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ADAPTABLE CONTROL FOR ELECTRICAL GENERATION AT IRREGULAR WIND SPEEDS

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Abstract: The main aims of this work are the development and the validation of one generic algorithm to provide the optimal control of small power wind generators. That means up to 40 kW and blades with fixed pitch angle. This algorithm allows the development of controllers to fetch the wind generators at the desired operational point in variable operating conditions. The problems posed by the variable wind intensity are solved using the proposed algorithm. This is done with no explicit measure of the wind velocity, and so no special equipment or anemometer is required to compute or measure the wind velocity.

Keywords: control, power systems, energy, smart power applications, wind turbines.

1. INTRODUCTION

The ecologic grownup conscience and the increase of the energy consumption in the entire world are the most relevant aspects that justify the interest in renewable energies, in particular the wind energy. The wind energy is the kinetic energy in the mass of air in movement. As is known, the kinetic energy is proportional to the square of the velocity. Therefore, the power available in the turbine area has a cubic relation with the incident wind velocity. Subsequently to this relation, small variations on the wind velocity can produce significant variations in the production of energy.

The wind velocity and its presence along all the year as well as its constancy are the most important factors in the quality of the energy produced using wind generators. Frequently, the better places to install the wind generators are the top of the mountains and close to the sea line on shore. Unfortunately, not all the places are in these conditions. A lot of places have enough wind velocities but those are not constancy enough. This makes difficult the connection with the power line and decrease the energy quality.

This problem can be solved in several stages. First, the maximum power is extracted from the wind in the alternated current form (AC). Second, The AC current is converted to unidirectional current (AC-DC). At last, a controlled solid-state inverter is used to interface with the power line (DC-AC).

By means of the type of conversion explained above and using some capacity of energy storage the impact of the wind velocity variations in the power line currents and voltages are reduced. In this way, the production of electrical energy with high quality is possible using the turbulent wind. This conversion of wind energy to electrical energy at variable frequency allows achieving high efficiencies for a large bandwidth of wind velocities (B. Neammanee, 2006).

2. PROBLEM DESCRIPTION

2.1. The fundamentals

The low power wind turbine generators have maximum powers up to 40 kW without regulation of the pitch angle. In this kind of generators reduced or no maintenance is required (Ricardo Puga, 2003). One wind turbine with 2 or 3 blades and one electrical machine to convert the mechanical to electrical power are the two principal components of this kind of wind generators.

The impact of the air in the blades of the turbine produces aerodynamic forces that compel the turbine in a movement of rotation. These forces can be decompounded in two components, one of tracking with the same direction of the wind and other force of sustainability perpendicular to the wind velocity. The movement of rotation is transmitted to one electrical machine that converts the mechanical power in electrical power. The simplest mathematical model of the wind turbine is based on the torque produced in an uniform disc when it is crossed by one column of air producing one pressure discontinuity. The figure 1 shows one column of air with wind velocity (V_1) and output velocity (V_2) crossing one disc with area (A).

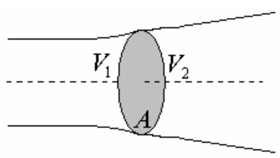

Fig. 1. Air flow crossing one turbine with horizontal rotation axis.

The air is supposed to reach the disc at a angle of 90 degrees and with constant velocity. The air is also supposed to be uncompressible (Ricardo Puga, 2001). The application of the relations of momentum and energy demonstrates that the axial average velocity (V) in the disc is given by:

$$V = \left(\frac{V_1 - V_2}{2} \right) \quad (1)$$

The kinetic energy extraction by unit of time from the mass of the air is the goal of the wind turbine. This power is expressed by equation 2 as a function of the air density (ρ) and the variables defined above (Spera, 1994; Manwell *et al.*, 2004).

$$P = \frac{1}{2} \rho \cdot A \cdot V . \left(V_1^2 - V_2^2 \right) \quad (2)$$

The delay coefficient of the air flux (a) gives the relation between V and V_1 as:

$$V = V_1 \cdot (1 - a) \quad (3)$$

The concept of power coefficient (Cp) is the ratio between the power absorbed by the disc and the power that go by its area when it isn't present. Using the concept of Cp and the equations (1) and (3) to eliminating V and V2 in the equation (2), it follows that:

$$\mathrm{P} = \frac{1}{2} \mathrm{C_P} \cdot \rho \cdot \mathrm{A} \cdot \mathrm{V_1^3} \quad (4)$$

$$C_P = 4 \cdot a \cdot (1 - a)^2 \quad (5)$$

In the case of null axial factor interference the disc does not affect the air flow. In this case the Cp is null and no power is extracted by the wind turbine. In theory the Cp maximum has the value of 1/2. This means null velocity for V_2. In this case, the radius of the outing column of air will be infinite. The maximum extraction of energy occurs when the delay coefficient is 1/3. In this case the coefficient Cp is equal to 16/27 this is the Betz Limit (Burton *et al.*, 2004). The Cp isn't a constant value for any type of turbine. It is a function of the Tip-speed ratio (λ) as is presented in figure 2.

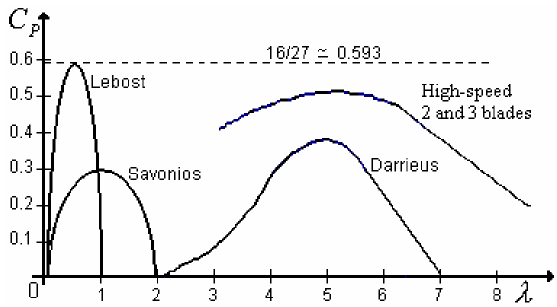

Fig. 2. Cp as a function of λ for several turbines

The λ is the ratio between the linear blade edge speed (tip speed) and the wind velocity V_1. The tip speed of the blades is given by the product of the radius of the blades (r) by the turbine instantaneous angular velocity (Ω), as showed in equation 6.

$$\lambda = \frac{\Omega \cdot r}{V_1} \quad (6)$$

2.2. The electrical machine coupled to the turbine

In synchronous generators the rotation velocity is proportional to the frequency of the generated voltages. The same happens in the DC generators with respect to the frequency of the ripple voltage that is proportional to the angular rotation in the generator. Attending to this aspect, it is possible to draw the generated power in function of frequency of the machine relation. For each wind velocity (V_1) and for each Ω the equation 6 gives the value of λ.

Using the respective curve to the wind turbine in the Fig. 2 then the correct value of Cp is obtained. For last, equation 4 is applied to find the value of the extracted power. Repeating this process for several points the extracted power curve in the figure 3 is obtained for each wind velocity. The horizontal axis in the figure 3 can be Ω or its related frequency (*f*) in function of the pairs of poles of the machine and of the gear box ratio.

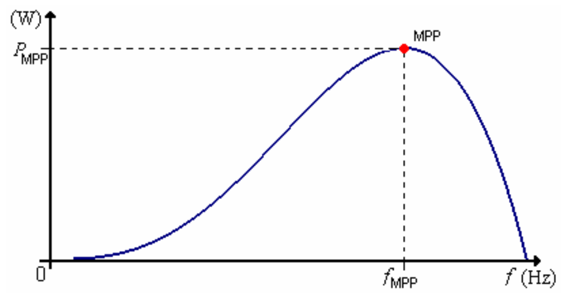

Fig. 3. Curve $p(f)$, with indication of the MPP.

For different values of (V_1) the Maximum Power Point (MPP) is shifted as showed in figure 4.

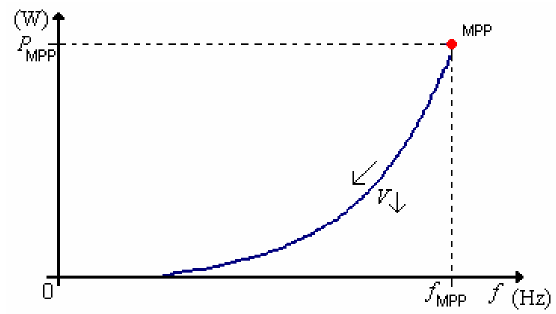

Fig. 4. Shift of the MPP for the evolution of the wind velocity.

2.3. Principles of a dynamic control approach

It is clear expressed in figures 3 and 4 that for the maximum conversion of wind in electrical energy the operation point (QF) of the turbine has to flow to the MPP. A Maximum Power Point Tracker (MPPT) (De Broe, 1999) is the device that implements this task. The operation of the MPPT has basically two steps. The first is to locate QF with respect to the MPP and the second is to generate the control references to move the QF towards the MPP.

The graphic presented in figure 3 shows that the MPP is the unique relative extreme of the function p(*f*) and that it is the maximum. The figure 4 shows that the increase of the wind speed implies the increment of the f_{MPP} and that the decrease of the wind implies the decrement of the f_{MPP}. The unique extreme relative is well identified by the null value of the derivative dp/df (f_{MPP}) that is shown in figure 5.

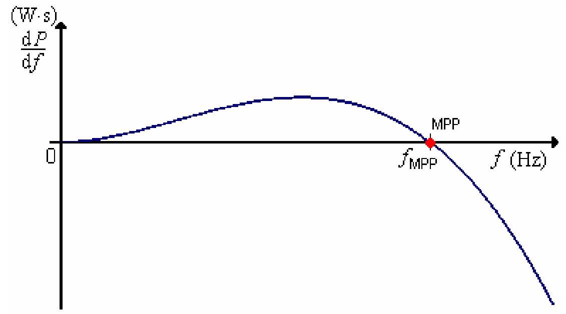

Fig. 5. Derivative of the power extracted with respect to the frequency for a particular wind velocity.

For different wind velocities different curves dp/df will be find and consequently different locations of the fMPP. The same conclusion can be achieved interpreting the graphic presented in figure 4. As it is shown in figure 5 the MPP is the point for that the dp/df is null and this function is continuous. The dp/df function is positive and negative at the left and at the right of the f_{MPP}, respectively.

When the QF is not in an area marginally-stable, then dp/df is null only in the MPP point. Considering these aspects and observing the graphic in the figure 5, the desired MPPT needs to have the behavior presented in the equation 7.

$$\begin{cases} \dfrac{dp}{df} > 0 \xrightarrow{MPPT} \dfrac{df}{dt} > 0 \\ \dfrac{dp}{df} = 0 \xrightarrow{MPPT} \dfrac{df}{dt} = 0 \\ \dfrac{dp}{df} < 0 \xrightarrow{MPPT} \dfrac{df}{dt} < 0 \end{cases} \tag{7}$$

Close to the origin of the axis in the graphic of the figure 5 the dp/df is null and the point QF needs to be moved to the right side. For this, between the turbine rotation velocity and the electrical variables of the generator is required one adequate relation. Both, the DC machine and the synchronous generators produce one higher resistant torque in the turbine for a higher current generated.

The increase of the resistant torque reduces the angular velocity of the turbine and one decrease of the torque originates one increase of the turbine rotation for each wind velocity. One relative increase in the turbine rotation velocity originates one equal increase in the electrical frequency generated on the electrical machine.

If the temporal law evolution of the function $f'(f)$ is imposed by the MPPT, as presented in equation 8 the MPPT will have the proper behavior. Because *f'(f)* is null for *dp/df* null, the f_{MPP} that corresponds to the MPP is called a fix point (Edward R. Schinerman, 1996). This function is negative at the right of the MPP and positive at the left. Therefore, the QF point will be moved always to the MPP.

$$f'(f) = \begin{cases} +\alpha \ \ se \ \ \dfrac{dp}{df} > 0 \\ 0 \ \ se \ \ \dfrac{dp}{df} = 0 \\ -\alpha \ \ se \ \ \dfrac{dp}{df} < 0 \end{cases} \quad (8)$$

(where α is a positive real number)

Using equation 8 to implement the MPPT algorithm and assuming $dt \approx \Delta t$, it is obtained the following control law:

$$f_{n+1} = f_n + K \cdot sign\left(\frac{\Delta p}{\Delta f}\right) \quad (9)$$

2.4. The control algorithm

One possible implementation of the control law algorithm given by equation 9 is depicted in the flowchart of figure 6.

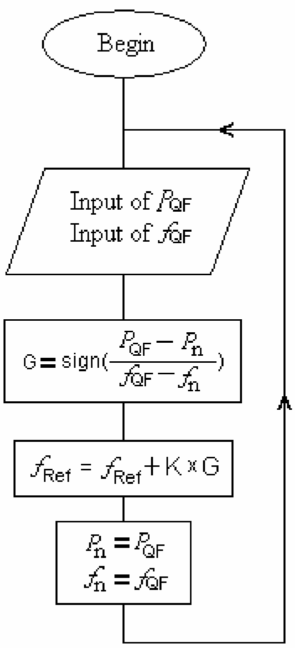

Fig. 6. Flowchart of the MPPT proposed

The variables f_{n+1} and f_n are the reference frequencies with respect to successive interactions and *K* is the product of Δt by α. The function *sign(.)* returns -1 for an argument ($\Delta p / \Delta f$) negative and 1 for a null or positive argument. One very small value of *K* makes the system very slow. In this case for a constant wind speed the controller will take a large time period to get the target (MPP). For a very high value of *K*, the system will be instable and no efficient control can be achieved.

The variables f_n and P_n are related, respectively, to the reference frequency and the power extracted in the last interaction. The frequency f_{QF} and the power P_{QF} are related to the present interaction and f_{REF} is the reference frequency computed by the algorithm.

3. EXPERIMENTS

Several simulations were realized considering three blades turbines with different areas. Distinct wind velocities and variable wind situations were also studied. In all the simulations the MPPT started the operation when the frequency of rotation of the turbine was of 3.3Hz.

The block diagram of the model used in the simulations is the present in figure 7. It is composed of three blocks: wind; generator and MPPT. This last one is detailed below.

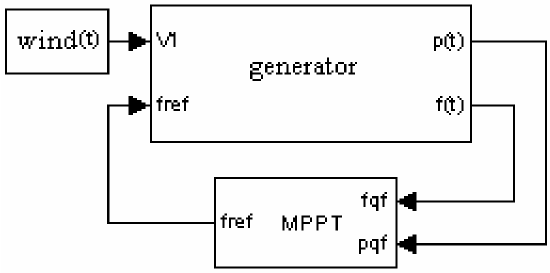

Fig. 7. Block diagram of the system in study

The first block has as output the variable that represents the wind velocity along the time. The parameterization of this block allows the simulation of diverse and adverse climatic conditions. The second block represents the wind generator formed by the turbine and the electrical machine based in the equation 4. For last, the MPPT implements the algorithm presented in the figure 6. The air density is of 1.293 kg/m^3. It is important to refer that this block does not use the value of the wind velocity to calculate the reference frequency.

Assuming that the *sign(.)* function has no units, in all the simulations the constant *K* is fixed at 15 mHz and the time step is fixed in 0.1 s. Attending to *K* and to Δt the slew-rate of the MPPT controller is of 150 mHz/s. This value is small enough to allow this algorithm to run in real-time in almost of the actual processors.

4. RESULTS

In this section are presented simulations with constant and variable wind speeds for wind turbines with 3 blades and 2 different diameters. Also, the problems raised by an improper parameterization of the controller are focused.

4.1. Test 1: Constant wind velocity and 3 blades, 5 m^2 turbine

The first set of results is respected to one turbine with 3 blades and 5 m^2 of area. Wind velocities of 4 m/s, 7 m/s and 10 m/s that with this turbine are related to the maximum powers of 103 W, 554 W and 1614 W, respectively, were considered.

The results in these conditions are presented in the graphics of Fig. 8. It is obvious that the MPPT has controlled the system to the maximum power extracted from the wind. This means that the QF and the MPP were stabilized very close. This graphic shows that the rotation frequency response of the turbine along time present oscillations. However, these oscillations do not have effect in the power generated. This is due to the fact that, in this kind of turbines, near the MPP the QF point changes produces little variations in the Tip-Speed Rate, and so they produce small effects in the power generated, as can be observed in the figure 2.

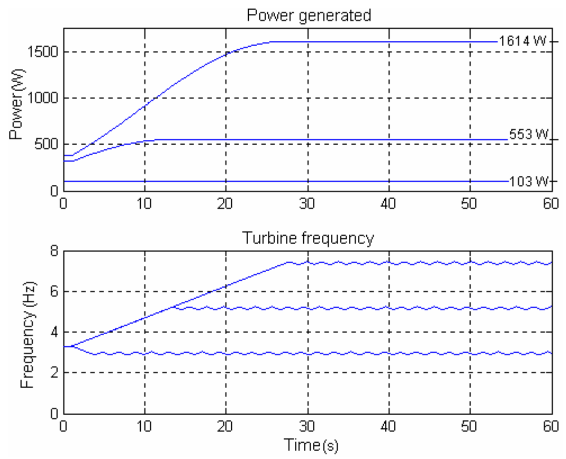

Fig. 8. Power and frequency at wind velocities of 4, 7 and 10m/s for a turbine with 5 m^2 of area.

It must be pointed that the power extracted for the wind velocity of 10 m/s is $(10/4)^3$ times upper than for the wind velocity of 4 m/s, which is in conformity with the equation 4.

4.2. Test 2: Constant wind velocity and 3 blades, 10 m^2 turbine

The second set of results was carried out with the same type of turbine and wind velocities as above but with one upper area of 10 m^2 in the turbine. With this turbine, for the same wind velocities as in the last case, the maximum powers extractable from the wind were duplicated. The results, showed in figure 9, are in agreement with equation 4.

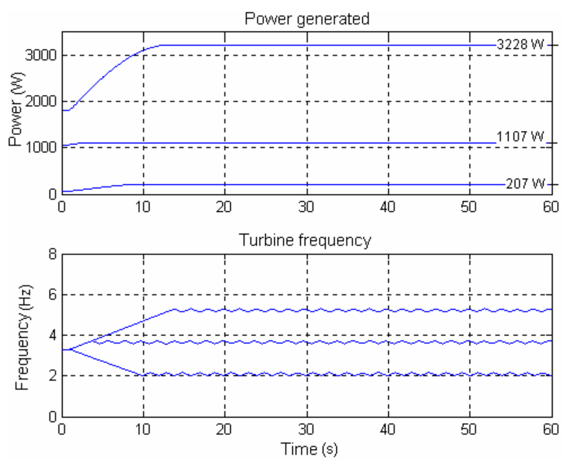

Fig. 9. Power and frequency in the generator for 3 different wind velocities for a 10 m^2 turbine.

As in the last case, the controller prompts the system to the optimal operation point. The maximum extraction of energy from the wind was carried out. It should be noted that when the area of the turbine was increased two times no parameterization in the MPPT controller was required for the proper operation.

4.3. Test 3: Tracking the variable wind velocity

The next experiment simulates the wind speed variation. The graphics in Fig. 10 show the wind speed, the power and the frequency of the 10 m^2 turbine rotation over the time.

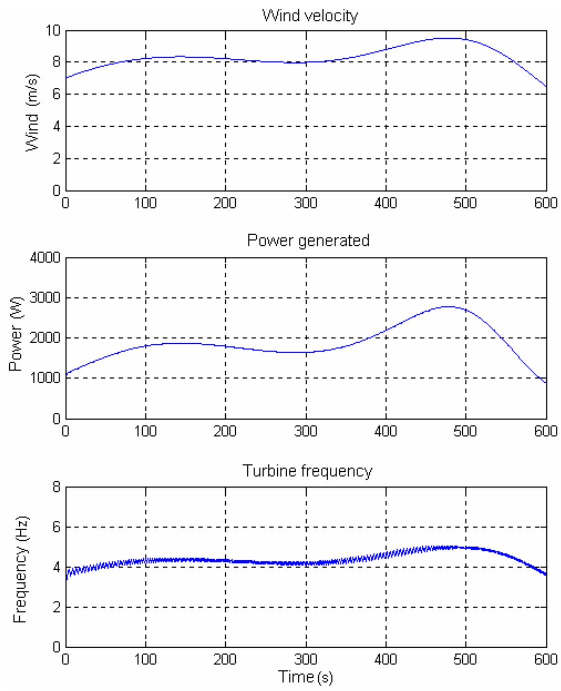

Fig. 10. Wind velocity, power and frequency in a generator with a 10 m^2 turbine area.

The graphic in figure 11 shows the absolute difference between the maximum power extractable and the power effectively extracted from the wind in the conditions of the experience. This plot shows that the power at the QF point is in the maximum 30 W distant from the MPP. This value represents less than 2% of the maximum extractable power which is of 1700 W.

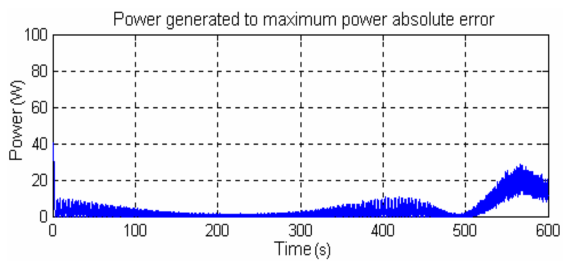

Fig. 11. Absolute difference between the QF and the MPP points along time.

4.4. Test 4: The risk of wrong parameterization

A last simulation was carried out to demonstrate the consequences of a wrong parameterization of the controller. The turbine is the same as in the last simulation above. The wind velocity is 10 m/s and the constant *K* was changed to a very high value of 300 mHz. The consequence of this bad parameterization was the oscillation of the system, as it can be observed in the plot of figure 12.

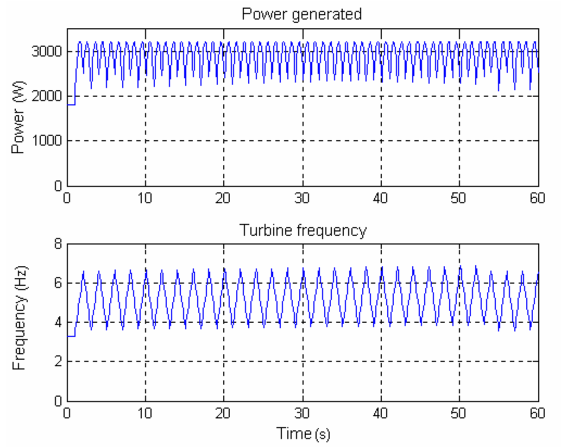

Fig. 12. Bad parameterization forces oscillations in the controller.

5. CONCLUSIONS

The MPPT controller proposed in this article presents well adapted functionality to the conditions studied. For constant and variable wind velocities and for different sizes of the turbines the controller has presented good performances. For adequate parameterization in all the situations the target (MPP) was obtained. It was verified that only one parameter is required to tune the controller. In the last simulation, we can observe the expected consequences of a wrong parameterisation of the parameter *K*. The algorithm presented in the flowchart of figure 6 is simple and efficient for this kind of applications. Moreover, it is not required the use of an anemometer to explicitly measure the wind velocity.

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