Design of PM generator for a vertical axis wind turbine

Mateusz Rynkiewicz
Abstract

Design of PM generator for a vertical axis wind turbine

Mateusz Rynkiewicz

The task in this project is to design a generator for a vertical axis wind turbine with power rated to 20kW at a wind speed of 10m/s. The project is conducted at the Division of Electricity at Uppsala University with collaboration from Electric Generation AB. The design has just a few moving parts, which decreases maintenance costs and increases its toughness. The turbine absorbs wind from every direction but its rotation speed ratio is lower than horizontal axis wind turbines. It means that the generator must be bigger and therefore more expensive. Price is an important criterion for the generator. Neodymium magnets are expensive so the amount of this material must be limited.

Several designs have been simulated but one final design has proven the most promising. It fulfills all specifications such as efficiency above 95%, 20kW output power and it also has a relatively low amount of hard magnetic material.

A design with a single row of cables per slot was decided upon to eliminate heat pockets between cable rows, which can occur in designs with two cable rows per slot. It would be interesting to study designs with two or more cable rows per slot, as it could lead to a smaller and more efficient machine.
List of variables

\[ E \] = voltage (V)

\[ \omega_{\text{mech}} \] = angular frequency (rad/s)

\[ f_{\text{mech}} \] = mechanical frequency (1/s)

\[ f_{\text{el}} \] = electrical frequency (1/s)

\[ v \] = wind speed (m/s)

\[ P \] = power (W)

\[ \text{TSR} \] = tip speed ratio

\[ R_0 \] = turbine radius (m)

\[ \rho_f \] = electric charge (C)

\[ \vec{D} \] = displacement field (C/m²)

\[ \vec{E} \] = electric field (V/m)

\[ \vec{B} \] = magnetic field (T)

\[ \vec{H} \] = magnetic field in material (A/m)

\[ \phi \] = magnetic flux (Wb)

\[ Q \] = number of slots in stator

\[ p \] = number of poles

\[ m \] = number of phases

\[ k_p \] = pitch factor

\[ k_d \] = distribution factor

\[ k_w \] = winding factor

\[ k_c \] = classical eddy current loss coefficient

\[ k_h \] = hysteresis loss coefficient \((mW/T^2 Hz^2 kg)\)
\(k_e\) = excess loss coefficient \((mW/T^{3/2}H^{3/2}kg)\)

\(A_{Cu}\) = cables cross-section area \((m^2)\)

\(R\) = resistance \((\Omega)\)

\(P_{Loss}\) = power losses \((W)\)

\(\sigma\) = conductivity \((S/m)\)

\(\mu\) = permeability \((H/m)\)

\(N\) = number of turns
# Contents

Abstract ................................................................................................................................. Error! Bookmark not defined.

List of variables ......................................................................................................................... 1

1. Introduction .......................................................................................................................... 4
   1.1 Background ......................................................................................................................... 4
   1.2 Project description ............................................................................................................. 5

2. Theory .................................................................................................................................. 6
   2.1 Turbine theory ..................................................................................................................... 6
   2.2 Generator theory ............................................................................................................... 7
      2.2.1 Maxwell’s equations ....................................................................................................... 7
      2.2.2 Number of cable slots in stator per poles and phase ...................................................... 8
      2.2.3 Pitch factor .................................................................................................................... 8
      2.2.4 Distribution factor ......................................................................................................... 9
      2.2.5 Winding factor ............................................................................................................. 9
      2.2.6 Mechanical and electrical frequency ............................................................................. 9
      2.2.7 Magnetic field in rotor and stator .................................................................................. 9
      2.2.8 Induced voltage ............................................................................................................ 10
      2.2.9 Generator losses and efficiency .................................................................................... 11
      2.3 Statistical wind distribution ............................................................................................. 12

3. Method .................................................................................................................................. 13
   3.1 Calculations ....................................................................................................................... 13
   3.2 Drawing the design ........................................................................................................... 14
   3.3 Simulation ......................................................................................................................... 15

4. Results .................................................................................................................................. 21
   4.1 Generator design and simulations ...................................................................................... 21
   4.2 Final designs properties ..................................................................................................... 24

5. Discussion and Conclusions ................................................................................................. 26

6. Summary in Swedish ........................................................................................................... 28

7. References ............................................................................................................................ 29

8. Appendix ............................................................................................................................... 30
1. Introduction

1.1 Background

In times of increasing energy consumption and diminishing natural resources, it is important to produce energy in a way that is sustainable and climate friendly. Wind is a natural resource, which can be used to produce energy without contributing to the emission of greenhouse gases.

Wind turbines can be divided into two main groups: horizontal axis wind turbines (HAWT), and vertical axis wind turbines (VAWT). The main difference between these two is the orientation of the rotational axis. The advantage of having a vertical axis of rotation is that wind can be absorbed from all directions without the need for a yawing mechanism. The blades do not require to be pitched to compensate for fluctuations in wind speed. These factors make the VAWT simpler to build and maintain than a HAWT. Also, VAWTs are generally less noisy than HAWTs. However, the VAWT is not self-starting meaning that it will not begin to rotate of its own accord. This is easily overcome by running the generator as a motor during initialization.

Recent increases in mineral prices have led to permanent-magnet materials being ever more costly making the material aspect of having as little permanent-magnet material as possible in the design of permanently magnetized generators.

*Pictures 1(left) and 2 (right): To the left a VAWT, to the right a HAWT.*
1.2 Project description
The aim of the thesis is to design a generator for a VAWT. The project is conducted at the Department of Electricity at Uppsala University with collaboration from Electric Generation AB. The maximum height of the VAWT will be 20m, the turbine will be 10m high and have a radius of 5 m. The generator should be designed according to its placement where the wind speed is around 8 m/s, wind turbine properties, and within this speed 20kW might be produced with efficiency above 95%. Using the finite element method and calculations, the properties of design should be evaluated. Because of high price of the neodymium magnets, the magnetic material of the design should be kept to a bare minimum. The height of the generator shall be greater than conventional machines to act as a structural element, instead of attaching beams to the machine, for the connection of the turbine struts to reduce the machines vibrations. The machine will be mounted to the turbine directly, therefore it is easier to use a setup where the rotor is outside of the stator.

The generator will be connected to the main grid through a rectifier and a power inverter to achieve proper voltage. The induced voltage at nominal wind speed shall be adapted to a power inverter with maximum values for voltage and frequency. The phase voltage will be limited to 260V, which results in a DC-voltage of 600V after rectification, and the frequency should be kept below 50Hz.

The criteria for the wind turbine and the generator are:

**Preliminary data for wind turbine:**
- Turbine radius, \( R = 588 \) m
- Blade length: 10 m
- Total height (from the ground to the tips of the blades): 20 m
- Number of blades: 3
- Struts per blade: 2
- Optimum TSR, \( \lambda = 3.5 \)
- Nominal wind speed: 10 m/s
- Blade profile: NACA0015 eller NACA0018
- Nominal rotational velocity: \( \omega_{\text{nom}} = \lambda_{\text{opt}} U_{\text{nom}} / R \)

**Preliminary data for PM generator:**
- Topology: Outer pole machine with struts attached directly to the rotor
- 20 kW at \( \omega_{\text{nom}} \)
- Efficiency 95% or more at 8 m/s (a goal)
- Efficiency at 100% load: above 92% (a goal)
- Permanent magnet material: Nd-Fe-B
• Airgap: 3 mm
• Electrical frequency kept below 50 Hz at nominal rotational velocity.
• The generators output voltage will be adapted to a power inverter with a DC/DC-converter on the low voltage side.

Responsibilities of Mateusz Rynkiewicz were to make a variable-dependent model of the generator in SolidWorks. Using that method, the drawing should be done quickly. His responsibility was also to make simulation of the drawn generator design by using Comsol Multiphysics. The simulations should include magnetic field simulations. Based on this information, induced voltage should be calculated.

Responsibilities of Jonas Norström Parliden were to make the initial calculations using the code written. He also made most of the SolidWorks drawings. This proved most efficient as the MATLAB calculations did not provide enough information as to whether the design would be possible to produce practically. It was difficult to know if, for example, the slots would fit within the stator without overlapping.

2. Theory

2.1 Turbine theory
The angular frequency, \( \omega_{mech} \), of the turbine is related to the wind speed, \( v \), and the turbines tip speed ratio (TSR) and is described using equation 1

\[
\omega_{mech} = TSR \frac{v}{R_0}
\]  
(1)

Where \( R_0 \) is the turbine radius [1].

Equation 2 shows a relation between the wind speed (\( v \)) and mechanical power.

\[
P_{mech} = \frac{1}{2} C_p \rho A_t v^3
\]  
(2)

Where \( C_p \) is the power coefficient, \( \rho \) is the density of air and \( A_t \) is the cross sectional area of the turbine. In this project the mechanical power is assumed to be equal to the generated power minus generator losses. The efficiency of the generator is initially approximated to 95% in this project to simplify further calculations. TSR is kept fixed to achieve optimum \( C_p \) by controlling rotational velocity, thus maximizing power output.
The turbines behavior is described by Figure 1 where it is easy to see that the turbine starts to rotate above a certain wind speed. While wind speed is growing, the Power does the same until it reaches its maximum rotational speed which is kept until a point when the turbine can be destroyed so it is stopped.

2.2 Generator theory

In this section the basic theory used during designing of a generator is described. There are other expressions and aspects of generator design that are not discussed here but this section involves all the aspects that have been studied in this project.

2.2.1 Maxwell’s equations

Generator design is based on electromagnetism and the four laws that describe electromagnetism by Maxwell’s equations.

\[
\nabla \cdot \vec{D} = \rho_f \tag{3}
\]

\[
\nabla \cdot \vec{B} = 0 \tag{4}
\]

\[
\nabla \times \vec{E} = \frac{\partial \vec{B}}{\partial t} \tag{5}
\]

\[
\nabla \times \vec{H} = \vec{j}_f + \frac{\partial \vec{D}}{\partial t} \tag{6}
\]
Here the arrows above the variables denote vector fields. Equation (3) is Gauss law for electric field, and it describes how electric charges ($\rho_f$) produce electric displacement fields ($\vec{D}$). The second equation (4) is well known, it is Gauss’ law for magnetic fields which says that there are no magnetic monopoles and through any closed surface the magnetic flux ($\vec{B}$) is zero. The third equation (5) is Faraday’s law of induction and it says that changing magnetic fields ($\frac{\partial \vec{B}}{\partial t}$) produce electric fields ($\vec{E}$). And finally equation (6) is Ampère’s law. It tells us that currents ($\vec{J}_f$) and changing electric fields ($\frac{\partial \vec{D}}{\partial t}$) produces magnetic fields ($\vec{H}$) [1].

2.2.2 Number of cable slots in stator per poles and phase
An important part in generator design is the relation between stator cable slots, number of poles and phases. This relation is described with variable $q$ in equation 7

$$q = \frac{Q}{pm}$$

(7)

Where $Q$ is the number of slots in the stator, $p$ is the number of poles in the machine and $m$ is the number of machine phases. If $q=1$ it should mean that for one pole in a three phase machine, there would be three cable slots in the stator. It also means that the stator teeth will leave the magnetization area of a pole simultaneously and jump to the next, oppositely magnetized pole. These jumps will cause a lot of vibrations, the phenomenon is called cogging. This is the main reason for not choosing $q=1$ but something else e.g. $q=\frac{5}{4}$, this will result in the teeth leaving the area of magnetization at different times along the perimeter of the stator. Another reason to have $q>1$ is to get less overtones in generated voltage [2].

2.2.3 Pitch factor
If a machine has $q\neq1$ the magnetic flux will not be used in its entirety. This effect is reflected by the pitch factor which is factor that lowers the induced voltage.

$$k_p = \sin \left( \frac{180pn}{2Q} \right)$$

(8)

Where $p$ is the number of poles, $n$ is the coil slot span and $Q$ is the number of slots. If calculation will be made with radians, 180 in equation should be substituted for $\pi$ [3].
2.2.4 Distribution factor
In order for the machine to induce a more sinusoidal voltage, void of the most prominent harmonics, the phases must be distributed over more than one slot per pole in the machine. This distribution results in a decrease in voltage amplitude which is usually added as a factor when calculating peak or effective voltage.

\[ k_d = \frac{\sin\left(\frac{\alpha}{2}\right)}{q \sin\left(\frac{\alpha}{2}\right)} \]  

(9)

Where \( \alpha \) is the angle between slots [3].

2.2.5 Winding factor
The combination of the aforementioned factors is usually indicated by the winding factor. This is the final factor added in when calculating induced voltage later [3].

\[ k_w = k_p k_d \]  

(10)

For further information on the winding factors refer to the references in this section.

2.2.6 Mechanical and electrical frequency
The mechanical frequency is proportional to the rotation velocity of the turbine, which can be described by equation 11, and electrical frequency is described by equation 12.

\[ f_{\text{mech}} = \frac{\omega_{\text{mech}}}{2\pi} \]  

(11)

\[ f_{\text{el}} = \frac{\omega_{\text{mech}}}{4\pi} p \]  

(12)

Where \( f_{\text{mech}} \) is the mechanical frequency, \( f_{\text{el}} \) is the frequency of voltage, \( \omega_{\text{mech}} \) is the angular velocity of the turbine [2].

2.2.7 Magnetic field in rotor and stator
Unlike the magnetic field in a conventional generator, where a coil carrying DC-current magnetizes the rotor, a permanently magnetized generator uses permanent magnets (PM) whose magnetization cannot be controlled after they have been manufactured. A PM is characterized by its remanence, which is a measure of the remaining magnetization when an external field is removed. PM’s, as their name implies, retain their magnetization and therefore have high remanence.
The material in the stator consists of a material with low remanence. This is desired as the direction and magnitude of magnetization changes when the poles pass by. Another important property of the stator steel is permeability, which indicates how well a material can conduct magnetic flux.

Magnetic materials are often described by their BH-curve, which represents the magnetization process of a material. BH-curves are different for soft magnetic materials, such as the stator steel and hard magnetic materials, the PM’s. The main difference is permeability ($\mu$), which decreases the energy necessary to complete a lap of the BH-curve. The relationship between the magnetic H-field and the material specific B-field is described by equation 13

$$B = \mu H$$  \hspace{1cm} (13)

In *Figure 2* are two BH-curves with different permeabilities. The right curve has lower permeability than the curve on the left.

![Figure 2: B-H curves for materials with different permeability](image)

The magnetic flux ($\phi$) in a generator can be described by equation 14.

$$\phi = \hat{B_r} hr \frac{4}{p}$$  \hspace{1cm} (14)

Where $\hat{B_r}$ is the peak magnetic flux density in the airgap, $h$ is the height of the generator, $r$ is the radius in the airgap and $p$ is the number of poles [2].

### 2.2.8 Induced voltage

The main theory explaining the induced voltage in a generator is Faraday’s law.
\[ E_i = -N \frac{\partial \phi}{\partial t} \quad (15) \]

Where \( N \) is the number of conductor turns in the stator per phase and \( \frac{\partial \phi}{\partial t} \) is the time-derivative of the magnetic flux [1]. A simplified expression can be derived from Faraday’s law where the time-derivative is exchanged for a time-independent factor.

\[ E = \sqrt{2} \pi f_{el} N \phi \quad (16) \]

Where \( E \) is the effective value of the induced phase voltage (RMS), \( f_{el} \) is the electrical frequency from (12) and \( \phi \) is the magnetic flux from (16) [2].

If the relation between the number of slots, poles and phases is different from 1, a winding factor must be added to the equation to compensate for the drop in peak voltage.

\[ E = \sqrt{2} \pi f_{el} N \phi k_w \quad (17) \]

Where \( k_w \) is the winding factor from equation (10) [2].

### 2.2.9 Generator losses and efficiency

The losses of a generator can be divided into electromagnetic and mechanical losses.

Mechanical losses consist of friction in bearings and couplings. As this project is centered upon the electromagnetic properties of a generator and the mechanical losses in this type of machine are relatively low the mechanical losses will not be mentioned further in this work.

Electromagnetic losses include copper losses due to resistance in the wires and iron losses from complex magnetic phenomenon in the stator steel, which correspond to the B-H curve and the rate at which it is traversed, i.e. electrical frequency.

The copper losses include resistive losses in the conductor wires and eddy current losses. The eddy current losses are usually small and will be omitted here. The resistive losses relate to the inner resistance \( R \) of the cable.

\[ R = \frac{l}{\sigma A_{Cu}} \quad (18) \]

Where \( l \) is the length of wire per phase in the stator, \( \sigma \) is the conductivity of copper and \( A_{Cu} \) is the cables cross-sectional area [1].
The copper losses, where $I$ is the current, can then be written as [1].

$$P_{loss}^{Cu} = 3RI^2 \quad (19)$$

The iron losses can be described using an empirical expression, which gives the losses in W/m$^3$.

$$P_{loss}^{Fe} = k_h B_{max}^2 f_{el} + k_c B_{max}^2 f_{el}^2 + k_c B_{max}^{3/2} f_{el}^{3/2} \quad (20)$$

Where $B_{max}$ is the maximum magnetic flux density and $k_h$, $k_c$ and $k_e$ are parameters derived from curve fitting of measured specific loss from previous experiments [5]. The parameter $k_c$ is associated with the properties of stator and rotor sheet thickness $d$, its conductivity $\sigma$, and the mass density of the core $\rho_m$, which can be calculated using the given equation 21 [5].

$$k_c = \frac{\pi^2 \sigma d^2}{6 \rho_m} \quad (21)$$

The total losses are found by adding the iron and copper losses.

$$P_{loss}^{tot} = P_{loss}^{Cu} + P_{loss}^{Fe} \quad (22)$$

The efficiency of the generator is described by the following expression.

$$\eta = \frac{P}{P + P_{loss}^{tot}} \quad (23)$$

Where $P$ is the generated power [1].

2.3 Statistical wind distribution

Wind speed varies all year round, which is a natural phenomenon. It is important to know how the wind is behaving at the place where the wind turbine will be installed. The design should be adapted to the wind speeds which are most probable to occur. Probability of wind distribution can be statistically described by using a Rayleigh distribution model which follows equation 24.

$$p(v) = \frac{v}{\bar{v}^2} e^{-\frac{v^2}{2\bar{v}^2}} \quad (24)$$

Where $v$ is given wind speed and $\bar{v}$ is mean value of wind speed [1]. Distribution off mean wind speed of ten meters per second follows figure (3).
Besides of Rayleigh distribution, the Weibull distribution can be used to calculate the wind speed probability. In this project the Rayleigh distribution was used because of its simplicity and because it was used by other authors of this kind of thesis.

3. Method
The project started with studies about permanent magnetized generator design and vertical axis wind turbines. The basic design parameters and procedure was inspired by previous theses made at the department of electricity.

The power output of the generator and the induced voltage specified by the power inverter set the nominal current to around 27A.

The nominal wind speed which the generator is designed for is 10m/s. But statistically the most common wind speed will be 8m/s.

3.1 Calculations
A numeric model for generators was created in MATLAB to test a large number of designs and find the ones that achieved the specified requirements for size, induced voltage, efficiency and as far as possible, minimize the magnetic material. The ones most suitable were chosen for further simulation.

The maximum frequency of 50Hz at a wind speed of 10m/s gave the maximum number of poles, 88. However, a greater number of poles lead to a greater number of slots, increasing the minimum diameter, which in turn decreases the height of the generator that was to be kept rather large and also increases the amount of magnetic material.
Other properties calculated are the amount of iron necessary to build the stator, the length of cables in the windings, the resistance of those cables. Power output and loss was calculated for an array of wind speeds along with nominal values. To approximate the length of cable where it passes from slot to slot a semi-circle was added with diameter equal to the distance from one slot to next slot of this cable. Adding this length to the length of the generator and multiplying it by the number of slots per phase and cables per slot resulted in the total cable length per phase.

A design with a single row of cables was settled upon early on. What was to be decided was how many cables would be placed in each slot as more cables yield more voltage. Because the stator is placed in the middle of the machine more cables per slot makes a larger diameter necessary, or fewer slots resulting in fewer poles and more magnetic material.

A few error messages were created to alert the user if the distance between slots is too small or the electrical frequency was too high.

3.2 Drawing the design
The chosen designs from the MATLAB calculations were drawn in SolidWorks. The method used here was first a universal, variable dependent model of a generator. With this technique generator dimensions like outer diameter, stator diameter followed the diameter in the airgap.
when it was changed. These following dimensions were steered by equations which were depending on each other. The numbers of poles and slots in the stator have their own linked values which could also be changed depending on the design.

Figure 5: Design drawing in SolidWorks

However, this method proved too difficult to implement on the accessible computers. Computer calculations became very slow and ineffective.

To make the drawing process more efficient, the universal model solution was substituted with drawing every design new from the beginning. That method needed more work by hand but from one or two models, four or six models per day were obtained. After drawing the design, its image is saved as a .dxf file which is able to handle by COMSOL Multiphysics.

3.3 Simulation
The most promising designs from the MATLAB-calculations were drawn in SolidWorks where a portion or slice of the generator was drawn to decrease computational time. The drawings were made with detailed slots. A main part was made where all dimensions were connected so only a few values, such as the diameter in the airgap and the number of poles, had to be
changed between designs. The designs were exported to COMSOL Multiphysics where magnetic and electric fields were simulated using the finite element method (FEM).

For magnetic field behavior simulations in the generator the Rotating Machinery physics mode was chosen. It contains magnetic and electric field analysis and can apply both stationary and time dependent studies on the model.

Ampère’s law with constitutive relation of magnetization was used for simulation of permanent magnets. Using the cylindrical coordinate system the magnetization was set to $PM$ for north magnets and $-PM$ for south magnets. The variable $PM$ was initialized in the definitions window in COMSOL.

Another important property to get simulations done was Periodic Condition. It was necessary to simulate the behavior of the entire generator using only one slice of it. This adjustment creates a continuous type of periodicity and puts equal slices of the selected boundaries along the whole of the generator.

![Figure 6: Applying the Periodic condition in Comsol Multiphysics](image)
To tell Comsol how many sectors must be simulated to obtain the whole generator Sector Symmetry adjustment was used. An Identity Pair was selected as Pair selection. This pair consists of two boundaries in the middle of the airgap.

Figure 7: Applying the Sector symmetry in Comsol Multiphysics

Choosing HB-curve in Constitutive relation field in a new Ampère’s law node made simulation of the magnetic field behavior possible for iron material domains of the generator. In the Domain Selection field the rotor yoke and stator iron was marked.
To make simulations possible, a mesh with normal *Element size* had to be created. Better resolution of mesh made simulations impossible to converge, and coarser ones made results crude.

![Image of mesh structure in a generator design](image)

*Figure 8: Part of the mesh structure in a generator design. One pole is marked red.*

Initially the COMSOL simulations were to be made using time-dependent studies where the permanent magnets were to be given a certain magnetization. This would then result in a magnetic field described by equation (13). The magnetic field would then induce an electric field in the stator cables using Ampère’s law (6). The electric field would then be integrated along the cables to calculate the induced voltage.

This however proved impossible. The time-dependent studies failed to converge properly and no useful results were found. A different method was used where stationary studies were used instead of time-dependent studies. The magnetic field was simulated for a number of different rotor positions. The maximum value in the airgap was used to calculate the induced voltage.
using equation (17) and the maximum value in the stator was used to calculate the iron losses using equation (20).

To do the simulation of rotating machine, a Parametric Sweep in stationary study was carried out. That function used a variable called Rot to sweep the rotational angle of the rotor from zero to eight degrees with steps of one degree. This step size was the smallest possible that could be used without the study failing to compile. That study showed magnetic field behavior in the generator for different rotor positions. This data made it possible to calculate the induced voltage. In Results / Derived Values a Point Evaluation was created to get the magnetic field at a point in the middle of the airgap. These values were then manipulated in the Expression field to obtain the induced voltage expressed in DC voltage using equation 25.

\[
V_{DC} = \left( r_{mm,\text{norm}B} hr \frac{N f \sqrt{2} \pi}{p} \right) \sqrt{3} * 1.35 * k_w \tag{25}
\]

This equation is a combination of equations (14) and (14) where \( r_{mm,\text{norm}B} \) is the peak magnetic field, \( h \) is the generator height, \( r \) is the radius in the airgap, \( N \) is the number of winding turns, \( f \) is the electrical frequency, and \( k_w \) is the winding factor. The number 1.35 is there to calculate the corresponding DC voltage from a three-phase voltage that is found by multiplying by \( \sqrt{3} \). This calculation was made in Comsol for every rotor position and displayed in the Results table, below the graphic window.

To check if the solution has converged, an Arrow Surface was added to the solution graphics. The model is solved correctly when the vector arrows in stator are pointing in the same direction as the others in the same tooth. Such solutions were not possible to obtain while solving the model with Time dependent studies. Figure 8 shows a non-converged solution.

![Figure 8: No convergent solution.](image)

Figure 9: Incorrectly solved model. A time dependent study was used.
Here in the *Figure 9* the arrows pointing in random directions can be easily seen as well as the B-field varying for different tangential positions in the teeth, which is not realistic.

For comparison, a correctly solved model is shown in the *Figure 10*. Here all of the vector arrows are homogenously placed and are pointing in the right direction. The B-field is also nice and even.

*Figure 10: A correctly solved generator model. Stationary study was used.*

All models were solved with the same method, to obtain results which do not differ from each other by different method using. To see other designs see appendix 1.
4. Results

4.1 Generator design and simulations
To execute this project right, several prototypes of the generator were simulated. These were first calculated in MATLAB, then drawn in SolidWorks and finally simulated in COMSOL Multiphysics and properties of these ones were compared to each other. These methods are described in Simulation and Drawing the design sections.

The generators have been designed so they fulfill the specifications. Differences between the designs are mostly the machines height, magnetic material weight, iron weight and radius.

From a large number of different designs, only the three best will be presented in this thesis. The table below presents the final designs and their properties.

<table>
<thead>
<tr>
<th>Name</th>
<th>Gen_1</th>
<th>Gen_2</th>
<th>Gen_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height [m]</td>
<td>1.025</td>
<td>0.925</td>
<td>1.095</td>
</tr>
<tr>
<td>Diameter [m]</td>
<td>0.62</td>
<td>0.60</td>
<td>0.59</td>
</tr>
<tr>
<td>Diameter in airgap [m]</td>
<td>0.58</td>
<td>0.56</td>
<td>0.55</td>
</tr>
<tr>
<td>Airgap [mm]</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Poles</td>
<td>48</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>Cable slots</td>
<td>168</td>
<td>165</td>
<td>165</td>
</tr>
<tr>
<td>Q</td>
<td>7/6</td>
<td>5/4</td>
<td>5/4</td>
</tr>
<tr>
<td>Cables per slot</td>
<td>5</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td>95.6</td>
<td>95.6</td>
<td>95.5</td>
</tr>
<tr>
<td>Electrical frequency [Hz]</td>
<td>26.7</td>
<td>24.5</td>
<td>24.5</td>
</tr>
<tr>
<td>Weight of magnetic material [kg]</td>
<td>46.0</td>
<td>40.1</td>
<td>46.7</td>
</tr>
<tr>
<td>Weight of iron material [kg]</td>
<td>804.4</td>
<td>778.2</td>
<td>776.5</td>
</tr>
<tr>
<td>Length of cables per phase [m]</td>
<td>294.7</td>
<td>313.6</td>
<td>414.1</td>
</tr>
</tbody>
</table>
Comparing design properties from data in Table 1 the final design can be chosen. The height of the machine should be adapted to the attachment of struts, it means that the machine should be longer. The difference between these machines heights is 0.17m which is a little difference so here any of the designs can be chosen. Comparing the diameter in the airgap you will find it is almost the same, the largest difference being 0.03m.

Gen_2 is the design with the lowest amount of permanent-magnet material used. This will lower the price of construction because these magnets are very expensive.

Cables per slot have lots of influence on the generator. First of all the greater number of cables per slot the greater the induced voltage will be. It reduces the amount of iron material because of one additional hole for cables per pole, but instead a greater amount of cable must be used to wind the stator which increases the total resistance. So if induced voltage is higher compared to machines with fewer cables per slot then its dimensions can be smaller to obtain the same voltage level. It means that the total amount of magnetic material will be lower too. That’s why it is wise to choose design Gen_2 as the final candidate.

The frequency of induced voltage affects iron losses so lower frequency is sought. However these designs have rather similar frequencies so the difference in iron losses is more attributed to iron volume and B-field.

The ratio between slots, poles and phases (q) which is ≠1 suppresses the overtones of the induced voltage and reduces cogging. If q is 5/4 it means that there is symmetry in the design every four poles which in a 44 pole machine means that there are eleven symmetrical parts. On the other hand when q is 7/6, there is symmetry in the generator every 6 poles which lead to slightly more than seven symmetrical parts. The less symmetry in the generator, the more cogging will be suppressed. But q around 25/24 which is close to 1 can make the cogging and overtones higher again. So looking in this aspect, Gen_1 is best because it has q=7/6 which lead to low cogging and suppressed overtones.
The less iron material the generator uses, the lower is its weight, price and iron losses. Here the best are Gen_3 and Gen_2 where the difference is only 1.7kg.

When comparing resistance in the cables it can be seen that because of having six cables per slot, Gen_1 has the lowest resistance. However the difference is only 0.02Ω so any of the designs is fine in this aspect.

The B-field in the airgap in all of the designs is pretty much the same, but the maximum B-field in stator should be held under 1.8T because of hysteresis / magnetization losses. The generators have the same output power. The conclusion is that less iron material is needed to obtain a certain voltage with higher B-field, but at the same time lower losses are produced with a lower B-field which makes efficiency higher. A general rule of thumb is to have the maximum B-field between 1.6-1.8T to compromise for iron material and efficiency. Design Gen_2 has maximum B-field of 1.66T so it is the most suitable one.

Comparing the total amount of losses, generator Gen_2 looks best, but since these values are quite similar it does not pose enough of a reason to dismiss the other designs. The same can be said of efficiency which is around 95% for all three designs.

Because these designs are similar to each other in most attributes, it is difficult to choose the best one. That’s why the aspect of cost will be one of the main factors which will steer the decision of choosing the final design. The biggest costs in generator manufactory are the neodymium magnets. Gen_2 needs the lowest amount of magnets, and iron weight is only 1.7kg higher than the lightest one. That’s why Gen_2 is chosen as the best design.
4.2 Final designs properties
In this section the design of Gen_2 will be shown in more detailed.

Figure 11 below shows the magnetic field in the generator Gen_2.

![Figure 11: magnetic field in Gen_2 design](image)

Figure 12: Losses grow with higher wind speed.

As the wind speed increases the electrical frequency increases along with the current. This raises losses.
Figure 13: Power grows with greater wind speed.

Figure 13 shows how wind speed affects generated power. In reality no power will be produced with wind speeds below 3m/s because the turbine will stall.

Figure 14: Wind speed vs. efficiency

In Figure 14 it can be seen that efficiency is enough to satisfy the condition of 95% efficiency at 8m/s. Since load is maximized at 10m/s it can also be seen that the condition of 92% efficiency at 100% load is satisfied.

The final design will be both longer and wider than table 1 says. Additional height will come from the cables where they pass from slot to slot and also the attachments for the generator.
will increase the total height. The value for the diameter is the minimum value and attachments will be added here also.

5. Discussion and Conclusions

The goal in this project was to design a 20kW, PM, outer rotor-type generator for a vertical axis wind turbine. A number of generators has been designed and simulated with the same FEM-based method. Only three best designs were chosen to present in this thesis.

To design a proper generator the wind speed, magnetization, losses, vibrations, magnet weight and many other aspects were analyzed.

After studying generator design a program was written in MATLAB to calculate the generator parameters. More parameters were added as the project went on, such as iron weight, resistance and losses. These calculations were successful.

The drawings in SolidWorks were based on a part where all dimensions were interconnected and it was sufficient to change a few values to get a new design. This method would have been ideal if the computers available would have been more powerful. However since all available computers were quite weak it proved quicker to make each design from the beginning. This should have been realized earlier to save time and reduce frustration.

After finally completing a drawing and exporting it to COMSOL a simulation environment was created. Initially the voltage was supposed to be calculated using time-dependent studies. These kinds of time-consuming simulations were lost or impossible to complete because of low memory capacity in the computers used. Two weeks before the deadline of the project another method was suggested. This method used only stationary studies to calculate the voltage but it proved reliable enough to find proper results. However, these studies did not make it possible to see which overtones were the most prominent in the induced voltage.

In the beginning of the project q was instinctively chosen to one, but it soon became apparent that it can contribute to many problems. It was recommended to change the q ratio to 5/4 to reduce cogging and overtones. The new ratio was often used in previous generator-projects and described as a rule of thumb in these cases. That’s why it was more or less assumed that q = 5/4 would be used. But after some time a design with q=7/6 was tested and showed to be one of the better ones. After that more energy was used to know how q really works. And it became clear that a properly selected q can make the generator more efficient and stabile.

Further designs that could be attempted could have two rows of cables per slot. This could reduce the amount of iron and magnetic material in the generator, it is however speculated
that having two rows of cables could produce heat pockets between cables that are difficult to simulate [1].

A modification to the designs where ferrite magnets would be used was suggested. Ferrite magnets are much cheaper than neodymium magnets so this could cut costs significantly. Since ferrite magnets are a lot less powerful a lot of changes would need to be made to the designs to allow proper fittings for the larger ferrite magnets to achieve the same magnetic field strength.
6. Summary in Swedish


Flera olika designer har simulerats men en slutgiltig design har visat sig mest lovande. Den uppfyller alla krav så som verkningsgrad över 95%, 20kW genererad effekt och den har dessutom en relativt låg mängd permanentmagnetiskt material.

En design med enkla spårrader användes för att eliminera varma områden mellan kabelrader vilket kan förekomma i designer med två kabelrader per spår. Det skulle vara intressant att studera designer med två eller fler kabelrader per spår då det skulle leda till en mindre och effektivare maskin.
7. References

[1] Sandra Eriksson, “Direct Driven Generators for Vertical Axis Wind Turbines”, Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology, ISSN 1651-6214; 547, p. 25, 27, 32, 34, 35, 48

[2] Karl-Erik Hallenius, Elektriska maskiner, Chalmers, 1972, p. 8:12, 8:9, 8:17,


### 8. Appendix

1

<table>
<thead>
<tr>
<th>Prototype name</th>
<th>Thinner magnets</th>
<th>Large gen_96pole</th>
<th>tall</th>
<th>1035h &amp;44pol</th>
<th>50p_ 6/5</th>
<th>840h_4 8p7%6</th>
<th>740h_5 60&amp;44</th>
<th>905_2 70</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer diameter (mm)</td>
<td>957.69</td>
<td>957.69</td>
<td>957.69</td>
<td>532.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height (mm)</td>
<td>655</td>
<td>730</td>
<td>365</td>
<td>1895</td>
<td>1035</td>
<td>1190</td>
<td>760</td>
<td>840</td>
</tr>
<tr>
<td>Diam in airgap</td>
<td>900</td>
<td>900</td>
<td>500</td>
<td>600</td>
<td>480</td>
<td>600</td>
<td>580</td>
<td>560</td>
</tr>
<tr>
<td>Poles</td>
<td>60</td>
<td>48</td>
<td>96</td>
<td>30</td>
<td>44</td>
<td>32</td>
<td>50</td>
<td>48</td>
</tr>
<tr>
<td>q</td>
<td>(5/4)</td>
<td>(5/4)</td>
<td>5/4</td>
<td>5/4</td>
<td>5/4</td>
<td>6/5</td>
<td>7/6</td>
<td>5/4</td>
</tr>
<tr>
<td>Slots</td>
<td>225</td>
<td>180</td>
<td>360</td>
<td>108</td>
<td>165</td>
<td>120</td>
<td>180</td>
<td>168</td>
</tr>
<tr>
<td>Calculated DC-voltage (V)</td>
<td>595.7917</td>
<td>597.192</td>
<td>597.3</td>
<td>599.5</td>
<td>598.8</td>
<td>600.9</td>
<td>601.1</td>
<td>600.5</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>30.0803</td>
<td>26.0642</td>
<td>53.48</td>
<td>16.7</td>
<td>24.5</td>
<td>17.8</td>
<td>27.9</td>
<td>26.7</td>
</tr>
<tr>
<td>Simulated DC-voltage (V)</td>
<td>570.4249</td>
<td>644.82</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnet weight (kg)</td>
<td>53.5878</td>
<td>70.2678</td>
<td>35.14</td>
<td>73.4</td>
<td>48</td>
<td>44.3</td>
<td>35.33</td>
<td>37.8</td>
</tr>
<tr>
<td>Inner Resistance (ohm)</td>
<td></td>
<td></td>
<td>0.31</td>
<td>0.28</td>
<td>0.35</td>
<td>0.25</td>
<td>0.25</td>
<td>0.26</td>
</tr>
<tr>
<td>Cables per slot</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Magnet size (thXwh)</td>
<td></td>
<td></td>
<td>5X31.4</td>
<td>5 X 31.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum B-field [T]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.48</td>
<td>1.6616</td>
</tr>
<tr>
<td>B-field in airgap (At PM 0.9 MA/m)</td>
<td>0.63</td>
<td>0.62</td>
<td>0.64</td>
<td>Gen_1</td>
<td>Gen_2</td>
<td>Gen_3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### New values

<table>
<thead>
<tr>
<th>Height (mm)</th>
<th>Magnet weight (kg)</th>
<th>Inner Resistance (ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1025</td>
<td>925</td>
<td>1095</td>
</tr>
<tr>
<td>46</td>
<td>40.1</td>
<td>46.7</td>
</tr>
<tr>
<td>0.31</td>
<td>0.33</td>
<td>0.32</td>
</tr>
</tbody>
</table>
%PM generator

clear all
close all
format shorteng

%Turbinparametrar
Lambda=3.5; %Löptal
Cp=0.34;
R=5;  %Turbinradie
vv=10;  %Vindhastighet
vvvek=(0.1:.1:10);  
A=2*R*10; %Turbinens tvärnittsarea
rotfrekv=Lambda*vv/R;  %Rotationsfrekvens
rotfrekvvek=Lambda*vvvek/(R);
varvtal=Lambda*vv/(R*2*pi);  %varv/sek
varvtalvek=Lambda*vvvek/(R*2*pi);
rpm=varvtal*60;  %varv/min
Luftrho=1.23;  %Luftdensitet

%Vindfördelningsfunktion (Rayleigh)
u=(0.2:0.2:20);
m=7;
p=(pi.*u).*(exp(-(pi/4).*(u/m).^2))/(2*m.^2);
figure;
plot(u,p);title('Fördelning av vindhastigheter');
xlabel('Vindhastighet [m/s]');ylabel('Sannolikhetsfunktion');

%Generatorparametrar
H=925e-3;  %Höjd
r=280e-3;  %Radie i luftgapet
Poler=44;
Magnettjocklek=5e-3;
q=5/4;  %Spår per pol och fas
Ledareperspar=6;

Magnetbredd=(2*r*pi)/(1.5*Poler);
Spar=q*3*Poler;
elvinkel=Poler*pi./Spar;
elfrekvens=Poler/2*varvtal;
elfrekvensvek=Poler/2*varvtalvek;
ku=(sin(q.*elvinkel/2))/(q.*sin(elvinkel/2));  %Utbredningsfaktorn
kst=sind(180*Poler*3.5/(2*Spar));  %Stegförkortningsfaktorn
kr=ku*kst;  %Lindningsfaktorn
N=(Spar./3).*Ledareperspar/2;  %Lindningar per fas
Mr=0.62;  %PM remanence
Kabelbredd=4.5e-3;
Kabelarea=pi*(Kabelbredd/2)^2;

%Beräknade värden
Fi=Mr.*H*r.^4/Poler;  %Flöde
ELN=sqrt(2).*pi.*elfrekvens.*kr.*N.*Fi;  %Fasspänning
ELNvek=sqrt(2).*pi.*elfrekvensvek.*kr.*N.*Fi;
ELL=ELN.*sqrt(3);  %Huvudspänning
ELLvek=ELNvek.*sqrt(3);
EDC=ELL.*1.35; %DC-spänning
EDCvek=ELLvek.*1.35;

%Generatorgeometri
Ytterdiameter=2*r*1.0641;
Sparavstånd=(2*pi*(r-Ledareperspar*Kabelbredd-2.5e-3)/Spar)-Kabelbredd-1e-3;
Kabellangd=(Spar*Ledareperspar/3)*(H+Sparavstånd*4*pi/2);
Minimumhöjd=H+Sparavstånd*4;
Statorvolym=(pi*(r-1.5e-3)^2-pi*(r-1.5e-3-Ledareperspar*Kabelbredd-Kabelbredd*2)^2-(pi*(Kabelbredd/2)^2) *(Ledareperspar+1.5)*Spar)*H;
Statorvikt=Statorvolym*7650;
Rotorvolym=((r+5e-3+30e-3)^2*pi)-(pi*r^2);
Jarnvikt=(Statorvolym+Rotorvolym)*7650;

%Förluster
Innrreresistans=Kabellangd*0.00104;
Magnetvolym=Magnetbredd*H*Magnettjocklek*Poler;
Magnetvikt=Magnetvolym*1e6*7.4;
Effekt=0.5*Luftrho*A*(vv^3)*Cp*0.95;
Effektvek=0.5*Luftrho*A*(vvvek.^3)*Cp*0.95;
Last=((3*(ELN.^2))/Effekt);
Lastvek=((3.*(ELNvek.^2))./Effektvek);
I=Effekt/(3*ELN); %Ström
Ivek=Effektvek./(3.*ELNvek);
Id=I/(Kabelarea*1e6); %Strömtäthet
Bmax=1.48;
Kh=8.5e-3;
Ke=1.6e-3;
Kc=((pi^2)*(1.8182e6)*((.5e-3)^2))/(6*7650);
Pcu=3*Innrreresistans*I^2;
Pfe=(Kh*Bmax^2*elfrekvens+Kc*Bmax^2*elfrekvens^2+Ke*Bmax^1.5*elfrekvens^1.5)*Statorvikt;
Ptot=Pfe+Pcu;
Verkningsgrad=(Effekt/0.95)/( (Effekt/0.95)+Ptot);
Pcuvek=3*Innrreresistans*Ivek.^2;
Pfevek=(Kh*Bmax^2.*elfrekvensvek+Kc*Bmax^2*elfrekvensvek^2+Ke*Bmax^1.5*elfrekvensvek.^1.5)*Statorvikt;
Ptotvek=Pfevek+Pcuvek;
Verkningsgradvek=(Effektvek./0.95)./( (Effektvek./0.95)+Ptotvek);

%Beteendefunktion
Effvek=ones(1,length(Effektvek)*2);
vvek=0:(length(vvvek)*2-1);

for o=1:length(Effvek)
    if o <= 35
        Effvek(o)=0;
    end
    if o <= length(Effektvek) && o > 35
        Effvek(o)=Effektvek(o)*Verkningsgradvek(o);
    end
    if o >= length(Effektvek)-2 && o < 180
        Effvek(o)=Effekt*Verkningsgrad;
    end
    if o >= 181
Effvek(o)=0;

%Plottar
figure;
plot(vvvek,Ivek);title('Wind speed vs. Current');
xlabel('Wind speed [m/s]');ylabel('Current [A]');

figure;
plot(vvvek,EDCvek);title('Wind speed vs. Induced DC-Voltage');
xlabel('Wind speed [m/s]');ylabel('DC-Voltage [V]');

figure;
plot(vvvek,elfrekvensvek);title('Wind speed mot Electrical frequency');
xlabel('Wind speed [m/s]');ylabel('Frequency [Hz]');

figure;
plot(vvvek,Effektvek);title('Wind speed vs. Power');
xlabel('Wind speed [m/s]');ylabel('Power [W]');

figure;
plot(vvvek,Verkningsgradvek*100);title('Wind speed vs. Efficiency');
xlabel('Wind speed [m/s]');ylabel('Efficiency [%]');

figure;
plot(vvvek,Ptotvek);title('Wind speed vs. Losses');
xlabel('Wind speed [m/s]');ylabel('Losses [W]');

figure;
plot(Effektvek,Verkningsgradvek*100);title('Power vs. Efficiency');
xlabel('Power [W]');ylabel('Efficiency [%]');

figure;
plot(Lastvek,ELNvek);title('Load vs. Line Voltage');
xlabel('Load [Ohm]');ylabel('Voltage [V]');

figure;
plot(Lastvek,Ivek);title('Load vs. Current');
xlabel('Load [Ohm]');ylabel('Current [A]');

figure;
plot(Lastvek,Effektvek);title('Load vs. Power');
xlabel('Load [Ohm]');ylabel('Power [W]');

figure;
plot(Lastvek,Verkningsgradvek*100);title('Load vs. Efficiency');
xlabel('Load [Ohm]');ylabel('Efficiency [%]');

%Beteendeplot
figure;
plot(vvvek/10,Effvek);title('Wind speed vs. Power');
xlabel('Wind speed [m/s]');ylabel('Power [W]');

%Utskrift
disp('Generator 2');
disp(['Beräknad Huvudspänning: ' num2str(ELL) 'V']);
disp(['Beräknad Likspänning: ' num2str(EDC) 'V']);
disp(['Frekvens: ' num2str(elfrekvens) 'Hz']);
disp(['Beräknad Ytterdiameter: ' num2str(Ytterdiameter*1000) 'mm']);
disp(['Diameter: ' num2str(r*2000) 'mm']);
disp(['Höjd: ' num2str(H*1000) 'mm']);
disp(['Antal Poler: ' num2str(Poler)]);
disp(['Antal Spår: ' num2str(Spar)]);
disp(['Total Magnetvikt: ' num2str(Magnetvikt/1000) 'kg']);
disp(['Innre Resistans: ' num2str(Innreresistans) 'ohm']);
disp(['Strömtäthet: ' num2str(Id) 'A/mm²']);
disp(['Förluster: ' num2str(Ptot) 'W']);
disp(['Verkningsgrad: ' num2str(Verkningsgrad*100) '٪']);
disp(['Minsta avstånd mellan spår: ' num2str(Sparavstand*1000) 'mm']);

% Varningsmeddelanden
if Sparavstand <4e-3
    disp('För tätt mellan spår');
end
if elfrekvens >= 50
    disp(['Frekvens för hög: ' num2str(elfrekvens)]);
end;
format
m=3;
if mod(round(Spar),m) ~=0
    disp('Antal spår inte jämt delbart med 3');
end;
disp('-');
disp('-');