Control and Operation of a Vertical Axis Wind Turbine

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***Abstract* - This project aims to develop and implement an automatic operation and control system for an experimental vertical axis wind turbine (VAWT) located at Lunds Tekniska Högskola, Sweden. Real-time monitoring of the operation was made possible by setting up a supervisory control and data acquisition system (SCADA). A state-machine model was developed to manage the operation of the turbine system and a variable speed control method was implemented in order to maximize power extraction. Hill Climb Search (HCS) was the chosen control method, since there is no knowledge about the optimum tip speed ratio of the rotor or the wind turbine power curve. The control sequence is implemented in programmable logic controllers from National Instruments, and data from the power converters and wind speed measurement is acquired and analyzed in the controllers. Performance test results have confirmed the functionality of the implementation, although wind conditions were not favourable and power production was not feasible. Nevertheless, an estimation of the wind speed at which the wind turbine is capable of starting power production was made and the optimal tip-speed ratio was investigated. The control system is fully operational but further studies of the setup are required in order to have it running autonomously.**

***Keywords*: Wind turbine control, Supervisory Control and Data Acquisition, PLC programming, LabVIEW, Maximum Power Point Tracking, Hill-Climb search.**

Nomenclature

ρ - Air density [kg/m^{3}]
A - Rotor swept area [m^2]
U - Wind speed [m/s]
C_P - Power coefficient
β - Pitch angle
λ - Tip-speed ratio
Ω - Wind turbine rotor angular speed [rad/s]
R - Wind turbine rotor radius [m]
ω_{opt} - Optimum rotor speed [rad/s]
λ_{opt} - Optimum tip-speed ratio
ω_{WT} - VAWT rotor speed [rpm]
ω_{GEN} - Generator rotational speed [Hz]
T - Torque [Nm]
$\bar{U}$ - Average wind speed [m/s]

PMSG - Permanent magnet synchronous generator
GRID SIDE - Electrical grid power converter
GEN SIDE - PMSG power converter
MPPT - Maximum Power Point Tracking

1. Introduction

There is a growing awareness of the urgent need to find an alternative to the finite fossil resources on which our energetic and industrial systems are based. The continuous growth of energy demand of the last decades, aggravated by the exponential increase in consumption from emerging economies (IEA, Key World Energy Statistics, 2013), has compelled governments and institutions to intervene by stimulating technological advances in the renewable energy field, due to environmental considerations in an effort to slow down climate change.

Wind power is considered to be one of the renewable energy conversion technologies showing most developments in the recent years (IEA, Technology Roadmap Wind Energy, 2013), as researchers and industries invest their knowledge in improving and optimizing wind turbine systems for optimal energy yield and maximum performance. The author's intention is that this project may contribute as a small step on that path.

Modern wind power plants rely on complex monitoring and control systems that allow controlling individual turbines and displaying detailed information about their operating conditions. Supervisory Control and Data Acquisition (SCADA) systems establish the communication between the plant supervisor and the individual wind turbines, allowing starting and stopping power production and gathering relevant information. This information typically includes wind speed and direction, turbine operating states, individual power production, wind turbine rotor speed, pitch angle, internal sensor signals, fault reports or maintenance requests. This data can be accessed remotely by an operator and analysed in real-time, to assess the performance of the turbines by visualizing the power curve and other parameters, enabling to maximize power production (Manwell, 2009).

A method for maximizing wind power extraction consists in implementing variable rotor speed through the use of power converters. Static converters, used as an interface to the electric grid, enable variable speed operation allowing to control the extracted power.

The main purpose of this project is to fully develop and implement an automatic monitoring and control system for the small-scale vertical axis wind turbine, sited on top of the Mechanical Engineering building in Lunds Tekniska Högskola (LTH), to perform overall control tasks and monitoring to guarantee a safe and optimized operation. The project goals are:

- Design an overall control system to enable automatic operation of the wind turbine setup and implement it on the programmable logic controllers;
- Implement an efficient control algorithm for maximum power extraction;
- Install an automatic mechanical brake system on the wind turbine shaft to improve safety;
- Update the functions of the web based remote panel interface to LTH science observation centre, Vattenhallen;
- Evaluate the performance and controllability of the wind turbine;
- Investigate the efficiency of the system through performance tests.

The installation of the wind turbine in the university facilities is itself a visible manifestation of the interest and commitment of the university in exploring and developing new technologies for renewable energy generation, contributing for a cleaner environment and a more self-sustainable energetic system. The wind turbine setup results from the cooperation between the manufacturing company EXAMEC and LTH, and was erected in 2011 as part of a master's thesis project (Petitfils, 2011).

The programming tool used for the implementation is NI LabVIEW and the program is operating in a commercial real-time embedded reconfigurable controller from National Instruments, widely used throughout wind power industry (Dvorak, Windpower Engineering & Development, 2014).

2. Wind power overview

The most common design is the horizontal axis type (HAWT), however experimental research is increasingly focusing on vertical axis wind turbines (VAWT). Due to the nature of this project, this introduction focuses primarily on VAWT. Vertical axis wind turbines are suitable to be mounted on top of buildings or setup in higher places instead of ground level. In addition, researchers think that the VAWT design can be scaled to larger capacities (10 MW) more easily than conventional HAWT, especially if it is designed to be on a floating platform offshore (Wind Basics, 2014).

However, up until now none of the types of VAWT could be developed to such a point that their theoretical advantages would outweigh their practical disadvantages, in order to surpass the matured technology of HAWT. The fact that the generator is located on the base limits the height of the tower, which implies that a fraction or the whole rotor tends to be located close to the ground in a region where wind is not as strong as in greater heights. A solution to overcome this limitation is to install the VAWTs on top of buildings.

This section addresses the theory behind power production due to aerodynamic forces in the turbine rotor, to provide a better understanding of how the performance of a wind turbine is influenced by different parameters.

The power available in an air flow is calculated from equation (1):

$$P = \frac{1}{2}\rho A U^3 \qquad (1)$$

The efficiency with which a wind turbine can extract the power present in the wind and convert it into mechanical power is quantified by the power coefficient C_P, dependent from the tip speed ratio λ, and the pitch angle β, given by (2).

$$C_P(\lambda,\beta) = \frac{\text{Extracted power}}{\text{Available power}} = \frac{P}{\frac{1}{2}\rho A U^3} \qquad (2)$$

As a brief note, it is relevant to mention that the projected area of the rotor of a VAWT is calculated as:

$$A = 2RH \qquad (3)$$

with R as the rotor radius and H as blade height.

The tip speed ratio λ is defined as the ratio between the blade tip speed and the free stream wind speed, given by (4):

$$\lambda = \frac{\Omega R}{U} \qquad (4)$$

C_P determines how efficient is the power extraction from the wind. Since C_P is dependent on the tip speed ratio λ, it is immediate to understand that to maximize mechanical power output there is an optimum relation between rotor speed and wind speed. In other words, different rotor speeds achieve maximum efficiency at different wind speeds, as illustrated in Figure 1.

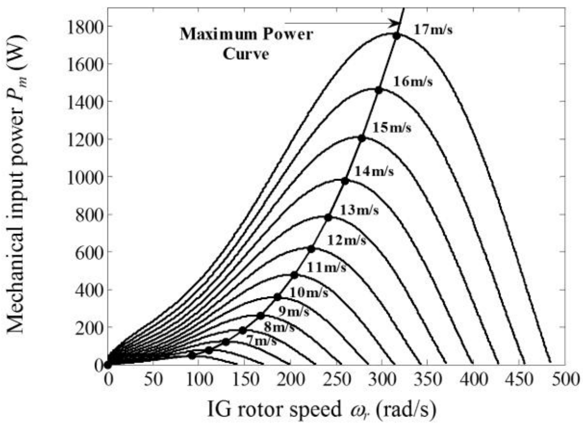

Figure 1 - Power output as a function of rotor speed and optimal rotor speed points [www.intechopen.com]

SCADA (Supervisory Control and Data Acquisition) systems are significantly important control systems used in large scale industrial infrastructures such as electric grids, water supplies and power plants.

Its function is to control and monitor industrial processes and to apply intelligent management algorithms in order to make decisions over the system operation, taking into account the acquired data and the status of the different components. An important function is to monitor alarm signals in the system and apply safety measures or inform the control room of the detailed alarm conditions.

The downtime from a turbine that is permanently monitored is significantly reduced and this contributes for a higher return and better economical viability. Also, by avoiding hazardous operating conditions, the lifetime of the wind turbine components is extended. Performance analysis can improve wind turbine operation in a significant way and contribute to larger energy yields by allowing for immediate action when under-performance problems arise.

3. Wind turbine control theory

Wind turbine control systems are usually hierarchically separated in different levels, each with different tasks and responsibilities:

- **Wind farm controllers** (SCADA systems): responsible for monitoring the operation of several units and the communication of power between the wind power plant and the electrical grid, and usually provided with the possibility to start and shutdown the individual turbines and coordinate operation between them;
- **Supervisory controllers:** supervise the operation of an individual turbine and react to changes in environment and operation conditions, monitoring the wind data, changing between operating states, sending command signals to the lower level dynamic control layers;
- **Dynamic controllers:** control the different subsystems in the wind turbine and make continuous adjustments to actuators and components as a reaction to the operating conditions. Different dynamic controllers usually operate different subsystems and the coordination between them is performed by the supervisory controller. These are used for tasks such as adjustment of blade pitch, control of the power flow on the power converters and operation of actuators in the system.

Several control strategies to maximize energy yield could be applied. In the cases when the power-rotor speed curve of the wind turbine is known, it is possible to control the power electronics converter to deliver a predefined electric power as a function of the rotor speed ω to optimize power extraction. However, this control strategy requires detailed knowledge of the Cp curve of the turbine and the electrical machine parameters.

Since there is no trustworthy information about the electrical generator parameters or operation curves for the wind turbine in this project, a different approach for achieving maximum power generation is necessary.

The purpose of a Maximum Power Point Tracking (MPPT) method is to maintain the tip-speed ratio, λ, of the wind turbine as close as possible to the optimal tip-speed ratio, λ_{opt}, in order to achieve maximum power extraction from the wind.

The Hill-Climb Search method acts by continuously searching for the peak power of the wind turbine, using only measured data. For this tracking algorithm there is no need for information about the Cp curve, optimum tip-speed ratio λopt or wind speed. This method verifies the location of the operating point and establishes relations between the variations in power output and rotor speed to assess if the rotor speed should be increased, decreased or maintained to drive the system to the point of maximum power.

The implementation of this method consists in guiding the system to achieve the top of the curve, which represents the maximum power extraction point, by either incrementing ($\Delta\omega>0$) or decrementing ($\Delta\omega<0$) the generator speed in small steps depending on the sign of $\Delta P/\Delta\omega$.

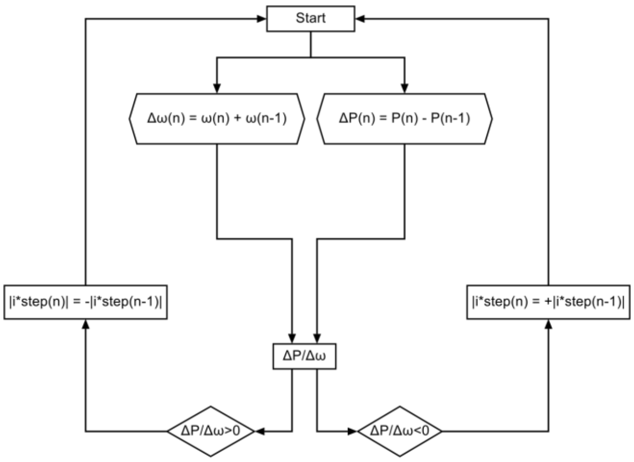

Figure 2 - Flow chart of the HCS control method (ΔP: variation in power; $\Delta\omega$: variation in rotor speed; i^*_{step}: current reference step between iterations)

If $\Delta P/\Delta\omega>0$, the operating point is located on the up-hill slope. To move towards the optimal operating point, the rotor speed should be increased ($\Delta\omega>0$) by reducing the module of the current reference I_{SG} of the generator. Decreasing the load current I_{SG} will reduce the electromagnetic torque on the generator and consequently accelerate the wind turbine rotor.

If $\Delta P/\Delta\omega<0$, the operating point is located on the down-hill slope, so the rotor speed should be reduced ($\Delta\omega<0$) by increasing the synchronous generator current reference I_{SG} in module, which enhances the electromagnetic torque demand and thus decelerates the wind turbine rotor in order to extract more power from the mechanical rotation.

If incrementing the shaft speed results in $\Delta P/\Delta\omega<0$ or decrementing the shaft speed results in $\Delta P/\Delta\omega>0$, the signal of the shaft speed variation must be reversed. This perturbation and observation routine is repeated iteratively, until the point where ΔP/Δω=0 is reached and maximum power extraction is achieved. In practice, the exact maximum efficiency point is not kept constant, but rather approximated by small steps in rotor speed change around the optimal operating point.

4. LTH Wind Power unit

Having an experimental wind turbine setup of its own, the IEA (Industrial Electrical Engineering and Automation) department can use it to test different experimental devices and software, such as generators or data acquisition and control systems. It is intended to study the behaviour of the wind turbine and be able to relate the setup to large scale power production systems, such as offshore wind power plants or multi source renewable energy setups.

The specific goals of the implementation are:

- Guarantee the safety of the setup and the university surroundings by constantly monitoring the rotor speed to avoid hazardous situations in case of strong winds;
- Inform the operator of any irregular situations related to the power converters, generator voltage, current or the DC connection, and react accordingly;
- Provide the operator with the possibility of stopping the wind turbine through a mechanical brake, in case of emergency;
- Apply the brake automatically in case of power failure to prevent the turbine from rotating in 'freewheel', which could accelerate the rotor to dangerous speeds for which the structure is not prepared and thus increase the probability of accidents;
- Brake the turbine automatically in case the wind speed exceeds a maximum value (cut-out wind speed);
- Implement a control algorithm in order to extract the maximum amount of energy from the wind;
- Allow the operator to select the desired mode of operation.

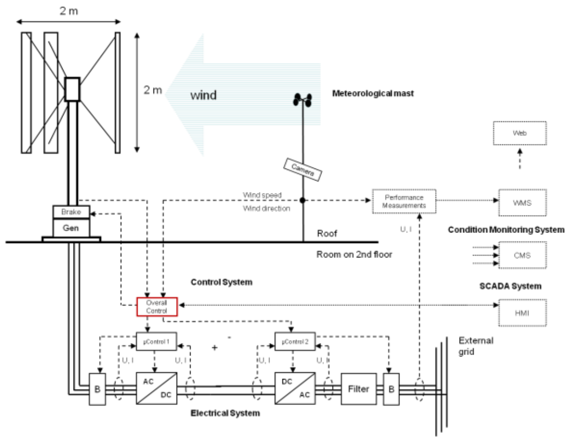

Figure 3 - Wind turbine setup and control structure

The setup consists of a vertical axis wind turbine equipped with a permanent magnet synchronous generator and a mechanical drum brake, a meteorological mast where wind speed, wind direction, air pressure and temperature are measured, a camera for monitoring the operation of the wind turbine and two cabinets located in a room below the WT setup that contain the power converters and the microcontrollers (Figure 3).

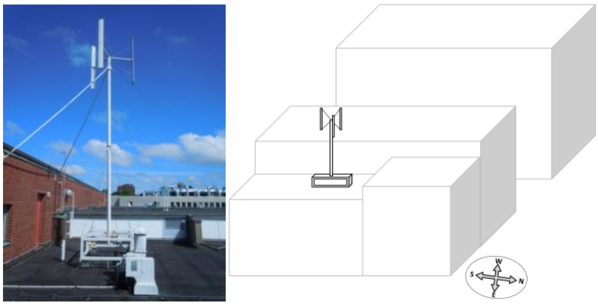

Figure 4 - LTH Vertical wind turbine

5. Control Implementation

The control system was designed in a similar configuration and inspired in what is procedure in commercial large-scale wind turbines, e.g. Vestas Wind (Dvorak, Keep the control hardware but make the algorithms easy to change, 2013). The control architecture used in this system is represented in Figure 5.

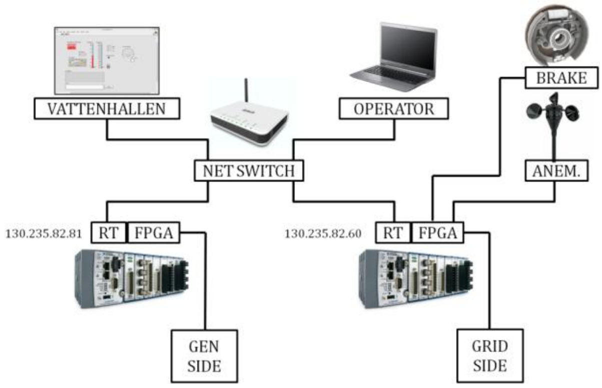

Figure 5 - Wind turbine setup and control scheme

Both microcontrollers are connected to the department's network via an Ethernet connection from the real time part. The communication with the operator's PC, where the Human Machine Interface is displayed, which also requires an attributed IP address, is achieved via IP communication. The microcontrollers' FPGAs acquire the signals from the converters and communicate them via the communication path to the real time part of the grid side Compact RIO, where the overall control program is implemented. The measurements from the meteorological mast are acquired as an input to the grid side cRIO, as well as the command signal to the mechanical brake.

Constant speed mode

A speed reference is provided to the control system and is kept regardless of the wind conditions. This means that for high wind speeds the system will produce power, but for low or inexistent winds the PMSG will behave as a motor and consume power instead, in order to keep the speed defined for the rotor to work at. Keeping a constant speed also implies that the wind turbine will be operating outside its maximum efficiency point most of the time except for a narrow range of wind speeds, attending to the fact that the rotor speed is constant and thus the tip speed ratio λ varies only with the wind speed, according to equation (4) in section 2.3.

Maximum Power Point Tracking

The method used for tracking the optimal operating point is illustrated on Figure 6. On the location of the setup, it was not so often to register wind speeds high enough to induce rotation in the wind turbine rotor capable to start production by itself, so this method is implemented with the option of providing an initial acceleration of the rotor using the PMSG as a motor by setting a positive current reference.

After spinning the rotor up to the necessary speed to overcome the inertial forces and sustain the negative electromagnetic torque that comes with power extraction, a negative current reference ($i^*<0$) is set in order to start requesting power from the PMSG shaft. The resultant variation in the rotor speed will dictate if the step in current reference will be positive or negative, i.e. increase or decrease the rotor speed. The iterative repetition of this process is expected to reach the maximum power point of the P vs ω curve, when ω_{opt} of a certain wind speed is reached. The rotor speed will then alternate around the maximum power point, depending on the size of the reference current step.

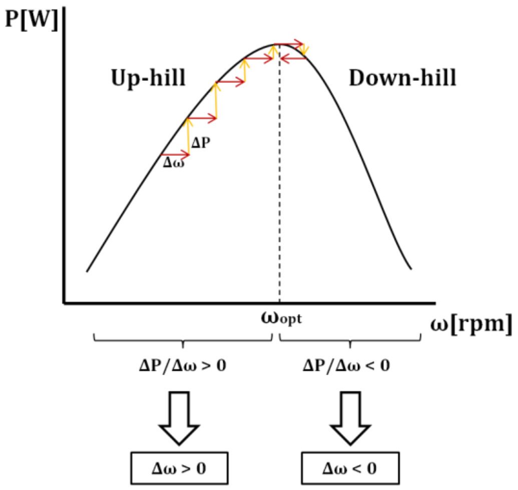

Figure 6 - Optimum Power Production mode

Since the initial rotation is provided by the motor, the cut-in wind speed defined for this mode is the same as for constant speed mode, 5 m/s. This parameter is also suitable to be changed by the operator.

State-machine model

The main sequence is presented on the left side of Figure 7, where the main states are set. The different states perform specific tasks and are separated by defined transition conditions. The main states of operation are OFF, ACTIVATE, READY, START UP, ON, SHUTDOWN and DEACTIVATE. Some sub-sequences are extended from the high-level blocks START UP, SHUTDOWN and DEACTIVATE, because generally more than one start-up and shutdown sequences are possible according to different conditions of operation of the wind turbine (Svensson, 2006).

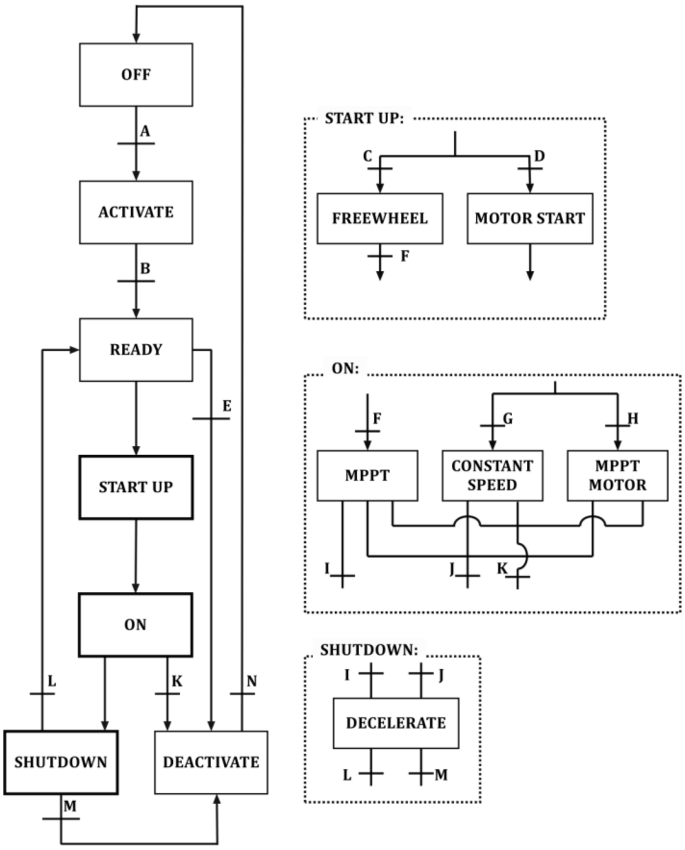

Figure 7 - Wind Turbine control sequence

The inputs to the block structure are the real-time command signals from the Human Machine Interface in the form of button presses or definition of values, the wind speed measurement, the wind direction assessment, rotor speed and status signals from the controlled components such as the synchronous generator and the power converters. The HMI has a *Start* button to start the operation, a *Stop system* button to stop the system safely through a speed reduction shutdown sequence and an *Emergency* button to interrupt operation immediately and stop the turbine shaft using the mechanical brake. A mode selector allows the operator to decide in which production mode the turbine will be operating. Several LEDs and parameter controls are implemented for monitoring purposes and experimental research.

The operator has access to the commands of the system via the Human Machine Interface, illustrated in Figure 8. The goal of the HMI is to present the data generated by the system operation in an organized manner for monitoring and supervision and it also contains the controls that allow to start or to shutdown the wind turbine, as well as the mode selection controller and more features, as described below.

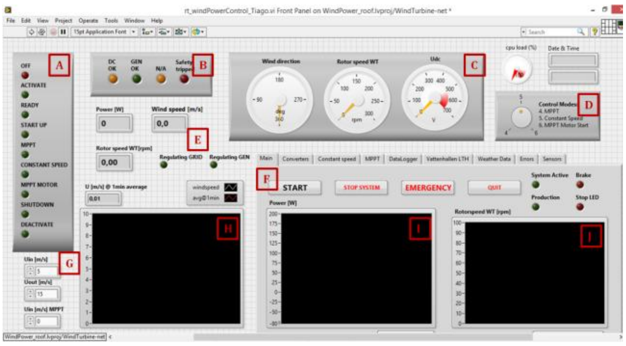

Figure 8- Human Machine Interface with Main tab

6. Performance tests on the wind turbine

Constant rotor speed

This test shows the system functioning in constant speed mode. Due to the inexistence of adequate wind speed for the performance tests ($\bar{U}$~1,5m/s), a fake variable was used in the control sequence to substitute the wind speed in this case, only to overrule the state-machine's condition of having a wind speed greater than 5 m/s to initiate production state.

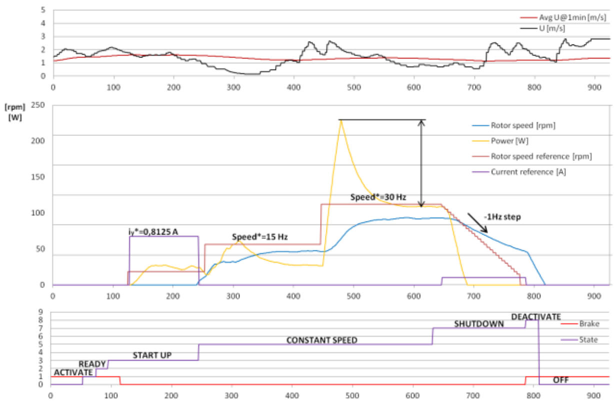

Figure 9 - Constant mode performance test

The control system is initiated by pressing the *Start* button, which forwards the state machine from OFF to ACTIVATE state. After the internal checks take place, the system proceeds to READY state. The START UP is initiated and a positive current reference is set, that creates the necessary torque to start rotation.

After the 10 seconds of acceleration, the regulation mode is changed to speed control and the state machine enters CONSTANT SPEED state. The 15 Hz (56 rpm) speed reference induces an increase in power consumption that is gradually decreased as the inertial resistance is overcome. In this particular test, after the rotor speed is stabilized, an increase in the speed reference is manually introduced, raising the mark to 30 Hz (112 rpm). The system is then sent to SHUTDOWN, where a step reduction in speed reference is applied and the wind turbine rotor is smoothly decelerated down to a full stop, which sends the instruction to lock the mechanical brake as illustrated in the bottom plot. The power converters are deactivated and the system is turned OFF.

At wind speeds of this magnitude it is unthinkable to yield any power from the wind whatsoever. At higher wind speeds, the decrease in power after the initial acceleration is expected to be accentuated and drop below the zero line and start production, provided that the rotor speed choice is adequate. However, the wind speeds at which this particular wind turbine starts producing are unknown. A test at different rotor speeds was made in order to observe the influence of the wind speed in power consumption, this time at more relevant wind speeds in the order of 4 to 6 m/s, although still not enough to invert the power signal.

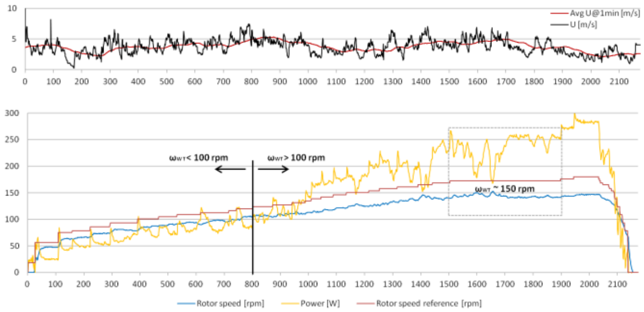

Figure 10 - Test at different rotor speeds up until 150 rpm

Figure 10 plots the power consumption, rotor speed reference and actual rotor speed at a rate of 500 ms, i.e. 2 data values per second. The system was ran in constant speed mode and the speed reference was manually increased in steps in order to assess the variations in power consumption at different rotor speeds. After each step, there is a spike in power consumption that is due to the effort of the motor in overcoming the inertia of the rotor. Then it is observable that for rotor speeds below 100 rpm, wind speeds in the order of 5 m/s have no influence in power consumption. Above 100 rpm, it is noticeable that the wind starts to have an influence in power consumption. In order to exclude rotor speed variations from the equation, one can focus exclusively on the 150 rpm speed reference step and evaluate the fluctuations in power due to the wind.

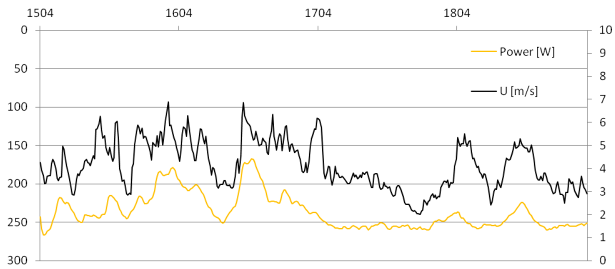

Figure 11 - Power fluctuations due to the wind at 150 rpm

Figure 11 shows that at 150 rpm the influence of a 5 m/s wind gains relevance comparing to lower rotor speeds. The power scale is inverted to clearly show that for higher wind speeds there is an associated reduction in power production. This behaviour suggests that optimum power generation takes place at higher rotor speeds, at least higher than 100 rpm.

Since there is no information about the wind speed interval at which this experimental turbine is designed to produce power, an approach to roughly estimate an interval was attempted. Based on the observation that the wind speed produces perturbations in power consumption above a rotor speed of 100 rpm, the wind speeds were sorted in ascending order and plotted against the power levels that resulted. The outcome of this test for a rotor speed of 150 rpm is shown in Figure 12. The nonlinear relation between wind speed and power can be estimated by applying a polynomial regression on the power data dispersion. By calculating the roots of the polynomial approximation and applying the result on the linear function that models wind speed, it is possible to obtain an estimation of around what value of wind speed power production would start (i.e. at what wind speed the power signal switches from positive to negative).

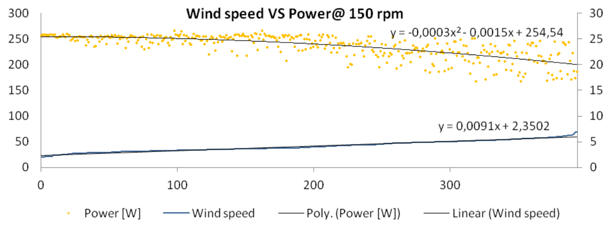

Figure 12 - Polynomial regression of the power and wind speed

It is relevant to mention that a quadratic approximation is not adequate to obtain a reliable result since, as shown in equation (2) from section 2.3, the power has a cubic relation to wind speed. However, for lack of a better approximation since a cubic regression yielded no meaningful results, this approach is the best possible estimation of the minimum wind speed necessary to produce power with the information available and should be taken merely as an educated guess.

Rotor speed	$P(x^2)=0$	$U(P=0)$
150 rpm	x=918,626	**U=10,71 m/s**

Table 1 - Polynomial regression result

Since no power production coming strictly from the wind was registered, it was not possible to plot a Cp curve of the type of Figure 1. It is however possible to investigate the tip speed ratio λ (TSR) occurring at the situation of minimum power consumption. It is possible to sort the consumed power in descending order against the tip speed ratio λ and observe at which λ the minimum power is produced.

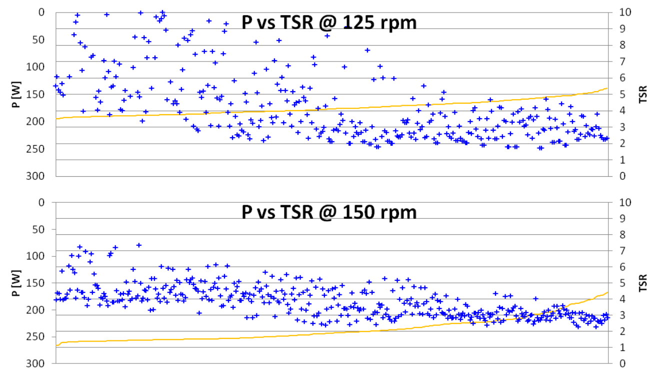

Figure 13 - Plot of power VS tip speed ratio dispersion

As mentioned previously the wind speed only influences power consumption for rotor speeds above 100 rpm. Thus, the data was observed on the tests at 125 and 150 rpm and plotted in Figure 13. The results show that the minimum power consumption is attained for a λ of around 2,5 for the rotor speeds tested (Table 2).

Rotor speed	$\lambda(P_{min})$
125 rpm	~2,5
150 rpm	~2,7

Table 2 - Tip speed ratios correspondent to minimum power consumption

Maximum power extraction with induced start-up

In this test, the MPPT mode with motor start-up is put in operation.

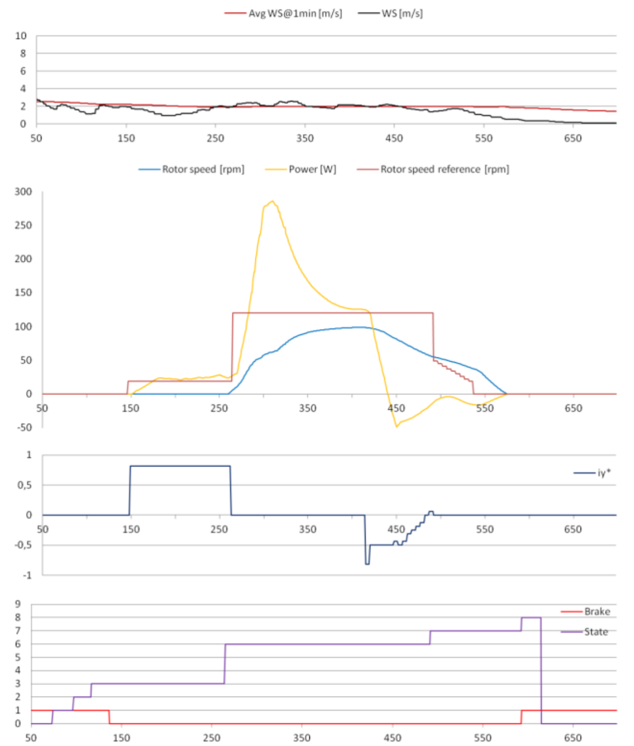

Figure 14 - Performance test of the MPPT Motor method

In this mode, the control system must reverse the direction of power flow from motor to generator mode and search for the peak power operation point using the method described in section 5.

The wind speed range for which this mode is programmed to work is between 5 and 15 m/s. However, during the testing period very poor wind conditions were available, so the sequence was ran but the wind speed had no influence in the results. It is still possible to observe the operation of the method with the power generated by the deceleration of the PMSG with a negative current reference.

The system is started and the initial checks take place, as the sequence proceeds through the ACTIVATE and READY states, illustrated in the bottom graph of Figure 14. In the START UP state, a positive current reference in current control mode is provided to the PMSG to accelerate it as a motor without any load until reaching a suitable speed. After a defined period of time, the regulation mode is switched to speed control and a defined speed reference accelerates the rotor up to around 100 rpm, already in the MPPT MOTOR state. The requested power is initially high, but decreases as the inertial load is overcome. Next, the regulation mode is changed back to current control and the direction of the power flow is reversed as a negative current set-point is provided to the current PI. The power consumption decreases sharply as mechanical energy is drawn from the PMSG, turning over to power production. The maximum power point tracking method starts being applied at this point. A close-up of the plot is illustrated in Figure 15 for a more detailed visualization.

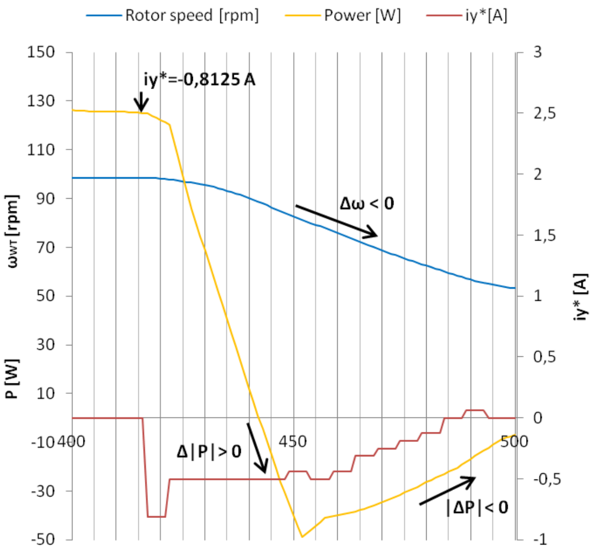

Figure 15 - Close-up of the MPPT Motor test

After the first negative current set-point, the reference is reset to *iy*=-0,5* as a starting point for the MPPT method. The first step shown in the plot is in the positive direction due to the 500 ms delay imposed in the code sequence, meaning that the first current step is still reacting to the decreasing consumed power (Δ|P|<0) before it crosses the zero line. After turning over to power production, the power starts increasing in module while the rotor speed decreases (i.e. Δ|P|/Δω<0), which the algorithm recognizes as the situation to correct the rotor speed by applying a negative step to the already negative reference current. After the peak of the power production is reached, the power starts decreasing in module while the rotor speed keeps dropping, which means that a positive current reference is to be applied in order to increase rotor speed. Since there is no wind to counteract the negative torque, the PMSG eventually stops and the power goes to zero. The code defines the transition to shutdown as the moment when the current reference turns positive, which can be verified in Figure 14 as the step reduction of the speed reference gradually decelerates the rotor to a full stop. The normal sequence is then performed, the rotor shaft is locked with the mechanical brake and the power converters are disconnected.

7. Discussion

The polynomial regression suggests that power production will not start below wind speeds in the order of 10 m/s (Table 1), for the tested rotor speed of 150 rpm. There is no information that allows to obtain a confirmation of these results unless by eventually observing the power production when the wind is blowing at those speeds. It is important to keep in mind that a quadratic regression is not the adequate mathematical approximation and adds error to the estimation, but then again these estimations are merely indicative of what should be expected, without any quantitative relevance, also because the data sample was narrow and subject to irregularities such as acceleration and deceleration of the rotor, inducing error in the equivalence of power that is directly attributed to wind speed.

The values of tip speed ratio that originated the lowest power consumption $\lambda(P_{min})$, of around 2,5 and 2,7 for 125 rpm and 150 rpm respectively (Table 2), are coherent with the values of λ_{opt} that are to be expected from small scale VAWTs, which are documented to have its optimum power coefficient for tip speed ratios around 2 or 3 (Ryan McGowan).

The wind speeds at which the turbine was operated are far too low for what is adequate for wind turbine operation in general, and especially for this specific VAWT configuration. During the performance tests phase, in rare occasions the average wind speed measurements went over 5 m/s.

The location of the wind turbine setup is not the most adequate due to the proximity of obstacles like trees and higher buildings, which may disturb the air flow and reduce the quality of the incoming wind. But then again, the purpose of this installation is not performance and power production, but rather to have a setup suitable for testing components and control systems.

8. Conclusion

The development of the automatic operation strategy and the implementation of the control system were successful. The wind power plant control sequence is implemented and fully operational, acquiring the wind speed measurement to the monitoring system with accurate values and no disturbances. The mechanical brake is installed and tested and Vattenhallen's remote panel connection is up and running.

The HMI was designed with the aim of providing a flexible experimental tool and highly customizable environment to allow the operator to change the parameters that rule the speed control modes and experiment in order to optimize and fine tune the methods that are implemented.

The implementation of the monitoring and control system was not affected by the lack of wind conditions, but the performance tests on the speed control modes were impaired by the absence of adequate wind speeds.

Anyhow, the algorithm for optimal wind energy yield seems to behave according to the theory that supports it, although no relevant conclusions about its effectiveness can be taken from the testing results. It is recommended that further experimentation should be made at higher wind speeds in order to assess the method's real performance.

The main advantage of the Hill Climb Search method is that it does not require prior knowledge of maximum power at different wind velocities nor electrical machine parameters. In this case, none of these are known. It was intended to investigate the C_p of the rotor and plot a power curve but the wind conditions were not favourable during the performance testing.

Owing to the poor wind conditions or to the aerodynamic design of the wind turbine or to a combination of both, no power was produced from the wind during the testing performed on this project. It is recommended to perform further studies on the experimental setup, both to confirm the estimations that resulted from this study and to fine tune and improve the implementations and the installation.

The control modes were implemented and tested, proving to be operating as intended although the wind speeds were not strong enough to produce power. The constant speed mode was ran for different rotor speeds and an estimation of the minimum wind speed necessary for power production was performed, suggesting a value of around 10 m/s for a rotor speed of 150 rpm. These results should not be taken as scientific measurements, but rather as an educated guess based on an extrapolation from the sampled data at low wind speeds. The Maximum Power Point Tracking method was implemented through current control and the results from the current reference variation and power produced from the rotor deceleration show that the algorithm follows the changes in power and rotor speed in the correct direction.

Due to the absence of power production, it was not possible to investigate and determine the power coefficient of the rotor.

The overall safety of the installation was improved with the implementation of the control system through the addition of wind speed monitoring, the *Emergency* stop button for the operator and the mechanical brake system that can physically stop the turbine shaft in case of necessity.

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