VARIABLE SPEED CONTROL OF WIND TURBINES USING TUNING FUNCTIONS DESIGN

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Abstract

In recent years, wind energy has become an important part of the electrical power generation. Wind variations produce mechanical power fluctuations and consequently the speed changes in the turbine rotor lead to variations in the currents and voltages produced by the wind generators. The purpose of this paper is the setpoint regulation of the angular speed of a wind turbine via the control of a rectified voltage produced by a secondary synchronous generator despite wind variations. The procedure based on the adaptive tuning functions and the backstepping design permits to adjust the rotational speed in order to maintain the tip speed ratio to its optimal value with the purpose of optimising the maximum available power. It has only been simulated the particular case of the design of the control algorithm that carries out its angular speed to its nominal value for the protection against the gusts wind whose speed values can be superior to the designed furling wind speed.

1 Introduction

The control of a system, that generates power from an unsteady input as the wind, presents a formidable problem. The wind speeds can be varied from a steady value or almost stationary one to varying from time to time due to gusts, and are further disturbed by the effect of the supporting tower shadow. The proposed control design is shown in Figure 1, where the blade pith angle is maintained constant in its optimum value and only the variable wind speed is considered. This is the solution commonly accepted in the smallest and the most medium turbines. Nevertheless, in this type of turbines the protection system for superior winds to the superior limit of design is carried out by means of the employment of brakes by friction. The novelty of this paper consists on the employment of the generator itself as limiter and controller of the angular speed of the rotor blades. The asynchronous generators are adequate for this purpose for they are rugged, brushless, and need little maintenance and have a low unit cost. The new recursive design called the adaptive backstepping [3] is based on three types of techniques which differ in the construction of adaptation law: (i) Adaptive backstepping with overparametrization, when at each design step and new vector of adjustable parameters and the corresponding adaptation law are introduced [1], (ii) Adaptive backstepping with modular identifiers when a slight modification of the adaptive control allows one to independently construction estimation-based identifiers of unknown parameters [3], (iii) Adaptive backstepping with tuning functions, when at each design step a virtual adaptation law called tuning function is introduced, while the actual adaptation algorithm is defined at the final step in terms of all the previous tuning functions [2].

2 System's modelling

The wind turbine of horizontal axis (HAWT) is characterized by non-dimensional curves of the power coefficient C_p as a function of both tip speed ratio, λ and the blade pitch angle, β. The tip speed ratio is the ratio of linear speed at the tip of blades to the speed of the wind. It can be expressed as follows,

$$\lambda = \frac{R \cdot w}{u} \qquad (1)$$

where R is the wind turbine rotor radius, w is the rotor mechanical angular velocity and u is the wind velocity. For the wind turbine analysed in this study the following equation approximates C_p as a function of λ and β [7],

$$C_p = (0.44 - 0.0167 \cdot \beta) \cdot \sin\left[\frac{\pi \cdot (\lambda - 3)}{15 - 0.3 \cdot \beta}\right] - 0.00184 \cdot (\lambda - 3) \cdot \beta \qquad (2)$$

The power produced by the wind is given by [4] [5]

$$P_m(u) = \frac{1}{2} \cdot C_p(\lambda, \beta) \cdot \rho \cdot \pi \cdot R^2 \cdot u^3 \qquad (3)$$

where ρ is the air density. This power can be expressed by the (1) and (3) equations in the form,

$$P_m = K_w \cdot w^3 \tag{4}$$

where

$$K_w = \frac{1}{2} \cdot C_p \cdot \rho \cdot \pi \cdot \frac{R^5}{\lambda^3} \tag{5}$$

The dynamics of the subsystem formed by the rotor blades and the gear box, is characterized by the following equations [6],

$$T_m - T = J_m \cdot \dot{w} + B_m \cdot w + K_m \cdot \theta \tag{6.a}$$

$$T_p - T_e = J_e \cdot \dot{w}_e + B_e \cdot w_e + K_e \cdot \theta_e \tag{6.b}$$

$$T_p \cdot w_e = T \cdot w \tag{6.c}$$

where B_m, K_m, B_e, K_e are the friction and torsion constants, T_m, T_e, T, T_p the shaft torque seen at the turbine end, at the starting point of the secondary generator , before and after gear box, J_m, J_e the equivalent moment of inertia of the turbine and the generator, and w, w_e the angular velocity of the shaft at turbine end and generator end. (Fig. 1). The gear ratio is defined by

$$\gamma = \frac{w_e}{w} = \frac{T}{T_p} \tag{7}$$

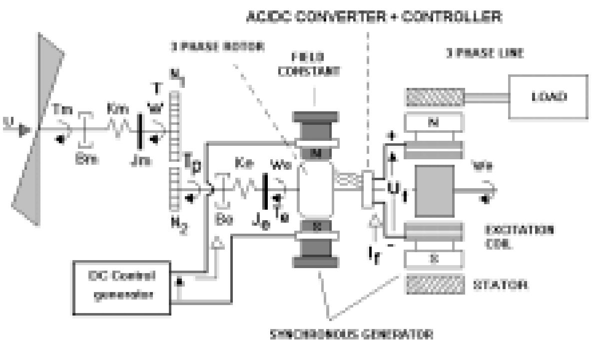

Figure 1.

Combining the (6.a), (6.b) equations, together with (7), the following equation is obtained,

$$T_m - \gamma \cdot T_e = J \cdot \dot{w} + B \cdot w + K \cdot \theta \tag{8}$$

being,

$$J = J_m + \gamma^2 \cdot J_e \tag{9.a}$$

$$B = B_m + \gamma^2 \cdot B_e \tag{9.b}$$

$$K = K_m + \gamma^2 \cdot K_e \tag{9.c}$$

In the commercial three phase generators (when the output power is greater than 5 kW) it is more economic, sure and practical the employment of an excitation without brushes. The nominal power of the main generator depends on the nominal power of the alternator. To excite an alternator of 100 kW a generator of 2.5 kW is required (2.5% of their nominal power). The objective of the control is the regulation of the reactive power supply to the load by means of the control of the excitement tension. The used procedure is based on the backstepping design with tuning functions [2].
The electromagnetic torque T_e is

$$T_e = K_\phi \cdot \phi\left(I_f\right) = K_\phi \cdot K_f \cdot I_f \tag{10}$$

where K_ϕ , K_f are the torque and flux constants, ϕ (I_f) is the flux produced by the excitation current I_f. The exciter dynamics is governed by the equation,

$$L_f \cdot \dot{I}_f + I_f \cdot R_f = U_f \tag{11}$$

being L_f and R_f the inductance and resistance of the circuit, while U_f is the field voltage (control signal).
Combining the equations (4), (8) , (11) it is possible to meet the dynamic equations of the whole system,

$$\dot{w} = a \cdot I_f + b \cdot w + c \cdot \int_0^\tau w \cdot d\tau + d \cdot w^2 \tag{12.a}$$

$$\dot{I}_f = f \cdot U_f + e \cdot I_f \tag{12.b}$$

where,

$$a = -\frac{\gamma \cdot K_\phi \cdot K_f}{J} \tag{13.a}$$

$$b = -\frac{B}{J} \tag{13.b}$$

$$c = -\frac{K}{J} \tag{13.c}$$

$$d = \frac{K_w}{J} \tag{13.d}$$

$$e = -\frac{R_f}{L_f} \tag{13.e}$$

$$f = \frac{1}{L_f} \tag{13.f}$$

3 Tuning functions design

The control objective is to maintain the angular velocity of the synchronous generator in the desired setpoint despite the variation in the wind speed. It is necessary to design an adaptive control with a identification of the unknown but constant parameters whose values are subject to uncertainties.
The equations (12.a-b), can be written in matricial form,

$$\dot{w} = a \cdot I_f + \varphi_1^T \cdot \Theta \tag{14.a}$$

$$\dot{I}_f = f \cdot U_f + \varphi_2^T \cdot \Theta \tag{14.b}$$

being, $\varphi_1^T = \left[w \quad \int_0^\tau w \cdot d\tau \quad w^2 \quad 0 \right]$,

$\varphi_2^T = [0 \quad 0 \quad 0 \quad I_f]$, $\Theta^T = [b \quad c \quad d \quad e]$

where b, c, d, e are an unknown constant parameters. The block's diagram is showed in Fig.2.

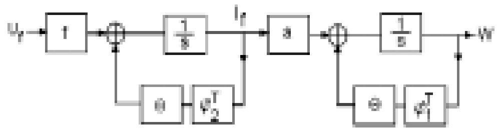

Figure 2. Block diagram of second order parametric strict feedback system.

The preliminary step of synthesis is to define a change of coordinates,

$$z_1 = w - w_r \qquad (15.a)$$

$$z_2 = I_f - \alpha_1 \qquad (15.b)$$

where w is the actual angular speed and w_r the desired one.
The field intensity I_f is treated as a virtual control for the w equation, α_1 is the stabilizing function and z_2 is the error variable, expressing the fact that I_f is not the true control. Due to existence of two states, the tuning functions procedure has been made in two steps.

STEP1

Once the change of coordinates has been defined, it is possible to set up the Liapunov function that will be used to synthesize the virtual controls and eventually the true control. Generally, the form of this function is,

$$V_1 = \frac{1}{2} \cdot z_1^2 + \frac{1}{2} \cdot \tilde{\Theta}^T \cdot \Gamma^{-1} \cdot \tilde{\Theta} \qquad (16)$$

where $\tilde{\Theta} = \Theta - \hat{\Theta}$ is the parameter error and Γ is a positive definite matrix referred to as adaptive gain . Differentiating the equation (15.a),

$$\dot{z}_1 = a \cdot z_1 + a \cdot \alpha_1 + \varphi_1^T \cdot \Theta \qquad (17.a)$$

the derivative of Liapunov function (16) is

$$\dot{V}_1 = a \cdot z_1 \cdot z_2 + a \cdot z_1 \cdot \alpha_1 + z_1 \cdot \varphi_1^T \cdot \Theta - \tilde{\Theta}^T \cdot \Gamma^{-1} \cdot \dot{\hat{\Theta}} \qquad (17.b)$$

Choosing the stabilizing function as,

$$\alpha_1 = \frac{1}{a} \cdot \left[-C_1 \cdot z_1 - \varphi_1^T \cdot \hat{\Theta} \right] \qquad (18)$$

the (17.b) is transformed on,

$$\dot{V}_1 = -C_1 \cdot z_1^2 + a \cdot z_1 \cdot z_2 - \tilde{\Theta}^T \cdot \left[\Gamma^{-1} \cdot \dot{\hat{\Theta}} - \tau_1 \right] \qquad (19)$$

where τ_1 is the first tuning function, and W_1 the first regressor, defined as,

$$\tau_1 = z_1 \cdot \varphi_1 \qquad (20.a)$$

$$W_1 = \varphi_1(w, I_f) \qquad (20.b)$$

In this step the presence of the quadratic term is tolerated, the purpose is its elimination in the next step. This completes the first step of the design.

STEP 2

Differentiating (15.b) and substituting $\dot{I}_f$ of (14.b), the second state equation in the new dynamics is,

$$\dot{z}_2 = f \cdot U_f + \varphi_2^T \cdot \Theta - \dot{\alpha}_1 \qquad (21)$$

the derivative of the stabilising function α_1 can be computed from (18),

$$\dot{z}_2 = f \cdot U_f + \varphi_2^T \cdot \Theta - \frac{\partial \alpha_1}{\partial w} \cdot \left[a \cdot I_f + \varphi_1^T \cdot \Theta \right] - \frac{\partial \alpha_1}{\partial \hat{\Theta}} \cdot \dot{\hat{\Theta}} \qquad (22)$$

and the second Liapunov function is defined as,

$$V_2 = V_1 + \frac{1}{2} \cdot z_2^2 \qquad (23)$$

and

$$\dot{V}_2 = -C_1 \cdot z_1^2 + z_2 \cdot \left\{ a \cdot z_1 + f \cdot U_f - \frac{\partial \alpha_1}{\partial w} \cdot a \cdot I_f + \left[\varphi_2^T - \frac{\partial \alpha_1}{\partial w} \cdot \varphi_1^T \right] \cdot \hat{\Theta} - \frac{\partial \alpha_1}{\partial \hat{\Theta}} \cdot \dot{\hat{\Theta}} \right\} + \tilde{\Theta}^T \left\{ \tau_1 + \left[\varphi_2 - \frac{\partial \alpha_1}{\partial w} \cdot \varphi_1 \right] \cdot z_2 - \Gamma^{-1} \cdot \dot{\hat{\Theta}} \right\} \qquad (24)$$

the W_2 the second regression function defined by,

$$W_2\left(w, I_f, \hat{\Theta}\right) = \varphi_2 - \frac{\partial \alpha_1}{\partial w} \cdot \varphi_1 \qquad (25)$$

$$\dot{V}_2 = -C_1 \cdot z_1^2 + z_2 \cdot \left[a \cdot z_1 + f \cdot U_f - \frac{\partial \alpha_1}{\partial w} \cdot a \cdot I_f + W_2^T \right.$$

$$\left. \cdot \hat{\Theta} - \frac{\partial \alpha_1}{\partial \hat{\Theta}} \cdot \dot{\hat{\Theta}} \ \right] + \tilde{\Theta}^T \cdot \left[\tau_1 + W_2 \cdot z_2 - \Gamma^{-1} \cdot \dot{\hat{\Theta}} \right] \qquad (26)$$

with the objective eliminating the error $\tilde{\Theta}$ in the unknown vector parameter Θ the following update law is chosen,

$$\dot{\hat{\Theta}} = \Gamma \cdot \tau_1 + \Gamma \cdot W_2 \cdot z_2 \qquad (27)$$

with the regression matrix

$$\mathbf{W}\left(z, \hat{\Theta}\right) = \begin{bmatrix} W_1 & W_2 \end{bmatrix} \qquad (28)$$

The update law is now

$$\dot{\hat{\Theta}} = \Gamma . \mathbf{W}\left(z, \hat{\Theta}\right) \cdot z \qquad (29)$$

Also, with the purpose of eliminating the z_2 coefficient in (26), the control signal is chosen in the form

$$U_f = \frac{1}{f} \cdot \left[-a \cdot z_1 - C_2 \cdot z_2 + \frac{\partial \alpha_1}{\partial w} \cdot a \cdot I_f - \right.$$

$$\left. W_2^T \cdot \hat{\Theta} + \frac{\partial \alpha_1}{\partial \hat{\Theta}} \cdot \dot{\hat{\Theta}} \right] \qquad (30)$$

with the update law (29),

$$U_f = \frac{1}{f} \cdot \left[-a \cdot z_1 - C_2 \cdot z_2 + \frac{\partial \alpha_1}{\partial w} \cdot a \cdot I_f - \right.$$

$$\left. w_2^T \cdot \hat{\Theta} + \frac{\partial \alpha_1}{\partial \hat{\Theta}} \cdot \ \Gamma \cdot \tau_2 \ \right] \qquad (31)$$

where τ_2 is the second tuning function defined by,

$$\tau_2 = \tau_1 + W_2 \cdot z_2 \qquad (32)$$

being the Liapunov function of the whole system

$$\dot{V} = -\sum_{i=1}^{2} C_i \cdot z_i^2 \qquad (33)$$

the dynamic of the original system in closed loop form and in the new coordinates (z_1, z_2) is

$$\begin{pmatrix} \dot{z}_1 \\ \dot{z}_2 \end{pmatrix} = \begin{pmatrix} -C_1 & a \\ -a & -C_2 \end{pmatrix} \cdot \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} + \begin{pmatrix} W_2^T \\ W_1^T \end{pmatrix} \cdot \tilde{\Theta} \qquad (34)$$

By Liapunov stability theorem the global stability of the equilibrium point $\left(z, \hat{\Theta}\right)$ is achieved as consequence that along with the solutions of (29), (34) the $\dot{V}_2$ is given by (33), provided that C_1, C_2 >0.

4 System's simulation

The typical characteristics of a HAWT of 100 kW are defined in Table 1.

Allowable rotor speed	40 rev/min	Type of connection	Direct grid connection
Generator output power	100 kW	Number of poles	P=12
Optimal coefficient of performance	0.375	Angular velocity (main generator)	500 r.p.m
Cut-in wind speed	4.3 m/s	Frequency	50 Hz
Rated wind speed	7.7 m/s	Voltage produced	380/220 V
Furling wind speed	1.9 m/s	Equivalent inertia moment	$J=16\ Kg.m^2$
Rotor diameter	37.5 m	Friction constant	B=52 N.m.s/rad
Hub height	30 m	Speed constant	$K_w=128786\ W/rad^3$
Coning angle	7^o	Torsional flexibility	$K \approx 0$
Effective swept area	$1072\ m^2$	Machine-related constant	$K_\phi=1.7$ N.m/Wb
Weight of blades	2090 kg	Flux constant	$K_f=15.9$ Wb/A

Table 1

The immediate application of the equations (29) and (31) to the system dynamics represented by (14.a.b), leads to the following ones, representing the control if driven train torsional flexibility is ignored ($K \approx 0$),

$$U_f = \frac{1}{f} \cdot \left[-a \cdot z_1 - C_2 \cdot z_2 - \left(\beta \cdot a + \hat{e}\right) \cdot I_f - \beta \cdot w \cdot a \cdot \right.$$

$$\left. \left(\hat{b} + \hat{d} \cdot w\right) - \frac{\Gamma \cdot w^2}{a} \cdot \left(1 + w^2\right) \cdot \left(z_1 + \beta \cdot z_2 \cdot a\right) \right] \qquad (35)$$

and the adaptation laws,

$$\dot{\hat{b}} = \Gamma \cdot (z_1 + \beta \cdot z_2 \cdot a) \cdot w \qquad (36.a)$$

$$\dot{\hat{d}} = \Gamma \cdot (z_1 + \beta \cdot z_2 \cdot a) \cdot w^2 \qquad (36.b)$$

$$\dot{\hat{e}} = \Gamma \cdot z_2 \cdot I_f \qquad (36.c)$$

where the parameter β is given by

$$\beta = \frac{C_1 + \hat{b} + 2 \cdot \hat{d} \cdot w}{a^2} \qquad (37)$$

while the new state equations that expressed the error dynamics are,

$$\dot{z}_1 = -C_1 \cdot z_1 + a \cdot z_2 + \tilde{b} \cdot w + \tilde{d} \cdot w^2 \qquad (38.a)$$

$$\dot{z}_2 = -a \cdot z_1 - C_2 \cdot z_2 + \tilde{b} \cdot \beta \cdot a \cdot w + \tilde{d} \cdot \beta \cdot a \cdot w^2 + \tilde{e} \cdot I_f \qquad (38.b)$$

The proposed control should be able to carry out the rotor speed from its maximum value (near of cut-out wind velocity) to the nominal one (see Table 2). Simultaneously, the error signal should complete some certain optimisation criteria. Among the multiple optimisation criteria have be chosen integral of the absolute value of error (IAE) by their simplicity and use. This procedure jointly with the Polak-Ribiere optimisation algorithm lets us the determination the design constants C_1, C_2 and the adaptation gain, Γ. The obtained results are shown in Table 3. The integration algorithm of backward Euler with a step size of 0.1 s has been utilised.

u	7.7 m/s	T_p	2256.65 N.m
w	1.38 rad/s	P_m	118170 W
w_e	52.38 rad/s	U_f	36.75 V
T	85522.7 N.m	I_f	70.7 A

Table 2: Some nominal values in HAWT 100 kW.

Criteria	Cost	C_1	C2	Γ
IAE	0.282	10^8	98.10^4	2210

Table 3

The procedure is capable of the determination of the unknown parameters. The results are indicated in Table 4.

Parameter	Real value	Initial estimation	Estimation error (%)
b	-3.25	-4	1.5
d	2799.98	2700	3.5
e	-390.977	-380	3.0

Table 4. Values obtained under the criteria ISE.

The simulation results shown that the nonlinear control algorithm is able to cause the system to go from the furling speed of rotor to the nominal speed. Its form of the variation is showed in Fig. 3, jointly with the variation of the error variables z_1, z_2 (Figs. 4, 5).

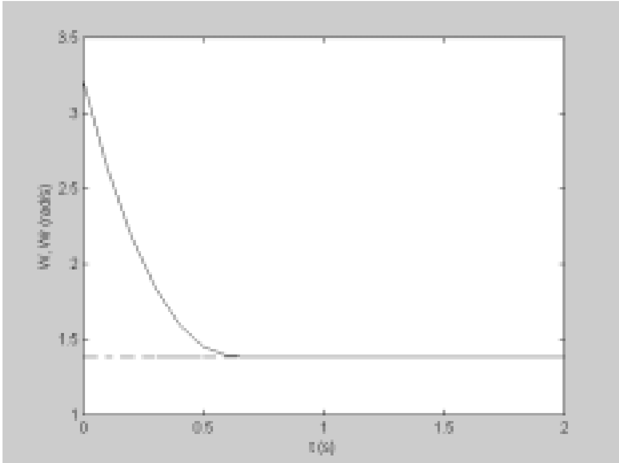

Figure 3. Variation of the angular velocity. Continuous line (actual speed w), dashed (desired one w_r).

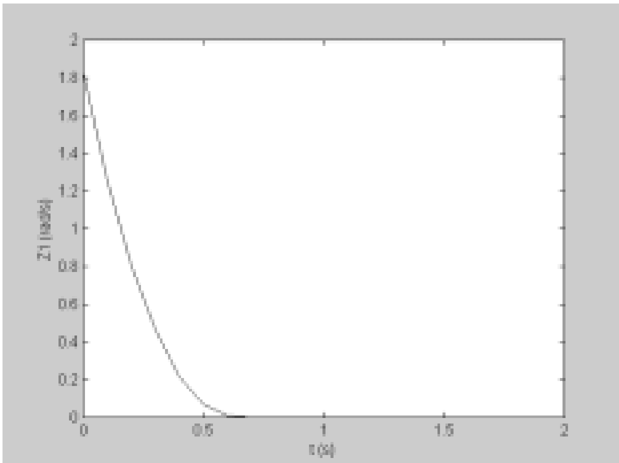

Figure 4. Temporal variation of z_1 variable.

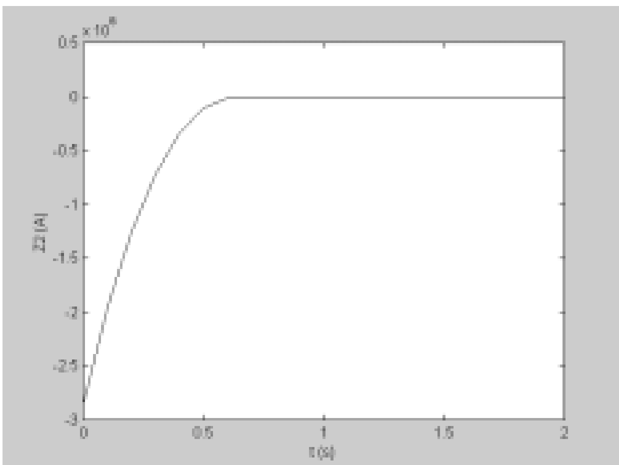

Figure 5. Temporal variation of z_2 variable.

The field intensity in the main generator (I_f), and the control signal (limited among the values ±500 V) of the nonlinear controller is indicated in Fig. 6. The variation of the stabilizing function α_1 (18), and the auxiliary variable β (37) appears in Figs.7,8, respectively.

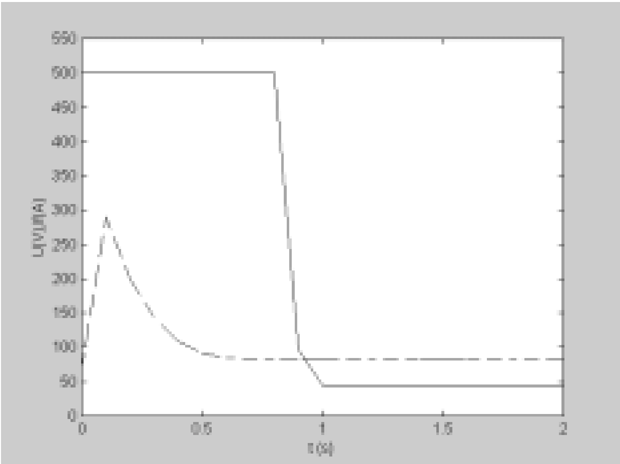

Figure 6. Variation of the I_f (– –), and the controller signal U_f (—) in the regulation process.

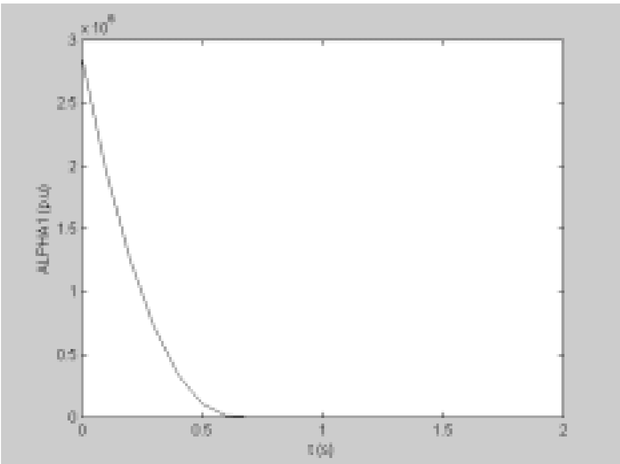

Figure 7. Temporal variation of α_1.

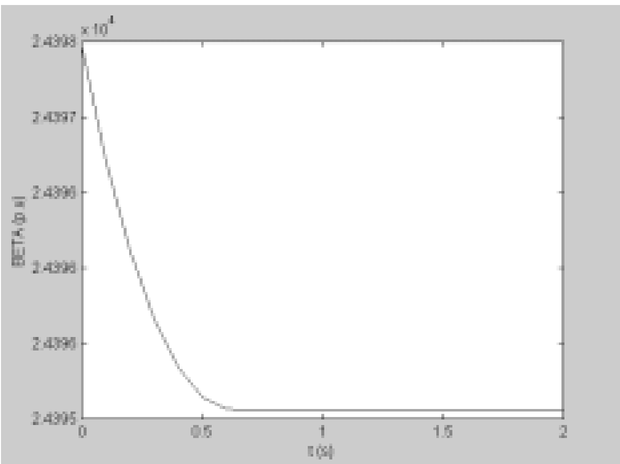

Figure 8. Temporal variation of β.

Conclusions

The problem of regulation in a wind turbine of horizontal axis with direct grid connection has been carried out by the backstepping procedure and the tuning functions design. The control algorithm is capable of changing the winding voltage so that the rotor speed of an asynchronous generator and the consequent angular speed of the rotor blades are correspondingly adjusted to get the asymptotically stability of the whole system.

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