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Robust control for wind power systems

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Abstract: This paper presents an RST controller design applied to a horizontal wind turbine, functioning in the above rated wind speeds area. The controller presented here, is a robust digital controller which aims to regulate the wind turbine rotor speed through collective blade pitch control.
The paper starts with a state of the art of wind turbines and their problematic and continues with the design of the controller. The robustness of the controller will be shown through the robustness indicators values and also will be tested through the variation of the model's parameters. This control method provided a good response by eliminating the steady state error after a step input and has shown good robustness indicator values.

Keywords: Wind power, robustness, renewable energy, pitch control.

1. INTRODUCTION

Wind energy has proved to be an important source of clean and renewable energy, as no fossil fuels are burnt in order to produce electrical energy.
Lead by the numerous advantages of wind turbine usage, engineers build different control systems and optimized their functioning for cost and performance. They used the robust control theory to measure the performance changes in wind turbines with changing the system 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 is the energy source, having a stochastic nature, the wind turbine has to be able to work under different wind velocities that determine its functioning regimes. For each of these regimes, certain characteristics are to be considered.
In order to keep a wind turbine's performance within these conditions, robust controllers must be designed so as 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 rotor.
The turbines chosen for study in this paper are variable speed wind turbines and the main focus will fall on the analysis of the robustness of a digital controller designed for such a turbine.

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 consequently, 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 Fig 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.

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

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 the 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 (Fig 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.

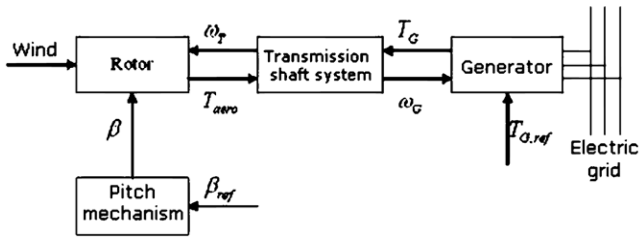

Fig 1 Energy conversion system [1]

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.

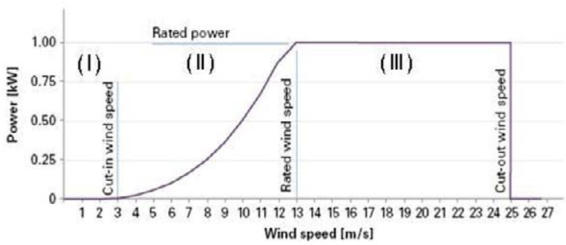

Fig 2 The working regions of a variable speed turbine

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. 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 (λ, β) has a polynomial form, an example of this 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 Fig 3.

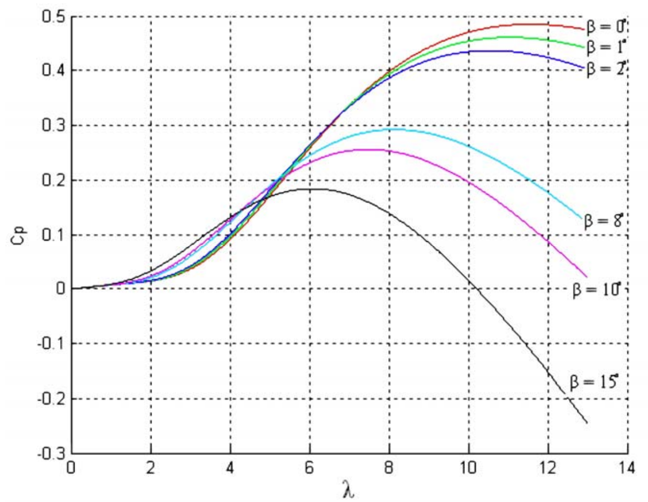

Fig 3 The power coefficient of a variable speed turbine

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

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

In the next section we present in detail a control method developed for this region, a method that is based on a digital controller.

After this section, the study will focus on the robustness evaluation of the closed loop system.

This paper will only focus on the third operational regime.

3. MATHEMATICAL MODEL

At present, there are several variable speed wind turbines configurations being widely used.

The wind turbine chosen for this study is a horizontal axis variable speed wind turbine and it was modeled as a simplified two mass model with flexible drive train and collective pitch. The compliance of the drive train was included in the model of the shaft between the rotor and the gearbox. The generator's dynamics was neglected as it is much faster than the shaft dynamics when modeling the pitch control.

The variable speed wind turbines is currently the most used technology. By allowing the rotor to operate at various speeds, one can obtain a more efficient capture of wind energy and less stress in the turbine drive train at wind gusts.

The reader can find different wind turbine modeling

techniques, summarized in [2] and also detailed explanations regarding the use of each type of model.
The purpose of the chosen model is to predict the behavior of the wind turbine sufficiently well for the design and analysis of the pitch controller. In this respect, it is important that the model be simple and linear but detailed enough to permit to be used for controller optimization. A more detailed discussion on model types and characteristics can be found in [3].
The goal in this study is to maintain a constant electrical voltage, produced by the turbine, and this can be expressed in terms of constant angular velocity of the turbine rotor.
As a result, we used the angular position of the rotor as the output of the system, the reference $\Delta\beta_{ref}$ is the control signal, while 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:

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

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:

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

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). [4] [5]
The drive train is modelled by a spring coefficient K_s and a damping coefficient D_s that provide a spring damping model as:

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

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:

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

The control method proposed must ensure the desired behavior of the closed loop system, in such a manner that 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 described in terms of mass and stiffness distribution is required.
The tower is then affected by an aero-dynamic torque T and a thrust represented by the generalized force F. [5]
The first mode of the tower bending is described by:

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

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:

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

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:

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

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

The obtained model of the open loop system has the degree equal to 5.
Once we obtained the transfer function of the system, one can determine the step response of the open loop system. The open loop response is depicted in Fig 4 below.

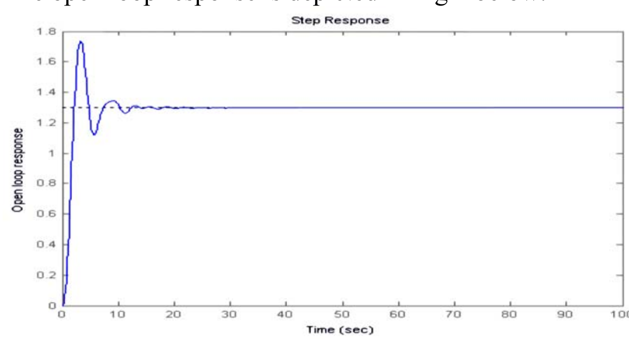

Fig 4 Step response of the system

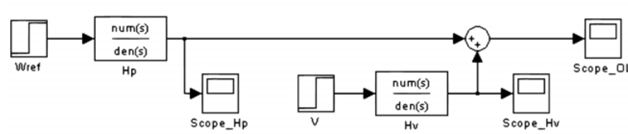

Fig 5 The open loop system

As it can be observed, the step response of the system presents a significant overshot and an oscillatory aspect.
Therefore, the control law will have to eliminate all these inconvenient.
The open loop structure of the system is presented in Fig 5.

4. CONTROL DESIGN

4.1 RST polynomial control 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.
Classical techniques have been used extensively for control design, leading to miscellaneous results. Different control

methodologies and their problematic according to the functioning zone are given in [2].
The control law that we will refer to, has the advantage that it can be implemented on a digital computer (microprocessor, microcontroller).
We chose to use a three branched RST controller. The controller will be designed using the poles placement method.
with the shaping of the sensitivity functions.
This type of controller is a structure with two freedom degrees and compared to a one degree of freedom structure, it has the main advantage that it allows the designer to specify performances independently with reference trajectory tracking (reference variation) and with regulation (Fig 6). A systematic analysis of the advantages brought by the two degrees of freedom controllers can be found in [6].
The poles placement with shaping of sensitivity functions is a general methodology of digital control design that allows one to take into account simultaneously robustness and performances specifications for the closed loop of the system.
This is also a model based control method, for which one needs to know the discrete time model of the plant.
Therefore, we will have to determine the discrete model.

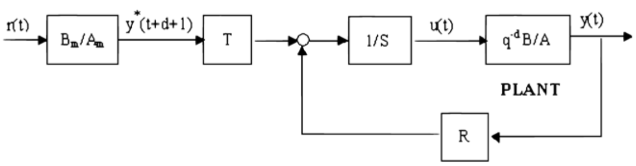

Fig 6 System controlled with a RST controller

The scheme of the system with the RST controller is (Fig 7).

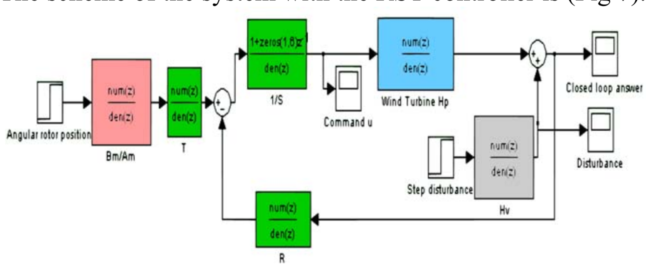

Fig 7 Wind turbine with RST controller

This controller design method makes it possible to specify the desired tracking behavior (with the changing of the reference) by the choice of the tracking dynamics (Am, Bm polynomials) and also the desired regulation behavior (rejection of an output disturbance) by the choice of the regulation dynamics, defined by the system poles in closed-loop.
The R, S, T blocks of the controller can be written in a polynomial form:

$$\begin{aligned} R(q^{-1}) &= r_0 + r_1 \cdot q^{-1} + \ldots + r_{nr} \cdot q^{-nr} \\ S(q^{-1}) &= s_0 + s_1 \cdot q^{-1} + \ldots + s_{ns} \cdot q^{-ns} \\ T(q^{-1}) &= t_0 + t_1 \cdot q^{-1} + \ldots + t_{nt} \cdot q^{-nt} \end{aligned} \tag{14}$$

The R and S polynomials define the closed loop regulation performances and can be determined through the matrix computation of the following equation:
$P(q^{-1}) = A(q^{-1}) \cdot S(q^{-1}) + B(q^{-1}) \cdot R(q^{-1})$, where P is the characteristic polynomial of the system.
For the calculation of $T(q^{-1})$, one must assure an unitary static gain between the generated trajectory and the output of the system.
Finally, the RST command will result in the form:
$u(k) = \frac{T(q^{-1})}{S(q^{-1})} \cdot r(k) - \frac{R(q^{-1})}{S(q^{-1})} \cdot y(k)$, where r(k) is the discrete reference and y(k) represents the output of the system.
The poles of the system are:
- a real pole corresponding to $\omega = 2.51$ rad/s
- $\omega_0 = 2.1214$ rad/s with $\zeta = 0.053$ and
- $\omega_0 = 1.2119$ rad/s with $\zeta = 0.308$

In the first stage, we have computed a controller with imposed tracking performances.
As the overshoot of the system increases with the decrease of damping, the time rise also decreases with the decrease of the damping ζ, we imposed the following tracking pair of poles: $\omega_0 = 1.2119$ rad/s with $\zeta = 0.8$.
For the disturbance rejection problem we imposed $\omega_0 = 1.2119$ rad/s with $\zeta = 0.8$,
$\omega_0 = 2.1214$ rad/s with $\zeta = 0.053$, $\omega = 2.51$ rad/s.
We wanted a robust controller for our system and so we improved this classical RST controller by imposing a pole with multiplicity 5 (desired polynomial $P_F(q^{-1})=(1-0.5q^{-1})^5$).
As a general rule, the auxiliary poles are chosen in order to be faster than the dominant poles of the system.
The introduction of these poles in the closed loop system reduces the stress on the actuators in the transient for the disturbance rejection. [7]
It is well known that if the feed forward channel contains the reference model, then the steady-state error is eliminated and as a plus, one obtains a significant attenuation of the disturbance effect on the output of the system.
Therefore we factorized the R and S polynomials as:

$$\begin{aligned} S(q^{-1}) &= S'(q^{-1}) H_S(q^{-1}) \\ R(q^{-1}) &= R'(q^{-1}) H_R(q^{-1}) \end{aligned} \tag{15}$$

where $H_S(q^{-1})$ and $H_R(q^{-1})$ are the fixed parts.
$H_S(q^{-1}) = 1 - q^{-1}$ (An integrator)
$H_R(q^{-1}) = 1 + q^{-1}$ (Open loop behavior to avoid disturbance amplification).
The response of the system with the designed controller can be seen in Fig 8.
One can see that the system tracks the reference and that the perturbation is rejected.
The overshot is very small and thus, it can be neglected. The raising time is approximately of 3.6s.

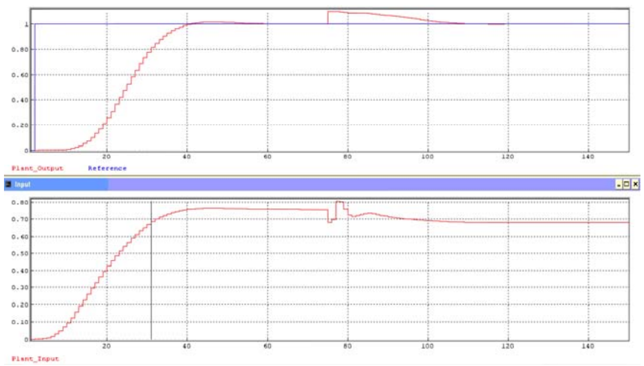

Fig 8 Pitch angle of the system controlled with RST controller

As for the robustness margins, the obtained values were: Gain = 11.88dB, Phase = 67.8°, and Modulus = -3.19dB

5. ROBUSTNESS EVALUATION

5.1 SHAPING OF THE SENSITIVITY FUNCTION

In order to assure robustness of the closed loop system, one must take into account the input sensitivity of the system, S_{py}.

The analysis of this function allows evaluating the influence of a disturbance on the plant input.

The zeroes of the inverse of this function define the poles of the closed loop system. Therefore, in order to have stability in closed loop, the zeros of this function must be inside the unit circle. [7]

The input sensitivity function is defined as:

$$S_{yp}\left(z^{-1}\right)=\frac{A\left(z^{-1}\right)S\left(z^{-1}\right)}{A\left(z^{-1}\right)S\left(z^{-1}\right)+B\left(z^{-1}\right)R\left(z^{-1}\right)}=\frac{1}{1+H_{OL}\left(z^{-1}\right)} \tag{16}$$

The robustness of the closed loop system can be evaluated by looking at the opened loop Nyquist plot. The minimal distance between this graphic and the critical point [-1,j0] is the modulus margin, *ΔM*, and it is a measure of the nominal systems closed loop robustness. Fig 9 [8]

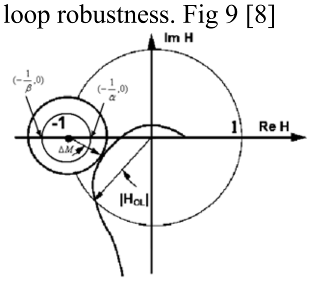

Fig 9 Modulus margin on Nyquist plots of the opened loop transfer function. [9]

From the definition we can find the following formula for the modulus margin:

$$\Delta M=\left|1+H_{OL}\left(z^{-1}\right)\right|_{\min}=\left|S_{yp}^{-1}\left(z^{-1}\right)\right|_{\min}=\left(\left|S_{yp}\left(z^{-1}\right)\right|_{\max}\right)^{-1} \tag{17}$$

This formula gives the upper margin of the output sensitivity function and proves that sensitivity functions can be used in designing robust controllers. [8]

For a robust system it is necessary to have a modulus margin greater or equal to 0.5 (-6 dB) implying a maximum of 6dB for the output sensitivity function.

As previously said, we first computed a controller by imposing tracking and regulation performances in order to have a good response of the system. This controller proved not to be robust, and this can be seen by analyzing the input sensitivity function. One can see that in this case, the closed loop system is not robust as the sensitivity function has a maximum value grater than 6dB ($\left|S_{yp}(e^{j\omega})\right|_{\max}=6.19dB$) which leads to a modulus margin of ΔM = 0.49. In Fig 10, one can observe the S_{py} magnitude variation, and also the fact that the maximum value exceeds 6dB.

In Fig 11 one can see by comparison, the two sensitivity functions that correspond to the two controllers used and in the same time, one can see the improvement in the RST controller design.

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

a) presence of nonlinear elements
b) model parameter variations

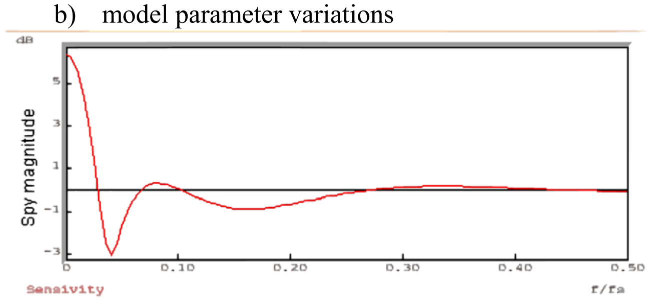

Fig 10 The sensitivity function of the non-robust controller

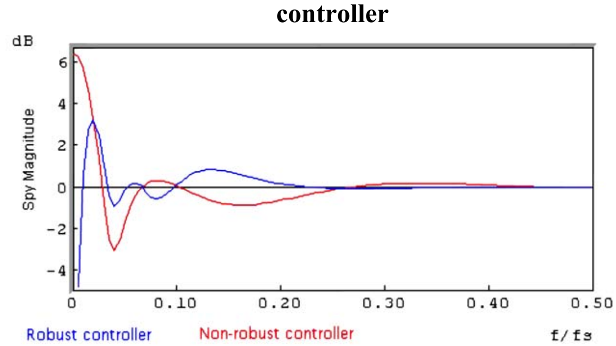

Fig 11 The sensitivity function for both robust and non-robust RST controllers

5.2 TOLERANCE WITH RESPECT TO NONLINEAR ELEMENTS AND PLANT MODEL VARIATIONS

Over the years, scientists have shown a great interest towards robust control applied on wind turbines. The techniques employed vary from simple to complex. In [10], for example, one can find a robust design method of a QFT controller to reduce the effects of the plant model uncertainties, while in [11] the reader can observe an LPV approach that proposes to minimize the mechanical stresses of the plant and to improve the overall performances of the wind turbine.

This paper aims to test and measure the robustness of the designed controller towards 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.

In control systems, certain components often introduce static, nonlinear or time varying characteristics.

Many nonlinear physical systems can be represented as a feedback connection of a linear dynamical system and a nonlinear element.

The characteristics of the nonlinear elements generally lie inside a conic region defined by two parameters: a minimum linear gain α, and a maximum linear gain β (Fig 12).

As an important particularity of the nonlinear systems, one should mention the stability problem. For systems, such as the one mentioned above, in order to check its stability, one should use the "circle criterion" (Popov - Zames).

This criterion states that *"A feedback system is asymptotically stable for a set of non linear and time varying characteristics lying in the conic domain [α; β], with α, β >0 if the plot of the open loop system transfer function, traversed in the sense of growing frequencies, leaves on the left, without crossing it, the circle centered on the real axis and passes through the points [-1/β, j0] and [-1/α, j0]"* [8].

By using the Nyquist representation of the open loop system, one can emphasize a circle centered in the [-1,0j] point and with a radius equal to the modulus margin ΔM (Fig 9). Therefore, this circle is tangent to the Nyquist representation of the open loop system. In the same time, the Popov circle is also centered on the real axis and intersects the points [-1/β, j0] and [-1/α, j0].

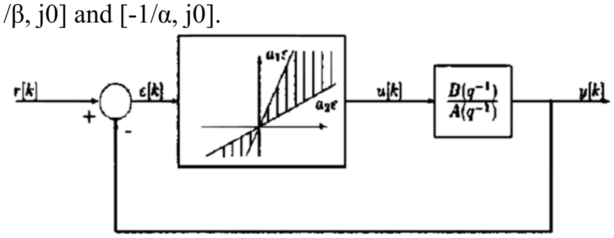

Fig 12 A discrete system with a nonlinear characteristic [8]

If one superimposes the two circles and then forces α = 1/(1+ΔM) and β = 1/(1- ΔM), then one can conclude that the closed loop system, with a robustness given by ΔM, can tolerate nonlinear elements found inside of the conic sector defined by α and β.

Then we can write the following inequalities:

$$\frac{1}{1-\Delta M} \geq \beta \geq \alpha \geq \frac{1}{1+\Delta M}$$

In order to test the robustness of our system, we have to find the values of the two parameters that fulfill the Popov criterion.

The value of the modulus margin corresponding to the robust controller is of ΔM = 0.693 (-3.19dB) at a normalized frequency of 0.02 rad/sec.

This means that our closed loop system can tolerate nonlinearities that are contained in the conic sector defined by α = 0.59 and β = 3.257.

In order to check the robustness of the controller with respect to plant model variations, we ran the simulation with the thrust and torque values modified. We have reduced and then increased them with 25%.

These 25% variations represent slower and faster wind speeds and therefore a change in the wind turbine dynamics.

The comparison of the different dynamic values with the same controller is shown in the picture below (Fig 13).

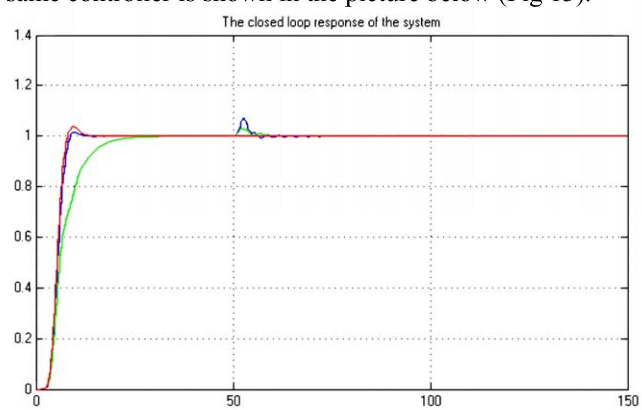

Fig 13 Closed loop responses of the system with modified parameters

One can observe in red, the response of the system with an increase in parameter values, with green the response in the case of a decrease of the parameter values and with blue the initial system.

As it can be appreciated, the controller responds properly for the changes that appear in the system dynamics and therefore is proving its robustness.

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 a digital RST controller, due to its simplicity in designing and operation.

The difficulties encountered in the wind turbine control involved both the necessity of maintaining the output of the generator at a value which must correspond to maximization of captured energy and reducing 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 and element nonlinearities.

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