Robust model based control method for wind energy production

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Abstract: By continuing to use fossil fuels we are bound to pollute the atmosphere, and consequently, unwanted greenhouse and climate change effects will come to dominate every part of the earth. Wind power energy represents an interesting alternative to traditional forms of obtaining energy. However, the efficiency of wind power strongly depends on the control methods that play a significant role in eliminating the perturbing factors, decreasing the structural loads and increasing the amount and quality of the energy that is produced.
A design of a model based control algorithm for a horizontal wind turbine is proposed. In a model-based control approach, increased model accuracy implies reduced uncertainty. The paper will include an analysis of the advantages that may arise from using such a control technique and also will focus on the robustness of the closed loop system.

1. INTRODUCTION

Wind energy has proved to be an important source of clean and renewable energy because no fossil fuels are burnt in order to produce electrical energy.
As the source of energy, the wind, has a stochastic nature, a special attention was given to the necessity of building robust controls systems that will optimize the functioning of the wind turbines and improve as much as possible performances with cost reduction.
The robust control theory was used to measure the performance changes of the system with the variation of the turbine parameters.
The goal is to allow exploration of the design space for alternatives that are insensitive to changes in the model parameters and that respond well with the uncertainties that may appear in the system.
As the wind has an extremely unpredictable behavior, it is very important to use solutions that are able to generate predictions regarding this aspect.
Such predictions are still very difficult to obtain and even so, the precision of such calculus remains a significant open issue.
The variations in wind speed determine the existence of different working regimes of a wind turbine, each with its own characteristics and problematic.
Consequently, in order to keep a wind turbine's performance within these conditions, controllers must be designed and

implemented. These controllers must be robust enough to be able to perform properly in the presence of uncertainties and nonlinear elements.
The output power of the turbine strongly depends in a non-linear form on the wind speed, the rotation speed of the turbine and the pitch angle of the blades.
The designed controller must be able to adjust the torque of the generator and as well the pitch angle of the blades in order to adapt the rotational speed of the turbine which moves the generator rotor.
The turbines chosen for study in this paper are horizontal axis variable speed wind turbines and the main focus will fall on the design of a model based controller computed for such a turbine.
Also in the end of the paper, a robustness test with respect to parameter variation will be analyzed.
In this paper we propose a control method based on an internal model controller (IMC). This is a model based control technique.
In process control applications, model based control systems are often used to track set points and reject disturbances. Therefore, by explicitly using process knowledge, by virtue of the process model, improved performance can be obtained.
The method is easy to implement and it has shown good performances within many applications.
Wind systems provide difficulties in regulation due to the sudden changes that appear in their functioning and so we

have chosen this type of controller to study its behavior and effectiveness within such situations.

2. THEORETICAL BACKGROUND

The wind turbine cannot generate unlimited power due to its physical limitations.

Some of these limitations are the tolerable rotational speed of the shafts and the maximum power the generator can produce before getting damaged.

At high wind speeds, the forces on the machine increase so much that can determine the generator to overheat, and by thus, causing important losses.

An energy conversion system can be de-composed in several sub-systems. The main components refer to the rotor, the transmission system and the generator.

In Figure 1 one can observe a simplified energy conversion system scheme [1].

The mechanical power received by the turbine, P_{aero}, depends in a nonlinear way on the air density, wind speed and power coefficient C_p.
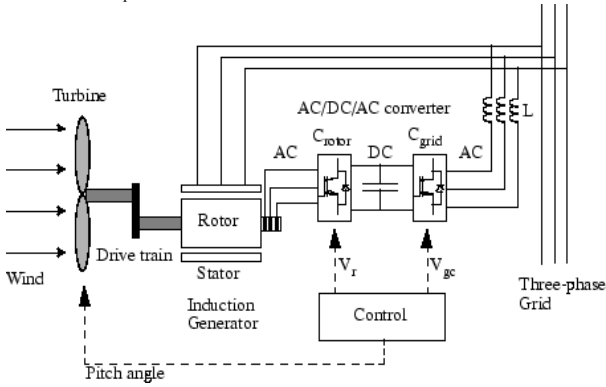

Figure 1 Energy conversion system [1]

$$P_{aero} = \frac{1}{2} \cdot \rho \cdot \pi \cdot R^2 \cdot v^3 \cdot C_p \tag{1}$$

Where R is the radius of the area covered by the blades, v is the wind speed and ρ is the air density.

The power coefficient, C_p is a non-linear function of the blade pitch angle β and the λ parameter, which is the ratio between the peripheral speed of the blades and wind speed.

This coefficient is specific to each turbine and it has an important role in establishing the control objectives. Also this coefficient gives information upon the aerodynamic efficiency of the turbine.

Variable speed wind turbines have three main regions of operation (Figure 2).

Region 1 is the zone that includes the times when the turbine is not operating and when it is starting up. Usually, control in this region implies monitoring the wind speed to determine whether it lies in the specifications for turbine operation and in this case, perform the tasks needed to start the turbine. Normally this happens for wind speeds around 5m/s.

The second region is the operational mode in which the goal is to capture as much power as possible from the wind. In this area one faces important aerodynamic losses that stop the turbine from reaching its maximum theoretical power from the wind.

In this area, the power delivered to the generator is controlled by adjusting the torque that is given to the generator, and thus the maximum value of C_p is maintained by varying the turbine speed.
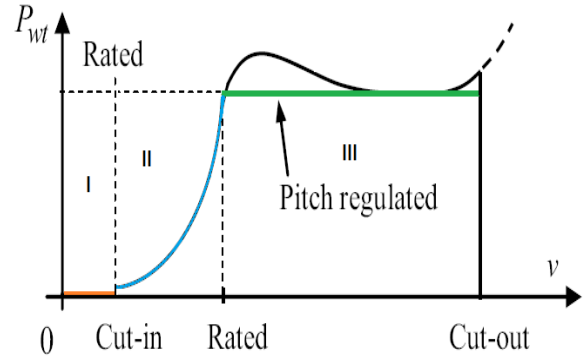

Figure 2 The working regions of a variable speed turbine

In this area, the power delivered to the generator is controlled by adjusting the torque that is given to the generator, and thus the maximum value of C_p is maintained by varying the turbine speed.

The third region occurs above the so called "rated wind speed", which is the wind speed above which maximum power peak is produced.

This area corresponds to high wind speed values and important mechanical solicitation of the system.

The control objectives on the full load area are based on the idea that the control system has to maintain the output power value to the nominal value of the generator.

This will also be the approach followed in this paper. Through this, the rotational speed of the turbine is equal to its nominal value, while the pitch angle and electromagnetic torque are varied in order to obtain:

$$C_p(\lambda, \beta) = \frac{P_{nom}}{\frac{\rho}{2} \cdot \pi \cdot R^2 \cdot v^3} \tag{2}$$

The relation between the tip speed λ and the angular speed of the turbine's rotor is given by the formula:

$$\lambda = \frac{\omega_T \cdot R}{v}, \tag{3}$$

where ω_T is the rotational speed of the rotor.

The power coefficient $C_p(\lambda, \beta)$ has a polynomial form, an example of its mathematical expression can be seen below:

$$C_p(\lambda, \beta) = c_1 \cdot (\frac{c_2}{\lambda_i} - c_3 \cdot \beta - c_4) \cdot e^{\frac{-c_5}{\lambda_i}} + c_6 \cdot \lambda \tag{4}$$

$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08 \cdot \beta} - \frac{0.035}{\beta^3 + 1}$, and the coefficients c_1 to c_6 are: $c_1 = 0.5176$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = 21$ and $c_6 = 0.0068$. The variation of this coefficient with tip ratio speed and pitch angle is given in Figure 3.

The aerodynamic torque that drives the wind turbine rotor and thus the generator is given by:

$$C_{aero} = \frac{1}{2} \cdot \frac{\rho \cdot R^2 \pi \cdot v^3 \cdot C_P(\lambda, \beta)}{\omega_T} \tag{5}$$

As previously said, in the next section we present in detail a control method developed for this region, a method that is based on an internal model controller.
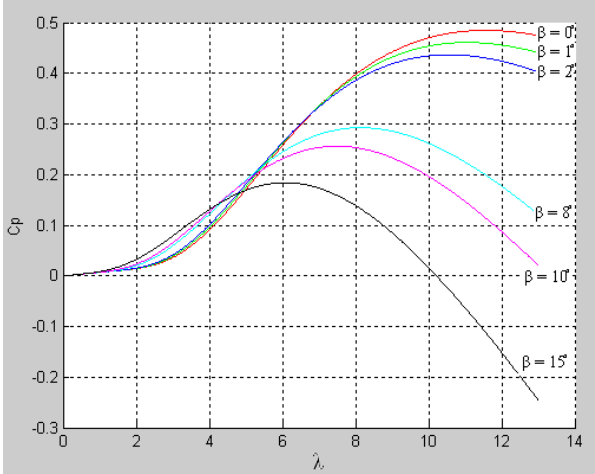

Figure 3 The power coefficient of a variable speed turbine

After this section, the study will be orientated towards a robustness analysis of the designed controller in order to see its behavior with wind speed change.

This paper will only focus on the third operational regime.

3. MATHEMATICAL MODEL

The control method that will be presented in the next section was designed for the third functioning zone of the turbine and this is why, the model will be computed in accordance with the control objectives in this regime.

Although in the third functioning regime of a wind turbine, the models are usually multivariable and therefore the control objectives are expressed accordingly, for this study we have chosen to reduce the model to a single-input single-output one and to try to regulate only the rotational speed of the turbine, independently of the torque regulation.

Torque regulation in this region is not the subject of this study.

The reason was to use a simple linear model that will allow the design of a pitch regulator but in the same time to have a sufficiently complete model to emphasize the real behavior of the controller system.

To conclude, we used the angular position of the rotor as the output of the system, the reference $\Delta\beta_{ref}$ will be the control signal and the wind speed Δv, will be treated as the disturbance that has to be compensated by the controller.

The dynamic characteristics of a wind power plant are determined by components such as: the drive train, the generator, the blades and the tower bending.

The equation that describes the rotor motion is given by:

$$J_t \cdot \dot{\omega} = T - T_s,$$ (6)

Where, J_t is the rotor inertia, ω represents the angular speed of the rotor, T is the aero-dynamical torque and T_s is the reaction torque that appears in the drive shaft system.

The power is regulated by adjusting the shaft rotational velocity. The faster the shaft turns the more power the generator can give as output. The equation that models the generator's motion is:

$$J_g \cdot \ddot{\theta}_m = T_m - T_g$$ (7)

Where J_g is the generator inertia, $\ddot{\theta}_m$ is the angular acceleration of the generator rotor, T_m is the torque driving the generator's rotor and T_g is the electrical torque produced in the generator (it includes losses). [1] [2]

The drive train is modelled by a spring coefficient K_s and a damping coefficient D_s that provide a spring damping model as:

$$T_s = K_s \cdot \gamma + D_s \cdot \dot{\gamma},$$ (8)

where γ is the torsion of the drive train. Also we assumed that all blades have the same pitch angle, and this is known as "collective pitch". The blade servo is modelled as a first order system with T_{bs} as a time constant:

$$T_{bs} \cdot \dot{\beta} + \beta = \beta_r$$ (9)

The control method proposed must ensure the desired behavior of the closed loop system, in such a manner that a maximum power output is obtained and a decrease in structural loads and fatigue is achieved. As turbine towers grow in height, tower oscillations cannot be ignored. In this situation, a model of the wind turbine with distributed parameters is required and a description in terms of mass and stiffness distribution. The tower is then affected by an aero-dynamic torque T and a thrust represented by the generalized force F. [2]

The first mode of the tower bending is described by:

$$M_T \cdot \ddot{z} = F - D_T \cdot \dot{z} - K_T \cdot z$$ (10)

where z is the displacement of the nacelle in the direction perpendicular to the rotor disc. The turbine's mass is given by M_T, the damping factor by D_T and a spring constant K_T.

After linearization and switching to the Laplace complex domain, the model results in the following form:

$$A \cdot \Delta\psi = B \cdot \beta_{ref} + C \cdot \Delta v$$ (11)

where A, B and C are polynomials in complex variable s (Laplace domain).

From the equation above, closed loop transfer functions with respect to wind speed change and reference signal respectively, can be obtained:

$$H_p = \frac{\Delta\psi(s)}{\Delta\beta_{ref}(s)}$$ (12)

$$H_v(s) = \frac{\Delta\psi(s)}{\Delta v(s)}$$ (13)

A short analyze on the equations 12 and 13 brought into attention the fact that the obtained model of the open loop system has the degree equal to 5.

In order to design the controller one also needs to know the problems encountered in the system behavior. In consequence, we represented the step response of the open loop system and we depicted it in Figure 4 below.

As it can be observed, the step response of the system presents a significant overshot and steady state error, and also an oscillatory aspect.

Therefore, the control law that we propose will try to eliminate all these inconvenient.

The representation of the open loop structure of the system is presented in Figure 5.
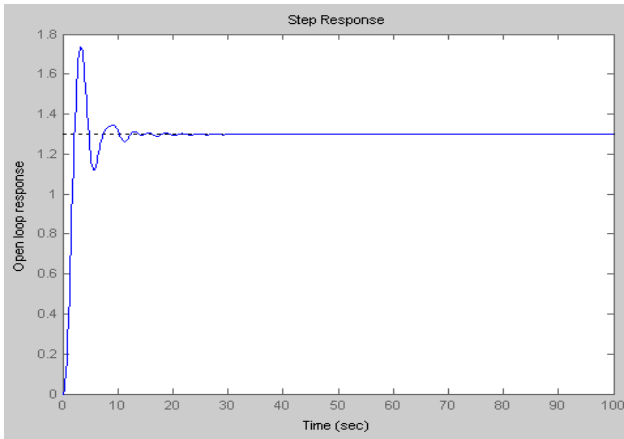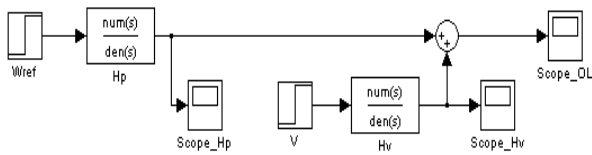
Figure 4 Step response of the system

Figure 5 The structure of the open loop system

4. CONTROL METHOD

4.1 Internal Model Controller for the full-load area of a wind turbine

Given the complexity of a wind turbine system, many control methods have been proposed and implemented, each having both advantages and disadvantages.

The Internal Model Control (IMC) strategy relies on the Internal Model Principle which states that control can be achieved only if the control system encapsulates a representation of the process to be controlled.

In particular, if the control scheme has been developed on the exact model of the process, then perfect control is theoretically possible.

In practice, however, process model mismatch is always present. The process model might not be invertible and the system is often affected by unknown disturbances.

Using the IMC design procedure, controller complexity depends exclusively on two factors: the complexity of the model and the performance requirements stated by the designer.

In this paper we want to study the performances that this type of controller might provide for the wind turbine system that we presented above.

In Figure 6 one can observe the closed loop of the system with the internal model controller.

In the picture below, G_1 represents the process transfer function on the manipulated variable to the controlled variable path, G_d is the transfer function of the disturbance, G_2 represents the mathematical model of the process, and C is the transfer function of the IMC controller.

Besides these components, one can add a supplementary filter F, in order to increase the robustness on the closed loop system with respect to the modeling errors.
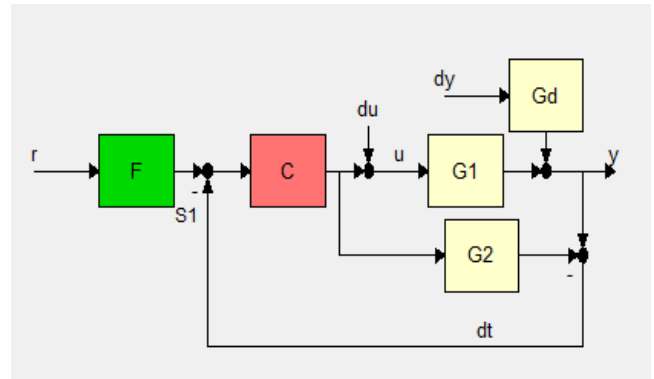

Figure 6 Control structure for IMC control

As may be observed from the block diagram of the IMC structure, there are two parallel paths starting from the manipulated variable u(s), one passing through the real process G_1, and one passing through the model of the process G_2.

The role of the parallel containing the model is to make possible the generation of the difference between the actual process output and the estimation (model based prediction) of the command signal on the process output.

Assuming that the process model is a perfect representation of the real process, $G_1=G_2$, the difference signal represents the estimated effect of the disturbances on the controlled variable. [3]

If the process model is not perfect, the difference signal includes both the effect of disturbances on the output signal and the process model mismatch.

Considering again the control structure presented in Figure 6 the disturbance estimation may be regarded as a correction for the reference point in order to generate the correct command signal that will eliminate this estimated disturbance.

One can also observe that the feedback of the control system is zero when the model is perfect and there are no disturbances, resulting in an open loop situation.

This fact brings into attention one of the most important properties of this structure that refers to the stability issue. This property states that if the process model is a perfect approximation of the real process and the process is stable, the IMC control loop is stable if and only if the process G1 and the IMC controller C are stable.

The stability of the IMC controller results in physically realizable command responses.

The benefits that the IMC structure offers are linked to the fact that there is no need to solve the roots of the characteristic polynomial and therefore, one only examines the poles of the process. The general design algorithm states that the design principle of the IMC controller relies on the factorization of the process model:

$G_2(s) = G_{2+}(s) \cdot G_{2-}(s)$, where $G_{2-}(s)$ contains all the time delays and the right half plane zeros.

The second step is to define the IMC controller as:

C(s) = G_{2+}^{-1}(s) * F(s), where F(s) is usually a low pass filter with a steady state gain of one. Besides the increase in the robustness of the controller, this filter's role is also to assure the physical realisability of the IMC controller. [4]

The simplest filter has the following form:

$$F(s) = \frac{1}{(\lambda \cdot s + 1)^n}$$, where λ is the filter parameter and n is

the order of the filter. The order of the filter is usually chosen such that C(s)*F(s) is proper, while λ is adjustable and determines the speed of response. [5]

Increasing λ increases the closed loop time constant and slows the speed of response; decreasing λ does the opposite.

In this section, below, we will show the design of a discrete IMC controller. For this purpose, one needs to know the zeros and poles of the system, and this will be done by analyzing the open loop transfer function.
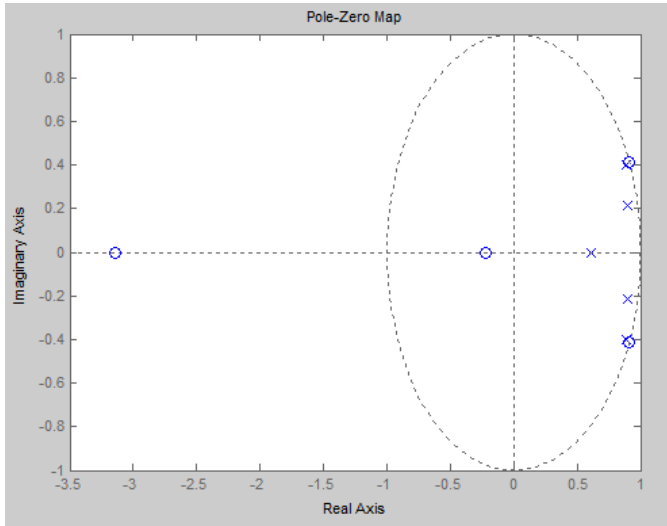

Figure 7 The poles and zeros of the discrete system

In the figure Figure 7 above, we have illustrated the discrete zeros and poles of the studied system, as their representation in this form is more intuitive for interpretation.

We designed the controller as follows.

Given the fact that the system has two unstable zeros and that by inverting them in the controller, the system would become unstable, these poles have to be put into the non-invertible component of the transfer function.

In the same time, all the poles of the system are stable and so, by inversion, they become the zeros of the controller.

The steps followed for the computation of the controller are:

1) The poles of the model become the zeros of the controller;
2) The poles of the discrete IMC controller are computed like this:
    i) One keeps the zeros of the process model that have a positive real part and that are contained in the unit circle.
    ii) The inverse of the zeros of the process model that have a positive real part and that are not contained in the unit circle.
    iii) One adds a pole in the origin for each zero of the process model that has a negative real part.
3) The gain of the controller is chosen such as: $C(1) * G_2(1) = 1$; [6]
4) One should also add a filter that will handle the modeling errors. The filter in this case was chosen in the following form:

$$F(z) = \frac{(1-\alpha) \cdot z}{z - \alpha}, \ 0<\alpha<1.$$
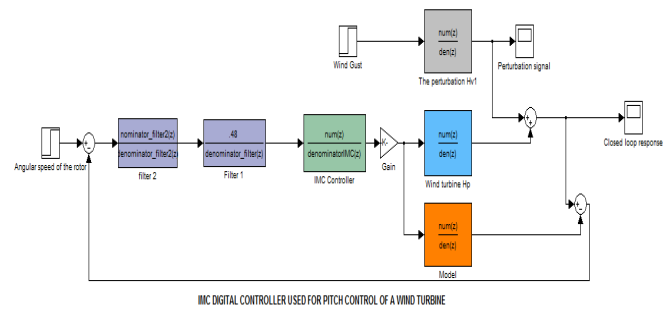

Figure 8 The system controlled with IMC controller

We did not obtain the desired results with only one filter, and so we added a second one of the same form, and the combination of the two gave us a satisfactory response of the system. This filter provided a certain softness of the system response and also reduced the controller's sensitivity to the modeling errors.

The parameters used for the filters are: α1 = 0.48 and α2 = 0.1.

The control system can be observed in Figure 8 above. The controller design and simulations were done in MATLAB and Simulink.

5. ROBUSTNESS EVALUATION

We run the simulations for our system in two major situations that are listed below, to test the robustness of the closed loop:

    a) Process parameter increase with 25%
    b) Process parameter decrease with 25%

When designing a control system, one has to take into account the plant model uncertainties. It is therefore extremely important to assess if the stability of the closed loop is guaranteed in the presence of the plant model uncertainties.

The closed loop is termed "robust" if the stability is guaranteed for a given set of model uncertainties.

By process parameter variations, we have tested both the case in which the model and the process differ, and the case of model uncertainty.

In the figure below, Figure 9 one can observe the compared responses in the three cases.

Figure 9 The system's response

With blue one can find the response of the system when the process and the model are identical.

The red answer corresponds to the increase in the parameter values and the green signal represents the response of the system in the case in which the parameters of the process decrease with 25%.

As it can be observed, the response is about 4s, which is satisfactory, the disturbance is rejected, and the system also tracks its reference.

6. CONCLUSIONS

This paper has presented a modeling technique and a control method proposed for variable speed wind turbines.

Such systems are strongly nonlinear and require an important analysis concerning their stability.

The study was focused on designing a robust controller for the third functioning regime of a turbine. The proposed controller was an IMC controller, due to its simplicity in designing and operation.

The internal model controller strongly relies on the process model so this is why modeling uncertainties are of great importance in obtaining control performances.

The difficulties encountered in the wind turbine control involved both the necessity of maintaining the angular speed of the rotor at a value which must correspond to a limitation of the captured energy around the nominal value of the generator with an essay of reducing the mechanical oscillations of the structure that supports the turbine.

All this makes the controller design a non trivial task. This method has shown a good regulation of rotor speed and a good response of the pitch angle.

The steady state error was eliminated and the system showed a good tolerance with respect to model variations, by thus proving its robustness.

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