Overall Description of Wind Power Systems

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Abstract

This paper presents a general overview of the main characteristics of the wind power systems, also considerations about the simulation models and the most used *Maximum Power Point Tracker* (MPPT) techniques are made. Some simulation results are shown and conclusions about the work are given.

Key words: wind energy; wind turbines; MPPT control; DC-DC power converter; simulation.

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Descripción general de sistemas de potencia eólicos

Resumen

Este artículo presenta una visión general de las principales características de los sistemas eólicos, también se hacen consideraciones acerca de modelos para simulación y sobre las técnicas *Maximum Power Point Tracker* (MPPT) más utilizadas. Algunos resultados de simulación se presentan y se dan conclusiones al respecto.

Palabras clave: energía eólica; turbina eólica; control MPPT; convertidor DC-DC; simulación.

1 Introduction

Generation systems based on alternative power sources have become in a stronger option to the growing power demand and the purpose of reducing the use of fossil fuels. The development of modern wind power conversion technology has been going on since 1970s, and it has been faster from 1990s [1]. Those contributions have been accompanied with important breakthroughs in power electronics and signal processors devices which encourages to continue with the development of this kind of systems. Wind energy conversion systems (WECS), have an average annual growth rate of 30% during the last ten years, most of them are located in Germany, Spain, USA, Denmark and India [1], however countries like New Zeland and Ireland have increased their wind system penetration [2]. One of the most innovative researching areas, is modeling and control of wind systems. The design of an interface between the energy source and the load, capable of making the system work under suitable conditions, is one of the main current challenges. Therefore, one of the first tasks is the definition of the system characteristics: the wind turbine, the generator, the power interface and the load. All those components have to be involved in the modeling and implementation of control technique.

Wind turbines can operate in two different ways: with fixed speed or with variable speed. Fixed-speed wind turbines are equipped with an induction generator; they are designed to operate with the maximum efficiency at one particular wind speed [3]. This type of wind

turbine has the advantage of being simple and cheap, but the disadvantage of being poor controllable and unstable [4]. On the other hand, variable-speed wind turbines are designed to work with maximum efficiency over a wide range of wind speed. They are typically equipped with an induction or synchronous generator [3], and even when their electrical system is more complex than that of a fixed speed wind turbine, they have the advantage of increasing the captured energy and improving power quality through control actions implemented on the power interface [5].

Wind energy can be easily found in nature, but the sudden changes throughout the day can represent a drawback to the WECS [6]. That drawback can be solved by the implementation of control actions like Maximum Power Point Tracking or MPPT control. This control strategy allows to achieve the maximum power at any wind speed [7] and it is implemented commonly through a DC-DC converter. In Figure 1 a simple diagram of wind power system is shown, the load can be modeled according to the final application of the system: DC loads, AC loads or both.
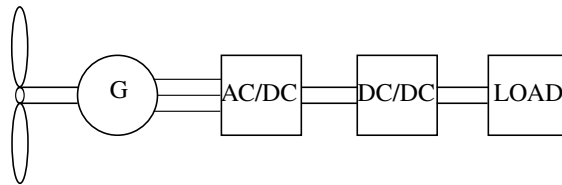

Figure 1: Basic diagram of wind power system.

MPPT algorithms have been widely studied, not only for wind systems, photovoltaic systems are also a typical application area for MPPT techniques [5],[8],[7],[6]; it can be said that the implementation of those techniques, for PV systems or WECS is the same, except for the variables involved in the algorithms.

A large number of MPPT techniques for WECS has been studied and reported in literature, they can be grouped in three main methods: hill-climb search (HSC) control, tip speed ratio (TSR) control and power signal feedback (PSF) control [6]. The application of one

or another depends on the characteristics of the wind system and the requirements of techniques, this means, the amount and type on sensors and computational demand. Some techniques need an accurate knowledge of the turbine parameters and the measurement of the wind speed [9]; some of them do not require the measurement of the wind system, but do implement an estimator [10]; some recent techniques do not require to measure any parameter, normally they are based in conventional algorithms improved by intelligent techniques like fuzzy logic, neural networks or genetics algorithms [11].

This paper provides an overview of the most significant characteristics of wind systems, and considerations about models for simulation are made, also some of the most used MPPT techniques are studied. This paper makes emphasis on HCS control techniques and their application in permanent magnet synchronous generator (PMSG) with a variable-speed wind turbine. An application example is presented, its implementation is made by simulation in Matlab/Simulink®. Finally some conclusion of the paper and simulation results are given.

2   Wind Energy Conversion Systems Background

In WECS the energy from wind is used to cause a rotation motion in turbine. This motion will make the generator produces electrical energy which can be regulated and controlled by the power interface. The mechanical power produced by a wind turbine can be represented by (1), where ρ is the air density, R is the turbine radius, V_w is the wind speed measured in meters per second (m/s) and C_p is the power coefficient which depends on the tip speed ratio λ and the pitch angle β [6], [5], [8].

$$P_m = \frac{1}{2}\rho\pi R^2 V_w^3 C_p\left(\lambda, \beta\right) \tag{1}$$

The tip speed ratio is given by:

$$\lambda = \frac{\omega_r R}{V_w} \tag{2}$$

Where ω_r is the turbine angular speed. The power coefficient C_p is normally defined by (3) and (4) [12].

$$C_p\left(\lambda,\beta\right) = 0.5\left(116\frac{1}{\lambda_i} - 0.4\beta - 5\right)e^{-\left(\frac{21}{\lambda_i}\right)} \tag{3}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1 + \beta^3} \tag{4}$$

However, the non-linear, dimensionless C_p characteristic can be represented by (5). Constants c_1 to c_6 are obtained through experimental tests [13].

$$C_p\left(\lambda,\beta\right) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{-\left(\frac{c_5}{\lambda_i}\right)} + c_6\lambda \tag{5}$$

If a fixed pitch rotor is assumed, β is equal to zero, which makes C_p depends only on λ and from (3) the graphical relationship between them can be obtained as is shown in Figure 2. This relationship gives the first key in the characterization of WECS [12], [5].
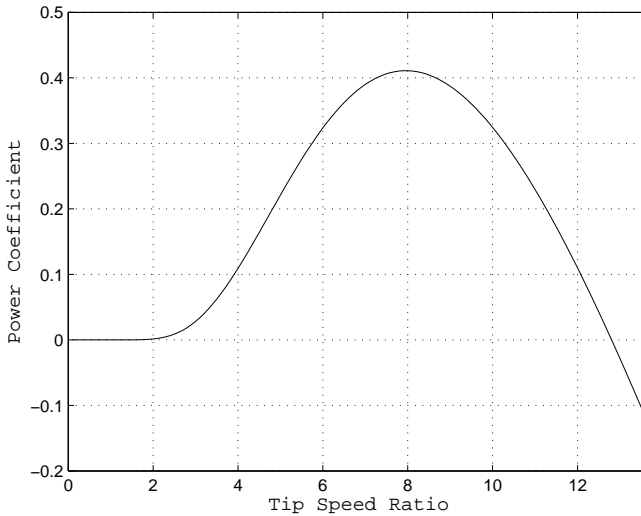

Figure 2: C_p vs λ characteristic.

In Figure 3, the behavior of mechanical power for a turbine air-breeze is shown. It can be seen how the curve has a maximum point for each wind speed condition (from V_w1 to V_w5); this simple idea leads to the question: how to get that point?, that is the work of MPPT algorithm.
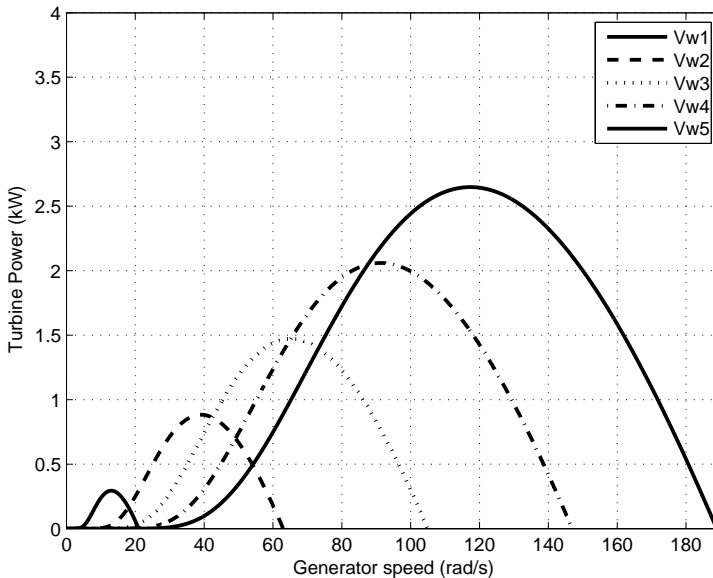

Figure 3: P_m vs ω_r characteristic.

3   Models for Simulation of Wind Systems

In general, the simulation of any system is an important tool for validating theoretical analysis and propose adjustments if they are needed. Simulation of wind systems must begin with the model of the different elements of it, and one of the most important elements is obviously the wind turbine. Wind turbines convert the kinetic energy present in the wind into mechanical energy by means of producing torque which is injected to a generator. In the previous section, it

was explained, that the power (1) depends on different parameters, one of them is the power coefficient C_p, from where another important parameter is defined, the torque coefficient C_T. The relationship between power and torque coefficients is shown in (6). By combining (1), (2), and (6), the torque of the turbine (7) can be obtained. This expression can be very useful if the input for the generator is the produced torque.

$$C_T = \frac{C_p}{\lambda} \tag{6}$$

$$T_T = \frac{1}{2}\rho\pi R^3 V_w^2 C_T \tag{7}$$

In [14], the curves for C_p and C_T are obtained and used later as lookup tables to model the wind turbine in PSIM®, as is shown in Figure 4. By using different forms of equations (1) and (2), Joshi et al. [15], present basic wind turbine models and simulate them on Matlab®and PSIM®. The results allow to analyse the behavior of the wind turbine to changes in different parameters, additionally the models can be used as a base for other studies. In [16], a model in Matlab/Simulink®based on a lookup table for the power and a second order system to model the wind turbine dynamics, is shown. In that case a double-fed induction generator is used and modelled through vector approach.

As it was seen through the different aforementioned cases, the choice of a suitable model for simulation is an important part of the analysis process. The more information is taken from the real system, the more accurate model will be simulated. One of the most significant parameters of the wind turbine, is the power coefficient. Its characteristic, which is a non-linear curve, represents the aerodynamic behavior of the wind turbine. By means of different experimental tests, it is possible to find the parameters of C_p function, which can represent a powerful tool for implementing MPPT control algorithm, as it is shown in [13], where special attention is given to inertia system analysis. Analogy between electrical and mechanical parameters is carefully studied with the aim of create a custom
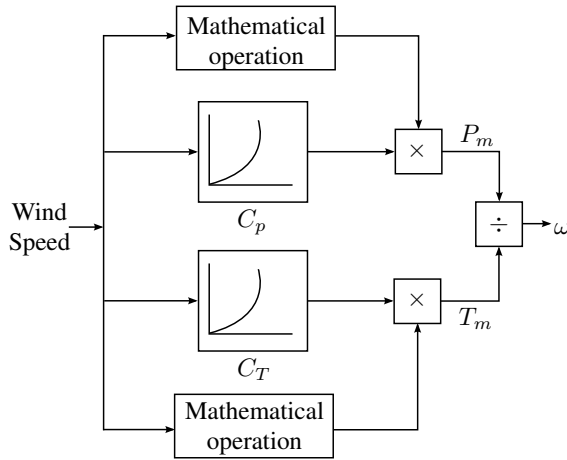
Figure 4: Wind turbine model based on lookup tables.

model using PSIM®. Similar considerations are made in [12] by using Matlab/Simulink®, a block with the C_p equation is used to calculate the mechanical power and later the mechanical torque.

Simulation issues are commonly related with the approaches and estimations made on the real model, despite the simulation software chosen for the analysis. There are simulation packages, which in principle can describe a complete wind turbine with all units, however the turbine description used in those programs requires certain parameters that are not easy to know by the user, at least in initial condition which is critical since correct initialisation of a model in a power system simulation tool, avoids fictitious electrical transients and makes it possible to evaluate correctly the real dynamic performance of the system [17]; another situation related with that turbine description is that it can not be viable in grid simulations packages because of high computational burden and can not be used to represent wind farms containing hundred of wind turbines in grid simulations without proper simplifications. Some problems that arises in implementing the model of a wind power system into commercial power system simulation tools, include the simulation time step having into account that a transient simulation requires very small time

steps and consequently very long simulation time, compatibility constraints, inability of the tool to spot phenomena such as the presence of dc-offset and unbalanced events; moreover in grid-connected wind power systems, detailed validation of the model especially during grid fault conditions, is still hard to found in the literature [18], [19]. It is not impossible to carry on good simulations, but one must be very responsibly interpreting and analysing the results in the right context, otherwise the results of the computer simulations can be insufficient and unreliable in the research work.

3.1 Wind Speed Distribution Models

The primary source of energy in wind systems is the wind, and it is necessary have its behavior into account for simulation and implementation of any wind system. Among the wind characteristics, its speed is the most important parameter in the design and study of wind energy conversion systems. In practice, it is very important to describe the variation of wind speeds for optimizing the design of the systems, which leads to actual values on wind energy potential. An important tool from probability theory is used to analyze the wind speed: probability density function (PDF), which is a function that describes the relative likelihood of a random variable to take on a given value [20]. The PDF of wind speed predominantly determines the performance of a wind energy system in a given location for the period involved [21], that depends on several factors like weather and topography of the place on. The following briefly describes the most widely accepted PDF's.

Weibull distribution is highly used and recommended in wind systems analysis; it uses three parameters α, β and γ, which correspond to the shape parameter, the scale parameter and the location parameter, respectively. Weibull distribution has found diverse application areas such as the survival and reliability analysis, and it is by far the most popular statistical distribution for wind speed modeling. Its capability to mimic exponential distribution and normal distribution through adjusting scale and shape parameters contributes to the

scope of this distribution for various applications [22], [23]. Along with the Weibull distribution the *Rayleigh* distribution is one of the most used statistical distributions in reliability theory; is a special case of Weibull distribution, where the shape parameter is equal to two, and the scale parameter is $\sqrt{2}$ times of the scale parameter of the corresponding Weibull distribution [21]. Other distribution that have been reported in literature are *Lognormal* distribution, which is a special form of the normal distribution, *Gamma* and *Erlang* distributions which uses exponential approximations, *inverse Gaussian* distribution is also used and is popular in meteorology studies, additionally other alternatives for wind speed analysis include *Skewed generalized error* distribution, *Skewed t* distribution and *Burr* distribution [24]. In [25] and [26], *Maximum Entropy Principle* (MEP) is proposed to overcome the inaccuracy of Weibull and other distributions in some cases. The maximum entropy principle is based on the premise that when estimating the probability distribution, one should select the distribution model which gives the largest remaining uncertainty, and is consistent with the existing constraints, then no additional assumptions or biases, such as a prior distribution and the range of parameters in the distribution model, are introduced into the model.

3.2   Power Interface

Figure 1 shows the basic form of a wind power system. The power interface is placed between the generation section and the load, it is mainly composed by an uncontrolled rectifier, a DC-DC converter and a DC-AC inverter. The main purpose of the rectifier is to deliver a DC voltage signal to the converter, so some control actions can be made. The power extracted from the wind turbine could be maximized by the addition of control algorithms known as maximum power point tracking methods. They are mainly implemented through the DC-DC converter. Figure 5 shows a typical scheme of a WECS with maximum power point tracking controller.

The DC-AC inverter is the interface between the wind turbine

system and the grid, by controlling this inverter it is possible to control the power factor which provides better performances [12].
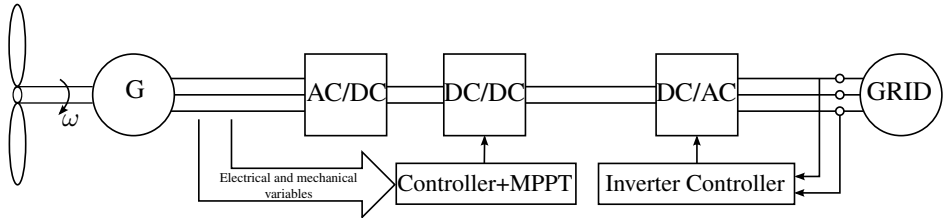
Figure 5: Wind system with controllers.

Several topologies for the DC-DC converter and the DC-AC inverter have been proposed. For the DC-DC converter is common to use the boost, and buck-boost converter [12], while for the DC-AC inverter the options include typical full bridge converter, multilevel inverters and matrix converters [27] [28]. An important aspect to consider for choosing the topology of the DC-DC converter and DC-AC inverter is the losses which implies the performance of the elements of the circuitry: power switches, resistors, capacitors, inductors among others [29].

3.3 Maximum Power Point Tracking Control Methods

Due to the sudden changes in wind, which cannot be predicted and controlled, it is necessary to control the WECS through its power interface, to achieve satisfactory results.

There are three main control methods to extract the maximum power available: hill-climb search (HSC) control, tip speed ratio (TSR) control and power signal feedback (PSF) control. Next, the most significant characteristics of these methods are described.

3.4 Hill-climb Search (HCS) Control

The curve of the power produced by the wind has one maximum power point (MPP). HCS techniques track this point by searching in the curve making variations of a determined variable and comparing the previous and actual power. One of the most widely used techniques, which is based in this principle, is perturbation and observation or P&O. In Figure 6, the principle of P&O is shown. It can be seen that if the operating point is to the left of the MPP, the control must move it to the right and vice versa if it is to the right.
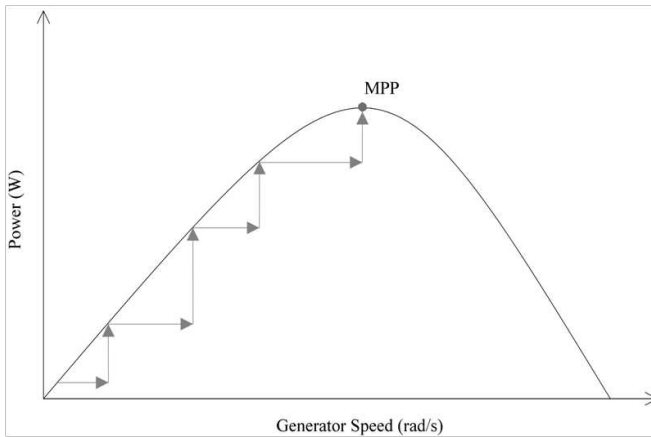

Figure 6: Operating principle of P&O.

This technique can be implemented perturbing the rotational speed and observing the mechanical power, perturbing the inverter input voltage and observing the output power or perturbing the DC-DC converter duty cycle D and observing the output power [5]. Figure 7 shows the flow chart of the P&O algorithm where the perturbed variable is D which is defined by (8) [6] [7].

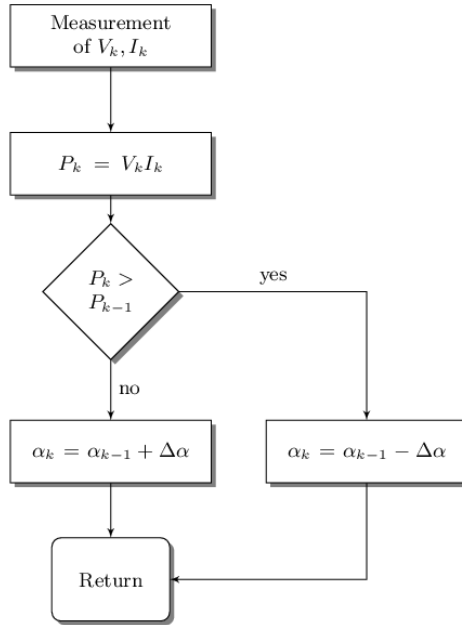$$\alpha_k = \alpha_{k-1} + \Delta\alpha \tag{8}$$

Figure 7: P&O flowchart.

Choosing an appropriate step-size is the main task to implement the algorithm and sometimes is not an easy task. Larger step-size can generate faster responses and more oscillations around the MPP which can represent low efficiency; on the other hand, smaller step-size improves efficiency but reduces the convergence speed [5]. The initialization of parameters is also an important aspect of this technique, some reported works suggest to run a related algorithm to find the suitable values and then run the P&O algorithm [10].

One of the main advantages of this technique is that it does not require knowledge of system characteristics, which makes it cheap and easy to implement. But on the other hand, one significant drawback is the possibility of failure to quick changes in wind speed [8] [30]. To improve the conventional P&O algorithm, several modifications have been proposed, one of the most representative is the variable step-size [30] [27] [31], where the step-size is automatically updated depending

on the operating point, then if the system is working on a point far from the MPP, the step-size should be increased to accelerate the searching and if the system is working on a point near to the MPP the step-size must be reduced. With this principle the algorithm will be fast, little oscillating, therefore efficiency will be improved.

3.4.1 Hill-climb search for PMSG based WECS As it was mentioned, variable-speed wind turbines are designed to work with maximum efficiency over a wide range of wind speed and they are normally equipped with a PMSG. This kind of system have been widely studied and reported in literature, and remains as a suitable option for WECS.

In [32], a MPPT based on the optimum power versus speed characteristic and a conventional P&O, is presented while in [33] and [34], artificial neural networks are used to improve the performance of a conventional P&O algorithm; the controller is implemented through a DSP (Digital Signal Processor), which ensures fast responses.

Several novel HCS-based methods, include the principle of search-remember-reuse. Those methods requires storing data of peak points obtained and training stage. The maximum power error driven mechanism (MPED) has been recently use [35]; it provides a preliminary optimized operating point from which the memory begins storage process. The direct current demand control (DCDC) makes use of optimized functions to calculate the initial state of the variables of HCS algorithm, normally MPED and DCDC are implemented together in a structure which is known as advanced hill-climb search [6].

3.5 Tip Speed ratio (TSR)

Figure 8 illustrates the structure of this MPPT control method. The tip speed ratio, as given in (2), is the relationship between the speed at the tip of the turbine blade and the speed of the wind and as is shown in (1), the power is a function of the wind speed and the rotor speed. When the TSR is optimal, the extracted energy will be

maximized besides, the optimal value of TSR is constant regardless of wind speed. The principle of this method is to force the system to remain at the optimal TSR by comparing with the actual operating point and sending this information to the controller [5] [7]. This method is mainly use in large systems due to the need of measuring the wind. It is one of the major drawbacks of this method.
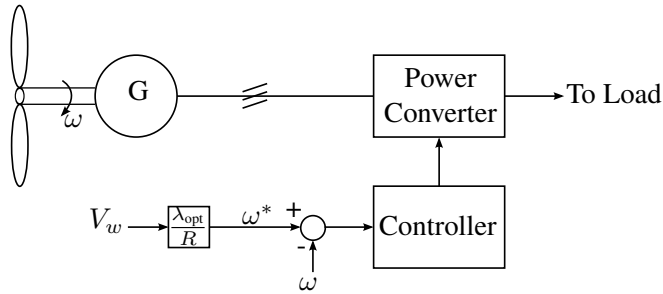

Figure 8: Tip speed ratio control scheme.

Some reported works propose an estimation of wind to avoid the installation of anemometers and related equipment. In [36] a TSR observer based in adaptive perturbations is proposed which is implemented in a DSP. In [37] a system with two series connected wind turbines is presented; the dynamic performances of the wind turbines are analysed to design the controller.

Estimators are commonly implemented trough advanced control techniques like neural networks, fuzzy logic, among others. In [34], [38] and [39] neural networks are used to assess the TSR, in [40] growing neural gas learning method is used to improve MPPT controller, while in [41] and [42] TSR method based on fuzzy logic is presented.

3.6 Power Signal Feedback (PSF)

In this method, the reference obtained from simulations or experimental tests, is the curve of rotational speed vs. optimal power [5]. If the system is operating with wind speed V_1, shaft speed ω_{T1}, and maximum output power P_1, and the wind speed change to V_2, the new

optimum output power should be P_2, but the real output power will be P_2' due to the inertia of the shaft. Then the shaft will accelerate under additional turbine torque and operations point will be moved to P_2 and ω_{T2}. To implement PSF technique, the maximum power is tracked by the shaft speed measurement and corresponding power reference determination. No wind velocity measurement is required in this method [43]. However, measuring the mechanical shaft speed and wind turbine output power is a drawback of this method. Figure 9, shows the classical structure for this control method.
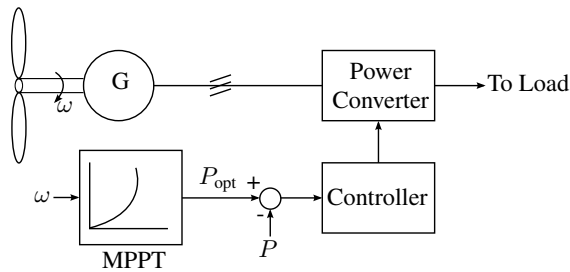

Figure 9: Power signal feedback scheme.

In [44] a mechanical speed-sensorless PSF method is implemented for induction generator. The method provides the power reference for the controller corresponding to maximum power point. A look-up table containing generator synchronous speeds corresponding to the optimal generator power and the wind turbine must keep adjusting its speed to track the optimum speed shaft. The generator synchronous speed can be increased or decreased by modifying the induction generator terminal frequency. In [7] the rotor speed is sensed with an encoder and then the optimal value of the electrical power is computed. It requires a pre-recorder relation between the rotor speed and the optimal power. In [45] a fuzzy logic based PSF controller is designed for a doubly fed induction generator. The data driven design methodology is capable of generate a Takagi-Sugeno-Kang fuzzy model for maximum power extraction. The controller has two inputs (the rotor speed and generator output power) and one output (the estimated maximum power). In similar way, a fuzzy controller is used

to track the maximum power point in [46], but in this case is for a squirrel cage induction generator. Maximum power output of the system at different wind velocity is computed using a polynomial curve fit of third order.

3.7   Additional Control Considerations

As it was said before, the implementation of a MPPT control technique can be done through the power converter; by controlling the duty cycle of the converter, the apparent load developed by the generator can be adjusted, and thus its output voltage and shaft speed can also be adjusted. However tracking the MPP is not the only objective of the control structure. WECS are exposed to disturbances that can affect its performance; those disturbances may include voltage imbalances (flicker, dip), harmonics, reactive power imbalances, etc specially when the system is connected to the grid [3]. To reject perturbances and ensure a good performance of any wind system additional control actions must be done, commonly they are made through the power interface. Several studies have been made on the configuration of the converter who is the central component of the power interface; the main characteristics of the system as the type of wind turbine and the type of the generator, may define the topology. In [47] and [48], different configurations are discussed for variable-speed wind turbine systems; in [49] is it recommended using a boost converter because its low cost and reliability for PMSG, while in [5] it is considered that the power interface can be composed by a back-to-back converter or by a three-phase diode rectifier connected to a boost converter; nevertheless equipment like STATCOM and matrix converters are commonly used in WECS. Besides MPPT technique, the control loop can be conformed by a voltage control, current control or duty cycle control, which can be implemented using diverse control techniques. Classical controllers like PI is widely used in industry applications since it is simple to design and easy to implement. Useful details about PI controlling of wind turbines are given in [50] and [51]; three kinds of control loops for tracking the optimal ro-

tor speed are used, in all of them the target rotor speed. In [52], a simple approximate model of a large wind farm is modeling, which attempts to mimic the active and reactive power dynamics of two generic wind turbine control systems based on PI controller. Adaptive control schemes continuously measure the value of system parameters and then change the control system dynamics in order to make sure that the desired performance criteria are always met, in [53] a model reference fuzzy adaptive controller was proposed for harvesting the maximum power from wind, authors highlight that the proposed controller has the advantages of shortening the time for system adjustment and quickening the response speed over conventional PID controllers. In [54], a proportional-resonant controller is proposed, which is adopted in a current loop, by giving a suitable current reference value for the controller, the problem of ac-side line-current asymmetry can be solved, and the effect of unbalanced grid voltages on the system can be avoided as well. Fuzzy logic control and other advanced control techniques are an effective approach to design wind systems due to their high nonlinear characteristics; in [55] a robust control algorithm for wind turbines subjected to a wide range of wind variation is presented, the algorithm utilizes fuzzy systems based on Takagi-Sugeno models and combines the merits of the capability for dealing with non-linear uncertain systems and the powerful Linear Matrix Equalities approach to obtain control gains while in [56] an on-line training recurrent fuzzy neural network controller is proposed, the control strategy is achieved without mechanical sensors such as the wind speed or position sensor, instead the estimation of the rotor speed is based on the model reference adaptive system, obtaining a sensorless vector-control scheme.

4 Simulation Results and Discussion

To keep an optimal C_p value, control techniques must adapt the generator angular speed ω_r according to current wind speed value V_ω. In this sense, there is a relation between the parameter D at the DC-DC converter side and the generator angular speed. Tip Speed Ratio

based control is adopted to present the incidence of parameter D in the generator angular speed. Simulations were carried out with Wind Turbine and Permanent Magnet Synchronous Generator parameters as in [57] and DC-DC Boost Converter parameters as in [12]. The load resistance was set to 20 Ω for all simulations. The simulated system diagram is shown in Figure 10.
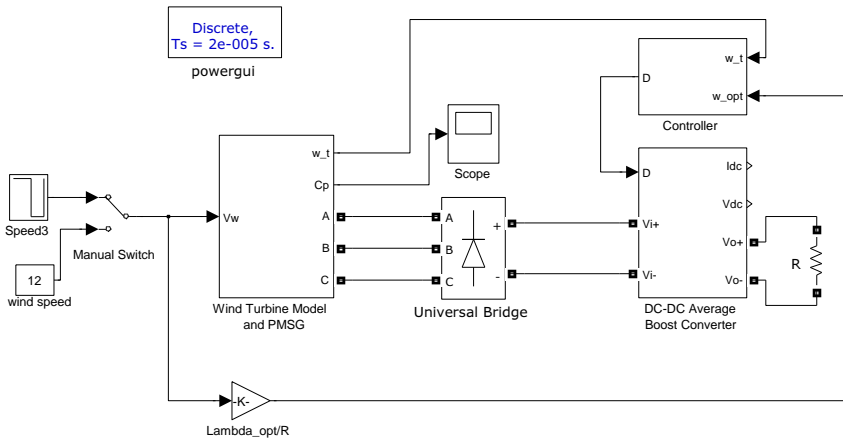

Figure 10: The simulated system diagram.

A detailed description of Wind Model, Converter and Controller blocks from Figure 10 are shown in Figures 11,12 13, respectively.
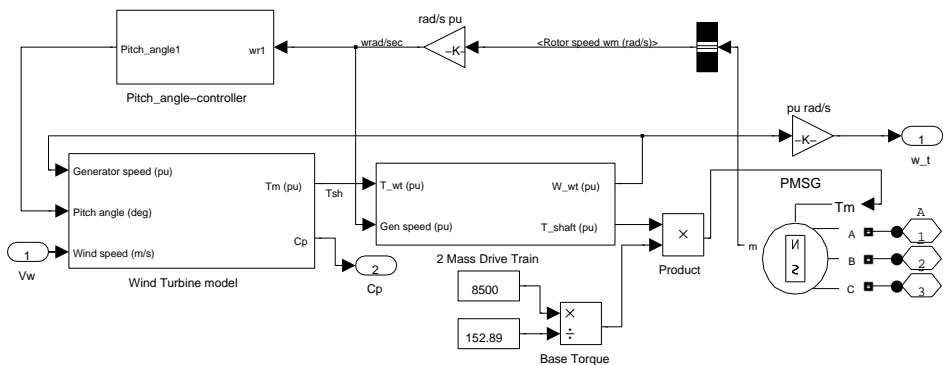

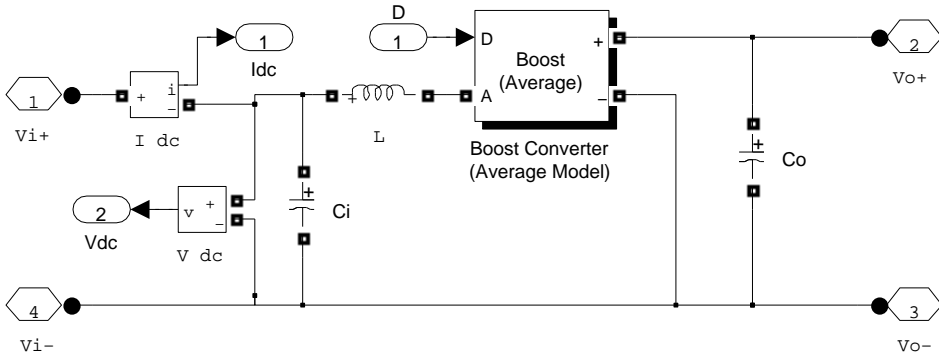**Figure 11:** Simulink diagram of Wind Turbine model and PMSG.

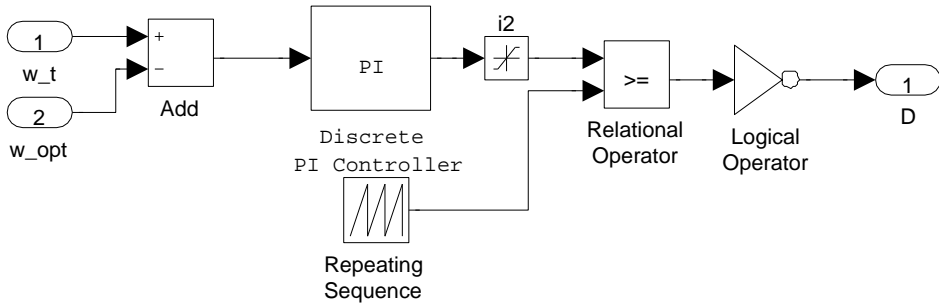**Figure 12:** Simulink diagram of DC/DC boost converter.

Figure 13: Simulink diagram of PI controller.

For the first experiment a step-like wind speed signal was generated(similar to optimal generator speed signal shown in Figure 14. The performance of the adopted controller is shown in Figures 14 and 15. C_p maximum value 0.48 is maintained for the first 3 seconds before the negative step change in the wind speed occurred. To achieve again the optimal C_p value, wind generator speed was decreased in the controller by increasing D to its top value. At time 5 s a positive step change in the wind speed occurred. Then, parameter D is decreased to increase wind generator speed and improve the C_p value.
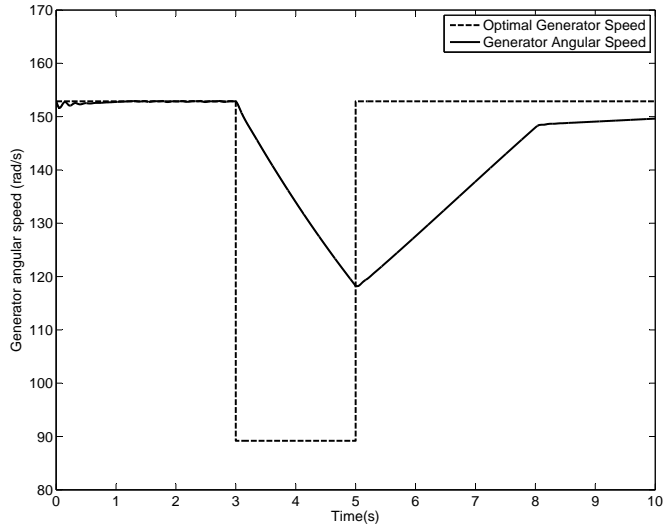
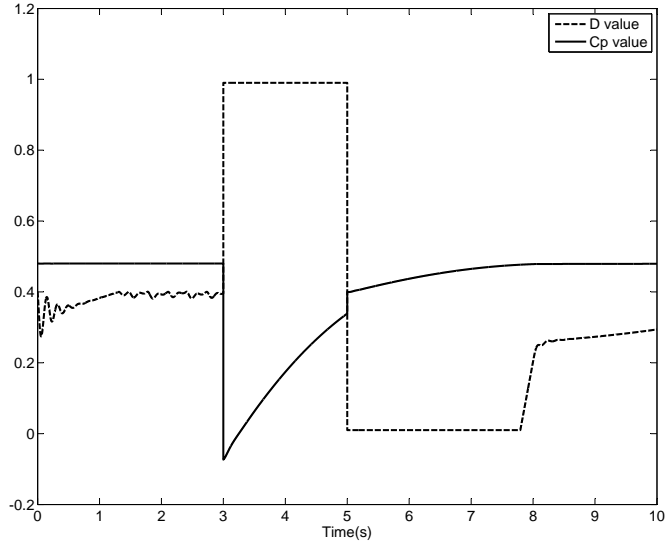**Figure 14:** Current and Optimal Wind Angular Speed.

Figure 15: The power coefficient and parameter D.

5 Conclusions

An overview of the most important concepts related to wind power systems have been shown in this paper. Aspects like the composition of the system and their behavior due to different conditions have been presented. It is important to highlight the role that the control plays, in these systems. The MPPT algorithms represent an suitable tool for improving the performance of the system. Besides, it helps to encourage the wind power systems like a good choice to the current challenges in energy matter. The models for simulations are the first step in the way of the designing process. Several models and related concepts have been studied, however there is no a established metodology to develop a model for a particular type of analysis, but the equations related with the power of the wind and the turbine are the main fundamentals for modeling. In the simulation results, the behavior of the power coefficient C_p is highlighted. The relationship between C_p and the duty cycle D of the DC-DC converter is given, and it lets show the importance of the power interface.

Acknowledgments

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