CONTROL IN VARIABLE SPEED WIND TURBINES BASED ON SYNCHRONOUS GENERATORS

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Abstract: In recent years, wind energy has become an important part of the electrical power generation, however, the 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 set-point regulation of the voltage produced by a main synchronous generator of a wind turbine via the control of a rectified voltage produced by a secondary synchronous generator. The procedure based on the adaptive tuning functions and the backstepping design permits to obtain a nonlinear controller capable of carrying out the control goal for wind variations around nominal values in plants with a uncertainty on the real parameters values.

Keywords: Industrial production systems, nonlinear systems, modelling, adaptive control, identification algorithms.

1. INTRODUCTION

The correct design 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. Its design requires the skills of a multidisciplinary team of engineers with expertise in diverse areas: atmospheric wind flow, rotor aerodynamics, control, mechanical systems, electrical systems and civil engineering. In front of the oldest design based on wind generators with fixed speed, the variable speed one promise to achieve maximum aerodynamic efficiency over to wide range of wind speeds and thereby significantly increase energy captures with lower loads (Wright, *et al*., 1997) and lower acoustic noise (Vilsboll, *et al.*, 1997). The proposed control strategies must be significantly more intelligent in order to take advantage of this new potential with more sophisticated control algorithms. Henrichsen (1985) in an early paper about the variable speed objectives appointed on the desirability of additional mechanical mechanisms to limit the aerodynamic torque, such as pitch control or ailerons. He suggests an inner high-speed control loop to limit the aerodynamic torque to maintain the rotor speed proportional to the existing wind and thereby hold a constant tip speed ratio and a slow outer loop that controls the rotor speed when the power produced by the turbine starts to exceeded its

rating by means the control of the pitch. Usually this is the solution commonly accepted in the smallest and the most medium turbines (Carlin, *et al.*, 2003). 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 synchronous generators are adequate for this purpose for they are rugged, brushless, and need little maintenance and have a low unit cost. The controller design is based on a relatively new recursive procedure called the adaptive backstepping (Krstić, *et al.*, 1992) 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 is introduced (Kanellakopulos, *et al.* , 1991), (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 (Krstić, *et al.*, 1992), (iii) Adaptive backstepping with tuning functions, when at each design step to 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 (Krstić,*et al.,* 1995).
The control of the speed proposed in this paper is showed in Figure 1. Fundamentally it uses an auxiliary synchronous generator with to very inferior power to the main one and one converter (AC/DC) instead of the two converters (AC/DC) and (DC/AC) that are habitually used. The controller acts on the voltage rectified that feeds the excitation coil of the main generator and thereby controls the torque of the main generator and its speed.

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,

$$\lambda = \frac{R \cdot w}{u} \tag{1}$$

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, (Ezzeldin and Wilson, 2000),

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

The power produced by the wind is given by (Wasynezuk, 1981)

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

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

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

where

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

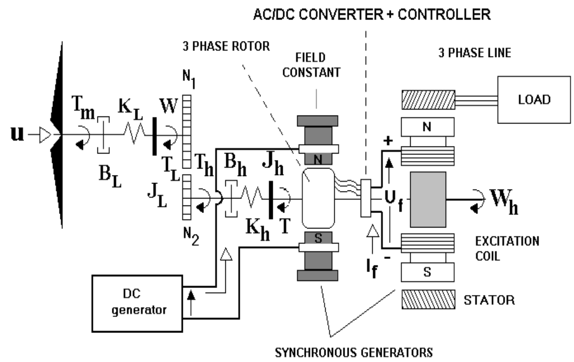
The dynamics of the subsystem formed by the rotor blades and the gear box, is characterized by the following equations (Song, 2000),

$$T_m - T_L = J_L \cdot \dot{w} + B_L \cdot w + K_L \cdot \theta \tag{6.a}$$

$$T_h - T = J_h \cdot \dot{w}_h + B_h \cdot w_h + K_h \cdot \theta_h \tag{6.b}$$

$$T_h \cdot w_h = T_L \cdot w \tag{6.c}$$

where B_L, B_h, K_L, K_h are the friction and torsion constants, T_m, T, T_L, T_h the shaft torque seen at the turbine end, generator end, before and after gear box, J_L, J_h the moment of inertia of the turbine and the generator, and $\dot{w}, \dot{w}_h, \theta, \theta_h$ the accelerations and angular displacements, of the shaft at turbine end and generator end. The gear ratio is defined by



$$\gamma = \frac{w_h}{w} = \frac{T_L}{T_h} \tag{7}$$

Fig.1. Schematic diagram of the generator system proposed.

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

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

being,

$$J = J_L + \gamma^2 \cdot J_h \quad B = B_L + \gamma^2 \cdot B_h \tag{9.a.b}$$

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

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. The electric power P_e is

$$P_e = K_\phi \cdot \phi\left(I_f\right) \cdot w_h = K_\phi \cdot K_f \cdot I_f \cdot w_h \qquad (10)$$

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

$$L_f \cdot \dot{I}_f + I_f \cdot R_f = U_f \qquad (11)$$

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), (10) and considering the relation between the power and the torque, is possible to meet the dynamic equations of the whole system,

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

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

where,

$$a = -\frac{\gamma \cdot K_\phi \cdot K_f}{J} \qquad b = -\frac{B}{J} \qquad (13.a,b)$$

$$c = -\frac{K}{J} \qquad d = \frac{K_w}{J} \qquad (13.c,d)$$

$$e = -\frac{R_f}{L_f} \qquad f = \frac{1}{L_f} \qquad (13.e,f)$$

3. TUNING FUNCTIONS DESIGN

The control objective is to maintain the angular velocity of the asynchronous generator in the desired set-point 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 strict - feedback form,

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

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

being, $\varphi_1^T = \begin{bmatrix} w & \int_0^\tau w \cdot d\tau & w^2 & 0 \end{bmatrix}$

$\varphi_2^T = \begin{bmatrix} 0 & 0 & 0 & I_f \end{bmatrix}$, $\Theta^T = \begin{bmatrix} b & c & d & e \end{bmatrix}$

where b, c, d, e are an unknown constant parameters.

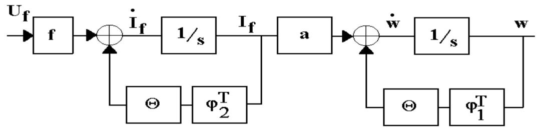


Fig. 2. Block diagram of the analysed system.

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

$$z_1 = w - w_r \qquad z_2 = I_f - \alpha_1 \qquad (15.a,b)$$

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.

3.1. Design procedure: Step 1

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),

$$\dot{z}_1 = a \cdot z_2 + a \cdot \alpha_1 + \varphi_1^T \cdot \Theta \qquad (17.a)$$

the derivative of Liapunov function 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,

$$\tau_1 = z_1 \cdot W_1 \qquad W_1 = \varphi_1(w, I_f) \qquad (20.a,b)$$

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.

3.2. Design procedure: Step 2

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

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

with the definition of the stabilizing function (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,

$$V_2 = V_1 + \frac{1}{2} \cdot z_2^2 = \frac{1}{2} \cdot z_1^2 + \frac{1}{2} \cdot \tilde{\Theta}^T \cdot \Gamma^{-1} \cdot \tilde{\Theta} + \frac{1}{2} \cdot z_2^2 \qquad (23)$$

and its temporal variation and considering that $\Theta = \tilde{\Theta} + \hat{\Theta}$

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

the W_2 the second regression function defined by,

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

$$\dot{V}_2 = -C_1 \cdot z_1^2 + z_2 \cdot \left[a \cdot z_1 + f \cdot U_f - \frac{\partial \alpha_1}{\partial w} \cdot a \cdot I_f + W_2^T \cdot \hat{\Theta} - \frac{\partial \alpha_1}{\partial \hat{\Theta}} \cdot \dot{\hat{\Theta}} \right] + \tilde{\Theta}^T \cdot \left[\tau_1 + W_2 \cdot z_2 - \Gamma^{-1} \cdot \dot{\hat{\Theta}}\right] \qquad (26)$$

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

$$\dot{\hat{\Theta}} = \Gamma \cdot \tau_1 + \Gamma \cdot W_2 \cdot z_2 = \Gamma \cdot (W_1 \cdot z_1 + W_2 \cdot z_2) \qquad (27)$$

with the regression matrix

$$\mathbf{W}\left(z, \hat{\Theta}\right) = [W_1 \quad W_2] \qquad (28)$$

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

$$U_f = \frac{1}{f} \cdot \left[-a \cdot z_1 - C_2 \cdot z_2 + \frac{\partial \alpha_1}{\partial w} \cdot a \cdot I_f - W_2^T \cdot \hat{\Theta} + \frac{\partial \alpha_1}{\partial \hat{\Theta}} \cdot \dot{\hat{\Theta}} \right] \qquad (30)$$

with the update law (29),

$$U_f = \frac{1}{f} \cdot \left[-a \cdot z_1 - C_2 \cdot z_2 + \frac{\partial \alpha_1}{\partial w} \cdot a \cdot I_f - W_2^T \cdot \hat{\Theta} + \frac{\partial \alpha_1}{\partial \hat{\Theta}} \cdot \Gamma \cdot \tau_2 \right] \qquad (31)$$

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

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

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 $\dot{V}$ 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 Song (2000).In Figures 3-4 are represented the angular speed of the rotor and its power at nominal wind speed and the corresponding to the nominal speed increased in 20% .

5.CONTROLLER DESIGN

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 ,

$$U_f = \frac{1}{f} \cdot \left\{ -a \cdot z_1 - C_2 \cdot z_2 - (\beta + \hat{e}) \cdot I_f - \beta \cdot \left(\hat{b} \cdot w + \hat{c} \cdot \int_0^\tau w \cdot d\tau + \hat{d} \cdot w^2 \right) - \frac{\Gamma \cdot (z_1 + \beta \cdot z_2)}{a} \cdot \left[w^2 + \left(\int_0^\tau w \cdot d\tau \right)^2 + w^4 \right] \right\} \quad (35)$$

and the adaptation laws,

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

$$\dot{\hat{c}} = \Gamma \cdot (z_1 + \beta \cdot z_2) \cdot \int_0^\tau w \cdot d\tau \quad (36.b)$$

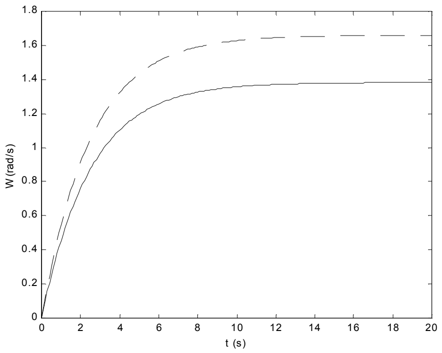


Fig.3. Rotor speed at a) u=7.7 m/s (—).,b) u=9.24 m/s (— —).

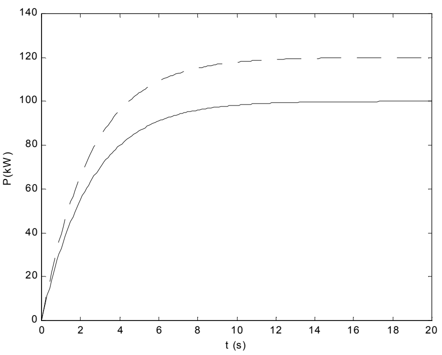


Fig. 4. Power generated at a) u=7.7 m/s (—)., b) u=9.24 m/s (— —).

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

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

where the parameter β is given by

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

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

$$\dot{z}_1 = -C_1 \cdot z_1 + a \cdot z_2 + \tilde{b} \cdot w + c \cdot \int_0^\tau w \cdot d\tau + \tilde{d} \cdot w^2 \quad (38.a)$$

$$\dot{z}_2 = -a \cdot z_1 - C_2 \cdot z_2 + \tilde{b} \cdot \beta \cdot w + \beta \cdot \tilde{c} \cdot \int_0^\tau w \cdot d\tau + \tilde{d} \cdot \beta \cdot w^2 + \tilde{e} \cdot I_f \quad (38.b)$$

The equation (1) it shows that at the point of maximum power operation , the speed of turn of the turbine is proportional to the speed of the wind. The control strategy for the pursuit of the maximum power is based in obtaining an adequate turn speed. In the turbine analysed this value is 13.1947 rev/min, with a nominal wind speed of 7.7 m/s, an optimal coefficient of performance C_p=0.375 and an optimal tip speed ratio of 3.3155.
The strategy of control system designed in this paper should be able to maintain this speed for variations in the speed of the wind upper than 20% to the speed of the nominal wind, likewise should be capable of determining the values of the parameters that are subject to uncertainties. The system's optimisation can be carry out either without a specific criteria or with a specific criteria according to the specifications demanded for the control. Among the multiple optimisation criteria have be chosen the integral of the square of the error (ISE), integral of the absolute value of error (IAE) , integral of time-weighted absolute error (ITAE) 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.
For upper speeds to the nominal one the turbine should work to constant speed with the purpose of limiting the maximum power. This control is carried out by the control of the pitch angle.
For lower speeds to the nominal one the system of control of the speed should follow the curve of maximum power.
The simulation results are indicated in Figures 5-8, and the absolute errors committed by the identification algorithm are showed in Table 1 (when a specific criteria is no applied).
The whole results, the regulator constants and the cost indexes with the several criteria that can be utilised are indicated in Table 2.

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 rotor speed of an synchronous generator and the consequent angular speed of the rotor blades when a disturbance in the wind speed appears . The identification algorithm also is capable of determining the actual values of the wind generator system.

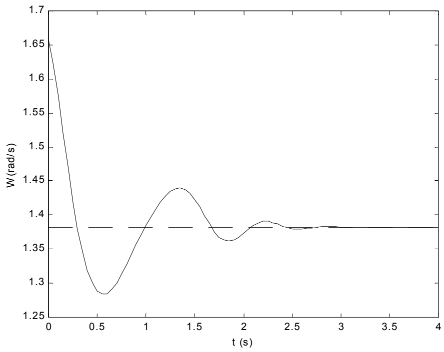


Fig.5.Temporal variation of the rotor speed. Its initial value is 1.65809 rad/s when the wind speed is u=9.24 m/s with a set-point value 1.38174 rad/s.

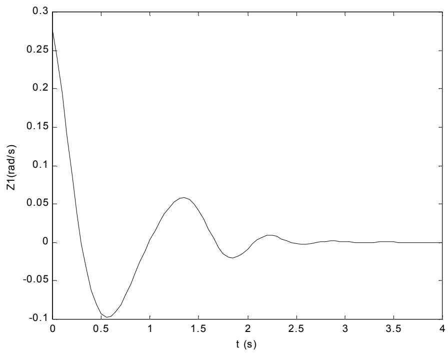


Fig. 6. Temporal variation of the z_1 variable.

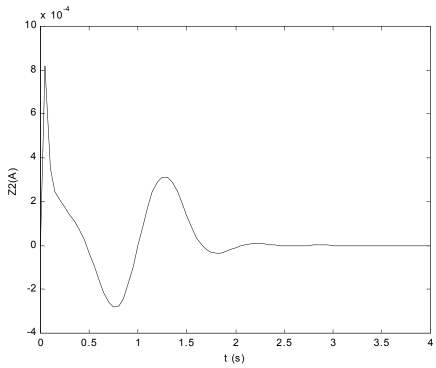


Fig. 7. Temporal variation of the z_2 variable.

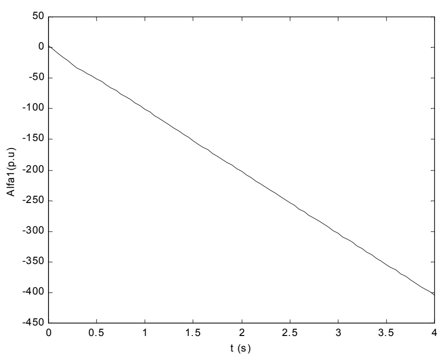


Fig.8. Variation of the stabilizing function (18).

Table 1.

Parameter	Real value(p.u)	Absolute error(p.u)
b	-3.23699	$1.99 \cdot 10^{-2}$
c	-4675.65	$3.66 \cdot 10^{-2}$
d	2802.11	10^{-1}
e	-390.977	$1.21 \cdot 10^{-3}$

Table 2. Values of the cost indexes and the constants of the nonlinear controller in p.u.

Criteria	Cost	C_1	C2	Γ
ISE	7.63312	6916	60826	0.18
IAE	5.52871	129	104689	0.46
IAET	11.1924	47	113554	1.20

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