Research Article GU J Sci 32(2): 509-522 (2019)

Gazi University

Journal of Science

http://dergipark.gov.tr/gujs

Dynamic Analysis of Turbo-Wind Generators and Real-Time Control Using Weighted Adaptive Method Considering Uncertainties

Akbar YAZDANI[1*], Vahid BEHJAT[2], Mojtaba SHARIFZADEH[3]

[1]*Thermal power plant Research Center, Tabriz, Iran*

[2]*Electrical Engineering Department, Engineering Faculty Azarbaijan Shahid Madani University, Tabriz, Iran*

[3]*Department of Industrial Engineering, University of Salerno, Salerno-Fisciano, Italy*

Article Info

Received: 13/06/2018
Accepted: 17/12/2018

Keywords

Stability
Real-time control
Turbine dynamics
Modeling
Control design

Abstract

Variable speed turbo-generator control systems are considered as challenging issues for engineers. Some of these issues are type of machines to be used, location assessment, pitch angle control and maximum power extraction. Almost all of these issues are facing a common problem which is changing in wind speed affects power delivered to the network. There is a novel idea in active control of wind turbine which has been developed to obtain maximum utilization of energy. In this study, adaptive BACK-STEPPING control laws were designed and implemented for variable speed turbo-wind generator. In order to consider adaptability of the method, final coefficients of the control system were considered to be weighted and stability is shown in simulation results. The back-stepping method allows for the design of adaptive control with the return process, and it can simultaneously regulate the stability of the closed loop system at the same time as design the control law. The addition of uncertainties to the problem in the form of specific coefficients due to the present of uncertainties due to the electrical and mechanical parameters. In the following, the designed method is simulated in MATLAB and SIMULINK. Simulation results show favorability and effectiveness of the proposed method.

1. INTRODUCTION

Variable speed wind turbine systems are able to deliver maximum energy production. However, some uncertainties of dynamics and electrical issues affect this capability, but they have been improved to obtain maximum energy utilization. Introduces an experimental setup for the study of different types of electrical generators and their feasibility for different conditions [1]. There are different methods to implement a real-time control strategy for these dynamics [2,3,4]. In [5] a synchronous generator is used and speed of the turbine is kept close to generator speed using rise angle of blades. In [6] control laws are used to control excitation voltage of synchronous generator and firing angle of a THYRISTOR. In recent years, inductive generators have been used more in wind energy converters which is due to their higher reliability and lower cost [6,7]. In [8] nonlinear control is applied to the converter. Using this method, the system tracks wind fluctuations better. In [9] active power and flux control are studied in inductive generators instead of synchronous generators. In [10] a revolution is developed in the performance of wind turbine through considering a new strategy. Realization of wind generators has changed and control techniques are used. In [11] two control methods have been proposed; one is used to control accuracy of the system model and the other one is used to track rotor's speed. In [12] nonlinear control is presented with a different and real structure. Researches in this context are still being done and novel methods are proposed to add a feature to the problem [13,14]. Another problem which has attracted attention recently is to consider the uncertainty of the problem [15]. This feature is being studied in this paper. An example of an adaptive back-stepping method with the mentioned capability is proposed in a same system [16].

*Corresponding author, e.a.yazdani@gmail.com

2. PROBLEM FORMULATION

Power of the turbine generated (w) by wind is described as follows:

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

Where ρ (kg/m^3) is wind density, R is the radius of the rotor (m), u is wind speed (m/s), C_p is power coefficient of the wind turbine, λ is speed coefficient and β is pitch angle (deg). By defining k_w as below, we have:

$$k_\omega = \frac{1}{2} C_p \rho \pi \frac{R^5}{\lambda^3}. \tag{2}$$

Where the following equation is obtained:

$$P_m(\omega) = \mathrm{k}_w \, \omega^3. \tag{3}$$

By considering figure 1 and defining T_m = Shaft torque (Nm) at the end, T_e = Generator torque (Nm) at the end and T = Torque before gearbox (Nm) and T_p = Torque after gearbox (Nm), we have the following:

$$T_m - T = J_m \dot{\omega} + B_m \omega + K_m \theta, \tag{4}$$

$$T_p - T_e = J_e \dot{\omega}_e B_e \omega_e + \mathrm{K}_e \, \theta_e, \tag{5}$$

$$T_p \omega_e = T \omega, \tag{6}$$

Such that B_m, K_m are friction coefficients and B_e, K_e are pitch coefficients. By $\gamma \triangleq \frac{\omega_e}{\omega}$ defining, we have:

$$J \dot{\omega} + B\omega + K \int_0^t \omega(\tau) \, \mathrm{d}\tau = T_m - \gamma T_e,$$

(7)

Or equivalently:

$$J \dot{\omega} + B\omega + K\theta = \frac{P_m}{\omega} - \gamma \frac{P_e}{\omega_e}, \tag{8}$$

Such that P_m (w) is wind power and P_e (w) is electrical power; ω and $\dot{\omega}$ are the angular velocity of shaft (rad/s) and time derivative of angular speed of shaft at the end of the turbine; ω_e is the angular speed of the generator (rad/s) and J is inertia of coupled turbine-generator, where its relation is as follows:

$$\begin{cases} J = J_m + \gamma^2 J_e \\ B = B_m + \gamma^2 B_e \\ K = K_m + \gamma K_e \end{cases} \tag{9}$$

In which, J_m and J_e are inertia of turbine and generator, respectively. Similarly, B and K are total friction of coupling and total rotation of coupling which are defined as mentioned through considering variables B_m, B_e for the turbine and K_m, K_e for the generator. Electrical power can be described as

$$P_e = K_\phi \omega_e c(I_f) \tag{10}$$

$$T_m = k_w.\omega^2, \tag{11}$$

$$T_e = k_\phi.c(I_f), \tag{12}$$

where k_w is a parameter of transmitting power to wind's speed. Machine's constant is k_ϕ and $c(I_f)$ in the internal function of the generator and I_f is its field current (mA). Since direct impact of factors like wind speed, wind density variations, pitch angle and radius of rotor has made parameters and dynamic relation more complicated, control computations of the problem has become more difficult; therefore, all parameters are represented as k_w it is clear that considering this possibility, the proposed control system is able to analyze advanced systems. The overview of wind turbine-generator system shown in figure 1.

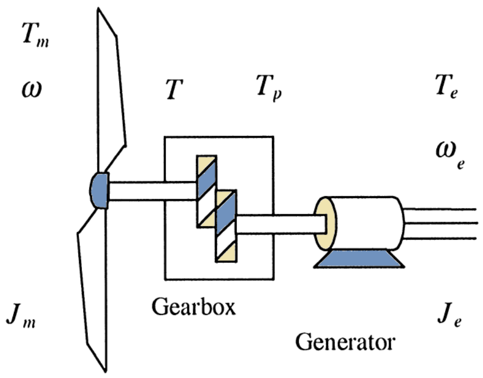

Figure 1. *Schematic of wind turbine generator*

By applying (11) and (12) in the initial equation of the problem (7), the following dynamic form for angular speed is obtained:

$$J\dot{\omega} + B\omega - k_w\omega^2 + K\int_0^t \omega(\tau)d\tau = -\frac{\omega_e}{\omega}K_\phi c(I_f). \tag{13}$$

The electrical sub-system of wind turbo generator as the following linear equation is considered.

$$u_f = L\dot{I}_f + R_f I_f, \tag{14}$$

where, L is inductance constant (H) and R_f is field resistance (Ω) of the rotor and u_f is field voltage (V) shown in Figure 2.

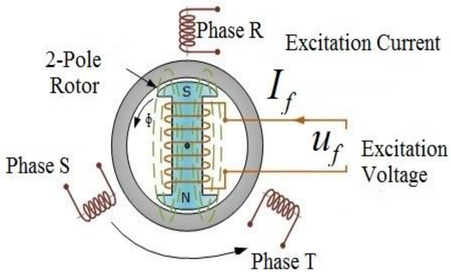

***Figure 2**. Electrical system of turbo generators*

The idea of solving the problem is to supply the field voltage, so that the angular velocity of the turbine end shaft ω (rad/s) can track the ω_d (rad/s) reference angular velocity. The required condition for ω_d (rad/s), definition, control and stability analysis is a first order integrity capacity as follows:

$$\int_0^T |\,\omega_d(\tau)\,|\,\mathrm{d}\tau < \infty\,. \tag{15}$$

3. DESIGN AND IMPLEMENTATION OF CONTROL LAWS ON THE SYSTEM

In order to test control results, angular speed tracking error $e(t)$ is defined as follows [17]

$$e = \omega_d - \omega\,. \tag{16}$$

By differentiating $e(t)$ and multiplying it by the inertia of coupling system and employing 13, the following is obtained:

$$J\dot{e} = J\dot{\omega}_d + B\omega + K\int_0^t \omega(\tau)d\tau - k_w\omega^2 + \gamma K_\phi c(I_f), \tag{17}$$

By defining a desired dynamic function $f_d(\dot{\omega}(t), \omega(t))$, as following form:

$$f_d = J\dot{\omega}_d + B\omega_d - k_w{\omega_d}^2 + K\int_0^t \omega_d(\tau)d\tau, \tag{18}$$

Finally, by applying the auxiliary sentence above in equation 17 we get the following equation.

$$J\dot{e} = \Omega + f_d - K\int_0^t e(\tau)d\tau + \gamma K_\phi c(I_f),2 \tag{19}$$

Such that in the above equation Ω is defined as follows:

$$\Omega = B(\omega - \omega_d) - \mathrm{k}_w(\omega^2 - \omega_d^2). \tag{20}$$

Final equation (19) of the closed-loop dynamic of tracking error is proposed; thus, the adaptive nonlinear control method can be applied to it.

3.1. Remark 1

The auxiliary term defined in (18) can be considered as multiplication of regression vector by uncertain parameters' vector as follows:

$$f_d = W_d \theta, \tag{21}$$

In which, regression vector $W_d \in \mathbb{R}^{1\times4}$ and uncertain constant parameters vector $\theta \in \mathbb{R}^{4\times1}$ are defined as follows:

$$\begin{cases} W_d = \begin{bmatrix} \dot{\omega}_d & \omega_d & \int_0^t \omega_d(\tau)d\tau & -\omega_d^{\ 2} \end{bmatrix}, \\ \theta = \begin{bmatrix} J & B & K & k_\omega \end{bmatrix}^T, \end{cases} \tag{22}$$

3.2. Remark 2

Considering the structure of equation (20), an upper bound as follows:

$$\|\Omega\| \le \zeta_B |\omega_d - \omega| + \zeta_K |\omega_d - \omega| |\omega_d + \omega|, \tag{23}$$

In which, ζ_B and ζ_K are positive bound coefficients for variables. And $\|\,.\,\|, B, k_w$ are the standard norms. By employing a definition of tracking error and algebraic equations, equation (23) can be converted to the following bounded form:

$$\|\Omega\| \le \rho(\|\mathrm{e}\|)\|\mathrm{e}\|, \tag{24}$$

In which $\rho(.)$ is a positive function as follows:

$$\rho = \zeta_K \|e\| + (\zeta_B + 2\zeta_d \zeta_K), \tag{25}$$

In which ζ_d is the upper vector bound of ω_d (rad/s) as a reference signal. Bound defined in equation (20) is employed in the following to obtain stability results.

4. IMPLEMENTING THE BACK-STEPPING METHOD

By employing the back-stepping method [17] in equation (17), equation (19) can be written as follows:

$$J\dot{e} = \Omega + f_d - K\int_0^t e(\tau)d\tau + z + \alpha \tag{26}$$

In which $\alpha(t)$ is auxiliary control variable and $z(t)$ is the back-stepping auxiliary variable defined as follows:

$$z \triangleq \gamma K_\phi c(I_f) - \alpha. \tag{27}$$

Auxiliary control variable $\alpha(t)$ in the following form is considered:

$$\alpha = -k_0 e - W_d \hat{\theta} - k_n \rho^2 e, \tag{28}$$

Where ρ is defined in equation (25); k_0 and k_n are positive control gain coefficients; regression vector $W_d \in \mathbb{R}^{1\times 4}$ is defined as in equation (22) and dynamic estimation parameter vector $\theta \in \mathbb{R}^{4\times 1}$ is updated using the following equation:

$$\dot{\hat{\theta}} = \Gamma_\theta W_d^T e, \tag{29}$$

Where $\Gamma_\theta \in \mathbb{R}^{4\times 4}$ is the positive definite diagonal gain Matrix. After applying equation (28) in equation 26, closed-loop dynamic $e(t)$ is obtained as follows:

$$J\dot{e} = -k_0 e - K\int_0^t e(\tau)d\tau + \lim_{x\to\infty} W_d \tilde{\theta} + \Omega - k_n \rho^2 e + z, \tag{30}$$

In which $\tilde{\theta} = \hat{\theta} - \hat{\theta}$ is parametric estimation error for the mechanical subsystem. Equation (27) is differentiated and multiplied by L inductance (H):

$$L\dot{z} = \gamma K_\phi \frac{\partial c(I_f)}{\partial I_f} L\dot{I}_f - L\dot{\alpha}. \tag{31}$$

By applying equations (28) and (14) in the above equations, we have:

$$L\dot{z} = \gamma K_\phi \frac{\partial c(I_f)}{\partial I_f}(u_f - R_f I_f) + L((k_0 + k_n \rho^2)\dot{e} + \dot{W}_d \dot{\hat{\theta}} + W_d \hat{\theta}), \tag{32}$$

By applying $\dot{e}$ from equation (17) and applying changes, an equation is obtained as follows:

$$L\dot{z} = \gamma K_\phi \frac{\partial c(I_f)}{\partial I_f} u_f + Y\phi, \tag{33}$$

Where $Y(\dot{\omega}_d, \omega, \mathrm{I}_f) \in \mathbb{R}^{1\times 6}$ is regression vector including functions with definite signal variables while $\phi \in \mathbb{R}^{1\times 6}$ is electrical and mechanical uncertain unknown parameter vector. Considering results and structure of equations (33) and (30), field voltage u_f (V) is obtained as follows:

$$u_f = \frac{1}{\gamma K_\phi (\partial (C(I_f)) / \partial I_f)}(-k_z z - e - Y\hat{\phi}), \tag{34}$$

Such that K_Z is positive control gain, regression vector $Y(\dot{\omega}_d, \omega, \mathrm{I}_f) \in \mathbb{R}^{1\times 6}$ is defined before and $\hat{\phi} \in \mathbb{R}^{6\times 1}$ is similar to the definition of $\hat{\theta}$ which includes dynamic unknown estimation parameters obtained as follows:

$$\dot{\hat{\phi}} = \Gamma_\phi Y^T z, \tag{35}$$

In which $\Gamma_{\phi} \in \mathbb{R}^{6\times 6}$ is the positive definite diagonal gain matrix. By substituting equation (34) in equation 33, closed-loop dynamic for the back-stepping variable z is obtained as follows [17].

$$L\dot{z} = -k_z z + Y\tilde{\phi} - e, \tag{36}$$

Such that $\tilde{\phi} = \phi - \hat{\phi}$ is internal parametric estimation error.

4.1. Convergence of the Designed Control Method

Convergence of dynamic error to zero can be seen in simulation results. But this convergence can be proved mathematically for this a LYAPUNOV function among these functions is considered; a non-negative LYAPUNOV function which has negative derivative should be found [18,19].

4.2. Theorem

Adaptive controller (34) and auxiliary input (28) guarantee accurate tracking of angular speed for a variable speed wind turbine with dynamic (35) and sub-system (29) considering parametric update laws of equations (17) and (14). [17,19].

$$\lim_{x\to\infty} e(t) = 0. \tag{37}$$

In order to prove the above relation, we start with defining a nonnegative scalar function as follows:

$$V = \frac{1}{2}(Je^2 + Lz^2 + K\xi^2 + \tilde{\theta}^T \Gamma_{\theta}^{-1}\tilde{\theta} + \tilde{\phi}^T \Gamma_{\phi}^{-1}\tilde{\phi}), \tag{38}$$

where ξ is defined as:

$$\xi \triangleq \int_0^t e(\tau)d\tau \tag{39}$$

After differentiating the function of (38) with respect to time and using equations (29), (30), (35) and (36), finally the differentiated function is represented as follows:

$$\dot{V} = -k_0 e^2 - k_z z^2 + [\Omega - k_n \rho^2 e]e, \tag{40}$$

By adding and subtracting $\|\mathrm{e}\|^2 / 4k_n$, and completing square root of the bracket, the LYAPUNOV derivative is converted to the following form:

$$\dot{V} \le -\left(k_0 - \frac{1}{4k_n}\right)\|\mathrm{e}\|^2 - k_z \|\mathrm{z}\|^2 \quad \le -\min\left\{\left(k_0 - \frac{1}{4k_n}\right), k_z\right\}\|\mathrm{x}\|^2, \tag{41}$$

In which, $x \in \mathbb{R}^{2\times 1}$ is defined as follows:

$$x = [e^T \quad z^T]^T. \tag{42}$$

Now, considering the above equation and equation (38), if k_n is a large value, function derivative would be negative, thus the error of all closed-loop signals would be limited and convergent to zero. Equation (43) is the final designed control law to track reference angular speed applied to the above design.

$$u_f = \frac{1}{\gamma K_\phi (\partial (C(I_f)) / \partial I_f)} (-k_z z - e - Y\hat{\phi}), \tag{43}$$

Control gain values are selected as follows:

$(k_0 = 50)$, $(k_z = 2.5)$, $(k_n = 50)$, $(\rho = 15)$

5. SIMULATION

Simulation is performed in MATLAB/SIMULINK R2013 a with B970 processor. Sampling time is selected 0.001 (s). The correlation time of the noise is chosen as $6.28*10^{-4}$.

5.1. Simulation Results

The differential equation are solved in Simulink using ODE3 and ODE45 methods. The excitation current coefficients c is selected equal 1000. Parameters of Table 1 are used in simulation [11].

Table 1. *Simulation parameter values*

Unit	Value	Parameter
Ω	0.2	R_f
H	0.01	L
kgm^3	24490	J
V	480	V_L
-	$1000I_f$	$C(I_f)$
Hz	60	f
-	3	K_ω
-	52	B
-	52	K
-	17	k_ϕ

Figures 3 and 4 show dynamic analysis results of wind turbo-generator which include voltage and current; the current of output field of the electrical subsystem which determines angular speed of turbine's output shaft and a function with a high factor

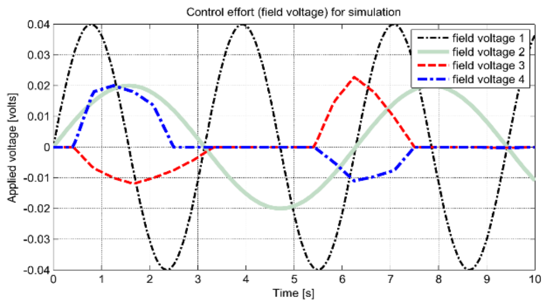

Figure 3. *Different values of the excitation voltage used as input of the problem*

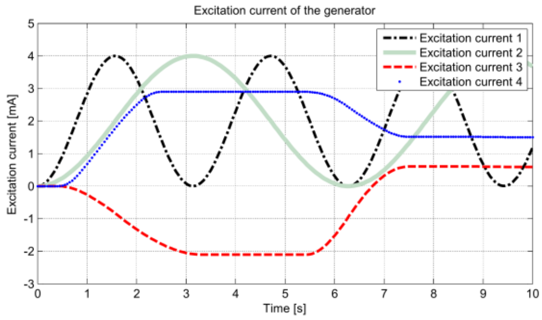

Figure 4*. Excitation current for different voltage inputs*

Results of shaft speed output are shown in Figure 5 for different values of control inputs.

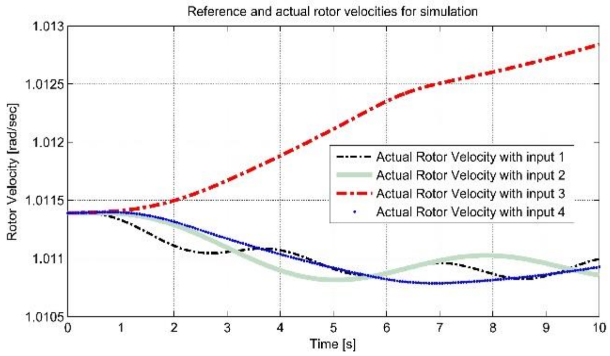

Figure 5. *Results of the rotor angular velocity for different input voltages*

By applying proper field voltage, desired angular speed is expected; this feature is used to design a suitable control system. In the following and considering reference angular speed for the turbine, control voltage value is applied as Figure 6 to the system.

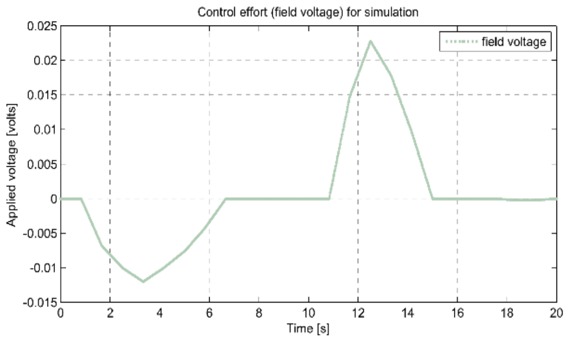

Figure 6*. Control voltage designed by the controller*

The proportional current is shown in Figure 7.

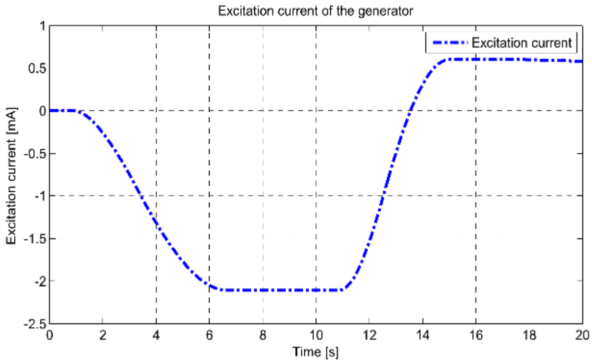

Figure 7. *The result excitation current simulation*

Due to the direct interference of factors such as wind speed, wind density changes and rotor radius, therefore these parameters are calculated and represented in the form of the k_w coefficient. The uncertainties in the coefficients, include the uncertainties of the friction and mechanical components of system and uncertainty of the structure of the power transmission coefficient and the uncertainty considered for the structure of the problem of torsion coefficient and the electrical parts of the system. To apply these, white Gaussian noise with zero mean and limited variance is added to B, K_{ω}, K input [20]. Figures 8, 9 and 10 represent applied changes.

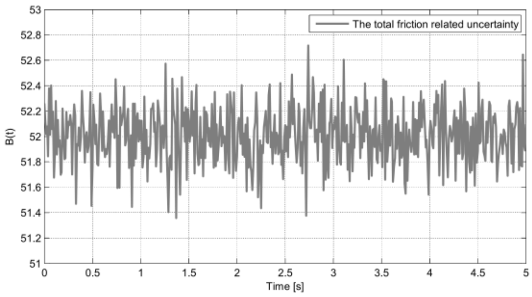

Figure 8. *Uncertainties of the friction and related to the mechanical part*

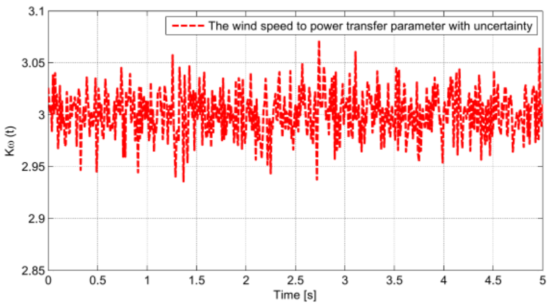

Figure 9. *Uncertainties of the power transfer coefficient*

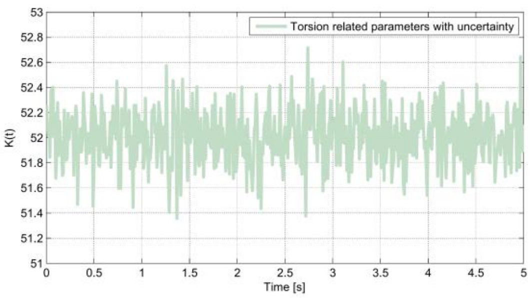

Figure 10. *Uncertainties of the torsion and related to the electrical part*

It can be seen in Figure 11 that angular speed obtained using control and estimation system, tracks reference speed very well. As it can be seen, the convergence speed of this method is desirable and its accuracy is high despite the existence of uncertainties. One of the advantage of this technique is its adaptability. Another advantage is handling nonlinear factors, since a flexible procedure is proposed.

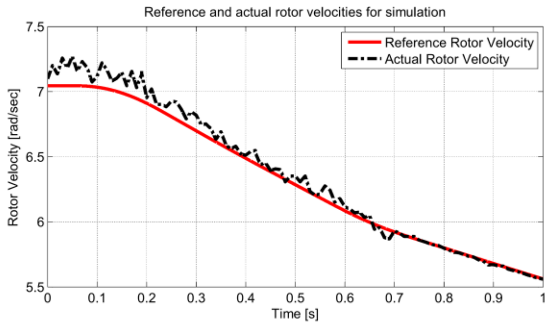

Figure 11. *The angular velocity reference and the angular velocity result*

In Figure 12, tracking error of reference speed is shown. It can be seen that error has decreased gradually. It should be mentioned that results are obtained for other different cases and convergence to zero is desirable for all convergence cases.

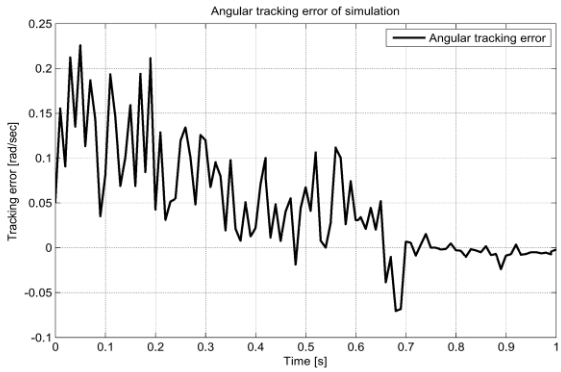

Figure 12. *Tracking error of rotor angular velocity reference*

In order to test the control method, the process is presented again for different inputs and result are shown in Figure 13. In the second simulation to avoid repetition, the result of uncertainties has not been repeated.

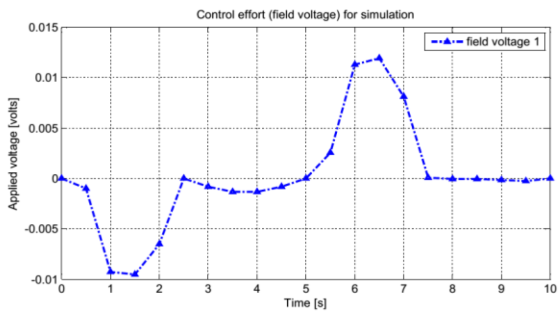

Figure 13. *Control voltage designed by the controller*

As it is shown on the Figure 14, the result of the simulated excitation current is related to the design voltage of the second reference.

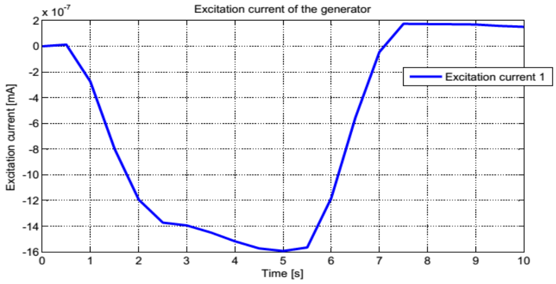

Figure 14. *The result of the simulated excitation current*

As shown in Figure 15, the angular velocity result from the estimation system accurately tracking the reference speed and has a high accuracy. It is observe that the error decreases and eventually converges to zero after 0.7 (s).

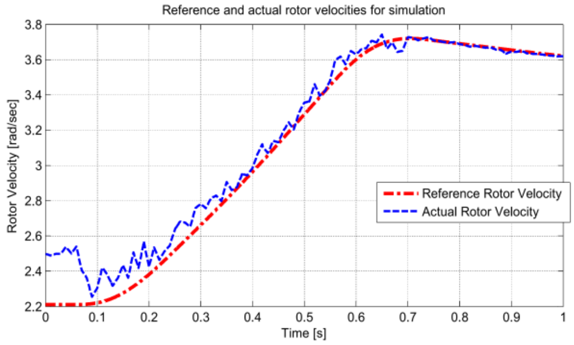

Figure 15. *The angular reference velocity and the angular velocity result*

In Figure 16, tracking error of second reference speed is shown. It is expected that by adding uncertainties to the system which makes conditions more practical and real, the designed controller can obtain desired convergence and tend towards zero in the shortest time.

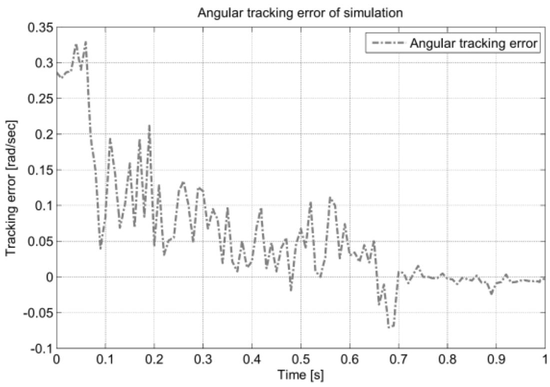

Figure 16. *Tracking error of the second rotor angular velocity reference*

As shown in Figure 17 the general objective of problem control was to supply a field voltage so that the ω (rad/s) angular velocity of the turbine's ending shaft can track the ω_d (rad/s) angular velocity reference. Where, $e = \omega_d - \omega$ define angular velocity tracking error.

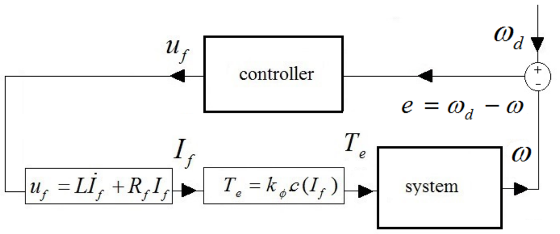

Figure 17. *Total dynamic of the plan*

The dynamic formulation of the problem indicates that adaptive back-stepping method can be better option for the control purpose. The reason for this is that the method is stable against uncertainties and on the other hand, against alternation and unplanted various, this dynamics are also adaptable and convergent.

7. CONCLUSION

In order to control the wind turbine at variable speeds, the control procedure was designed and implemented so that it could follow the reference input of turbine shaft. As result, the tracking error was negligible and convergence speed was desirable. In this study that adaptive back-stepping control laws were designed and implemented for variable speed wind turbo-generator. Final coefficients of the control system were weighted and their adaptability was shown in simulation result. It was obvious that by applying a suitable control voltage, the system could track reference speed, so the current and generated power were available, therefore the efficiency of the system would increase. Considering the obtained result, it can be declared that compared to previous methods, the proposed method, has higher flexibility. As shown in simulation result, the system has obtained desirable performance and robustness against uncertainties of the structure.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

REFERENCES

[1] Babu, S., Loganathan, A.k., Vairavasundaram, I., "Optimizing Electrical Generators of Wind Energy Conversion System for Efficient Power Extraction," Gazi University Journal of Science, 31:(4), 1141-1154, (2018).

[2] Güneş, H., Kunt, M.A., "Control unit design for a pneumatic engine working with an electromagnetic valve and its effect on the performance of the engine," Journal of the Faculty of Engineering and Architecture of Gazi University, 31:(1), 1-8, **(**2016)**.**

[3] Özkan, B., "Implementation of the sliding mode control method with a varying sliding surface on an electromechanical fin actuation system," Journal of the Faculty of Engineering and Architecture of Gazi University, 32:(3), 987-998, (2017).

[4] Kiyak, E. and Ermeydan, A., "Fault tolerant flight control system design to a rotary wing aircraft," Journal of the Faculty of Engineering and Architecture of Gazi University, 32(1), 21-34. doi: 10. 17341/ gazimmfd. 300591, (2017).

[5] Winkelman, J.R. and Javid, S.H., "Control design and performance analysis of a 6MW wind turbine generator," IEEE Trans on PAS, Vol. 102, No. 5: 1340-1347. May, (1983).

[6] Chedid, R. and Morad, F. and Basm, M., "Intelligent Control of a Class of Wind Energy Conversion Systems," IEEE Trans on energy conversion, Vol. 14, No. 4, Dec, (2009).

[7] Agnė, B. and Azzopardi, B., "Synergies of Wind Turbine control techniques," Renewable and Sustainable Energy Reviews 45: 336-342, (2015).

[8] Battista, H.D., R., Mantz, R.J., "Sliding mode control of torque ripple in wind energy conversion systems with slip power recovery," IEEE, (2000).

[9] Na, W., Muljadi, E., Leighty, B. and Kim, J., "Active Power and Flux Control of a Self-Excited Induction Generator for a Variable-Speed Wind Turbine Generation," Green Technologies Conference, Ninth Annual IEEE, (2017).

[10] Mahieddine, K.B., Rachedi, A., Bahi, T., Lakel, R. and Grid, A., "Robust Control of Doubly Fed Induction Generator for Wind Turbine under Sub-Synchronous Operation Mode," Elsevier, Energy Procedia 74: 886–899, (2015).

[11] Song, Y. D., Dhinakaran, B. and Bao, X.Y., "Variable speed control of wind turbines using nonlinear and adaptive algorithms," Journal of Wind Engineering and Industrial Aerodynamics 85: (3), 293-308, (2000).

[12] Fernando, B. Battista, D.H. and Mantz, R.J., E-ISBN 1-84628-493-7. Wind turbine control systems principles, modeling and gain scheduling design, Springer Science & Business Media, (2006).

[13] Kyung-Hyun, K., et al., "Maximum output power tracking control in variable-speed wind turbine systems considering rotor inertial power". Industrial Electronics, IEEE Transactions on 60: (8), 3207-3217, (2013).

[14] Peter, O.F., Stoustrup, J. and Kinnaert, M., "Fault-tolerant control of wind turbines A benchmark model". Control Systems Technology, IEEE Transactions on 21:(4),1168-1182, (2013).

[15] Fatao, S., et al., "Adaptive Fuzzy Dynamic Surface Control for Induction Motors via Back-stepping". Proceedings of the 2015 Chinese Intelligent Automation Conference. Springer Berlin Heidelberg, (2015).

[16] Wang J., "Speed-assigned Position Tracking Control of SRM with Adaptive Back-stepping Control". Ieee/Caa Journal Of Automatica Sinica. 10.1109/JAS. 7510019, (2016).

[17] Kokotovic, P.K. and Kanellakopoulos, I., Nonlinear and adaptive control design. John Wiley & Sons, Inc, (1995).

[18] Yang, Z., Su, H. and Krstic, M., "Adaptive back-stepping control of uncertain linear systems under unknown actuator delay." Automatica 54: 256-265, (2015).

[19] Fang, W., Hua, C. and Zong, Q., "Attitude control of reusable launch vehicle in reentry phase with input constraint via robust adaptive back-stepping control." International Journal of Adaptive Control and Signal Processing, (2015).

[20] Sharifzadeh, M., Timpone, F., Senatore, A., Farnam, A., Akbari, A., & Russo, M. (2017). Real time tyre forces estimation for advanced vehicle control. International Journal of Mechanics and Control, 18:(2), 77-84, (2017).