Vertical Axis Wind Turbines

Electrical System and Experimental Results

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Abstract

The wind power research at the division of Electricity at Uppsala University is aimed towards increased understanding of vertical axis wind turbines. The considered type of wind turbine is an H-rotor with a directly driven synchronous generator operating at variable speed. The experimental work presented in this thesis comprises investigation of three vertical axis wind turbines of different design and size. The electrical, control and measurement systems for the first 12 kW wind turbine have been designed and implemented. The second was a 10 kW wind turbine adapted to a telecom application. Both the 12 kW and the 10 kW were operated against dump loads. The third turbine was a 200 kW grid-connected wind turbine, where control and measurement systems have been implemented.

Experimental results have shown that an all-electric control, substituting mechanical systems such as blade-pitch, is possible for this type of turbine. By controlling the rectified generator voltage, the rotational speed of the turbine is also controlled. An electrical start-up system has been built and verified. The power coefficient has been measured and the stall behaviour of this type of turbine has been examined. An optimum tip speed ratio control has been implemented and tested, with promising results. Use of the turbine to estimate the wind speed has been demonstrated. This has been used to get a faster regulation of the turbine compared to if an anemometer had been used.

Keywords: VAWT, H-rotor, start-up, all-electric control, Power Coefficient, stall, tip speed ratio, Renewable energy, Measurement systems, PM-generator

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List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


Reprints were made with permission from the publishers. The author has also contributed to the following paper not included in the thesis.

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<tr>
<td>$\lambda_{opt}$</td>
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<td>Optimal tip speed ratio</td>
</tr>
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<td>$\lambda_m$</td>
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<td>[W]</td>
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<tr>
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<td>[\Omega]</td>
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</tr>
<tr>
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<td>[s]</td>
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</tr>
<tr>
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</tr>
<tr>
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<tr>
<td>$V_{z0}$</td>
<td>[m/s]</td>
<td>Reference Wind speed</td>
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<tr>
<td>$z$</td>
<td>[m]</td>
<td>Height</td>
</tr>
<tr>
<td>$z_0$</td>
<td>[m]</td>
<td>Reference height</td>
</tr>
<tr>
<td>$Z_{LL}$</td>
<td>[Ω]</td>
<td>Line to Line impedance</td>
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</table>

**Abbreviations:**

- AC: Alternating Current
- BLDC: BrushLess Direct Current
- CO: Controller Output
- DAQ: Data AcQuisition (system)
- DC: Direct Current
- emf: Electromotive force
- HAWT: Horizontal Axis Wind Turbine
- IGBT: Insulated Gate Bipolar Transistor
- MOSFET: Metal Oxide Semiconductor Field Effect Transistor
- ODE: Ordinary Differential Equation
- PID: Proportional-Integral-Derivative (controller)
- PLC: Programmable Logic Controller
- PLL: Phase-Locked Loop
- PM: Permanent Magnet
- PWM: Pulse Width Modulation
- SCADA: Supervisory Control And Data Acquisition
- SPWM: Sine-Triangle Pulse Width Modulation
- THD: Total Harmonic Distortion
- VAWT: Vertical Axis Wind Turbine
- VI: Virtual Instrument
1. Introduction

Even though the first wind turbine\(^1\) was built around 900 A.D. [1], wind power is today a small addition to the world's energy demand when compared to coal, nuclear, hydro and oil. However, today there is a global discussion about if the greenhouse effect [2] exists or not and if an oil crisis is waiting to happen [3]. Whether or not this is the case, it is a good idea to investigate more environmentally friendly energy sources. A growing number of installed wind turbines is not the single solution for the world's growing energy demand, but can be a part of a more environmentally friendly solution. To be competitive, wind turbine developers need to reduce the cost per installed kW and the maintenance needs have to be as low as possible to reduce downtime. In a study from 2007, it was stated that failures in gearboxes, pitch and yaw systems together stand for 42.1% of the downtime in Swedish wind turbines [4]. This indicates that a less complex system without these parts has the potential to reduce the downtime and thereby increase the profit of a wind turbine. Vertical axis wind turbines (VAWT) can be built without these parts, but have today a very small part of the wind power market in favor of the horizontal axis wind turbines (HAWT).

Lift-based vertical axis turbines were invented by Darrieus in 1931 [5]. Darrieus’ patent covers both the H-rotor type turbine and the classic ‘egg whisk-shaped’ Darrieus turbine. The turbine considered in the thesis is the H-rotor (also called straight-bladed Darrieus turbine or Giromill). Several Darrieus turbines have been built during the years. Canada and the United States had large research programs during the 1970s and 1980s in which several turbines were tested and the largest one was a 4.2 MW machine called EOLE C in Quebec [6]. Sandia National Laboratories (USA) have tested different configurations and sizes of the Darrieus turbine, e.g. [7]. In the Altamont pass in California, several Darrieus turbines were operating in farms during the 1980s [8]. A 130 kW straight-bladed Darrieus turbine was built for research purposes at the same time period in a vertical axis wind turbine research programme in the U.K. [9]. A major drawback of the designs in the research of the 1980s was that aluminium was commonly used for constructing the blades of the classic Darrieus turbines. The material fatigue due to allowing the blades to flex led to failures. These failures led to that the company Flowind went bankrupt. With no American companies interested in the technology, the governmental research programme was ended. In another project, the turbine was

\(^1\)A Persian vertical axis wind turbine used to run a millstone placed beneath the turbine.
carried by one main bearing which failed, causing the governmental funding to be withdrawn and thereby terminating the project [6]. Today, most of the VAWT projects are in smaller scale e.g. the Italian Ropatec [10] or Turby [11] from the Netherlands.

Horizontal axis wind turbines (HAWT) have evolved to be the most common type of turbine operating today. There are several different brands of HAWTs on the market, most of which use a blade pitch-regulated turbine connected to a gearbox that speeds up the rotation to fit the commonly used induction generator. Another HAWT technique is a pitched turbine directly connected to a large synchronous generator [12]. However, some believe that HAWT technology soon will peak in size due to mechanical constraints [6,13]. This may open for a comeback of the VAWT technology, which has the potential to grow larger than the HAWTs of today [9]. VAWT may also be a more economical solution for large offshore installations, which has trigged Sandia National Laboratories to restart their VAWT research programme [14]. Additionally, recent results indicate that vertical axis turbines can perform better in farms than horizontal axis turbines [15]. The material use for building an H-rotor VAWT is about the same or less compared to a HAWT of corresponding size. However, the overall structure of the VAWT will be simpler [16].

The developments in power electronics during the last decades have given new opportunities to control and regulate wind turbines. The power ratings of components are increasing and the prices are going down [17]. This development gives the possibility to reconsider the whole design of a wind power plant. For example; generators and drivelines do not have to be designed to run synchronously with the grid, but can instead be optimized for the turbine (variable speed), and then be connected to the grid through an AC-DC-AC converter. Thus, the chances for succeeding with a VAWT may have increased since the previous large projects during the 1980s.

1.1 Wind turbine concept

The wind power research at the division of Electricity at Uppsala University is aimed towards investigating and increase the understanding of vertical axis wind turbines. The study has focused on a concept with an H-rotor without blade-pitch control connected by a shaft directly to the generator placed on ground. The generator is a permanent magnet synchronous generator with cable windings; the generator design is inspired by ABB’s Windformer project [18]. The turbine operates at variable speed. Since there are deliberately no possibilities for mechanical control, the turbine is controlled electrically by regulating the power from the generator. The variable speed operation gives varying generator voltage that is handled by a inverter after rectification. Thus, one inverter should be able to collectively control several wind turbines connected to a common DC-bus by separate diode rectifiers. Storm protection is
provided by passive stall, which is possible since the generator is designed to have a sufficient overload capacity. By keeping the number of moving parts to a minimum, the maintenance needs are expected to be low. The division of Electricity has built three vertical axis wind turbines so far and a spin-off company from the division has built one within this concept. The first turbine built was a 1.5 kW turbine that is not included in this thesis. The other three is a 12 kW VAWT, a 10 kW VAWT for telecom applications and a 200 kW VAWT. The 12 kW wind turbine is shown in figure 1.1. The group working with this wind turbine project currently consists of five senior researchers and eight Ph.D. students. The research related to these turbines has resulted in two doctoral theses [19, 20] and five licentiate theses [21–25] so far.

1.2 About this thesis

The scientific goal with this thesis has been experimental verification of vertical axis wind turbines. Experimental results are important since they show the behaviour of the complete system under realistic conditions, which can’t be studied in a laboratory. Furthermore, experimental results are essential to improve and verify models of the system. To reach the scientific goals, sub-goals in engineering had to be reached, i.e. to investigate how the electric, control, and measurement systems for this type of turbine could be implemented. The work in this thesis towards the scientific and engineering goals has had a strong experimental approach.
2. Theory

This chapter summarises the theoretical foundation of this work.

2.1 Aerodynamics

The kinetic power flow, $P_{\text{wind}}$, of the wind passing through an area $A$ is given by

$$P_{\text{wind}} = \frac{1}{2} \rho A V^3,$$  \hspace{1cm} (2.1)

where $\rho$ is the air density and $V$ is the wind speed. The power coefficient, $C_p$, of a turbine is defined as

$$C_p = \frac{P_{\text{mech}}}{\frac{1}{2} \rho A V^3},$$  \hspace{1cm} (2.2)

where $P_{\text{mech}}$ is the power absorbed by the turbine. $C_p$ indicates how much of the available power a specific turbine can absorb and is limited by the Betz limit \cite{26}, which numerically is 16/27 for a HA WT and is believed to be roughly the same for a VAWT. By rewriting equation 2.2 the absorbed mechanical power by a turbine can be described as

$$P_{\text{mech}} = \frac{1}{2} \rho A V^3 C_p(\lambda),$$  \hspace{1cm} (2.3)

where $C_p$ is a function of the tip speed ratio $\lambda$ for a turbine with fixed blade pitch. The tip speed ratio is defined as

$$\lambda = \frac{\Omega r}{V},$$  \hspace{1cm} (2.4)

where $\Omega$ is the rotational speed of the turbine, $r$ is the radius and $V$ is the wind speed. The dependence between $C_p$ and $\lambda$ is vital to know, to optimize the operation of a turbine. A typical $C_p(\lambda)$-curve of a VAWT is presented in figure 2.1. As can be seen in the figure, there exists an optimal tip speed ratio that gives the highest $C_p$ and thereby the highest absorption of the turbine. The shape of the $C_p$-curve is unique for every turbine design. For turbines that can change the blade pitch-angle, the optimum tip speed ratio can be adjusted by altering the pitch-angle, \textit{pitch control}. Hence, optimum control of a turbine can be achieved either by altering the rotational speed of the turbine or by changing blade pitch angle. All turbines considered in this work are variable speed vertical axis turbines with a fixed pitch-angle.
Figure 2.1. The relationship between $C_P$ and $\lambda$. The dashed line indicates the optimal tip speed ratio. To the left of the dashed line the turbine is operating in the stall region.

For wind speeds lower than rated, the control system aims to keep an optimal tip speed ratio to maximize the absorption. For wind speeds close to rated wind speed and higher, the tip speed ratio is decreased to assure constant power absorption from the turbine. In this region, the tip speed ratio is regulated to decrease power output for increasing wind speeds, i.e. the turbine is stall-regulated. The turbine is, during generation, controlled so that it always operates at optimal tip speed ratio or lower to ensure stable operation, which in figure 2.1 corresponds to the part of the graph placed to the left of the dashed line.

The turbine is not aerodynamically self-starting in all wind conditions due to the low $C_P$ at start-up, i.e. until the turbine has gained some tip speed ratio, see figure 2.1. In conventional HAWTs and some VAWTs this is solved by blade pitching [27]. It is possible to design a turbine to self start [28] or by adding a small Savonius type turbine to start the main turbine as done in [10, 29]. Optimizing the turbine to self start as in the examples above might affect the power coefficient for the turbine at optimum operation and require excessive amount of blade area. In large scale commercial wind turbines, producers aim to build the blades as small as possible to obtain a cost-effective design. However, it is also desirable to have a fast and well-controlled start of the turbine in which possible eigenfrequencies can be avoided. An alternative to aerodynamic start is to start the turbine electrically, which reduces the number of mechanically vulnerable parts (compared to pitch control) and is controllable. For the turbines considered within this work, an electrical starter system is used since it allows the turbines to be optimized for power conversion rather than for self-start.

The wind speed varies with height due to the friction against the structure of the ground. The average wind speed $V_z$ at the height $z$ can roughly be described
as
\[ V_z = V_{z0} \left( \frac{z}{z_0} \right)^\alpha, \]  
(2.5)

where \( V_{z0} \) is the wind speed at the reference height \( z_0 \) and \( \alpha \) is a site dependent constant due to the ground roughness.

### 2.2 Generators

A generator is an electrical machine that converts mechanical energy into electrical energy. In principal there is no physical difference between a generator and an electrical motor. The only practical difference is in how it is operated i.e. if rotational energy is converted to electrical energy or vice versa. This is a good feature in a wind turbine that is not aerodynamically self starting - the direction of energy is changed and the generator can be used as a motor to start the turbine. There are several types of generators; synchronous, asynchronous, DC etc. with different types of rotor configurations within the different types. However, all generators considered in this work are three phase permanent magnet synchronous generators with cable wound stator and surface mounted magnets.

The induced electromotive force (emf), \( \varepsilon_a \), of one phase in a generator can be described as
\[ \varepsilon_a = -N_T \frac{d\Phi_B}{dt}, \]  
(2.6)

where \( N_T \) is the number of turns in the windings of the stator and \( \frac{d\Phi_B}{dt} \) is the time-dependent change of magnetic flux through the stator due to the movement of the rotor. \( \varepsilon_a \), also called the internal voltage of the generator is proportional to the rotational speed of the generator. However, the stator windings that \( \varepsilon_a \) is induced in have some internal resistance and inductance, which results in that the generator output voltage is affected by the current through the stator as
\[ U_a = \varepsilon_a - I_a R_a - L_a \frac{dI_a}{dt}, \]  
(2.7)

where \( U_a \) is the phase voltage, \( R_a \) is the resistance per phase, \( L_a \) is the phase inductance and \( I_a \) is the current.

The mean power output, \( P_{el,mean} \), from a balanced three phase generator can be calculated as
\[ P_{el,mean} = \frac{3}{N_S} \sum_{i=1}^{N_S} I_{a,i} U_{a,i}, \]  
(2.8)

where \( I_a \) is the instantaneous phase current, \( U_a \) is the instantaneous phase voltage and \( N_S \) is the number of samples used to calculate the mean value. To use this method the sampling frequency must be much higher than the electrical frequency of the machine and the sampling time much longer than the period.
time of the AC-voltage. The measured electric power from a PM generator corresponds to the mechanical power from the turbine as

$$P_{el,mean} = P_{mech} - P_{losses}(\Omega, I_{a,b,c}),$$

(2.9)

where $P_{losses}$ is the sum of iron-, friction-, windage- and copper-losses in the machine. The properties of losses in the considered type of generators are further investigated in [30, 31].

Within this work calculations on generators have primarily been made to simulate starting performance of wind turbines (generator run as an electric motor), which is the reason for negative signs in the following equations describing the used generator model. Thus, the expressions describe the circuit equivalent of an electric machine with notation for more intuitive understanding of it running as a motor. During start-up the generator, acting as a motor, can be described with a circuit equivalent (figure 2.2) as:

\[
\begin{align*}
I_a + I_b + I_c &= 0, \\
U_{ab} &= I_a R_a + L_a \frac{dI_a}{dt} + \varepsilon_a - I_b R_b - L_b \frac{dI_b}{dt} - \varepsilon_b, \\
U_{cb} &= I_c R_c + L_c \frac{dI_c}{dt} + \varepsilon_c - I_b R_b - L_b \frac{dI_b}{dt} - \varepsilon_b,
\end{align*}
\]

(2.10, 2.11, 2.12)

where $I_{a,b,c}$ is the phase currents, $R_{a,b,c}$ is the phase resistances, $L_{a,b,c}$ is the phase inductances, $\varepsilon_{a,b,c}$ is the induced emf in the phases, $U_{ab}$ and $U_{cb}$ are phase to phase voltages. The emf, $\varepsilon_{a,b,c}$, for the three phases is described by
the vector
\[
\varepsilon_{a,b,c} = \omega_{el} \lambda_m \left[ \cos(\theta_{el}), \cos\left(\theta_{el} - \frac{2\pi}{3}\right), \cos\left(\theta_{el} + \frac{2\pi}{3}\right) \right],
\]
(2.13)

where \(\omega_{el}\) is the electrical angular frequency, \(\theta_{el}\) is the electrical angle and \(\lambda_m\) is a constant that describes the peak strength of the flux linkage due to the permanent magnets. The model to calculate \(\varepsilon\) is taken from [32]. \(\lambda_m\) is calculated using equation (2.13) for one phase using the nominal \(\omega_{el}\) and the peak no-load voltage at nominal rotational speed for \(\varepsilon\). The electrically induced torque, \(\tau\), on the rotor shaft of the generator is
\[
\tau = \frac{\varepsilon_a I_a + \varepsilon_b I_b + \varepsilon_c I_c}{\Omega}.
\]
(2.14)

The resulting change in rotational speed is described by
\[
\frac{d\Omega}{dt} = \frac{\tau}{J},
\]
(2.15)

where \(J\) is the moment of inertia of the rotating system.

To regulate the speed of a generator in operation (wind turbine producing) the current is controlled. An increased current is equivalent to an increased braking torque acting on the rotor of the generator according to equation 2.14. Hence, the turbine speed is regulated by controlling the generator current in a way so that the generator is braking the turbine enough to prevent it from being accelerated by the wind.

Another equation that is good to keep in mind when designing inverter control for an electric motor is
\[
Z_{LL} = (R_a + R_b) + j2\pi f (L_a + L_b),
\]
(2.16)

where \(Z_{LL}\) is the line to line impedance, \(R_{a,b}\) is the phase resistances, \(f\) is the frequency and \(L_{a,b}\) is the phase inductances. If the machine is at standstill or rotating slowly with a low internal voltage, the inverter will see it as a frequency-dependent impedance. Thus, without any filters, a high switching frequency will equal a high impedance in the generator and thereby a low generator torque on the shaft.

2.2.1 Auxiliary generator winding

If an auxiliary winding is present in a generator, the generator has two separate electrical systems galvanically isolated from each other. Similar to a transformer, the voltage levels at the different windings can be modified by changing the number of turns in the stator (the length of the winding). This extra winding can, for example, be used to supply power plant auxiliaries at a
more suitable voltage level [33]. For wind power systems where the generator is run in different modes during operation and start-up; one may consider having an auxiliary winding in the stator dedicated to starting, in order to reduce the voltage needed for starting. In such a system, power electronics with a lower voltage rating can be used for starting, compared to the power electronics used for power production. The two systems can also be completely electrically separated from each other. However, using an auxiliary winding in the stator reduces the fill factor of the main stator winding. Another method to reduce the voltage needed for starting is to only use a part of the winding during start-up. In this work generator windings are only considered during start-up of the turbine. In the three wind turbine generators presented in chapter 4, three different types of configurations are used; in chapter 4.1 a completely galvanically isolated auxiliary winding with one tenth of the voltage in the main winding is used for starting. In chapter 4.2, half the main winding is used for starting to reduce the voltage needed. Finally in chapter 4.3 the main winding is used as is for starting.

It is important to remember that the power needed to start a machine is independent of which winding is used. Hence, if the voltage is lowered, the current has to compensate for it. The choice of using a auxiliary winding or not during start-up depends on the surrounding electrical properties. If an island operation is desired it may be good to use an auxiliary winding (or part of the main winding) to reduce the voltage needed for starting and thereby reducing the amount of batteries needed. If it is desirable to have galvanic isolation between start system and production system, it might also be good with an auxiliary winding. However, the benefits of an auxiliary winding must be balanced against the fact that it reduces the fill factor of the main winding in the stator slots.

2.3 Power electronics

Power electronics is a vital part of a load controlled variable speed wind turbine. During operation, the generator gives a voltage that varies with the rotational speed of the turbine and is controlled by adjusting the generator current. Many commercial inverters demand a fixed DC-voltage in order to function. This means that to operate the turbine with variable speed, the DC-voltage has to be adjusted either with a DC/DC converter as in [34] or with an active IGBT rectifier as done in [35]. With DC/DC or active rectification the DC-voltage is usually boosted to match the grid voltage. Another approach to controlling the DC voltage is to build the generator to have a higher voltage and thus remove the need to boost the voltage before the inverter. If the varying DC voltage is handled by the inverter modulation, the DC/DC converter or active rectifier become superfluous. In this case, a simpler system with a passive diode rectifier can be used.
2.3.1 Inverters

Inverters, used to convert DC-voltage to AC-voltage, can be used for grid connection or motor control. A typical three phase inverter consists of six transistors (figure 2.3). Each of the three phases has one high side that connects to DC positive and one low side that connects to DC negative. More complex multi-level configurations with more than six transistors [36] are not covered in this thesis. The transistors are individually connected to a controller that fires the transistors after a modulation scheme. One of the simplest kinds of modulation is the six-step modulation where each phase is switched between being connected to either the positive or negative DC-bus with the same frequency as the modulated "sine" wave. With a balanced three phase load, each phase connected to the inverter will see a signal with two discrete positive voltages and two discrete negative voltages as shown in figure 2.4(a). This type of modulation can be made with slow-switching transistors due to the low frequency, as long as the switchings of high and low side transistors do not overlap each other. However, due to the square-shaped output voltage, the harmonic content is high for this type of modulation, which is one of the reasons it is seldom used nowadays [32].

Another type of modulation used in motor control is the BLDC (BrushLess Direct Current) algorithm in which each phase has three different states; high side conducting, low side conducting or floating potential (neither high nor low side conducting). The two conducting states last for 120 electrical degrees each, with a 60 degree period of floating potential between. This modulation puts less stress on the transistors than six-step since it is not switching directly from high side to low side. An example of one phase in a BLDC inverter is shown in figure 2.4(b). Only two phases are conducting at a given time in BLDC, which gives a higher line-to-line voltage than with six-step modulation. In this thesis, six-step and BLDC have been used for motor control. To run a motor, the inverter has to be in phase with the generator. This has

![Figure 2.3. A typical inverter with two transistors per phase.](image-url)
Figure 2.4. Example of phase voltages from a three phase inverter modulated with six-step modulation to the left and BLDC modulation to the right. The lower figure shows an example of a SPWM phase voltage plotted together with a sine-wave for reference. In this type of modulation the high-side transistor conducts when the PWM-signal is equal to plus one, and the low-side transistor conducts when the PWM-signal is equal to minus one.

been achieved either by measuring the rotor position, with Hall latches, or by measuring the internal voltage of the generator to find zero-crossings.

Inverters for grid connection require more advanced control than the methods mentioned above. The inverter has to be synchronized to the grid voltages, which can be done with a phase-locked loop (PLL). The PLL measures the phase angle of the grid voltage. A PI-controller\(^1\) is used to calculate an output sine from the inverter based on measurements of phase angle and DC voltage, which are compared to desired values of power delivery and power factor. This sine is then compared to a bipolar triangular wave to create the PWM-output (Pulse Width Modulation) signals used to control the transistors of the inverter. The frequency of the PWM-output is usually some kHz. The sampling frequency has to be at least 100 times higher than the PWM-

\(^1\)Proportional-Integral controller; the same as a PID controller with \(K_D = 0\) (described further in chapter 2.4)
frequency to get a good accuracy of the control. An example of output on one phase for this type of inverter is shown in figure 2.4(c). This type of inverter control, where PWM is used to create a sine, is called SPWM (Sine-Triangle Pulse Width Modulation) and is further described in [37].

Irrespective of which type of modulation is used, low pass filtering of the signal is needed to achieve a smooth sine wave with a low harmonic content. However, an inverter with six-step or BLDC modulation requires more filtering than an inverter with SPWM for an output with the same total harmonic distortion (THD). In this work, six-step modulation is used in the inverter dedicated to starting the 12 kW VAWT. BLDC-modulation is used in the start-inverters of the 10 kW and 200 kW VAWTs. None of the start inverters has a low pass AC-filter. SPWM is used in the inverters for grid connection of the 12 kW and the 200 kW VAWTs.

2.4 Control

If the wind speed and the $C_P(\lambda)$ dependence of the turbine are known, it is easy to calculate the rotational speed for the turbine in order to run it in an optimal way using equation 2.4. However, accurate wind measurements can be hard and costly to achieve and need to be performed as close to the turbine as possible without being disturbed by the turbine. If an anemometer is placed 2–4 turbine diameters from the turbine, according to the standard for $C_P$-measurements [38]. The distance can be too long for an accurate regulation of the turbine based on the anemometer measurements. To circumvent this problem a MPPT algorithm can be used to find the optimal operating point [39]. Another solution is to use the turbine as an anemometer, which has the advantage that it measures the active wind speed but demands more knowledge about the aerodynamic properties of the turbine, as done in [40] and [41]. In these two methods, the use of an anemometer as feedback to the control system is replaced by measurements of absorbed power and rotational speed of the turbine. However, an anemometer might still be needed to indicate cut-in and cut-out wind speed, since those wind speeds occur outside the optimal operational range of the turbine. This anemometer may be less accurate than needed for regulation. Within this work the following method, based on equations 2.3 and 2.4, has been used to estimate the present tip speed ratio $\lambda_t$ of the turbine;

$$\lambda_t = \sqrt[3]{\frac{0.5\rho A\eta C_P(\lambda_{t-1})\Omega^3 r^3}{P_{el}}},$$

(2.17)

where $P_{el,\text{mean}}$ is the absorbed electric power, $C_P(\lambda_{t-1})$ is the value of $C_P$ based on the tip speed ratio from the previous iteration and $\eta$ is the efficiency from power absorbed by the turbine to electric power. The values of $C_P$ are taken from a look-up table based on the aerodynamic models of the turbine described
in [20]. This method is similar to the one used in [40], but instead of controlling the optimal torque, the control is focused on finding the optimal tip speed ratio by measuring the absorbed power. The error between the optimal tip speed ratio, $\lambda_{opt}$, and the result from equation 2.17 is calculated as

$$e(t) = \lambda_{opt} - \lambda_t$$

and is used in a PID regulator described as

$$u(t) = K_P e(t) + K_I \int_0^t e(T) dT + K_D \frac{d}{dt} e(t), \quad (2.19)$$

where $K_P$, $K_I$ and $K_D$ are constants regulating the properties of the proportional, integral and derivative parts of the regulator. The new set-point for DC voltage is calculated as

$$U_{DC}(t) = U_{DC}(t-1)\{1 + u(t)\}. \quad (2.20)$$

There are two reasons for using a regulator controlled by the error in tip speed ratio to set the DC voltage; a rapid change in voltage is avoided at gusty wind conditions and the influence of the current dependent voltage drop across the generator (in equation 2.7) can be avoided. The drawback with this type of regulation is that for equation 2.17 to make any sense, the turbine must be absorbing power, which means that boundary conditions must be defined for the system on how to react to low powers. The reaction time of the turbine is faster for higher wind speeds, which has to be considered when defining the constants of equation 2.19. Hence, to get a decent behavior throughout the whole operating span of the turbine it can be good to define different operating spans in the system with different PID-constants.
3. Method

3.1 Engineering science

The work within engineering sciences can be seen as an iteration towards a better understanding of a system. Thus, it begins with an idea from which theoretical simulation models are designed (in this case aerodynamical, mechanical and electrical models). To verify the models, a small prototype is built and tested. Experimental results from the prototype are used to improve the models. Simulations give input on how to improve the experimental prototype, or indicate how the design can be changed or scaled. Then, a new experimental prototype is designed and so on. This thesis is mainly focused on the experimental part of this iterative process. However, the experimental work itself can be an iterative process that leads to improvements. With this type of iteration, the experiments are not fully defined in the beginning of the process, instead new questions arise along the way. The experimental work comprises investigation of three vertical axis wind turbines of different designs and sizes. The turbine projects have been progressing in parallel, which has enabled knowledge transfer in both directions. The 12 kW turbine was the first to be erected and results from that turbine have been implemented in the 10 kW and the 200 kW VAWT. The second turbine was the 10 kW, results from that have been used to improve the 12 kW and 200 kW. The third and last turbine was the 200 kW VAWT, and results from that one is currently being implemented in the 12 kW VAWT.

3.2 Experimental work

The experimental setups are described in chapter 4. The carried out experiments are described further in chapter 5, together with results and discussions.

3.2.1 Data acquisition

Proper data acquisition is essential in experimental work. The first experiments, described in papers I and II, were performed with oscilloscopes for data logging. Consequently, the length of those data series were limited in time. Synchronization of data collected by the different oscilloscopes was an issue. Thus, to improve the measurements a computer-based DAQ system was needed. The primary goal with longer measurements was to experimentally
investigate the $C_P(\lambda)$-behaviour for this type of wind turbine. A measurement system based on an eight channel 12 bit DAQ-card was implemented, which is presented in paper III. The same type of DAQ-solution was used to achieve the results presented in paper IV and for the measurements on the 10 kW VAWT in chapter 5.1. In papers VII and VIII, another method for data acquisition was used. In that case, the control system and data acquisition system were combined, which resulted in a system with more flexibility and capacity for more sensors than the previous experiments. The strategy with data acquisition has been to have the wind turbine running as much as possible with continuous data logging. Consequently, more data than needed for a specific experiment is collected and may thereby be used to answer other experimental questions. The measurement systems are further described together with the experimental setups in chapter 4.

3.2.2 Data treatment

The measurements have resulted in large amounts of data to analyse\textsuperscript{1}. In most of the experiments, the interesting data had to be distinguished and in some cases bundled into 10 minute averages before analysis.

The method of bins can be used to treat large amounts of data from a varying wind climate [42]. The data is sorted into small bins, e.g. if the $C_P(\lambda)$-dependence is calculated, $\lambda$ is sorted into bins where each bin corresponds to a small interval in tip speed ratio. In this way, data from real wind conditions can be used instead of benchmarking the turbine in a wind tunnel. The method of bins is the method recommended to use in the IEC standard [38] for data analysis when measuring the power coefficient for wind turbines. The measured $\lambda$ is divided into bins as

$$\lambda_i = \frac{1}{N_i} \sum_{j=1}^{N} \left( \frac{\Omega_{i,j} r}{V_{i,j}} \right), \quad (3.1)$$

where $\lambda_i$ is the mean value of all calculated values of $\lambda$ which fits in the bin. $\Omega_{i,j}$ is the measured rotational speed, $V_{i,j}$ is sample $j$ of the wind speed that belongs to bin $i$, $r$ is the turbine radius. For each $\lambda$-bin, a $C_P$ is calculated as

$$C_{p_i} = \frac{1}{N_i} \sum_{j=1}^{N} C_{p_{i,j}}, \quad (3.2)$$

where $C_{p_{i,j}}$ is calculated as in equation (2.2) using the power calculated from the wind speed for each sample compared to the mean absorbed power $P_{el}$ for the same sample. 10 minute average values are used as data to solve equation (3.1) and equation (3.2).

\textsuperscript{1}For the 12 kW VAWT eight channels are logged at 1 kHz and for the 200 kW VAWT 45 channels are logged at 1 Hz, which corresponds to 3.9-690 Msample per 24 h.
3.3 Simulations

To enhance the understanding of the start-up system, simulations were made of the interactions between inverter, generator and turbine, which are presented in paper III. The simulations were based on the models described in chapter 2.2 and done in a MATLAB solver for systems of ordinary differential equations (ODE). The simulations were performed assuming a negligible wind speed to reduce the complexity of the turbine simulation. Input parameters were based on experimental data from the wind turbine. The only parameter, for the simulations, that was not possible to get an accurate measurement of during experimental verification, was the Hall latch\(^2\) position relative to the generator phases. Thus, the electrical position of the Hall latches was decided through trial and error in the simulation model as well as in the experiments.

\(^2\)Hall Effect sensor that gives a digital signal that corresponds to the direction of the magnetic flow.
4. Experimental setups

In this chapter, the considered experimental setups are described.

4.1 12 kW VAWT

In 2006, a 12 kW vertical axis wind turbine was built by Uppsala University.

4.1.1 Site

The site chosen for the prototype turbine is Marsta Meteorological Observatory (N 59° 55’ 32", E 17° 35’ 12"), 5 km north of Uppsala, Sweden. The site has been used for meteorological measurements by the meteorological department at Uppsala University for several decades [43]. The characteristics of the site and examples of meteorological activities at the site can be found in [44]. The layout of the site is shown in figure 4.1. The wind climate is described in paper I. The winds are more or less turbulent depending on the wind direction. If the wind comes from the south, the observatory building will add a lot of turbulence to the wind hitting the turbine. On the other hand, if the wind comes from the west or the east, the flow will be more laminar, since the land is quite open in those directions. These are good properties for testing a research prototype in different turbulence intensities. However, due to the low mean wind speed, it is not an optimal spot for erecting a commercial wind turbine.

4.1.2 Turbine specifications

The constructed straight-bladed Darrieus type turbine has blades with NACA-0021 section profile. The blades have tapered ends and are made from carbon fiber and fiberglass. Each blade is mounted on two streamlined struts, which are bolted to the hub. The struts are made from laminated wood, coated with fiberglass. The profile of the struts is modified NACA0025, with the trailing edge shortened. The most important turbine properties are listed in table 4.1. The design choices made for this turbine are described in [45] and more aerodynamic data can be found in paper III. The turbine was designed using analytical and numerical models describing the behavior of an H-rotor [46,47].
Figure 4.1. Photo of the site with wind turbine, meteorological measurement tower and observatory building containing the control room for the wind turbine. The photo is taken from a position south of the site.

Table 4.1. Nominal properties of the wind turbine

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (kW)</td>
<td>12</td>
</tr>
<tr>
<td>Wind speed (m/s)</td>
<td>12</td>
</tr>
<tr>
<td>Rotational speed (rpm)</td>
<td>127</td>
</tr>
<tr>
<td>Number of blades</td>
<td>3</td>
</tr>
<tr>
<td>Projected area (m²)</td>
<td>30</td>
</tr>
<tr>
<td>Hub height (m)</td>
<td>6</td>
</tr>
<tr>
<td>Turbine radius (m)</td>
<td>3</td>
</tr>
<tr>
<td>Blade length (m)</td>
<td>5</td>
</tr>
<tr>
<td>Aerodynamic control</td>
<td>Passive stall</td>
</tr>
<tr>
<td>Blade airfoil</td>
<td>NACA0021</td>
</tr>
</tbody>
</table>

4.1.3 Generator specifications

The generator connected to the turbine is a permanent magnetized cable-wound synchronous generator, designed and constructed at Uppsala University. The cables used for the stator winding are MK16 cable with a cross section area of 16 mm² and PVC insulation. The rotor is magnetized with Neodymium-Iron-Boron permanent magnets. It is designed to have good overload capacity with a load angle of 5.8° at nominal operation, and can thereby handle the turbine in all possible operational conditions. The generator was designed using an in-house finite element method software, and the simulations have been validated experimentally [48, 49]. The nominal properties of the generator are
described in table 4.2. In the outermost lap of the stator slots, an auxiliary winding is placed. This extra three-phase winding is separated from the main winding and is dedicated to running the generator as a motor during start-up of the turbine. The auxiliary winding is one tenth of the length of the main winding, which gives a lower nominal voltage on that winding compared to the main winding. The auxiliary winding is made from the same type of cable as the main winding. The properties of the auxiliary winding, useful when designing an inverter for starting, are described in table 4.3. The generator is shown in figure 4.2(a) showing the process of mounting of the generator in the wind turbine.

Table 4.2. Nominal properties of the generator

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (kW)</td>
<td>12</td>
</tr>
<tr>
<td>Phase voltage (V)</td>
<td>156</td>
</tr>
<tr>
<td>Current (A)</td>
<td>25.7</td>
</tr>
<tr>
<td>Electrical frequency (Hz)</td>
<td>33.9</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>95.9</td>
</tr>
<tr>
<td>Number of poles</td>
<td>32</td>
</tr>
<tr>
<td>Load angle</td>
<td>5.8°</td>
</tr>
</tbody>
</table>

Table 4.3. Nominal properties of the auxiliary winding

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance (Ω/phase)</td>
<td>0.0151</td>
</tr>
<tr>
<td>Inductance (mH/phase)</td>
<td>0.0617</td>
</tr>
<tr>
<td>Phase voltage (V)</td>
<td>17.2</td>
</tr>
<tr>
<td>Electrical frequency (Hz)</td>
<td>33.9</td>
</tr>
</tbody>
</table>

4.1.4 Mechanical setup

Optimum energy production was not a design criterion, since this wind turbine is a small research prototype designed to test and evaluate the concept. Thus, the tower is quite low. The tower is designed to be a stiff tower, i.e. the eigen-frequency of the tower is higher than the maximum rotational frequency of the turbine. In small scale like this, it is not economical to build a conical tube tower, as would have been done in a larger installation; instead the tower consists of a straight tube supported by spars. The shaft connecting the turbine and generator, inside the tower, is supported by two ball bearings, one in the top of the tower and one in the bottom of the tower, just above the generator. The shaft is connected to the generator by a curved-tooth coupling in order to only transfer torque around the same axis as the shaft. A disc brake is placed on the shaft inside the generator housing; two hydraulic calipers are used for
braking this system manually. The disc brake is only used during maintenance, the rest of the time the generator is used to electrically brake the turbine. The generator is placed inside a generator housing, on top of which the rest of the tower is mounted. The tower, support spars, shaft and generator housing are made from steel. The whole structure is placed on a concrete foundation. The mechanical design and dimensioning of the tower, shaft and foundation are further described in [50]. Between the generator housing and the nearby observatory building, housing the control room, two cable channels are buried. One channel is for power cables and the other is for signal cables. The erection of the turbine and the tower can be seen in figure 4.2(b). Due to the small size, neither a large crane nor much manpower was needed.

Figure 4.2. To the left: the generator during the mounting of it into its housing. To the right: the mounting of the blades and struts on the 13th of December 2006.

4.1.5 Electrical System

This wind turbine is not grid-connected; instead, a switched load has been used to simulate a grid in the system. A dump-load is much easier to control than the grid. This allows more experimental activity than with an inverter and grid codes to follow.

The three phase output current from the main windings in the generator is rectified with a six-diode (Semikron SKKD 100) passive rectifier. The DC voltage is stabilized with a filter consisting of two electrolytic capacitors (RIFA 6800 μF 400 V) and an inductance. On the DC side, 12 electrical loads are connected in parallel. Each load is an oil-filled radiator heater (Duracraft CZ-190820E) with a resistance of 26.5 Ω and a power rating of 2 kW. The total load connected is roughly 2.2 Ω and 24 kW, which is twice the rated power of the turbine. Connected in series with the loads are two parallel IGBT modules (Semikron SKM 300GA123D) that control the current through the loads. The voltage from the generator is proportional to the rotational speed of the generator, as stated in equation (2.6). A constant DC voltage keeps the
rotational speed of the turbine approximately constant. The voltage is kept constant by switching the loads when the output voltage from the generator is higher than the desired level. When the loads are switched on, a current starts to flow from the generator, which increases the torque added to the shaft by the generator, causing the turbine to slow down. When the voltage has fallen below the desired level, the loads are disconnected again. The load switching is pulse width modulated with a frequency of 500 Hz. The set point (desired rotational speed) is set electrically according to a sliding average of the wind speed by the control system. However, the set point can also be set manually. The chosen control system can only slow the turbine down, not actively accelerate it, i.e. if the wind speed decreases the turbine will slow down.

To achieve a higher safety (and redundancy) in the system, two IGBT modules are used in parallel with separate drivers. The control of the IGBTs is configured so that one of the IGBTs is primary and takes most of the load. When there is a peak in the power production from the turbine (rapid increase in voltage), the secondary IGBT is activated to reduce the load on the primary. The IGBT temperature is monitored and the IGBT drivers are configured so that the secondary IGBT takes over if the primary is overheated. If both are close to overheating, the turbine will be slowed down and stopped until the IGBTs have cooled down. An auxiliary emergency system has been constructed to brake the turbine in case of failure of the control system or power outage to the control system. The emergency system is powered by batteries and connected directly to the generator. If the rotational speed of the turbine is higher than allowed, a separate three-phase dump load is connected to the generator that will stop the turbine in a couple of seconds. The same happens if the power supply of the control system fails. The emergency system has to be manually reset after being enabled.
Starter circuit

Since the wind turbine is not self-starting, an electrical starter system has been designed for the prototype. The starter system uses the auxiliary winding of the generator as a motor, described in table 4.3. Since the auxiliary winding is shorter than the main winding, the back emf is less than for the main winding, which gives a system that can start on the voltage two car batteries can deliver (24 V). A three phase inverter, connected to the auxiliary winding, is controlled by a six-step modulation scheme.

The inverter is built from six MOSFETs (IXFN200N07), each controlled by an IR2121 driver with individual power supply by a DC/DC converter (TME 1215S). Feedback of rotor position is achieved by three Hall latches (Allegro A3280EUA) placed in the air-gap of the generator (figure 4.3). The digital signals from the Hall latches are interpreted by a microcontroller (ATmega16) which generates the firing pulses for the inverter. The microcontroller supports both six-step and BLDC modulation and can limit the inverter current by superposing a PWM on the control signals. The resistance and inductance of the auxiliary winding are quite low, as can be seen in table 4.3. To protect the MOSFETs, the start currents are passively damped by two power resistors\(^{1}\) (ARCOL HS300 0.1 Ω) connected in series with the batteries. A diode (IRF 85HF20) is placed in series with the batteries, in order to prevent them from parasitic charge from the generator during operation of the wind turbine. The starter system is further described in paper IV, where it is also compared to a simulated model of the system during start-up.

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\(^{1}\)These resistors may be replaced by the PWM limitation in the microcontroller in order to increase efficiency during start-up, but are still connected since they reduce the stress on MOSFETs in case of a microcontroller failure.

4.1.6 Control

A control system based on a microcontroller (PIC18F6680 together with a Modtronix SBC68EC Web Server), originally designed to be used within the
10 kW VAWT, has also been used for control of the 12 kW VAWT. A cup anemometer is used for measuring wind speed. A Hall latch (Allegro A3280-EUA) is placed in the air gap of the generator to measure the rotational speed by sensing the passages of rotor magnets. The control system has one digital output that controls the starter circuit and one that controls the loads (Controller Output, CO). When the wind speed has increased over cut-in wind speed, the starter output digital signal goes high to activate the starter inverter until the turbine is started. CO is a PWM signal where the duty cycle is proportional to the rotational speed of the turbine. The CO signal is low pass filtered to convert it into an analogue signal compatible with the load control. The control system can be operated to run the turbine at a fixed rotational speed or at a variable rotational speed which depends on the present wind speed. When operating at variable speed, a look-up table is used to find the CO that corresponds the measured wind speed. The mean of the wind speed is calculated as well as the present mean rotational speed. The controller system has two web interfaces, one for settings and one for diagnostics, enabling the system to be controlled remotely via Internet. This system has been used during the experiments presented in paper III. After the $\lambda$-control strategy described in paper VIII was implemented on the 200 kW VAWT, it was also implemented on the 12 kW VAWT. The new control system is based on an Arduino Ethernet2 microcontroller board and have the same types of output as the previous system but measures the DC-voltage and current to be able to use the turbine as an anemometer. This new system is still a work in progress and has not delivered any results yet.

4.1.7 Inverter for grid connection

In parallel with the on site work with the electrical system, another system has been designed in the lab. The aim of this new system is to implement grid connection of the 12 kW VAWT. This system uses a clone of the generator installed in the 12 kW VAWT, driven by an electrical motor as power source. As in the 12 kW system, the current from the generator is rectified by a passive diode bridge to a DC-capacitor. Connected to the DC-capacitor is an inverter bridge controlled by a NI cRIO3-9074. On the AC-side of the inverter is an LCL-filter to reduce the harmonics caused by the inverter switching. The filter is connected to a transformer, which in this case is a tap transformer that delivers four different AC-voltage levels for the inverter to work against. The use of a tap transformer can reduce the need for a DC/DC-converter or similar to boost the voltage and can also reduce the losses in the inverter. However, it put higher demands on the design of the AC-filter, since a change of tap also changes the inductance of the system and thereby the filtering properties.

[^3]: CompactRIO, which is a reconfigurable embedded control and acquisition system.
Paper VI presents the first results from this setup, where the filter properties are investigated. During that experiment, the inverter was working against a three phase dump-load connected to the secondary side of the transformer. Since no grid was connected to provide feedback, the inverter control was simplified by using a fixed PWM-modulation from a lookup table.

4.1.8 Measurement system

During the first experiments performed on the prototype, described in paper I, all data were logged with oscilloscopes (Textronix TDS 2024 and TPS 2014), connected to high voltage probes and current shunts (Cewe Instrument shunt 6112). The current shunts give a weak signal, which is on the same electric potential as the node being measured on. The shunts were replaced with current transducers (LEM HAL 50-S) to increase the current signal and eliminate the risk of short circuit through the oscilloscopes. In paper II, current transducers were used. The oscilloscopes could only measure a fixed number of samples per measurement campaign. Before the next measurement campaign could start, data had to be saved to a flash memory. The maximum time to measure with reasonable sampling rate was about 50 s with the oscilloscopes used. A better logging system had to be built before a long time measurement of $C_P(\lambda)$ could be done. The new logger system was put together by combining a 12 bit DAQ card\(^4\) and a remotely controlled Linux computer. The voltages were measured with voltage transducers (LEM LV 25-P), which isolate the measured voltage from the DAQ card. The DAQ logged the fol-

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\(^4\)http://www.linux-usb-daq.co.uk/tech2_usbdux/ 2012-09-12
following signals from the wind turbine setup: AC-voltage, AC-current from one phase, DC-voltage and DC-current after rectification and filtering, wind speed from two anemometers and one more AC-current from another phase. The AC-voltage was measured relative to the neutral of the generator and the DC-voltage was measured between DC positive and DC negative. The wind speed was measured with an anemometer (VAISALA WMS302) placed on a 4.64 m pole placed 2.5 rotor diameters north of the turbine shaft. The choice of placement of the anemometer was inspired by the recommendations in [38]. A secondary anemometer was placed on the roof of the observatory building used by the control system. This signal was also logged by the DAQ, but was not used for efficiency analysis. This setup was used in paper III.

A secondary measurement system was built, to avoid interfering with the main measurement system during the work with the start-up system, described in paper IV. In the second setup, the same type of DAQ was used and logged by the same computer. In this setup, voltages were logged from the three phases
of the inverter and from the batteries. All the voltages were measured relative to the negative pole of the batteries. Resistive voltage dividers were used to convert the measured voltages into acceptable voltages for the DAQ. Currents were measured using current transducers (LEM HAIS 50-P) attached to two of the phases and to the supply from the batteries. The last channel of the DAQ was connected to an R-2R ladder used to convert the three digital signals from the Hall latches into an analogue signal. The two DAQ-based measurement setups have been calibrated against a high precision multimeter (APPA 207), prior to the measurements. The placement of all the measurement probes in the wind turbine system are shown in figure 4.5.
4.2 10 kW VAWT for telecom applications

During autumn 2008, a second turbine was erected in Marsta, roughly 300 m south of the 12 kW turbine described in chapter 4.1, and shown in figure 4.6. This was a joint research project between Uppsala University, Ericsson AB and Vertical Wind Communications AB a spinoff company from the division of Electricity at Uppsala University. The constructed wind turbine is a prototype to test a concept for supplying power to radio base stations in remote areas, where no electric grid is available (island operation), e.g. in the countryside of India and Africa. By using a wind turbine in these locations, the use of diesel generators can be reduced and thereby decrease the costs for operating the station. The turbine is dimensioned with a higher nominal power than demanded to enable storage of excess energy for less windy days in a battery bank. The wind turbine prototype is built on the Ericsson Tower Tube, which is a concrete radio base tower with all the radio equipment inside. The antennas are covered by a composite material radome at the top of the tower. The tower is designed to have an elevator to hoist the radio equipment, figure 4.8(b). Thus, the generator must be placed on the outside in order to not interfere with the elevator. Furthermore, the turbine cannot be placed at the top of the tower, since it would then disturb the radio transmission.

4.2.1 Generator and Turbine

A ring-shaped outer-rotor generator had to be constructed with a 1.8 m hole in the middle to fit around the tower. Due to the large diameter of the generator it was neither economical nor practical to use a standard ball bearing in this construction. An existing application for ball bearings with this diameter is

5http://www.ericsson.com/ourportfolio/products/tower-tube 2012-09-04
6http://www.verticalwind.se 2012-09-04
to support multi MW shafts for hydro power plants. The used bearing solution was instead a bearing integrated with the generator, based on four steel wires that make a track for the bearing-balls. This type of bearing puts high demands on the manufacturing accuracy and materials used in the structure. The built permanent magnet generator is cable wound. The cables used for the stator winding are MK16 cable with a cross section area of 16 mm$^2$ and PVC insulation. Half the winding can be disconnected by a contactor to reduce the voltage needed for starting. The generator is further described in [51] and the most important parameters of it are described in table 4.4. The stator of the generator, mounted on a segment of the tower during construction, is shown in figure 4.7.

Table 4.4. Nominal properties of the telecom generator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (kW)</td>
<td>10</td>
</tr>
<tr>
<td>Phase voltage (V)</td>
<td>240</td>
</tr>
<tr>
<td>Current (A)</td>
<td>24.1</td>
</tr>
<tr>
<td>Electrical frequency (Hz)</td>
<td>76</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt;95%</td>
</tr>
<tr>
<td>Number of poles</td>
<td>102</td>
</tr>
<tr>
<td>Load angle</td>
<td>5.4°</td>
</tr>
</tbody>
</table>

This wind turbine is direct driven, since the struts of the turbine are mounted directly on the rotor of the generator. The four blades of the turbine are 5 m long and have NACA0021 profiles. Four blades instead of three were chosen to compensate for the aerodynamic disturbance from the tower that goes
through the turbine. The nominal properties of the turbine are described in table 4.5 and one of the blades is shown in figure 4.8(a). The turbine and generator, mounted 30 m up on the outside of the tower, can be seen in figure 4.9. They are further described in paper V.

Table 4.5. Nominal aerodynamic properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (kW)</td>
<td>10</td>
</tr>
<tr>
<td>Wind speed (m/s)</td>
<td>12</td>
</tr>
<tr>
<td>Rotational speed (rpm)</td>
<td>89</td>
</tr>
<tr>
<td>Number of blades</td>
<td>4</td>
</tr>
<tr>
<td>Projected area (m²)</td>
<td>40</td>
</tr>
<tr>
<td>Hub height (m)</td>
<td>30</td>
</tr>
<tr>
<td>Turbine radius (m)</td>
<td>4</td>
</tr>
<tr>
<td>Blade length (m)</td>
<td>5</td>
</tr>
<tr>
<td>Aerodynamic control</td>
<td>Passive stall</td>
</tr>
<tr>
<td>Blade airfoil</td>
<td>NACA0021</td>
</tr>
</tbody>
</table>

Figure 4.8. To the left is one of the blades of the 10 kW VAWT and to the right is the shaft-free inside of the tower.
Figure 4.9. The wind turbine built on an Ericsson Tower Tube radio base tower: The generator is mounted on the outside of the tower with the struts connected directly to the rotor.
4.2.2 Electrical system

Since the considered application for this wind turbine is island operation, the produced power is dissipated in a DC load, which in this case represents a radio base station with a varying demand, or its energy storage. This electrical control system is similar to that of the 12 kW turbine described in chapter 4.1. However, the power output from generator and the demand from the DC load are not always matched. There may occur times when more power than consumed needs to be extracted to keep control of the turbine. To handle these occasions, a dump-load with separate control is connected in parallel with the DC load. In the erected wind turbine, neither radio base station nor battery bank was installed, since the purpose of the installation was to experimentally verify the concept with a wind turbine mounted on a telecom tower - all absorbed power was dissipated in the dump load during experiments. During operation, the voltage from the generator is rectified by a passive diode bridge and then stabilized by a capacitor bank. The power is dissipated in a switched load (figure 4.10), connected to the capacitor bank, controlled in the same way as the loads described in chapter 4.1.5. For control, a clone of the Modtronix system described in chapter 4.1.6 was used. The start-up is powered from eight 12 V lead acid batteries connected in series. The start inverter is IGBT-based and controlled by an ATmega microcontroller, which runs a modified version of the system described in [52]. For this generator, no Hall latches are used for rotor feedback. Instead, the BLDC modulation is generated based on measurements of the internal voltage in the generator. To reduce the number of batteries needed for starting, half the stator winding is disconnected by a contactor during start-up. The electric cabinet housing the electrical system is shown in figure 4.11.

For measurements, a 12 bit DAQ and a laptop were used (also shown in figure 4.11). DC voltage and current were measured by transducers\(^7\) after the rectifier. Wind speed was measured by a cup anemometer placed on a six meter pole placed roughly 20 m west of the tower.

\(^7\)LEM LV25-P for voltage and a LEM transducer for current
Figure 4.10. The dumpload used to dissipate the power produced by the 10 kW VAWT.

Figure 4.11. The electrical cabinet containing the electrical system and the DAQ system mounted on the door.
4.3 200 kW grid-connected VAWT

4.3.1 Site

The 200 kW VAWT was erected in 2010 by Vertical Wind AB\(^8\), a spinoff company from the division of Electricity at Uppsala University. The project was funded by the Swedish Energy Agency and the two wind turbine customers were E.ON and Falkenberg Energi. It was decided to erect the wind turbine in Falkenberg, which is one of the most wind power friendly counties in Sweden [53]. Another reason for establishing in Falkenberg was that municipality-owned Falkenberg Energi could assist in finding a site and factory premises. The turbine is erected in Torsholm 4 km north of the town center of Falkenberg. The layout of the site is shown in figure 4.12. According to the MIUU model [54] the annual average wind speed at the site\(^9\) is roughly 6 m/s.

![Figure 4.12. The site of the 200 kW VAWT.](http://www.geo.uu.se/vind/vindkartor/årsmedelvind_27_03_49m.jpg)

4.3.2 Tower and turbine

The 40 m high conical tower is made from wood composite, which is an environmentally friendly material, compared to steel and concrete. The tower structure is based on 12 laminated wood beams glued together to form two 20 m conical tube sections that are bolted to each other. The outside of the

\(^8\)http://www.verticalwind.se 2012-09-04

\(^9\)http://www.geo.uu.se/vind/vindkartor/årsmedelvind_27_03_49m.jpg 2012-09-06
tower is weather-protected by a layer of fiberglass laminate. The tower en-
cases and carries the steel drive shaft that connects the turbine and generator. The shaft is carried by two bearings in the top of the tower and the bearings of the generator. Inside the tower are six levels of support wheels that keep the shaft in radial position. The shaft, support wheels and the inside of the wood tower are shown in figure 4.13. The tower is a soft tower, i.e. it has an

eigenfrequency placed between the rotational frequency and the blade passing frequency. The eigenfrequencies of this type of wind turbine have been analytically examined in [55], but not yet verified experimentally against the 200 kW VAWT. On site experience has shown that the tower had an eigenfrequency that was excited at about 15 rpm before attaching the guy-wires shown in figure 4.14. After the guy-wires were mounted, two new turbine eigenfrequencies were found around 17 and 23 rpm. However, due to the higher powers at these rotational speeds, the new eigenfrequencies are easier for the control system to avoid than the previous at 15 rpm. A disc brake is placed at hub height with two different hydraulic brake caliper systems; the first is for emergency braking the turbine, while the second is a parking brake to be used during maintenance.

The turbine consists of three 24 m long straight blades with a standard NACA profile. Each blade is connected to two struts bolted to the hub. The blades and struts are made from fiberglass. The nominal properties of the turbine are listed in table 4.6.

Figure 4.13. The lower part of the shaft with one level of support wheels.
Figure 4.14. The 200 kW VAWT in Falkenberg with three guy-wires attached.
Table 4.6. Nominal properties of the wind turbine

<table>
<thead>
<tr>
<th>Nominal Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (kW)</td>
<td>200</td>
</tr>
<tr>
<td>Wind speed (m/s)</td>
<td>12</td>
</tr>
<tr>
<td>Rotational speed (rpm)</td>
<td>30</td>
</tr>
<tr>
<td>Number of blades</td>
<td>3</td>
</tr>
<tr>
<td>Projected area (m²)</td>
<td>624</td>
</tr>
<tr>
<td>Hub height (m)</td>
<td>40</td>
</tr>
<tr>
<td>Turbine radius (m)</td>
<td>13</td>
</tr>
<tr>
<td>Blade length (m)</td>
<td>24</td>
</tr>
<tr>
<td>Aerodynamic control</td>
<td>Passive stall</td>
</tr>
</tbody>
</table>

4.3.3 Generator

The generator design is adapted to the direct drive torque and rotational speeds of the turbine. It is designed to have good overload capacity with a low load angle of 9.9°, so that it can handle the turbine in all possible operational conditions. The 36 pole rotor is permanent magnetized with neodymium-iron-boron magnets. The stator is cable wound with 50 mm² PVC-insulated stranded copper conductors. The generator is mounted in the bottom of the tower, directly attached to the concrete foundation of the tower. A part of the generator, visible through one of the service hatches in the floor of the tower is shown in figure 4.16(b). The design of the generator is further described in [56]. Nominal properties of the generator are listed in table 4.7.

Table 4.7. Nominal properties of the generator

<table>
<thead>
<tr>
<th>Nominal Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (kW)</td>
<td>225</td>
</tr>
<tr>
<td>Phase voltage (V)</td>
<td>484</td>
</tr>
<tr>
<td>Current (A)</td>
<td>160</td>
</tr>
<tr>
<td>Electrical frequency (Hz)</td>
<td>9.9</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>96.7</td>
</tr>
<tr>
<td>Number of poles</td>
<td>36</td>
</tr>
<tr>
<td>Load angle</td>
<td>9.9°</td>
</tr>
</tbody>
</table>

4.3.4 Electrical system

A dump-load placed in the bottom of the tower is used for braking the turbine during shutdown. It is connected to the generator by a contactor that switches the generator between being connected to the dump-load or to the substation. For increased safety, the normal case for the contactor, no voltage across the control coil, is that the dumpload is connected to the generator. The rest of
the electric system fed by the generator is placed in a nearby substation. The substation is divided into three parts; a high voltage room where the substation is connected to the grid, a transformer room and a low voltage room where the power electronics and control system are placed. The generator is connected to the low voltage room where it is rectified by a passive diode bridge, see figure 4.15(a). The rectified voltage is connected to a capacitor bank, see figure 4.15(b), through an inductance, which is used to filter out rapid changes in current. The DC voltage across the capacitor bank varies with the rotational speed and has a span from 520 V up to 950 V during operation. The DC voltage is controlled by the inverter through regulation of current fed to the electric grid. The current from the inverter is low pass filtered in an LC filter, figure 4.15(c), to eliminate traces of the high frequency IGBT switching. The 400 V output from the inverter is then transformed up to 10.8 kV, figure 4.15(d), which is the grid voltage at the point of connection for the substation.

A separate smaller inverter is used for start-up of the turbine and is connected in parallel with the diode rectifier. That inverter is powered from the DC-bus. For feedback of rotor position, three Hall latches are placed in the air-gap of the generator. The Hall latches are mounted on a movable fixture attached to the generator beams. The movable fixture gives the possibility to calibrate the feedback of rotor position, figure 4.16(b). The start-up uses a BLDC modulation with a superposed PWM signal that controls the current. The DC voltage fed to the start-up is regulated by the main inverter. The start-up inverter has a lower power rating than the main inverter and is shown in figure 4.16(a). The basic layout of the electric system is shown in figure 4.17.

4.3.5 Control system

The control system is developed in Labview\textsuperscript{10}, which together with cRIO modules give the possibility to easily add or remove sensors during the development of the control system. The hierarchy of the control system is described below and shown in 4.18. On top is a computer acting as a server for the system, on which the SCADA\textsuperscript{11} server VI\textsuperscript{12} is run. The SCADA server is the main user interface in the system. Here, the wind turbine is started, stopped and relevant status and alarms from the system are shown. This server can be remotely accessed by an operator to control the SCADA server. The next level in the hierarchy is two cRIO modules, the first of them a cRIO 9074, which is used to control the inverter and various functions in the substation. The second cRIO is a 9073 that controls the inverter used for starting and var-

\textsuperscript{10}www.ni.com/labview 2012-09-05
\textsuperscript{11}Supervisory Control And Data Acquisition
\textsuperscript{12}Virtual Instrument - a program in Labview
Figure 4.15. Different parts of the electrical system; (a) is the three phase rectifier, (b) is the capacitor bank connected to the DC-bus mounted in front of the inverter, (c) is the coils and capacitors used to filter the AC-current, (d) is the transformer.

ious functions in the wind turbine tower. Four PLCs\textsuperscript{13} (Crouzet Millennium 3XD26) are working as slaves to the cRIOS; one for the cRIO-9074 and three for the cRIO-9073. The PLCs measure and control less time critical tasks as temperature monitoring and control of brake pressure. The control algorithm running on this system is further described in paper VIII and chapter 2.4.

\textsuperscript{13}Programmable Logic Controller
Figure 4.16. To the left is the inverter used for starting the 200 kW turbine and to the right a part of the generator mounted in the tower with the fixture to hold the Hall latches in the air gap.

Figure 4.17. The electric system for the wind turbine.

Figure 4.18. The hierarchy of the Labview based control system.
4.3.6 Measurement system

Most of the measurements are handled by the cRIO modules that have a fixed sampling frequency of 1 Hz and log almost all the sensors in the system. Some values e.g. the DC voltage, can be logged in burst mode, i.e. faster logging for some seconds. The measurements used within this work are DC voltage measured with a Tektronix P5200 voltage transducer (measured by a NI9215), DC current measured with a SSET CEIZ04-55E4-1.0/0-400A current transducer (measured by a NI9201). The rotational speed of the turbine is measured by a 10 bit rotational encoder placed on the drive shaft just above the generator. Wind speed is measured by a Thies Clima 4.3351.00.161 cup-anemometer, placed 42 m up in a wind measurement tower, placed 100 m from the turbine. The signals from anemometer and rotational encoders are interpreted by a PLC. The wind speed is logged both by one of the cRIOS and by a dedicated weather server that also logs wind speed and wind direction as well as air pressure and temperature at 39 m. The measurement tower is shown in figure 4.19, which also shows the small and cosy cabin, where a substantial part of the code for the control system has been developed and tested.
Figure 4.19. The measurement tower located 100 m from the 200 kW turbine.
5. Results and discussion

5.1 First measurements

The first measurement results from the 12 kW prototype are presented in paper I. The measurements were performed using oscilloscopes that could only measure a limited number of samples per data set. Furthermore, the measurements were performed before the electrical control system was installed. The turbine was regulated manually by switching the number of loads connected to each phase. The results are shown in figure 5.1, where the measured electrical power is correlated with the wind speed and the rotational speed of the turbine.

No experimental results have been published yet from the 10 kW VAWT. The data presented below were not logged during optimal operation of the system and can therefore not be used to evaluate the turbine. However, the data do show that the built system has produced power, i.e. the concept is working. The results are shown in figure 5.2, where the measured electrical power is plotted against the wind speed.
Figure 5.1. Results from the first measurements of the 12 kW turbine.
Figure 5.2. Power absorbed by the turbine mounted on the telecom tower.
5.2 Electric control system

The first results from the electric control system are presented in paper II. A system that controls the extracted power from the generator and thereby the rotational speed of the turbine has been implemented for the prototype. The control system can be used both to maintain a constant rotational speed, as shown in figure 5.3, and to maintain a constant tip speed ratio. In the latter case, an anemometer is used together with the $C_p(\lambda)$-dependence to set the generator voltage. This is an important result for all the turbines included in this thesis since it shows that by having control of the generator voltage, the rotational speed is also controlled. However, it was later noticed that the voltage drop across the generator at high powers can allow the rotational speed to drift from the set voltage. Practically, this means that the rotational speed can be controlled by controlling the voltage, but the voltage cannot alone be used as feedback on generator speed.

![Figure 5.3](image)

*Figure 5.3.* The figure on top shows the wind speed, the lower figure shows the rotational speed of the turbine when the control system is set to maintain a fixed rotational speed.

5.3 Electrical starter

An electrical starter system for the 12 kW prototype has been designed and experimentally validated. This work is described in detail in paper IV. An example of a start performed with the electrical starter is shown in figure 5.4, which shows the experimental data compared to a simulation of the system.
The start-up time with this system is about 20-30 s and the energy consumption for a start is roughly 10.5 Wh, which corresponds to around 3 s of nominal power of the turbine. The phase voltage during start-up is six-step modulated, as shown in figure 5.5. The six-step shape of the voltage is a bit deformed due to the back emf of the generator and switching transients, as can be seen in figure 5.5.

During simulation, the inertia of the system was assumed to be 300 kgm$^2$. For friction, experimental data of $\frac{d\omega}{dt}$ as a function of $\omega$ were used. The inner resistance of the battery was simulated, based on experimental data, as

$$R_{batt} = -0.0011I_{batt} + 0.1117,$$  \hspace{1cm} (5.1)

where $I_{batt}$ is the battery current.

Simulation and experimental results show similar behaviours. The turbine can in real experiments be successfully started with this method, as indicated by simulations. Both the inductance and the resistance of the generator auxiliary winding are quite low as can be seen in table 4.3, which results in large currents during start-up. Current limitation is needed to prevent the current from increasing to levels that could damage the power electronics. In this experiment, a passive current limitation (power resistor in series with batteries) was used. Passive current limitation causes high losses in the system, in this case 48% of the power is lost in the resistors. A system using pulse width modulation would probably give lower losses, but would instead have higher complexity in the control of the inverter. The overall energy consumption is low for this system and since the inverter only is used for short times (about 20-30 s each time), high efficiency of the starter system is not a key issue; it is more desirable to have a simple, robust system. However, for a large scale system, a pulse width modulated solution might be preferred to reduce the need for large high power resistors.

As shown in paper IV and in chapter 5.3, having an electrical start instead of an aerodynamic start is not an issue. The design of inverter and inverter control for such a system does not need to have the same complexity as a grid-connected inverter. The energy consumed during start-up corresponds to 3 s of nominal power for the turbine.
Figure 5.4. The rotational speed of the turbine during start-up.

Figure 5.5. The behaviour of the phase voltage during start-up.
5.4 Measurement of power coefficient

During the spring of 2009 a long time measurement of the power coefficient as a function of tip speed ratio was performed on the 12 kW prototype. A more detailed description of this experiment can be found in paper III. The constant speed measurements gave an optimum $\lambda$ of 3.3, which corresponds to a $C_P$ of 0.29. The measurement campaign resulted in roughly 350 h of operational data, shown as 10 minute average values in figure 5.6. The measured data were treated using the method of bins, as recommended in the international standard IEC 61400-12-1.

The $C_P(\lambda)$-curve is quite flat around its maximum, which makes it easier for the control system to find the optimum $\lambda$ when operating the turbine at constant tip speed ratio. The spread of the data samples is quite low, despite the high number of collected samples. The measured $C_P(\lambda)$-curve corresponds well to the samples, as can be seen in figure 5.6. A more accurate wind speed measurement might move the curve slightly. Data published for Sandia’s 5 m Darrieus turbine present almost the same value of $C_P$ [57]. The original Sandia turbine had a maximum $C_P$ of 0.27, which is close to the result showed in this paper. Later, with improved blades $C_P$, was increased to 0.39. Likewise, improved blade and strut profiles, for the prototype presented here, may increase the power coefficient similarly to the latter Sandia turbine. However, the main goal for the present prototype has been to verify the whole system (aerodynamically, mechanically and electrically), rather than optimizing the aerodynamic performance.

![Figure 5.6](image_url)

*Figure 5.6. Results from the measurements of $C_P(\lambda)$, showing both the measured 10 minute average samples and the estimated $C_P(\lambda)$-curve.*
5.5 Inverter for grid connection

Current measurements on the secondary side of the transformer shows that it is possible to design an LCL-filter that meets the requirements for harmonics in IEEE 519-1992 for all four taps. The total harmonic distortion was measured with a constant voltage over the dumploads connected to the transformer and is presented in table 5.1. The THD limit for grid connection is 5 %, which the filter can achieve for all the transformer taps. The use of a look-up table to control the inverter and unbalances in the dump-load has affected the results negatively. Thus, the THD may be lower when the system is connected to a grid. The filter behaviour for the different taps, together with simulations of the system, are presented in figure 5.7.

Table 5.1. Measured total harmonic distortion for the different taps of the transformer.

<table>
<thead>
<tr>
<th>Transformer tap</th>
<th>Primary side voltage</th>
<th>Experimental THD [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>57 V</td>
<td>2.7</td>
</tr>
<tr>
<td>2</td>
<td>100 V</td>
<td>2.3</td>
</tr>
<tr>
<td>3</td>
<td>133 V</td>
<td>2.8</td>
</tr>
<tr>
<td>4</td>
<td>200 V</td>
<td>1.8</td>
</tr>
</tbody>
</table>
Figure 5.7. Filter properties for the different taps of the transformer.
5.6 Stall regulation

The control system of the 200 kW VAWT is able to limit the rotational speed of the turbine, even under conditions with high variation in wind speeds, as shown in figure 5.8. During this experiment, the mean power delivered from the turbine was 85 kW, the wind speed varied between 8 m/s and 18 m/s and the rotational speed was kept at 20 rpm with a standard deviation of 0.2 rpm. The tip speed ratio varied between 1.6 and 3. In figure 5.8, the difference between available power in the wind and absorbed power shows that the turbine is operating in stall, i.e. the power absorption is stall-regulated. A strong gust passes the turbine roughly 950 s into the experiment, which strongly increases the available power in the wind, but does not make a distinguishable impact on the absorbed power. During this gust, the tip speed ratio decreases (moving towards zero on the $C_P(\lambda)$-curve) and thereby increases the stall of the turbine. The turbine was not run at optimal $C_P$ regulation during the test of stall operation, since stall occurs at lower tip speed ratios than optimal.

![Graphs showing rotational speed, wind speed, tip speed ratio, available power, absorbed power](image)

*Figure 5.8. Results from experiment on stall regulation on the 200 kW VAWT. The top graph shows the rotational speed in rpm, the wind speed in m/s and the tip speed ratio during 1400 s. The lower graph shows the available power in the wind and the absorbed power, both in kW, during the same time interval as the top graph.*

The results show that it is possible to maintain control of a turbine in strong gusty winds without any mechanical control systems such as pitching
of blades. The electric system can handle the turbine by passive stall. This result implies that no other active storm protection is needed, as long as the generator voltage can be kept at a desired level over the entire operating span. Instead, the design of the control system can be focused on optimizing power production. Furthermore, this may simplify the control of a wind farm: if the turbines are working against the same DC bus, the production of the entire farm can be controlled without the need of individual speed control. However, the results only suggest that this type of wind farm control is possible; experiments are needed to validate the performance of such a wind farm.

5.7 Tip speed ratio control

The control system of the 200 kW VAWT was tested during a measurement campaign that resulted in 1488 hours of operational data. The tip speed ratio was estimated by the turbine, as described in chapter 2.4, using a $C_P(\lambda)$-curve from aerodynamic simulations of the turbine and an estimated $\eta$ of 0.9. A comparison of measured and estimated tip speed ratio for eight hours of operation are shown in figure 5.9. The control system was set to aim for a tip speed ratio of 3.8, which corresponds to the optimal $C_P$. The mean value of the tip speed ratio based on anemometer measurements was 3.76 during the eight hours compared to a mean value of 3.96 for the tip speed ratio estimated by the turbine. However, the standard deviation is lower for the estimated tip speed ratio, 0.41 compared to 0.57 for the anemometer. The low deviation in tip speed ratio shows that the control system can maintain a desired tip speed ratio. The wind speed was underestimated by the turbine by roughly 7% as shown in figure 5.9. The mismatch in wind speed and tip speed ratio is caused by an overestimation of $C_P$ in the aerodynamic model by not including the generator losses in the algorithm, which have a high impact at low wind speeds. The underestimation of tip speed ratio results in that the control system attempts to increase the rotational speed. If the generator efficiency is taken into consideration, together with a better $C_P(\lambda)$-curve, the tip speed ratio control will improve. The behaviour of absorbed power at different wind speeds is shown in figure 5.10, together with a theoretical power curve scaled with $\eta$. It is visible that the wind speed is overestimated by the turbine. However, the estimated power curve follows the shape of the theoretical power curve well, without fluctuations in absorbed power.
Figure 5.9. The upper figure show a comparison of measured and estimated wind speeds. The lower figure show the tip speed ratio for the same wind speeds. Wind speed and tip speed ratio are from the same eight hours of data. The graphs are shown as 25 s sliding averages.
Figure 5.10. 10 min averages of absorbed power plotted against the wind speed measured by the anemometer (blue) and against the estimated wind speed (red). The black line corresponds to running at optimal tip speed ratio with $\eta=0.9$. 
6. Conclusions

This thesis covers work with the electrical systems and results from three different vertical axis wind turbines. An all electric control, substituting mechanical systems such as blade pitch, is possible and has been experimentally verified. The turbine design is not aerodynamically self-starting in all wind conditions. However, the generator can be used as a motor during start-up. An inverter for starting the generator can be built with low power rating and complexity. For the 12 kW VAWT, the energy used for starting corresponds to nominal production of the turbine for 3 s. This ratio is roughly the same for the 200 kW VAWT. A longer measurement campaign has been performed to find the power coefficient of the 12 kW turbine. The measurement resulted in a database of around 350 h of data that, treated with the method of bins, gave a maximum $C_P$ of 0.29 at a tip speed ratio of 3.3.

Stall regulation has been demonstrated in gusty winds above nominal wind speed for the 200 kW VAWT. The rotational speed was kept constant in wind speeds varying from 8 m/s to 18 m/s. Previous results in [56] state that the generator is capable of electrically induce stall, which was verified for the complete system. The use of turbine to estimate the wind speed with some knowledge about the $C_P(\lambda)$-behaviour has been demonstrated. This gives the possibility for faster control than if an anemometer is used. Experiments with the 200 kW turbine show that it is possible to keep a set value of $\lambda$ during variable speed operation of the turbine.

A system for grid connection of the 12 kW VAWT has been investigated. The system consists of an inverter and a tap transformer with four different voltage levels. It is possible to design an LCL-filter that works with all four taps and still meet the demands on power quality set up by IEEE 519-1992.
7. Suggestions for future work

7.1 12 kW VAWT
During maintenance of the 12 kW turbine, the pitch angle of the blades was changed, which is believed to increase the maximum power coefficient of the turbine. Hence, a new measurement campaign as described in paper III is needed to experimentally verify this. During this maintenance, the weights of the blades and struts were increased. This may have moved some of the eigenfrequencies of the system down to the operation range. Experimental and analytical investigations of this need to be done and may demand some modifications of the control system to avoid these frequencies. Some preparations for force measurements on the struts have been started, in parallel with the work by a previous doctoral student. To finalize this measurement setup, a measurement system that rotates with the turbine needs to be implemented. This measurement will show the forces acting on a blade during operation and give useful input for calibration of aerodynamic and mechanical models of this type of turbine.

7.2 10 kW VAWT for telecom applications
The electric system for this turbine was based on the electric system of the 12 kW turbine as it was in mid 2008. Many improvements have been done to that system afterwards, which should also be implemented in the system of the 10 kW VAWT, to improve the reliability. The generator bearings will need some maintenance before the turbine can be started again.

7.3 200 kW VAWT
For the 200 kW VAWT to run in its full operation interval, a jump routine needs to be implemented in the control system to avoid the eigenfrequency at around 23 rpm. After this, a proper $C_P$ measurement can be done. However, before starting the $C_P$ measurement campaign, one has to decide what type of $C_P$-curve that is desired ($C_P(\lambda)$ or $C_P(V)$) since they demand different control strategies to get good results. To improve the estimation of tip speed ratio at low wind speeds, the generator efficiency has to be considered in the control algorithm. Thus, the efficiency is lower at low powers, which gives a slightly overestimated tip speed ratio.
8. Summary of Papers

In this chapter, the appended papers are summarized and the author’s contribution to each paper is given. Papers I - IV and paper VI present results from the 12 kW VAWT. Paper V describes the 10 kW VAWT for telecom applications. Papers VII and VIII present results from the 200 kW VAWT. Papers I, II, V and VI have been presented at conferences. Papers III and IV are published in journals. Papers VII and VIII are submitted to journals.

Paper I

Experimental results from a 12 kW vertical axis wind turbine with a direct driven PM synchronous generator

This paper gives the specifications of the turbine and generator and briefly goes through the building and mounting of the wind power plant. It describes the wind climate of the site chosen for the prototype. Furthermore, results from the first measurements done on the turbine before the control system was designed are presented. The results shown are measured power, rotational speed and wind speed during 25 s and a short time measurement of $C_p(\lambda)$.

The author has taken part in the installation of the wind turbine and has taken part in the experiments. The author has written a small part of the paper. Presented with a poster in Milan, Italy at the European Wind Energy Conference & Exhibition 2007.

Paper II

Progress of control system and measurement techniques for a 12 kW vertical axis wind turbine

This paper describes the electronics used to start and control the 12 kW VAWT. The starter is a specially designed inverter to accelerate the turbine until its tip speed ratio is high enough to get a positive power coefficient. The basics of the load control are described. A measurement of wind speed and rotational speed during start-up is presented, showing that the starter is working. The second result is a graph of wind speed and rotational speed during operation, showing that the load control can keep the rotational speed constant during varying wind speeds.
The author has designed and built the electrical system and measurement setup described in the paper. The author has written most of the paper.


Paper III

Power Coefficient Measurements on a 12 kW Straight Bladed Vertical Axis Wind Turbine

This paper presents the results of long time measurements of the power coefficient on the 12 kW VAWT. The measurement was performed during spring 2009 and the data were treated with the method of bins. The maximum power coefficient was measured to be 0.29 at a tip speed ratio of 3.3.

The author has designed and built the electronics controlling the wind turbine and most of the measurement setup. The author has done half the data treatment and written most of the paper.

The paper is published in Renewable Energy.

Paper IV

Electrical starter system for a H-rotor type VAWT with PM-generator and auxiliary winding

This paper describes the design and simulation of an electrical starting system designed for the 12 kW VAWT. The proposed starter uses an auxiliary winding in the stator of the generator to run it as a motor during start-up. The paper presents experimental results from the starter circuit connected to the wind turbine. An electrical starter is proposed to be better than a mechanical starter system such as blade pitch of the turbine.

The author has designed and constructed the starter system and the measurement setup. The author has simulated the system and compared simulations with experimental data and written the paper.

The paper is published in Wind Engineering.

Paper V

Adapting a VAWT with PM generator to telecom applications

This paper describes the design of a wind energy conversion system adapted to a Ericsson Tower Tube radio base tower. The wind turbine is dimensioned for the energy needs of the radio base station to replace the use of diesel in remote areas without electric grid. Due to an elevator shaft inside the tower,
the generator had to be fitted on the outside of the tower with the turbine struts directly connected to its rotor. The electric system is designed for island operation, with the radio base station and its energy storage as load.

The author has been working with the design and the commissioning of the electrical system for the generator. The author has been involved in discussions regarding the content and structure of the paper. Presented with a poster in Warsaw, Poland at the *European Wind Energy Conference & Exhibition 2010*.

**Paper VI**

**Laboratory verification of system for grid connection of a 12 kW variable speed wind turbine with a permanent magnet synchronous generator**

This paper describes the design of an inverter setup for the 12 kW wind turbine and the first laboratory experiments verifying its operational properties against simulations. In the setup, a transformer with four taps is used to give four different operating voltages for the inverter to work against. The paper focuses mainly on the design and experimental verification of the LCL filter designed to handle harmonics from the inverter, regardless of which tap is being used.

The author was involved in the design of the inverter and IGBT drivers for the inverter. Presented with a poster in Copenhagen, Denmark at the *EWEA Annual Conference and Exhibition 2012*.

**Paper VII**

**Electric control substituting pitch control for large wind turbines**

This paper is the first about the 200 kW VAWT built on the West Coast of Sweden. It is focused on the passive stall regulation of the turbine. Experimental results from gusty wind conditions show that the electrical system can handle the turbine by passive stall. No other storm protection is needed, except as backup.

The author has worked with the electric, control, and measurement systems of the turbine. The author has treated the data and written the paper.

The paper was submitted to *Renewable Energy* in June 2012.

**Paper VIII**

**Tip Speed ratio control of a 200 kW VAWT with synchronous generator and variable DC voltage**

This paper is about the control algorithm used to control the tip speed ratio of the 200 kW VAWT. The measured absorbed power and rotational speed
are used to estimate the tip speed ratio of the turbine. Therefore, the control is independent of costly and possibly inaccurate wind speed measurements. Experimental results are presented, showing the accuracy of the wind speed estimation as well as of the power absorbed when this control strategy is implemented. The paper also shows that a variable speed system can be implemented without the use of DC/DC converters or active rectifiers.

The author has worked with the control and electric system of the 200 kW VAWT, done the data treatment and written half the paper.

The paper was submitted to *Energies* in October 2012.

8.1 Errata to papers

In paper I, p. 5 last sentence: the turbine was completed 13th of December 2006 (not 2007).

In paper III, Discussion p. 3053: ‘The original Sandia’s turbine had a top $C_P$ of 0.29 ...’ should be replaced by: ‘The original Sandia’s turbine had a top $C_P$ of 0.27 ...’.
9. Svensk sammanfattning

Trots flera stora forskningssatsningar på vertikalaxlade vindkraftverk (VAWT) under 70- och 80-talet, så domineras idag vindkraftmarknaden av horisontalaxlade vindkraftverk (HAWT). Det finns dock ingen gemensam nämnare för försöken på 80-talet som antyder att vertikalaxlade vindkraftverk inte fungerar, utan den horisontalaxlade tekniken lyckades slå igenom snabbare och blev därmed den teknik som man valde att vidareutveckla. I en undersökning från 2007 visade det sig att 42,1% av stältiden vid fel i svenska vindkraftverk berodde på fel i girningssystem, växellåda och system för att reglera bladvinkeln, vilket är delar som går att bygga bort i ett vertikalaxlat vindkraftverk. Vidare kan vertikalaxlad teknik vara intressant när man börjar bygga större vindkraftverk ute till havs, då den har potential att bli billigare att underhålla än horisontalaxlade verk i samma storlek.


Det vetenskapliga målet med detta arbete har varit experimentell verifiering av vertikalaxlade vindkraftverk. Fullskaliga försök är viktiga, eftersom de visar hela systemets beteende under realistiska förhållanden, något som är svårt eller omöjligt att uppnå i ett laboratorium. Dessutom är experimentella resultat viktiga för att verifiera och förbättra teoretiska modeller av systemet. För att uppnå de vetenskapliga målen, var även ingenjörmässiga delmål nödvändiga att uppnå. Dessa innefattade konstruktion av el-, kontroll- och mätsystem för denna typ av vindkraftverk. Arbetet som har lett fram till denna avhandlings vetenskapliga och tekniska mål har haft en starkt experimentell karaktär.

ett närliggande hus, i vilket kontrollrum med styrelektronik finns. Till detta vindkraftverk har el-, kontroll- och mät-system konstruerats och byggts inom doktorandprojektet.


De första experiment som gjordes var för att undersöka om den här typen av vindkraftverk levererar effekt som förväntat, i förhållande till rådande vindhastighet. Det har gjorts experiment för att mäta upp effektfaktorn för 12 kW-turbinen och för att undersöka hur den här typen av vindkraftverk beter sig vid stallreglering. Eftersom vindkraftverk av denna typ inte är aerodynamiskt självstartande, så har ett elektriskt startsystem utvecklats och testats. Det har gjorts experiment på att styra vindkraftverkets rotationshastighet genom att kontrollera generatorspänningen. Slutligen, har ett system där turbinen används som anemometer utvecklats, för användning i löptalsstyrning av vindkraftverket. Även detta har experimentellt verifierats.

**Slutsatser**

Denna avhandling omfattar arbete med elektriska system och resultat från tre olika vertikalaxlade vindkraftverk. En helt elektrisk styrning, som ersätter mekaniska system för t.ex. reglering av bladvinkel, är möjlig och har experimentellt verifierats. Den valda turbintypen är inte aerodynamiskt självstartande i alla vindförhållanden, men generatörn kan användas som en motor under start. En växelriktare för att starta generatorn kan byggas med låg märkeffekt och komplexitet. För 12 kW-vindkraftverket motsvarar den energi som används för att starta kraftverket nominell produktion under 3 s. Ungefär samma tid gäller även för 200 kW-vindkraftverket. En längre mätkampanj har genomförts för att experimentellt finna effektkoefficienten \((C_P)\) för 12 kW-turbinen. Mätningen resulterade i en databas bestående av cirka 350 h av data,
Först vill jag tacka min huvudhandledare Hans Bernhoff för att jag fick detta spännande doktorandprojekt, som utöver experiment på och driftsättande av tre vindkraftverk, även innebar att jag fick lära mig att konstruera och bygga elsystem för vindkraftverk. Tack för bra handledning, uppmuntran och stort engagemang i vindkraftprojektet.

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```
tail -n +23 *.lvm | tr , . | grep -v == | awk '{print $1,$9,$13,$14}' >> data.txt
```

vilket kortade ner några dagars arbete till under en minut.

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References


A doctoral dissertation from the Faculty of Science and Technology, Uppsala University, is usually a summary of a number of papers. A few copies of the complete dissertation are kept at major Swedish research libraries, while the summary alone is distributed internationally through the series Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology.