the PM synchronous machine. The radial-flux PM synchronous machine has smaller outer diameter and it is cheaper than the axial-flux machine.

Cheap ferrite magnet material can be used in the buried-magnet machine, but the rotor is heavier and the mechanical design more complicated than those in the surface-magnet machine with high energy magnets. The radial-flux PM machine with surface mounted
magnets seems to be a good choice for the design of a large-scale directly driven wind-turbine generator.

5.3. Aim Of This Work

The aim of this research is to find an optimal design for a low-speed generator for gearless wind turbines. The investigation is limited to the electromagnetic part of the machine. The hypothesis in this work is that the typical generator-gear solution in the wind power plant can be replaced by a low-speed PM synchronous generator.

A multipole, radial-flux PM synchronous machine is chosen for further investigation. According to the earlier research, this generator type is very suitable for low-speed applications. The combination of the electromagnetic characteristics, the weight, the size and the cost of the radial-flux PM machine is capable of competing with those of the other low-speed machines. The design of the radial-flux machine is simple and widely used in different types of direct current, asynchronous and synchronous machines. The structural stability of the radial-flux design, despite of its large outer diameter, is easy to make sufficient. The efficiency of the PM machine can be made high and the pole pitch small. Furthermore, the characteristics of permanent-magnet materials are improving and their prices are decreasing.

Two types of radial-flux PM synchronous machines are designed and optimised. The first machine has a conventional three-phase diamond winding. The second one has an unconventional, three-phase single-coil winding. The coils are placed in slots around every second tooth, i.e. there is no overlap in the overhang winding between the coils. Therefore, the insulation system is very reliable. The mechanical design of the stator winding is very simple and the machine is easy to manufacture. High-energy NdFeB magnets are chosen to be used. These magnets give a sufficient air-gap flux density with a low volume of the magnet material.

The electrical characteristics of the machines are analysed by the finite element method. The torque ripple and the minimum flux density in permanent magnets are also taken into account in the design. The electromagnetic optimisation of the machines is done by a genetic algorithm combined with finite element method. The machines compared are first optimised by using equal constraints and after that compared with each other. The rated powers of the machines optimised are 500 kW, 10 kW and 5.5 kW. Two prototype machines will be introduced.

5.4. Contents of The Analysis

The analysis of the conventional PM machines with a diamond winding. The electromagnetic design and the analysis of a 500 kW machine is presented [30]. The characteristics of a 500 kW machine with a sinusoidal and a diode rectifier load are compared [31]. The characteristics of a 500 kW machine with different magnet width is analysed in a diode rectifier[33]. The losses of a 500 kW machine are analysed in a diode rectifier load. Different rotor designs of 5.5 kW and 10 kW machines are compared [34].
The design [35-37] and the analysis of the unconventional PM machines with a single-coil winding. An optimisation of a 500 kW machine is presented [35]. The objective function of the optimisation is the efficiency at rated load. The electromagnetic design and the optimisation of a 5.5 kW machine with two different magnet designs is presented [36]. The objective function of the optimisation is the cost of active materials. The design and the analysis of the prototype machine is presented. The optimisation and the comparison of the two types of the PM machines are presented [37].

The optimisation and the comparison of 5.5 kW, 10 kW and 500 kW machines are presented in [38-39]. The objective functions of the optimisations are the cost of active materials and the pull-out torque per the cost of active materials [38]. The optimisation of a 500 kW conventional machine with different pole numbers is presented [39]. The objective function of the optimisation is the cost of active materials.
CHAPTER 6

6. Discussion

The aim of this research is to find an optimal design for a low-speed generator for gearless wind turbines. The hypothesis in this work is that the typical generator-gear solution in the wind power plant can be replaced by a low-speed PM synchronous generator.

6.1. Wind Generators [49]

The rotor of a present day typical wind turbine rotates at a speed of 20–200 rpm. The generator is coupled to the turbine via a gear so that it can rotate at a speed of 1000 or 1500 rpm. Usually, the generator is a four- or six-pole induction machine and it is connected directly to the grid.

The generator rotates at the same speed as the rotor of the turbine in a gearless wind turbine. Many types of low-speed generators have been designed, for instance, special machines like radial-axial- and transverse-flux synchronous machines, reluctance machines and a linear induction machine. The first commercial directly driven generator in the power range of some hundred kilowatts was a synchronous machine excited by a traditional field winding. Nowadays, the greatest interest is in PM generators for gearless wind power plants. The PM machines can operate with good and reliable performance over a wide range of speeds. The pole pitch of the PM machine can also be made small. Furthermore, the characteristics of permanent-magnet materials are improving and their prices are decreasing. According to the earlier research, a multipole radial-flux PM synchronous machine is a good alternative for the design of a large-scale directly driven wind turbine generator. Therefore, this type of machine was chosen for further investigation.

6.2. Optimisation Method

The electromagnetic optimisation of the machines was done using a genetic algorithm combined with the finite element method. The genetic algorithm belongs to the group of probabilistic searching methods, which have high probability of locating the global optimum in the multidimensional searching space discarding all existing local optima. The calculation of the operating characteristics of the machines is based on a finite element analysis of the magnetic field. To be able to evaluate the losses caused by higher harmonics, the rotation of the rotor is taken into account and, therefore, a time-stepping method is used in the analysis. In order to save optimisation time, the FEM analysis was made using first-order finite elements. The initial values are obtained from a magneto static solution. The period of line frequency is divided into at least 200 time steps and a total number of 250 time steps is used in the calculation of the operating characteristics at rated load. The calculation of the pull-out torque is based on the assumption of sinusoidal time variation of the stator voltages and currents. The open-circuit voltage and the cogging torque are calculated dividing the period of line frequency into 300 time steps and using a total number of 600 time steps in order to
obtain more accurate results of the local field variations. A typical first-order finite element mesh constructed for two pole pitches of the PM machine contains 700–900 nodes.

The other FEM analysis of this work was made using second-order finite elements. The period of line frequency is in most of the cases divided into 300 time steps and a total number of 600 times steps are used in the calculation. A typical finite element mesh constructed for the two pole pitches of the PM machine contains 2700–3500 nodes.

The optimisation results of the pull-out torque have been checked by using second-order finite elements and time-stepping FEM. The period of line frequency is divided into 300 time steps. The comparison of the pull-out torque per the cost of active material of the machines optimised using first order and second-order finite elements is shown in Fig 19 and 20. The pull-out torque of the conventional machines is on average 7% lower using second-order finite elements than using first order finite elements. The results of the conventional 10 kW machines differ by 4.5–7% and the results of the 5.5 kW machines by 7–9%, except for the solid pole-shoe designs. The difference of the results of the solid pole-shoe machines with constant air-gap, PS-1, is 9–10% and the machines with curved pole-shoes, PS-2, 3–7%. The pull-out torque of the single-coil winding machines differs on average by 20%, but on the other hand, the torque is also lowest in the optimisation. The pull-out torque of all the machines optimised is lower using second-order finite elements and time stepping FEM than in the comparisons. The field quantities of the real machine do not vary sinusoidally with time because of the saturation of the iron and the rotation of the rotor. Furthermore, the first-order mesh is rougher than the second-order mesh. However, the order of the machines in the comparisons is the same, except for the machines with solid pole shoes. The difference of the results of the machines from each other is more important than the absolutely right values in the comparisons. Therefore, the results are available for comparisons of the machines with each other.

![Fig. 6.1: Pull-out torque per the cost of active materials of the 10 kW machines optimised.](image1)

![Fig. 6.2: Pull-out torque per the cost of active materials of the 5.5 kW machines.](image2)
The stator resistive losses, the stator and rotor iron losses and the rotor eddy-current losses of the 10 kW machines using first-order and second-order finite elements are shown in Fig. 21. The period of line frequency is divided into 300 time steps in the first-order FEM and into 300 time steps in the second-order FEM. The electrical power of the machines is 10 kW in the comparison the losses are lower in all the cases using second-order finite elements than using first-order finite elements. The difference of the efficiency is 0.3-0.4% without rotor eddy-current losses and 0.5-0.8% with rotor eddy-current losses. The largest difference is in the eddy-current losses of the solid pole shoes. The reason for the difference is that the first-order mesh is rougher than the second order mesh, and this affects the losses, especially in the air-gap region. Furthermore, the line frequency of the first-order calculation is divided into fewer time steps than that in the second-order calculation, which affects, for example, the voltage waveform.

The evaluation of the best design of the optimisation is shown in Fig. 22. The optimisations of this study were made using a population size of 50 and the total number of generations was at least 60. The duration of one optimisation of 60 generations was 5–10 days using one processor of an IBM AIX SP2 computer. After the first 40 generations, the results improve very little, less than 0.5%, and after the 60 generations less than 0.2%. Thus, the number of the generations in the calculations was sufficient and they could even be smaller than used.

![Fig. 6.3: The stator resistive losses, the iron losses and the rotor eddy-current losses of the machines using first-order (left side) and second-order finite elements (right side).](image)

![Fig. 6.4: Time evolution of the best design. The objective functions are the pull-out torque and the cost of the material.](image)
The genetic algorithm combined with the finite element method was successfully used for optimisations of low-speed PM machines for gearless wind turbines. The finite element method gives detailed information of the electrical characteristics of the machines, and various machine designs can reliably be compared with each other. However, the genetic algorithm combined with the finite element method used consumes plenty of computer time.

6.3. Electromagnetic Characteristics of The Machines

Two types of multipole, radial-flux PM synchronous machines are designed and optimised. The first machine has a conventional three-phase diamond winding. The second one has an unconventional, three-phase single-coil winding. High-energy NdFeB magnets are chosen to be used. These magnets give a sufficient air-gap flux density with a low volume of the magnet material. The rated powers of the machines optimised are 500 kW, 10 kW and 5.5 kW.

The electromagnetic properties of the conventional PM machine are highly dependent on the design, i.e. the number of stator slots per pole and phase as well as the shape of the magnets, the stator slots and the slot openings. Very much magnet material would have to be used in the machine designed if the peak air-gap flux density should exceed 0.8 T. The pull-out torque versus magnet weight is highest when the width of the magnets is 65–80% of the pole pitch. Furthermore, the efficiency of the machine is also high in this case. If the magnet width is large, the leakage flux between the magnets becomes high. The voltage waveform is almost sinusoidal, when the magnet width is two thirds of the pole pitch. The eddy-current losses in rotor iron (solid steel) and magnets are very high, when the number of slots per pole and phase, \( q \), is 1 or 1.25. With so few slots per pole and phase, the stator magneto motive force contains a lot of harmonics. When \( q \) is more than 1.5, the rotor eddy-current losses are low. A low-speed machine has many poles and the diameter of the wind-turbine generator should not be too large, i.e. the number of the stator slots should be small. Therefore, the machine with \( q=1.5 \) is chosen for further analysis.

The torque ripple can cause problems of noise and vibration and the cogging torque especially can make the machine difficult to start. When the rotor rotates and the flux from the magnets jumps sharply from one stator tooth to another, the force caused by the magnetic field changes direction rapidly. The result is a torque ripple around the average torque. The torque ripple is also partly caused by the higher harmonics in the supply voltage. The stator winding is not sinusoidally distributed along the air gap surface but embedded in the stator slots. This induces higher harmonics in the flux distribution, which affects the torque.

The conventional machines have three different torque ripple minima within the magnet width of 60–100% of the pole pitch. The torque ripple can be made low by using fractional slot winding, suitable magnet width and small slot opening width. A good compromise for the magnet width is two thirds of the pole pitch, if the torque ripples and voltage waveform are also taken into account. The analysis of the unconventional single-coil winding machine shows that the torque ripple minimum is obtained at a magnet width of
about 75% of the pole pitch when the slot width is half of the slot pitch. The torque ripple can also be reduced by decreasing the slot opening width and it is rather low even with open slots. The cogging torque can be reduced to less than 2% of the rated torque by choosing a suitable magnet width and the stator slot opening width in both the designs analysed. The torque ripple can also be reduced by skewing the stator slots or magnets. However, the skewed design is more complex than the unskewed one.

The efficiency, the load capacity and the maximum output power of the PM machine are lower in diode rectifier loads than when connected directly to a sinusoidal grid. A diode rectifier causes harmonics and is not able to deliver reactive power to the machine. The power factor and the terminal voltage of the machine are lower and the stator resistive and the rotor eddy-current losses higher in diode rectifier loads than when connected directly to a sinusoidal grid.

Various rotor designs of the conventional PM machine were investigated: curved and rectangular surface-mounted magnets as well as rectangular magnets equipped with pole shoes. The investigation shows that the rotor equipped with curved surface-mounted magnets has several advantages. The cost of active materials is the lowest and the pull-out torque per the cost of active materials the highest in this design. The rotor design is also simple. The second best rotor design has three parallel rectangular surface-mounted magnets in each pole. If the machine has only one rectangular magnet per pole, the pull-out torque per the cost of the active material is the lowest in the optimisations. The air-gap length is larger in the middle than at the edge of the magnet, and this affects the air-gap flux density. The main advantage of the pole-shoe machines is that the magnets can be reliably protected mechanically and magnetically.

According to the optimisation of the machines with different stator winding, the pull-out torque per cost of active material of the conventional PM machine is higher and the cost of active material smaller than those of the single-coil winding machine, providing the other main electromagnetic characteristics are equal. The single-coil winding machines have higher eddy-current losses in the rotor than the conventional machines. On the other hand, the design of the single-coil winding machine is very simple and the machine is easy to manufacture. The machine can be divided into many identical sectors, which can be mounted in their places during the installation of the whole wind turbine. The sectors can also be changed separately which makes the maintenance easy. The length of the overhang winding is short and the number of stator slots per pole and phase is small, and therefore, the diameter of the machine can be smaller than that of the conventional machine with equal output frequency. The single-coil winding machine has a reliable insulation system because there is no overlap in the overhang winding.

6.4. Demagnetisation of The Magnets

Demagnetisation can be a problem in a PM machine. The properties of the magnets depend highly on the temperature of the magnets. The machine should be designed so that
demagnetisation can be avoided, or a certain percentage of demagnetisation at a possible maximum current and temperature is allowed. One of the most critical situations is a short circuit at the machine terminals. A sudden three-phase and a two-phase short circuit at the machine terminals at rated load are analysed in this study. The minimum radial flux density in the permanent magnets is calculated during the transient phenomenon.

The lowest minimum flux density of the magnets in the 5.5 kW machines optimised is minus 0.45 T, and the magnets can be protected against demagnetisation at a magnet temperature of 60 °C. The 10 kW machines have better magnets and the maximum allowed temperature of the magnets is more than 130 °C at the minimum flux density of minus 0.4 T. If the temperature is higher, the magnets can be partially demagnetised. On the other hand, the efficiency of the machines is high and the cooling surface of the multipole design is large.

The risk of demagnetisation can be decreased by using solid pole shoes and by using advanced magnet materials and sufficient magnet thickness. Furthermore, the eddy-current losses, i.e. the heating of the magnets, can be decreased by dividing the magnets into smaller parts. The demagnetisation of permanent magnets is easier to avoid in the single-coil winding machines than in the conventional machines analysed because of the stator tooth saturation. The demagnetisation is not a problem in the conventional surface-magnet machines either.

6.5. Gearless and Geared Solutions

The electromechanical system of a conventional wind power plant consists of three main parts: turbine, gearbox and generator. The generator is usually an induction machine and it is connected directly to the grid. The speed of the generator is 1000 or 1500 rpm and this means that a gear is needed between the turbine and the generator. However, the gearbox adds to the weight, generates noise, demands regular maintenance and increases losses. Furthermore, there can also be problems with materials, lubrication and bearing seals in cold climates.

The wind power plant can be simplified by eliminating the gear and by using a low-speed generator the rotor of which rotates at the same speed as the rotor of the turbine. The number of moving components and the noise caused mainly by high rotational speed of the gear can be reduced. The advantages are also high overall efficiency and reliability, and diminished need for maintenance. The cross-sectional geometry of the low-speed radial-flux PM synchronous generator designed is shown in Fig.23. The stator frame is made of welded steel. The rotor supporting structure consists of two rings of solid steel below the rotor core and around the shaft. The spokes between the rings are made of iron sheets.

A comparison of the directly driven generators designed with a conventional commercial generator-gear solution is shown in Table 11. The conventional generator-gear solution consists of a four-pole induction generator and a three-stage gear with a planetary and parallel stage design. The gear contains the main shaft bearing and the gear ratio is 50.
Fig. 6.5: Cross-sectional geometry of the low-speed generator.

The efficiency of the conventional PM machine with diamond winding is easy to make higher than that in the conventional generator-gear solutions. On the other hand, the single-coil winding machine has high losses in the rotor. The rotor losses should be reduced so that the design would be more suitable. One way to reduce the eddy-current losses in the rotor is to divide the magnets into many small parts. Because of the two-dimensional FEM program used, the magnets are modelled as bars continuous over the length of the machine and, thus, it is not possible to take the effect of the dividing of the magnets into account.

The active material of the generators in Table 11 includes the electromagnetic part of the machines, i.e. the winding, the stator and rotor cores and the magnets. The non-active material includes the other parts of the machine, i.e. the stator frame, the rotor supporting structure, the shaft and the bearings. The conventional generator-gear solution was optimised by the manufacturer. The design of the non-active part of the low-speed machines is not optimised but calculated like a design of a large synchronous machine. The total weights of the 500 kW directly driven generators and the conventional generator-gear solution are between 8000–9000 kg. The total weight of the low-speed machines is a little bit higher than that of the conventional generator-gear solution. The relative weight of the non-active parts of the low-speed generators is higher than that in the four pole induction generator, 62–65% and 33% of the total weight, respectively. One reason for this is that the low-speed machines must have very strong rotor supporting structures because of the high torque. The nominal torque of a 500 kW, 40 rpm machine is $T=120\text{kNm}$. As a comparison, a 7.5 MW, 600 rpm machine has the same torque. Furthermore, the outer diameter of the low-speed machines designed is large, 3–3.5 m. The optimisation of the non-active part of the low-speed machines may decrease the total weight of the low-speed machines.

The wind power plant can be simplified by removing the gear and by using a directly driven generator. Both types of the PM machines would be available solutions for a directly driven wind generator. The active material cost of the diamond winding PM machine is lower, but the design is more complex than that in the single-coil winding PM machine. The
gearless design with a low speed radial-flux PM generator is a promising design for the wind turbines.
CHAPTER 7

CONCLUSIONS:

The objective of this study has been to investigate the feasibility of low-speed generators for gearless wind turbines. The investigation is limited to the electromagnetic part of the machine. According to the analysis, a typical generator-gear solution of the wind power plant can be replaced by a multi pole radial-flux PM synchronous machine.

Two types of radial-flux PM synchronous machines are designed and optimized. The first machine has a conventional three-phase diamond winding, the second one has an unconventional, three-phase single-coil winding. The coils are placed in slots around every second tooth, i.e., there is no overlap in the overhang winding between the coils. High-energy NdFeB magnets are chosen to be used. These magnets give a sufficient air-gap flux density with a low volume of magnet material. The rated power of the machines optimized is 500kW, 10kW and 5.5 kW. Two prototype machines were built and tested.

Various rotor designs of the conventional PM machine were investigated: Curved and rectangular surface-mounted magnets as well as rectangular magnets equipped with pole shoes. The optimization shows that the cost of active materials is the lowest and the pull-out torque per the cost of active materials the highest in the design with curved surface-mounted magnets. If the rotor has surface mounted rectangular magnets. They should be divided in parallel parts in each pole. The advantage of the pole shoe rotor is that the magnets can be reliably protected mechanically and magnetically.

The suitable design of the conventional surface magnet PM machines analyzed has a fractional slot winding. The number of stator slots per pole and phase of this design $q=1.5$ and the magnet width is two thirds of the pole pitch. Then the torque ripple is low, voltage wave form almost sinusoidal and the efficiency good.

The pull-out torque per cost of active materials is higher and the cost of active materials smaller in conventional PM machine than in the single-coil winding PM machine. The single-coil winding machine has higher eddy-current losses in the rotor than the conventional machine. On the other hand, the design of the machine is very simple and the machine is easy to manufacture. The demagnetization of permanent magnet is easier to avoid in the single-coil winding machine than in the conventional design analyzed. The cogging torque can be reduced to less than 2% of the rated torque by choosing a suitable magnet width and the stator slot opening width in both the designs analyzed.

The total weights of the 500kW directly driven generator and the conventional generator solution are almost the same. The conventional diamond winding machine is a better choice for the design of a directly driven wind turbine generator but the single-coil winding machine is also suitable because of its simplicity.
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