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Review

A Review of Research on Large Scale Modern Vertical Axis Wind Turbines at Uppsala University

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Abstract: This paper presents a review of over a decade of research on Vertical Axis Wind Turbines (VAWTs) conducted at Uppsala University. The paper presents, among others, an overview of the 200 kW VAWT located in Falkenberg, Sweden, as well as a description of the work done on the 12 kW prototype VAWT in Marsta, Sweden. Several key aspects have been tested and successfully demonstrated at our two experimental research sites. The effort of the VAWT research has been aimed at developing a robust large scale VAWT technology based on an electrical control system with a direct driven energy converter. This approach allows for a simplification where most or all of the control of the turbines can be managed by the electrical converter system, reducing investment cost and need for maintenance. The concept features an H-rotor that is omnidirectional in regards to wind direction, meaning that it can extract energy from all wind directions without the need for a yaw system. The turbine is connected to a direct driven permanent magnet synchronous generator (PMSG), located at ground level, that is specifically developed to control and extract power from the turbine. The research is ongoing and aims for a multi-megawatt VAWT in the near future.

Keywords: wind power; vertical axis wind turbine (VAWT); permanent magnet synchronous generator (PMSG)

1. Introduction

Wind power energy has in the last century emerged as a new large scale renewable energy technology. The drivers of the new technology have been a combination of technical development and political ambition. The main political incentive relates to the ongoing discussions on global climate change and the desire to reduce carbon dioxide emissions [1]. In this respect, wind power represents an environmental friendly energy source without fuel cost and without gas emissions [2]. Present technology, dominated by the megawatt-scale Horizontal Axis Wind Turbines (HAWT), has demonstrated the viability of large scale systems capable of supplying a substantial part of the electric energy supply on the national and even continental level.

The development of Vertical Axis Wind Turbines (VAWT) has been pursued in a number of different projects, but none has yet reached significant commercial take off. One of the more famous projects is the Eole, a joint venture project between Hydro-Quebec and the National Resource Council of Canada to develop a large-scale Darrieus VAWT in the early 1980s. The Eole, a 96 m high Darrieus turbine built in 1986, was built with a rated maximum power of 3.8 MW and a swept area of 4000 m^2 [3]. It produced close to 13 GWh of electric energy during the five years it was running. The machine was shut down in 1993 due to failure of the bottom bearing. Another example is the American company FloWind that in the 1980s built several wind farms with Darrius turbines [4]. The machines had problems with fatigue of the blades, which were designed to flex [5].

In more recent years, several new VAWT projects have started with a strong focus on offshore. One of these efforts is the DeepWind project where a floating offshore vertical wind turbine with a Darrieus type rotor is proposed [6,7]. The aim of the VAWT project is to investigate the possibility of building a 5 MW offshore wind turbine.

The aim of the work presented in this paper is to give a review of the research done on VAWT at Uppsala University over the past decade with focus on the experimental sites and turbines. The paper presents an overview of the 200 kW VAWT located in Falkenberg, Sweden, as well as a description of the work done on the 12 kW prototype VAWT in Marsta, Sweden. The VAWT project presented here aims at developing a robust large scale VAWT technology based on an electrical control system with a direct driven energy converter. This approach allows a simplification where most or all of the control can be managed by the electrical system, reducing investment cost and the need for maintenance. The main idea behind the concept is to reduce the number of moving parts and achieve a cost-efficient and robust design. The concept features an H-rotor that is omnidirectional in regards to wind direction, meaning that it can extract energy from all wind directions without the need for a yaw system. A direct driven permanent magnet synchronous generator (PMSG) is specifically developed to match the turbine speed and torque. The generator is designed to be direct driven for a number of reasons:

- A direct driven generator is spared from losses, maintenance and costs associated with a gearbox [8].
- It has been shown that the gearbox is a critical component when it comes to wind turbine failures [9].
- A gearbox would reduce the overall efficiency.
- The overall system becomes simpler.
- The wind turbine will be able to react more rapidly to changes in the wind and the load [10].

For a VAWT, the generator can be placed on ground level where the generator's weight is of less concern. The generator can therefore be optimized considering efficiency and cost instead of focusing on low weight and volume.

A Swedish study reports results from an investigation of failure statistics from four sources and a large number of wind turbines: two separate sources from Sweden, one from Finland, and one from Germany [9]. The gearbox is identified as the most critical part, as downtime per failure is higher for the gearbox than for other components. Several failures were linked to the electric system followed by sensors and blades/pitch components. When discussing the results of this study in relation to the presented vertical axis wind turbine, some important observations can be made. First and foremost, the direct driven topology eliminates the gearbox and all failures associated with it. The same can be said about all systems and sensors needed for the yaw and blade pitch as the H-rotor can take wind from all directions. Gears and yaw system represent one third of the downtime according to [9]. Furthermore, the direct driven generator on ground level can be designed to be more robust as size and weight is a smaller issue, further increasing reliability. With this stated, it is believed that downtime and the number of failures can be decreased significantly for vertical axis wind turbines. One of the major incentives for pursuing the vertical axis technology is to reach a higher degree of reliability.

1.1. History of VAWT

Vertical axis wind turbines have been developed from the earliest of times [2]. It has been argued that the reason for HAWTs being more common commercially is due to investment priorities rather than technical advantages [11]. Some main benefits of using VAWTs rather than HAWTs [12] include the fact that a VAWT does not need a yaw mechanism, since it is omnidirectional. The generator can be placed at ground level, which makes installation and maintenance simpler. Furthermore, a VAWT is expected to produce less acoustic noise than a HAWT [13]. The most common VAWT is the 'Darrieus wind turbine' described by Darrieus in 1931 [14]. In the 1970s and 1980s, several countries conducted research on the Darrieus turbine [15]. Commercial wind farms with Darrieus turbines were built [16,17]. A disadvantage with the Darrieus turbine is that the blades are difficult to manufacture [17] and that the turbine is usually situated very close to the ground where the wind speed is lower and wind shear may cause structural problems. The straight-bladed vertical axis wind turbine is commonly called the 'H-rotor', the 'straight-bladed Darrieus rotor' or the 'Giromill'. The Darrieus turbine has curved blades fixated to the top and bottom of the tower while the H-rotor has straight blades usually fixated to the tower via one or several struts. The H-rotor can be placed on a higher tower and is normally not as close to the ground like a Darrieus turbine. The H-rotor has better aerodynamic performance than the Darrieus rotor, but has larger bending moments on the blades [11]. Furthermore, the H-rotor has a simpler construction due to the straight blades, which makes it cheaper and easier to manufacture.

2. Fundamentals

This section covers some of the fundamentals regarding power extracted from a wind turbine and the operation of the VAWTs presented in this paper. The amount of power, P_t, that can be extracted from a fixed-pitch turbine is given by Equation (1):

$$P_t = \frac{1}{2} \rho A C_p \left(\lambda\right) v_{wind}^3. \tag{1}$$

where ρ is the air density, A the turbine cross section area, Cp the power coefficient and v_{wind} the wind speed. The power coefficient is a function of the tip speed ratio (TSR) λ and represents the aerodynamic efficiency of the turbine. The tip speed ratio is defined in Equation (2):

$$\lambda = \frac{\omega_t R}{v_{wind}}, \tag{2}$$

where ω_t is the rotational speed of the turbine and R is the turbine radius.

A typical scheme of operation for the VAWTs presented in this paper is characterized by three wind speeds: rated wind speed, and cut-in and cut-out wind speed as shown in Figure 1. The rated wind speed is the speed at which the system delivers nominal power. The cut-in and cut-out wind speeds are, as the names suggest, the speeds at which the system begins to operate and the highest speed the system can deliver power at, respectively. At wind speeds greater than the cut-out speed, the turbine is stopped to prevent damage to the system and goes into parking mode.

As illustrated in Figure 1, the turbines starts to generate power at the cut-in wind speed. The VAWTs presented in this paper are usually not self-starting and need to be started to extract power from the wind. This is done by using the generator as a motor for a brief period of time. A start-up is usually done close to cut-in wind speeds but can be done at any wind speed if desired, such as restarting after a cut-out wind speed while there are still winds above rated wind speed. The power captured by the turbine is a cubic function of the wind speed as shown in Equation (1) until the wind speed reaches rated value. In this area, the generator is used to control the speed of the turbine keeping it at optimal TSR and thereby maximizing the power extraction. Once the wind speed exceeds the rated value, the turbine is controlled using a passive stall. This is because all turbines must have ways to reduce the power absorption as the power increases with the wind speed. When the wing is operating at maximum power, there are two ways to reduce the force on the wing and thus reduce power. Either the angle of the blade can increase above stall, called stall regulation, or the angle of the blade can be reduced, which is called pitch regulation. To reduce the angle of the blade, the profile has to be turned into the wind about its long axis (pitching the blades). To increase the angle of the blade for increasing wind speeds, the rotational speed of the turbine can be maintained, thus passively forcing the blade into stall, called passive stall. For a large horizontal axis wind turbine, the pitch regulation has become dominant. The use of passive stall for the vertical axis wind turbines reduces the mechanical complexity, increases reliability and above all allows for a full electric control of the turbine via the generator. Furthermore, in the event of extreme wind gust, the turbine that is controlled by the substation will automatically stall regulate, allowing for more of the wind energy to pass through the turbine rather than being absorbed. In brief, a constant rotational speed will induce passive stall regulation. A constant rotational speed for a permanent magnet synchronous generator corresponds to a constant voltage level. Thus, a constant voltage keeps the generator at a constant speed. This allows for a very powerful and easily automated control of power absorption from the turbine by controlling the voltage with the substation. The generator is used to start, stop and control the absorbed power of the VAWT at all wind speeds as well as to keep it standing still when stopped.

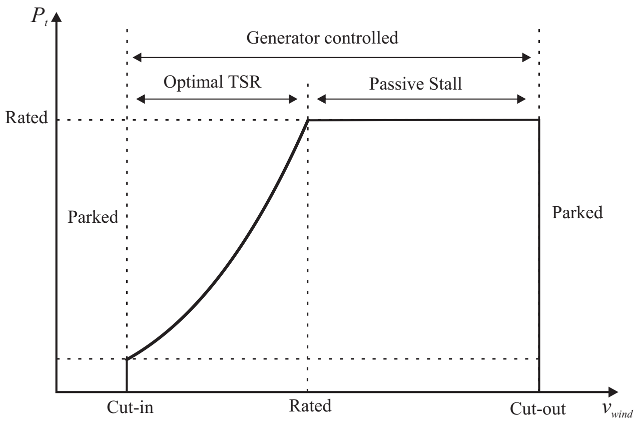

Figure 1. Qualitative mechanical power as a function of wind speed for the VAWTs presented in this paper.

3. 200 kW VAWT

The 200 kW VAWT was installed in the beginning of 2010 by Vertical Wind AB (Sweden) in collaboration with E.ON, Falkenberg Energi AB (Sweden) and The Swedish Energy Agency. The 200 kW VAWT is seen as an important step to gain experience and data for the future construction of multi-megawatt VAWTs. The VAWT can be seen in Figure 2. At the end of a series of tests in March 2012, the turbine had around 1000 h of operation and had delivered roughly 22.5 MWh to the grid during the test period. In the period between March 2012 and the time of writing, the turbine has been operated for another 500 h. No evaluation of the energy production for these 500 h has been done. This section focuses on the 200 kW VAWT and gives an overview of the main systems of the wind energy converter.

Figure 2. The three bladed 200 kW vertical axis wind turbine in Falkenberg, Sweden.

3.1. Turbine

The 200 kW VAWT was installed at Torsholm east of Falkenberg on the Swedish west-coast with an estimated yearly average wind speed of 6.5 m/s at hub height. The direct driven passively rectified vertical axis wind power system is shown in Figure 3. The figure shows the main parts of the system and presents the terminology. The system is split into two main parts, namely the VAWT and the substation. In the following subsections, the system is presented in greater detail presenting, among others, the generator, the noise emissions from the turbine and the control system. For overall specifics, see Table 1.

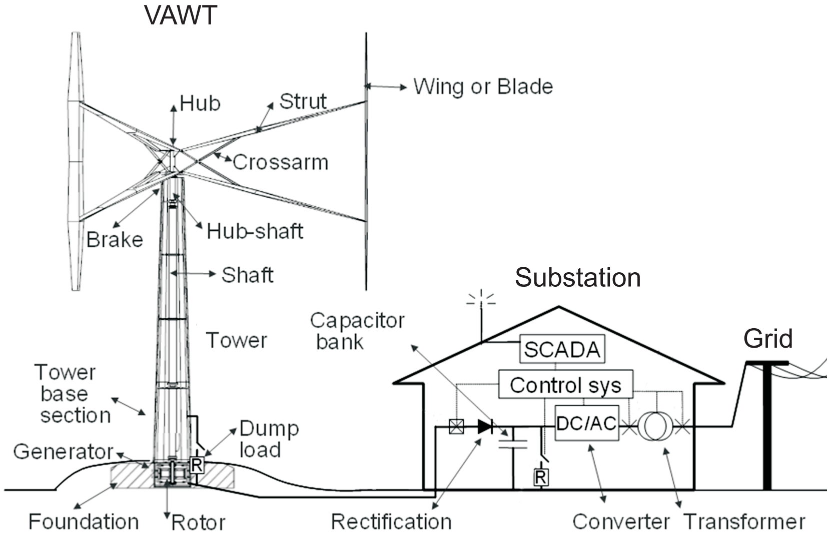

Figure 3. Converter system for the 200 kW VAWT.

Table 1. Overview of the characteristic for the 200 kW VAWT.

Characteristic	Rated
Number of blades	3
Rated wind speed (m/s)	12
Cut-in wind speed (m/s)	4
Cut-out wind speed (m/s)	25
Swept area (m^2)	624
Starting wind speed (m/s)	4
Shut down wind speed (m/s)	25
Blade length (m)	24
Hub height (m)	41

The anemometer (Thies Clima 4.3351.00.161, Adolf Thies GmbH Co. KG, Göttingen, Germany) was placed in a measurement tower 100 m from the turbine at a height of 42 m, as required by the International Electrotechnical Commission (IEC) standard IEC 61400-12-1. The 200 kW system has been designed for modest wind conditions with an average wind of 6.5 m/s at hub height but rated as an IEC class II turbine, surviving extreme wind gusts of 60 m/s. Parking strategies for an H-rotor in a more general aspect are the focus of the work presented in [18]. The work considers a straight-bladed VAWT with a direct driven permanent magnet synchronous generator. The authors propose that, during storm conditions, the generator can provide sufficient dampening to keep the turbine parked. This is done by short-circuiting the generator once the turbine has been stopped due to storm. The main advantage of this approach is that oscillations that can occur if a nondamped brake is used can be avoided.

3.2. Tower

An innovative wood composite tower design has been implemented in the 200 kW turbine. The tower is made of wood-fiberglass composite and was built in two 12-sided segments, and one of the segments can be seen in Figure 4. One of the reasons for a wooden tower is that it gives a thicker tower wall than a steel tower. A soft tower made out of steel would be difficult to design as it would have problems with buckling. With a wooden tower, there is no need for excessive over-dimensioning to handle buckling, while still keeping the characteristics of a soft tower. However, a great advantage with a wooden tower is its environmentally friendly composition and low cost. A soft tower is a consequence of the lower elastic modulus of wood as compared to steel for the same strength. The thicker wall is a consequence of the much lower yield strength of wood, in the range of 30 MPa as compared to steel with 510 MPa. A soft tower has a fundamental natural frequency lower than the blade passing frequency. A steel tower would represent a more traditional design choice. However, it could be hard to accomplish a soft tower of steal as the tower top mass for a VAWT is lower compared to a horizontal axis turbine. A study looking at the eigenfrequencies of the tower is presented in [19].

Figure 4. A 12-sided tower segment of the wooden tower for the 200 kW turbine.

3.3. Generator

A direct driven three phase 225 kW permanent magnet synchronous cable wound generator was designed for the wind power converter. The generator can be seen in Figure 5. The simulations have been verified through laboratory testing of the generator [20,21]. The laboratory testing included measurement of the magnetic flux density in the airgap of the generator as well as measurements of the induced voltage. The electrical efficiency of the generator was calculated according to the planned variable speed control strategy with operation at optimum tip speed ratio. The generator efficiency is higher than 96% at all wind speeds higher than 6.6 m/s. The generator is located at ground level and the concrete foundation is used as stator support. This approach is expected to substantially reduce cost for large multi-megawatt generators. Generator parameters are presented in Table 2.

Figure 5. A direct driven three phase 225 kW permanent magnet synchronous cable wound generator.

Table 2. Generator parameters at rated load.

Characteristic	Rated
Rated power (kW)	225
Voltage LL (V_{rms})	810
Number of poles	36
Efficiency (%)	96.6

3.4. Substation and Turbine Operation

The main purpose of the substation is to connect the turbine to the grid by converting the voltage output from the generator to a voltage fitting the grid. Due to the direct driven generator, the output voltage will have variations in both amplitude and frequency as a function of the available wind. With passive rectification, this leads to the fact that the Direct Current (DC) bus voltage will vary as the wind speed shifts due to the changes in generator voltage. During our experiments, the DC voltage was allowed to vary between 510 V and 720 V, i.e., the inverter was subject to a variable DC voltage. The successful 1500 h of grid-connected operation shows that it works to run a turbine with a variable DC voltage to the inverter. A schematic drawing of the system is presented in Figure 6. The topology of the inverter for the grid connection of the turbine is the commonly used, insulated-gate bipolar transistor (IGBT) based, two level voltage source inverter. The inverter is connected to the grid via an LCL-filter, consisting of two three-phase inductors and three capacitors, using the transformer winding as the second three-phase inductor. This grid connection scheme is well known and tested in wind power applications [22]. As we do not deviate from the normal operation of this topology, we expect the power quality at grid connection to be well within the limits specified in the standard.

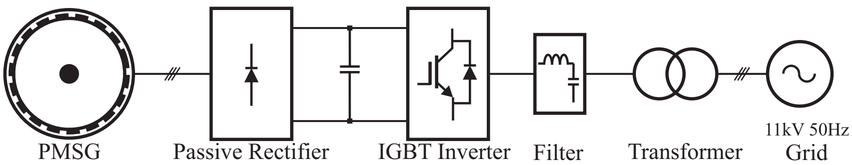

Figure 6. Converter system for the 200 kW VAWT.

A control method for a fixed-pitch variable speed wind turbine has been implemented and tested on the 200 kW turbine [23]. The measured power and rotational speed of the generator, together with a look-up table for the aerodynamic efficiency, are used to estimate the wind speed at the turbine as well as the tip speed ratio. Thereby, the control is independent on wind speed measurements and the wind turbine itself is used as an anemometer. Tip speed ratio control is implemented by comparing the estimated tip speed ratio to a reference value and adjusting the DC voltage level accordingly. Tip speed ratio control benefits from the aerodynamic efficiency hardly varying with changing tip speed ratio when close to its optimum value.

Experimental results where the estimated wind speed is compared to wind speed measurements from the anemometer for eight hours are shown in [23]. The results are shown as 25 s moving average values to increase visibility and to compensate for the distance between turbine and anemometer. The estimated wind speed follows the variations in measured wind speed closely. However, the estimated wind speed is roughly 7% lower than the wind speed measured by the anemometer.

In the work presented in [24], stall regulation of the 200 kW turbine is successfully tested. Results are shown for about 24 min of operation in gusty winds. The aim of the study was to demonstrate stall control by keeping the rotational speed at a fixed value at gusty winds. In the study, the rotational speed of 20 RPM corresponds to similar stall conditions as if the turbine was run at nominal rotational speed of 33 RPM with wind ranging between 12 m/s and cut-out, 25 m/s.

The study shows that the control system is able to limit the rotational speed of the turbine even under conditions with high variations in wind speed. During this experiment, the mean power delivered from the turbine was 85 kW, the wind speed was between 8 m/s and 18 m/s and the rotational speed was kept at 20 RPM with a small deviation of 0.2 RPM. The work demonstrates that the electrical system and the control system operate as designed and intended. The control is able to keep the turbine at an optimal tip speed ratio for variable speed operation and effectively keep the power fixed using stall control during high wind speeds and gusty conditions.

3.5. Aerodynamics

Several aerodynamic performance prediction models have been developed. Different models are necessary, since aerodynamics are very complicated to predict theoretically. Accurate models do usually have a high computational demand, and therefore, simplified models have to be used for more basic design. To predict the performance of the turbine, models that use experimental data were used. One model used is the double multiple streamtube model [11]. This is a particularly well verified model for turbines operating without stall and has been used to generate the presumed performance curves of the 200 kW turbine. The simulated power coefficient has a peak of roughly 0.38 and the power coefficient as a function of the tip speed ratio is presented in [23].

The relationship between power performance and turbulence intensity for the 200 kW VAWT is studied in [25]. The study uses logged data from a 15-month period with the turbine operating in wind speeds up to 9 m/s. The turbine operated during this period mostly in a restricted mode due to mechanical concerns and reaches power levels up to about 80 kW. Two different approaches are used for presenting results, one that can be compared to power curves consistent with the IEC-standard and one that isolates the effect of turbulence from the cubic variation of power with wind speed, by using the mean wind cube value. Accounting for this effect, the turbine still shows slightly higher efficiency at higher turbulence, proposing that the H-rotor is well suited for wind sites with turbulent winds. The study also presents a power coefficient generated from the logged data, showing slightly lower Cp compared to the simulated value.

3.6. Simulations of Farm Operation

In the work presented in [26,27] farm operation of VAWTs is examined with the use of the vortex method coupled to an electrical system. The focus is on different farm configurations and the power absorbed as a function of the electrical system topology. The work evaluates individual control of each turbine and compares it to linked control where all turbines are passively connected to a mutual DC-bus. The latter is the electrical system topology proposed in the vertical wind concept. A farm configuration with four turbines in a straight line was used. The farm operates at a mean wind of 7 m/s during 1200 s. The wind is correlated, but the specific wind at each turbine is different. The mean wind of 7 m/s corresponds to a power of approximately 50 kW from each turbine resulting in a total power from the farm close to 200 kW [27]. The study shows that there are local differences in power production between the two electrical system topologies. However, the total difference between the two electrical system topologies in regards to mean production is only 1.7% in favour of the individual control. The results from the study suggest that a mutual DC-bus with passive rectification is a viable design choice and that the performance, in regards to power production, of the individual and linked system is almost the same.

3.7. Turbine Noise

Close to a wind turbine, the dominating sound is usually from the machine house. Far away from the turbine, the dominating sound is the aerodynamic noise from the blades. Since the machine house for a VAWT is placed on the ground, the sound at a very close distance can be expected to be higher for a VAWT than for a HAWT, whereas at a close/medium distance, the noise from the machine house can be expected to be lower for a VAWT than for a HAWT.

A study on noise emissions from a VAWT can be found in [13]. This study claims that a VAWT can be expected to have a lower noise level than a HAWT operating at the same power coefficient.

The noise is highly dependent on the tip speed of the blade. The VAWT normally has a much lower tip speed than a HAWT. The 200 kW VAWT has a maximum blade tip speed of 45 m/s. A HAWT normally has a blade tip speed up to 80 m/s. The design of a wind turbine can be adapted to decrease noise as much as possible. When designing the first 200 kW VAWT prototype, the noise level was not considered and a standard blade profile was chosen.

The noise emission from the 200 kW VAWT has been investigated in [28]. The noise emission from the wind turbine was measured at different wind speeds. At the wind speed of 8 m/s, 10 m above ground, the noise emission was measured to 96.2 dBA. At this wind speed, the turbine was stalling as it was operating at a tip speed lower than optimal due to constructional constraints. The noise emission at the wind speed of 6 m/s, 10 m above the ground was measured while operating at optimum tip speed and was found to be 94.1 dBA. A comparison with similar size HAWTs indicates a noise emission at the absolute bottom of the range.

A study of the noise propagation for the 200 kW VAWT is presented in [29]. In the study, results from initial noise measurements from the 200 kW VAWT are compared with a Vestas V27 HAWT. The frequency distribution of the noise was analyzed indicating that the VAWT has lower levels for frequencies under 3000 Hz. There are indications from the propagation measurements that the sound from the 200 kW VAWT declines more rapidly with distance then that of the reference HAWT.

4. Marsta Research Site

Before the 200 kW VAWT was designed, a prototype turbine was built during 2006 at the Marsta meteorological observatory located five kilometres north of Uppsala, Sweden. The site was chosen for several reasons, one of them being that the site has been used by the meteorological department at Uppsala University for several decades [30]. Furthermore, the site is well characterized [31]. The wind climate at the site is discussed in [32]. The Weibull fit of the wind speed data gives a form factor of 1.94 and a scale factor of 5.24 m/s. Although the average wind speed at the site is not high, it is still deemed sufficient for research purposes [33].

4.1. 12 kW Turbine

The 12 kW prototype is a three bladed H-rotor with NACA0021 wind sections. The main parameters for the turbine are shown in Table 3. The turbine is attached to the hub via streamlined struts and the hub is connected to the generator via a steel shaft enclosed by the turbine tower. The turbine can be seen in Figure 7. The power coefficient of the turbine has been experimentally derived in [34]. The paper presents the measured power coefficient for the turbine as a function of the tip speed ratio. The power coefficient peaks at 0.29 at a tip speed ratio of 3.3. Recently, two papers presenting measurements of the tangential and normal forces on the 12 kW turbine have been presented [35,36]. As with the 200 kW VAWT, the power extracted by the turbine is limited by passive stall.

Table 3. Turbine parameters for the 12 kW turbine.

Characteristic	Rated
Number of blades	3
Rated wind speed (m/s)	12
Swept area (m^2)	30
Blade length (m)	5
Hub height (m)	6
Rated blade tip speed (m/s)	40
Chord length (m)	0.25

Figure 7. Three bladed 12 kW prototype vertical axis wind turbine located north of Uppsala.

4.2. Generator

A cable-wound permanent magnet synchronous generator designed and constructed at Uppsala University is placed at ground level and directly connected to the turbine via the shaft. The generator is designed to be able to fully control the turbine in all operating states with good overload capacity. Design and simulations of the machine have been done using in-house FEM software, and the generator design was experimentally validated before deployment [37,38]. A study of the no-load core losses of the machine is presented in [39] showing somewhat higher losses in the measurements then the simulations. The main parameters for the generator at nominal load are found in Table 4.

Table 4. Generator parameters for the 12 kW turbine.

Characteristic	Rated
Rated power (kW)	12
Voltage LL (V_{rms})	156
Number of poles	32
Efficiency (%)	95.9

4.3. Control System

The on-site control system for the 12 kW turbine is presented in [40], where the output voltage of the generator is rectified using a passive diode rectifier and then connected to a DC-bus. Power is drawn from the DC-bus to control the rotational speed of the turbine and keep it within desired operation. This is done by using a DC chopper and a resistive load. The turbine is normally not self starting and needs a external start-up circuit [40]. In the present set-up the start-up is done using a auxiliary winding on the generator [41]. An IGBT based inverter is used to spin up the machine until it reaches a desired operating speed. The results from [41] show that the energy spent to start the turbine is regained in three seconds of nominal operation.

A tap transformer based grid connection topology has been proposed for the turbine and validated in the laboratory in [42,43], where a full range variable speed operation of the turbine is achieved using a tap transformer with variable step-up ratios. The concept is believed to be robust and requires less maintenance due to the low number of active components. The system shows overall good performance and a low harmonic content [44]. A similar concept was also suggested in [45], where the grind side filter has been moved to the grid side of the tap-transformer. The benefits of this topology are reduction in switching filter size as well as filter losses. Drawbacks include higher stress on the transformer windings and higher transformer magnetization losses [45].

4.4. VAWT Adapted to an Existing Telecommunications Tower

During 2008, a vertical wind turbine was adapted to fit on the Tower tube telecommunications tower. The project was a collaboration between Eriksson AB, Vertical Wind Communications AB (Sweden) and Uppsala University (Sweden) with the intent to build a wind turbine that could power telecommunications equipment in remote areas [46]. A unique generator with a large radius was developed to fit on the outside of the telecommunications tower [47] and is shown in Figure 8. The tower and turbine were constructed in Marsta north of Uppsala, Sweden. Some of the main parameters for the turbine can be seen in Table 5. The concept was deemed to have several advantages, among them the environmental friendly solution and the use of the existing telecommunication tower. The prototype has now been decommissioned after several years of testing. The concept is yet to reach commercial breakthrough.

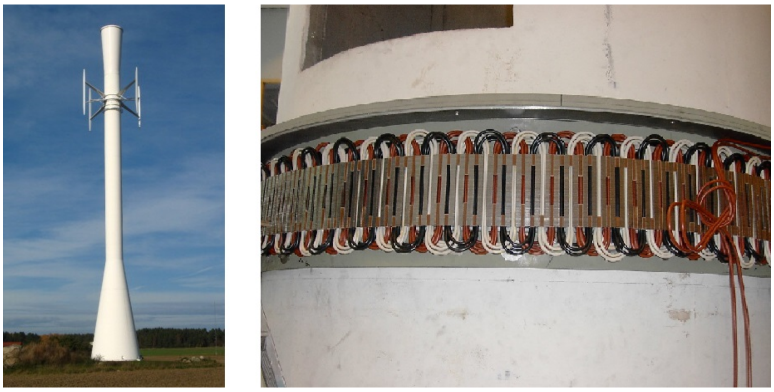

Figure 8. Four bladed 10 kW vertical axis wind turbine adapted to fit on an existing telecommunications tower to the left and the stator of the permanent magnet synchronous generator mounted on a tower section during construction to the right.

Table 5. Turbine parameters for the 10 kW VAWT adapted to an existing telecommunications tower.

Characteristic	Rated
Number of blades	4
Rated wind speed (m/s)	12
Swept area (m^2)	40
Blade length (m)	5
Hub height (m)	30

5. Research on Generators for VAWTs

The cost fluctuations and environmental concerns with permanent magnets based on rare earth metals, such as Neodymium-Iron-Boron (NdFeB) magnets, have spurred an interest in substituting NdFeB with other magnet materials. A research project has investigated designing a new generator for the 200 kW VAWT, where NdFeB is substituted with ferrite magnets. Results show that very similar electromagnetic characteristics can be achieved [48] only differing slightly in overload behavior [49]. The next step in this project is to build a first ferrite generator prototype based on a developed 12 kW design [50].

Studies have been performed on the risk for demagnetization of permanent magnets in generators, to ensure reliability and improve design methodology. The demagnetization risk has been analysed for the 12 kW generator installed in the Marsta wind turbine, and has shown no risk of demagnetization [51]. A simulation model studying partial demagnetizing of permanent magnet has been developed and experimentally verified [52]. The risk for partial demagnetization for the ferrite 12 kW generator has been investigated and compared to the risk for the NdFeB generator, showing that both generators have a reliable design if operated as intended [53].

Other studies on improving generator design for vertical axis wind turbines includes a study on minimizing losses in generators with high overload capacity, showing that both high overload capacity and high efficiency can be achieved with the same generator design [54]. A study comparing direct-driven generators and geared generators concerning torsional vibrations in the shaft of a VAWT, has been performed in [55], showing advantages for direct driven generators when vibrations are concerned. In addition, a study on overload capacity for cable-wound generators has been performed with focus on thermal issues, indicating an advantage for high-voltage generators and a possibility for overloading the generators as is necessary when electrically controlling a VAWT [56].

6. Research on Aerodynamics for Vertical Axis Turbines

Aerodynamic aspect of the VAWTs have been an important part of the research at Uppsala University. The aim is to develop efficient and accurate tools for aerodynamical simulations of the VAWTs. The research has mainly been focused on two methods. The first is the streamtube model, which is a very fast method for evaluating turbine performance. This method has been used to study how the turbine is affected by a velocity gradient over the turbine surface [57] and how the effects of strut losses affect the turbine performance and design [58,59]. The second method that has been applied is the vortex method, which is a time dependent model for more complex situations. Studies have been performed on how conformal mappings can be used for accurate blade calculations [60,61]. Work has also been carried out on how the vortex method calculations can be accelerated through the fast multipole methods and the usage of GPUs [62,63]. The vortex method has been applied to calculate the effects of flow confinement on the turbine performance [64], and also to calculate the performance of farms of vertical axis turbines [26,27,65,66]

The work on improving the models is ongoing and a study looking at finding a suitable dynamic stall model for vertical axis wind turbines is presented in [67]. A study comparing two dynamic stall models is presented in [68] and a study using a free vortex model coupled with a dynamic stall model to further investigate dynamic stall effects on VAWT operation is presented in [69]. An investigation on the resonances and aerodynamic damping for a VAWT is presented in [70].

7. Multi-MW

Scaling of the VAWT concept is an important part of the work as larger turbines in general have a better payoff time. The 200 kW VAWT is considered an important step towards multi-MW VAWTs. That is, the 200 kW turbine can be seen as a scaled down version of a multi-MW VAWT.

Based on the 200 kW prototype H-rotor design, a structural upper size for the turbine has been proposed in [71]. The upper size that is suggested represents when the gravitational forces become important and put a substantial load on the unit. As gravity has a much worse scaling behavior than the aerodynamic and centrifugal forces, the construction work will become increasingly more difficult above this size. This is due to that the mass of the turbine increases faster than the power absorption when scaling up. The upper size was estimated to be in the area of 30 MW for a VAWT. For conventional HAWT, further reduction in cost of energy due to up-scaling relies on continuous technology breakthroughs concerning blade manufacturing and materials, breakthroughs that are not certain to take place.

8. Conclusions

This paper presents a review of over a decade of research on VAWTs conducted at Uppsala University. Several key aspects have been tested and successfully demonstrated at our two experimental research sites. Several advanced simulation tools have been developed for VAWT research. A large number of papers have been published in several key areas such as aerodynamics, control systems and generator design with strong focus on development and experimental verification. The research is ongoing and aims for a multi-megawatt VAWT in the near future as a natural next step.

A modern vertical axis wind turbine system has been developed and investigated as well as demonstrated in a grid connected large scale VAWT. The design is based on successful scaling of the first 12 kW VAWT to the 200 kW model and several key aspects have been tested for even further upscaling. Several potential challenges have been solved, such as electric control of the turbine with the direct driven PM generator. An effective electrically induced stall control of the turbine has been demonstrated in strong wind and high turbulence intensity conditions. An innovative wood composite tower design has been implemented and tested in the 200 kW design. The technology shows promise and could be scalable to sizes surpassing today's commercial scale. The robustness of the configuration, with only one moving part—the shaft, and all sensitive equipment such as generator and control on the ground has several advantages such as easier maintenance and less maintenance overall. Furthermore, the technology offers substantial advantages when it comes to environmental impact with reduced noise as well as reduced use of steel. The 200 kW is, at the time of writing, the largest known research prototype H-rotor VAWT. This gives unique opportunities to perform further tests and contribute to the growing research in vertical axis wind turbines.

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