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Control and Operation of a Vertical Axis Wind Turbine

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Abstract

Research in wind power generation technology is a topic of high relevance in the context of renewable energy systems. 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, in Sweden.

Supervisory control and data acquisition systems (SCADA) are increasingly considered indispensable in industrial scale wind power plants with the purpose of optimizing power production and monitoring the operation conditions in real-time to improve safety and reduce downtime and costs.

Variable speed control is widely used for maximizing power extraction. In this project, a Maximum Power Point Tracking (MPPT) algorithm was successfully implemented in order to optimize power production. 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 maximum power curve.

A state-machine model was developed to manage the operation of the wind turbine. 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 system.

Performance tests were ran to investigate the optimum C_P and the wind speed at which the wind turbine is capable of producing power.

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

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Nomenclature

Symbols

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]

$\overline{U}$ - Average wind speed [m/s]

Abbreviations

PMSG - Permanent magnet synchronous generator

GRID SIDE - Electrical grid power converter

GEN SIDE - PMSG power converter

MPPT - Maximum Power Point Tracking

1 Introduction

1.1 Background

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.

The success of the implementation of renewable energy systems has been driven by policy support that has grown considerably during the last decade. Either focused on utility-scale or small-scale generation systems, policies continue to evolve in order to address market developments and reduce costs to promote massive installation. The EU 2020 Climate and Energy Package is an example of policy making in Europe, consisting of a set of binding legislation which aims to ensure that the European Union meets its targets for 2020: achieving 20% reduction in greenhouse gas emissions from 1990 levels; raising the share of renewable energy consumption to 20% and making a 20% improvement in EU's energy efficiency (EU, 2007).

The path for the creation of a global clean and sustainable energy platform is being walked one step farther every day, as research in renewable energies is strongly encouraged and new technologies emerge as a result. 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.

Wind is a renewable, plentiful and widely distributed source of energy that has proved to be an excellent solution for the need to generate mechanical power. The technology for extracting power from the wind is not new to Man, it has in fact been a valuable tool since ancient civilizations. Generally it has been used for purposes such as driving windmills with grinding stones for cereal milling, and later for water pumping, but most recently its main application has been electricity generation. Generating electrical power from the wind is an idea as old as electricity itself, but technological developments have only made it viable as a large scale solution in the recent decades (Manwell, 2009). Wind has great potential for powering civilization, since it exists everywhere on earth and with a considerable energy density in some places, which justifies the great investment and fast spreading of this renewable energy conversion system.

Wind power industry has experienced tremendous growth over the last decade, with the global installed capacity increasing from 18 GW in 2000 to approximately 300 GW in 2013, which represents more than a 16 fold increase. Wind power now provides 2,5% of global electricity demand, with some countries having considerable shares of their electricity production coming from wind, with up to 30% in Denmark, 20% in Portugal and 18% in Spain (IEA, Technology Roadmap Wind Energy, 2013).

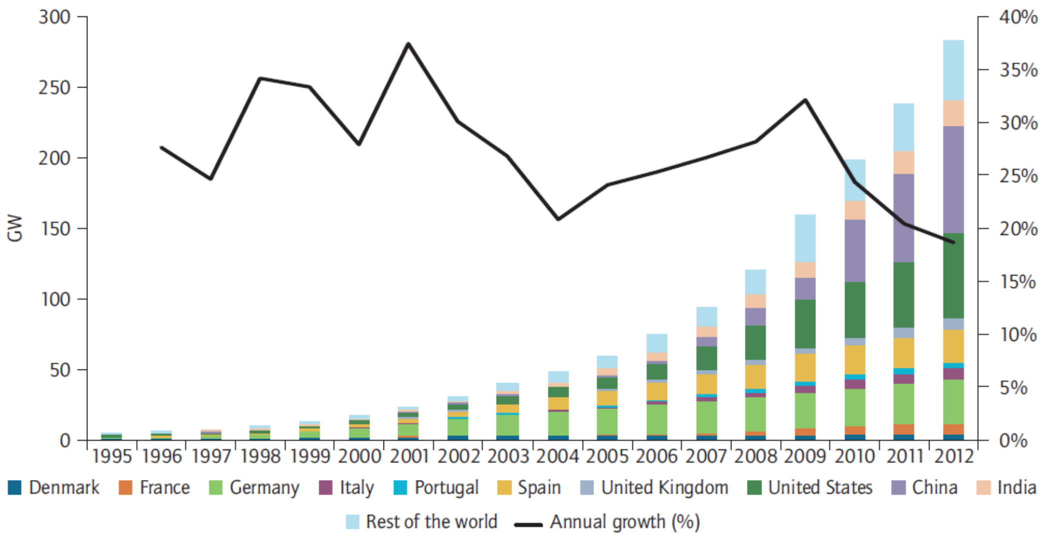

Figure 1 - Global cumulative wind power capacity 1995-2012 (IEA, Technology Roadmap Wind Energy, 2013)

Achieving the policy targets requires scaling up the current annual installed power capacity and improving energy yields, while reducing downtime and operation and maintenance costs (O&M). The installed capacity is increasing globally at a fast pace due to turbine technological maturity, policy development and higher economical viability (IEA, Technology Roadmap Wind Energy, 2013).

Turbine technological improvements have been one of the main reasons for the significantly increased capacity of the past decade, but even with such improvements turbines must be properly maintained to achieve optimal production and meet revenue targets. Nowadays, monitoring is indispensable to ensure that the turbines are operating at optimum conditions and maximum performance (Sharpley, 2014).

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 operation through the use of power converters. Static converters, used as an interface to the electric grid, enable variable speed operation allowing for active control of the extracted power. Due to external perturbations such as wind shear, tower shadows and random wind fluctuation, variable speed control seems to be a good option for optimizing wind turbine operation (D. Zinger, 1997). The energy available in the wind varies continually as wind speed changes, and the amount of power output from a wind energy conversion system is highly dependent upon the relation between wind speed and rotor speed. By controlling rotor speed to achieve an optimal relation with wind speed, improvements of over 10% in energy output have been documented, as well as lower mechanical stress and less power fluctuation (Wang, 2004). In order to fully avail the advantages that outcome from variable speed wind generation systems, it is necessary to develop advanced control methods to extract maximum power output at different wind speeds. Research has been made on several different strategies to achieve this, such as tip speed ratio control, power signal feedback control and hill-climb search control (Thongam & Ouhrouche, 2011).

1.2 Objectives

In this context, 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. It is intended to:

- 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 wind turbine setup was designed in such a way to allow expansion to a multi-source station, with the possibility to install new generation units. Modularity and adaptability are important features of the system. This work is thus relatable to what is implemented in large scale installations such as offshore wind power plants, since the monitoring of the experimental setup and the control philosophy and structure are the same as in industrial scale applications. 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).

1.3 Report outline

This paper is organized in eight chapters, from which the present section constitutes the introduction and includes an overview of the background and relevance of the study of wind power systems, as well as a description of the overall project objectives.

Chapter 2 provides an overview on wind power technology and addresses the different wind turbine types available, the importance of studying wind characteristics for the siting of a wind power generation unit, the aerodynamics of wind turbines and its role in power production and also an overview on SCADA systems.

Chapter 3 presents the theory behind wind power plant control, including variable wind speed control and the method to optimize power production in which this work was based.

In chapter 4 the wind turbine setup in which the control is performed is thoroughly described.

Chapter 5 presents the implementation, describing control architecture, the plant system block structure, the operating modes and the programming in LabVIEW.

In chapter 6 the results from the performance tests ran on the system are presented.

Chapter 7 presents a discussion of the results and the main considerations about the experimental conditions and the performance assessment, and an evaluation of the success of the project. Recommendations for future experimental research on the setup are provided.

Chapter 8 encloses this document with the essential conclusions taken from the work performed.

2 Wind Power overview

It is useful to consider some fundamental facts underlying wind turbine operation before proceeding. To understand how wind turbines function, this chapter provides a brief overview on the available technology of modern wind turbines, wind resource characteristics and the physics behind the aerodynamic interactions that ultimately result in power production.

2.1 Technology

A wind turbine is a machine that converts the kinetic energy present in the atmospheric air flow into usable electricity. Wind turbines produce energy only in response to the immediately available wind resource, thus the resultant power output is inherently fluctuating and non-dispatchable.

Wind turbines are connected to an electrical network, which can be residential or industrial scale power systems, isolated or island networks, and large utility grids. In terms of generating capacity, the turbines that make up the largest share of power production are generally rather large-scale turbines - 2 to 5 MW rated power (Manwell, 2009). However, small scale turbines (kilowatts scale) are becoming gradually marketable, especially in remote places where grid based electricity is not available or unreliable.

Figure 2 - Left: Large-scale HAWT Siemens SWT-6.0MW-154m [www.siemens.com]; Right: Small-scale VAWT in Environment Energy Centre, Leyland, UK [www.quietrevolution.com]

The layout of the blades of a wind turbine can have two major different configurations, either rotating around a horizontal or a vertical axis. 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).

A variety of different concepts for HAWT and VAWT have been proposed throughout the years, as illustrated in Figure 3 and 4. Typically, commercially available wind turbines have two to three blades, although many other designs have been tried.

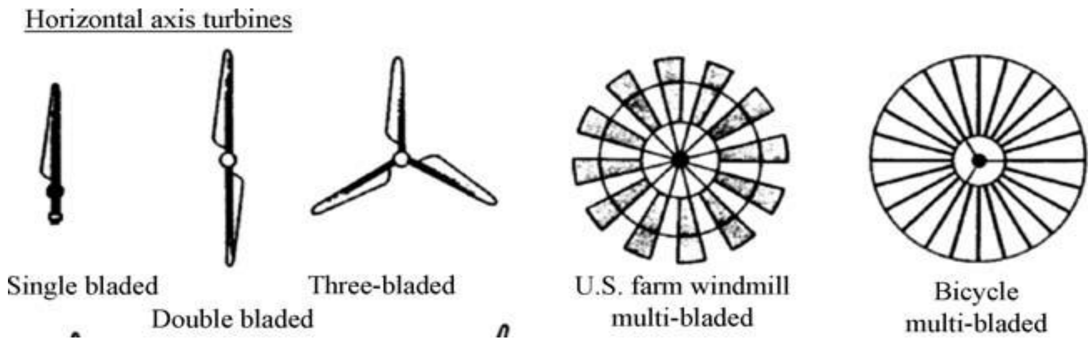

Figure 3 - Lift and drag type horizontal axis wind turbines (Eldrige, 1980)

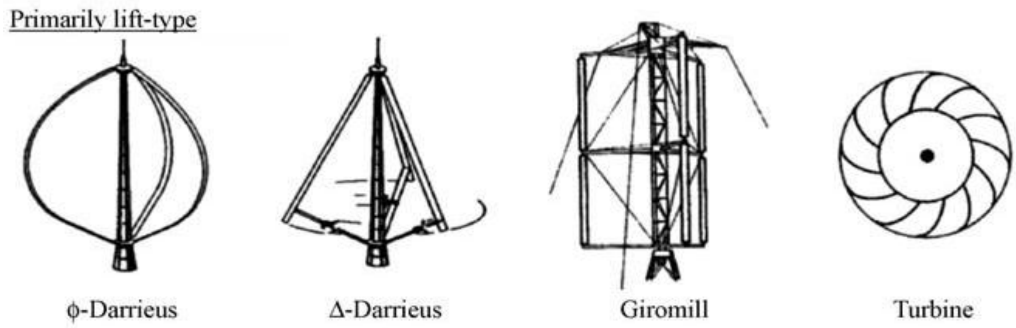

Figure 4 - Lift type vertical axis wind turbines (Eldrige, 1980)

In comparison to horizontal axis wind turbines, VAWTs have the following advantages:

- Performance is independent from wind direction, thus not requiring any special mechanisms for yawing into wind;

- Blades can be manufactured by mass production extrusion, since they are often untwisted and of constant chord;
- The generator is installed on the base, which makes maintenance simpler and cheaper.

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, as explained in section 2.2. A solution to overcome this limitation is to install the VAWTs on top of buildings.

The principal subsystems of a typical wind turbine include (Manwell, 2009):

- **Rotor**: The rotor consists of the hub and blades of the wind turbine. The blades are often considered the most important components of a wind turbine since they are responsible for the aerodynamic interaction with the wind, from which performance is largely dependent. The blades are commonly manufactured from composites, primarily fibre glass or carbon fibre reinforced plastics.

- **Drive train**: The drive train consists of the rotating parts that follow the rotor. This is typically constituted by a low-speed shaft on the rotor side, a gearbox and a high-speed shaft on the generator side. The purpose of the gearbox is to increase the rate of rotation of the rotor to a higher speed, suitable for driving the electrical generator.

- **Generator**: Induction or synchronous generators are the most commonly used in wind turbines. The generator is of course the component responsible for transforming the mechanical power harnessed from the wind into usable electricity.

- **Tower**: The principal type of tower design currently in use is free-standing type using steel tubes or lattice towers, although the latter is less common and usually for small-scale turbines. The stiffness of the tower is an important factor since it is subject to cyclic loads and there is the possibility of coupled vibrations between the rotor and the tower.

- **Controls**: The control system of a wind turbine is a central subsystem, relevant both from the machine operation and power production point of view. The control system is responsible for keeping performance at optimum levels, by monitoring the operating conditions and respond accordingly in an intelligent manner. The design of a control system for a wind turbine application follows traditional control engineering practices. A wind turbine control system includes the following components:

○ **Sensors**: measurement of important quantities such as rotor speed, yawing position, internal temperature, current, voltage, etc.

○ **Controllers**: mechanical mechanisms, electrical circuits;

○ **Power amplifiers**: switches, electrical amplifiers, hydraulic pumps and valves;

○ **Actuators**: motors, pistons, magnets and solenoids;

○ **Intelligence**: computers, microprocessors, programmable embedded systems.

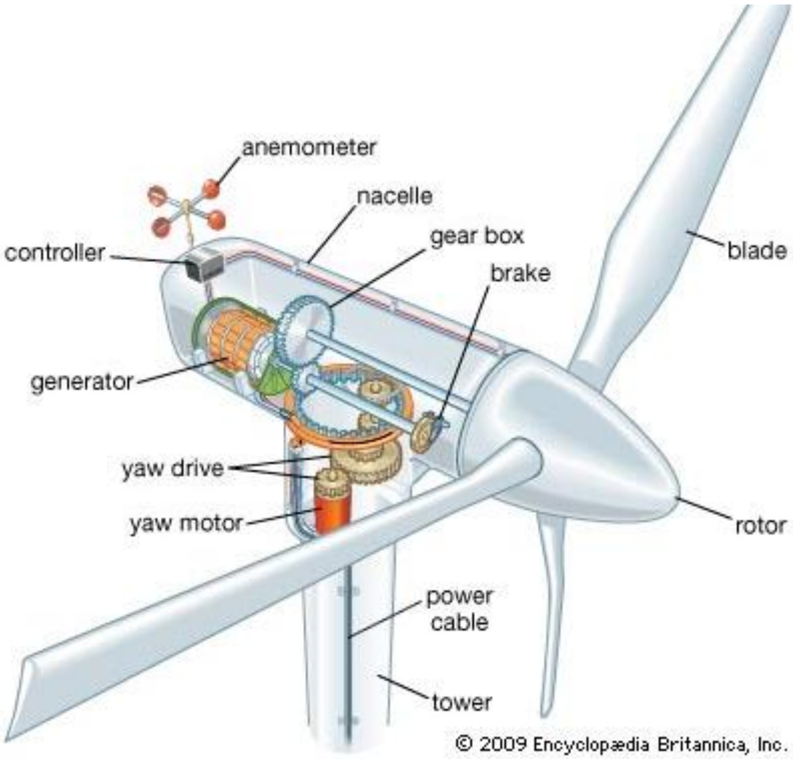

Figure 5 - Main components of a wind turbine system [Encyclopædia Britannica, Inc.]

2.2 Wind characteristics and siting

The source of atmospheric air movement is the uneven heating of the Earth's surface by solar radiation. Pressure differences across the globe cause air masses to dislocate and thus create the phenomenon called wind. Wind is an intermittent and unpredictable phenomenon, varying significantly both in time and space.

The variations of wind occur stochastically over both the long and short time scope. The variations can be observed in an annual, diurnal or short-term scale. Short-term variations usually mean variations over time intervals of ten minutes or less, including gusts and turbulence (Figure 6) that cause significant fluctuations around an average value. The annual average wind speed is obtained by monitoring wind speed on a site for at least a one year period and represents a crucial parameter when planning or optimizing a wind power plant. Wind speed is the most influential parameter in wind turbine performance and power production, as demonstrated in section 2.3.

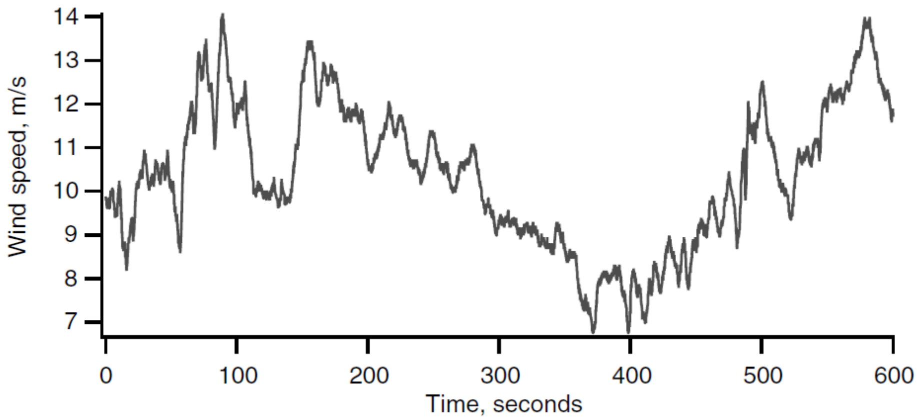

Figure 6- Sample wind data (Manwell, 2009)

Wind is often studied as having a vertical distribution well described by a logarithmic profile. The atmospheric boundary layer generates a wind gradient, which is the quantity that indicates the vertical variation in wind speed relative to the height above the ground, caused by the direct interaction of the atmosphere with the earth's surface. The wind speed is lower near the ground due to the presence of obstacles such as buildings, trees, hills or surface roughness. The fluctuation is still present due to turbulent phenomena, as illustrated in Figure 7 (Left).

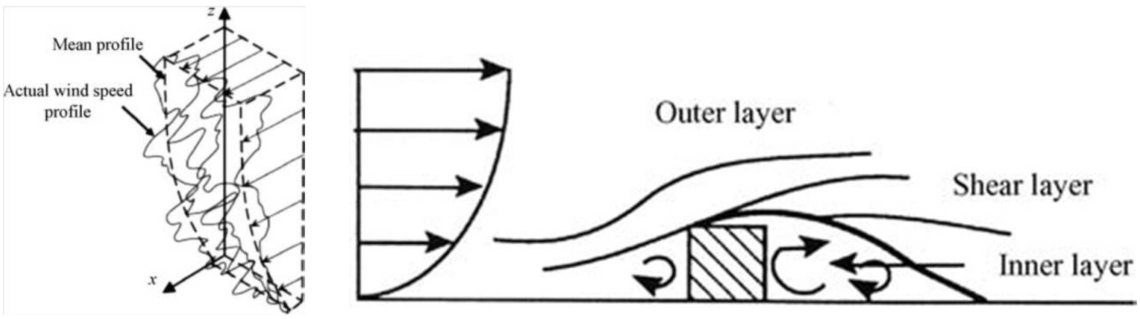

Figure 7 - Left: Experimental speed profile (Tempel, 2006); Right: Schematic of a momentum wake over a building (J. S. Rohatgi, 1994)

The study of the air flow over buildings is a subject of interest, since the understanding of this phenomenon can improve the performance of wind turbines located on building roof tops by gaining knowledge of the regions in which wind speed is accelerated due to the altered shape of the streamlines. The increase in wind speed can represent considerable gains in energy yield, however the turbulent vortexes that are formed on the wake of the building can dramatically decrease performance of a wind turbine if the siting is not carefully planned and taking the surrounding obstacles and prevalent wind direction in consideration. The schematic in Figure 8 provides a good illustration of the disturbances caused by the urban geometries.

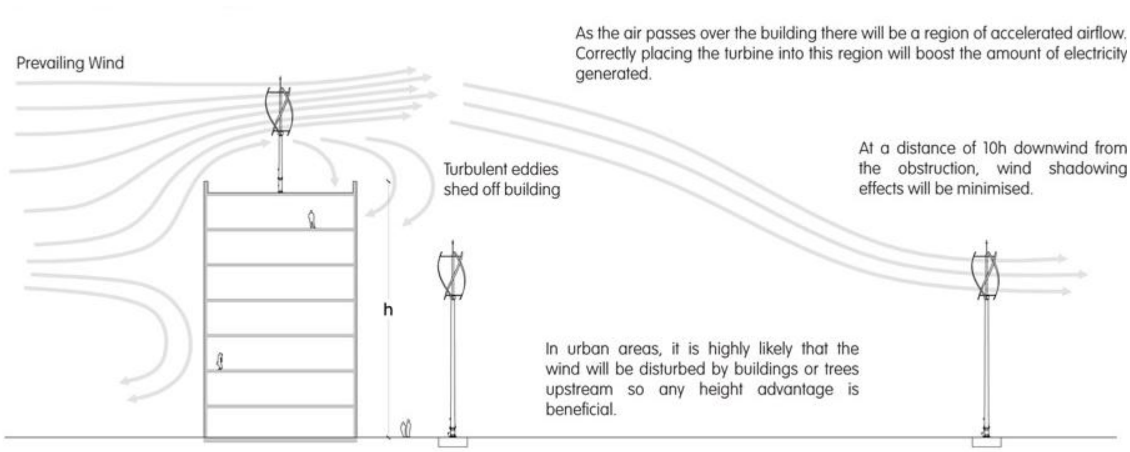

Figure 8 - Schematic of wind distribution over a building for the installation of a small-scale VAWT [www.quietrevolution.com]

2.3 Aerodynamics and power production

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):

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

However, not all the available power can be effectively converted. 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 the power extraction from the wind is and it has a maximum theoretical value of approximately 59%, the Betz limit (Manwell, 2009). 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 9. This relation varies considerably depending on the type of wind turbine, as Figure 10 graphically explains.

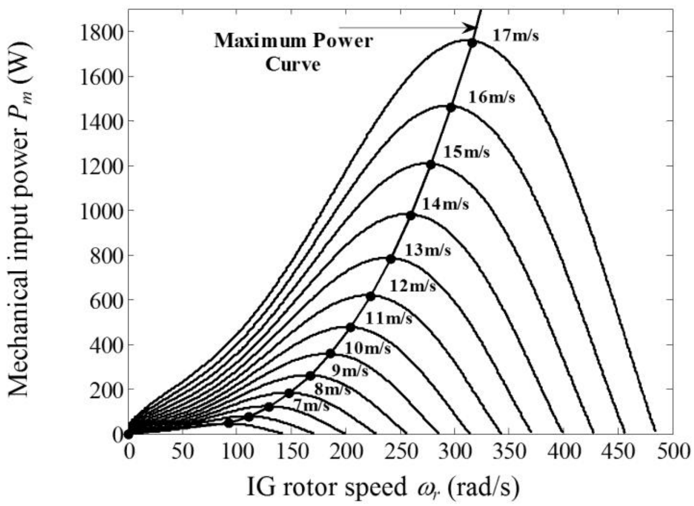

Figure 9 - Power output as a function of rotor speed and optimal rotor speed points [www.intechopen.com]

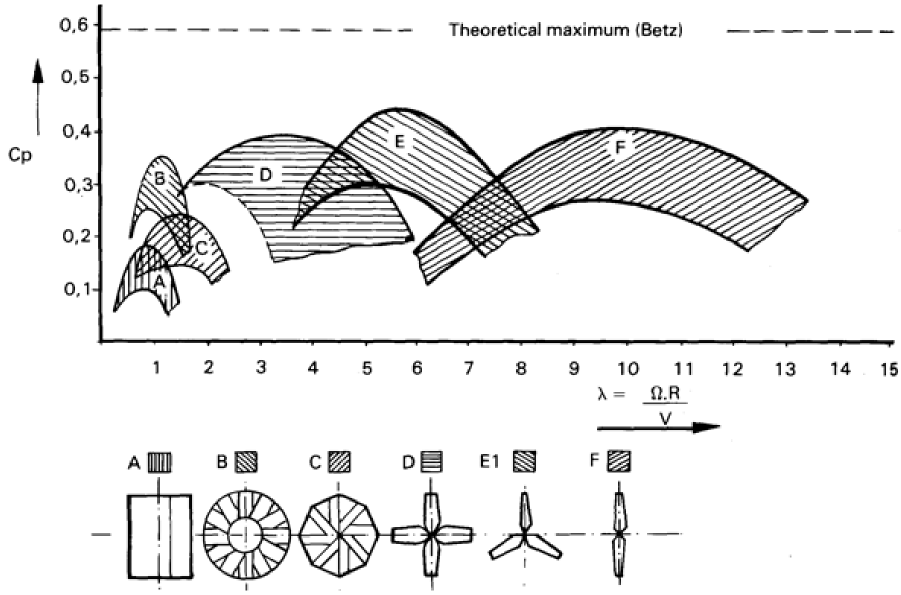

Figure 10- Power coefficient Cp plotted against tip speed ratio for various types of wind turbines (Örs, 2009)

For a specific wind turbine, the rotor speed for which the power output at a certain wind speed is maximum is defined as optimum rotor speed ω_{opt}, corresponding to the points marked on Figure 9. For different wind speeds, there is a corresponding value of rotor speed ω_{opt} that enables extracting the maximum possible power from the wind. In Figure 9, all points of maximum power extraction are connected by a line that represents the optimal tip speed ratio λ_{opt}. In order to maximize power extraction, a wind turbine should always operate as close to λ_{opt} as possible. A way to achieve this is by controlling the turbine rotor speed, to ensure that optimum rotor speed ω_{opt} is maintained for every wind speed value.

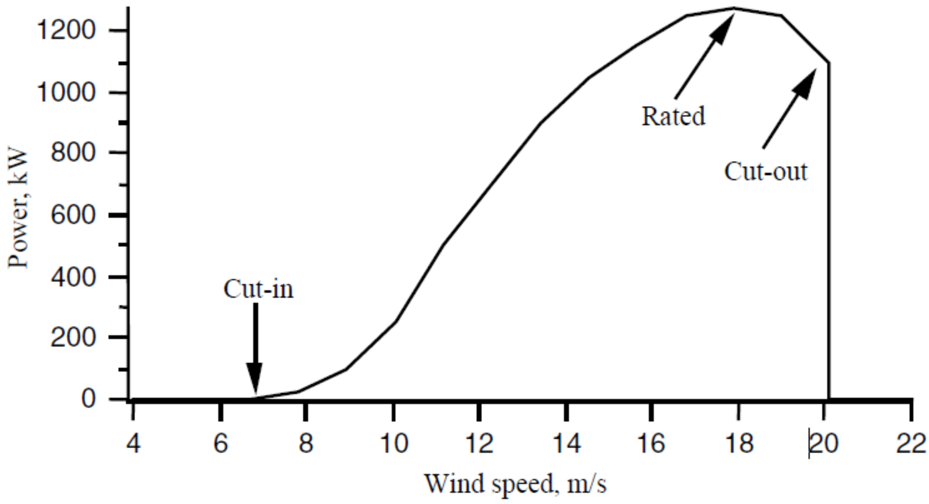

Figure 11 - Typical wind turbine power curve (Manwell, 2009)

The power curve of a wind turbine allows predicting the energy production without considering all the inherent technical details of its various components (Manwell, 2009). With knowledge of the power output and a measurement of wind speed, a characteristic power performance curve of the wind turbine can be mapped, which usually can be obtained from the turbine manufacturer.

The relevant points of the curve are:

- Cut-in wind speed: the minimum wind speed at which the machine will deliver power output, although far from its optimum performance;
- Rated wind speed: wind speed at which the turbine delivers its rated power;
- Cut-out wind speed: the maximum wind speed at which the turbine is allowed to deliver power, usually limited by structural and safety constraints.

The control strategy varies depending on if the turbine is operating below or above rated speed. At low wind speeds the turbine control aims to maintain an optimum power coefficient Cp to extract as much energy as possible, by operating at optimal rotational speed ω_{opt}. Once the maximum allowable rotor speed is reached, the mode of operation is changed in order to limit the power (rated power), which involves reducing the rotor speed and the rotor efficiency using mechanical or electrical mechanisms. This can be done with fixed rotor speed or variable rotor speed strategies. Figure 12 provides an overview of typical control strategies for wind speeds below and above rated power production.

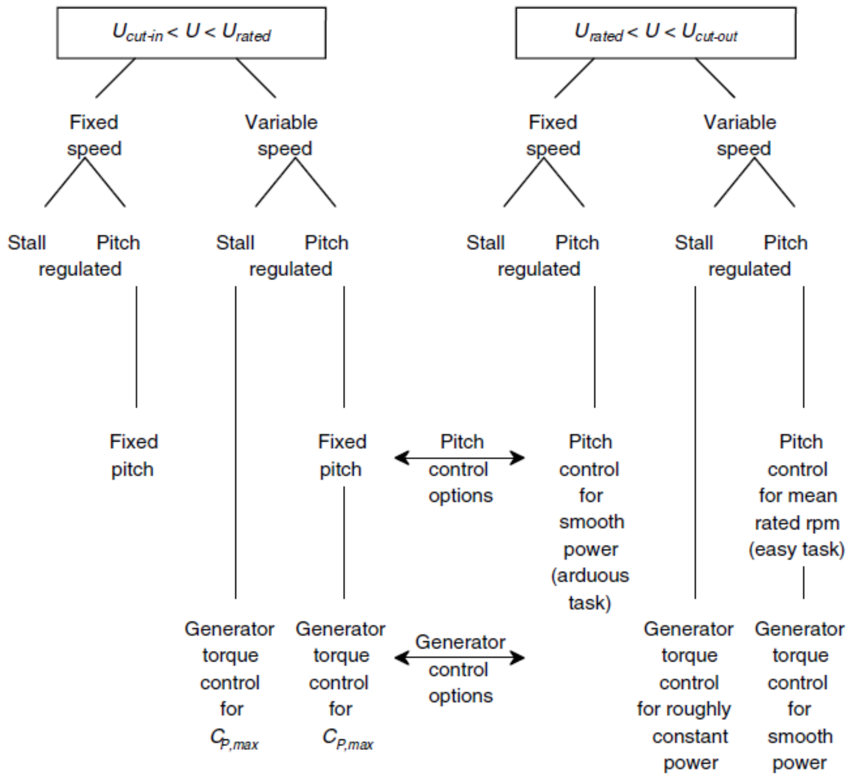

Figure 12 - Overview of typical control strategies (Manwell, 2009) p.371

There are different strategies to achieve the same goals. Pitch and stall regulation are two common ways of controlling the power coefficient and power output, both for variable speed and fixed speed wind turbines. Details about pitch control, stall control and power control are provided in chapter 3.3.

To gather information about the parameters that control the efficiency and power production of a wind turbine, it is necessary to have systems that accurately monitor the operation and provide relevant data to better understand the conditions and maximize the performance. The next section provides an overview on the control systems that are implemented to satisfy this necessity.

2.4 SCADA (Supervisory Control and Data Acquisition)

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.

Data acquisition is performed by the measurement equipment and communicated to the overall control system. The data is then compiled and formatted in such a way that the system can analyze it and behave according to the control algorithm designed for the setup. It also provides the control operator with the possibility to override the normal operating sequence through a Human Machine Interface (HMI), if necessary.

Real-time monitoring and control systems are common in most electric power-generation utilities. However, these systems were not used in early wind power plant facilities. As the number of installed capacity increased and the share of power from wind integrated in power grids became relevant, the industry recognized the value of optimizing production around the clock.

In case of a safety fault, the control system acts by removing the turbine from service as a security measure. Typical faults are for example when the wind shifts directions quickly and the yaw system is not able to keep up, or when the wind is gusting and possibly the pitch system cannot perform within the pre-programmed parameters (Dvorak, Windpower Engineering & Development, 2014).

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.

Routinely acquiring data from the wind turbines on an industrial wind power plant via the SCADA system provides an additional opportunity to discover losses in production and ensure that the wind power plant is operating at its maximum performance. The data, collected on a nearly real-time basis, annually creates many terabytes of information about e.g. wind speed, generator power output, rotor speed, pitch and yaw angles, etc (Dvorak, Windpower Engineering & Development, 2014). 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.

A critical benefit of SCADA systems is improved safety for wind turbine technicians that may need to operate in the turbines. When a climb is needed, the turbine can be remotely started and stopped only after a confirmation contact from the technician in order to prevent accidents. Furthermore, access to performance engineering has potential to eliminate unnecessary turbine climbs in an attempt to diagnose the problem (Dvorak, Windpower Engineering & Development, 2014).

The SCADA system consists of the bi-directional interaction between the acquired signals in the wind turbine components, communicated to a data acquisition centre where the data is analyzed and pre-programmed signals are sent back to the wind turbine as a response to the status and operating conditions. The data is recorded and can be used for tracking errors and performance analysis.

A brief description of the main subsystems of a SCADA system follows (Boyer, 2010) and an illustration of an example of SCADA system architecture is provided in Figure 13:

- **Programmable Logic Controllers** convert the acquired signals to digital data and have sophisticated embedded control capabilities and are used because of their versatility, configurability and economical advantages;
- **Telemetry hardware** is the communication path used by the system to communicate between the field data acquisition hardware and the data warehouses and control centres via telephone lines, WAN circuits, satellite, microwave, etc;
- **Data acquisition server** is the software service that uses industrial protocols to connect to the devices and access the data;
- **Human-Machine Interface** is a device or computer application that presents the processed data to a human operator, providing trending, schematic representations, diagnostic data and management information, allowing the control operator to monitor and interact with the process and make decisions based on the status of the system;
- **Data Logger** is a device that gathers and saves data generated by the system, such as the measurements as a function of time, system status, error alarms, boolean indicators, etc., which can be used to present trends and graphical visualizations in the HMI.

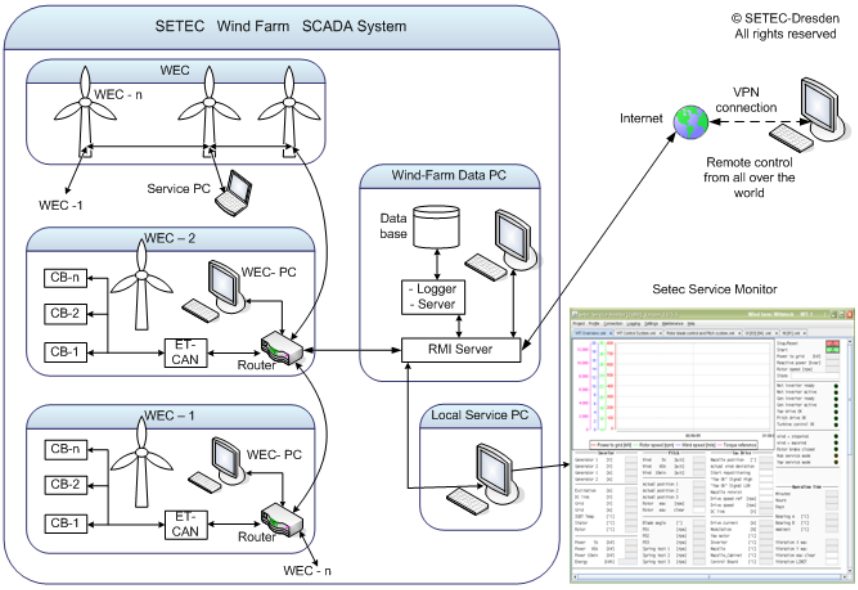

Figure 13 - Example of SCADA system control architecture [www.setec-windpower.com]

3 Wind turbine control theory

3.1 Control and operation

Without some form of control system, a wind turbine cannot successfully and safely produce power. This section provides an insight on wind turbine control structure and the important aspects of control systems that are relevant to wind turbine control. In general, the purpose of wind turbine operation monitoring and control is to:

- Ensure safety of the setup and the surroundings by continuously monitoring the internal operation conditions, such as gearbox lubrication and temperature, as well as structural loads and fatigue loads caused by the inherent aerodynamic load fluctuations;
- Enable quick reaction in case of system failure or malfunction;
- Define clear operation states for full power production (cut-in and cut-out wind speeds), start-up, shutdown, and allow interaction with an operator for the eventuality of an emergency shutdown, performing maintenance tasks, etc;
- Maximize power production according to wind conditions using an optimum power extraction control strategy;
- Optimize economical return by minimizing maintenance interventions, increasing availability and power production, and also by avoiding hazardous operating conditions to protect the system and extend its lifetime.

Protection function (example)	Required performance level (example)
Protection against excessive rotor speed	d
Protection against excessive power production	d
Protection against short circuit	d
Protection against wrong pitch angle	d
Protection against rotor blade exceeding the 90° pitch angle	d
Shut-down in case of excessive shock	d
Protection against excessive cable twisting	d
Shut-down to standstill in case of emergency stop button activation	d
Protection against hazardous effects of faults in the control system	d
Protection against operation at excessive wind speed	d
Shut-down after grid loss	d
Protection against excessive generatur temperature	c
Shut-down at unacceptable brake wear	c
Protection against incorrect wind direction measurements	d
Protection against faults in machinery components (e.g. oil temperatures, oil pressure, vibration from worn machinery components, …); necessity depending on the application	c

GL

Figure 14 - List of protection functions from "Guideline for the Certification of Wind Turbines", Germanischer Lloyd (GL Renewables Certification), *Edition 2010 [www.dnvgl.com]*

Figure 14 presents the list of protection functions for which the control system of a wind turbine should be programmed, according to the certification and technical assurance organisation GL Renewables Certification. Some of the functions worth to mention are to limit excessive rotor speed and excessive power production, protect the system against short circuits, enable emergency shutdown through stop button activation, shutdown in case of grid power failure and shutdown in if a fault is detected on the braking system or other machinery components.

3.2 Control levels

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.

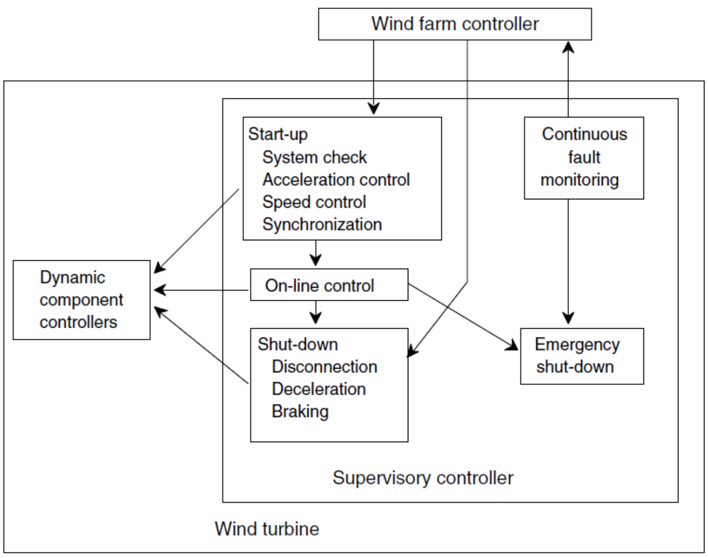

Figure 15 - Control sub-systems (Manwell, 2009)

3.2.1 Wind power system block structure

The block structure that rules wind turbine operation usually starts from a main sequence of states, from which several sub-sequences can be extended. The sequential execution of these blocks is made through status signals that activate different states according to environmental or internal changes. The main states of the wind power system block structure are usually "Off", "Activate", "Ready", "Start-up", "On", "Shutdown" and "Deactivate", that can branched to lower level blocks with specific tasks, such as different start-up sequences according to different conditions (Svensson, 2006).

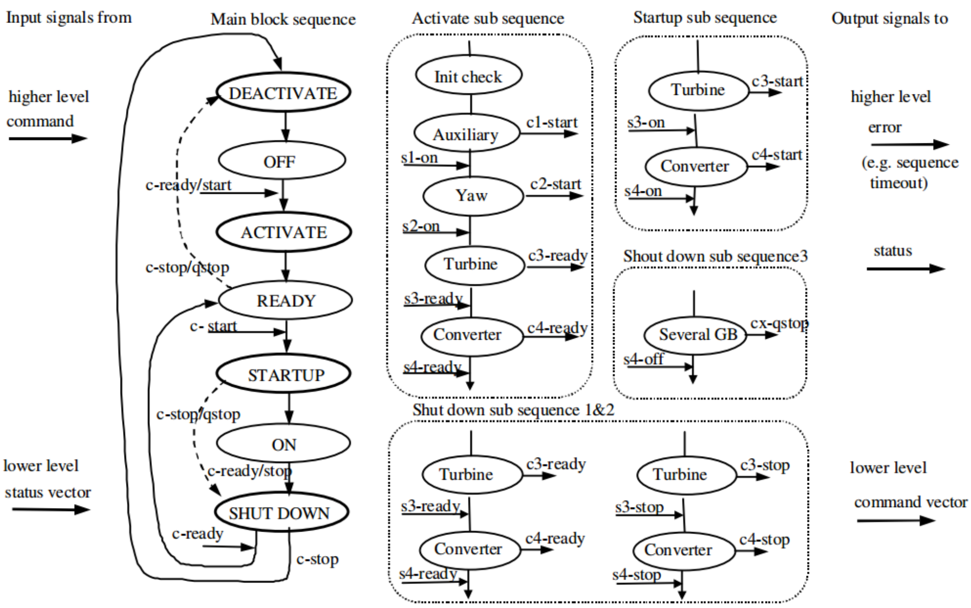

Figure 16 - Wind power system block overview (Svensson, 2006)

Initial internal checks and verifications take place, after which the auxiliary systems of the wind turbine are activated and send ready signals to different components before a start command signal is received or adequate wind conditions occur. After these initialization checks, the wind turbine enters normal operation mode, in "On" state. The system remains in this mode until a command signal instructing otherwise is sent, in case wind conditions become inadequate or if any failure occurs. Then, when the conditions for activating "Shutdown" are fulfilled, several sub-sequences can become active depending on the situation, i.e. if it is a regular shutdown procedure or if it is any type of emergency. After shutdown, the sub-systems of the wind turbine are deactivated and the main sequence is sent to "Off" state (Svensson, 2006).

3.3 Variable speed control

The energy available in the wind varies continually as wind speed changes, which means that the amount of power output that can be extracted from the wind is highly dependent on the accuracy with which the maximum efficiency operating points are tracked by an effective optimum power extraction strategy.

Wind turbines can be designed to work at a fixed or variable rotor speed. A fixed-speed wind turbine operates always at roughly the same angular speed, which is dependent on the gearbox gear ratio, the number of pole pairs of the generator and the grid electrical frequency. Such wind turbine can only operate at maximum C_P for one wind speed, to which corresponds the λ_{opt}. As the wind speed varies from the optimal speed, λ varies along with it and the power coefficient decreases.

Several control strategies are used to vary the rotor speed and optimize or limit power output, depending on whether the turbine is operating above or below rated wind speed. It is relevant to refer some of the most used strategies:

Pitch control: Pitch regulation consists in actively varying the angle between the chord line of the blades and the rotor plane of rotation, i.e. the pitch angle β. This is one of the most used control strategies in industry and enables an accurate control of power output. Below rated power, the operation strategy is to operate in the C_{Pmax} curve and extract maximum power. Whereas for operation above rated wind speeds, the blades can be rotated further into the oncoming wind direction (furl) or away from the wind direction (stall) to change the aerodynamic forces on the blades in order to decrease torque generation and consequently the power output (Manwell, 2009).

Stall control: A stall-regulated variable speed wind turbine has no pitch mechanism. The control is performed by causing the blades to stall above a certain wind speed, reducing power output. The angle of attack between the apparent wind speed (from Blade Element Momentum Theory) and the plane of rotation is dependent on rotor speed. For further reading on BEM theory the reader can refer to (Manwell, 2009).

Power control: Grid connected generators operate over a very small speed range and provide the torque that is required to maintain operation at synchronous speed, so any mechanically imposed torque results in almost instantaneous compensating torque. Alternatively, the generator can be connected to the grid through an electronic power converter that allows the generator torque to be very quickly set to any desired value. The converter determines the frequency, phase and voltage of the current flowing from the generator, thus controlling the generator torque and rotational speed. This is done by supplying the synchronous generator with a magnetization current I_{SG}, setting a reference torque (Manwell, 2009).

3.3.1 Synchronous machines

Synchronous machines are used as generators in large power plants, as well as in wind turbine applications, usually installed in large grid-connected turbines or in conjunction with power electronic converters in variable-speed wind turbines.

The synchronous machine consists of an AC motor with a magnetic field on the rotor that rotates along with it and a stationary armature containing multiple windings. At steady state, the rotation of the shaft is synchronized with the frequency of the supplied current, which can be controlled externally.

It is important to note though, without entering too much in electrical machine theoretical details, that there is a constant angle between the rotor field and the resultant field, known as power angle, which increases with torque. As long as the power angle is positive, the machine behaves as a generator, however if the input torque drops, the power angle may become negative and the machine will act as a motor (Manwell, 2009). Detailed discussion of electrical machine theory is outside the scope of this text, so for a full development on this matter see (A. E. Fitzgerald, 2003).

3.4 Maximum power extraction strategy

This section focuses on the control algorithm implemented for maximum power extraction from the wind.

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.

3.4.1 Maximum Power Point Tracking method

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.

Three of the main control methods used for MPPT are Tip Speed Ratio control (TSR), Power Signal Feedback control (PSF) and Hill-Climb Search (HCS) control also known as Perturbation and Observation control (P&O). A brief overview of each method is provided in the following paragraphs.

The TSR control method consists in regulating the rotational speed of the generator in order to keep the tip-speed ratio λ at the optimum level, by knowing the value of the optimum speed ratio of the turbine λ_{opt}. This method requires knowledge of both the wind speed and turbine speed, in addition to the Cp curve of the wind turbine.

The PSF control method tracks the wind turbine's maximum power curve in order to extract maximum power. The maximum power curve is obtained through simulation or offline experiment of the turbine that is object of study. In this method, the reference power may be generated using the values recorded for maximum power from experimental operation or by calculating the power through the mechanical power equation (equation 2 from section 2.3), with knowledge of the wind speed and rotor speed.

The HCS control 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. Since it does not require prior knowledge of the maximum wind turbine power curve nor of the electrical machine parameters, this method seems to be more advantageous comparing to the previous ones for situations in which there is no reliable information about the wind turbine operation. For a more detailed description about MPPT methods the reader should refer to (Thongam & Ouhrouche, 2011).

3.4.1.1 Hill-Climb Search method(HCS) (review)

The HCS or Perturbation and Observation method consists in applying a perturbation to the turbine shaft speed in small steps and observing the variation in turbine power output that results from that change, hence Perturbation and Observation.

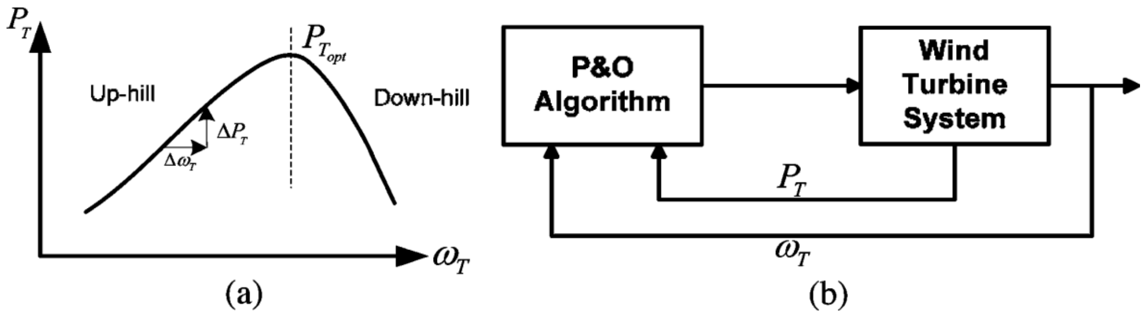

Figure 17 - HCS method. (a) Principle of the HCS method. (b) Control block diagram of the HCS method (Barakati, Kazerani, & Aplevich, 2009)

The HCS method is suitable for wind turbines with small inertia, but not for medium and large-inertia wind turbine systems, since it adds delay to the system by definition. The wind turbine that is object of study in this project is assumed to be a small inertia setup, with its 2 meters rotor diameter and relatively low inertia. For medium and large-inertia wind turbine systems, the turbine rotor has a larger resistance to speed changes which adds a delay in response to wind speed variations and prevents the HCS method from effectively control the wind turbine rotor speed. (Barakati, Kazerani, & Aplevich, 2009).

The idea of this algorithm is to analyse the variation in power output resulting from a rotor speed change and track the location of the optimal operating point. In Figure 17, the power curve can be seen as an up-hill slope ($\Delta P>0$) followed by a down-hill slope ($\Delta P<0$), between which lies the point of maximum power extraction.

Power control is performed by varying the current reference I_{SG} in the synchronous generator through the power converter. The generator side sets a torque reference that directly affects the wind turbine rotor speed.

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 $\Delta P/\Delta\omega$.

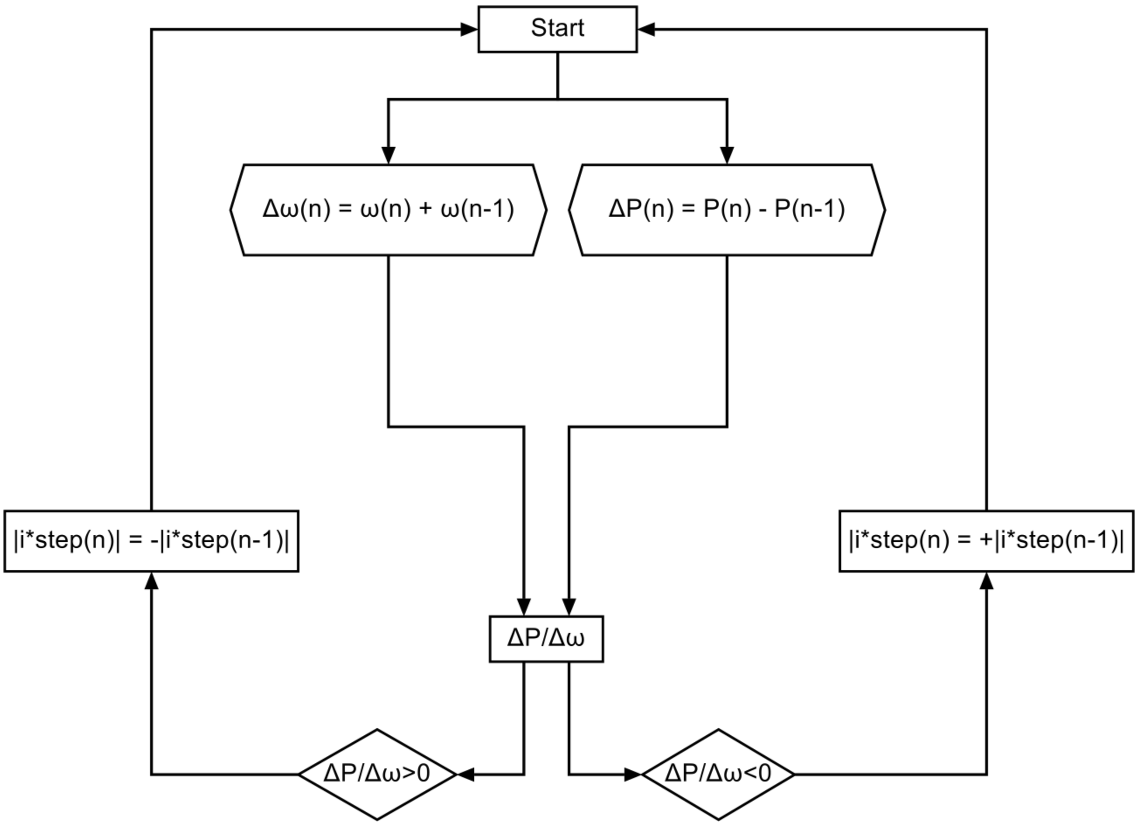

Figure 18 - Flow chart of the HCS control method (ΔP: variation in power; Δω: variation in rotor speed; i^*_{step}: current reference step between iterations)

If ΔP/Δω>0, the operating point is located on the up-hill slope. To move towards the optimal operating point, the rotor speed should be increased (Δω>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 ΔP/Δω<0, the operating point is located on the down-hill slope, so the rotor speed should be reduced (Δω<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 ΔP/Δω<0 or decrementing the shaft speed results in ΔP/Δω>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. The algorithm that rules this control method is briefly summarized as follows:

- Impose small variation in rotor speed, e.g. Δω>0 (Perturbation)

- Verify if the output power is increasing or decreasing (Observation)
    - Power decreasing:
        - Rotor speed was increasing:
            - Reduce rotor speed: Increase the load current I_{SG}
        - Rotor speed was decreasing:
            - Increase rotor speed: Reduce the load current I_{SG}
    - Power increasing:
        - Rotor speed was increasing:
            - Increase rotor speed: Reduce the load current I_{SG}
        - Rotor speed was decreasing:
            - Reduce rotor speed: Increase the load current I_{SG}

4 LTH Wind Power unit

4.1 Intended functions

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. Thus, the modularity of the system is anticipating future expansion of the production site by adding new generation units as illustrated further ahead in Figure 20.

In this project the work is focused on the control of the wind turbine setup, aiming to provide a safe operation control sequence and develop an effective supervisory and monitoring interface. The wind turbine setup is illustrated in Figure 19.

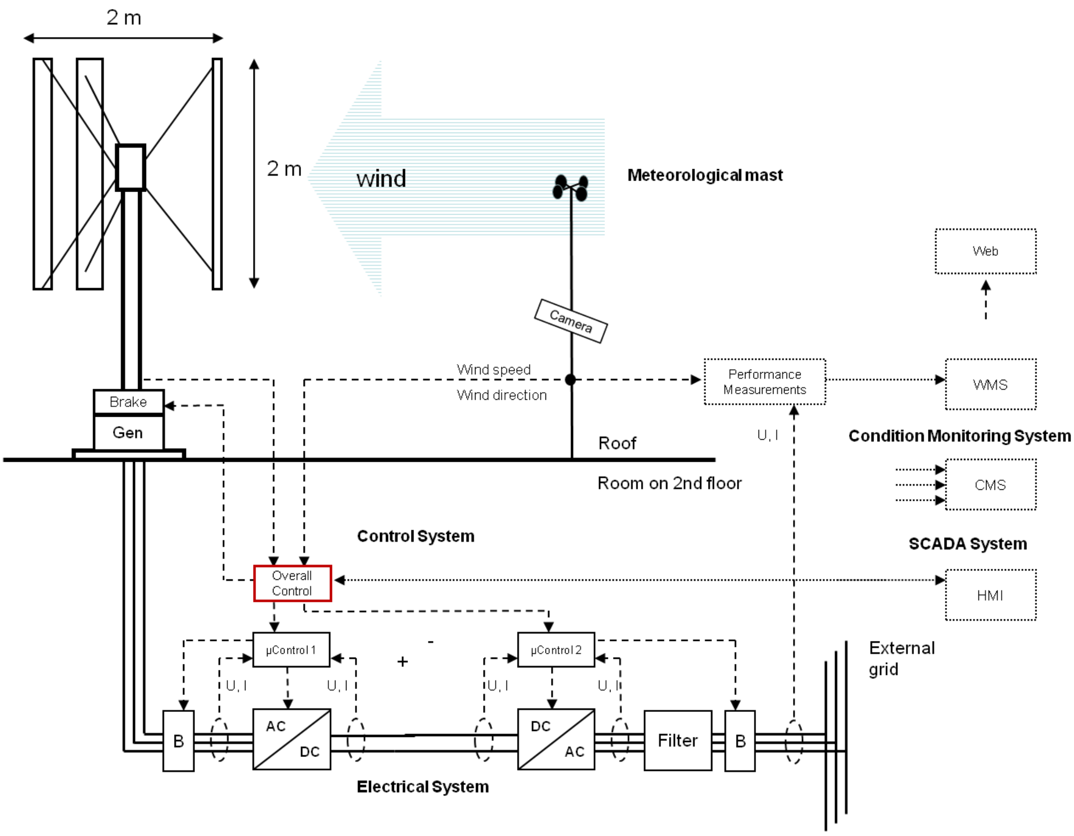

Figure 19 - Wind turbine setup and control structure

It is intended that at the completion date of this project the turbine is operating safely, automatically and in optimal conditions of power generation.

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.

The power production unit installed consists of a vertical axis wind turbine that feeds a permanent magnet synchronous generator, which is connected to the electrical grid through an AC/DC/AC connection with two power converters with rectifier, DC-link and inverter. The following sections provide an overview of the components of the system to present the elements with which the control system will interact.

4.2 Control structure

The control system is distributed in two levels: control of the power converters through two microcontrollers and overall control that performs high level control tasks on the setup. Communication between the two levels provides the main control with information about the power converters and real-time voltage and current measurements or error signals.

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 19).

The overall control is the object of study in this project. The main objective is to develop and implement a solution to perform high level control tasks on the system. The overall control is responsible for managing the internal functions of the system, establish a control sequence to guide the WT through the different states of operation, manage the occurrence of errors and provide an adapted response to different situations. It is designed to be a modular element that does not need to be embedded in the turbine setup to be implemented as a high level power-plant control unit.

The microcontrollers were previously installed and programmed by previous students before this project took place. The microcontrollers are dedicated to the regulation of power generation, by controlling the power converters. This project aims to integrate the microcontrollers in the control system and ensure communication with the overall control unit via predefined signals. Communication is established between the overall control unit and the microcontrollers by signal transmission through the data communication path, containing status information about the converters, voltage, current and generator speed measurements, error signals and high level control orders.

Microcontroller 1 acts on the turbine side converter and microcontroller 2 controls the grid side converter (Figure 19). Microcontroller 1 is responsible for controlling and regulating the power on the generator side according to the mode in which the turbine is operating. The main role of microcontroller 2 is to prepare the grid and the DC side for production by adjusting the voltage level to a preset value of 450V (Petitfils, 2011).

As mentioned before, the layout of the grid connection was projected anticipating a future expansion. Having a microcontroller dedicated to the grid side means that it can regulate the flow coming from several units, such as several wind turbines or photovoltaic arrays, as illustrated in Figure 20. The two power converters are located in two different cabinets in a room below the wind turbine setup, together with its respective microcontroller unit.

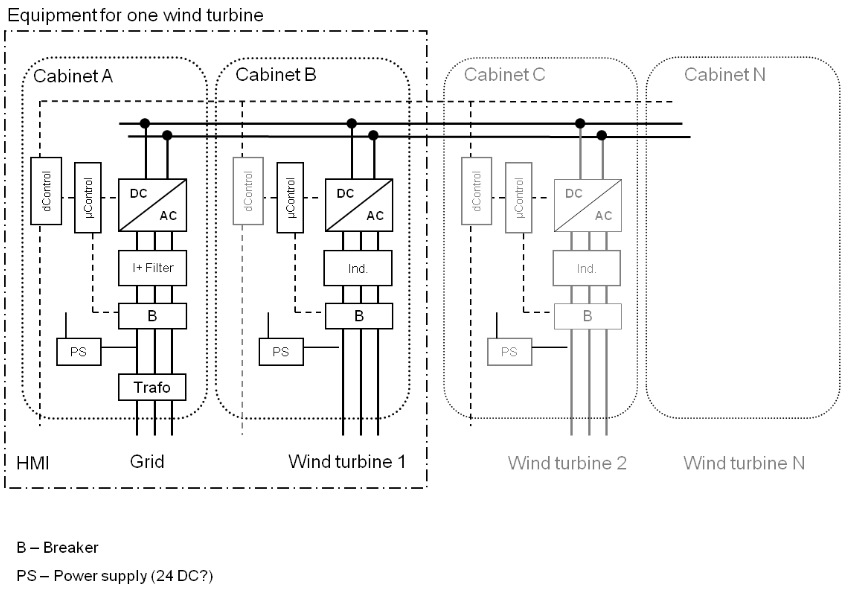

Figure 20 - Modular layout of the cabinets anticipating future expansion of the production site

The two converters are physically separated to ensure a modular layout, and the power is transmitted through a DC line, as it would be in a large-scale setup when the system is eventually extended to an industrial application. Further details about the cabinets are provided in section 4.4.5.

Figure 21 - Cabinets with the power converters and microcontrollers

4.3 Measurements and communication

The monitoring is performed through the implementation of sensors and the creation of safety signals that characterize the system's status of operation and allow the operator to gain knowledge about the atmospheric conditions. In an experimental setup it is useful to collect as much information about the operation as possible, however for commercial applications the sensors and data acquisition systems should be minimized to the strictly necessary.

4.3.1 Wind turbine

The wind turbine rotor speed ω_{WT} is calculated from the electrical generator rotational speed ω_{GEN}. The conversion is made simply by multiplying the measured rotational speed from the PMSG in Hertz by a factor of 3,75, providing the wind turbine rotor speed in RPM. Since no information about the gear ratio is available, this relation was obtained by observation of the revolutions per minute of the rotor while measuring the speed of the generator. It would be useful to implement a tachometer in the wind turbine rotor shaft to add redundancy to the measurement system and possibly calculate the losses in the electrical generator.

Torque T, can be calculated from the power output and the rotational speed ($P=\omega_{GEN}.T$). It would improve the safety of the setup to add a vibration sensor to monitor vibrations in the wind turbine mast, which would eventually make possible to shut down the system if the vibrations become close to levels that might cause structural damage.

4.3.2 Meteorological mast

Knowledge of the atmospheric conditions is a key asset to better understand the operating circumstances of the system. For this purpose there is a meteorological mast installed, with sensors that measure wind speed, wind direction, air temperature and air pressure.

The wind speed is measured by an anemometer and directly connected to the control system, where it is decoded and used in the state sequence. The wind direction is obtained analogously. Pressure and temperature are measured and the signals are connected to the weather station's data logger and can be downloaded via FTP communication with an embedded web-server at a defined rate.

4.3.3 Safety signals

The power electronics control implementation has a set of safety signals that assure that the converters are being regulated properly. These signals are triggered in the eventuality of system failure or component malfunction, informing the system of the fault or enabling an automatic reaction if that is the case. These safety signals alert for:

- Inverter error;
- Low voltage;
- High voltage;
- High current;
- High current (DC link).

The mechanical brake is activated via a logic signal sent by the control system that physically brakes the wind turbine shaft in the eventuality of an emergency shutdown or is applied for safety when the turbine is shut down and motionless.

4.4 Technical specifications

4.4.1 Wind turbine

The wind turbine installed on the roof top of the university is a vertical-axis turbine designed and manufactured by EXAMEC, a Swedish high precision engineering components manufacturer. It has a 2 meter rotor diameter, three 2 meter long blades and no option for pitch control, hence the control of the wind turbine is accomplished with power electronics to adjust the synchronous generator rotation speed. The generator has an expected rated electrical power of 1,8 kW, however the aerodynamic features of the wind turbine rotor and the power curve are not known. A table with the turbine specifications is presented below and the setup is depicted in Figure 22.

Technical Specifications	
Manufacturer/model	EXAMEC / 1,8 kW
Rotor diameter	2 m
Rotor height	2 m
Mast height	6 m
Tower type	Tubular
Rated power	1,8 kW
Rated wind speed	12 m/s (not confirmed)
Rotor speed range	0-240 rpm (not confirmed)
Fixed or variable pitch	No pitch control
Number of blades	3

Table 1- Wind turbine technical specifications

Figure 22 - Wind turbine installation on the rooftop

The setup is located on the rooftop of the southern end of the Mechanical Engineering building in LTH. The siting is not ideal for wind power production, however the main purpose of this wind turbine is to perform experimental tests rather than power generation for consumption. As represented in Figure 23, there are other buildings in the surroundings likely to create turbulent vortexes or even behave as obstacles to the air flow, which results in a decreased wind yield and therefore reduced performance.

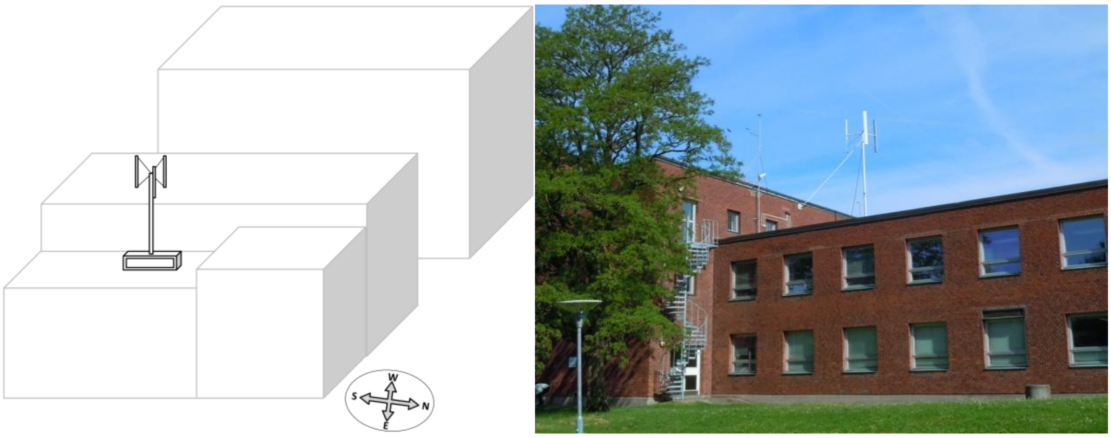

Figure 23 - Schematic and picture of the siting of the wind turbine

4.4.2 Transmission

The wind turbine shaft is followed by a conveyor belt that steps up the shaft speed with a gear ratio of 1/2, i.e. the generator shaft rotates at twice the speed of the rotor shaft, to prevent the generator from operating with low efficiency at low speeds.

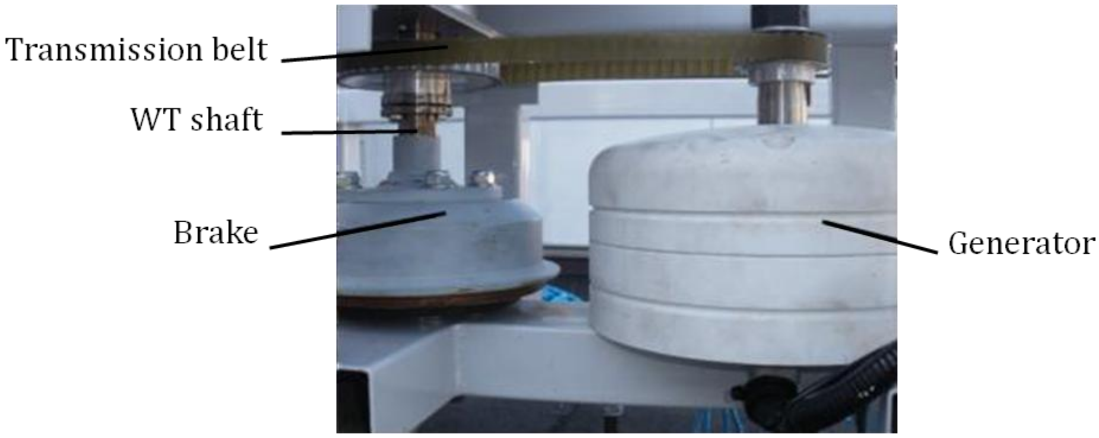

Figure 24 - Transmission belt, WT shaft, drum brake and PMSG

4.4.3 Mechanical brake

The turbine shaft is equipped with a drum brake as illustrated in Figure 24. Prior to this project the turbine brake had to be unlocked manually with a lever. One of the tasks was to install an automatic mechanical system in order to be able to brake the turbine by sending an electronic command signal from the control system.

The solution installed to achieve this consists of a pneumatic system which activates a piston that acts on the lever and brakes the turbine. This braking system was designed with safety as a first priority. The piston is activated by the compressed air tubing installed in the building, commanded by an electric signal to a relay sent by the control system. The piston is extended from its rest position to release the brake and allow the turbine shaft to spin. In case of a power outage the cylinder simply looses the electrical signal that keeps it extended and the piston returns to the braking position naturally. This design brakes the turbine automatically in case of a power failure, ensuring the safety of the installation and the surroundings by preventing the turbine from starting freewheeling and achieving hazardous rotational speeds.

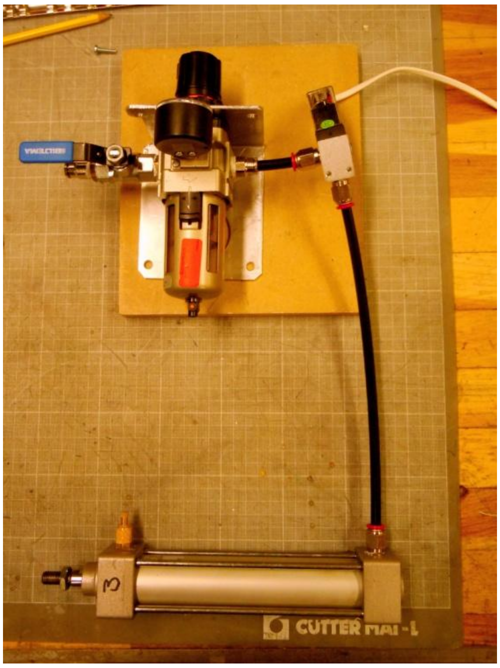

Figure 25 - Mechanical brake components

4.4.4 Meteorological mast

The meteorological mast carrying the sensors is located southwest from the turbine setup, as this was found to be the predominant wind direction and thus the air flow is more likely to be unperturbed by the turbulence generated by the WT rotor. The measurement equipment in the meteorological mast gathers information about wind speed, wind direction, air temperature and pressure (Figure 26). An IP webcam is installed on the mast that provides a real time image of the wind turbine, connected to the control system by an Ethernet connection to the network (http:// http://130.235.82.99/), making it easy to monitor its operation for testing (Figure 27).

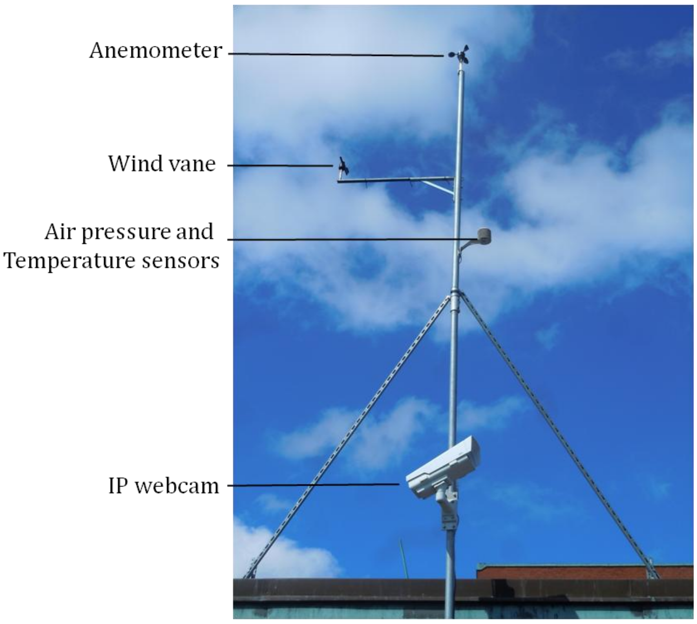

Figure 26 - Meteorological mast

Wind speed is measured by a MAX40 anemometer with a 0,1 m/s accuracy, and wind direction is assessed by a DIR21 wind vane. Both sensors are positioned five meters away from the centre of the wind turbine at the same height, according to the recommendation from International Electrotechnical Commission (IEC) spacing of two and a half times the diameter size. The atmospheric pressure and temperature are important to have a correct and real time value of the air density, which along with wind speed and rotor diameter can be used to calculate the power available in the wind for experimental purposes as detailed in section 2.3. Table 2 presents a summary of the measurement equipment models and component providers.

Measurement equipment		
Component	**Model**	**Provider**
Generator	1,8 kW	EXAMEC
Transformers	-	EXAMEC
Anemometer	MAX40	EKOPOWER
Wind vane	DIR21	EKOPOWER
Pressure sensor	APS21	EKOPOWER
Temperature sensor	TS21	EKOPOWER
Data logger	iBOX 16Hz	EKOPOWER
Microcontroller 1	cRIO 9024	National Instruments
Microcontroller 2	cRIO 9024	National Instruments
Camera	P1346	AXIS

Table 2 - Measurement Equipment

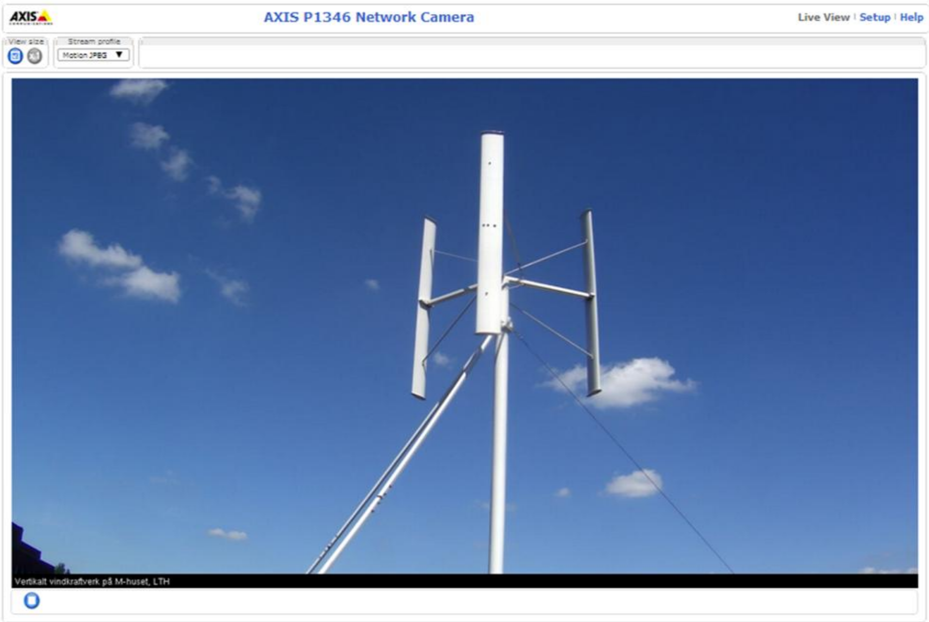

Figure 27 - Live webcam streaming of the wind turbine rotor

4.4.5 Power converters

The two cabinets shown in section 4.2 contain the electrical equipment in charge of the power conversion from AC/DC and DC/AC. One of the cabinets is responsible for regulating the grid side and the other for the wind turbine generator side. The only major difference between the two is that the grid side cabinet contains a LCL filter in order to eliminate unwished harmonics present in the electrical signal. A schematic with all the cabinet's components is presented in Figure 29. The cabinets also contain the voltage measurement equipment, as illustrated in Figure 28. Designed for a power higher than 1,8 kW, the system is once more anticipating the expansion to include additional power sources.

The DC link connects the two cabinets, modelling what would be used for power transmission in a full scale production site. High voltage DC (HVDC) transmission is suitable for long-distance transmission and entails lower electrical losses if compared to an AC system (Arrillaga, 1998). HVDC also allows transfer of power between grid systems operating at distinct frequencies and improves the stability and economy of each grid by allowing exchange of power between incompatible networks, for example for future applications in large-scale offshore multi-terminal HVDC grids.

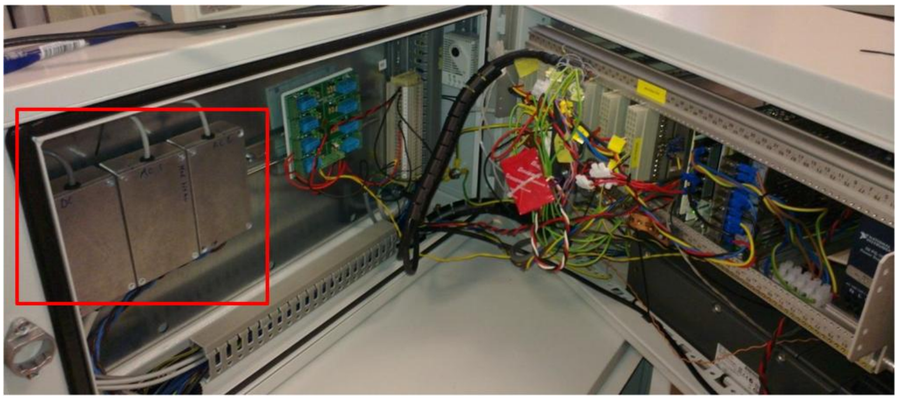

Figure 28 - Voltage measurement equipment

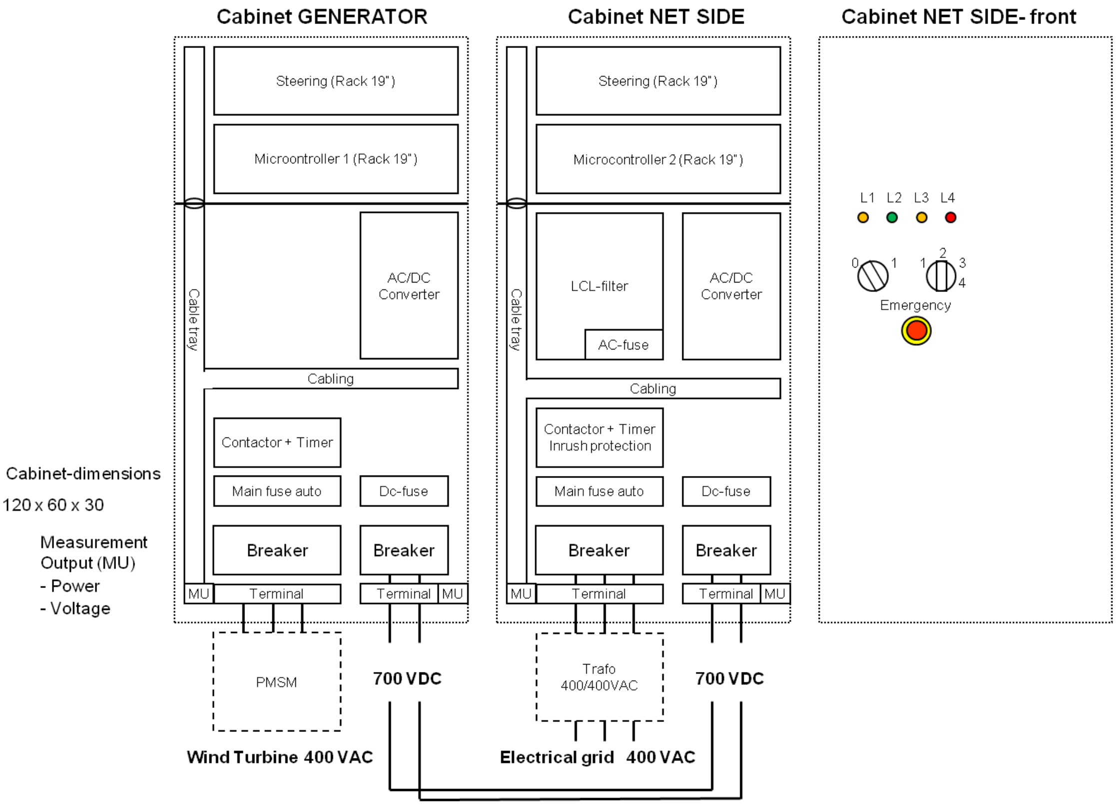

Figure 29 - Cabinets with the electrical converters

The front side of the grid side cabinet has a set of buttons and LED lights that can be attributed to the different control modes of the system and act as an alternative control interface to the HMI in a computer. The LED lights are programmed to indicate the status of the DC link and generator and to signal the occurrence of errors, as detailed in chapter 5.

4.5 Automation equipment and engineering tools

The characteristics of the control system that this project aimed to develop require data acquisition and manipulation from the measurement systems (both meteorological and electrical), signal communication with reliability and at high speeds to ensure performance and flexibility of programming since this is an experimental setup suitable to be upgraded and changed.

LabVIEW is a widely spread engineering tool throughout the industry and it is an adequate solution for the implementation. The following section explains its relevance in the project and provides the reader with an overview of its capabilities as well as the hardware where it is implemented. This overview was thought to be of importance in order to understand the implementation described in chapter 5.5.

4.5.1 Programming in LabVIEW

NI LabVIEW is a graphical programming environment and system design platform from National Instruments. It is widely used throughout the industry as an engineering tool for the development of sophisticated control systems implemented in a wide variety of applications. It is a high-level programming language, adequate for applications that require real-world data acquisition and manipulation, file input/output (I/O) and industrial automation, among many other uses, without the need of dealing with the smaller programming details of lower-level languages.

It enables engineers to develop effective solutions without the necessity of profound low-level programming skills, by dragging and dropping the desired virtual representations of laboratory equipment on the LabVIEW environment. However, it is compatible with C++ and other languages, making it flexible to satisfy the user's needs according to its programming skills. It consists of a dataflow programming platform, resembling a flowchart composed of icons and wires, which execution sequence is determined by the structure of the block diagram, with inherent capacity for multi-processing and multi-threading. Since it allows parallel execution, LabVIEW is adequate to program using parallel events and thus make the code easier to read and display, comparing to traditional sequential textual programming languages.

LabVIEW is extensively equipped with libraries for data acquisition, signal generation, signal conditioning, advanced control and data visualization that are suitable to interact with a wide range of hardware developed by NI (NI, Developer's Guide, 2013).

LabVIEW's programs or subroutines are called Virtual Instruments (VI), in which the functions, structures, controls and indicators are created and displayed.

Each VI is constituted by a block diagram, a front panel and a connector panel. The source code is implemented in the form of a block diagram, where indicators and controls are presented in a customizable front panel, while the connector panel is used to represent the connections and interactions between different VI's.

The use of LabVIEW together with a reconfigurable embedded system such as the NI CompactRIO was thought to be the most adequate solution for the design of the control system of the VAWT. The control sequence to perform high level control of the wind turbine setup is implemented in the hardware, which uses the reconfigurable I/O architecture to acquire and analyze the weather input data and power electronics status, as well as the commands and instructions given by the user through the Human Machine Interface (HMI), providing a quick and intelligent response to the system.

4.5.2 NI CompactRIO

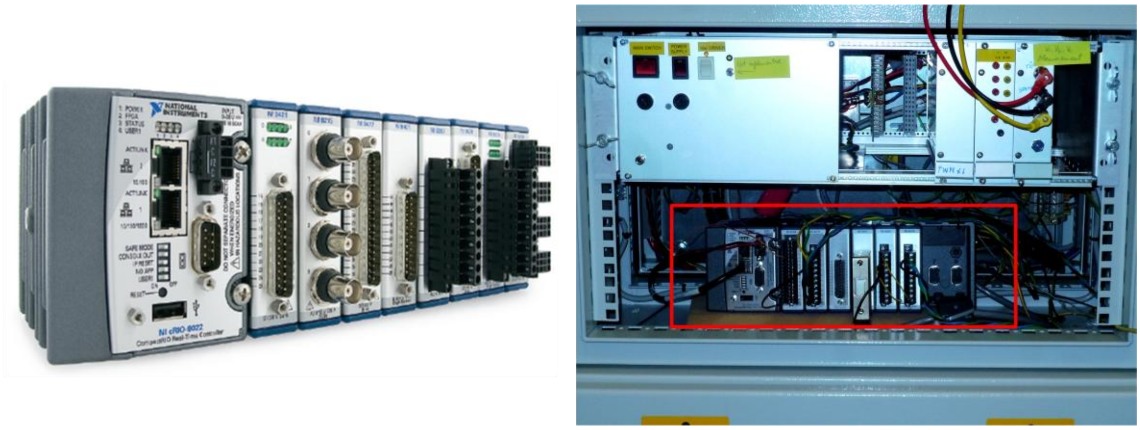

Figure 30 - NI Compact RIO 9022 [www.ni.com/compactrio]

The NI CompactRIO is a real-time reconfigurable embedded system produced by National Instruments. The equipment comprises a processor running a Real Time operating system (RTOS) and a reconfigurable I/O Field Programmable Gate Array (FPGA).

The Real Time (RT) controller is a powerful processor with a wide range of clock frequencies and the capacity to execute processes with an extremely accurate and controllable timing, for implementing the control algorithm with a reliable and predictable behaviour, as is required for many science and engineering projects. Running a measurement and control program that needs a precise and reliable execution is not acceptable with general purpose operating systems (such as Windows) since the background tasks of the OS might delay the processes and therefore not meet the timing requirements for tasks that need to run at certain rates without interruptions. The RT system is designed to be rugged and to resist harsh operating conditions for long periods, commonly used in headless operation

- without monitoring or interaction with the user - and can be set up to run for years without stopping, as it is often desirable for industrial large-scale applications in which maintenance is expensive or inaccessible, e.g. mining, defence, offshore wind power plants. (NI, NI Compact RIO Specifications, 2014)

The FPGA module is an array of silicon chips with unconnected logic gates. By configuring the FPGA gates in the hardware itself, its computing power is high and it is able to perform multiple processes simultaneously keeping deterministic execution and excel at tasks that require high-speed logic operations. It is directly connected to the I/O modules, from which data is acquired into the I/O circuitry almost without control latency or jitter and with high performance. Because the FPGA runs all code in hardware, it provides high reliability and determinism, with custom timing and high-speed acquisition. The I/O modules are chosen to suit the user's needs from a wide range of models and wiring options to connect sensors, actuators, accelerometers, signal processors, power measurement equipment and all kinds of analogical and digital input/output. The signals are then processed using LabVIEW. (NI, NI Compact RIO Specifications, 2014)

4.5.3 NI Compact RIOs in the control system:

Two Compact RIOs are connected to the sensors used in the measurement process and convert the sensor signals to digital data to be monitored, analyzed and recorded. They have communication capabilities to report the status of the system to the human interface that works as a supervisory system, and also to receive commands from the user to be applied in the system in real time. Further explanations on the system architecture are provided in section 5.2.

The Compact RIOs used for the implementation of the control system grant great flexibility to the experimental setup. As this VAWT system is installed for experimental purposes, it is intended to have extensive data acquisition and monitoring. However, once the algorithm is implemented and fully operational, the control system could be simplified and approximated to a commercial installation by reducing the amount of measurements to the strictly necessary for regular operation monitoring. In this case, it would be adequate to transfer the control program to e.g. an embedded system like a single board RIO in order to install it as a standard unit, cheaper and tailored to the needs of the algorithm and code.

The modules installed in the Compact RIOs on the laboratorial setup are:

- NI 9205 (32 terminal Analog Input)
- NI 9215 (+/- Input Analog terminals)
- NI 9263 (4-Channel, +-10V, 16 Bit Analog Output)
- NI 9474 (8-Channel Digital Output)
- NI 9401 (8-Channel, TTL Digital Input/Output).

4.5.4 CompactRIO VS myRIO

The NI myRIO was considered as an option for the implementation of the overall control code, although it has been decided for the Compact RIO instead, due to its characteristics that suit the project better. The myRIO is an academic learning module, an affordable tool intended to be used by engineering students for small projects and simple applications, and was thought perhaps not to have enough memory for the operations that will be performed. However, this is an option to consider in further works in order to have the overall control program in a separate device rather than embedded in one of the two microcontrollers as it is now. For further details on the system architecture refer to chapter 5.

5 Control implementation

5.1 Control requirements

The aim of the work is to ensure the safety of the installation and allow the system to operate automatically for an extended period of time, fulfilling the control requirements detailed in section 4.1.

The overall control system of the installation is responsible for:

- Monitoring the internal operating conditions;
- Operating the wind turbine on an automatic and sequential way;
- Navigating through the state sequence that composes the wind power system block structure;
- Acquiring signals from the wind conditions measurements and analysing the data;
- Allowing the operator to interact with the system to start and stop the generation unit;
- Allowing the operator to elect the control mode the turbine will be operating on;
- Allowing different modes for start-up and shutdown;
- Establishing a remote panel interface to allow communication with Vattenhallen for demonstration purposes.

This chapter describes the architecture of the system and the way how the different components interact, presents the control sequence designed for the wind turbine system and its operation modes of production, and finally an explanation of the programming in LabVIEW is provided.

5.2 System architecture

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 31.

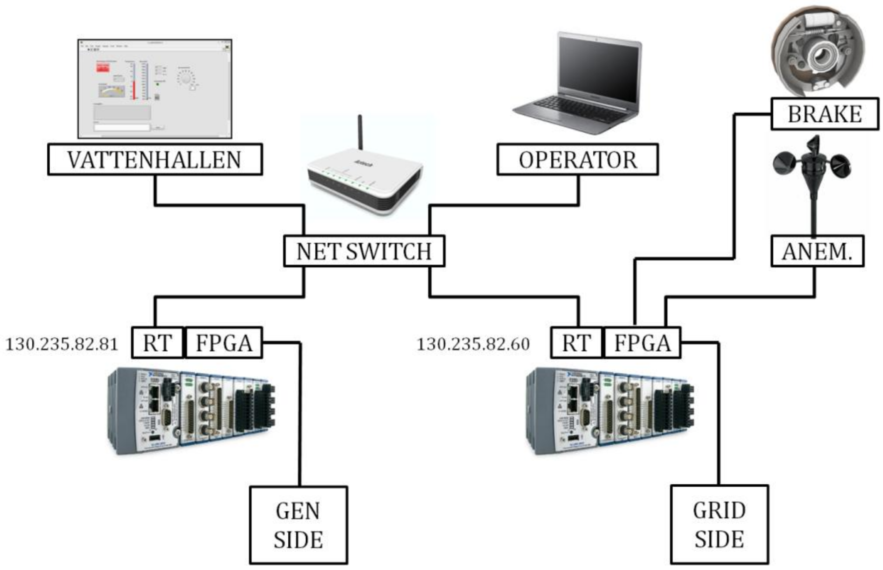

Figure 31 - Wind turbine setup and control scheme

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. The web-based remote interface is accessible by browsing the grid side cRIO's IP address on the web browser from any PC connected to the network. Further details about the actual implementation are provided in chapter 5.5.

The overall control application is installed in the real time controller of the grid side Compact RIO, while the power converter regulation applications and sensor decoding are installed in the FPGA modules of both sides.

5.3 Modes of operation

The system is programmed to operate under three different control modes, suitable to be selected by the operator. The control is performed by providing a speed or current reference to a PI controller, as will be further explained in section 5.5. This reference defines if the rotor should accelerate, decelerate or keep constant speed in accordance with the operating conditions.

5.3.1 Constant rotor speed

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.

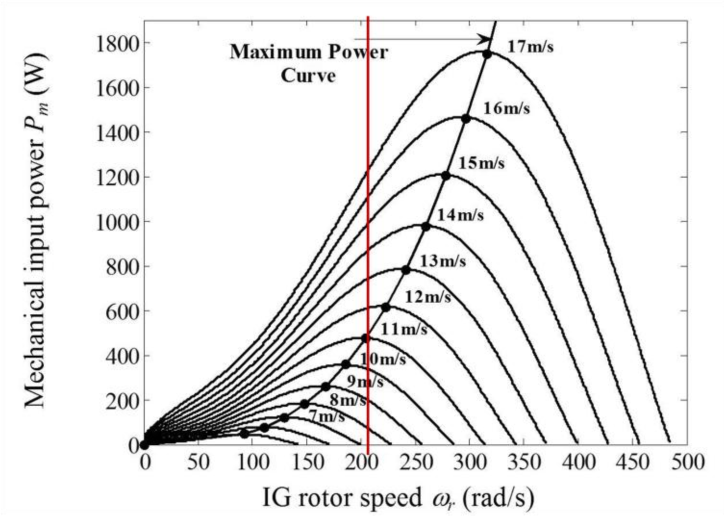

Figure 32 - Power output as a function of wind speed for a constant rotor speed [www.intechopen.com]

This can be visualized by drawing a straight line over a determined rotor speed and observing that the optimal operation point occurs for a single value of wind speed, as illustrated in Figure 32, 10 m/s in this case. A solution for this problem is to allow the PMSG to vary its speed according to wind conditions adapting to the peak of the power curve, thus achieving maximum efficiency operating states.

Notice how, for a wind turbine producing up to 1,8 kW as in Figure 32, the rotor speed range is expected to be roughly between 150 and 350 rpm for operation at maximum efficiency with winds between 7 and 17 m/s.

The default cut-in wind speed defined for this production mode in the control system was set to 5 m/s, although the control interface is programmed in such a way that the relevant parameters can easily be adjusted in further studies.

5.3.2 Maximum power point tracking with induced start-up

The method used for tracking the optimal operating point is illustrated in Figure 33. 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.

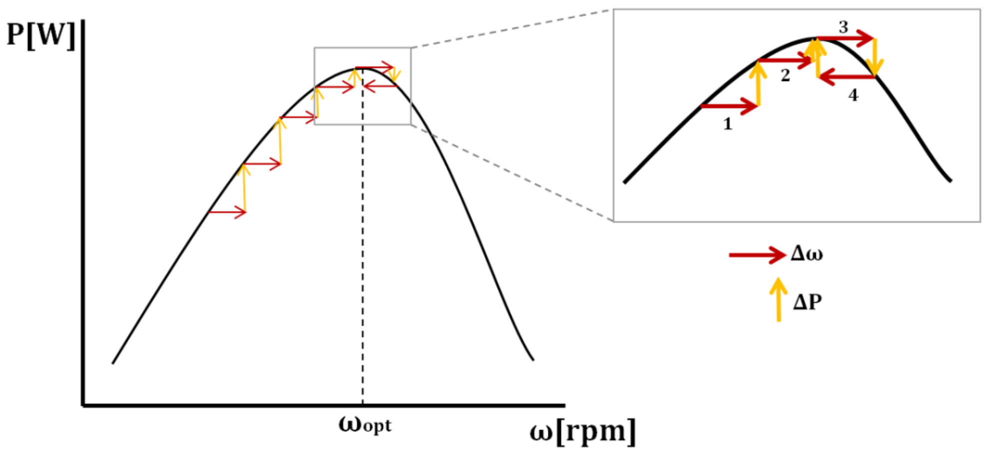

Figure 33 - Optimum Power Production mode

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.

For ease of understanding, the algorithm that rules this control method is once again provided below:

- Impose small variation in rotor speed, e.g. Δω>0 (Perturbation)
- Verify if the output power is increasing or decreasing (Observation)

- Power decreasing:
  - Rotor speed was increasing:
    - Reduce rotor speed: Increase the load current I_{SG}
  - Rotor speed was decreasing:
    - Increase rotor speed: Reduce the load current I_{SG}
- Power increasing:
  - Rotor speed was increasing:
    - Increase rotor speed: Reduce the load current I_{SG}
  - Rotor speed was decreasing:

Reduce rotor speed: Increase the load current I_{SG}

5.3.3 Maximum power point tracking with freewheeling start-up

The implementation of this method is exactly the same as the one described previously, with the difference that the initial rotation is created by the wind speed itself rather than by the motor. This mode is expected to be viable only for high wind speeds, since in previous observations the rotor barely seems to start freewheeling for wind speeds up to 7 m/s, moreover it needs to accelerate to a high enough rotational speed to start production, as explained in the previous section. Therefore, the default cut-in wind speed for this mode was set at 8 m/s.

5.4 Plant system block structure

The control sequence of the wind turbine system is designed as a state machine diagram, consisting of a sequence of states in which actions are applied to the system, separated by predetermined transition conditions. The transitions between states are triggered by command signals or specifically defined operating conditions as shown in Figure 34.

The main sequence is presented on the left side of Figure 34, where the main states are set, according to the theory in the sources referred in chapter 3. 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).

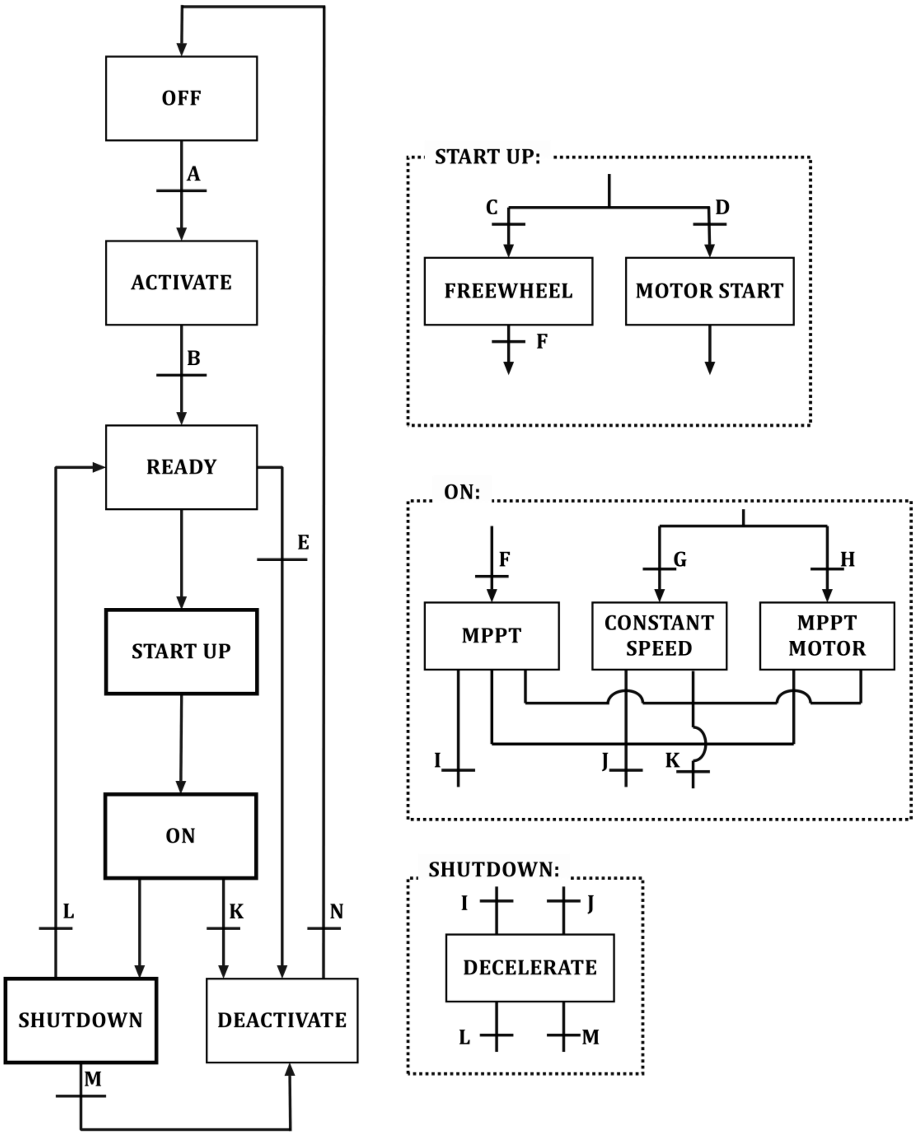

Figure 34 - Wind Turbine control sequence

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, only to be used in an extreme situation. 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, as described in section 5.5.1.

Table 3 presents the transition conditions used for the control sequence, and a detailed explanation of the tasks performed in each state follows.

A	"START" OR "Vattenhallen" button pressed
B	Regulating GRID SIDE converter
C	Mode 1 AND 8 > $\bar{U}$ ≥ 15 m/s
D	((Mode 2 OR Mode 3) AND 5 >$\bar{U}$ ≥ 15 m/s) OR "Start as motor" button
E	"STOP" OR "EMERGENCY" button pressed
F	ω_{GEN} ≥ 10 Hz AND Regulating GEN SIDE converter
G	Mode 2 AND t >10 seg AND Regulating GEN SIDE converter
H	Mode 3 AND t >10 seg AND Regulating GEN SIDE converter
I	$\bar{U}$ < 6 m/s
J	"STOP" button pressed OR $\bar{U}$ < 4 m/s OR ω_{GEN} ≥ 1 Hz OR ω_{WT} > 300 rpm
K	"EMERGENCY" button pressed
L	ω_{GEN} < 0,2 Hz AND "STOP" button not pressed
M	(ω_{GEN} < 0,2 Hz AND "STOP" button pressed) OR "EMERGENCY" button
N	Not regulating GEN SIDE converter AND Not regulating GRID SIDE converter

Table 3 - State sequence transition conditions

OFF

The OFF state is the situation in which the wind turbine system is completely inactive, with no electrical connection to the grid and immobilized by the mechanical brake. In order to initiate operation, the main sequence is activated by pressing the main *Start* button or the *Vattenhallen Start* button which gives the order for an initialisation check to take place.

ACTIVATE

Internal checks and verifications of the control system are started initially. In the ACTIVATE state, the status of the power converter on the GRID SIDE is verified and the voltage in the power lines is checked. If the converter responds with a fully working status defined by a logical variable, the system proceeds to the next state, otherwise the correspondent safety indicator is tripped and the system does not start.

READY

If not active already, the wind turbine rotor brake is activated, in case it is coming from SHUTDOWN state. The system waits for adequate wind conditions to start production and checks for the control mode that is selected, since the different control modes have different starting conditions. As mentioned in section 5.3, MPPT mode requires an average wind speed of 8 m/s, while the Constant Speed and MPPT Motor mode can start at 5 m/s.

The sequence is set to proceed if the average wind speed $\overline{U}$ is between 5 and 15 m/s. Below this cut-in wind speed the wind turbine has no capacity to produce power, and for safety reasons the production is interrupted in case the wind exceeds the cut-out threshold. For experimental purposes, this wind speed limitation can be overruled by pressing the *Start as motor* button, which will initiate the PMSG as a motor regardless of the wind speed. If at any time the STOP or EMERGENCY buttons are pressed, the system proceeds to DEACTIVATE state.

Before initiating power production, the turbine must be rotating at a minimum speed to overcome the electromagnetic torque imposed by the synchronous generator.

START-UP

To achieve this, the turbine is either accelerated using the PMSG as a motor (MOTOR START) or, if the wind is blowing at a sufficiently high speed, by releasing the brake and letting the rotor start spinning in FREEWHEEL until a threshold rotational speed is reached.

Constant Speed and MPPT Motor modes require to be started as a motor. The MOTOR START block verifies that the generator side converter is activated and working properly and then it will accelerate the rotor for 10 seconds to gain speed. MPPT mode will pick up speed from the wind until a generator speed ω_{GEN} of 10 Hz is reached.

ON

The wind turbine is in normal operation mode when reaching the ON state. This implies that the system is prepared to run in one of the three different control modes:

- MPPT: if the average wind speed drops below 6 m/s, the system proceeds to READY;
- Constant Speed: if the average wind speed drops below 4 m/s, the system proceeds to READY;

- MPPT Motor: if the average wind speed drops below 4 m/s, the system proceeds to READY;

In all three modes production can be intentionally interrupted by pressing the *Stop* button which leads to a gradual deceleration of the rotor in the SHUTDOWN state, or immediately stopped by pressing the *Emergency* button that sends the system into DEACTIVATE state. If for any other reason the rotor speed falls below a threshold level of 1 Hz, the system goes back to READY state. If the rotor speed accelerates up to a threshold limit defined by default at 300 rpm, which might mean that the system went out of control, the state sequence proceeds to SHUTDOWN.

SHUTDOWN

If the system is intended to be stopped in normal conditions, the generator rotor is gradually decelerated through power electronics to a full stop, and then proceeds to be deactivated. This block verifies whether the *Stop* button has been pressed or not and proceeds to READY or DEACTIVATE state accordingly. When the generator speed drops below 0,2 Hz, it is safe to apply the mechanical brake and fully immobilize the shaft.

DEACTIVATE

This state is reached either after a gradual shutdown or an emergency situation where the system needs to be stopped immediately by pressing the *Emergency* button. This stop mode is not advisable to be used unless in extreme situations, since an abrupt stop of the spinning rotor shaft using the mechanical brake can cause damage both to the mechanical and electrical system, especially if the turbine is rotating at high speeds.

The mechanical brake is locked in, and the power converters stop being regulated sequentially - first the generator side converter, and after confirmation of its deactivation without errors, the grid side converter is safely disconnected and the system is turned OFF.

After describing the control sequence in respect to which the system operates, it is pertinent to present the programming features and strategies that were implemented in order to bring this to reality in the wind turbine setup.

5.5 LabVIEW implementation

The focus of this project was to implement the high-level control that supervises and manages all the variables and inputs to monitor the system operation and provide an adequate response to dynamic variations. This section describes and explains the LabVIEW code developed to achieve this. The overall control application is installed on the real time controller, while the power converters regulation and the wind measurements are performed in the FPGA module.

Prior to this project, the two microcontrollers that regulate the power converters had been previously programmed to measure and regulate the grid side and generator side voltage and current with a phase locked loop (PLL) to calculate the frequency and pulse width modulation (PWM).

Two controllers to regulate the generator speed are implemented in the FPGA of the generator side microcontroller: a current PI controller and a speed P controller. The current control is performed by providing the current set-point to the PID block in LabVIEW in both the *x* and *y* coordinates in the rotor frame reference (*ix** and *iy**). The current reference can be set manually or calculated in the speed PID block, depending on the regulating mode (Figure 35). The speed PID basically creates a current reference based on the generator speed set-point (*speed*[Hz]*) and feeds it to the current controller, as Figure 36 shows.

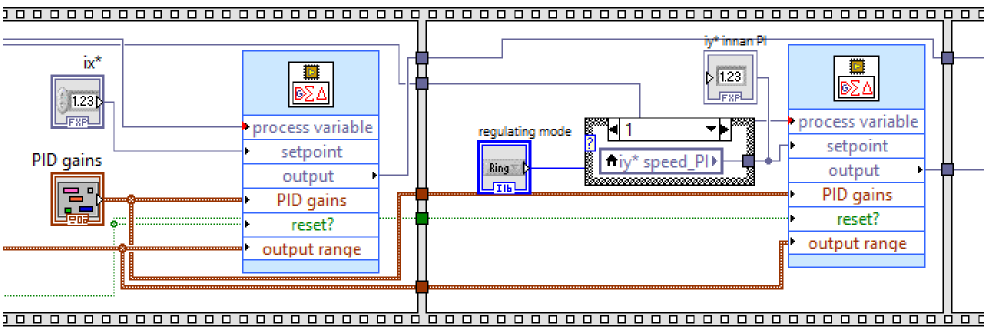

Figure 35- Current PID controllers

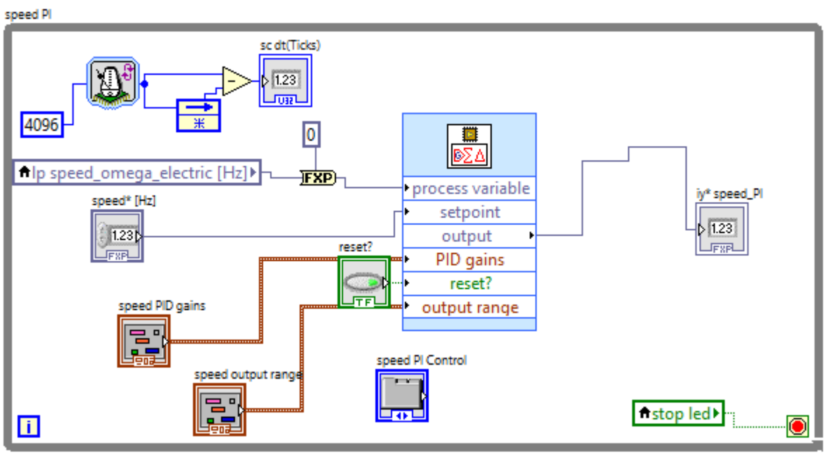

Figure 36 - Generator speed PI controller

The phase locked loop (PLL) is used to keep track of the voltage phase and calculate the generator speed (*lp speed_omega_electric [Hz]*) by measuring the frequency of the output voltage (*theta*). In the implementation, an auxiliary value of *theta* is created in order to start the speed reference, since in the first moments there is no output voltage to calculate *theta*. This has the drawback of not allowing measuring the rotor speed while using the *fake theta* when starting up the generator.

For further details regarding the electrical control and power converters programming refer to (Måns Andersson, 2013).

5.5.1 Human Machine Interface

The operator has access to the commands of the system via the Human Machine Interface, illustrated in Figure 37. 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.

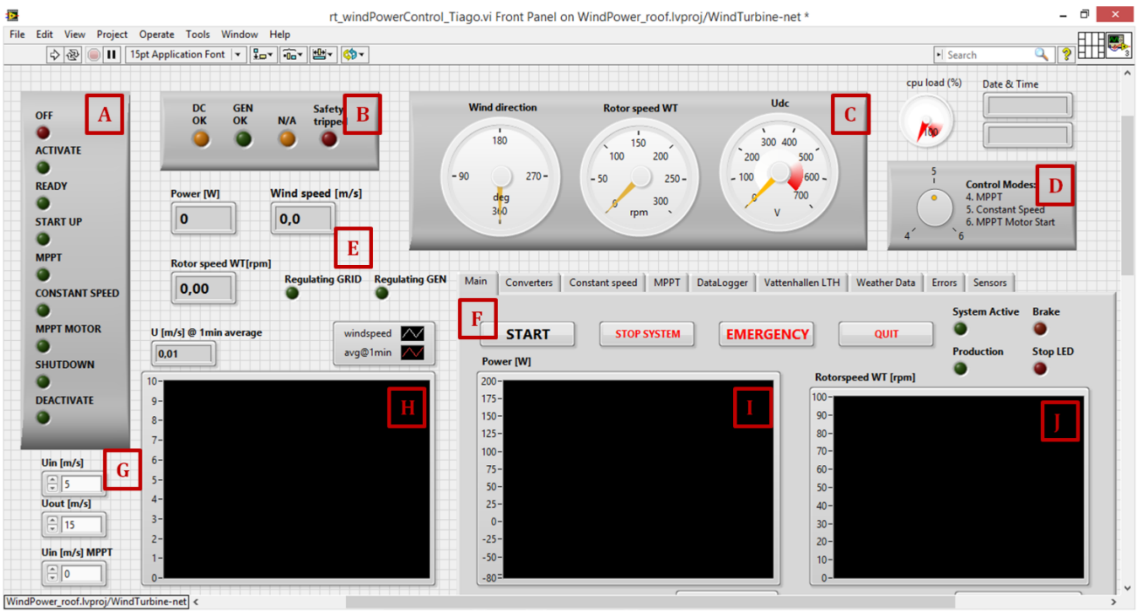

Figure 37- Human Machine Interface with Main tab

On the left hand side of the HMI there is a panel that shows all the possible states of the state sequence (A), to clearly visualize the progress of the operation and easily check in which state the system is currently working, by lighting up a LED indicator on each side.

The LED panel (B) reproduces the physical lights installed in the GRID side cabinet; the left yellow light indicates that the grid side converter is being regulated and that the DC link voltage is adequate, the green light indicates that the generator converter and the grid side converter are both being regulated, the second yellow light has no signal attributed for now and the red light to the right indicates that one of the safety checks has been tripped.

The gauges (C) indicate, from left to right, the wind direction, the rotor speed in rotations per minute and the voltage measurement in the DC link in Volt. The control mode selector (D) allows the operator to choose the desired control mode for production: MPPT, Constant speed or MPPT Motor. The mode should be selected before pressing the Start button. Just above the mode selector, a gauge displays the CPU usage and the current date and time information.

The power, wind speed and rotor speed values can be read in the indicators in (E), as well as the LED lights to indicate when the generator and grid side power converters have started regulation individually.

The tab selector (F) allows the user to better adapt the information that is relevant to display for the experiment in progress. In the main tab, there are the *Start* button to initiate operation, the *Stop system* button to stop the process in regular conditions sending the system to a gradual shutdown and deactivation, and the *Emergency* button, which should only be pressed in case of the occurrence of an extreme situation or to avoid an accident, since it brakes the turbine immediately locking the mechanical brake regardless of at what speed it may be turning, which can result in damage to the structure or the surroundings. The *Quit* button is to be used when the system is OFF to exit the VI safely, closing any open processes and resetting the variables of the system. The lights indicate when the system is active, when power is being produced, when the mechanical brake is applied and when there is a command to stop the system by the operator.

The cut-in and cut-out wind speeds can be modified by the operator using the numeric controls in (G). The charts marked with H, I and J display the instantaneous variation of wind speed (including a 1 minute average plot), power (consumption is positive and production is negative) and wind turbine rotor speed, respectively.

The remaining tabs display auxiliary variables and controls to manipulate some of the system's processes, more specifically for the MPPT mode and constant mode.

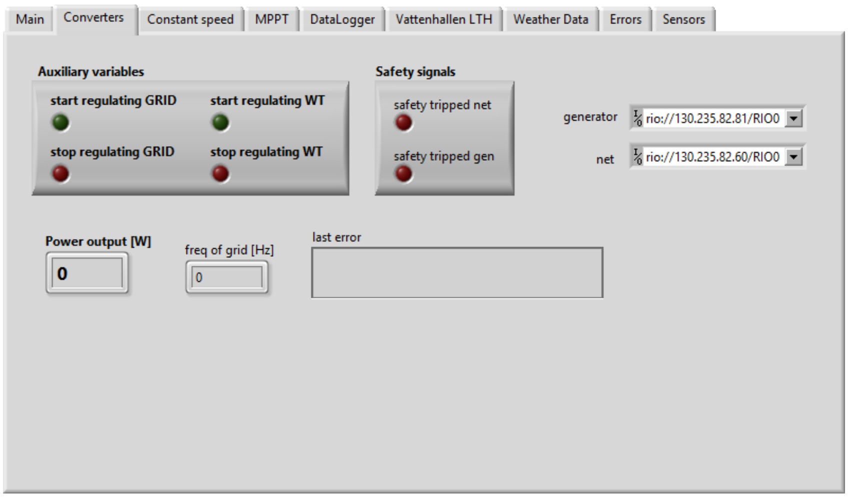

Figure 38 - HMI Converters tab

In the *Converters* tab (Figure 38) the auxiliary variables that send the command signals to the FPGA to start and stop regulating the power converters are displayed. The safety lights indicate the occurrence of inadequate conditions of operation either on the grid side or generator side converters, which are specified on the text box below explaining in what component the error was originated. In the right hand side, a controller for selecting the source of the FPGA Read/Write blocks is displayed. The instantaneous power [W] and the frequency of the grid [Hz] are displayed in numeric indicators. The *last error* box displays the origin of the last error that occurred, to complement the error alert given by the red LED.

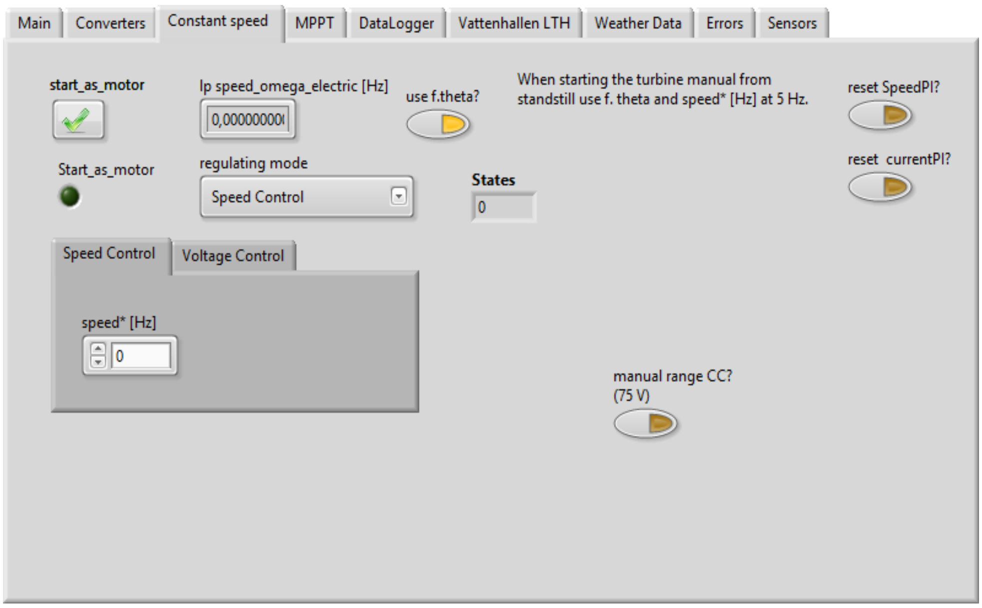

Figure 39 - HMI Constant speed tab

In the *Constant speed* tab, the speed reference can be set in the *Speed Control* box and the PMSG can be forced to start as a motor by pressing the button *start_as_motor*, regardless of the wind conditions. The generator speed in Hz is displayed as well as the *regulating mode* that is being used in the FPGA (i.e. speed control or current control). Auxiliary buttons to reset the speed and current PIs and control the use of *fake theta* can be found in this tab.

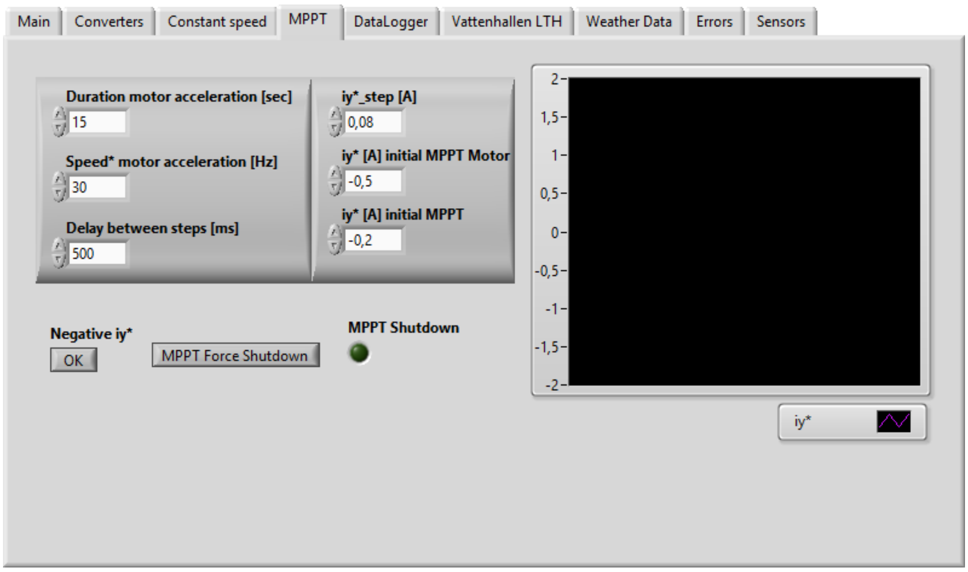

Figure 40 - HMI MPPT tab

The MPPT tab contains the relevant variables that characterize the algorithm implemented for maximum power tracking. It is useful for the operator to be able to manipulate these values in an effort for optimizing the algorithm and making it more effective by experimenting with different parameters. The *Duration of motor acceleration [sec]* defines for how long the PMSG is accelerated as a motor before starting production in the MPPT and the speed reference *Speed* motor acceleration* stipulates the rotor speed to reach before starting production. The *delay between steps* is an important parameter to fine tune, since it defines how long the system waits between applying the perturbation in rotor speed and observing its impact on the power production. The *iy** parameters on the right define the step in current reference to apply between iterations and the negative current reference at which the MPPT method is initiated. The variation in current reference *iy** is plotted on the graph to the right to provide a better visualization of the process.

The remaining tabs are provided in the Appendix section since they are less relevant for the operation of the control system: *Datalogger, Vattenhallen LTH, Weather data, Errors* and *Sensors.*

5.5.2 Communication with the FPGA

The VI that performs the overall control of the system is installed in the real time controller of the grid side, as mentioned previously. The command signals to the low level microcontrollers and the measurements from these are communicated to and from the FPGAs via the Read/Write function in LabVIEW, as illustrated in Figure 41.

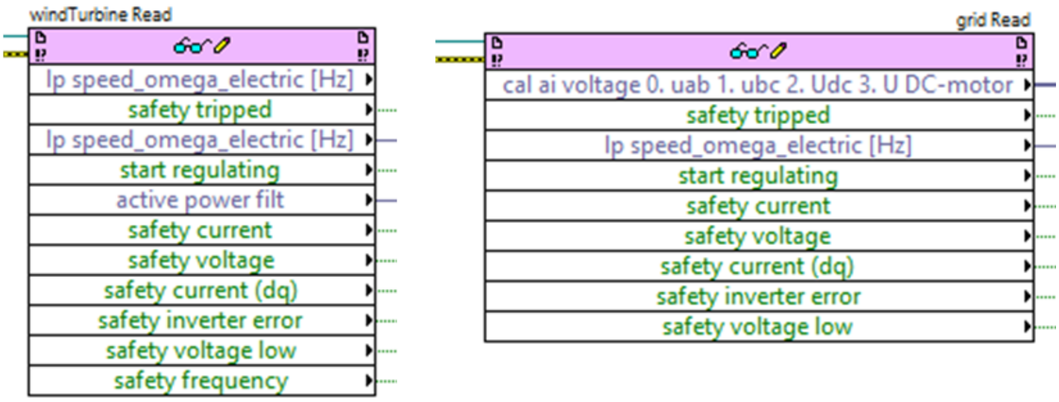

Figure 41 - Read from FPGA

The code on the FPGA of both microcontrollers imposes a series of safety limits to the power converters. A logic signal is sent from the FPGA in case any of the parameters exceeds the limitations established (*safety tripped*), such as:

Grid side	**Generator side**
High current (>20A)	High current (>20A)
High voltage (>300V)	High voltage (>300V)
High current dq (>20A)	High current dq (>20A)
Low voltage (<5V)	Low voltage (<5V)
Inverter error (signal from the inverter)	Inverter error (signal from the inverter)
High frequency (>1000Hz)	

Table 4 - Safety signals from the FPGA

The wind turbine FPGA also sends in the generator speed (*lp speed_omega_electric [Hz]*) and the active power (*active power filt*) in Watts, which is positive if power is consumed and negative if power is generated. The grid side provides the value of the DC link voltage (U_{DC}). Both sides send a logic signal once the respective power converter is being regulated (*start regulating*), as shown in Figure 41.

In Figure 42 the overall control sends the command signals to the FPGA to start and stop regulating the power converters on both sides, as well as the defined speed reference *(speed*[Hz]),* current reference (*iy*),* speed control mode (*reg m.*), and other logic variables used for testing (Figure 42).

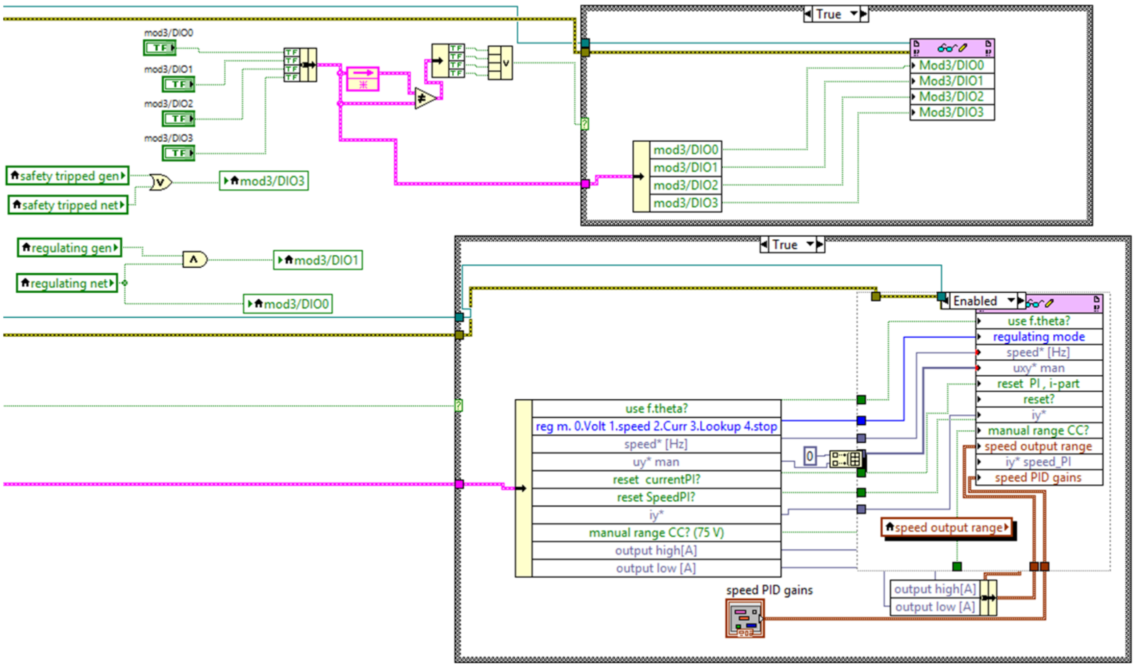

Figure 42 - Write to the generator side FPGA

The grid side cabinet has a set of 4 LEDs that are programmed to indicate the status of the power converters' regulation. As shown on Figure 42, the *safety tripped gen, safety tripped net, regulating gen and regulating net* variables send a logic output to the FPGA that is connected to the LED display. The yellow light to the left indicates that the grid side converter is being regulated, the green light indicates that both the grid side and the generator side converter are being regulated, and the red light to the right lights up in case any of the safety limits presented on Table 4 are trespassed.

Figure 43 - Notification lights on the grid side cabinet

5.5.3 Wind speed sensor decoding

Wind speed is acquired in the FPGA module in the form of a sinusoidal voltage signal from the MAX40+ anemometer. The signal is connected to the +-10V analog input module on the grid side Compact RIO and is decoded in the FPGA.

The decoding process consists in using the block Analog Period Measurement to calculate the period of the sampled voltage signal using threshold crossing detection with a defined hysteresis of 0,01 and a threshold level 0 (Figure 44).

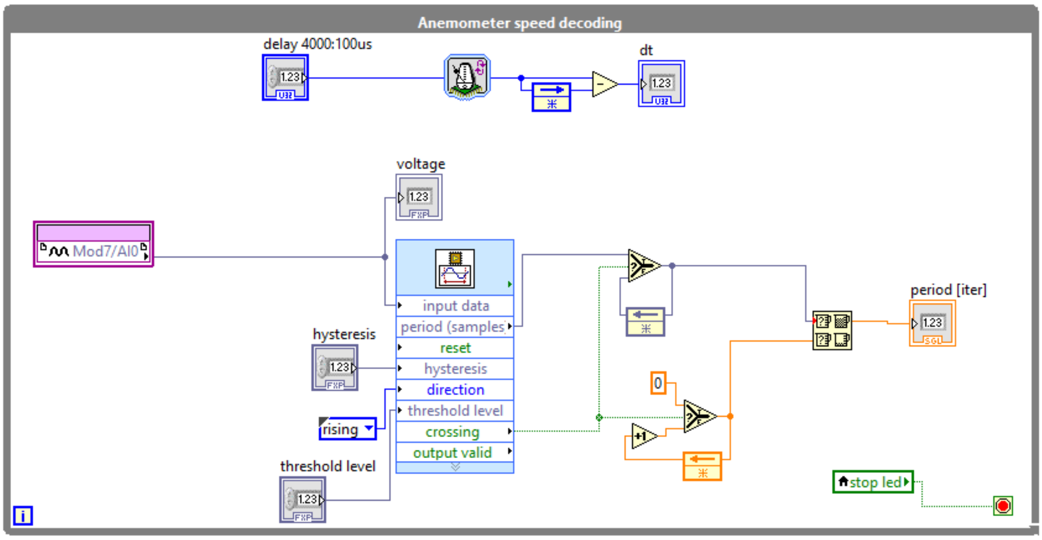

Figure 44 - Anemometer voltage decoding in the FPGA

The period is then communicated to the real-time overall control application using the Read/Write function (Figure 45) and the wind speed U [m/s] is calculated from the frequency f [Hz] using the calibration transfer function provided in the anemometer specifications:

$$U=0{,}77*f+0{,}4 \text{ [m/s]} \quad (5)$$

The instantaneous wind speed is plotted in a waveform chart with an update rate of 100 ms along with the 1 minute based average wind speed, which is the principal wind speed used as a reference for the whole control sequence in order to filter the stochastic and highly oscillating instantaneous values.

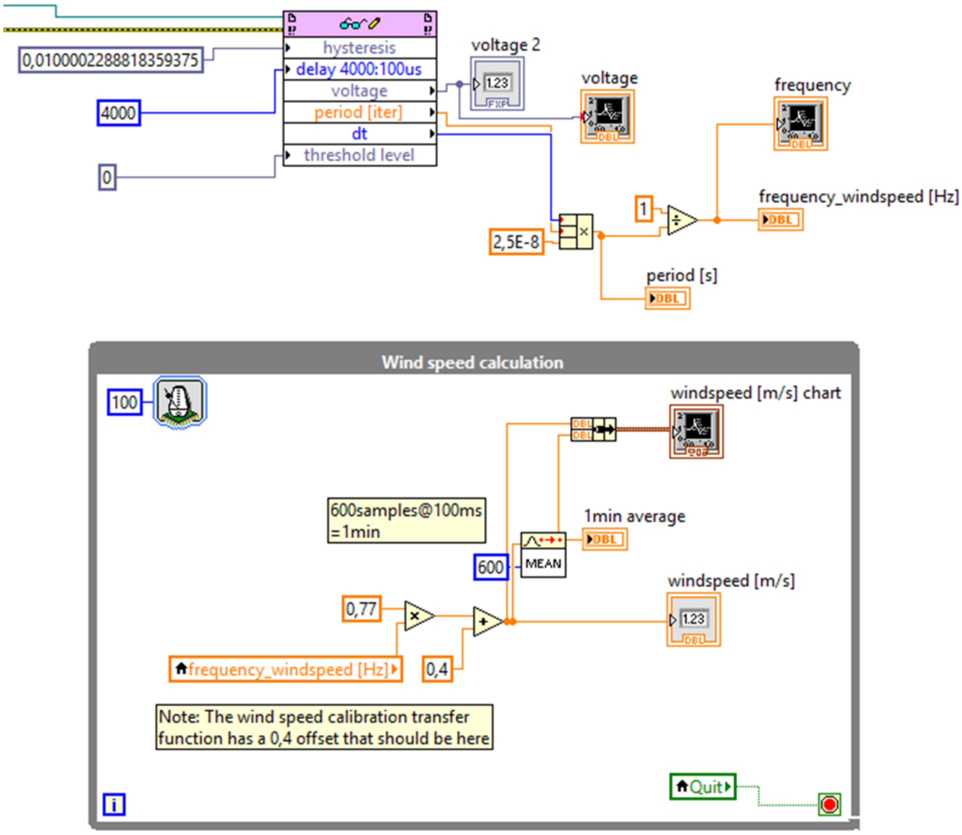

Figure 45 - Wind speed calculation in the real-time controller

The meteorological mast sensors were previously connected to a data logger for monitoring and control of the wind conditions through an embedded web-server that is suitable to be connected to the control system via an Ethernet connection to access the data files via FTP. However, due to difficulties in programming the FTP connection, a direct connection of the signal to the Compact RIO seemed to be the most reliable and straight forward solution to acquire the wind data.

5.5.4 State machine implementation

The state machine is implemented in the overall control VI in the form of a case structure with 8 different cases, each corresponding to one of the main states described in section 5.4 and listed in Table 5. The transitions between states take place inside the case structure, although some of the tasks are performed outside by sending local variables to parallel while loops in the code. The following paragraphs provide an extensive explanation of the implementations carried out. The order of description was chosen to provide a better understanding of the interactions between processes along the code.

The code is inserted in a flat sequence structure with three divisions, for initializing variables, running the program and finally shutting off the variables when the application is exited. The *Quit* button should be pressed to stop the VI, however it is recommended that the system is in OFF state so that no important processes are abruptly interrupted. The important variables to initialize are the auxiliary logic signals used for synchronization, the start and stop commands to the power converters, the web communication to Vattenhallen and the indicator LEDs on the HMI (Figure 46). Ten while loops are executed in parallel in the LabVIEW main control VI that contain different tasks, as will be described next.

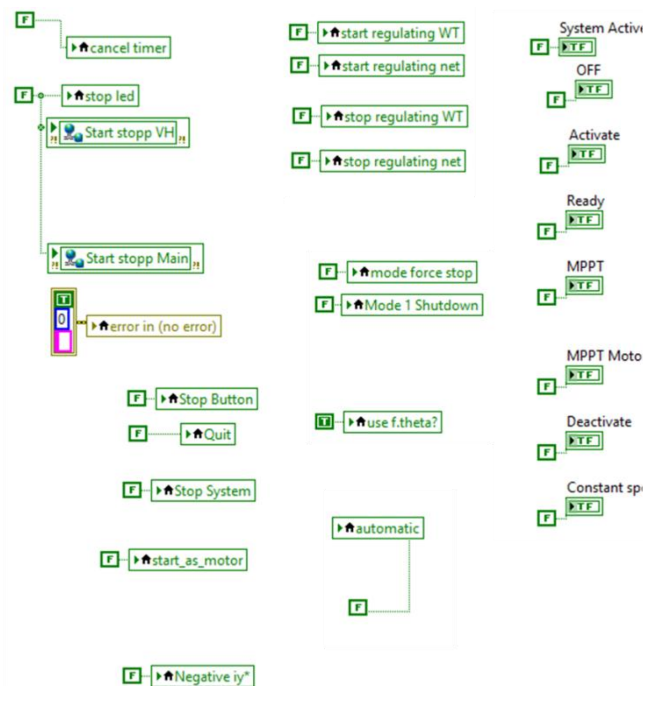

Figure 46 - Initialization of variables

Main states	
0	OFF
1	ACTIVATE
2	READY
3	START UP
4	MPPT
5	CONSTANT SPEED
6	MPPT MOTOR
7	SHUTDOWN
8	DEACTIVATE

Table 5- Control sequence main states variable *States*

0. OFF

The sequence begins in the OFF state, before the Start button is pressed. A type definition variable contains the 8 main states of the block diagram and defines which of the cases on the case structure is executed.

On the left side are the *Stop* button, the *Emergency* button, the *Start as motor* button and the average wind speed value. The only variable that influences the OFF state is the *Start system* button; in case it is set to true the system proceeds to ACTIVATE state, otherwise it remains in OFF state for another loop. The *Stop* button, the *Emergency* button and the *Start as motor* button are not connected to this inactivity case, so they do not start any action if pressed.

In this moment, the mechanical brake variable is active, the HMI light indicator for OFF state is turned on and the DEACTIVATE light indicator is turned off.

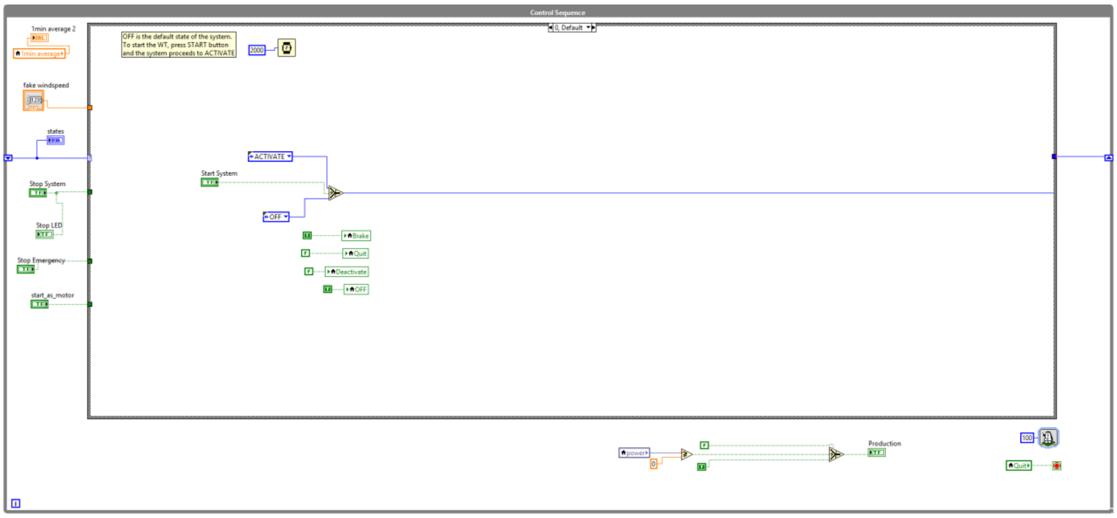

Figure 47 - State machine OFF state

1. ACTIVATE

In the ACTIVATE state, the command signal to start regulating the net side power converter is activated, after which there is a two seconds wait. This is done by simply switching the value of the variable, in case the program is run more than once. The *start regulating net* local variable is communicated to the FPGA (Figure 49) where it sets the power converters value to true and in the while loop of Figure 48 the information that the net side converter is being regulated is confirmed and the system proceeds to READY state.

In case the *Stop* or *Emergency* buttons are pressed, the system switches to DEACTIVATE mode, which is done by setting the type definition variable of the state to DEACTIVATE in the False case of the case structure. If the confirmation of *regulating net* never comes, pressing the *Stop* button sends the system to

SHUTDOWN. In this state, the *Activate* and *System Active* indicators are lit up in the HMI and the *Off* indicator is turned off.

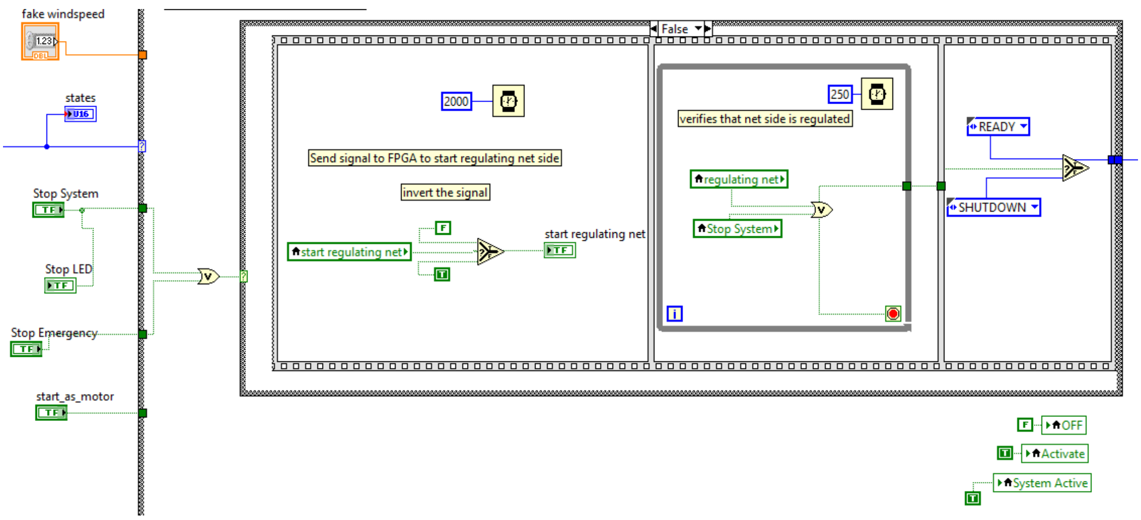

Figure 48 - State machine ACTIVATE state

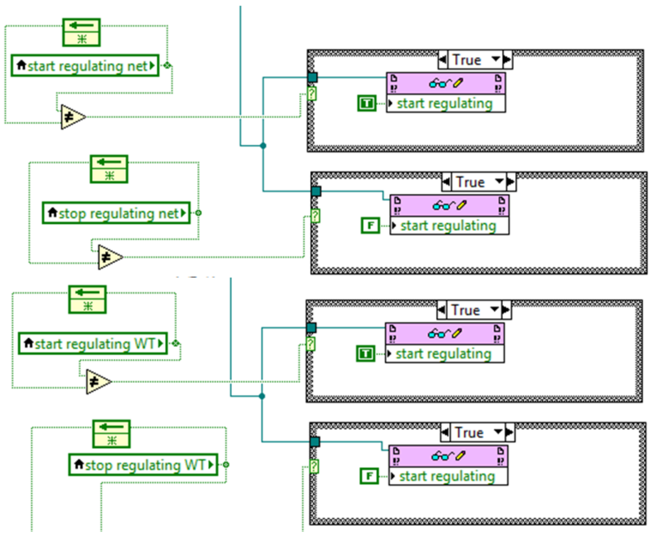

Figure 49 - Start/stop regulating signals to the generator and grid side FPGAs

2. READY

READY state performs the wind speed assessment to check if the system should proceed to START UP or remain in stand-by waiting for adequate wind conditions. If the wind speed is greater than or equal to the cut-off wind speed or if it is lower than the cut-in wind speed, a false logic signal is sent to the Select function and the system iterates back to this same state. If the wind speed meets the limitations or if the *Start as motor* button is pressed by the operator, the system proceeds to START UP state. In this state the brake variable is set to true, in case the sequence is coming from SHUTDOWN. The *Shutdown* and *Activate* indicators are turned off and the *Ready* indicator is turned on. In case the *Stop* or *Emergency* buttons are pressed, the system is immediately set to DEACTIVATE.

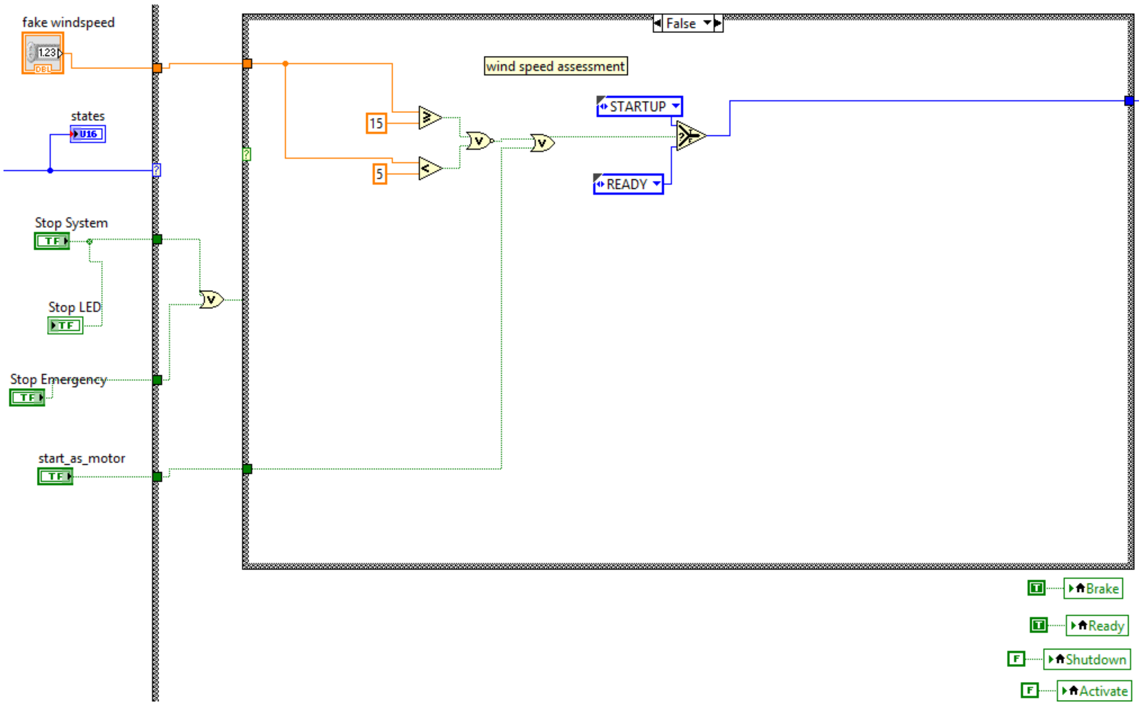

Figure 50 - State machine READY state

3. START UP

The START UP can be performed in two ways, depending on the selected mode of operation. Regardless, the *Start up* HMI indicator is set to true and the *Ready* indicator is turned off (Figure 52).

If the MPPT mode is selected (Control state 4) and the wind speed is greater than the threshold defined, a True signal is sent to the inner case structure (Figure 51). Here freewheel start-up is initiated by releasing the brake and allowing for the turbine to spin freely. The while loop keeps running until when the generator is rotating at a speed higher than 10 Hz or when the *Stop* button is pressed by the operator in case the rotor does not achieve the adequate speed for some time. If the target speed is fulfilled, a command signal to start regulating the generator side is sent to the FPGA and after positive confirmation that the power converter is being regulated the system is forwarded to the selected control mode which in this case is previously checked to be the MPPT mode as illustrated in Figure 52.

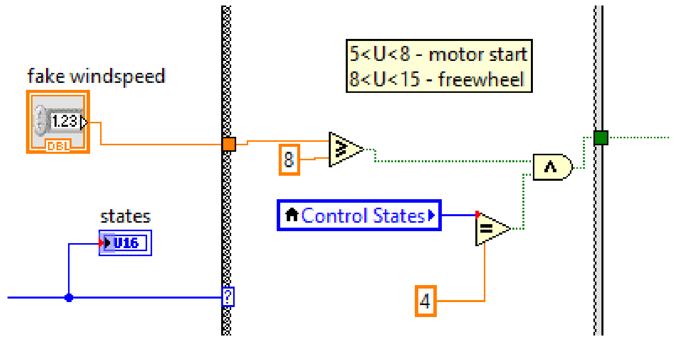

Figure 51 - Start-up control mode confirmation

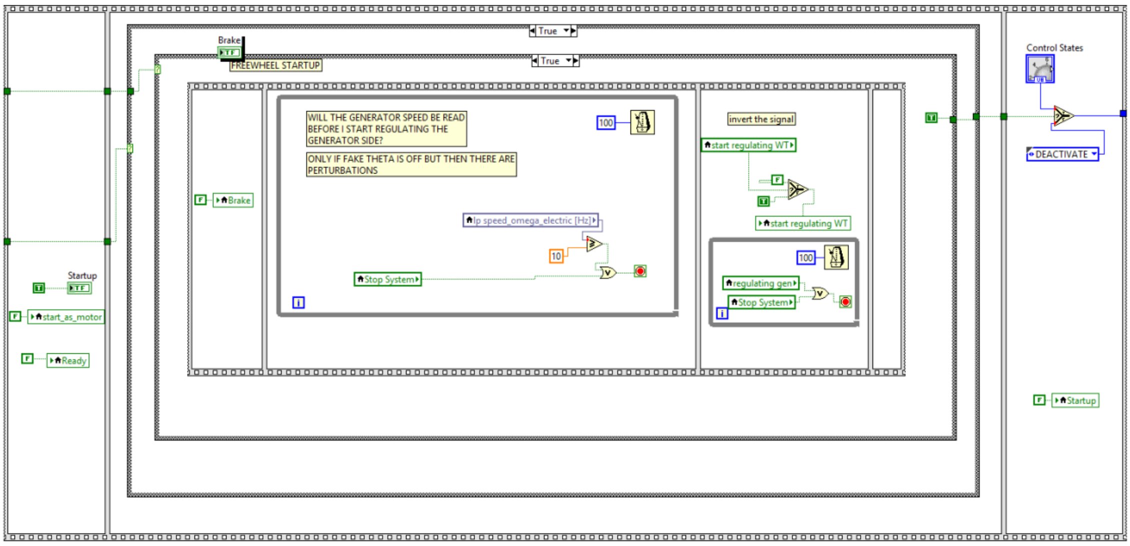

Figure 52 - State machine START UP state (Freewheel start-up)

If the CONSTANT SPEED or MPPT Motor modes are selected, the turbine starts up as a motor. Before that, a check for which control mode is selected takes place, because in case the operator had selected the MPPT mode with freewheel start-up, but the wind is blowing below the necessary threshold, the system will automatically switch to MPPT Motor mode, as seen on the top of the flat sequence's first slot in Figure 53. Then, as described for the previous case, a signal is sent to the power converter on the generator side to start regulation. After confirmation that the converter is being regulated with no errors, the brake is released and a logic signal *Start_as_motor* is sent from the START UP case to one of the other while loops of the VI with the instruction to start the motor acceleration

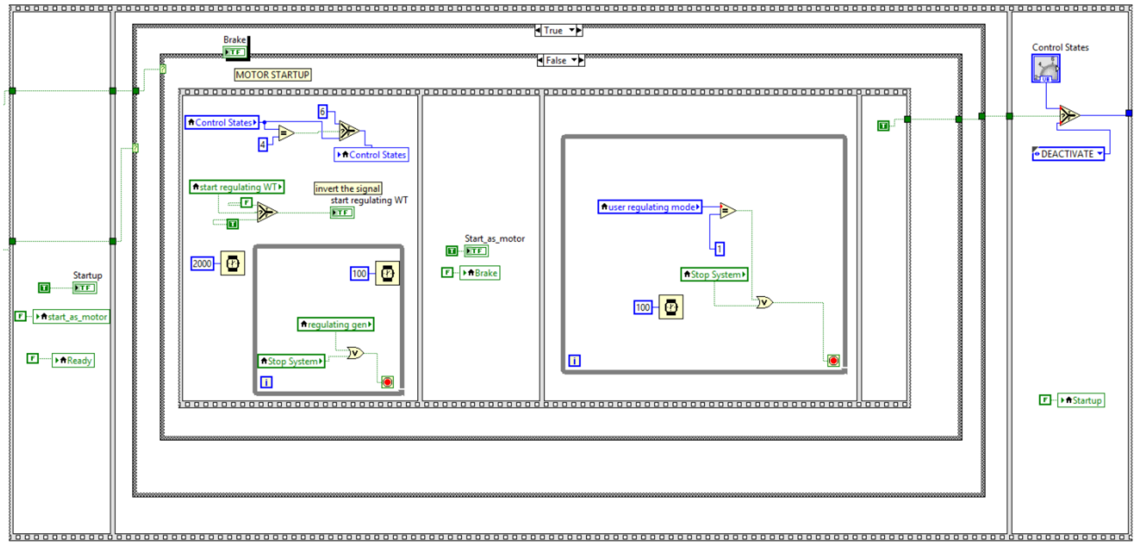

Figure 53 - State machine START UP state (Motor start-up)

This other while loop illustrated in Figure 54, contains a True/False case structure. The conditions to fulfil are that either the "Start as motor" variable or the signal from the remote panel interface is set to True, as well as having a confirmation that both the net side and generator side converters are being regulated. The flat sequence structure starts by setting the rotor speed regulation mode (*user regulating mode*) to *Stop* and resetting the current and speed PI controllers in the FPGA, as a good programming procedure. The different rotor speed regulation modes implemented in the FPGA's code are presented in Table 6 for a better understanding.

Rotor speed regulation		Setpoint to the FPGA
0	Voltage control	Not implemented
1	Speed control	*speed*[Hz]*
2	Current control	*iy**
3	Lookup table	Not implemented
4	Stop mode	*iy*=0*

Table 6 - Rotor speed control mode

As mentioned in the beginning of the chapter, an auxiliary variable named *fake theta* is used to provide an initial reference for the speed controller. This signal is set to True and the speed reference is defined as 5 Hz, although this will only be validated once the regulating mode is set to speed control.

The motor start is performed with current control. Initially, the PMSG is accelerated by setting the rotor speed control mode to current control and providing a positive current setpoint for a defined period of time (10 seconds by default) as shown in the right half of Figure 54. After that period of acceleration, the *fake theta* variable is disabled and the speed PI can start to use the true *theta* value for calculating the generator speed (*lp speed_omega_electric [Hz]*).

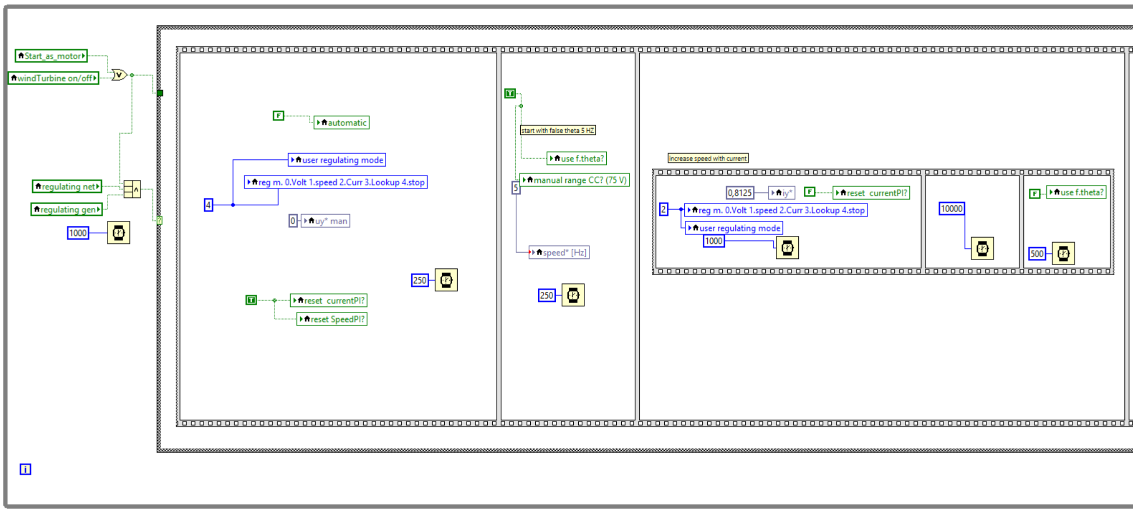

Figure 54 - While loop to start the generator as a motor

5. CONSTANT SPEED

At this point, CONSTANT SPEED mode was activated by the while loop back in the START UP mode of the main case structure on Figure 53, by setting up the flag that consists in verifying that the rotor speed regulation mode was switched to speed control. The sequence proceeds in the same flat structure to activating speed control regulation and resetting the current reference to zero, after which the speed set-point is set to 10 Hz, as illustrated on Figure 55.

The auxiliary variable *Negative iy** is used for the MPPT Motor mode as explained further ahead. In the present case this value is False and the *Start as motor* variable remains True. In the next case structure on the right, the set-point for speed control defined for the remote panel execution is checked for changes and the speed of the generator is verified. The generator speed is then kept at the reference defined by the user for an indefinite period of time until the *Stop* button is pressed, or the Vattenhallen signal is shut off or the generator speed falls out of the defined parameters. Once any of these events occur, the while loop is interrupted and the system proceeds to SHUTDOWN state.

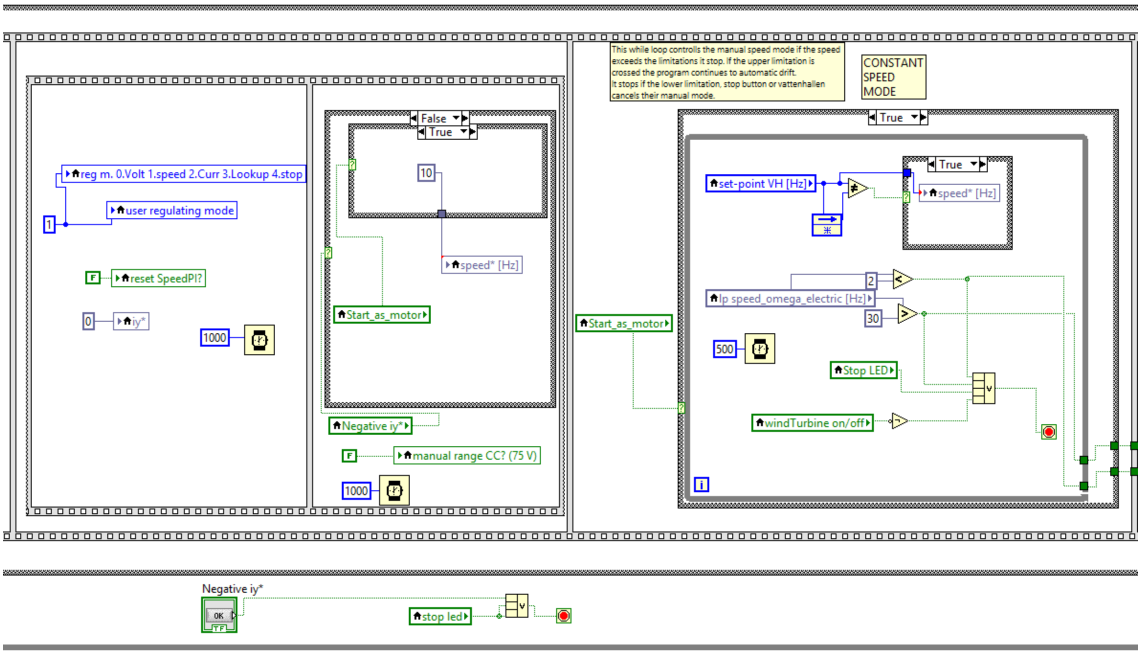

Figure 55 - While loop to run the generator at constant speed (continuation of Figure 54)

6. MPPT MOTOR

When the system enters the MPPT Motor state, the generator is already spinning due to the torque imposed by the current set-point from the START UP. The *Start_as_motor* variable is set to False and an auxiliary variable called *Negative iy** is set to True. *Negative iy** makes the distinction between sending the system to CONSTANT SPEED or MPPT MOTOR mode after the START UP.

The rotor speed regulation mode that is active is speed control, so in the second slot of the flat sequence structure in Figure 56, the generator is accelerated up to a defined speed for a defined period of time. After this acceleration period, the regulation mode switches to current control and a negative current is set in order to start extracting power from the rotor. After 500 ms, the negative current reference is slightly lowered to avoid having too much negative torque and this is kept until the PMSG starts generating power (*power_avg<0*) or the Stop button is pressed.

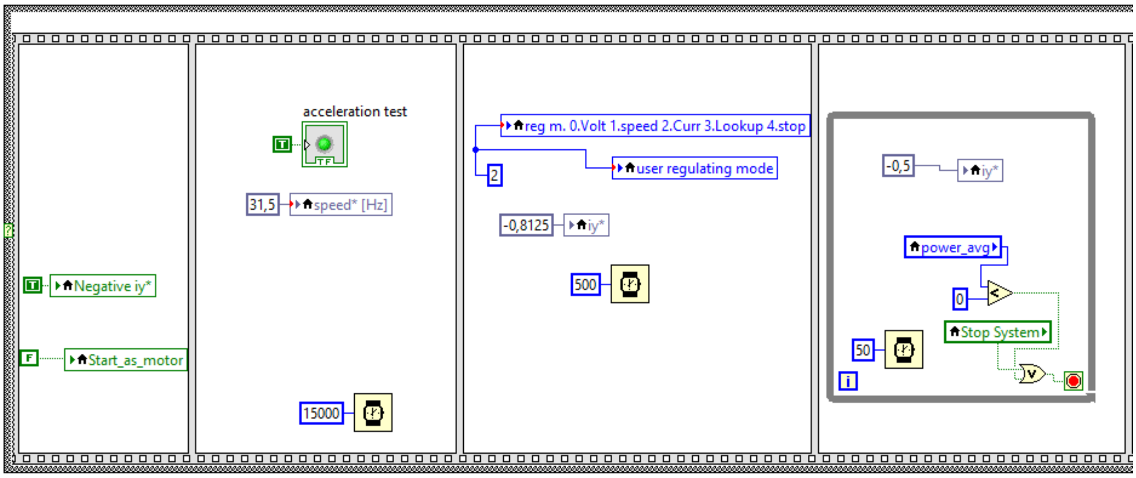

Figure 56 - MPPT Motor state (Part 1)

Immediately after exiting the while loop, the previous current reference is fed into the while loop shown in Figure 57, which contains the implementation of the MPPT method. As described in section 3.4.1.1 of the control theory chapter, the maximum efficiency point is tracked by observing the influence of speed perturbations to the rotor shaft in the variation of power production.

Here the variation in power production (*power_avg*) is measured by subtracting the value from the previous iteration from the actual value. The absolute value is taken since power production is a negative value and power consumption is a positive value. The variation in generator speed is measured in the same way and the signal of the quotient between the two is verified. A step for the current reference is defined and can be varied. If the quotient is a positive value, the reference current step is added to the actual reference - *iy** is negative, so adding a positive step represents a reduction of the current reference in module which results in a increase of speed - and if the quotient is negative, the reference current is subtracted from the actual value which causes an decrease in rotor speed. The True case of the case structure is executed if the quotient is different from zero. If the power is constant (*dP=0*), the False case is executed where the current reference is automatically defined to the same value as the last iteration (Figure 58).

In the beginning of the sequential structure, a delay of 500ms is applied in order to give some time for the current perturbation to affect the power before taking the new power and speed measurements in the next iteration.

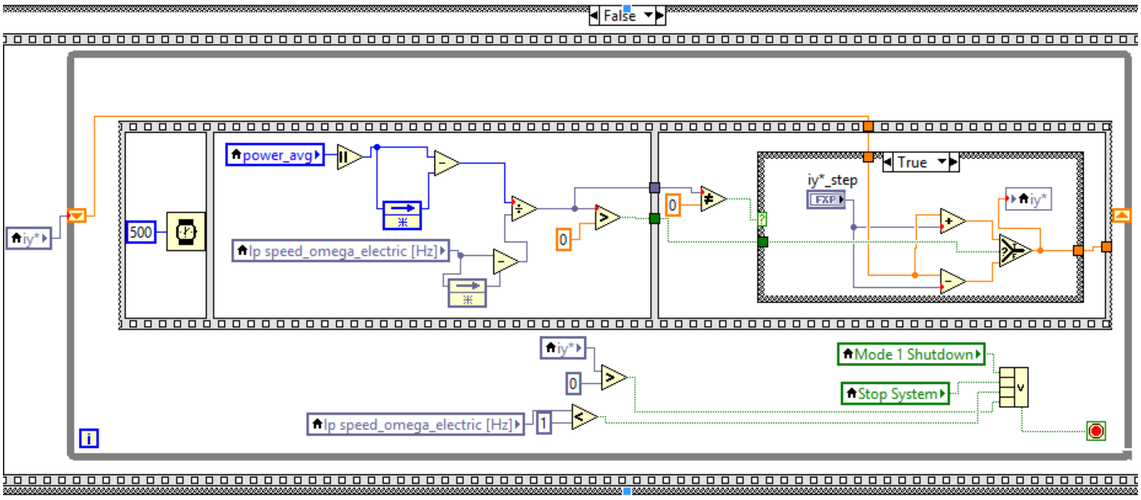

Figure 57 - MPPT Motor state (Part 2 True)

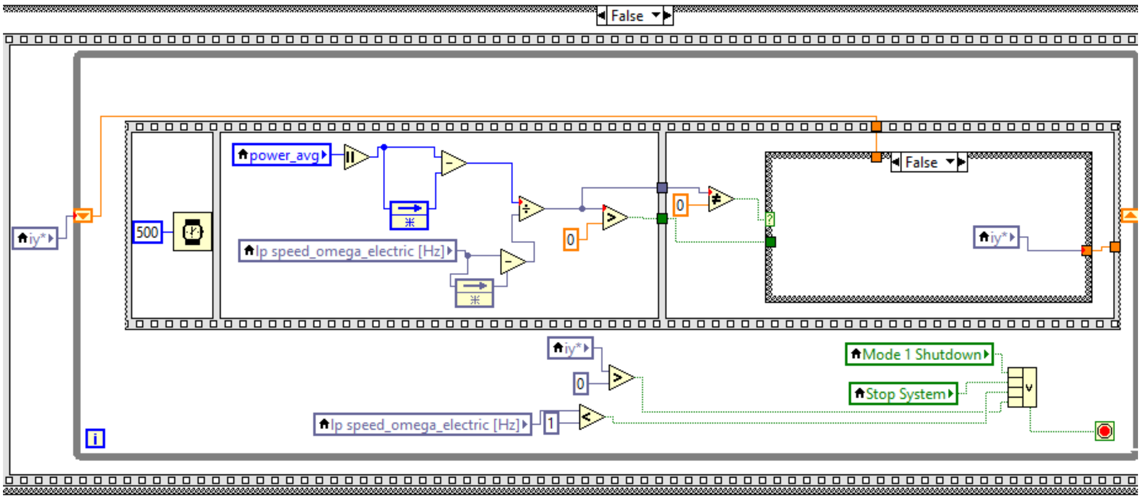

Figure 58 - MPPT Motor state (Part2 False)

The conditions that interrupt the MPPT mode are if the generator is required to start consuming power, which means setting the current reference *iy** as a positive value, if the *Stop* button is pressed or if the generator speed drops below a limit of 1 Hz.

7. SHUTDOWN

The SHUTDOWN commands for the MPPT and for the CONSTANT SPEED modes are located in different points in the code, although the shutdown strategy is the same.

Continuing in the MPPT case, when the system is sent to SHUTDOWN, the regulation mode is set to speed control and a while loop creates a step reduction in the speed reference, starting on the last measured speed, as illustrated in Figure 59. If at the moment of shutdown the generator speed is greater than 10 Hz, a 1 Hz decrement is applied every 500 ms in order to induce a gradual reduction in the rotor speed - this is especially important when the rotor is spinning at high rotational speeds -, otherwise it skips the while loop. When the speed reference reaches 5 Hz, the while loop is interrupted and the speed is set to zero. After that, the regulation mode is set to *Stop* which is one of the criteria to forward the system to DEACTIVATE mode in the SHUTDOWN case (Figure 60). The auxiliary variable *Negative iy** is set to false, as well as the *Start as motor* variable while the *fake theta* is activated. The *Shutdown* indicator is set to true and the *Production* indicator is deactivated while the process is taking place. Once the rotor is close to static, which is defined as having a speed below 0,5 Hz, it is safe to apply the mechanical brake and lock the turbine rotor.

The strategy for the shutdown when the system comes from the CONSTANT SPEED state is performed in the same manner, after which the regulation mode is set to *Stop*, *fake theta* is activated and the speed reference is set to zero. The specific code can be found in the Appendices section.

In the state machine case structure for the SHUTDOWN state, the variables *Stop system* and *Emergency* stop are checked. If any of the two is active, the system is sent to DEACTIVATE, otherwise it goes back to READY state and waits for adequate conditions to restart production.

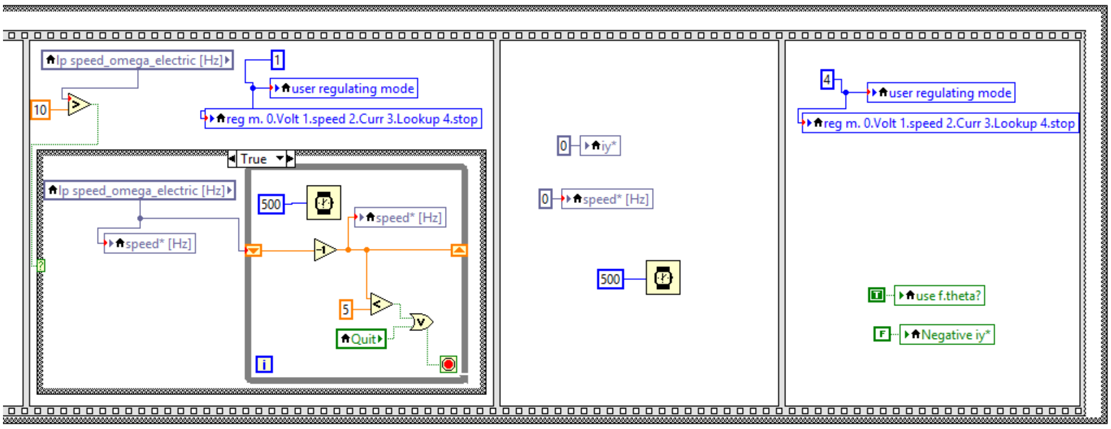

Figure 59 - MPPT Motor state (Part 3)

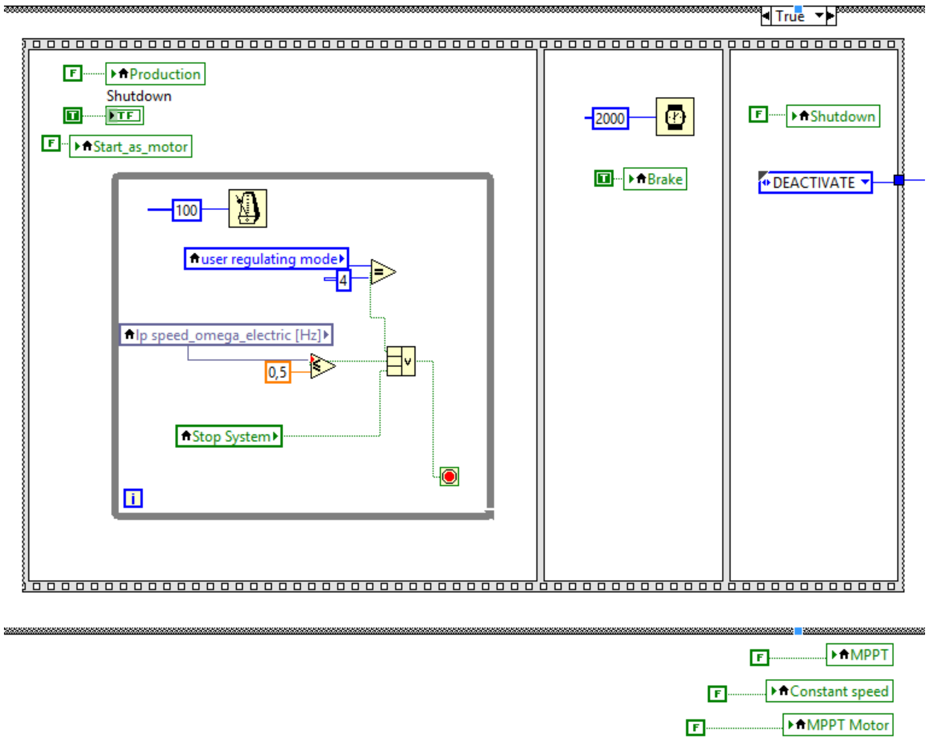

Figure 60 - State machine SHUTDOWN state

4. MPPT

The implementation for the freewheel start MPPT is the same as for the motor started case, with the difference that there is no acceleration previous to the current regulation, so the *Negative iy** is set to True and the *Start_as_motor* variable is deactivated in case it was active from a previous loop. Then the rotor speed regulation mode is set to current control and a negative reference starts requesting torque from the rotor inertia. When power production starts, the system is forwarded to the MPPT while loop that is the same as illustrated in Figure 57.

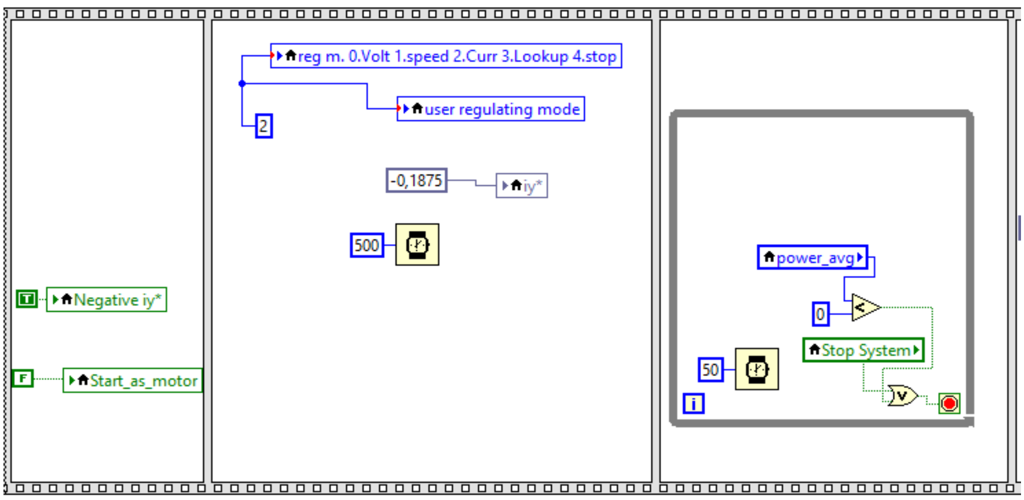

Figure 61 - State machine MPPT state

8. DEACTIVATE

The system can be sent to DEACTIVATE state either by an *Emergency* button pressing or after a regular shutdown sequence. This state is responsible for applying the mechanical brake by setting the *Brake* variable to True and by stopping the regulation of the power converters sequentially.

The rotor speed regulation mode is set to *Stop* and a command signal is sent to the FPGA to stop regulating the generator side converter. This is done by inverting the logical value of the variable *stop regulating WT*. Once the response from the FPGA is received and having the value of the variable *regulating gen* set to True, the sequence proceeds to stopping the regulation of the net side converter in the same way. When confirmation is obtained, the system is directed to OFF state. In this state, all the indicators from the other state machine cases are deactivated and the indicator *Deactivate* is turned on. The system is now back to OFF state waiting for a command to start.

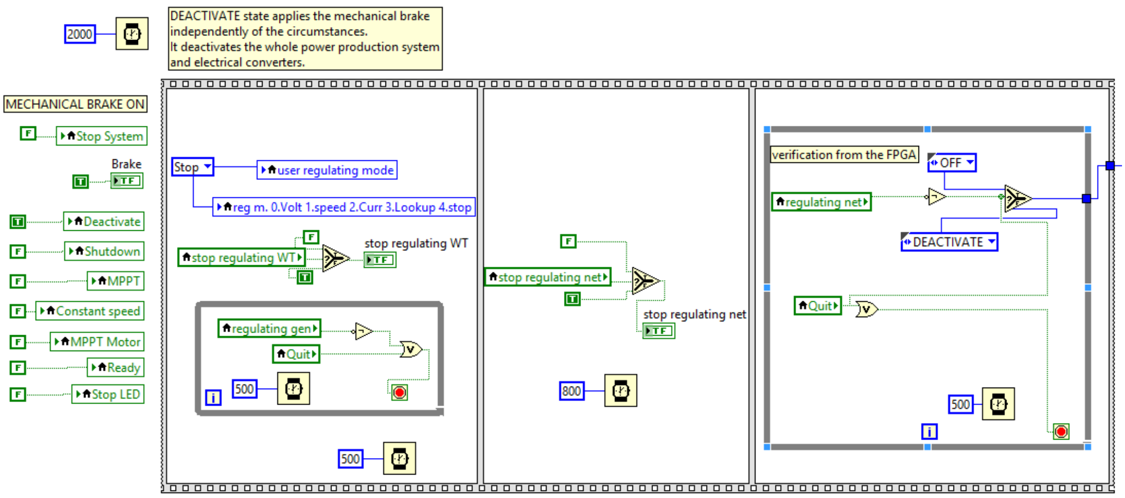

Figure 62 - State machine DEACTIVATE state

5.5.5 Data logging

Since this is an experimental system, it is important to have a reliable and practical data saving solution. To save data for condition monitoring and result analysis, the creation of a data logger was necessary. This was done by creating a Shared Variable called *data* that stores the following values:

Wind speed average	[m/s]
Wind speed	[m/s]
Rotor speed reference	[rpm]
Power	[W]
Rotor speed	[rpm]
Brake signal	Boolean
Control state	0-8
Current reference	[A]

Table 7- Variables saved by the data logger

The values of power and rotor speed are averaged from the 20 latest iterations in order to get a smoother curve instead of a digital square signal. The generator speed reference *speed*[Hz]* is multiplied by a constant of 3,75 to obtain the correspondent value in rotor speed reference in rpm (Figure 63).

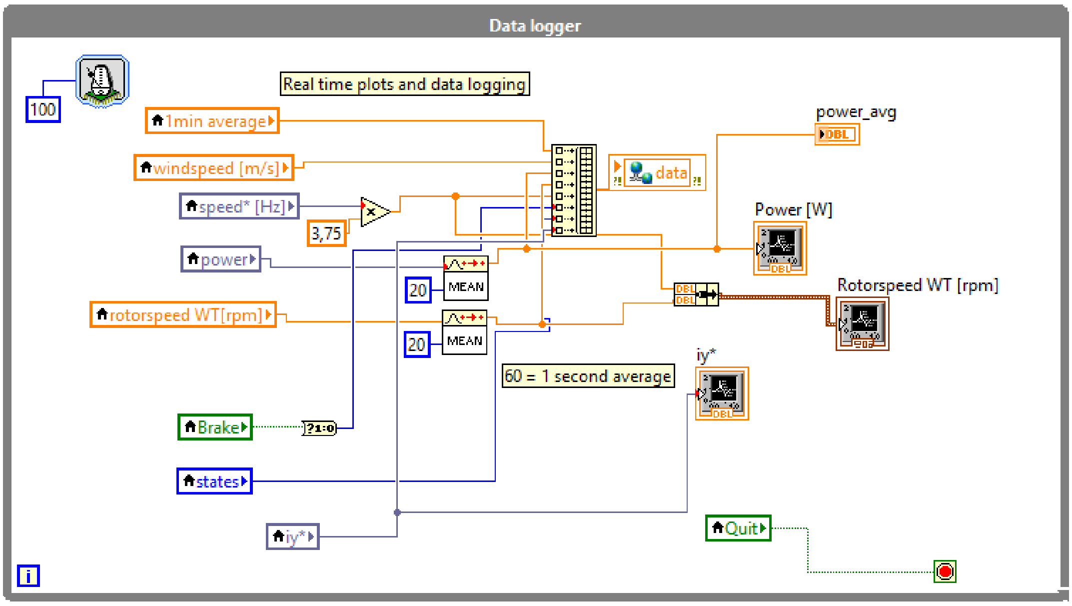

Figure 63 - Data logger while loop

The Shared Variable *data* is then communicated to a VI located on the operator's PC that unbundles the variables and saves them in a location defined by the user. The file is saved with a time stamp in .TDMS format, which can be opened in an Excel spreadsheet for analysis and manipulation.

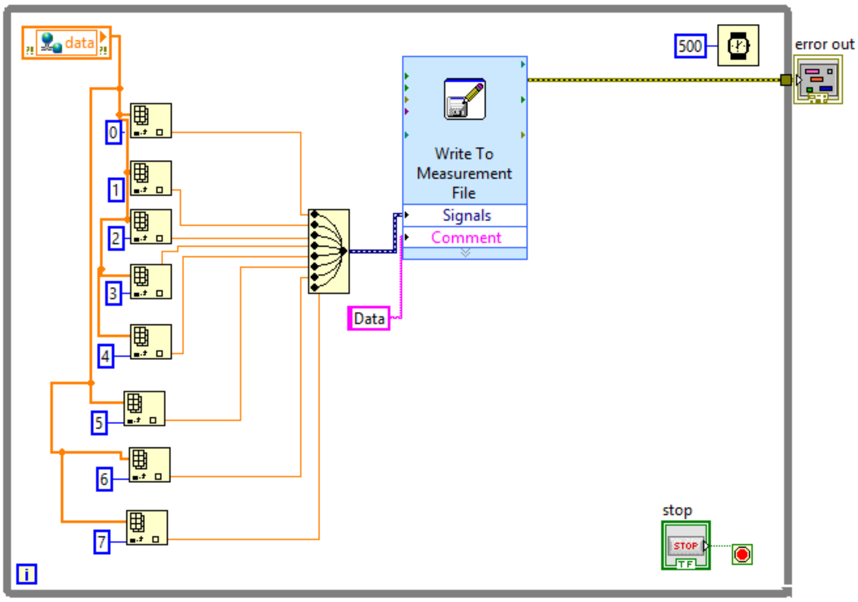

Figure 64 - Write to measurement file VI

5.5.6 Remote panel interface to Vattenhallen

This section is to be updated once the remote interface is up and running. The programming details will be explained and the interface will be described.

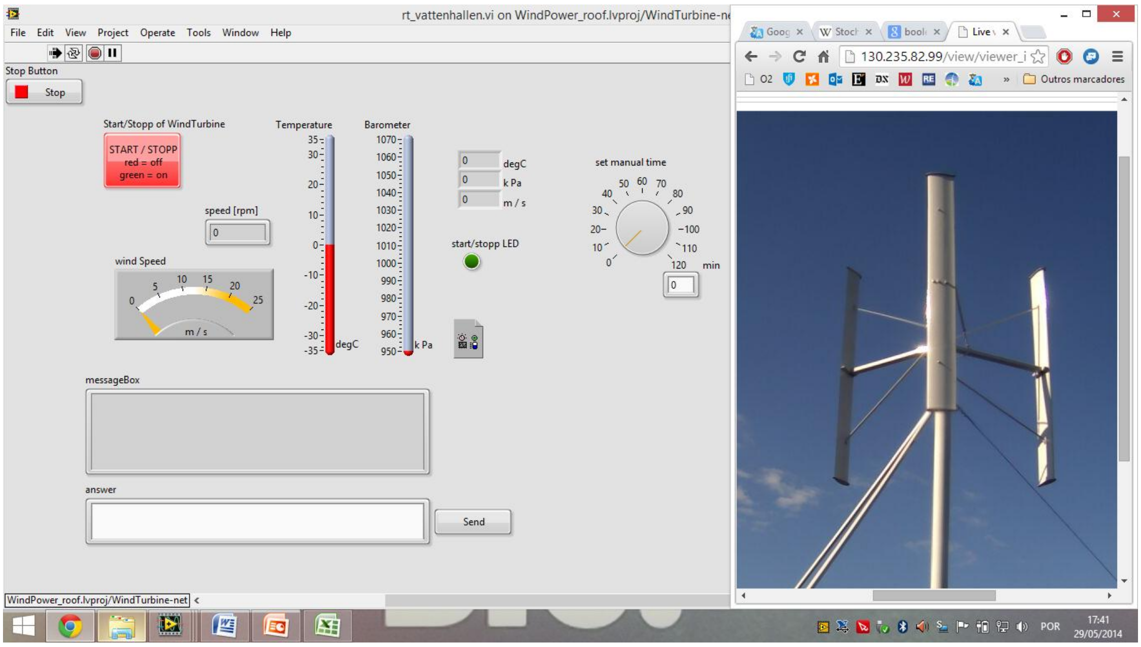

Figure 65 - Remote panel interface for Vattenhallen

6 Performance tests on the wind turbine

This chapter describes the experimental procedures performed on the system in order to test the functioning of the features implemented, and also the performance of the wind turbine in operation.

6.1 Communication between the PLCs

Data acquisition and communication are some of the most important factors when designing an embedded system. A series of tests were performed to ensure that the communication path between the programmable logic controllers was reliable. The Compact RIOs have a built-in communication line that ensures transfer of data between the FPGA module and the real time module. As described in section 5.2, the data transfer between the two microcontrollers is performed via Ethernet connection.

In this experiment, a simple program was developed to test the transfer of data between the net side real-time module and its FPGA module and also between the generator side real-time module and the FPGA on the net side Compact RIO, as illustrated in Figure 66.

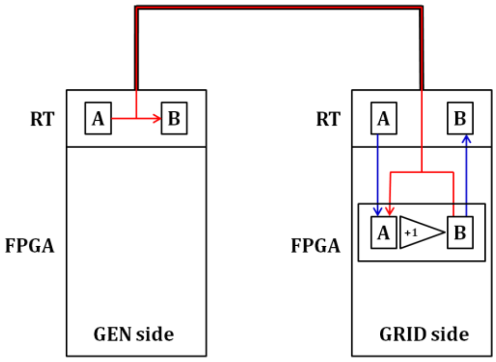

Figure 66 - Communication tests on the PLCs

The test program consists on sending a variable A from the real-time controller to an FPGA VI that applies a unitary increment to A and creates a new variable B, which is sent back to the real-time VI (Figure 67).

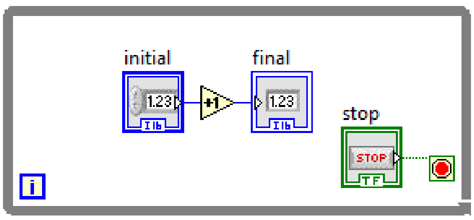

Figure 67 - Code of the communication test in the GRID side FPGA VI to apply the increment

As presented in the block diagram of Figure 68, a FPGA VI reference is opened on the real time VI and in the Read/Write block the value of A is written and the value of B is read from the FPGA. The control panel shows the variables A and B in two indicators.

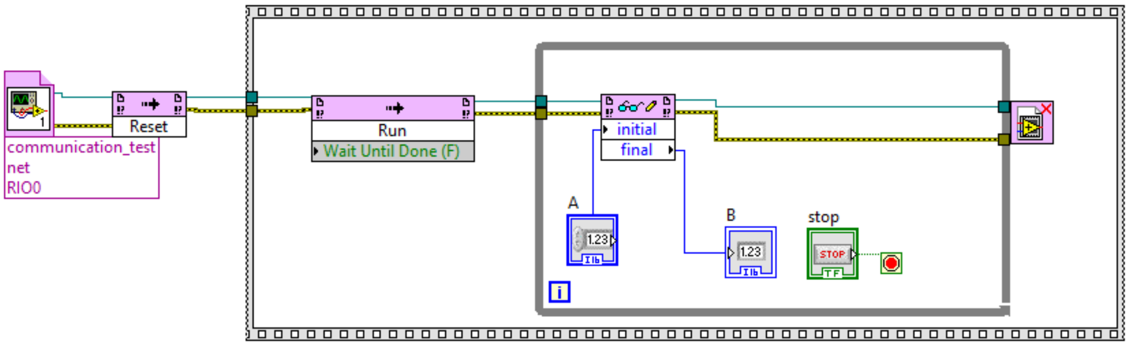

Figure 68 - Code of the communication test on the GRID side real time module

The tests were successful for both the GRID side test and for the GEN side/GRID side test, as Figure 69 shows, with the A variable being incremented one unit in both cases.

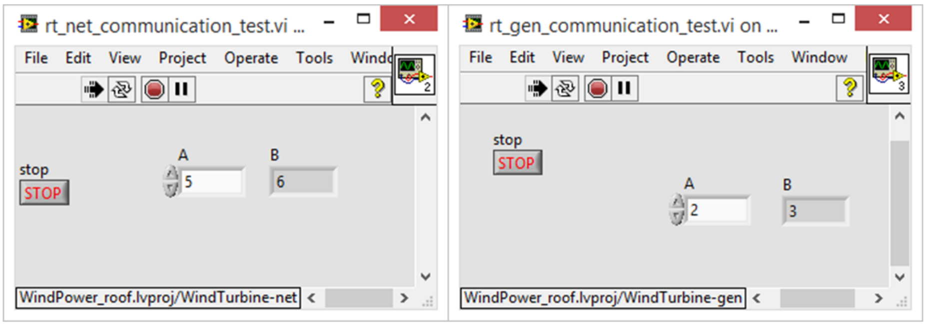

Figure 69 - Communication test with the NET side RT (Left) and with the GRID side RT (Right)

6.2 State machine sequence

In an initial phase of the project, a programme was developed for testing the state machine sequence and the wind measurement decoding before connecting to the power converters. A test Compact RIO was lent by the university to allow experimenting freely, without having to modify the implementations that were already deployed on the power converter's Compact RIOs and risk to accidentally impair the previously implemented programming.

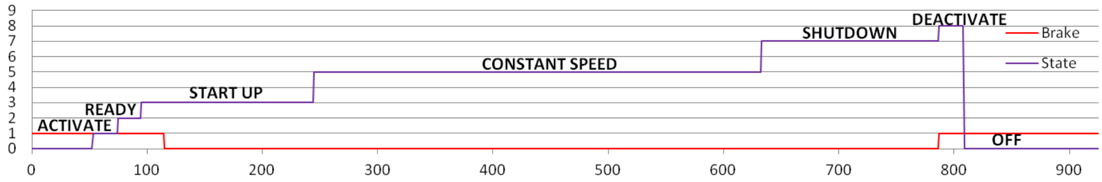

Figure 70 - Control sequence states in execution

This programme used dummy variables to substitute the command tags that would be later read and written to the converter's FPGAs. The wind speed sensor decoding was developed in this stage and the voltage signal from the anemometer was plotted for monitoring as shown in Figure 71. The case structure that constitutes the state machine sequence was also developed in this initial programme, and later adapted to be implemented in the main control system and interact with the generator speed, rotor speed regulation modes, converter's command signals, etc. In Figure 70 it is possible to observe the evolution of the control states while the sequence is in execution, recorded in a simple test in constant speed mode.

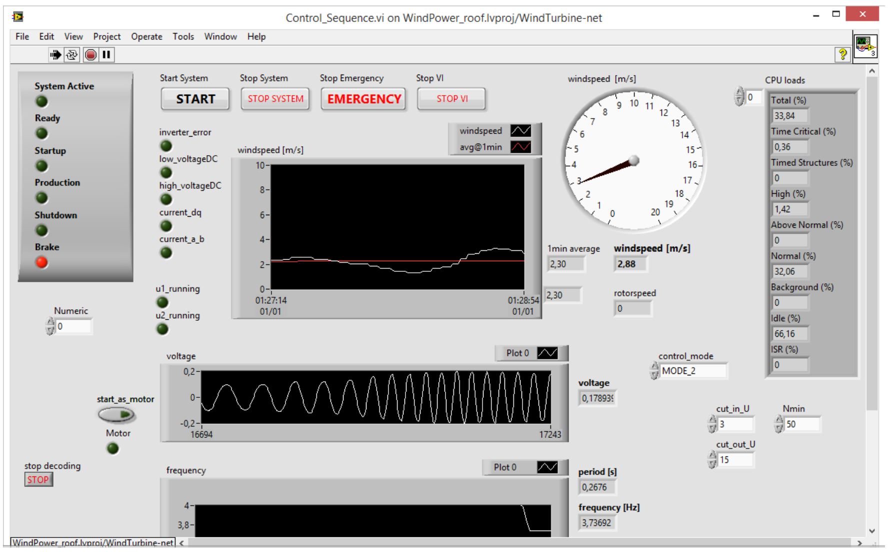

Figure 71 - Control sequence experimental VI

The wind speed was experiencing disturbances that caused unwanted spikes in the measurements. These disturbances were aggravated when the generator side power converter started being regulated and when the anemometer registered low wind speeds in the order of 2 m/s.

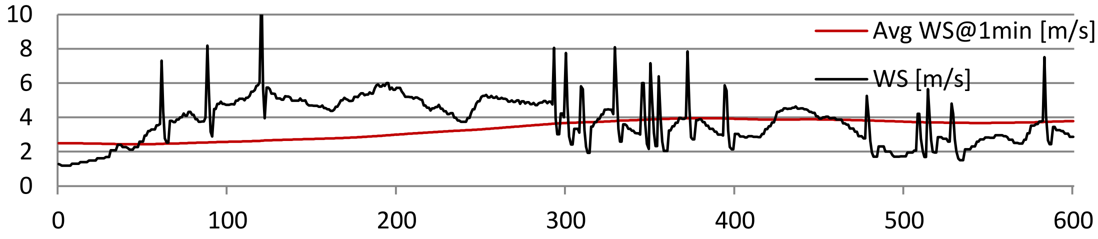

Figure 72 - Wind speed measurement before correction

This issue was caused by the interference of the current supplied to the generator with the small amplitude voltage of the wind speed measurement, which added noise to the voltage signal and misguided the crossings counting of the anemometer voltage frequency calculation, producing a wrong indication of high wind speeds in small time periods. The problem was solved by adding a 15μF capacitor to the voltage measurement on the Compact RIO I/O module, that acts by dampening the noise caused by the generator current and cleaning the voltage signal. Figure 73 shows a measurement of low wind speeds after the correction was applied.

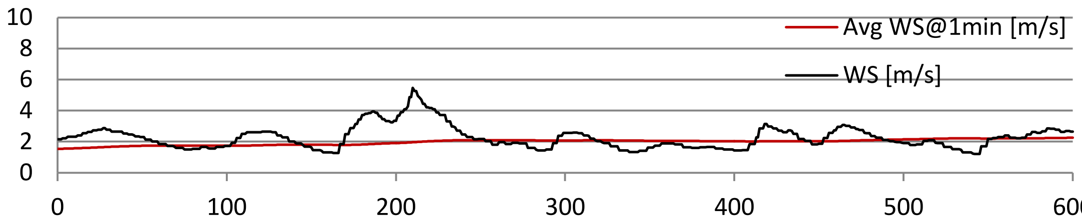

Figure 73 - Wind speed measurement after correction with a 15μF capacitor

6.3 Control modes

This section presents the performance tests ran in the different control modes: constant rotor speed, MPPT with motor start-up and MPPT with freewheeling start-up. It is important to remind that a positive power value corresponds to power consumption. Due to the lack of wind conditions, the turbine has not been able to produce any power from wind generation. The rotor speed and power are plotted in the same graph for a better comprehension of the influence of the changes in one another.

6.3.1 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 ($\bar{U}\sim 1{,}5$m/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. In this test the data was logged at a rate of 100ms (i.e. 10 times per second) and the X axis corresponds to each individual log, so 100 units in the X axis correspond to 10 seconds.

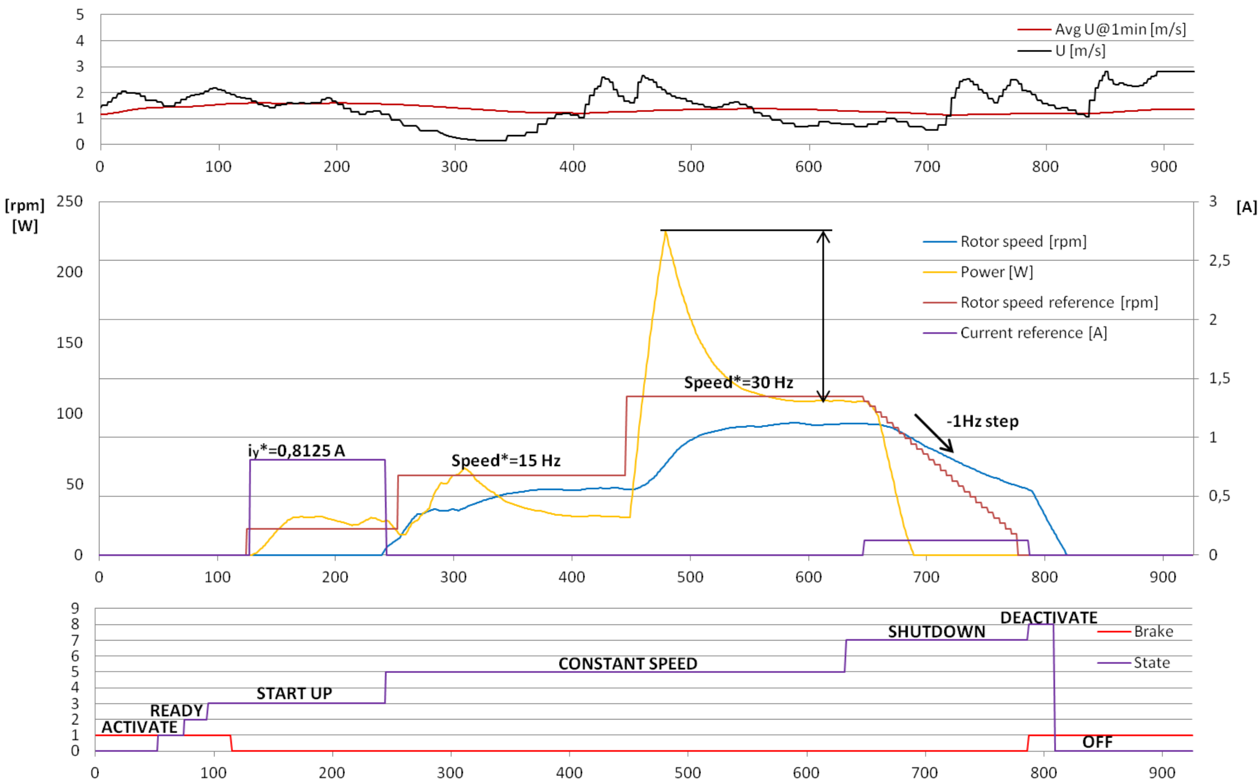

Figure 74 - Constant mode performance test

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.

As seen in Figure 74, during the acceleration stage the rotor speed in blue is plotted as zero. This is a drawback from using the *fake theta* to start-up the generator, which prevents the correct measuring of the generator speed during the acceleration stage by overwriting its value to zero to avoid measuring the high oscillating signal that is created before the generator starts spinning. This detail will be approached once again in section 6.3.3.

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 effort to accelerate the rotor is clear, and the consumed power drops from 220 W to around 100 W. 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.

The PI controller for the speed is clearly not performing optimally, since the actual rotor speed evidences an offset and never reaches the imposed reference. In a first approach, an attempt of tuning the integrator parameter on the speed PI was made, but no improvements were registered. The reason for this might be related to the word size attributed to the speed measurement fixed-point variable *lp_speed_omega [Hz]* in the FPGA, set as 16 bits. The offset may be a result from the error calculated between the speed reference and the speed measurement being rounded to zero when it is a very small value, due to the resolution of the word size, causing the system not to apply the adequate feedback correction. It is thought that an increase of the fixed-point word size from 16 to 25 bits would result in a better functioning of the integrator.

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.

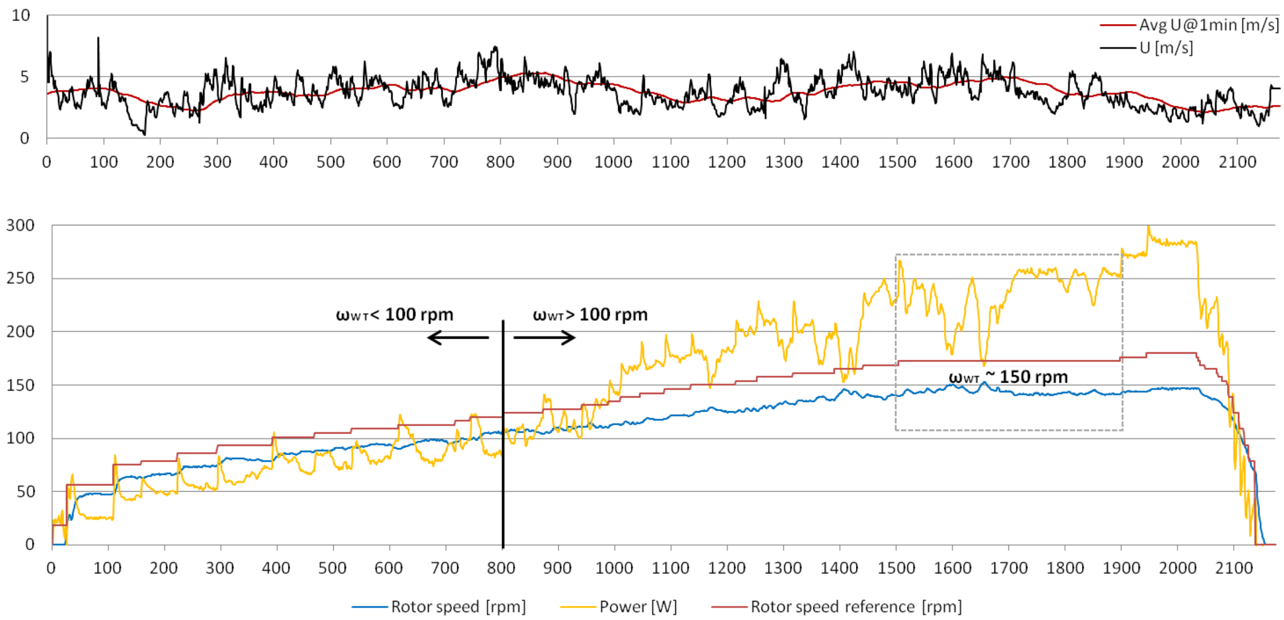

Figure 75 - Test at different rotor speeds up until 150 rpm

Figure 75 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, the power stabilizes regardless of the influence of the wind speed, which demonstrates that below this rotor speed value, wind speeds in the order of 5 m/s have no contribution to power generation. 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.

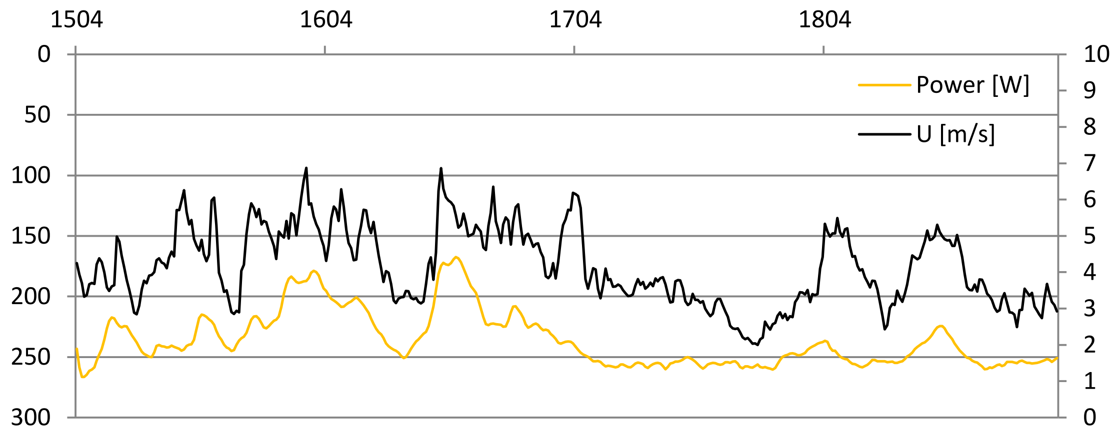

Figure 76 - Power fluctuations due to the effect of the wind at 150 rpm

Figure 76 illustrates the power fluctuations due to the wind, showing that at 150rpm 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. The turbine was ran at different rotor speeds and the power consumption was plotted against the instantaneous wind speed. 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 77. 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).

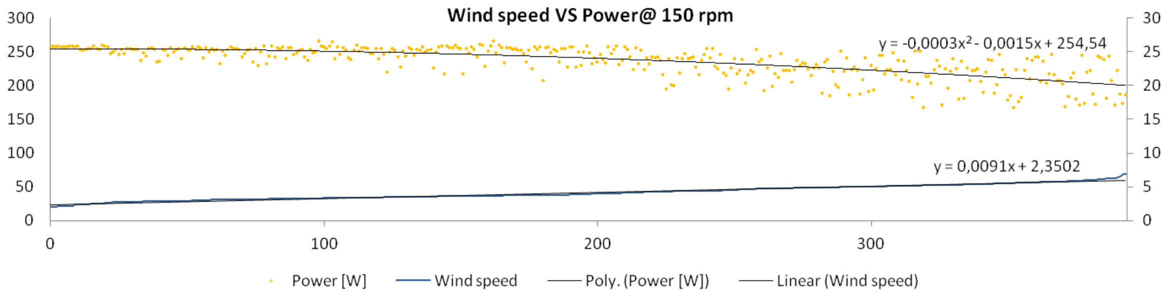

Figure 77 - Polynomial regression of the power and wind speed

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 8 - 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 9. It is however possible to investigate the tip speed ratio λ (TSR) occurring at the situation of minimum power consumption. Tip speed ratio is calculated with equation (4) given in chapter 2.3, using a rotor radius of 1 meter. 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.

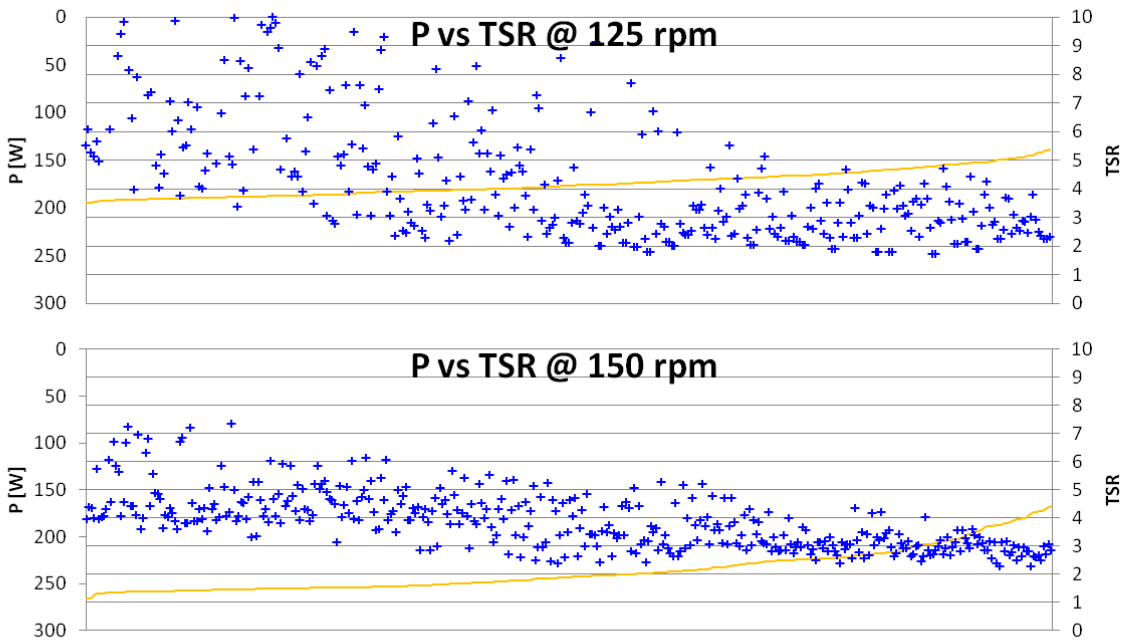

Figure 78 - Plot of power VS tip speed ratio dispersion

As mentioned previously, for the tests performed in a range between 50 and 150 rpm 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 78. The results show that the minimum power consumption is attained for a λ of around 2,5 for the rotor speeds tested (Table 9).

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

Table 9 - Tip speed ratios correspondent to minimum power consumption

6.3.2 Maximum power extraction with induced start-up

In this test, the MPPT mode with motor start-up is put in operation. In this mode, the control system must reverse the direction of power flow from motor to generator mode and keep the machine in a viable tip speed ratio regime in order to search for the peak power operation point using the method described in 5.3.2.

The wind speed 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.

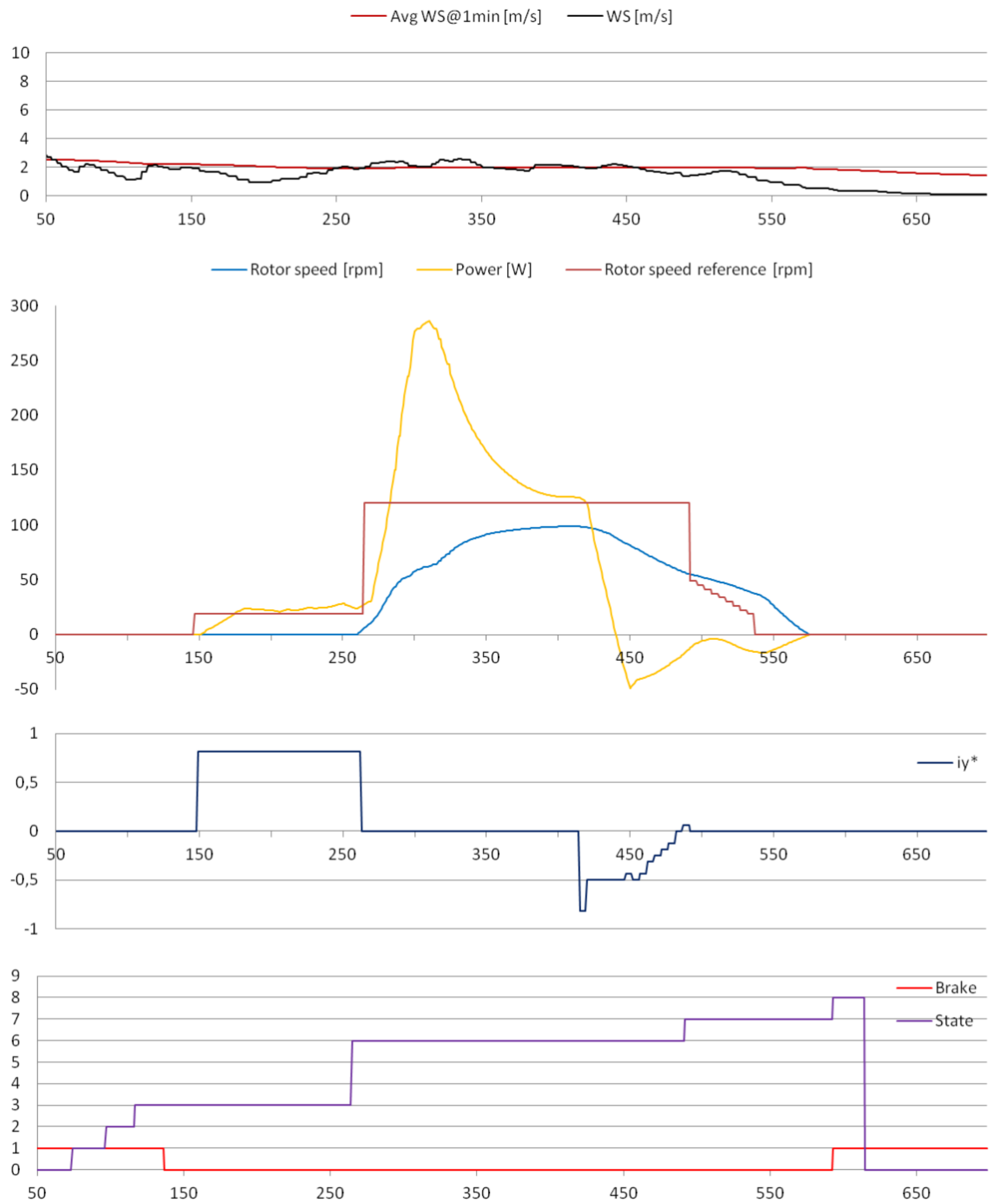

Figure 79 - Performance test of the MPPT Motor method

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 79. 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 80 for a more detailed visualization.

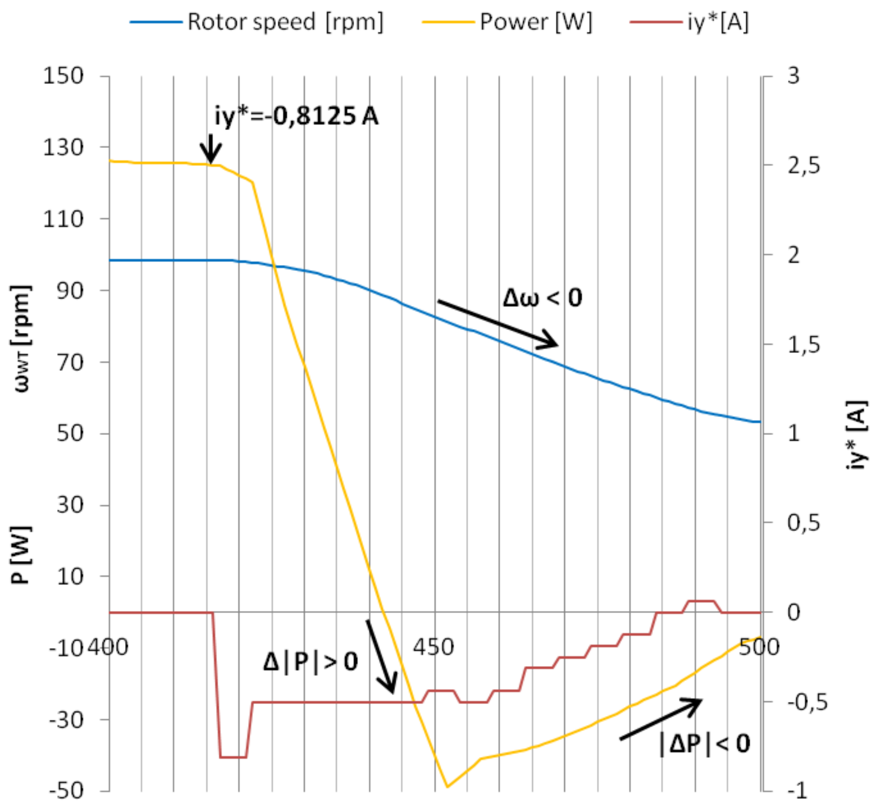

Figure 80 - Close-up of the MPPT Motor test

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 identifies 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 79 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.

6.3.3 Maximum power extraction with freewheeling start-up

During the performance tests phase no wind speeds were registered that were capable of making the wind turbine rotor start freewheeling reaching a sufficient rotation on its own to start production, so the programming of this mode was not effectively tested. However, as described in the implementation section, the code for the MPPT method is exactly the same except that the generator is not accelerated as a motor before starting production.

There is however a detail that should be considered regarding the measurement of the rotor speed while the rotor is freewheeling. The criteria that was implemented in the program to proceed from freewheel START UP to the MPPT mode is that the rotor reaches a minimum rotational speed suitable to start production. The problem here is that the generator side converter is not being regulated yet, which means that the *fake theta* variable is on, which by definition sets the generator speed reading *lp speed_omega_electric[Hz]* to zero. If the *fake theta* variable is disabled, large amplitude oscillations are generated in the rotor speed measurement. A simple test to verify this was made by rotating the wind turbine shaft manually while the *fake theta* was disabled and recording the rotor speed measurement, as illustrated in Figure 81.

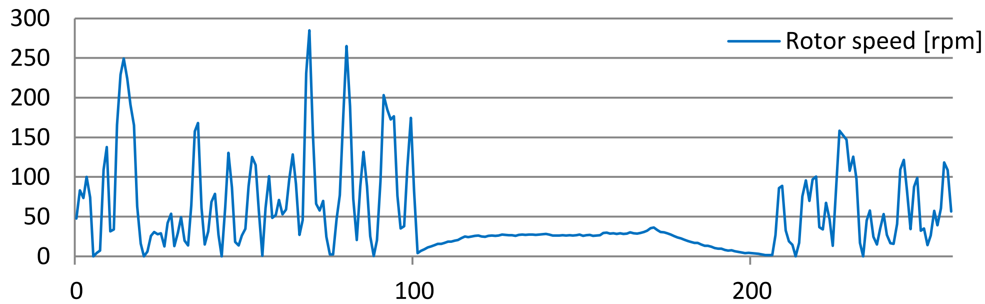

Figure 81 - Oscillations in rotor speed measurement with *fake theta* off

This rotor speed measurement problem needs to be taken in consideration in future works in order to enable this mode of operation.

7 Discussion

7.1 Performance tests

The polynomial regressions made on section 6.3.1 suggest that power production will not start below wind speeds in the order of 10 m/s (Table 8), 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 9), 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).

It was intended to investigate the power coefficient C_p of the wind turbine rotor, but this goal was not fulfilled. The fact that the wind varies stochastically with no immediate predictability, makes it is impossible to run tests at a fixed wind speed in order to plot individual power VS rotor speed curves. With the instantaneous wind speed oscillations, the variations in power cannot be related to a value of rotor speed because the wind speed is not constant and the operating points oscillate between wind speed "curves", as illustrated in Figure 82.

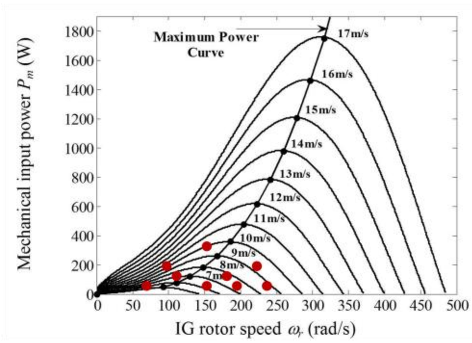

Figure 82 - Illustration of the dispersion of operating points due to unsteady wind speeds

7.2 Experimental conditions and sources of error

The wind turbine that is object of study in this project is an original and experimental design from the company EXAMEC, about which there are no previous aerodynamic studies.

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 1 minute average wind speed measurements went over 5 m/s. The statistical yearly distribution of wind speed for Malmö, Sweden shown in Figure 83 indicates that in the season of the year when the performance tests took place (June) the wind speed reaches its minimum annual average value.

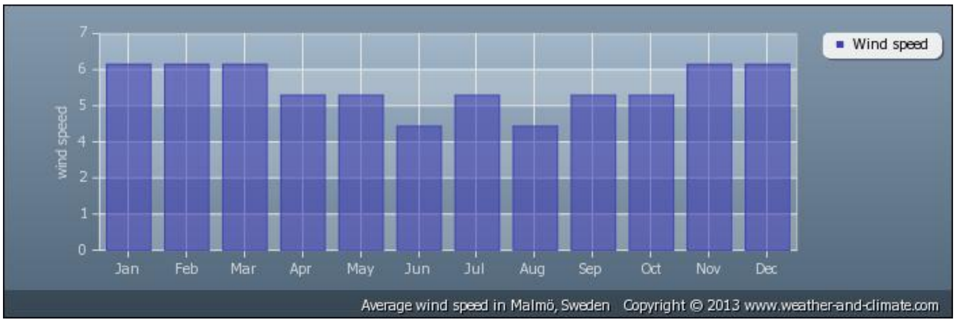

Figure 83 - Average wind speed in Malmö, Sweden [www.weather-and-climate.com]

The location of the wind turbine setup is not the most adequate due to the proximity of obstacles like trees and higher buildings, as shown in Figure 23 of section 4.4.1, which disturb the air flow and reduce the quality of the incoming wind. It is also possible that the rotor might be inside a wind shadow zone with high turbulence, as depicted in Figure 84. 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.

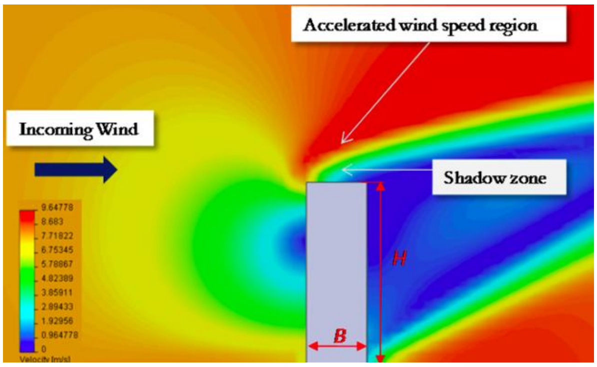

Figure 84 - CFD simulation of the wind speed distribution around a building

Since the turbine setup is installed on site as a real energy conversion unit and the stochastic and extremely variable wind is the only input available, it is not possible to run controlled laboratorial experiments with constant wind speeds as would be easy to do e.g. in a wind tunnel. Therefore, and in the absence of any technical information on the PMSG parameters, it is a very challenging task to assess the performance of the algorithms and evaluate the accuracy of the estimations produced from testing, at least during summer time.

7.3 Safety of the installation

One of the main goals of this project is to ensure that the turbine setup operates in safety conditions to extend its lifetime and most importantly, to avoid the occurrence of any accidents or damages caused by the wind turbine. This is achieved in a number of ways:

- The wind speed monitoring sets safe limits for the operation of the wind turbine, so it is not active during periods with very high wind speeds like storms, that could represent danger if the turbine was operating unmonitored;
- The creation of an *Emergency* button on the control interface provides an extra safety feature by allowing the operator to immediately interrupt operation in case of an extreme situation or if the turbine goes uncontrolled for some reason and possibly avoid an accident;
- The mechanical brake system installed works in a defensive way against power outages. As explained in 4.4.3, the piston that unlocks the drum brake is extended by an electrical command and kept in that position with compressed air until commanded to pull back. However, in the eventuality of a power outage while the turbine is in operation, the brake loses the electrical signal and automatically returns to the braking position thus protecting the rotor from freewheeling unloaded which in case of very high speeds could take it up to structurally hazardous speeds;
- The meteorological mast is directly connected to the Compact RIO which, due to its exposed location on the roof, could lead to material damage in case of a lightning strike. The cable with the wind speed measurement to the Compact RIO is going through a resistance that obstructs the transmission of very high currents but causes no effect on the low amplitude voltage signal from the anemometer.

7.4 Evaluation of the success of the project

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 programming was a long and iterative process, with situations of the kind "one step forward, two steps backward". 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, as explained in 7.2.

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.

8 Conclusions and recommendations for future work

The successful development and implementation of the control system enables automatic monitoring and operation of the wind turbine. The state sequence is up and running and the Human Machine Interface was programmed with the intention of facilitating experimentation and manipulation of relevant variables.

The wind speed measurement is accurately acquired to the control system and used as an input for the transitions between states. The mechanical brake is installed and connected to the control system. The remote panel interface to Vattenhallen and the webcam streaming are online so that the wind turbine can be displayed in the science centre of LTH while in operation.

The control modes were implemented and tested, proving to be operating as intended although the wind conditions have not allowed producing 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, although the wind speeds were not adequate for testing it, 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 lack of favourable wind conditions and the consequent 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.

Some suggestions of future improvements to be made to the system:

- The freewheeling start-up MPPT needs a rotor speed measurement as a transition from the start-up state to the production state. However, since the variable *fake theta* is active during the freewheel acceleration to set a reference for initiating the generator speed measurement, the generator speed value is set to zero by definition, although the rotor is already spinning. This can be solved in two ways, either by installing a tachometer in the rotor shaft to read the rotor speed directly and connect it to the system, or by creating a programming solution to distinguish the actual generator speed from the oscillations created from having the the *fake theta* disabled when the rotor starts from standstill, as illustrated in Figure 81.

- A suggestion to improve the effectiveness of the MPPT method is to make the current reference step variable, so that larger steps are taken when the operating point is further away from maximum extraction and smaller steps when it is reaching the peak of the curve. This implementation expected to cause the algorithm to reach the maximum power point faster with the larger steps and to stay closer to peak efficiency, by taking smaller steps around the maximum point.

- It is observable that the rotor speed reference is being tracked with an offset. The offset may be a result from the error calculated between the speed reference and the speed measurement in the speed PI controller being rounded to zero when it is a very small value, due to the resolution of the word size, causing the system not to apply the adequate feedback correction. It is thought that an increase of the fixed-point word size of the error variable from 16 to 25 bits would result in a better functioning of the integrator. A reduction on the sampling rate of the PID might also improve the speed reference tracking.

- If the turbine is to be operated at rotor speeds much higher than 150 rpm it is advisable that structural improvements are made to the turbine tower and fixings. Vibration and shaking were observed in the tower supports at rotor speeds above 120 rpm. It is important to gain knowledge about the structure's limitations to avoid reaching velocities that could lead to turbine damage or, even worse, to accidents or injuries to people passing by. It would be useful to install a vibration sensor in the turbine tower to monitor the oscillations and maximize the safety of the installation.

- It would be important to test the control modes at higher wind speeds, so testing the wind turbine during the winter, when average wind speeds are higher, might evidence a better performance on power production.

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10 Appendices

10.1 LabVIEW screenshots

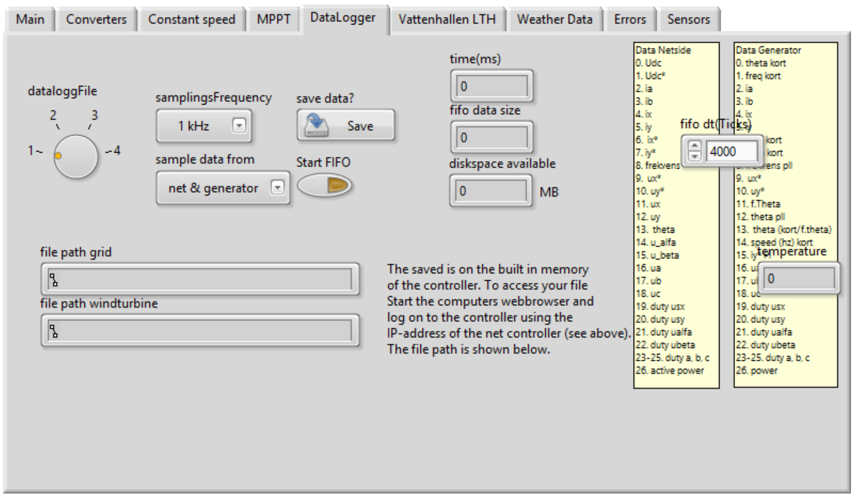

Figure 85 - HMI Datalogger tab

The *Datalogger* tab contains the controls for a secondary data logger that records data relative to the power converters' electrical parameters. This was programmed previously to this project.

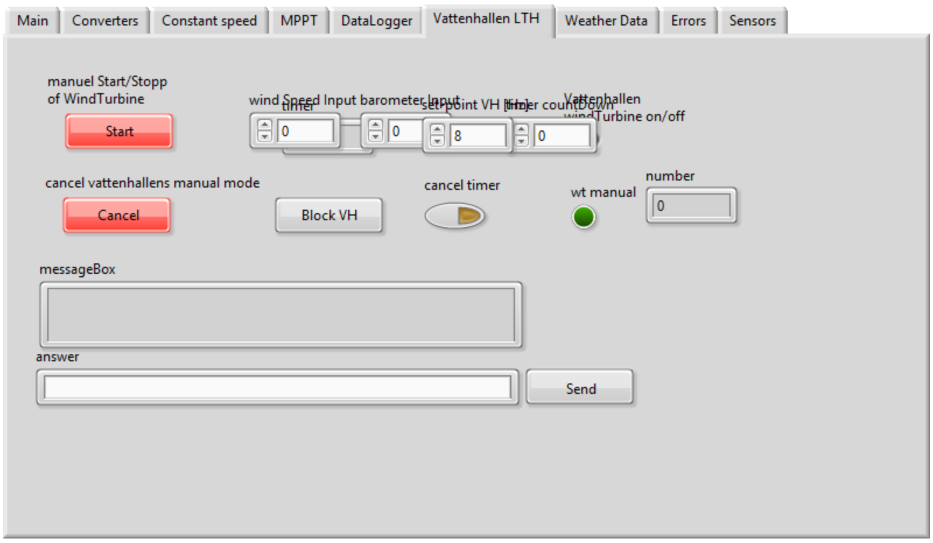

Figure 86 - HMI Vattenhallen LTH tab

The *Vattenhallen* tab allows the operator to decide if the remote panel interface can be used to start the turbine, or blocked. It also allows communication by instant messages.

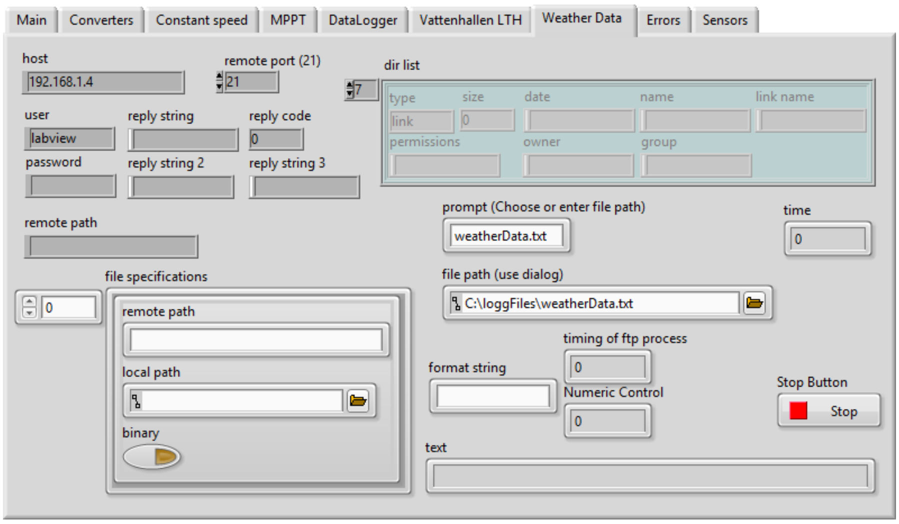

Figure 87 - HMI Weather data tab

The *Weather data* tab contains the indicators and controls for using the web-server data logger of the meteorological sensors to acquire the data, which is not operational since the wind speed is being acquired directly to the Compact RIO and not via FTP connection.

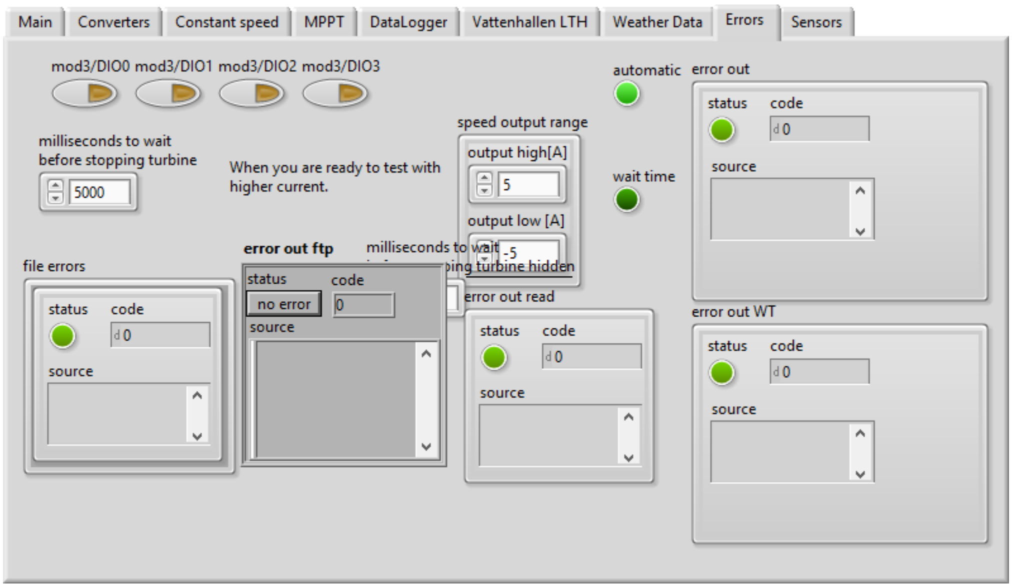

Figure 88 - HMI Errors tab

The *Errors* tab displays the status of the several error indicators throughout the code in order to identify the origin of possible programming mistakes or unusual situations.

Figure 89 - HMI Sensors tab

The *Sensors* tab displays the electrical signal coming from the wind speed measurement that is used for decoding, as well as indicators for the air temperature and pressure that are not being acquired to the control system yet.