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PARTICLE SWARM OPTIMIZATION BASED TUNING FOR A SMALL WIND TURBINE PITCH CONTROL

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Abstract- This work describes a simulation model that allows easily designing the control of a 100 kW wind turbine. The Particle Swarm Optimization has been applied in the control tuning. One of the key design elements of a wind turbine is the control, because it affects directly the solicitation values on the structure. For the approach treated here, the control design is considered a step in the mechanical design of the wind turbine.

Keywords: Wind Turbine, Pitch Control, Small Wind Turbine, Particle Swarm Optimization.

I. INTRODUCTION

In recent times, Wind Power has become an important Energy resource. For example, in 2011 the percentage of electricity obtained from Wind Power reached the 16.3% in Spain [1]. The weight of this energy resource in power generation companies has grown steadily, becoming nowadays one of the most dynamic sectors of the Spanish economy [2, 3].

However, in the field of wind energy, new trends are still being detected. One of them moves towards the creation of autonomous distributed generation plants. Actually, many manufacturers are involved in the development of small and medium size wind power plants. This kind of turbines is suitable for domestic or industrial autonomous applications that require electrical generation points close to the demand. Thus, the energy generated is used locally, while the surplus may be sold to the electrical grid.

Unfortunately, one of the most complex issues in the design of this kind of wind turbines is the mutual interference among the different phases of design. In particular, it is complex to separate the mechanical design of the structure from the control algorithm due to the great influence exerted by the efforts to support the wind turbine. Conversely, the control system needs to know certain mechanical and aerodynamic aspects. Therefore, the controller of a wind turbine must satisfy the following three main objectives:

1- Maximize the electric power produced. Obviously, the wind turbine controller should optimize the power production in order to reduce costs and increase the profitability of the turbine.

2- Control the rotational speed in the rotor. The controller must avoid rotor speeds that could induce high critical loads on the turbine structure.

3- Reduce the efforts on the structure. The controller of the turbine should minimize the regulatory activity, since an overly active control action implies that, the forces on the structure occur more frequently, producing greater structural fatigue on the machine components and reducing its lifetime.

Improving one of the previous objectives may interfere in the others. Therefore, the task of tuning the parameters of the turbine control is very complex. This work is aimed at simplifying the process of tuning the control parameters of a small or medium size wind turbine, while keeping the three previous objectives.

II. DESCRIPTION OF THE CONTROL MODEL

The three fundamental aspects to model the behaviour of a wind turbine and its power regulation or control are:

1-The aerodynamic performance of the blades, characterized mainly by the rotor power coefficient, cp.

2-The dynamic behaviour of the power train in the wind turbine.

3-The electrical behaviour of the generator and the power amplifier.

There are other aspects in the control design of a wind turbine, which are less important, such as:

- The structural design of the rotor
- The design of the tower

However, the modeling of these mechanical structures is not necessary to make a complete study of the controller of a wind turbine since they can be modeled with other methods at designing and sizing time.

A. Wind Turbine and Powertrain model

The most important characteristic of the wind turbine is the power coefficient (c_p) that defines the obtained wind power according to expression (1):

$$P = \frac{c_p \pi v^3 \rho_{air} R^2}{2} \quad (1)$$

where, P is Obtained power (W), v is wind speed (m), R is Radius of the blade (m), ρ_{aire} is Air density, c_p is Power Coefficient = f(wind speed, pitch, angular speed) and λ is defined as a dimensional parameter that establishes the relationship between the wind speed and the speed of the blade tip. The c_p can be traced down as shown Figure 1.

$$\lambda = \frac{R.w}{v} \quad (2)$$

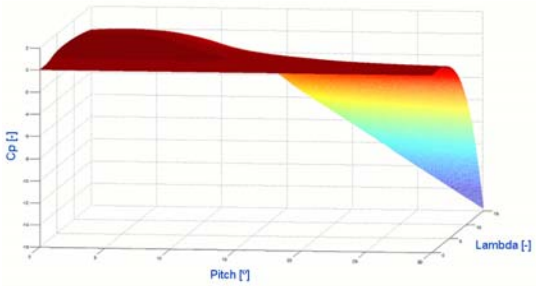

Figure 1. The trace of c_p

The Equation (3) produces the torque offered by the turbine:

$$T_{Turbine} = \frac{P}{w} = \frac{c_p(\lambda, \beta) \pi v^3 \rho_{air} R^2}{2w} \quad (3)$$

The power train model used in this paper is written in Equation (4).

$$T_{Turbine} - iT_{machine} = \left(i^2 J_{machine} + J_{turbine}\right)\frac{dw}{dt} \quad (4)$$

B. Power Stage and Electric Generator Model

Since the objective of this paper is designing the controller for a wind turbine, other issues related to power electronics, dynamics of the electric machine or the nature of the power grid have not been considered. This is because these power stages can be modeled from the wind turbine perspective as a first order system consisting of a pair of machines with a given time constant (See 5). Such devices usually are acquired from established vendors for this type of products [5]. From the point of view of a wind turbine builder it must only be considered the turbine torque and the performance of this stage.

$$\frac{dT_{machine}}{dt} = \tau_{PE}\left(T^*_{machine} - T_{machine}\right) \quad (5)$$

where, $T_{machine}$ is Torque imposed by the machine (N.m), $T^*_{machine}$ is Torque set point (N.m), and τ_{PE} is Time constant of the power stage and electric machine (s). A more exact description of the power stage and the electric generator model can been found in [6].

C. Modeling of Wind Speed

The wind is an input fundamental variable to the model which we go to work. For the correct modeling of wind will use two terms:

1. The wind speed average.
2. The turbulence: For this kind of terms exist different models [7]. Many of these models are fixed in military standards [8].

In the case of our wind turbine model will use a stepwise wind. There are other more realistic wind models such as the Von Karman [8].

D. Control Structure

The manipulated control variables are:

1. The torque set point requested by the power stage to the electric machine.
2. The pitch that are imposed to the turbine blades.

The controlled variable is the rotational speed of the wind turbine. The proposed algorithm is based mainly on split into two regimes of operation. The first is associated with a range of speeds ranging from the minimum speed at a speed somewhat lower than the nominal angular velocity. In this first range of velocities is imposed on the electric machine a torque such that in permanent regimen the wind turbines give us the maximum power. Not measured wind speed as it is assumed that forcing the torque-speed curve, the dynamics of steady wind turbine reaches the optimum point of operation. Similar strategies can be found in [9].

If you want to achieve maximum power for a given wind speed, you must achieve the maximum power coefficient. This power coefficient will be maximum for a particular pitch and λ_{optim}. Normally, the optimum "pitch" angle is usually 0º or an angle close to zero. In the case of λ_{optim} will depend on the blade profile to be taken. Based on the foregoing, the optimum torque can be defined as follows.

$$T_{optim} = \frac{c_{p,optim} \pi \rho_{air} R^5}{2\lambda^3_{optim}} w^2 \quad (6)$$

For the transition between the first and second stages it establishing a straight line from speeds close to nominal velocity to the rated speed of the turbine. In the second regime of operation, we will force them to absorb energy by the electric machine. This causes the torque is reduced in hyperbolic shape with respect to speed.

$$T_{machine,highrange} = \frac{P_{nominal}}{i.w} \quad (7)$$

The transition between the curves of both regimes is a ramp that connects them, to avoid as far as possible make sudden changes that make the structure have to support too much effort [10]. Concerning the pitch control has been proposed a PI control, with limit for its output value and the speed at which regulates the pitch angle. The output range can go from a value slightly lower than 0° to a maximum value, the limit being 90° in case of emergency stop. The maximum rate of change that is supported is 10° per second, which is the most appropriate speed to act on the blades.

It is recalled that a slow change speed of "pitch" makes the blades are not able to continue properly to changes in speed, which would endanger the installation. On the other hand, is not interesting a too rapid rate of change as it causes excessive stresses on the structure.

The set point in the case of rotational speed regulator is drive the wind turbine to the range of low speeds. To do this we must invert the sign of the output of the regulator, so that with a positive error (low speed in the wind turbine), the pitch angle must be as small as possible, and when he error be negative (high speed in the wind turbine) then the regulator give an angle as large as possible.

With this type of control will never have an overproduction from the viewpoint of the grid. In the other hand this type of control is complex to manage, because when there is an increase in the torque generated by the wind at high speeds, we need reduced the opposed torque of the electrical machine, this is to not to exceed the power sent to the network. This causes that the turbine increases its speed to absorb excess wind-energy captured.

To prevent the resonance of the turbine, the PI regulator must increase the pitch angle for reduce excess wind-energy captured. This means that we move along the surface c_p to place the system in a suitable yield point. It should be noted that the pitch change means changes in load on the blades and consequently, increase the fatigue of the structure. Accordingly, the tuning process should minimize the control of pitch, more specifically, its time derivative. This aspect is described in detail in the following section. The dynamic of the pitch loop is defined by the valve and with the pitch controller.

$$\frac{d\beta}{dt} = Sat_{-\dot{\beta}_{\max}}^{\dot{\beta}_{\max}}\left(\tau_{electroval}\left(\beta^{*}-\beta\right)\right) \quad (8)$$

where, β is Pitch angle imposed by the valve (rad), β^* is Pitch set point requested by the pitch controller (rad), $\tau_{electroval}$ is Valve time constant (s) and $\beta_{\max}$ is Maximum ratio f change of pitch (rad/s).

The pitch regulator controls the wind turbine speed. The speed error is defined as the difference between the speed of rotation of the blades and the rotational speed of the set point:

$$\beta^{*} = K_p\left(Error + \frac{1}{T_i}Error_{integral}\right) \quad (9)$$

$$Error_{integral} = Sat_{-L_{integral}}^{L_{integral}}\left(Error_{integral}\right) \quad (10)$$

The proposed regulator has the following parameters: K_p and T_i. The adjust of these parameters is often done with linear system theory in spite of the behavior of the wind turbine is highly nonlinear, the pitch PI controller is tuned using linearized models of the turbine. The biggest problem with this kind of strategy is that the operating point varies greatly and therefore the parameters must be gradually adjusted. This technique is called "gain scheduling". A good reference where you can get justification of expressions for K_p and T_i with "gain scheduling" is [11]. The formulas for the synthesis of the PI controller are as follows [12].

$$T_i = \frac{2\xi}{\omega_n} \quad (11)$$

$$K_p = \frac{2\xi}{\omega_n}\frac{K\Omega_0}{i.\frac{30}{\pi}}\left(-\frac{\partial P}{\partial \beta}\right)^{-1} \quad (12)$$

$$K = \omega_n^2 \quad (13)$$

where ξ and ω_n are design parameters. Usually, these values are ω_n=10 (rad/s) and ξ=0.66 (-) [12]. Furthermore, Ω_0 is the value of the rotational speed of the turbine around which the model is linearized. In our case, this speed is equal to the rated speed.

Finally, the term associated with the partial derivative of the power generated respect to "pitch" angle is function of this angle. Therefore, the gain must be changed depending on the value of the pitch. The change of this term usually is considered a linear change [12], because this term is usually considered to vary linearly [12], because depending on the operating point, this line varies strongly.

Due to this characteristic, this paper proposes to adjust using an algorithm set using Computational Intelligence PSO (Particle Swarm Optimization) parameters that modeling the sensitivity of the power by a line. These parameters have been designated S_1 and S_2 and its definition is described below.

The partial derivate of the generated power in the turbine respect to the pitch angle is routinely referred to as "power sensitivity" and generally dependent on three variables: the pitch, the speed of rotation of the blades and wind speed. Among these three variables, the wind speed is the magnitude more complex to use.

While it is relatively easy to measure is not easy to determine how to extrapolate measurement of wind speed at all the points involved in the blades, since the radius of the blades is so great that the speed that supports a shovel point varies greatly with regard to wind speed that supports another point.

Furthermore, the sensitivity of the power determines the gain K_p. Therefore, in general, is assumed that the power sensitivity is only function of pitch, and that this dependence is linear. Although most manufacturers use adjustments based on the surfaces of the turbine power, these sensitivities vary strongly depending on the tools and techniques [12]. In our case we have proposed to perform an optimization of the points that characterize the sensitivity by PSO technique.

Once it has set a line of sensitivities. The pitch control of turbine is fully defined. An appropriate development to understand the optimization algorithm is described in [13]. In our case, the optimization algorithm changes the sensitivities S_1 and S_2 these values are the sensitivities for two values of different pitch.

Therefore, the sensitivity can be defined mathematically as follows:

$$S = \frac{S_2 - S_1}{\beta_2 - \beta_1}\left(\beta - \beta_1\right) + S_1 \quad (14)$$

where,

S: Sensitivity of power for a given pitch (-)
S_1: Sensitivity of power for zero pitch (-)
S_2: Sensitivity of power to a certain maximum pitch (-)
β: pitch angle (rad)
β_1: Pitch minimum or zero (rad)
β_2: maximum allowable pitch (rad)

E. Control Structure

When establishing a criterion of tuning control parameters, there are three important issues:
1. Amount of energy can inject network after one year.
2. Equivalent efforts supported by wind turbine structure. Because of these efforts, depend of each structure as well as the geometry of the blades. To calculate this type of effort we must to use specific software tools [14] and [18]. They are particularly suitable programs that allow calculation of aeroelastic efforts together with the finite element models of the rest of the turbine, such as the tower or the foundation of the whole structure [15] that are properly certified for standardization organizations. In our case, we consider that a control algorithm, which minimizes the derivative of the pitch angle will, also minimizes fatigue, which are subjected to the turbine blades and the overall structure of the turbine. When choosing a criterion for selection of the control parameters, it has been established equivalence between the error in speed when the rotational speed it is above the transition speed.
3. The speed error in the high speed range. The speed error is taken into account only when it exceeds the threshold of the nominal rotational speed and it approaches the speed at which excites the first mode of vibration of the wind turbine. if the wind turbine would be in this conditions of speed over an interval of about a minute or so, the wind turbine would be destroyed. So this aspect is very important to control the wind turbine, because the integrity would be endangered.

The cost function proposed is the following one:

$$Cost = \lambda_1 P_{avg} + \lambda_2 Error_{speed} + \lambda_3 Activity_{pitch} \tag{15}$$

where λ_1, λ_2 and λ_3 are explained below. The term related to the mean power value is written below.

$$P_{avg} = \frac{1}{T_{simulation}} \int_0^{T_{simulation}} P.dt \tag{16}$$

The P average value is obtained over a period of time equal to the duration of the simulation. The most common simulation time is 300 seg.

$$Error_{Speed} = \frac{1}{T_{simulation}} \int_0^{T_{simulation}} Error_{w(high)}.dt$$
$$Error_{W(High)} = \begin{cases} \left| w^* - w \right| : w > w^* \\ 0 : w < w^* \end{cases} \tag{17}$$

As can be seen, the error is only important when the set point is exceeded. This is because the positive errors occur at low speeds and therefore the pitch value that should be taken at those speeds is limited to zero, to obtain the maximum possible power.

In the case where the rotational speed is above the set point speed, the error is negative and therefore will work with the absolute value. The higher this value, the resonance risk will be less. In the case of the term associated with the activity of the pitch, we define the following function.

$$Activity_{pitch} = \frac{1}{T_{simulation}} \int_0^{T_{simulation}} \left| \frac{d\beta}{dt} \right| .dt \tag{18}$$

Fatigue is heavily dependent on rapid changes in pitch angle because the turbine bearing loads vary strongly with him. This makes that a control very "nervous" is not interesting for the installation, since it forces oversize the structure of the tower and the blades, or to greatly reduce the life of the facility.

To finish completely define the cost function should explain how they have chosen the weights of the three terms discussed above. The value assigned to parameter λ_1 is -10, because it must obtain the maximum average power. The negative sign of this parameter is because we want to minimize the cost function. The parameter associated with the average error of speed, λ_2 is assigned a value of 10, because if this value is great, will be closer of the resonance in the structure. Finally, λ_3 parameter takes the value 1, as compared to the other two terms are considered 10 times less important economically.

III. SIMULATION

To support this section we performed the simulation of control of a small wind turbine

A. Characteristics of the Wind Turbine

The most important characteristics of the turbine are:
1. Power Rating: 100 (kW)
2. Inertia of the turbine: 28781: (Kg.m^2)
3. Inertia of the rotor of the electrical machine: 5.4 (Kg.m^2)
4. Curve of the blades, absolute optimum values of the surface of c_p:
• $C_{p\max}$ 0.47 (-)
• β_{optimo} 0 (rad)
• λ_{optimo} 6.5 (-)
5. Nominal speed which gives the nominal power of 100 kW: 50 (rpm)
6. Maximum rotational speed of the blades from which one runs the risk of coming into a resonance: 55 (rpm)
7. Reduction coefficient: 15 (-)
8. Total efficiency of the power stage of the electrical machine 0.9 (-)
9. Radius of the blade: 10 (m)

The wind speed was characterized as follows:
1. To control optimization has been proposed that the speed of wind behave step by step, in which each step remain for 60 s. The initial speed is 10 m/s and each increment is 2 m/s ending at a wind speed of 20 m/s. It seeks to precisely adjust the parameters of pitch control, as this speed from the turbine is able to give the power of 100 kW, and therefore must regulate the speed of the wind turbine with pitch angle of the blades. For our case, this profile is sufficient, because this ensures a good dynamic performance throughout the operating range.

The most important parameters in these models are:
• Height of tower: 36 (m)
• Average wind speed: 4.5 (m/s)
• Terms of turbulence: These terms are determined by the turbulent wind model [17].

The most relevant features and their respective control devices:
1. Rotational speed of the turbine from which starts the transition between two zones of operation
2. Rotational speed of the turbine from which completes the transition between two zones of operation. This speed is equal to the rated speed and is also the value assigned by the pitch controller set point (w^*).
3. Parameters of the cost function.
4. Dynamic characteristics desired in linear regime with the PI control running.
• ξ: Design damping factor. A good value is 0.66 (-) [12]
• ω_n: Design natural pulsation natural. A good value is given is 10 (rad/s) [12]
5. Time constant of the power stage of the electrical machine: 0.1 (s)
6. Time constant of the valves that sets the pitch of the blade: 10 (º/s)
7. Maximum rate of change of valves: 10 (º/s)
8. Maximum angle of pitch in normal operation in the area of high speeds: 45 (degrees)
9. Minimum angle of pitch in normal operation for both the area of high and low speeds: 0 (º)
10. Speed set point in high speed area, w×50 (rpm)

Features of the PSO optimization algorithm:
1. Number of particles: 15
2. Number of iterations: 100
3. Coefficients of inertia: 0.00009
4. Simulation horizon $T_{simulation}$: 300 (s)
5. Coefficients r_1 and r_2 of the PSO algorithm: uniform distributions between 0 and 0.1.

B. Simulation Structure

The simulation tries to adjust the wind turbine control based on the cost function proposed above. Therefore, the simulation has been designed in several modules.
1. General Module: This part has to obtain the S_1 and S_2, parameters following the PSO algorithm.
2. Evaluation module: This module is responsible for launching the simulation of the proposed model with the parameters proposed by the general module. Once the model returns the temporal behavior of the system, this module evaluates the proposed cost function.
3. Model Module: This module is responsible for system simulation with the parameters that have been transferred by the evaluator module. Once the simulation has been performed, the evaluation module returns the temporal behavior of the variables involved in the cost function.

C. Results

The results obtained with the optimization performed in the simulation are in Figures 2 and 3.

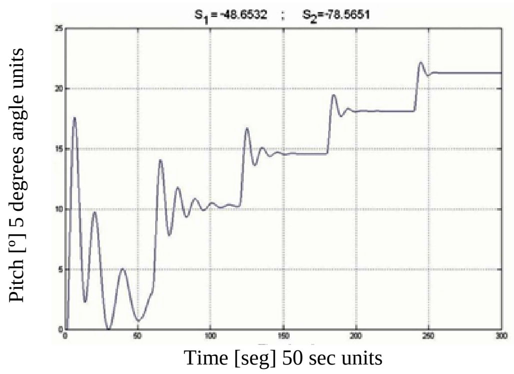

Figure 2. Pitch evolution with stepwise wind speed changes 12-20 (m/s)

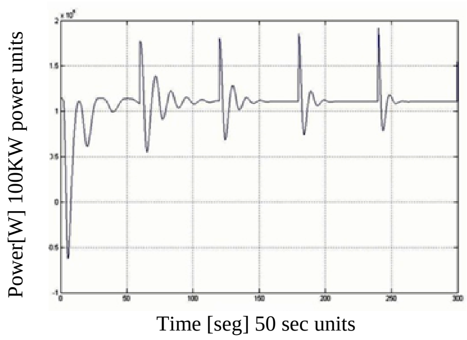

Figure 3. Evolution of the received power

The minimum cost has been achieved with S_1=-48.65663, S_2=-78.5651. The pitch control algorithm adapts to each new situation. Furthermore, the rotation speed has a similar behavior during the different steps, so we can consider that the adaptation to different working points is accomplished properly. Both in the power curve as the velocity curve, the first 50 seconds of time is a period in which the control system must be adjusted to have a rotational speed suitable for a wind of 12 m/s, and due to this presents a transient as pronounced.

IV. CONCLUSIONS

The most important contribution of this paper is to propose a modeling able to calculate the most important aspects of the wind turbine control but simple enough so that it can be simulated in any simulation platform of dynamic systems. The second conclusion is that by the results obtained with the simulation of the proposed model can take information from different platforms.

Finally, using the proposed model can propose different control strategies such as those proposed in [4] and other techniques for tuning of control parameters.

As a final conclusion it could to stress that the proposed model can be easily generalized [14], which makes it possible to reduce the number of iterations and time of each iteration in the design. Because, it allows a direct calculation of the most important efforts in the structural design of the installation, such as bending moments at the root of the blades of the turbine. The PSO technique is widely applied to many other control areas as control parameter optimization algorithm. Finally, good examples can be found at [19, 20].

Currently, the authors are working in the development of models that integrate the above aspects with the variables that best define the structural behavior of a wind turbine. On the other hand, the authors are also working on new wind turbine control strategies, in order to compare among different control strategies as applied to the control of wind turbines.

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