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Multivariable Centralized Control with Decoupling and Feedforward Compensation for Residential Wind Turbine

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Abstract: The small wind turbines for residential uses are multivariable processes that work under turbulent wind conditions and abrupt electrical load changes. In these processes, it is necessary to apply a complex control system that allows a good performance on the power production. For this aim, in this paper, a multivariable centralized control by decoupling is presented to control the wind turbine, in comparison with a decentralized control. The problems due to disturbances by wind turbulences and electrical load changes are reduced using feedforward compensation.

1. INTRODUCTION

The interest in the small wind turbines for residential use has grown recently, since with a small turbine (1 to 5 kW) and good wind conditions, it is possible to produce necessary energy for a home or a small business working the wind turbine on off-grid mode. In some countries of America and Europe, it is possible to sell energy or reduce the tariff of the conventional energy, working the wind turbine in on-grid mode (Milivojevic *et al*., 2010). The small wind turbines can basically provide electrical energy of two ways:

a) Storing it in a battery and transform it into an AC signal using an inverter; this scheme is usually used when the installation is very far from the grid.

b) Through a power converter that adapts the signal with magnitude and frequency like the signal of grid; this scheme is adequate for urban zones and can work on both modes: off-grid and on-grid mode (Remus and Frede, 2004).

Generally, the power converters for option b) are:

Rectifier – Boost converter – Inverter.

Back to back voltage source converter.

Matrix converter.

The converter based on rectifier is simple and economic; however, it requires that the wind turbine works with constant angular speed, whereas in the other two cases, the speed can be variable. Most of commercial small wind turbines regulate the angular speed of the rotor only with the variation of the electromagnetic torque of the generator, because they do not have a pitch control of blades angle. This produces vibrations in the mechanical structure, warming up in the power converter, excessive noise and low power efficiency. In addition, it is necessary to consider the problem of the wind turbulence in urban zones and electrical load changes (Martínez *et al.,* 2007).

In this paper, a residential wind turbine of 3 kW working in off-grid mode is considered, that delivers directly energy to a home through a converter (Rectifier - Boost - Inverter), operating with constant angular speed. This wind turbine (Nagai *et al.,* 2009) can be seen as a multivariable process with two outputs to be controlled (the turbine angular speed and the generated power), two manipulated inputs (the field current of the generator and the pitch control of blades angle), and two not manipulated inputs considered as disturbances (the variations of the wind speed and the electrical load).

In order to improve the performance of the wind turbine and reduce the interaction effects, a multivariable centralized control by decoupling is presented. In addition, in order to reduce the problems due to disturbances caused by the wind turbulence and the electrical load changes, a feedforward compensator is included.

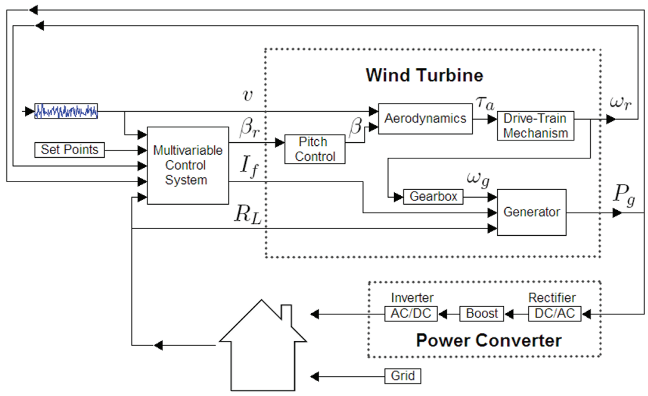

Fig. 1. Wind turbine and control system diagram.

To evaluate the wind turbine performance with the proposed controller, the mathematical nonlinear models of the wind turbine as well as a model to generate the signal of the wind are used. Figure 1 shows a block diagram of the process and the control system.

This paper is organized as follows: the mathematical model of wind turbine is described in Section 2. The corresponding linearization is obtained in Section 3. In Section 4, the design of the controller is explained. Finally, Section 5 shows the results, and conclusions are discussed in Section 6.

2. WIND TURBINE MODEL

The mathematical model presented in this section describes in detail the wind turbine behavior. It has been obtained from an analysis based on diagram of figure 1, which considers the mechanism of rotation, the aerodynamic of the blades and the electric generator. Also, a model is presented to describe wind speed signal, which allows to obtain more realistic results. With these models, it is possible to simulate the process under different operation conditions, applying disturbances that consist on electrical load variations and wind turbulences. These models are very useful to evaluate wind turbine performance with different controllers.

2.1 Mechanism of rotation

The schematic diagram of the rotation mechanism of the figure 2, shows how the wind force moves the propeller to generate the torque τ_a and produces the angular speed ω_r. The angular speed ω_g in the shaft of the generator, is produced after gearbox being two sections: low and high speed.

The moment of inertia in the section of low angular speed is:

$$J_r\dot{\omega}_r = \tau_a - B_r\omega_r - N\tau_{hs} \tag{1}$$

where J_r is the moment of inertia, B_r is the viscous friction coefficient and τ_{hs} is the torque required in the part of high speed to rotate the generator shaft. The gearbox ratio is $N=\omega_g/\omega_r$ (Boukhezzar et al., 2007).

The moment of inertia in the section of high angular speed is:

$$J_g\dot{\omega}_g = \tau_{hs} - B_g\omega_g - \tau_{em} \tag{2}$$

where J_g is the moment of inertia of generator, B_g is the friction and τ_{em} is the torque produced by the electromagnetic field of the generator.

The dynamics of wind turbine is obtained from (1) and (2) considering only the angular speed ω_r:

$$\begin{aligned} &J_t\dot{\omega}_r = \tau_a - B_t\omega_r - \tau_g \\ &J_t = J_r + N^2 J_g; \quad B_t = B_r + N^2 B_g; \quad \tau_g = N\tau_{em} \end{aligned} \tag{3}$$

2.2 Aerodynamics

The torque τ_a generated by the wind force depends on the aerodynamic properties of the turbine, aspects like: form, size and orientation of its blades, as well as speed, direction and wind density (García-Sanz and Torres, 2004).

The relation between wind speed v and angular speed of the turbine ω_r, is described by the tip-speed-ratio where R is the rotor radius:

$$\lambda = \frac{R\omega_r}{v} \tag{4}$$

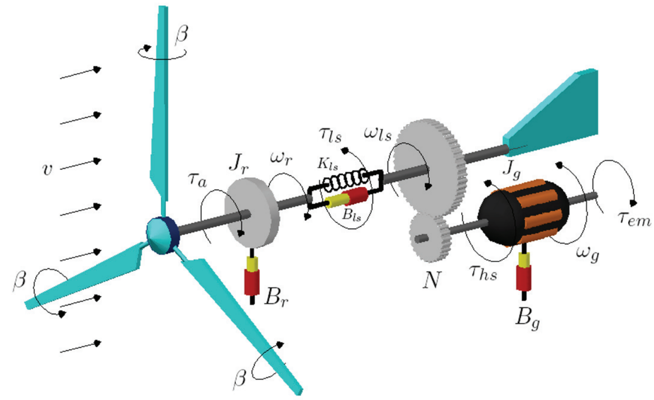

Fig. 2. Wind turbine rotation mechanism.

The study of the aerodynamics of the turbine is realised using the Blade Element Momentum (BEM) theory, that is based on the Glauert Propeller theory applied in wind turbines. These theories allow to know the efficiency of generated power $C_p(\lambda,\beta)$ and produced torque $C_q(\lambda,\beta)$, using the ratio λ and blades orientation angle β. The curves in the figure 3 describe aerodynamic efficiency behavior of a generator with three blades (model NACA4418).

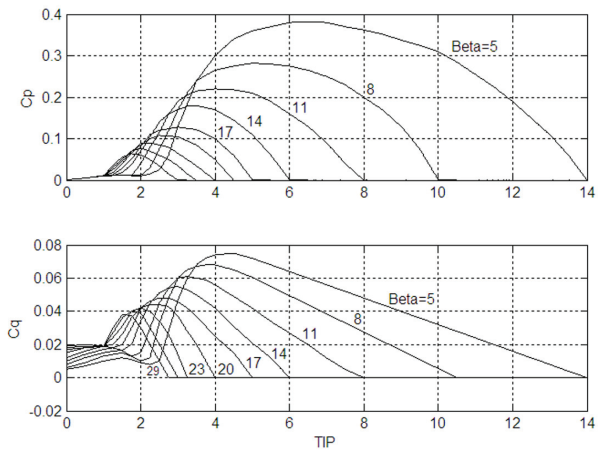

Fig. 3. Power $C_p(\lambda,\beta)$ and torque $C_q(\lambda,\beta)$ efficiency.

From the curves of $C_q(\lambda,\beta)$ and the following expression, torque τ_a can be determined as follows:

$$\tau_a = 0.5\rho\pi R^3 v^2 C_q(\lambda,\beta) \tag{5}$$

where ρ is the the wind density.

2.3 Electric generator

In order to determine the generated power P_g, it is necessary to consider the voltage E_g produced by the electric generator, according to the angular speed ω_g and the filed current I_f, as follows:

$$E_g = KI_f\omega_g \tag{6}$$

where K is a constant of the generator. For a resistive load R_L, the power is given by (7), where $X_g=\alpha N\omega_r$ is the generator reactance.

$$P_g = K^2\left(\frac{R_L}{R_L^2+(\alpha N\omega_r)^2}\right)I_f^2\omega_g^2 \tag{7}$$

Finally, the produced electromagnetic torque τ_g is:

$$\tau_g = \frac{P_g}{\eta_g\eta_m\omega_g} \tag{8}$$

where η_g is the electrical generator efficiency and η_m is the mechanical efficiency.

2.4 Equations of the nonlinear model

In summary, the following four equations describe the nonlinear model of the wind turbine:

$$J_t\dot{\omega}_r = \tau_a - B_t\omega_r - \tau_g \tag{9}$$

$$\tau_a = \frac{1}{2}\rho\pi R^3 v^2 C_q(\lambda,\beta) \tag{10}$$

$$P_g = K^2\left(\frac{R_L}{R_L^2+(\alpha N\omega_r)^2}\right)I_f^2N^2\omega_r^2 \tag{11}$$

$$\tau_g = \frac{P_g}{\eta_g\eta_m N\omega_r} \tag{12}$$

2.5 Wind speed model

The wind speed is a natural phenomenon described by a stationary stochastic process composed of a media speed v_m, gusts and turbulence v_n. The model in (13), and reported by (Masoud, 2008) to generate the turbulence signal, captures the behavior of this natural phenomenon in a proper way:

$$v = v_m + v_n; \qquad v_n = \sum_{i=1}^{M} A_i(\omega_i)\cos(\omega_i t + \phi_i),$$
$$A_i(\omega_i) = \frac{2}{\pi}\sqrt{\frac{1}{2}\left[S(\omega_i)+S(\omega_{i+1})\right](\omega_{i+1}-\omega_i)}, \tag{13}$$
$$S(\omega_i) = \frac{9{,}5\sigma^2 h/v_m}{\left[1+(20\omega_i h/v_m)^2\right]^{5/6}}$$

where h is the height of the point of wind measurement, σ is the standard deviation, φ a random signal with uniform distribution from $-\pi$ to π that reproduces the gusts and turbulence, with a spectrum distributed throughout the frequencies defined by ω_i with $M = 50$.

3. LINEAR MODEL

Using a first-order Taylor series to obtain wind turbine linear model for the operation point *eq*, the partial derivatives of the nonlinear equations (9 -12) are evaluated as follows:

$$\tilde{\tau}_a = \left[\frac{\partial\tau_a}{\partial v}\right]_{eq}\tilde{v} + \left[\frac{\partial\tau_a}{\partial\beta}\right]_{eq}\tilde{\beta} + \left[\frac{\partial\tau_a}{\partial\omega_r}\right]_{eq}\tilde{\omega}_r = b_1\tilde{v}+b_2\tilde{\beta}+b_7\tilde{\omega}_r,$$
$$\tilde{\tau}_g = \left[\frac{\partial\tau_g}{\partial I_f}\right]_{eq}\tilde{I}_f + \left[\frac{\partial\tau_g}{\partial\omega_r}\right]_{eq}\tilde{\omega}_r + \left[\frac{\partial\tau_g}{\partial R_L}\right]_{eq}\tilde{R}_L = b_3\tilde{I}_f+b_4\tilde{\omega}_r+b_8\tilde{R}_L,$$
$$\tilde{P}_g = \left[\frac{\partial P_g}{\partial I_f}\right]_{eq}\tilde{I}_f + \left[\frac{\partial P_g}{\partial\omega_r}\right]_{eq}\tilde{\omega}_r + \left[\frac{\partial P_g}{\partial R_L}\right]_{eq}\tilde{R}_L = b_5\tilde{I}_f+b_6\tilde{\omega}_r+b_9\tilde{R}_L \tag{14}$$

By considering that the following equation represents the electromechanical system that controls the blades angle:

$$\frac{\beta(s)}{\beta_{ref}(s)} = \frac{K_\beta}{T_\beta s^2+s+K_\beta} \tag{15}$$

and by applying Laplace transform in (14), the following representation of transfer function matrix (16) can be obtained. The Laplacian operator has been omitted for clarity.

$$\begin{bmatrix}W_r\\P_g\end{bmatrix} = \begin{bmatrix}g_{11} & g_{12}\\ g_{21} & g_{22}\end{bmatrix}\begin{bmatrix}I_f\\ \beta_{ref}\end{bmatrix} + \begin{bmatrix}g_{13}\\ g_{23}\end{bmatrix}V + \begin{bmatrix}g_{14}\\ g_{24}\end{bmatrix}R_L \tag{16}$$

The different transfer functions in (16) are given by

$$\begin{bmatrix}g_{11}(s) & g_{12}(s)\\ g_{21}(s) & g_{22}(s)\end{bmatrix} = \begin{bmatrix}\dfrac{-b_3}{d(s)} & \dfrac{b_2}{d(s)}\left(\dfrac{K_\beta}{e(s)}\right)\\ \dfrac{b_5 d(s)-b_3b_6}{d(s)} & \dfrac{b_2b_6}{d(s)}\left(\dfrac{K_\beta}{e(s)}\right)\end{bmatrix}$$
$$\begin{bmatrix}g_{13}(s)\\ g_{23}(s)\end{bmatrix} = \begin{bmatrix}\dfrac{b_1}{d(s)}\\ \dfrac{b_1b_6}{d(s)}\end{bmatrix}, \qquad \begin{bmatrix}g_{14}(s)\\ g_{24}(s)\end{bmatrix} = \begin{bmatrix}\dfrac{-b_8}{d(s)}\\ \dfrac{b_9 d(s)-b_6b_8}{d(s)}\end{bmatrix} \tag{17}$$
$$d(s) = J_t s + B_t + b_4 - b_7, \qquad e(s) = T_\beta s^2 + s + K_\beta$$

3.1 Calculation of parameters

The wind turbine constants of Table 1 are used to calculate the parameters from b_1 to b_9 of the linear model in (17).

Table 1. Wind turbine constants and constraints.

J_t	15 kg·m^2		h	9 m
B_t	0,0209 N·m/rpm		σ	2
N	11		v_{min} - v_{max}	4 - 13 m/s
η_g	0,6		P_{gnom}	3 kW
η_m	0,4		P_{gmax}	4 kW
ρ	1,225 kg/m^3		ω_{rnom}	315 rpm
K	0,223 Ω·s/rad		ω_{rmax}	400 rpm
α	0,0178 Ω·s/rad		R_{Lnom}	4 Ω
R	2 m		β_{min} - β_{max}	5 - 90 degrees
K_β	0,15		I_{fmax}	4 A
T_β	2			

Such constants and contraints correspond to a wind turbine with a synchronous electric generator (SG3000, Sawafuji Electric Co., Ltd.), gearbox (CNH-4115-11, Sumitomo Heavy Indsutries, Ltd.) and fiber glass blades (NACA4418).

Besides the constants of Table 1, it is necessary to know the values of inputs and outputs for the operation point. In this case, it is required that the wind turbine works at constant angular speed and good power efficiency conditions. According to the curves of figure 3, the wind turbine works with good power efficiency for values of $C_p(\lambda,\beta)\approx 0{,}31$ and $\lambda\approx 6$, for an angle $\beta\approx 7{,}12$. The efficiency can be increased; however, there exists the risk of saturating β to its minimum value. With these data and using (4) for a wind speed of 11 m/s, the turbine reaches its nominal speed ω_{rnom} of 315 rpm.

From the nonlinear model equations (9-12) in stationary state for the operation point in question, it is possible to find the following expression to calculate the field current I_f, beind 2.54 A.

$$I_{feq}=\sqrt{\left(\frac{1}{2}\rho\pi R^3 v_{eq}^2\,\frac{C_p(\lambda,\beta)_{eq}}{\lambda_{eq}}-B_t\omega_{rnom}\right)}\cdot\sqrt{\left(\frac{\eta_g\eta_m}{K^2N\omega_{rnom}}\right)\left(\frac{R_{Lnom}^2+(\alpha N\omega_{rnom})^2}{R_{Lnom}}\right)} \quad (18)$$

Finally, using (11), the generated power is very near from its nominal value 2926,5 W. With this numerical values, the transfer matrix of the process is:

$$G(s)=\begin{bmatrix}\dfrac{-70{,}55}{15s+0{,}233} & \dfrac{-1{,}56}{30s^3+15{,}47s^2+2{,}48s+0{,}035}\\ \dfrac{3458s+173.1}{15s+0{,}233} & \dfrac{-8{,}05}{30s^3+15{,}47s^2+2{,}48s+0.035}\end{bmatrix},$$
$$\begin{bmatrix}g_{13}\\ g_{23}\end{bmatrix}=\begin{bmatrix}\dfrac{27{,}18}{15s+0{,}233}\\ \dfrac{139.9}{15s+0{,}233}\end{bmatrix},\qquad \begin{bmatrix}g_{14}\\ g_{24}\end{bmatrix}=\begin{bmatrix}\dfrac{-9{,}985}{15s+0{,}233}\\ \dfrac{4893s+24.5}{15s+0{,}233}\end{bmatrix} \quad (19)$$

4. CONTROL SYSTEMS

Before designing the multivariable controllers, the process interaction is measured by means of the relative gain array (RGA) (Skogestad and Postlethwaite, 2005). The RGA element λ_{11} of the process in stationary state is 0,677. This indicates a considerable level of interaction and that the suitable pairing is to control the speed of the rotor ω_r with the field current I_f, and the generated power P_g with the orientation angle of the blades β_{ref}.

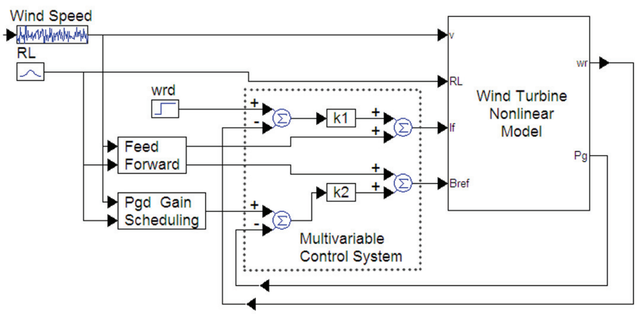

Fig 4. Decentralized PI control with feedforward.

4.1 Decentralized control

The solution for the control problem of the wind turbine can be approached using a decentralized control. The control scheme is depicted in figure 4. Using a PI structure, each controller is tuned for the corresponding transfer function in (20), that takes into account the interactions of the other loop.

$$q_1(s)=g_{11}(s)-\frac{k_2(s)g_{12}(s)g_{21}(s)}{1+k_2(s)g_{22}(s)}$$
$$q_2(s)=g_{22}(s)-\frac{k_1(s)g_{12}(s)g_{21}(s)}{1+k_1(s)g_{11}(s)} \quad (20)$$

There exist different methods for the tuning of controllers, like: heuristic, relay, Gershgorin bands, among others (Ho et al., 1997) and (Morilla et al., 2008). For this work, it has been decided to use the iterative process proposed by (Vázquez et al., 1999), that was implemented in the computer tool TITO, available in www.dia.uned.es/~fmorilla/. This tool facilitates the tuning of the gains of the controller, using gain margins, phase margins or both as specifications. For a phase margin of 60º in both loops and the transfer functions in (19), this tool obtains the following PI parameters:

$$k_{p1}=-6{,}19\cdot 10^{-3}\ \text{A/rpm};\quad T_{i1}=39{,}81\ \text{s},$$
$$k_{p2}=-5.43\cdot 10^{-3}\,\text{grados/W};\quad T_{i2}=31.24\ \text{s}. \quad (21)$$

Since the disturbances due to the wind turbulence as well as load electric changes affect considerably the performance of the wind turbine, a feedforward (FF) compensator have been designed to attenuate its effects. The feedforward elements to compensate the wind turbulence are approximated to the following transfer functions:

$$FF_{1v}(s)=\frac{-g_{13}(s)}{q_1(s)}\approx\frac{407.7s+6.322}{1058s+16.41}$$
$$FF_{2v}(s)=\frac{-g_{23}(s)}{q_2(s)}\approx\frac{139.9s+2.168}{3460s^2+107.3s+0.8315} \quad (22)$$

The feedforward compensation for load electric changes is given by:

$$FF_{1RL}(s)=\frac{-g_{14}(s)}{q_1(s)}\approx\frac{-149.8s\ -\ 2.323}{1058s+16.41},$$
$$FF_{2RL}(s)=\frac{-g_{24}(s)}{q_2(s)}\approx\frac{4893s^2+100.3s+0.3797}{3460s^2+107.3s+0.8315} \quad (23)$$

4.2 Centralized control by decoupling

Multivariable centralized control by decoupling is another approach to regualte the wind turbine. As it is a more complex strategy, it can be expected to obtain a better control performance and interaction attenuation. The scheme is shown in figure 5. A decoupler network *D(s)* is design, in such a way that the new apparent process *Q(s)=G(s)D(s)* is diagonlly dominant, where *G(s)* is the process transfer matrix in (19). Then, a decentralized control *K(s)* with two PI controllers is tuned for this apparent process *Q(s)*.

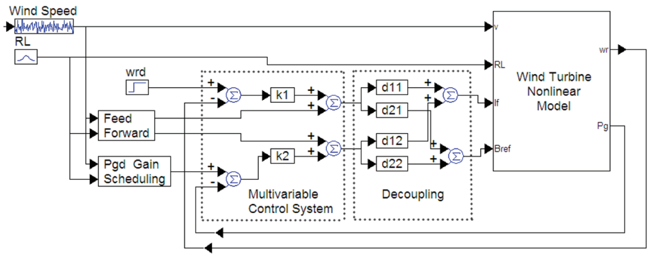

Fig. 5. Centralized control by decoupling with feedforward.

Two methods for the decoupler design exist: dynamic decoupling, when *D(s)* is calculated using the transfer functions of process *G(s)*, and static decoupling, when only steady state information *G(0)* is used. In this work, static decoupling is selected, since in previous publications it has shown good results (González *el al.,* 2010).

The design of static decoupler network is simple and it is based only on the process gains in stationary state. If two elements of the decoupler network are set to unity, for example $d_{11}(0)$ and $d_{22}(0)$, the other two elements are calculated as follows (Morilla *et al.,* 2005):

$$d_{12}(0)=\frac{-g_{12}(0)}{g_{11}(0)}, \qquad d_{21}(0)=\frac{-g_{21}(0)}{g_{22}(0)} \tag{24}$$

Then, the static decoupling with $d_{11} = d_{22} = 1$ for the process given in (19), is:

$$\begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix} = \begin{bmatrix} 1 & -0.1478 \\ 3.2255 & 1 \end{bmatrix} \tag{25}$$

Using a phase margin of 60º in both loops as performance specifications, the PI parameters of the decentralized control, obtained by TITO tool, are the following:

$$\begin{aligned} k_{p1} &= -0{,}085 \text{ A/rpm}; \qquad & T_{i1} &= 75{,}75 \text{ s}, \\ k_{p2} &= -5{,}8\cdot 10^{-3} \text{ grados/W}; \qquad & T_{i2} &= 7{,}12 \text{ s} \end{aligned} \tag{26}$$

The control strategy is completed again with a feedforward compensator; however, in this case, it is designed taking into account the apparent process *Q(s)=G(s)D(s)*. The approximated feedforward elements are:

$$FF_{1v}(s)=\frac{-g_{13}(s)}{q_1(s)} \approx \frac{27.18s+0.1318}{10.08s+0.1563}$$
$$FF_{2v}(s)=\frac{-g_{23}(s)}{q_2(s)} \approx \frac{0.104s+0.02744}{s+0.0155} \tag{27}$$

$$FF_{1RL}(s)=\frac{-g_{14}(s)}{q_1(s)} \approx \frac{-9.985s-0.04843}{10.08s+0.1563}$$
$$FF_{2RL}(s)=\frac{-g_{24}(s)}{q_2(s)} \approx \frac{40.77s^2+22.3s+3.058}{s^2+3.56s+3.168} \tag{28}$$

4.3 Gain scheduling for power reference

In Section 1, it is mentioned that the wind turbine must operate at constant angular speed in its nominal value. Nevertheless, the power cannot operate always in the nominal value, since it depends on diverse factors, like the wind speed and the energy demand of the electrical load. If the wind speed is high, the wind turbine will work near its nominal power; however, for small wind speeds, the power will have to fall trying to achieve a good power efficiency, $C_p(\lambda,\beta)>0.3$.

With regard to the electrical load, a small value of R_L implies a great demand of power; however, when the value of R_L is big, there is little power consumption and the generated power must decrease according to the demand.

Therefore, the power reference must depend on the wind speed, the electrical load and power efficiency. In this work, a gain scheduling is used to determine the power reference (29). This function is obtained substituting the field current in steady state (18) in the generated power (11) with the values of the constants of Table 1. This generates an expression for the power reference P_{gd} that depends on the wind speed v and the electrical load R_L, for angular speed constant ω_{rnom}.

$$P_{gd}=\left(\frac{R_L}{R_L^2+41{,}724}\right)\left(34{,}09v^3-3102{,}9\right) \tag{29}$$

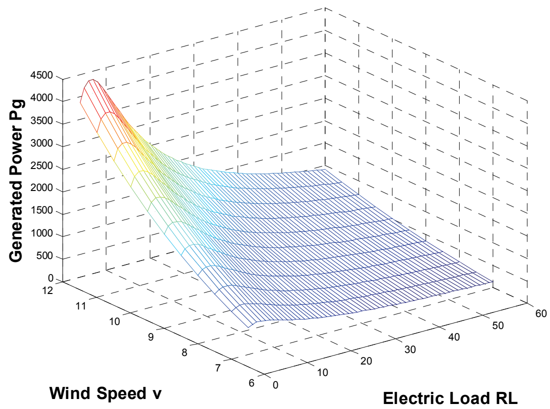

Fig. 6. Power based on the wind speed v and load R_L.

5. RESULTS

Some simulations are performed to evaluate the wind turbine performance with the proposed controllers. Figure 7 shows the responses to step changes in the wind speed without turbulence, from 12 to 8 m/s. The electric load R_{Lnom} is 4 Ω.

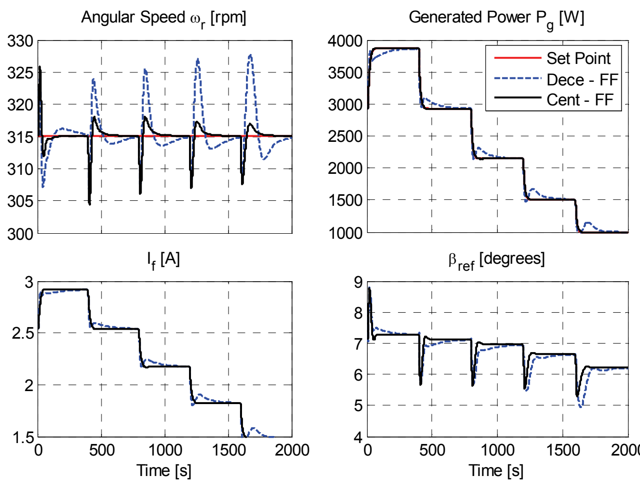

Fig. 7. Response to step changes in the media speed of wind.

In figures 8 and 9, the system is simulated under more realistic conditions, applying the same step changes in the wind but with turbulence, model given in (13). The electrical load has random variations from 4 to 12 Ω. The results show better performance of the wind turbine with centralized controller, maintains the angular speed very near his nominal value, also the tracking of the power reference is very good, adjusting to the changes of the wind and the electric load.

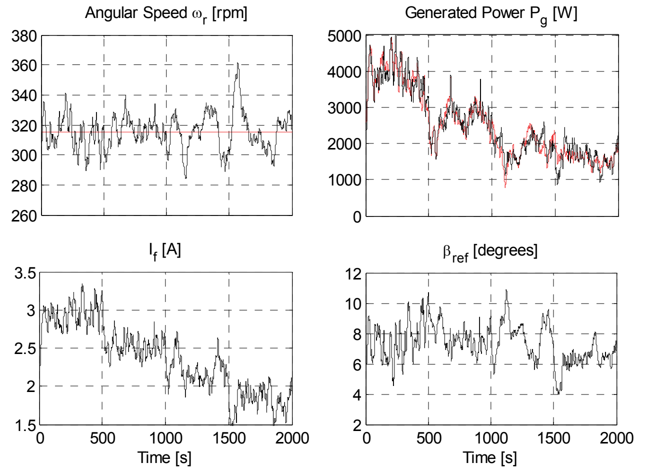

Fig. 8. Response with decentralized control and Feedforward.

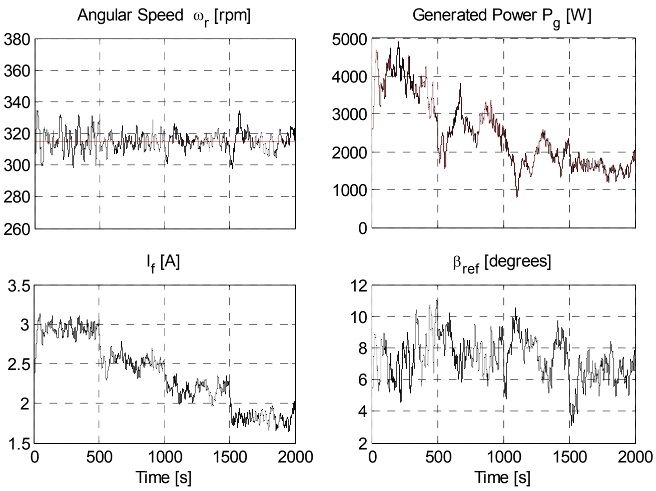

Fig. 9. Response with centralized control and Feedforward.

6. CONCLUSIONS

In this work, the model of a small wind turbine and its control is presented. The control objective is to regulate the angular speed in its nominal value and to fit the power generated based on the changes of the wind speed and electrical load, to maintain good efficiency of power. Two multivariable controllers are proposed: a decentralized and a centralized by static decoupling. In both cases, a feedforward compensation has been designed to attenuate the disturbance effects of the wind turbulence and the electrical load changes. The power reference changes according to a gain scheduling function.

The simulations show that the effects of the interaction between the variables are attenuated (figure 7), and that in particular the centralized controller is robust, since the wind turbine still has a good performance for high and low wind speeds and significant changes in the electrical load. The power reference is calculated with the media wind speed, and the disturbances caused by the turbulence are attenuated by means of the feedforward compensator.

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