MPPT P&O control system based on buck type converter for low power wind turbine.

Juan Ramos
Pontifical Javeriana University, Cali, Colombia, jgrm97@javerianacali.edu.co
ORCID: 0000-0002-5162-7909

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Abstract: In this paper, the basic theory about the aerodynamic phenomena in a turbine that are necessary to understand the flow of power through the system and how it is affected by different factors is exposed. Then, in the following sections, the different types of electrical and electronic elements that are implemented in wind turbine systems are explored, as well as the different types of more popular MPPT algorithms. Next, the mechanisms are shown by means of which the modification in the power extraction by the MPPT algorithms is explained.
Towards the end of the document, the wind turbine model implemented in Simulink is shown, the elements of the system are detailed, and output power measurements are made in order to determine the improvements in extraction provided by adding a P&O-type algorithm to through a Buck type DC converter on the generator side.

***Keywords**: MPPT, perturb and observe, wind turbine, buck converter.*

I. INTRODUCTION.

The consumption and production of energy can be seen as one of the most telling indicators about the level of development and economic-industrial growth of a country, so that the rapid increase in current economies goes hand in hand with an increase in the demand for energy. electric power generation. This situation is evidenced in countries with a high development index such as Norway, Switzerland, Australia, Iceland, Canada, the United States and Finland, which in turn are among the countries with the highest consumption of electrical energy per capita [1] [2]. Between 2006 and 2016, world consumption went from 130TWh to around 155TWh, a 19% increase. It is expected that by 2030 the increase will be 52% [3].

Currently the most widely extended ways to supply this gigantic consumption of electrical energy are based on conventional generation sources, through the exploitation of non-renewable resources such as hydrocarbons, coal, oil, natural gas, among others. For the year 2017, 75.5% of electrical energy production was supplied by non-renewable sources, while the remaining 24.5% corresponds to emerging generation systems with alternative sources, within this percentage is the traditional hydroelectric exploitation [4].

Representing, until 2016, 4% of the total produced with renewable sources, are the wind generation systems, one of the alternative forms that present greater development. In the period between 2005 and 2015 the global wind generation capacity increased by 63% with a generation of 433GW [5]. By 2019, wind power generation becomes about 25% of the total generated with renewable sources [6]. Wind energy is classified as one of the most attractive forms of renewable energy due to its characteristics, zero generation of waste, zero pollution to the environment, high energy production capacities (areas with wind potential) and its attractive costs of implementation, are some of its advantages.

II. THEORY.

The power generated by a wind turbine is the result of the transformation of the kinetic energy contained in the wind to electrical energy produced by the rotation of the generator rotor. However, the total kinetic energy of the wind cannot be fully exploited because, if this were the case, the wind passing through the wind turbine blades would have a speed equal to zero, which does not happen in reality.

In a way, the fact that not all the wind energy can be harnessed makes it possible for the wind turbine to rotate. This harvest limit is explained by Betz's law. Throughout this chapter, this theory, vital when it comes to understanding this limit, will be presented.

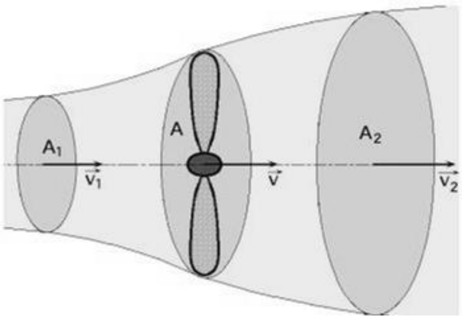

Figure 1. Air flow through the ideal wind turbine. Source: EADIC, University of Alcalá. [7]

As you can see in the Figure 1. the wind has a speed $v1$ with which it crosses the area 1 ($A1$), a speed v with which it crosses the area covered by the blades (A) and finally when crossing the blades the wind has a speed $v2$. Where $v2 < v < v1$.

Power due to the kinetic energy of the wind. [8]

The total power available in an air mass that passes through a certain area A, moving at a speed v, with density ρ, is given by the following equation [7]:

$$P_w = \frac{1}{2}\rho A v^3 \quad (1)$$

The Eq. (2) shows how the maximum power extracted by an ideal wind turbine is given in terms of a maximum power coefficient or Bezt limit.

$$P_{Útil} = \frac{16}{27}P_w = 0.5926 * P_w \quad (2)$$

Where the relationship between $P_{Útil}$ and P_w is the power factor or power coefficient of the wind turbine:

$$C_p = \frac{P_{Útil}}{P_w} \quad (3)$$

The maximum power factor will be $C_{pmax} = 0.5926$.

A convenient expression involving the effective area, the construction parameter of the wind turbine, is:

$$P_{Útil} = C_p * \frac{1}{2}\rho\frac{\pi D^2}{4}v^3 \quad (4)$$

Tip-speed ratio or TSR.

The blades of a wind turbine work optimally, that is, they produce maximum power, when they rotate at a certain speed. This speed is known as specific speed, although it is really a dimensional coefficient, it relates the speed of the blades to the wind speed and depends on the wind turbine's construction parameters such as the number of blades, inclinations or pitch angles, curvatures, among other factors.

$$\lambda_0 = \frac{u_0}{v} \quad (5)$$

u_0: *blade tip speed*
v: *wind speed*

The TSR can be expressed in terms of the rotation speed of the wind turbine (n in [r.p.m]) as follows:

$$u_0 = \frac{2\pi R}{60}n \quad (6)$$

$$\lambda_0 = \frac{\pi D}{60v}n \quad (7)$$

The Eq. (7) shows how depending on the variation of the rotational speed of the rotor, different values of specific speed can be obtained, which presumes the possibility of obtaining the optimal specific speed from the control of the rotational speed n.

It is possible to know what speed of rotation makes the specific speed the optimal one by clearing n from Eq. (7) and using the specific speed given by the wind turbine manufacturer for the calculation.

$$n_{opt} = \frac{60\,\lambda_{opt}\,v}{\pi D} \quad (8)$$

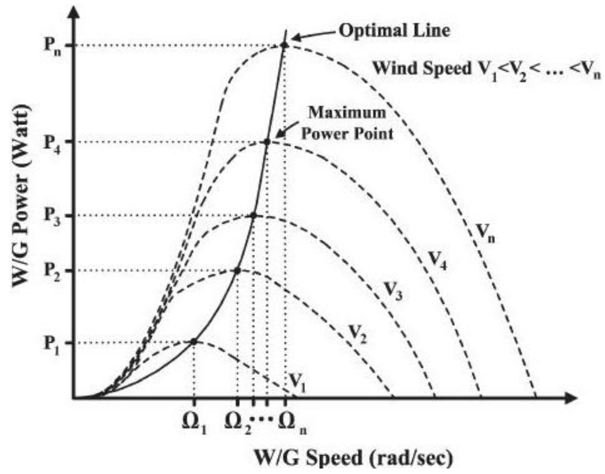

Figure 2. Generated power vs rotor rotation (consider Ω = n). Source: Eftichios Koutroulis and Kostas Kalaitzakis. [9]

This shows that, with a given wind turbine, for each wind speed there is a rotation speed at which the wind generator must operate in order for the power to be maximized. See Figure 2.

DC-DC CONVERTER.

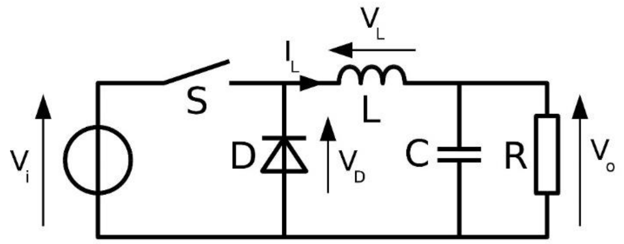

***Figure 3**. Topology of a Buck converter. Source: Wikipedia.* [10]

The buck converter is a device that converts a DC voltage signal to a lower value DC signal. In more detail, the operation of the DC converter can be analyzed through Kirchhoff's laws applied in both states of the circuit, when the switching device is "on" (short circuit) and when it is "off" (open circuit). Figure 3 shows the circuit topology for a Buck-type DC-DC converter. For the state or computing time “on” the power delivered to the load is supplied by the source, the reactive components such as inductance and the capacitor stores energy during this period. For the state where "off" the source is disconnected from the remaining circuit so the load is supplied with the energy stored in the inductance and the capacitor [11].

The behavior of the important variables in the converter such as the energy that is transferred to the capacitor and inductance, current relationships, voltages and how these interact in the impedance match between the source and the load, are described through the following mathematical analysis [12] [13]:

$\boldsymbol{D}$: $Duty\ cycle.$
$\boldsymbol{t_{off}}$: $"off"\ switching\ time".$
$\boldsymbol{t_{on}}$: $"on"\ switching\ time.$
$\boldsymbol{V_{dc_S}}$: $Voltage\ of\ the\ source\ or\ generator\ (rectified).$
$\boldsymbol{V_{dc\_C}}$: $DC\ voltage\ across\ the\ capacitor.$

$$V_{dc\_S}t_{on} = V_{dc\_C}t_{off} \qquad (9)$$

The capacitor voltage is given by:

$$V_{dc\_C} = DV_{dc\_s} \qquad (10)$$

With:

$$D = \frac{t_{on}}{t_{on} + t_{off}} \qquad (11)$$

As already mentioned, the converter connected to a load can be analyzed as a variable impedance seen from the generator side (R_{dc_S}). Its relationship with voltage and current obey Ohm's law, this relationship is shown in Eq. *(12)*.

$$I_{dc\_S} = \frac{V_{dc\_S}}{R_{dc\_S}} \qquad (12)$$

The power is the same at the input and output of the converter (Eq. *(13)*), which allows this same analysis to be performed on the load side, at the output of the converter, with which we will obtain an identical relationship for the impedance of the load. Shown in Eq. *(14)*.

$$V_{dc\_S}I_{dc\_S} = V_{dc\_RL}I_{dc\_RL} \qquad (13)$$

$$I_{dc_{RL}} = \frac{V_{dc_{RL}}}{R_L} \qquad (14)$$

Substituting Eq. *(10)* in Eq. *(13)* we obtain:

$$V_{dc\_S}I_{dc\_S} = DV_{dc\_S}\, I_{dc\_RL} \quad \rightarrow$$

$$I_{dc\_S} = D\, I_{dc\_RL} \qquad (15)$$

Returning to Eq. *(10)*, if both sides are divided by I_{dc_RL}, we obtain:

$$\frac{V_{dc\_C}}{I_{dc\_RL}} = D\frac{V_{dc\_S}}{I_{dc\_RL}} \quad \rightarrow$$

$$R_L = D\frac{V_{dc\_S}}{I_{dc\_RL}} \qquad (16)$$

If in Eq. *(16)* the equivalence for $I_{dc_RL}$of Eq. *(15)* is replaced, we obtain:

$$R_L = D\frac{DV_{dc\_S}}{I_{dc\_S}} \quad \rightarrow$$

$$R_L = D^2\frac{V_{dc\_S}}{I_{dc\_S}} \qquad (17)$$

Inserting R_{dc_S} in Eq. *(17)*, we obtain:

$$R_L = D^2\, R_{dc\_S} \quad \rightarrow$$

$$R_{dc\_S} = \frac{R_L}{D^2} \qquad (18)$$

Finally, Eq. *(18)* shows the relationship that exists between the impedances in the system and how it can be modified by varying the duty cycle of the converter.
The converter in this application can be understood as the actuator by means of which the MPPT algorithms can disturb and generate changes in the extraction of power in both turbines and photovoltaic panels. This effect is possible thanks to the fact that the converters, by varying their duty cycle, change the output voltage and current of the source, thus allowing to modify the apparent impedance that is seen by the generator (matching), which in turn allows matching the impedances between a generating source and a load[13].

MAXIMUM POWER POINT TRACKING ALGORITHMS (MPPT).

As already mentioned, MPPT algorithms are techniques that allow the system to locate its point of maximum power generation and follow this point when the conditions on which the generation depends change, such as temperature, radiation in photovoltaic panels or the wind in the case of wind turbines and the operating load in both cases.
There is a varied number of algorithms which can be classified based on aspects such as complexity, number of sensors, tracking strategies, among others. For example, depending on your monitoring strategy, they can be indirect and direct; the direct ones only measure physical variables of system operation while the indirect ones use tables or stored data which contain information on the behavior of the system[14].
These information tables characterize the behavior of the system, they are generally provided by the manufacturer. These indirect methods tend to be less efficient and more complex than direct methods. There are also hybrid algorithms that use a combination of both direct and indirect methods [15].

Hill Climb Search o perturbar y observar (P&O).

Also known as Perturb & Observe (P&O), this method seeks to generate changes in the system variables, either voltage, current or rotor speed, in order to produce a disturbance that accounts for the state in which the system is operating to determine the direction of the next disturbance and reach the point of maximum power.
If by increasing the generator voltage the power increases, the algorithm decides that the next disturbance will also be an increase in power, in case the power decreases the decision will be to decrease the voltage. In this way the algorithm is scaling in the turbine power curve.
Although the logic of the algorithm is quite simple, when it is integrated into the wind system, several important aspects must be considered such as the inertia of the system, oscillations in the measured signals, atmospheric conditions of rapid variations and the selection of step size. suitable, etc [16].
This algorithm is one of the most popular and used within the MPPT algorithms because it does not require prior knowledge of the system such as turbine characteristics, even variables such as wind and generator speed, while other methods must be reconfigured for some changes in the parameters. of the system [17].

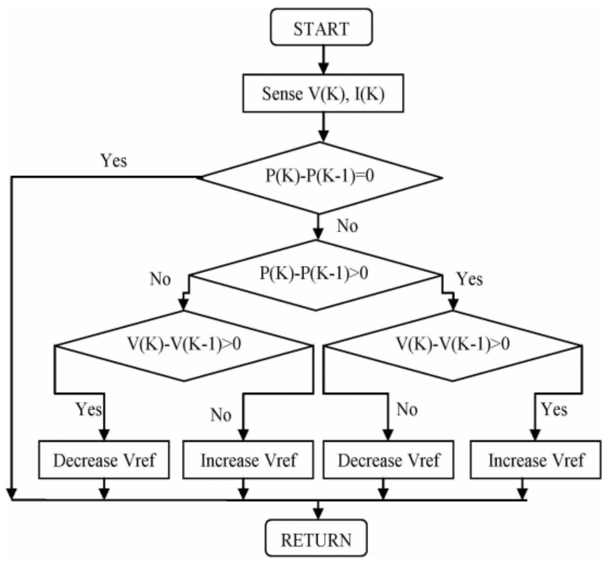

Figure 4. *P&O algorithm flow diagram. Source: L. Badreddine, S. Zouggar, M. L. Elhafyani and F. Z. Kadda.*[18]

In Figure 4 the operating mechanism is observed through a flow diagram of the disturb and observe algorithm. In this case the algorithm has the generator voltage as an output variable, as indicated, the final output is to increase or decrease "Vref".

MPPT RELATIONSHIP WITH THE THEORY OF WIND TURBINES.

Because renewable energy systems generally have low efficiencies and low generation capacities, it is crucial for these systems, photovoltaic, wind, hydroelectric, etc; be able to maximize power extraction and efficiency as much as possible. Therefore, maximum power point tracking algorithms or MPPT are of great interest in the field of renewable energy.
In wind turbines, the MPPT algorithms, through converters, allow to control the rotation speed of the rotor by means of the variation of the generator voltage when the wind speed changes, modifying the operating point of the system. In turn, modifying the turning speed changes the ratio of the tip speed ratio or TSR, tip speed ratio in English. The power

coefficient of the turbine depends mainly on the TSR and the power is proportional to the power coefficient, thus the MPPT algorithm provides a technique to maximize the extraction of power in the turbine. [19].
Mathematically the mechanism explained is given as follows [20]:

$$P = \frac{1}{2} C_p(\lambda, \beta) \rho A v^3 \qquad (19)$$

Eq. *(19)* indicates the power according to a certain power coefficient $C_p(\lambda, \beta)$, which if it is taken into account that the blades have no pitch or inclination, the value of $\beta$is equal to 0, so the coefficient power depends only on λ or TSR. The above indicates that there is a value of λ or λ_{opt} that maximizes the value of C_p. The behavior of C_p vs λ is shown in the following Figure 5.

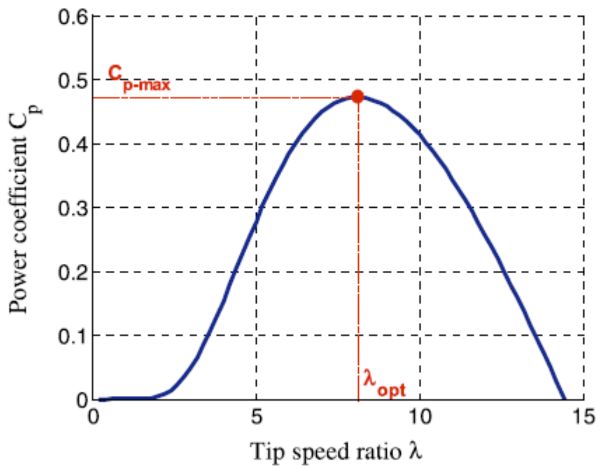

***Figure 5**. Power coefficient curve vs speed ratio at blade tip. Source: Mouna Ben Smida, Anis Sakly.* [21]

As can be seen in Figure 5, a maximum value of around 0.45 of the power coefficient is obtained, this is the maximum value achieved in practice, although the theory indicates that this has a maximum value of 0.59 [19].

$$C_p(\lambda) = 0.5176\left(\frac{116}{\lambda_i} - 5e^{\frac{-21}{\lambda_i}} + 0.0068\lambda\right) \qquad (20)$$

With:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda} - 0.035 \qquad (21)$$

In Eq.s *(20)* and *(21)* the consideration of $\beta = 0$ is already present, the blades have a fixed inclination.

$$\lambda = \frac{\omega R}{v} \qquad (22)$$

Eq. *(22)* shows that it is possible to vary the value of λ by changing the speed of rotation of the electric generator ω, since given a given wind turbine it is not possible to change R radius of the blades or v which is the speed of the wind.
In the end, the power generated depends on the output voltage and this in turn depends on the generator speed (*Figure 6*), which can be controlled by means of power converters with MPPT algorithms.

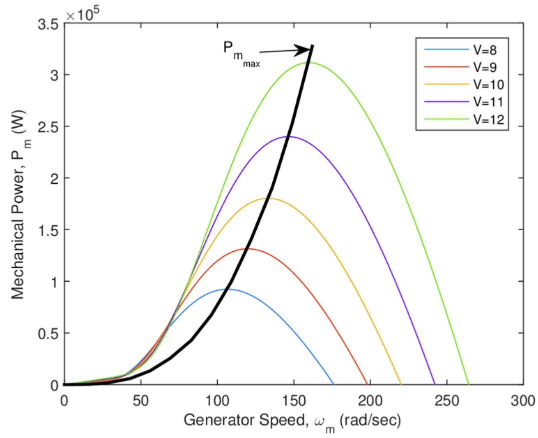

***Figure 6**. Mechanical power curve vs. generator (rotor) speed. Source: Mohamed Zribi, Muthana Alrifai and Mohamed Rayan.* [22]

WIND GENERATION SYSTEMS.

In general, a wind generation system consists of a rotor, a gearbox, and fixed speed generators, which seek to take advantage of the force and speed of the wind to move the blades connected to the rotor and induce electrical current in the generator.
At present the most robust designs of wind turbines already include power electronic devices such as converters, inverters, transformers, filters and even census and control systems that allow the maximum exploitation of the wind resource in addition to allowing an adequate interconnection of the turbines with the grid. Figure 7 shows an example of a possible design within the great variety of different configurations that can be implemented today.

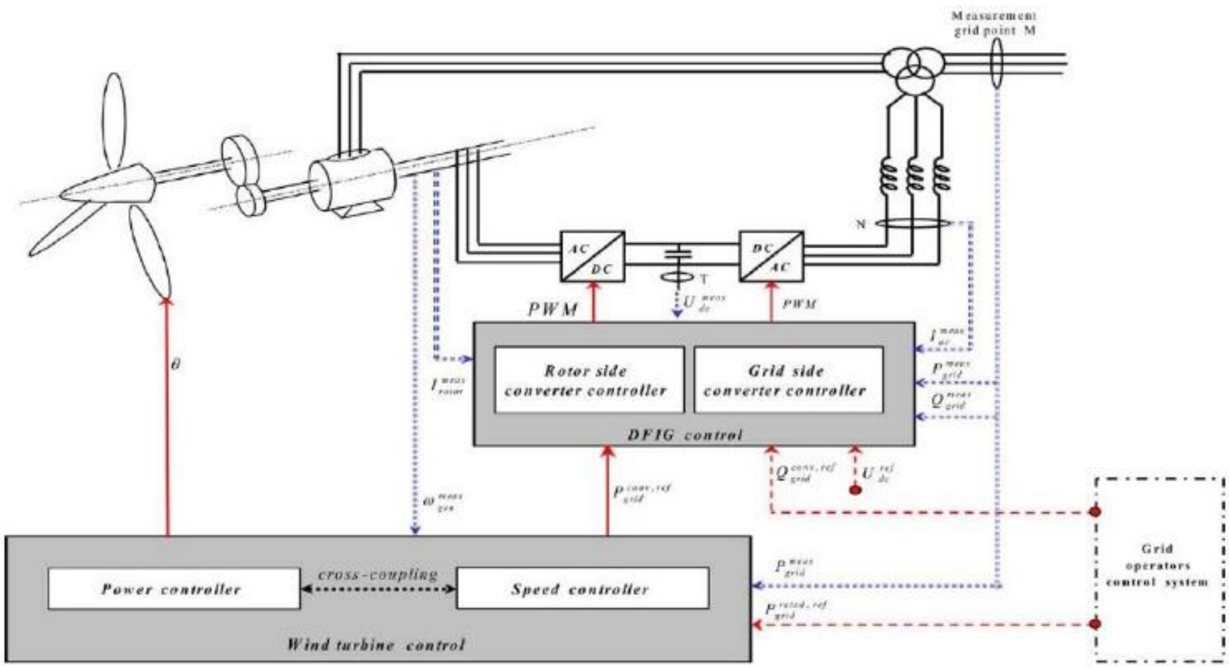

***Figure 7**. Block diagram of a current turbine. Source: Chen, Z. & Guerrero, Josep & Blaabjerg, F.* [23]

According to the wind turbine theory it is known that a wind turbine under certain conditions of wind, load, etc., can operate in different areas or points of its power curve, with which there are control techniques that allow finding and locating the turbine inside of these points. These control systems that allow to optimize the transfer of energy from wind currents to electricity to the maximum and to keep the turbine at the point of maximum power generation, are known as MPPT (Maximum Power Point Tracking).

MPPT control systems can be implemented through algorithms, using different logics, variables and approaches, depending on the type of algorithm in question, these algorithms drive and keep the wind system operating at the point of maximum power extraction. Although in recent years the literature about these algorithms has had a great development; comparisons, performance tests, stability studies, it is common to find that most of these works do not clearly or quantitatively show what is the improvement in efficiency that can be obtained when implementing them.

This fact, although basic, can be an aspect of vital importance when considering adding or not an MPPT system in the wind turbine, especially when it is required to build low-power wind systems, in which generally there are not so many technification. Having studies that show the improvements obtained through the MPPT algorithms can help to highlight the vitality of these systems in wind generation.

Conversion of mechanical to electrical energy.

The turbine by means of blades is the element in charge of taking advantage of the force and speed of the wind to provide a rotating mechanical movement, which makes it possible to convert mechanical energy to electrical energy with an electrical generator. Between these two processes, a gearbox is generally used that multiplies the speed of rotation towards the generator because the gigantic turbines used for wind generation rotate at low speeds with high torque, which are not suitable to induce energy generation. on the generator.

An important aspect of wind turbines is that it is not recommended that they rotate at speeds much higher than their maximum rated speeds, this causes excessive mechanical stress on the gearbox, blades and even on the tower, which can lead to deterioration and possible collapse of the structure. For this reason, modern turbines have power controls (turning speed) that are managed aerodynamically by turning the blades. Furthermore, this control in turn allows limiting the power generated in the turbine in order not to alter the voltage levels injected into the grid.

Aerodynamic control mechanisms.

Regarding the control through aerodynamics, there are two common ways in which this task is carried out, one of them is through the pitch angle control "Pitch control", in which the blades are rotated through a longitudinal axis that allows the angle of incidence with the wind to be freely rotated so that when a certain speed of rotation is exceeded (sometimes the power is had in advance with respect to the speed of the turbine so the power is sensed directly) change the step angle and decrease.Figure 8.

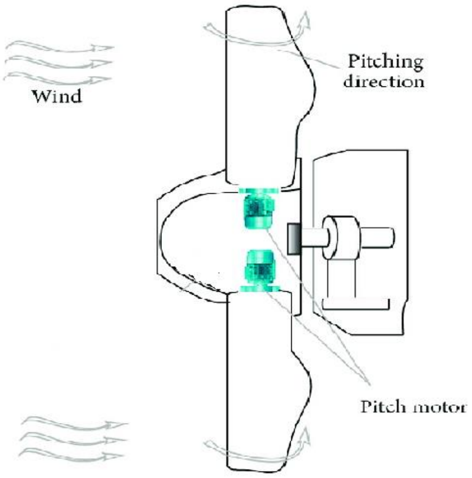

Figure 8*. Pitch control mechanism. Source: Jabir, Muhammad & Illias, Hazlee & Raza, Safdar & Mokhlis, Hazlie.* [24]

Another technique consists of the regulation by aerodynamic stall or "Stall control", this corresponds to a passive control since the blades are constructed in such a way that, if the wind exceeds a certain speed, the aerodynamic of the blade causes a loss of lift due to the increased turbulence behind the blades and therefore a decrease in the turning speed or total stop of the turbine. Figure 9.

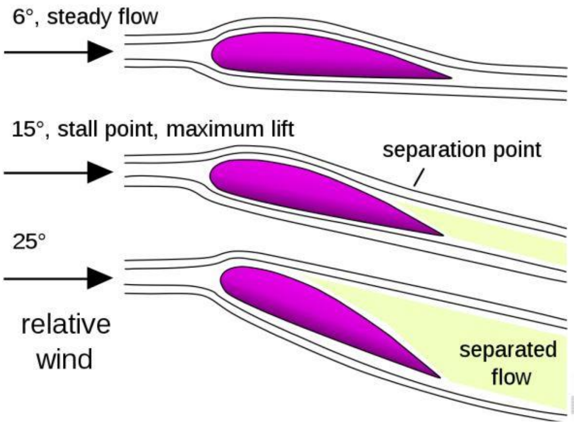

Figure 9*. Pitch control mechanism. Source: International Hellenic University*. [25]

Electricity generation.

Electric generators within a wind system play an important role, these can be of different types according to their operating principles such as synchronous and asynchronous. Synchronous generators are generally based on permanent magnets or electromagnets connected with DC voltage that polarizes the stator, these when rotating generate electrical energy at a fixed frequency synchronized with that of the polarization source, they are widely used because they can easily operate at different wind speeds.

On the other hand, there are asynchronous or induction generators, they are manufactured with configurations called squirrel cages due to their similarity to this object, they are characterized by having a fairly low operating range at different wind speeds, because at different speeds of wind generate variable frequencies. These drawbacks can be solved with power converters.

Power electronics.

From the field of electronics it is known that converter devices can be designed with different topologies, configuration and / or application of different techniques in order to solve different problems faced by wind systems such as improving efficiency, the quality of the energy and operation in a greater range of wind speeds, reactive energy compensation, among others.

With regard to induction generators, to preserve the exploitation of the wind at different speeds, it is necessary to introduce into the turbine a power electronics device known as a Back to Back converter which is responsible for converting AC energy of variable frequency to the Generator output to a DC signal and then again to be converted into AC, this time at a fixed frequency of the grid.

Grid connection/filtering.

The connection of the turbine with the network is also an important aspect because through these networks the generation system can provide the electrical energy generated to the end users. This correct connection must guarantee that the energy that is generated and injected into the network has certain quality parameters, such as low harmonic content, frequency and voltage levels regulated equal to those of the network, thus avoiding inconveniences and interferences between both. systems.

On the other hand, generators that in principle were directly connected to the grid to feed the reactive power necessary for induction in the generator, require reactive power compensation systems (SVC, STATCOM) which, as its name indicates, is responsible for to absorb reactive power in case the voltage to the grid increases and to deliver reactive power in case the voltage decreases, always leveling the voltage levels to the grid.

Elevation of voltages.

Finally, in wind systems, transformers are finally used that raise the signal to high voltages and low currents so that it can be transmitted while reducing transmission losses to the maximum.

Maximization of power extraction.

Regarding the amount of power that is extracted, because a wind turbine can operate at different speeds, this fact causes the system to be located at different operating points on the power curve. Due to the above, it is necessary to design MPPT maximum power point tracking systems that allow wind systems to be more efficient. There is a wide variety of these algorithms or MPPT techniques, among the most used are Perturb and observe (P&O), Optimal Torque Control (OTC), Power Signal Feedback (PSF), Hill Climbing Search (HCS), and Fuzzy Logic control (FLC), Tip Speed Ratio (TSR) [26] [27].

III. DISEÑO.

The configuration and elements in a wind system depend to a great extent on the type of electrical generator being used, which in turn depends on the power level at which the turbine will operate. In order to determine the right type of generator in the low power range being worked on, a review of commercial models of popular brands in the wind turbine market was made, it was found that most of these low power turbines power choose to implement a permanent magnet generator (PMSG). Regarding power electronics, complex configurations are not usually used in low power ranges. [28]

Wind Turbine	Power	Generator	Gearbox
XANT M-24	95 KW	PMSG	Direct drive
Aeolos-H	100 KW	PMSG	Direct drive
AVATAR-V	5 KW	PMSG	Direct drive
Hummer H13.2	30 KW	PMSG	Direct drive
Aeolos-H	50 KW	PMSG	Direct drive
Aeolos-V	1 KW	PMSG	Direct drive
Aeritalia AIT 03	17 KW	PMSG	Epicyclic
AIRCON 10 S	9.8 KW	PMSG	Direct drive
Anelion SW 3.5	3.5 KW	PMSG	Direct drive
Hummer H6.4	5 KW	PMSG	Direct drive

Figure 10*. Low power turbine models reviewed on the market. Source: Ramos J. G. [Own elaboration]*

Simplified wind system diagram.

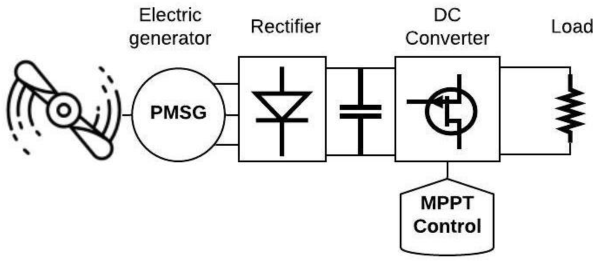

Figure 11*. Simplified wind system diagram. Source: Ramos J. G. [Own elaboration]*

Maximizing power extraction is not the only issue to improve in wind turbines, a complete wind system connected to the grid adds more problems such as turbine voltage instabilities due to variations in the grid voltage level, reduction of the power factor due to the incidence of reactive power, energy quality control associated with disturbances in the frequency, quantity of harmonics, instabilities in the dynamic behavior of the system, which require the development of reactive power compensation systems, control systems for the inverter, soft starters, power quality controllers among other elements [29] [30] [31].

For the present study, it is possible to simplify the system as shown in Figure 11, this is because for the purposes of the present work this system introduces several additional elements that are not necessary in the achievement of the proposed objectives, which seek to show the maximization in the extraction of power from the generator through an MPPT control system.

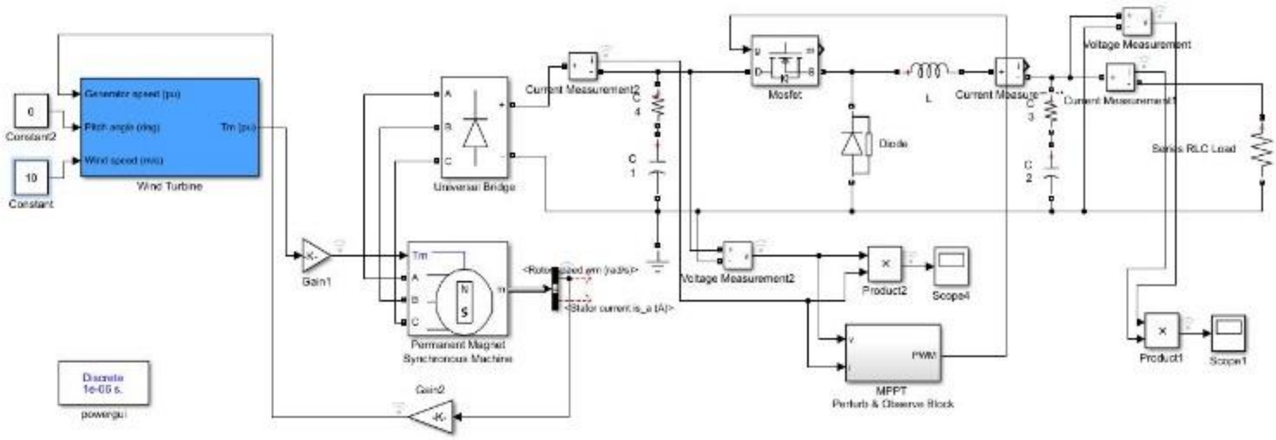

***Figure 12**. Wind system implemented in Simulink. Source: Ramos J. G. [Own elaboration]*

IMPLEMENTED COMPUTER MODEL OF THE WIND SYSTEM.

Figure 12 shows the implementation of the wind generation system that was previously indicated in Figure 11. The system has been implemented and simulated through the Simulink tool of the Matlab software.
Simulink is the most popular and used tool for modeling, testing and simulation of these generation systems, because it has extensive libraries and, above all, predefined models that speed up and facilitate their study.

Description of the elements of the model.

Turbine.
The turbine and its interaction with the wind is simulated through the predefined block "Wind Turbine" which models a turbine that outputs an amount of torque that will be delivered to the generator. The block receives as inputs a reference of the speed of the generator that serves to give it a gain at this speed, in this case it has been set to 1 by default. Additionally, it is possible to indicate the pitch angle of the turbine blades in case it has pitch control, it has been set at 0 which indicates that the blades are not rotating (without pitch control).

Generator.
In the wind system presented, the three-phase permanent magnet generator has been modeled with the "Permanent Magnet Synchronous Machine" block which receives an amount of torque as input and the three respective phases as outputs. It has been configured to model a generator with a nominal power of 10KW at a nominal wind speed of 10m / s.

Electric Generator Technical Parameters (PMSG)	
Rated power	10KW
Velocidad rotacional nominal	300rpm
Poles	20
Nominal torque	318Nm
Winding type	Y (star)
Rotor type	Salient
Torque constant	16,051
Inertia	0,2308Kgm2
Resistance per phase	0,926Ohm
Ld	11,55mH
Lq	21,7mH

***Figure 13**. Technical parameters of the modeled electric generator. Source: Ramos J. G. [Own elaboration]*

Figure 13 The parameters necessary for modeling the electric generator are shown, using the Simulink block. These data were obtained from the datasheet of a real electric generator manufactured in a Chinese company.

Rectifier.
As mentioned in the converters section, in the low power ranges manufacturers generally implement simple converters that do not increase the cost and complexity of the turbine [28]. The simulated rectifier through the "Universal Bridge" block corresponds to a three-phase full-wave rectifier bridge not controlled from diodes.

Converter (Buck Type).
The converter, as can already be guessed, is the most important part of the system and practically the entire design of the control system is concentrated there. The methodology used for this design is the one proposed in [32].
For the following design, it is assumed that the turbine is required to charge a DC battery bank that

has a charging voltage of 300v and supports a charging power of 10KW, with which there is a maximum charging current of 33.33A. The variation in the accepted charging voltage is around 1%.

Load (Battery Bank)	
Charging voltage	300V
Charging power	10KW
Current	33,33A
Ripple	1%

Figure 14. *Cargo Specifications. Source: Ramos J. G. [Own elaboration]*

To establish the criteria at the input of the converter, the maximum expected voltage at the input, a measurement of the output voltage of the electric generator was performed at 10m/s.

Salida del generador PMSG		
Wind speed	Voltage (rectified)	Ripple amplitude
10m/s	836V	122V

Figure 15. *Rectified generator output voltages. Source: Ramos J. G. [Own elaboration]*

Based on what was established above and what is specified in the chosen design methodology, the design can be continued as follows:

$D_{max}: Maximum\ duty\ cycle.$
$V_o = 300V; converter\ output\ voltage.$
$V_{inmax} = 836V; maximum\ input\ voltage.$

$$D_{max} = \frac{V_o}{V_{inmax}} = 0,75$$

Inductance.
$L_{min}: Minimum\ inductance.$
$f_{sw} = 20KHz; inverter\ switching\ frequency.$
$\Delta I_{Lpp} = 1A; Ripple\ of\ the\ current\ in\ the\ inductance.$

$$L_{min} = D_{max} * \frac{V_{inmax} - V_o}{\Delta I_{Lpp} * f_{sw}} = 20,1mH$$

Input capacitor.
$C_{inmin}: Minimum\ input\ capacitor.$
$ESR_{max}: Maximum\ equivalent\ series\ resistance.$
$\Delta V_{inpp} = 1,66V; voltage\ ripple\ accepted\ at\ the\ input.$
$\Delta I_{inpp} = 5A;\ current\ ripple\ accepted\ at\ input.$

$$C_{inmin} = \frac{\frac{D_{max}}{f_{sw}}}{\frac{\Delta V_{inpp}}{\Delta I_{inpp}} * ESR_{max}}$$

For the input capacitor the ESR must be:

$$ESR_{max} \leq 0,5 * \frac{\Delta V_{inpp}}{\Delta I_{inpp}}$$

$$ESR_{max} \leq 0,166\Omega$$

Then:

$$C_{inmin} = \frac{\frac{D_{max}}{f_{sw}}}{0,5 * \frac{\Delta V_{inpp}}{\Delta I_{inpp}}} = 225uF$$

Output capacitor.
$C_{omin}: Minimum\ output\ capacitor.$
$ESR_{max}: equivalent\ maximum\ series\ resistance.$
$\Delta V_{opp} = 0,1V;\ voltage\ ripple\ accepted\ at\ output.$
$\Delta I_{opp} = 1A;\ current\ ripple\ accepted\ at\ output.$

$$C_{omin} = \frac{\frac{D_{max}}{f_{sw}} * \Delta I_{opp}}{\Delta V_{opp} - (\Delta I_{opp} * ESR_{max})}$$

For the output capacitor the ESR must be:

$$ESR_{max} \leq 0,36 * \frac{\Delta V_{inpp}}{\Delta I_{inpp}}$$

$$ESR_{max} \leq 0,036\Omega$$

Then:

$$C_{omin} = \frac{\frac{D_{max}}{f_{sw}}}{0,36 * \frac{\Delta V_{opp}}{\Delta I_{opp}}} = 585,94uF$$

Power requirements of the converter elements [33].

Inductance.
$I_L = I_o = 33,33A$
I_L, Current that the inductance windings must withstand, corresponds to the maximum current supplied by the converter to the load.

Input capacitor.

$$V_C = V_{inmax} + \frac{rizado}{2} = 836 + \frac{122}{2} = 897V$$

V_C, minimum voltage that the input capacitor must withstand.

Output capacitor.

$$V_C = V_o = 300V$$

V_C, minimum voltage that the output capacitor must withstand.

Diode.

$$I_D \geq I_o * 1,1 = 33,33A * 1,1$$

I_D, is the current that the diode must withstand, which corresponds to the same output current, however, as a design criterion it is usually set at 1.1 times that value.

$$V_{rv} \geq V_{inmaxp} * 1{,}2 = 897V * 1{,}2$$

V_{rv}, is the minimum reverse voltage that the diode must withstand. The factor of 1.2 is also due to design criteria.

Mosfet.

$$V_{DS} \geq V_{inmaxp} * 1{,}2 = 897V * 1{,}2$$
$$I_D \geq I_o = 33{,}33A$$

V_{DS}, Drain-Source voltage of the mosfet and I_D, current that the mosfet must withstand through the Drain.

MPPT Perturb and Observe algorithm (P&O).

As mentioned earlier, the algorithm disturbs and observes the most misused ones in terms of following maximum power points and is due to the implementation speed that it has, besides the advantage that it does not need models. mathematicians in the knowledge of the characteristics of the turbine in the system in general. The P&O algorithm on the ground is common with wind turbines, and is also widely used in photovoltaic panels, since the photovoltaic panels have been more poorly studied than the turbines, there is much more literature on these algorithms applied to panels. In [34] [35] there are some examples of works that describe photovoltaic generation systems that make use of MPPT algorithms type disturb and observe, it is even common to find works such as [36] [37] where this algorithm is modified and compared against to its basic version.

Proposed P&O (flow chart).

Figure 16 shows the flow chart that describes the operation and general approach of the algorithm implemented in this work. The algorithm directly takes into account the generated power value to perform a control action, which is based on an increase or decrease in the duty cycle.

Initially the algorithm uses the generator voltage and current measurement to calculate the respective extracted power, then it calculates the difference between the power measured at that moment and the power measured at the previous sampling time in order to determine if the power increased or decreased. When the power difference is positive, it means that the disturbance had an increasing effect on power, therefore the algorithm must continue to disturb in the same direction (increasing the duty cycle), the opposite happens if the difference is negative. If there is no difference, the algorithm does not generate a new disturbance, leaving the same duty cycle. Finally, the "previous" power value is updated and the cycle is repeated. It is also necessary to consider the measurement of the voltage difference within the logic since an increase in voltage does not necessarily lead to an increase in power.

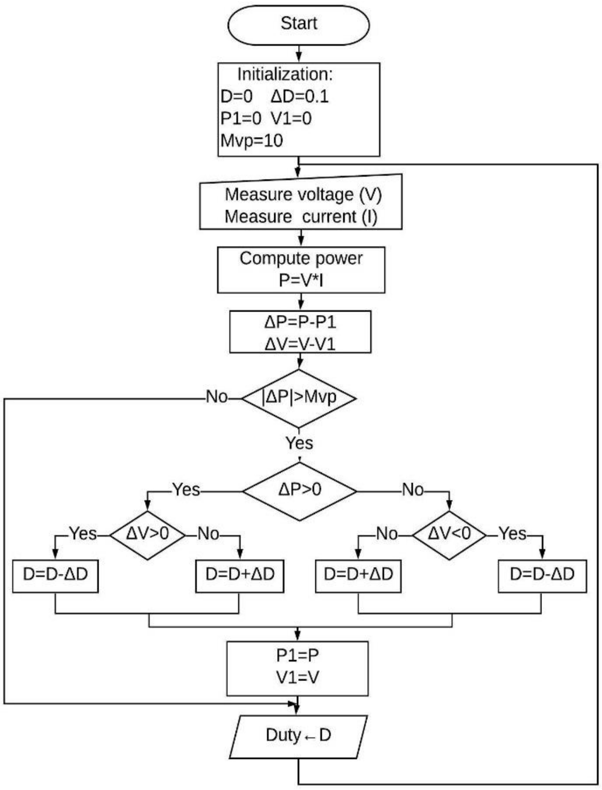

***Figure 16**. Flow diagram of the algorithm to implement. Source: Ramos J. G. [Own elaboration]*

Additionally, a minimum threshold ("Mvp") has been established that must exceed the power difference for the algorithm to act (change the duty cycle), this in order to avoid actions against variations in the power signal that do not really represent a change in the operating point such as oscillations, harmonics, gusts of wind, among others.

The algorithm has been implemented through the "Function block" that allows to execute code in the Simulink environment.

IV. RESULTS.

In order to know if the control system is actually operating correctly, it was decided to make a comparison of the operation of the turbine without the control system and with the system in place.

Turbine without MPPT.

In this test, the turbine is simulated without the MPPT control system at a wind speed of 10m/s.

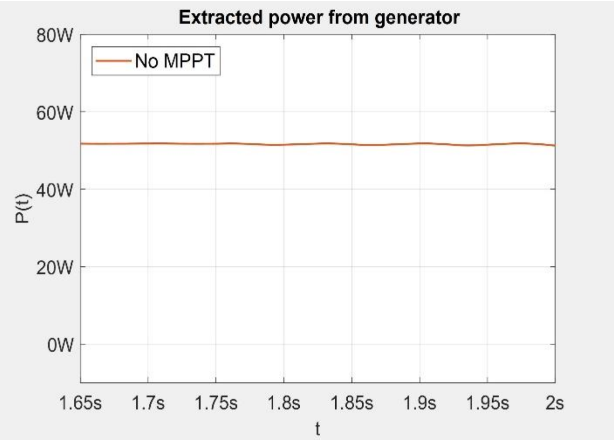

Figure 17*. Response without MPPT at 10m/s. Source: Ramos J. G. [Own elaboration]*

For this test, the turbine is connected to the same load stipulated for the converter system design, which corresponds to 300V. It can be seen that the power levels obtained, 51.8W on average, are much lower than the order of power in which the turbine should operate.

This behavior is due to the fact that the turbine, without a system that allows it to properly couple the loads, is practically incapable of supplying the current demand to the load used in the test, thus obtaining a considerable drop in power.

Turbine without MPPT with lower load.

Due to the previously observed behavior, it was decided to manually search for the optimal load for the turbine, which means reducing the current demand so that the power is not diminished.

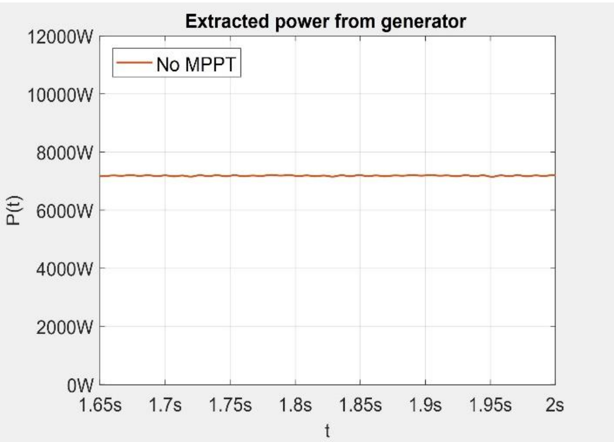

Figure 18*. No MPPT response with 764Vrms load at 10m/s. Source: Ramos J. G. [Own elaboration]*

For a wind speed of 10m / s the turbine can reach an average maximum of 7,186W when connected to a 764Vrms load of 10KW. Which even leaves this non-MPPT configuration at just 72% of rated power.

It is necessary to highlight that for this test it was necessary to search manually (trial and error) the load that generated the highest power at a speed of 10m/s, which infers that this configuration is not feasible to feed a specific load at different speeds of wind, which is desired for a practical implementation.

System with MPPT algorithm at 10m/s.

The system has been simulated with MPPT at a wind speed of 10m/s.

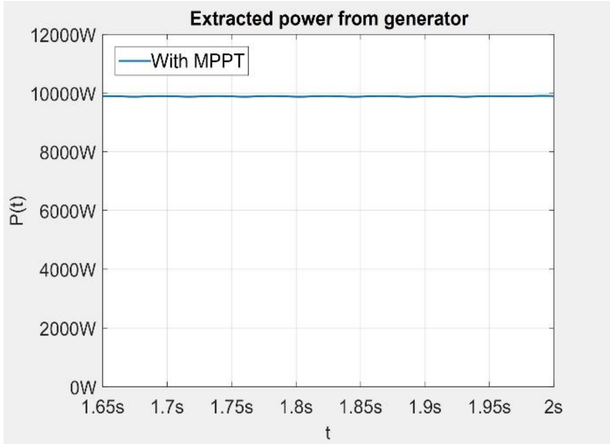

Figure 19*. Response with MPPT at 10m / s. Source: Ramos J. G. [Own elaboration]*

Figure 19 shows the power level reached by the system when the MPPT control system is implemented, the connected load is the one specified in the design with a value of 300Vrms. The power level reached is practically the nominal, of 9.887W average.

System with MPPT algorithm against changes in wind speed.

In this test the objective is to visualize the behavior of the control system when the wind speed decreases and increases.

Figure 20*. Response with changes in wind speed. Source: Ramos J. G. [Own elaboration]*

Figure 20 presents the results obtained from the average power when the wind speed changes. In the

interval from 0 to 2s the wind speed corresponds to 10m/s, from 2 to 3s the wind speed drops to 7m/s and from 3s the wind speed is 9m/s.
As can be seen both when the speed of the sight decreases and when it increases, the control system allows the turbine to continue supplying power in a stable way to the load. For the interval where the wind speed is 10m/s, the average power level is 9.887W; for the 7m/s interval, the power goes to 3.413W; for the 9m/s interval the average power is 7.297W.

V. CONCLUSION.

This study allows us to see that simple MPPT control systems such as the disturb and observe method allow to improve the operation and power extraction of wind systems that implement PMSG and that require operating at varied wind and load conditions.

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