

Analysis and design of wind energy system based on nonlinear speed controller

S. Bellarbi *

Centre de Développement des Energies Renouvelables, CDER
B.P. 62, Route de l'Observatoire, Bouzareah, 16340, Alger, Algérie

(reçu le 25 Juin 2019 - accepté le 30 Juin 2019)

Abstract - This paper presents a control fuzzy robuste strategy for a squirrel cage Induction generator (SCIG)-based wind energy conversion system. Control strategies is presented along with the mathematical modeling of the employed configuration. The maximum power point extraction of the wind turbine is addressed along with the proposed strategy. The approach method is introduced to control the generator speed and regulate the flux. The wind system is then simulated in Matlab-Simulink and the developed model is used to illustrate the behavior of the system. The simulation results are presented and discussed at the end of this paper.

Résumé - Cet article présente une stratégie de contrôle robuste floue pour un système de conversion d'énergie éolienne basé sur un générateur d'induction (SCIG). Les stratégies de contrôle sont présentées avec la modélisation mathématique de la configuration utilisée. L'extraction maximale des points de puissance de l'éolienne est abordée avec la stratégie proposée. La méthode d'approche est introduite pour contrôler la vitesse du générateur et réguler le flux. Le système éolien est ensuite simulé dans Matlab-Simulink et le modèle développé est utilisé pour illustrer le comportement du système. Les résultats de la simulation sont présentés et discutés à la fin de cet article.

Keywords: WECS - SCIG - MPPT - Wind turbine - TS fuzzy controller - Robust controller - Simulation.

1. INTRODUCTION

In recent years, there has been an evolution of wind electrical energy production. This source of energy has developed importantly considering the diversity of the exploitable zones and the relatively beneficial cost.

Now most wind turbines are equipped with a induction generator due to noticeable advantages: the variable speed generation (30 % around the synchronous speed) [1].

It is the reason for which one finds this device for the production in strong power. So, one of the most fundamental problems of the control theory of these systems types is the analysis of robust stability and synthesis of uncertain systems.

Recently [1, 2], the issue of stability of nonlinear systems begin to accrue interest for the researchers, because it can provide an effective solution for controlling complex processes, uncertain, unclear [3]. The robust stability is another important requirement to be considered in the control study of uncertain nonlinear systems [4].

To solve the problem of fuzzy control nonlinear system with uncertain parameters and subject to a disturbance of the wind, a robust controller for all non-linear systems [5] is used. This correspond to that proposed by (Takagi-Sugeno) which is close to the real system [6] models and to the nonlinear system [7].

In this context, many studies related to the control of the induction generator system have been developed over many countries worldwide by researchers [8-18].

* s.bellarbi@cder.dz

In this paper a proposed robust controller design makes it possible to control the wind turbine along the entire nominal operating trajectory using fewer controllers than ordinary robust design methods, while maintaining the required performance [17, 18].

Therefore, the principal goal of the present study is to show that the nonlinear controller with the parameter uncertainties have the better performance and better robustness, endure for wind turbine system stability under unstable wind circumstances.

The block diagram of a typical wind energy conversion system is shown in figure 1. The transfer of the power produced by wind power system is made by AC/DC converter. That operates as a rectifier [19].

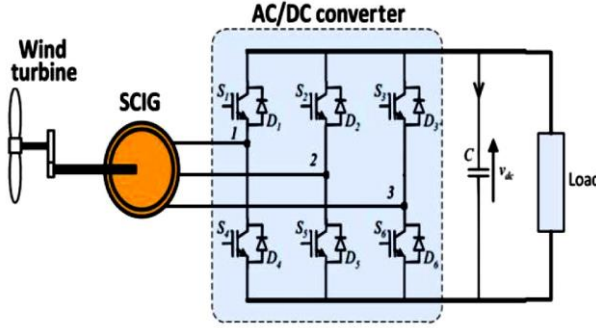


Fig. 1: SCIG-based Wind energy conversion system [19]

2. WIND ENERGY CONVERSION SYSTEM MODELING

2.1 The turbine model

The aerodynamic power P captured by the wind turbine is given by [20]:

$$P_{eol} = \frac{1}{2} \cdot C_p(\beta, \lambda) \cdot \rho \cdot S \cdot V^3 \quad (1)$$

$$\lambda = \frac{R \Omega}{V_V} \quad (2)$$

Where v is the wind, ρ is the air density, R is the rotor radius, C_p is the power coefficient and λ is the ratio of turbine blades tip speed to wind speed. Figure 2 illustrate generator power as a function of speed for different wind speeds.

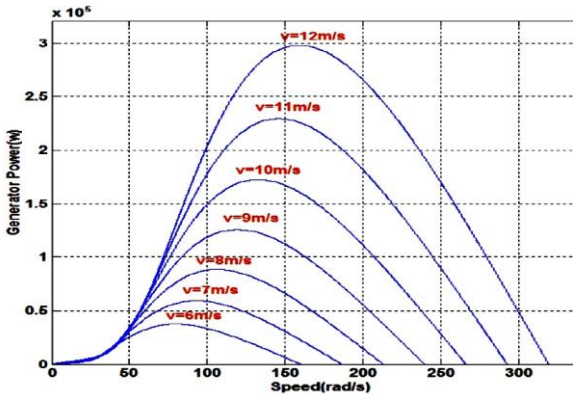


Fig. 2: Output power for different values of wind speed [21]

2.2 The SCIG model

The squirrel cage Induction generator voltages of the windings of the stator and the rotor according to the d-q axes are given by the following relations [22]

$$\begin{cases} V_{sd} = R_s i_{sd} + \frac{d\phi_{sd}}{dt} - \omega_s i_{sq} \\ V_{sq} = R_s i_{sq} + \frac{d\phi_{sq}}{dt} - \omega_s i_{sd} \\ V_{rd} = 0 = R_r i_{rd} + \frac{d\phi_{rd}}{dt} - \omega_r i_{rq} \\ V_{rq} = 0 = R_r i_{rq} + \frac{d\phi_{rq}}{dt} - \omega_r i_{rd} \end{cases} \quad (3)$$

The electromagnetic torque is given by the following relation,

$$T_{em} = P \times M(\Phi_{sq} \cdot i_{rd} - \Phi_{sd} \cdot i_{rq}) / L_s \quad (4)$$

The active and reactive stator powers are expressed by,

$$\begin{cases} P_s = V_{sd} I_{sd} + V_{sq} I_{sq} \\ Q_s = V_{sq} I_{sd} + V_{sd} I_{sq} \end{cases} \quad (5)$$

2.3 Fuzzy Takagi-Sugeno model

To achieve the wind energy maximum power point tracking (MPPT) control, we have to drive the DC voltage to follow the maximum power point voltage [23]. First, due to the fact that the SCIG is viewed as a current source, only the dynamics of the buck converter is considered and expressed in T-S fuzzy rules, the buck converter is described by the following T-S fuzzy [24],

$$\begin{aligned} \dot{x}(t) &= A(x).x(t) + Bu(t) \\ y(t) &= C(x).x(t) \end{aligned} \quad (6)$$

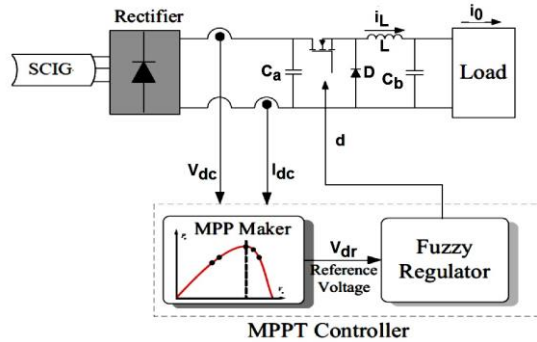


Fig. 3: Fuzzy control system [25]

for the state and input vector respectively, the SCIG state model can be presented as a eight-order model [25]

$$\begin{cases} \dot{x}_1 = a_1(x_2 \cdot x_3 - x_7 \cdot x_4) - a_2 \cdot x_1 - a_3 \cdot x_8 \\ \dot{x}_2 = -a_4 \cdot x_2 - a_5 \cdot x_4 + a_5 \cdot x_7 - a_7 \cdot x_1 \cdot x_3 + a_8 \cdot x_6 \\ \dot{x}_3 = -a_9 \cdot x_4 - a_{10} \cdot x_3 + a_5 \cdot x_7 - a_{11} \cdot x_1 \cdot x_7 \\ \dot{x}_4 = -a_4 \cdot x_4 + a_5 \cdot x_2 + a_6 \cdot x_3 + a_7 \cdot x_1 \cdot x_7 + a_8 \cdot x_5 \end{cases} \quad (7)$$

Where,

$$a_1 = \frac{P.M}{J.L_r}, a_2 = \frac{f}{J}, a_3 = \frac{1}{J}, a_4 = \frac{L_r^2.R_s + L_m^2.R_s}{\sigma.L_s.L_r^2}, a_5 = 1$$

$$a_6 = \frac{R_r.M}{\sigma.L_s.L_r^2}, a_7 = \frac{R_r.P}{\sigma.L_s.L_r^2}, a_8 = \frac{1}{\sigma.L_s}$$

$$a_9 = \frac{R_r.M}{L_s}, a_{10} = \frac{R_r}{L_s}, a_{10} = P$$

and,

$$x_1 = \omega_m; x_2 = i_{sd}, x_3 = \phi_{rd}, x_4 = i_{sd}$$

$$x_5 = V_{sd}, x_6 = V_{sq}, x_7 = \phi_{rq}, x_8 = T_m$$

Controls the electromagnetic torque and rotor direct flux will be obtained by controlling the d-q axes stator currents of the SCIG.

By choosing the two-phase d-q related to rotating rotor field, and placing the rotor flux vector on the d-axis, we have $\phi_{rd} = \phi_r = \phi_r$ and $\phi_{rq} = 0$. In this case, the model (7) becomes:

$$\begin{cases} \dot{x}_1 = a_1.x_2.x_3 - a_2.x_1 - a_3.x_8 \\ \dot{x}_2 = -a_4.x_2 - a_5.x_4 - a_7.x_1.x_3 + a_8.x_6 \\ \dot{x}_3 = -a_9.x_4 - a_{10}.x_3 \\ \dot{x}_4 = -a_4.x_4 + a_5.x_2 + a_6.x_3 + a_8.x_5 \end{cases} \quad (8)$$

4. RESULTS AND DISCUSSION

Simulations were performed in Matlab using the nonlinear model.

Figure 4 shows the wind profile applied to the wind turbine. Figure 5 show the rotational speed the wind turbine. Figure 6 show the power profile of the wind turbine. Figure 7 show the power coefficient.

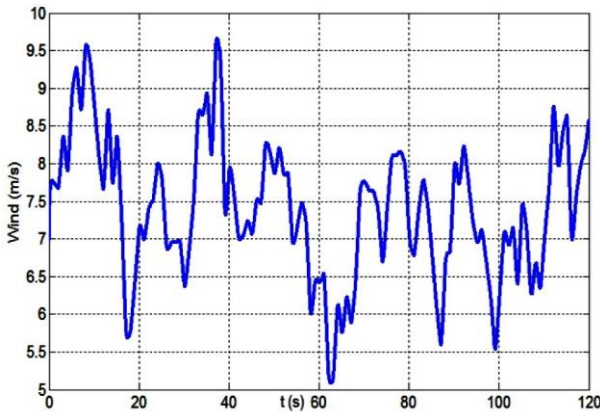


Fig. 4: Wind speed profile

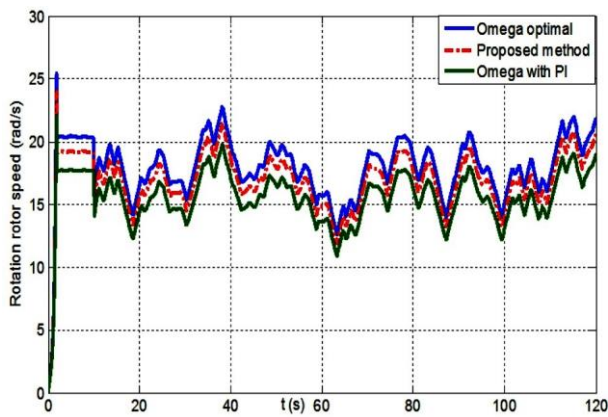


Fig. 5: Rotation speed profile (with three cases)

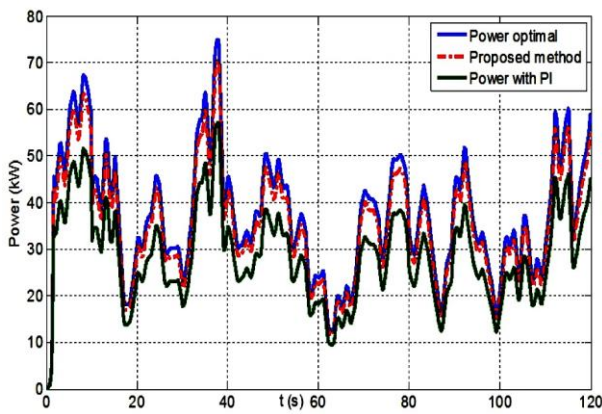


Fig. 6: Wind turbine power profile (with three cases)

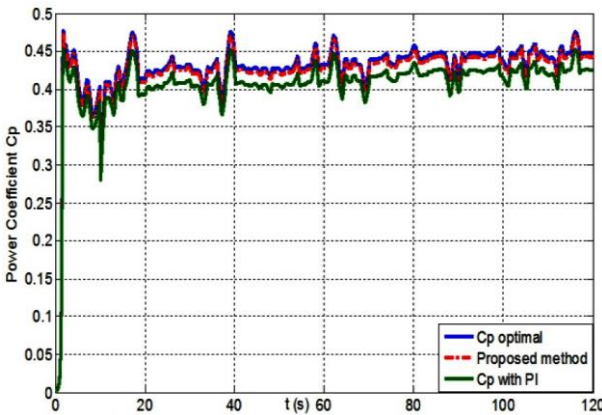


Fig. 7: Power coefficient profile (with three cases).

In summary results, we can be seen that the system trajectory follows the trajectory of the reference input. Thus, the TS fuzzy model based controller is robust against norm bounded parametric uncertainties, and wind disturbance.

Comparing the results of the proposed algorithm with those given by the previous algorithms, it can be noticed that the proposed controller has the following advantages:

- Control of the plant over a wide range of wind speeds;
- Stability over a wide range of uncertainties;
- Increased robustness over conventional controllers such as PI.

5. CONCLUSION

In this paper, a mathematical model of an asynchronous machine with variable wind turbine speed model has been proposed and simulated via simulation tool namely: Matlab using controller uses Fuzzy logic systems of Takagi-Sugeno models and operates local systems obtained by linearization around a few operating points.

In this article, the results obtained by the proposed control algorithm concept are well and suitable with that were intended which was shown in the simulation environment. The simulated consequences can be easily visualized in Sec. 3, have a good and stable performance for wind turbine system applications.

According to the simulation results, the control proposed ensured with better efficiency the regulation of the rotational speed of the turbine which allows operation of the wind power system at maximum power and providing a decoupling between the control flux and speed.

REFERENCES

- [1] S.A. El Mehdi Ardjoun and M. Abid, '*Fuzzy sliding mode control applied to a doubly fed induction generator for wind turbines*', Turkish Journal of Electrical Engineering & Computer Sciences, 2015, doi: 10.3906/elk-1404-64.
- [2] E. Kim and S. Kim, '*Stability analysis and synthesis for an affine fuzzy systems via LMI and ILMI: Continuous case*', IEEE Transactions Fuzzy System, Vol. 10, N°3, 2002.
- [3] C. Sloth, T. Esbensen, M.O.K. Niss, '*Robust LMI-based control of wind turbines with parametric uncertainties*', 18th IEEE International Conference Control Applications, Saint Petersburg, Russia, pp. 776 - 781, Jul. 8 -10, 2009..
- [4] K. Tanaka, T. Ikeda, and H.O.Wang, '*Robust stabilization of a class of uncertain nonlinear systems via fuzzy control: Quadratic stabilizability, H_{∞} control theory, and linear matrices inequalities*', IEEE Transactions on Fuzzy System, Vol. 4, N°1, pp. 1 - 13, 1996.
- [5] H.J. Lee, J.B. Park, and G. Chen, '*Robust fuzzy control of nonlinear systems with parametric uncertainties*', IEEE Transactions on Fuzzy System, Vol. 9, N°2, pp. 369 - 379, 2001.
- [6] S.C. Tong and H.H. Li, '*Observer-based robust fuzzy control of nonlinear systems with parametric uncertainties*', Fuzzy Sets and Systems, Vol. 131, N°2, pp. 165 - 184, 2002.
- [7] K.Z. Østergaard, J. Stoustrup, and P. Brath, '*Linear parameter varying control of wind turbines covering both partial load and full load conditions*', International Journal of Robust and Nonlinear Control, Vol. 19, pp. 92 - 116, 2009.
- [8] H.K. Lam and F.H.F. Leung, '*Fuzzy controller with stability and performance rules for nonlinear systems*', Fuzzy Sets and Systems, Vol. 158, N°2, pp. 147 - 163, 2007.

- [9] E. Kamal, A. Aitouche, and M. Bayart, 'Robust fuzzy fault-tolerant control of wind energy conversion systems subject to sensor faults', IEEE Transactions and Sustainable Energy, Vol. 3, N°2, pp. 231 -241, 2012.
- [10] A.M. Kassem, K.M. Hasaneen, and A.M. Yousef, 'Dynamic modeling and robust power control of DFIG driven by wind turbine at infinite grid', International Journal of Electrical Power & Energy Systems, Vol. 44, N°1, pp. 375 - 382, 2013.
- [11] Whei-Min Lin, Chih-Ming Hong, and Fu-Sheng Cheng, 'Fuzzy neural network output maximization control for sensorless wind energy conversion system', Energy, Vol. 35, N°2, pp. 592 - 601, 2010.
- [12] B. Boukezzar, and M'Saad Mohamed, 'Robust sliding mode control of a DFIG variable speed wind turbine for power production optimization', 16th Mediterranean Conference on Control and Automation, IEEE, 2008.
- [13] F. Amrane, A. Chaiba and S. Mekhilef, 'High performances of Grid-connected DFIG based on Direct Power Control with Fixed Switching Frequency via MPPT Strategy using MRAC and Neuro-Fuzzy Control', Journal of Power Technologies, Vol. 96, N°1, pp. 27 - 39, 2016.
- [14] M.H. Baloch, J. Wang and G.S. Kalo. 'Modeling and controller design for wind energy conversion system based on a cage generator using turbulence speed', Journal of Power Technologies, 2016.
- [15] F.D. Bianchi, H. De Battista, and R.J. Mantz, 'Optimal gain-scheduled control of fixed-speed active stall wind turbines', IET Renewable Power Generation, Vol. 2, N°4, pp. 228 - 238, 2008.
- [16] G. Salloum, 'Contribution à la Commande Robuste de la Machine Asynchrone à Double Alimentation', PhD Thesis in Electrical Engineering, Institut National Polytechnique de Toulouse, France, 2007.
- [17] C. Sloth, T. Esbensen and M. Niss, 'Robust LMI-Based Control of Wind Turbines with Parametric Uncertainties', 18th IEEE International Conference on Control Applications, Saint Petersburg, Russia, 2009.
- [18] S. Bellarbi, D. Saheb Koussa and A. Rennane, 'Power Control of a Wind Energy 2015.
- [19] H. Abouobaida and M. Cherkaoui, 'Robust and Efficient Control of Wind Conversion System based on a Squirrel Cage Induction Generator (SCIG)', International Journal of Energy, Information and Communications, Vol. 6, N°1, pp. 11 - 20, pp. 11 - 20, 2015.
- [20] S. Bellarbi, N. Kasbadji-Merzouk, and A. Malek, 'Double-fed Asynchronous Wind Power Generator by Fuzzy Logic', Journal of Physical Science and Applications, Vol. 3, N°6, pp. 366 - 373, 2013.
- [21] A. Sikorski and A. Kuzma, 'Cooperation of induction squirrel-cage generator with grid connected AC/DC/AC converter', Bulletin of the Polish Academy of Sciences Technical Sciences, Vol. 57, N°4, 2009.
- [22] S. Bellarbi, D. Saheb Koussa, 'Fuzzy Robust Control of DFIG with parameter uncertainties', 3rd Euro-Mediterranean Conference on Materials and Renewable Energies, EMCMRE-3', Marrakech, Morocco 2015.

[23] M. Budinger, D. Leray and Y. Deblezer, 'A Fuzzy Logic Controlled Power Electronic System for Variable Speed Wind Energy Conversion Systems', Revue 3EI, N°21, Juin 2000.

NOMENCLATURE

ω_s, ω_r , Stator, rotor angular frequency Ω_g , Mechanical generator speed i_{sd}, i_{rd} , Stator, rotor currents in axis d, R_s, R_r , Stator and rotor resistance, n_b , Gearbox ratio,	N_p , Number of pole pairs V_s , Stator voltage magnitude, i_{sq}, i_{rq} , Stator, rotor currents in axis q, L_s, L_r, L_m , Stator, rotor leakage, and magnetizing inductances
D_r, D_g, D_{ls} , Damping constants for the rotor, generator, the equivalent low-speed shaft, T_g , Time constant of the model, J_r, J_g , Moments of inertia of the rotor and generator.	K_{ls} , Equivalent torsional stiffness of the low-speed shaft, T_h , High-speed shaft torque, $T_g, T_{g,ref}$, Generator torque and required generator torque.

SCIG parameters are:

- $P_n = 75 \text{ kW}$, $V = 690 \text{ V}$ and $f = 50 \text{ Hz}$,
- Stator resistance: $R_s = 0.039 \text{ }\Omega$;
- Rotor resistance: $R_r = 0.022 \text{ }\Omega$;
- Stator inductance: $L_s = 0.017 \text{ H}$;
- Rotor inductance: $L_r = 0.017 \text{ H}$;