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The Use of Automation Applications for Efficient Braking of Modern Wind Turbines

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Abstract: *The purpose of this research is to study the wind turbine brake system in order to describe the structure, function and efficiency of automation that slows down and / or immobilizes a wind turbine in high-wind conditions in order to prevent the wind turbine being destroyed. A description of the modules / components that make up this system is provided through pictures and figures. Firstly presented all the existing forms of renewable energy sources. Secondly, a theoretical analysis of the structure and operation of the wind turbine is made in order to clarify its individual functions by emphasizing the braking system. In the end, there is a theoretical comparison of efficiency in high wind blowing phenomena between two wind turbines (Vestas-Enercon), which have a leading position in Greece.*

Keywords –*Wind turbines, Renewable Energy, Wind Power, Sensors*

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I. Introduction

Using the wind is not a new idea. For hundreds of years, the famous Dutch windmills have faithfully pumped water, keeping land reclaimed or grinding grain. Today, the windmill’s modern equivalent - a wind turbine, uses the energy in the wind to generate electricity. In the 19th century the first wind turbine for electricity generation came into use, constructed by Charles Brush (inventor of several key technologies in the electrical industry). The turbine was 17 meters tall and had 144 cedar made rotor blades. Soon thereafter, Poul la Cour, a Dane, discovered that fast rotating wind turbines with fewer rotor blades generated electricity more efficiently than a slowly rotating wind turbines with many rotor blades. This opened the door to a number of wind turbine advances during the 20th century. [1] [2]

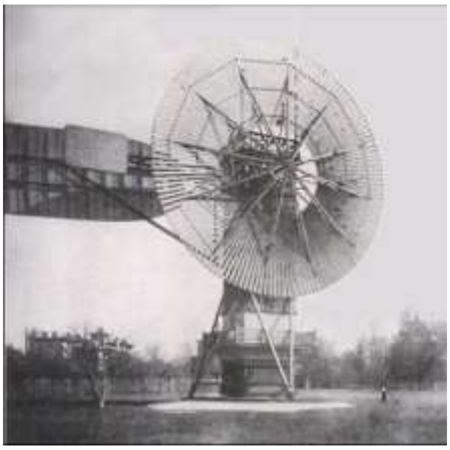

Figure 1: Charles Brush wind turbine

Nowadays, wind energy is one the fastest growing renewable energy technologies. The cumulative wind power capacity from 1999 to 2020 is shown in Fig. 2, and it can be seen that the wind power has grown fast to a capacity of 283 GW with ~45 GW installed only in 2012, and this number is expected to achieve 760 GW in 2020on moderate scenario. The wind power grows more significant than any other renewable energy sources and is becoming really an important player in the modern energy supply system. [3].

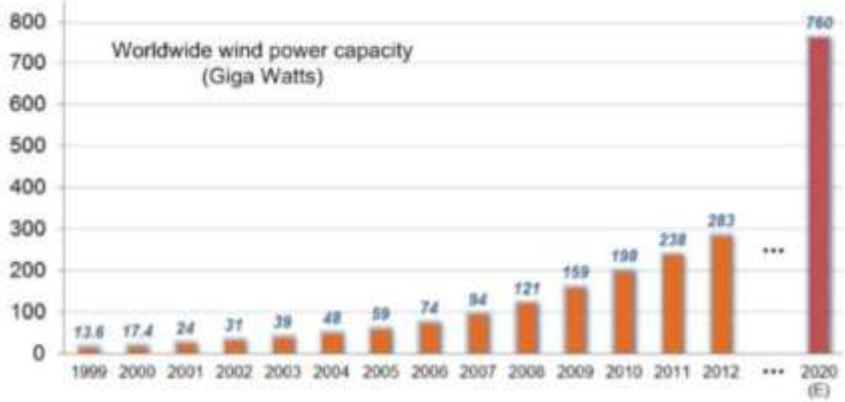

Figure 2: Global cumulative installed wind power capacity from 1999 to 2000

1.1 RENEWABLE ENERGY SOURCES (RES)

A wireless local area network (WLAN) connects two or more devices a short distance using a wireless distribution method, usually providing a connection through an access point for Internet access. The use of spectrum spreading or OFDM technologies can allow users to move within a coverage area, and still remain connected to the network (Stallings, 2011: 88).

There are many forms of renewable energy. Most of these renewable energies depend in one way or another on sunlight. Wind and hydroelectric power are the direct result of differential heating of the Earth's surface which leads to air moving about (wind) and precipitation forming as the air is lifted. Solar energy is the direct conversion of sunlight using panels or collectors. Biomass energy is stored sunlight contained in plants. Other renewable energies that do not depend on sunlight are geothermal energy, which is a result of radioactive decay in the crust combined with the original heat of accreting the Earth, and tidal energy, which is a conversion of gravitational energy. [4]

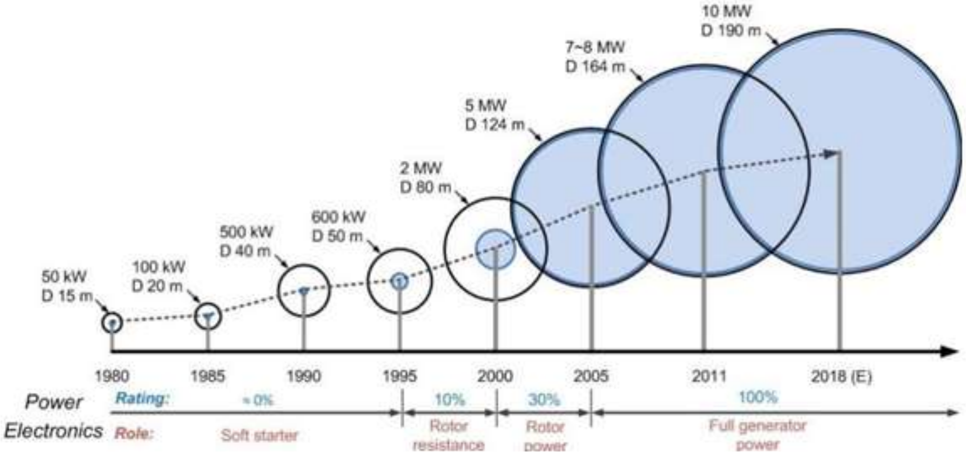

Figure 3: Power electronics rating and role

1.1.1 Solar

This form of energy relies on the nuclear fusion power from the core of the Sun. This energy can be collected and converted in a few different ways. The range is from solar water heating with solar collectors or attic cooling with solar attic fans for domestic use to the complex technologies of direct conversion of sunlight to electrical energy using mirrors and boilers or photovoltaic cells. Unfortunately these are currently insufficient to fully power our modern society.

1.1.2 Wind Power

The movement of the atmosphere is driven by differences of temperature at the Earth's surface due to varying temperatures of the Earth's surface when lit by sunlight. Wind energy can be used to pump water or generate electricity, but requires extensive areal coverage to produce significant amounts of energy.

1.1.3 Biomass

It is the term for energy from plants. Energy in this form is very commonly used throughout the world. Unfortunately the most popular is the burning of trees for cooking and warmth. This process releases copious amounts of carbon dioxide gases into the atmosphere and is a major contributor to unhealthy air in many areas. Some of the more modern forms of biomass energy are methane generation and production of alcohol for automobile fuel and fueling electric power plants.

1.1.4 Geothermal power

Energy left over from the original accretion of the planet and augmented by heat from radioactive decay seeps out slowly everywhere, every day. In certain areas the geothermal gradient (increase in temperature with depth) is high enough to exploit to generate electricity. This possibility is limited to a few locations on Earth and many technical problems exist that limit its utility. Another form of geothermal energy is Earth energy, a result of the heat storage in the Earth's surface. Soil everywhere tends to stay at a relatively constant temperature, the yearly average, and can be used with heat pumps to heat a building in winter and cool a building in summer. This form of energy can lessen the need for other power to maintain comfortable temperatures in buildings, but cannot be used to produce electricity.

1.1.5 Hydroelectric energy

This form uses the gravitational potential of elevated water that was lifted from the oceans by sunlight. It is not strictly speaking renewable since all reservoirs eventually fill up and require very expensive excavation to become useful again. At this time, most of the available locations for hydroelectric dams are already used in the developed world.

1.1.6 Tidal power or tidal energy

It is a form of hydropower that converts the energy obtained from tides into useful forms of power, mainly electricity. Tidal stream generators make use of the kinetic energy of moving water to power turbines, in a similar way to wind turbines that use wind to power turbines. Some tidal generators can be built into the structures of existing bridges or are entirely submersed, thus avoiding concerns over impact on the natural landscape. Land constrictions such as straits or inlets can create high velocities at specific sites, which can be captured with the use of turbines. These turbines can be horizontal, vertical, open, or ducted [5].

1.1.7 Other forms of energy

Hydrogen and fuel cells, these are also not strictly renewable energy resources but are very abundant in availability and are very low in pollution when utilized. Hydrogen can be burned as a fuel, typically in a vehicle, with only water as the combustion product. This clean burning fuel can mean a significant reduction of pollution in cities. Or the hydrogen can be used in fuel cells, which are similar to batteries, to power an electric motor. In either case significant production of hydrogen requires abundant power. Due to the need for energy to produce the initial hydrogen gas, the result is the relocation of pollution from the cities to the power plants. There are several promising methods to produce hydrogen, such as solar power, that may alter this picture drastically [4].

II. Wind Turbine Basics

The main components of a horizontal-axis wind turbine that are visible from the ground are its tower, nacelle, and rotor, as can be seen in Fig.4. The nacelle houses the generator, which is driven by the high-speed shaft. The highspeed shaft is in turn usually driven by a gear box, which steps up the rotational speed from the low-speed shaft. The low-speed shaft is connected to the rotor, which includes the airfoil-shaped blades. These blades capture the kinetic energy in the wind and transform it into the rotational kinetic energy of the wind turbine. [6].

Wind turbine control goals and strategies are affected by turbine configuration. HAWTs (Horizontal-Axis Wind Turbines) may be “upwind,” with the rotor on the upwind side of the tower, or “downwind.” The choice of upwind versus downwind configuration affects the choice of yaw controller and the turbine dynamics, and thus the structural design. Wind turbines may also be variable pitch or fixed pitch, meaning that the blades may or may not be able to rotate along their longitudinal axes. Although fixed-pitch machines are less expensive initially, the reduced ability to control loads and change the aerodynamic torque means that they are becoming less common within the realm of large wind turbines. Variable-pitch turbines may allow all or part of their blades to rotate along the pitch axis. [6]

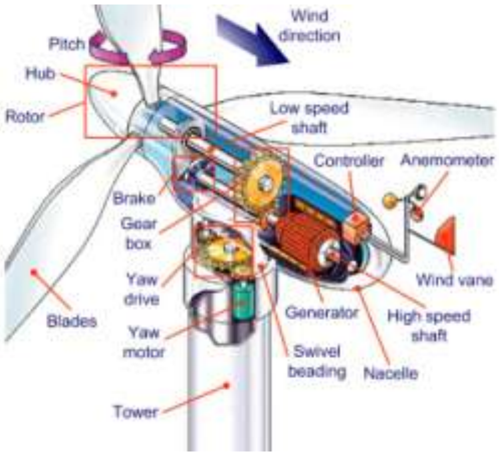

Figure 4: Main components of a horizontal-axis wind turbine

Moreover, wind turbines can be variable speed or fixed speed. Variable-speed turbines tend to operate closer to their maximum aerodynamic efficiency for a higher percentage of the time, but require electrical power processing so that the generated electricity can be fed into the electrical grid at the proper frequency. As generator and power electronics technologies improve and costs decrease, variable-speed turbines are becoming more popular than constant-speed turbines at the utility scale.

A perfect wind turbine cannot fully capture the power available in the wind. In fact, actuator disc theory shows that the theoretical maximum aerodynamic efficiency, which is called the Betz Limit, is approximately 59% of the wind power. The reason that an efficiency of 100% cannot be achieved is that the wind must have some kinetic energy remaining after passing through the rotor disc, if it did not, the wind would by definition be stopped and no more wind would be able to pass through the rotor to provide energy to the turbine. The aerodynamic efficiency is the ratio of turbine power to wind power and is known as the turbine's power coefficient, Cp. Cp can be computed as

$$Cp = \frac{P}{Pwind} \qquad (1)$$

where P is the power captured by the turbine and Pwind is the power available in the wind for a turbine of that size. The power Pwind is given by

$$P_{wind} = \frac{1}{2}\rho A {V_w}^3(t) \qquad (2)$$

where ρ is the air density, A is the 'swept area' of the rotor, and Vw is the instantaneous wind speed. The swept area is the circle described by the blade tip, or πR2, where R is the rotor radius. In (2), the wind speed Vw is assumed to be uniform across the rotor swept area.

Figure 5: Theoretical maximum power coefficient

III. Wind Turbine Operation

A wind turbine obtains its power input by converting some of the kinetic energy in the wind into a torque acting on the rotor blades (the actuator disc). The amount of energy which the wind transfers to the rotor depends on the wind speed, the rotor area, blade design (pitch angle) and the density of the air. Although there are many different configurations of wind turbines systems they all work in a similar way. [2].

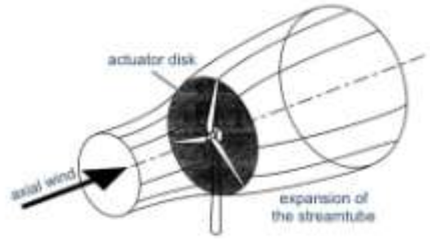

Figure 6: Wind Turbine operation

The turbine starts to produce energy when the wind speed is above Vcut −in and stops when the wind speed is below Vcut –off.

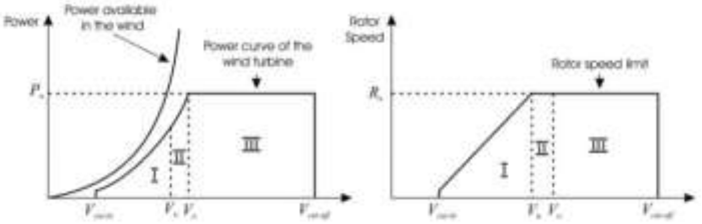

Figure 7: Different regions of wind turbine control

The control of a wind turbine consist three areas:

I. [$V_{cut\ -in}$ ... V_n] Area where the turbine operate at “variable-speed” with an optimal rotor speed giving maximal energy.
II. [V_n ... V_o] Operation around rated rotor speed, but below rated power.
III. [V_o ... $V_{cut\ -off}$] Turbine operate at full power and rated speed, pitch control active.

IV. Wind Turbine Control Loops

Utility-scale wind turbines have several levels of control, which can be called ‘supervisory control,’ ‘operational control,’ and ‘subsystem control.’ The top-level supervisory control determines when the turbine starts and stops in response to changes in the wind speed, and also monitors the health of the turbine. The operational control determines how the turbine achieves its control objectives in Regions II and III. The subsystem controllers cause the generator, power electronics, yaw drive, pitch drive, and other actuators to perform as desired. In this section, we will move through the operational control loops shown in Fig. 8, describing the wind inflow, sensors, and actuators in more detail while treating the subsystem controllers as black boxes. The details of the subsystem controllers are beyond the scope of this paper, and the reader is referred to [7], [8] for an overview of these lower-level controllers. [6].

4.1. WIND INFLOW

The differential heating of the earth’s atmosphere is the driving mechanism for the earth’s winds. Numerous atmospheric phenomena, such as the nocturnal low-level jet, sea breezes, frontal passages, and mountain and valley flows, affect the wind inflow across a wind turbine’s rotor plane [7]. From Fig. 3, the rotor plane of modern megawatt utility-scale wind turbines span from 15 D (diameter) to 190 D over the last decades. Given this large size of wind turbine rotor planes, and the variability of wind, it is virtually impossible to obtain a good measurement of the wind speed encountering the entire span of the blades from in situ sensors mounted on the nacelle or turbine blades. The available wind resource is often characterized by the average wind speed, the frequency distribution of wind speeds, the temporal and spatial variation in wind speed, the most frequent wind direction (i.e., prevailing wind direction), and the frequency of other wind directions [6]. How consistently the wind blows above the rated wind speed for a given turbine will determine how often the turbine will be operating in Region III at its maximum rated power generation capacity. To accurately predict capacity factors and maintenance requirements for wind turbines, it is important to be able to understand wind characteristics over long (multi-year) as well as short (second and sub-second) time scales.

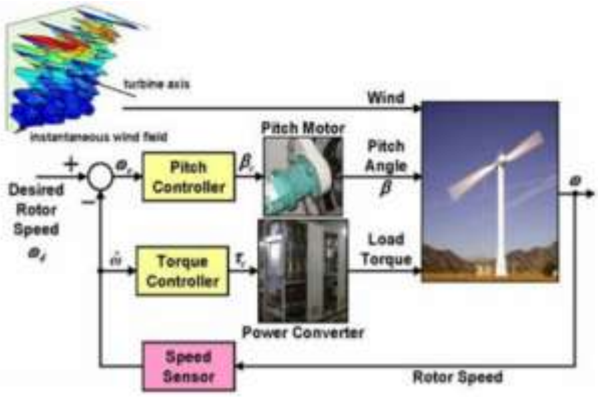

Figure 8: Wind Turbine operational control loops

4.2. SENSORS

A typical commercial wind turbine has surprisingly few sensors for its size and complexity. As shown in Fig. 8, only rotor speed measurements are typically used in feedback for basic control in both Region II and Region III. Since the gear box ratio is known, speed can be measured on either the high speed (generator) or low speed (rotor) shafts. In addition to rotor speed measurements, wind turbines usually have anemometers for supervisory control purposes, in particular to determine if the wind speed is sufficient to start turbine operation. Most turbines have an anemometer and a wind vane located on top of the nacelle (at approximately hub height) for measuring wind speed and wind direction. This anemometer provides limited measurements of wind speed only at hub height. Moreover, because of the interaction between the rotor and the wind, this usual placement of anemometers on nacelles leads to inaccurate wind speed measurements. In fact, the interaction extends both upwind and downwind of the rotor, so good wind measurements cannot be achieved during operation on either upwind or downwind turbines. Further, nearly all utility-scale wind turbines also have power measurement devices. Power measurement is necessary for keeping track of a turbine's energy generation. Other sensors that are sometimes found on wind turbines and whose measurements have been used in more advanced wind turbine controllers include [6]:

- Strain gauges on the tower and blades,
- Accelerometers,
- Position encoders on the drive shaft and blade pitch actuation systems, and
- torque transducers

When selecting sensors for use in wind turbine control, sensor reliability is of critical importance. A faulty sensor can reduce turbine availability, especially if the sensor is required for control.

4.3. ACTUATORS

Modern utility-scale wind turbines typically have up to four main types of actuators. They are important features of concern in the operation of the WT [9] [10]:

Pitch: The pitch system is a mechanical, electrical, or hydraulic device, acting on the blade root to turn it in both directions. The pitch system has a crucial role on the turbine, not only because it is the main actuator but also because of the safety of the machine. An incorrect operation of the pitch system causes the turbine to suffer dramatic and irreversible damage. To avoid this situation, in modern and large WTs, an autonomous and independent pitch system has to be implemented in each blade to achieve redundancy and reliability; if some error or malfunction occurs, the other two blades go to the safety position, stopping the machine. An energy storage device is also required to be able to move the blades during a grid loss.

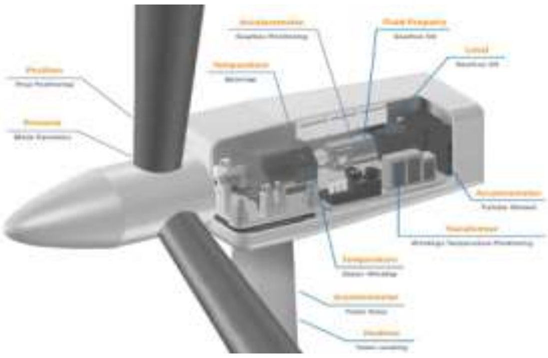

Figure 9: Wind Turbine sensors

- Torque: The generator torque is the other main actuator of a WT. It is manipulated by means of a power drive or electrical converter. Its action response is fast, but smaller than the one of the pitch system. Generator torque is used below rated with the aim of maximizing the aerodynamic efficiency, as explained below.

Figure 10: Wind Turbine Pitch

- Yaw: The yaw system is in charge of tracking the wind direction. It usually turns at a constant speed. Thus, a very simple configuration consisting of several motors working together is enough to position the nacelle.

Figure 11: Wind Turbine Yaw

- Brakes: The shaft brakes consist of some hydraulic devices that are able to actuate over the high-speed shaft. Modern direct-drive machines usually do not need a shaft brake, and the rotor is stopped only by means of a highly reliable pitch system.
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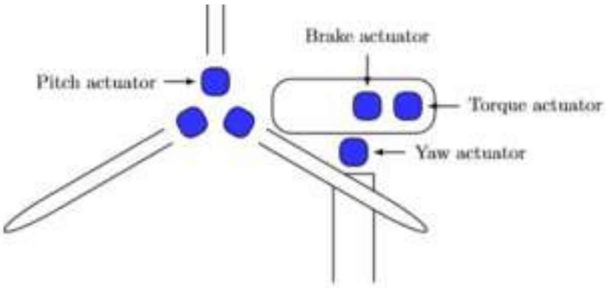


Figure 12: Wind Turbine Brakes System

4.4. MAIN CONTROL LOOPS

The main control loops of the WT are torque, pitch, yaw angle, external grid and supervisory control and data acquisition. Pitch and yaw control are the typical main loops for power limitation. The primary Region II control objective for a variable speed wind turbine is to maximize the power coefficient Cp. For modern HAWTs, this power coefficient is a function of the turbine's tip-speed ratio λ, which is defined as

$\lambda=(\omega\cdot R)/V$ (3)

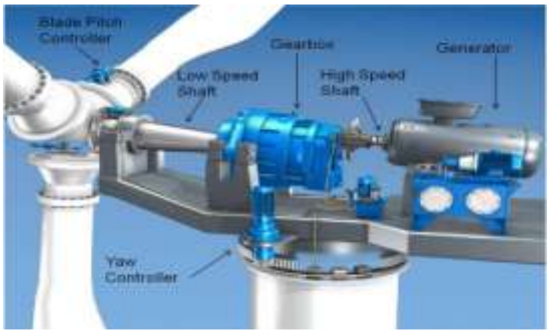


Figure 13: Wind Turbine Main Control Loops

In (3), ω is the rotational speed of the rotor, and R and v are the rotor radius and instantaneous wind speed, respectively. Thus, the tip-speed ratio is the ratio of the linear (tangential) speed of the blade tip to the wind speed, where R is fixed for a given turbine, V is always time-varying, and ω is time varying for a variable-speed turbine. For modern HAWTs, the relationship between the power coefficient Cp and the tip-speed ratio λ is a turbine-specific nonlinear function. Cp also depends on the blade pitch angle in a nonlinear fashion, and these relationships have the same basic shape for most modern HAWTs. [6] Tip-speed ratio depends on the incoming wind speed V and therefore is constantly changing. Thus, Region II control is primarily concerned with varying the turbine speed to track the wind speed. On utility-scale wind turbines, Region III control is typically performed via a separate pitch control loop, as shown in Figure 8. In Region III, the primary objective is to limit the turbine power so that safe electrical and mechanical loads are not exceeded. Power limitation can be achieved by pitching the blades or by yawing the turbine out of the wind, both of which can reduce the aerodynamic torque below what is theoretically available from an increase in wind speed.

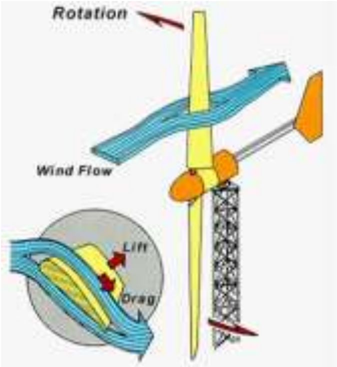


Figure 13: Principles of Wind Turbine Aerodynamic Lift

The main purpose of the pitch system is to control the rotor speed ω. This can be accomplished by limiting the incoming aerodynamic torque by moving the pitch angle β. There are two possible strategies to accomplish this: pitch to feather and pitch to stall. The methodology to design the pitch control loop is based on the dynamic model of the aerodynamic torque (see Chapter 12 of ref [9] for more details). Tr (is the mechanical torque at the shaft due to the wind) can be expressed as a nonlinear function that depends on the rotor speed ω, the wind speed V, and the pitch angle β. A simple linear proportional-integral-derivative (PID) controller is a good starting point, although further considerations need to be observed. As wind speed increases, the ∂ω/ ∂β ratio becomes higher (see Chapter 12 ref [9]). The controller will take this effect into account in order to keep the mechanical fatigue within the design limits and to guarantee the system stability. The design is carried out by using robust and/or adaptive control strategies. Additionally, a good controller should filter the resonance modes of the blades, tower, drive-train, gears, etc., as well as the frequencies related to the rotor revolution, blade crossing in front of the tower, and some multiple. The increasing size of WTs and the use of larger and more flexible structures result in a more demanding design of the pitch control system (see Chapters 14 and 15, Section 15.3 of ref [9]).

The main objective of the yaw controller is to follow the wind direction, maximizing the energy capture, unwinding the cable when necessary, and avoiding any kind of dangerous gyroscopic effects or oscillatory behavior. A closed control loop is needed to compensate this effect. A wind vane in the nacelle supplies the reference angle to the controller, which sends a signal to the yaw actuators to move the nacelle toward the wind direction.

4.4.1. Safety System

The safety system is a redundant hardwired security chain with autonomy to shut down the WT in a secure mode under all circumstances. The safety system is capable of driving back the blades to the feather position, to switch off every electrical device, to provide an emergency digital signal to the controller, and to generate an appropriate alarm for the maintenance staff. Physically, it consists of a long path of contacts in series, beginning by a power supply, which provides a reference voltage, and ending in a safety relay. The open¬ing of any contact causes the loss of that reference voltage. Thus, the safety relay breaks the "OK" hardwired signal of every subsystem (converter, pitch, yaw, brakes, etc.) causing the turbine to stop in a safe manner. [9]

4.4.2. Overspeed protection (V > cut-out speed)

The safety system is a redundant hardwired security chain with autonomy to shut down the WT in a secure mode under all circumstances. The safety system is capable of driving back the blades to the feather position, to switch off every electrical device, to provide an emergency digital signal to the controller, and to generate an appropriate alarm for the maintenance staff. Physically, it consists of a long path of contacts in series, beginning by a power supply, which provides a reference voltage, and ending in a safety relay. The open¬ing of any contact causes the loss of that reference voltage. Thus, the safety relay breaks the "OK" hardwired signal of every subsystem (converter, pitch, yaw, brakes, etc.) causing the turbine to stop in a safe manner. [9]

1. Aerodynamic Brake System: The primary braking system for most modern wind turbines is the aerodynamic braking system, which essentially consists in turning the rotor blades about 90 degrees along their longitudinal axis (in the case of a pitch controlled turbine or an active stall controlled turbine), or in turning the rotor blade tips 90 degrees (in the case of a stall controlled turbine). These systems are usually spring operated, in order to work even in case of electrical power failure. Experience has proved that aerodynamic braking systems are extremely safe. They will stop the turbine in a matter of a couple of rotations, at the most. In addition, they offer a very gentle way of braking the turbine without any major stress, tear and wear on the tower and the machinery.
2. Mechanical Brake System: For reliability, a mechanical brake supplements the aerodynamic braking system in wind turbines. It also doubles as a parking brake when a stall controlled turbine is stopped. Its design draws on automobile brakes designs, but on a larger size scale. In the case of a pitch controlled turbine, the mechanical brakes need to be used only during the blades are pitched to a 90o degrees angle. [11] Mechanical and aerodynamic brakes must work independently. Mechanical brakes consist of a steel brake disc acted on by one of more brake calipers. It can be situated on the rotor shaft (Low-speed shaft) or on between the gearbox and the generator (High-speed shaft). The latter option is the most used nowadays.

Figure 14: Mechanical Brake System

V. Comparison & Conclusions about Enercon-Vestas

Taking into account the power curve of each wind turbine (Figure 15, 16) and the characteristic values of the wind speeds (Figure 17, 18, 19), we remark that the cut-out speed, which represents the speed above which the wind turbine stops operating for safety and stress prevention purposes, it shows different values of each wind turbine, namely Enercon E-82 is 34m / s versus Vestas V90 which is 25m / s. In conclusion, in high wind gusts, Enercon is superior, as it shut down after higher wind speeds. Moreover we remark that Enercon's power output compared to Vestas remains at higher values for corresponding wind speeds. So the choice of wind turbine is a purely personal choice of the individual designer / interested buyer, who is also the one who determines the desired goals for the respective project.

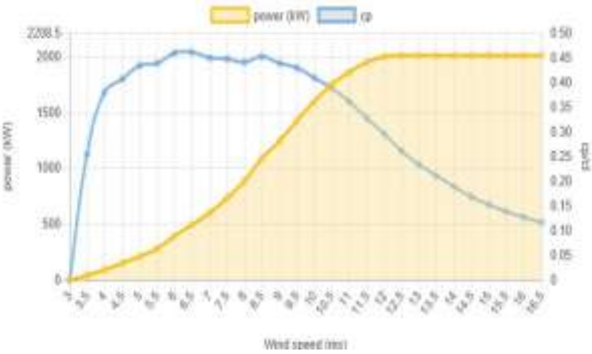


Figure 15: Vestas V90 power curve

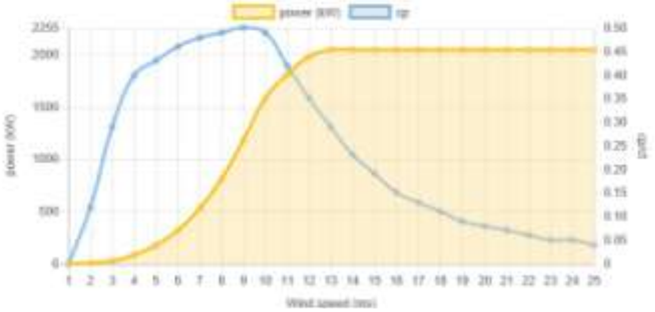


Figure 16: Enercon E-82power curve

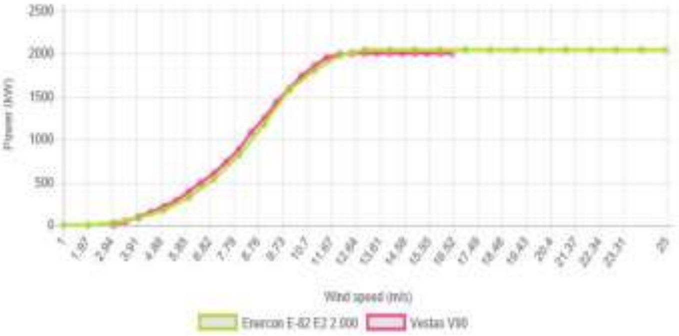
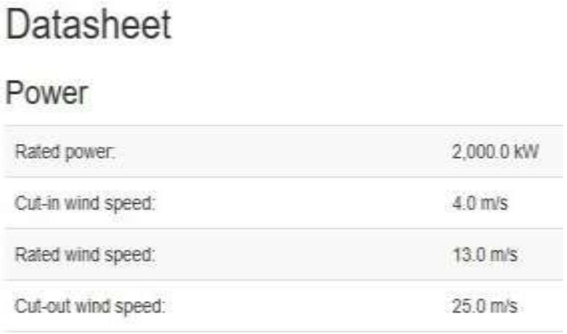


Figure 17: Characteristic values of the wind speeds Diagram

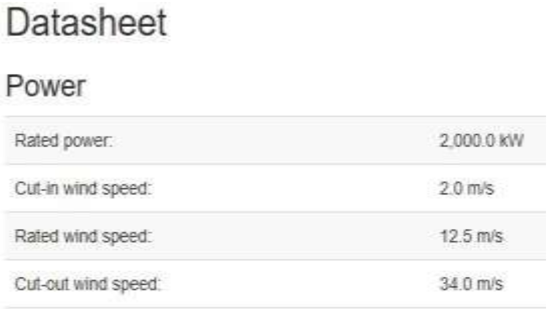


Datasheet

Power

Rated power:	2,000.0 kW
Cut-in wind speed:	4.0 m/s
Rated wind speed:	13.0 m/s
Cut-out wind speed:	25.0 m/s

Figure 18: Vestas V90 Characteristic values of the wind speeds



Datasheet

Power

Rated power:	2,000.0 kW
Cut-in wind speed:	2.0 m/s
Rated wind speed:	12.5 m/s
Cut-out wind speed:	34.0 m/s

Figure 19: Enercon E-82 Characteristic values of the wind speeds

VI. Acknowledgements

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