Sliding mode robust control of the horizontal wind turbines with model uncertainties

Reza Faraji Nayeh
Department of Mechanical Engineering
Sharif University of Technology
Tehran, Iran
r.farajinayeh@yahoo.com

Hamed Moradi*
Department of Mechanical Engineering
Sharif University of Technology
Tehran, Iran
hamedmoradi@sharif.edu

Gholamreza Vossoughi
Department of Mechanical Engineering
Sharif University of Technology
Tehran, Iran
vossough@sharif.edu

***Abstract*— Wind turbines are generally controlled based on two control objectives: turbine protection and the generation of acceptable power for the grid. In this paper, a robust control strategy is presented for switching between various operating modes of the turbine. The rotor angular speed is hold below the allowable speed in all operation time. It is also attempted to catch a constant power in a desirable amount during the most of operation time. For the elimination of model/environmental uncertainties, sliding mode controllers are used. For the objective of power tracking, the stability of sliding mode controller is proved for a set of sliding surfaces. Advantages and disadvantages of the selected sliding surfaces are discussed. Moreover, some operating conditions of the wind turbine are investigated to evaluate the effectiveness of the proposed control technique. Implementation of the above proposed control law in its related electronic circuit of the wind turbine will be considered as the future stage of the current research.**

Keywords— *Wind turbine; Uncertainties; Sliding mode control; Blade pitch angle; Generator torque; Power output.*

I. INTRODUCTION

Due to economic and environmental reasons, many countries are planning to use various sources of renewable energy. Among the various types of renewable energy, wind and solar equipment have the most installed capacity in the world. Due to technology advancement and reduce of production cost, installed capacity of wind turbines (WTs) has a remarkable growth of 28% from about 6.1 GW in 1990, reached about 238 GW in 2011 [1]. There exist different designs for the wind turbines, but regardless of the wind turbine type, control systems have undeniable role in its performance and protection. Control systems can regulate the rotor angular speed, generated power and grid frequency. In addition, control systems can be profitable in off-design condition, where unpredicted phenomena such noise, stormy winds and uncertainties exist.

Various control approaches have been used for the performance control of WTs. In the early studies, classical P/PI/PID pitch angle controllers based on linearized models of the WT have been implemented [2]. Among other advanced control techniques of this area, variable speed control of WT based on nonlinear and adaptive algorithms [3], Fuzzy [4], nonlinear sliding mode control [5], and a comparison between linear and nonlinear control methods [6] have been carried out. However, in these works, control strategies have acceptable results according to some simplifications and assumptions. But in none of these researchers, a clear logic for controlling of a horizontal wind turbine in off-design conditions is observed.

II. DYNAMICS OF THE HORIZONTAL WIND TURBINE

The aerodynamic power extraction of a wind turbine is a function of the wind speed (v), rotor angular speed (ω_r) and blade pitch angle (β); that is given by [7]:

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

where ρ is the air density, R is the rotor radius of the blade, and λ is the tip-speed ratio defined as:

$$\lambda = R\,\omega_r / v \tag{2}$$

C_p is the power coefficient which is a nonlinear function of the pitch angle and the tip-speed ratio. There are many empirical equations for describing the power coefficient. In most of the previous experimental/theoretical researchers [8], the following nonlinear equation has been used:

$$\frac{1}{\lambda^*} = \frac{1}{\lambda - 0.02\beta} - \frac{0.003}{\beta^3 + 1} \tag{3}$$
$$C_p(\lambda, \beta) = 0.73\left(\frac{151}{\lambda^*} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right)\exp\left(-\frac{18.4}{\lambda^*}\right)$$

Note that C_p is a semi-positive function and the above equation should be corrected to zero if C_p becomes a negative value. According to this equation, the maximum value of C_p is about 0.44 for the zero value of the blade pitch angle and a tip speed ratio of about 6.9077. This fact is in compliance with the Betz's law in wind turbine systems; that says the power coefficient is less than 0.59. For a three-bladed horizontal axis wind turbine, the power coefficient has a maximum value of 0.45 [9].

The aerodynamic torque (T_a) is related to the aerodynamic power (P_a) according to

$$T_a = \frac{P_a}{\omega_r} \tag{4}$$

Substituting Eq. (1) in Eq. (4), yields the aerodynamic torque (T_a) as:

$$T_a = \frac{1}{2\omega_r} C_p(\lambda, \beta)\rho\pi R^2 v^3 \tag{5}$$

If the torque coefficient, related to the power coefficient, is also defined as:

$$C_q = \frac{C_p}{\lambda} \tag{6}$$

Then the aerodynamic torque expression can be written in terms of C_q as:

$$T_a = \frac{1}{2} C_q(\lambda, \beta)\rho\pi R^3 v^2 \tag{7}$$

The 3D behaviour of the power (C_p) and torque (C_q) coefficient surfaces in terms of the blade pitch angle and tip-speed ratio is illustrated in Fig. 1.

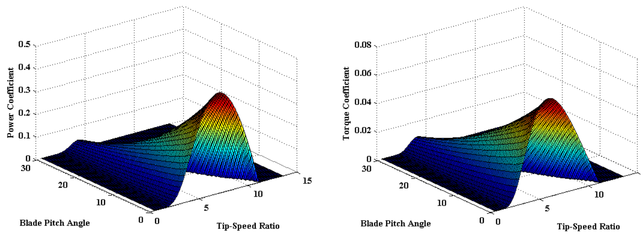

Fig 1. 3D behavior of the wind turbine power (left) and torque (right) coefficients (C_p and C_q) in terms of the blade pitch angle and tip-speed ratio

According to Fig. 2, the wind turbine consists of these five main parts: the rotor, the low speed shaft, the gearbox, the high speed shaft and the generator. According to this two mass model, the mechanical equation for the rotor and generator can be written respectively as:

$$J_r\dot{\omega}_r = T_a - T_{ls} - B_r\omega_r - K_r\theta_r \tag{8}$$

$$J_g\dot{\omega}_g = T_{hs} - T_{em} - B_g\omega_g - K_g\theta_g \tag{9}$$

where Jr and Jg are the rotor and generator torsion inertia, Br and Bg are the rotor and generator external damping, Kr and Kg are the rotor and generator external stiffness, θ_r and θ_g are the rotor and generator angle, ω_r and ω_g are the rotor and generator angular speed, $\dot{\omega}_r$ and $\dot{\omega}_g$ are the rotor and generator angular acceleration, T_{ls} and T_{hs} are the low and high-speed torque, respectively and T_{em} is the generator electromagnetic torque.

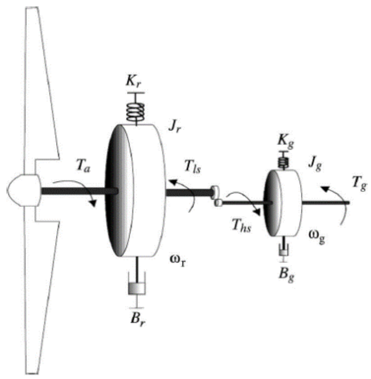

Fig. 2: Schematic view of the wind turbine-generator system [9]

The low speed shaft torque can be described as:

$$T_{ls} = B_{ls}(\omega_r - \omega_{ls}) + K_{ls}(\theta_r - \theta_{ls}) \tag{10}$$

where B_{ls} and K_{ls} are the low speed shaft damping and stiffness respectively and θ_{ls} is the low speed shaft angle. By assuming an ideal gearbox with ratio of n_g, defined as:

$$n_g = \frac{T_{ls}}{T_{hs}} = \frac{\omega_g}{\omega_r} \tag{11}$$

The generator dynamic can be written as:

$$n_g^2 J_g\dot{\omega}_r = T_{ls} - n_g T_{em} - n_g^2 B_g\omega_r - n_g^2 K_g\theta_r \tag{12}$$

If he above equation is added to Eq. (8), the system dynamics would be

$$J_t\dot{\omega}_r = T_a - T_g - B_t\omega_r - K_t\theta_r \tag{13}$$

where

$$\begin{aligned} J_t &= J_r + n_g^2 J_g \\ B_t &= B_r + n_g^2 B_g \\ K_t &= K_r + n_g^2 K_g \\ T_g &= n_g T_{em} \end{aligned} \tag{14}$$

Since the external coefficient K_t is negligible compared with other terms of Eq. (13), the system dynamics is simplified by elimination of $K_t\theta_r$ term [10]. So, the system dynamics can be written as:

$$J_t\dot{\omega}_r = T_a - T_g - B_t\omega_r \tag{15}$$

Equation (15) describes the behaviour of the single mass model of a wind turbine.

III. CONTROL LOGIC & OBJECTIVES UNDER VARIOUS OPERATION MODES

If we want to extract the wind power effectively while maintaining the safe operation at the same time, the wind turbine should work according to the following three modes schedule. As it is illustrated in Fig. 3, these three modes are described as follows:

Mode 1: Operating at variable speed/optimum tip speed ratio when $v_C \le v \le v_B$

Mode 2: Operating at constant speed/variable tip speed ratio when $v_B \le v \le v_R$

Mode 3: Operating at variable speed/constant power when $v_R \le v \le v_F$

Where v_C is the cut-in wind speed, v_B denotes the wind speed at which the maximum allowable rotor speed is reached, v_R is the rated wind speed and v_F is the furling wind speed at which the turbine needs to be shut down for protection [2]. In this research, according to Fig. 4, the modified design modes are expressed.

IV. STRUCTURE OF THE CONTROL STRATEGY

The difference between the actual and desired power is defined as the power error as:

$$e_p = P_{ref} - P_g \tag{16}$$

Derivation of Eq. (16) leads to the power error dynamics as:

$$\dot{e}_p = \dot{P}_{ref} - T_g\dot{\omega}_r - \dot{T}_g\omega_r \tag{17}$$

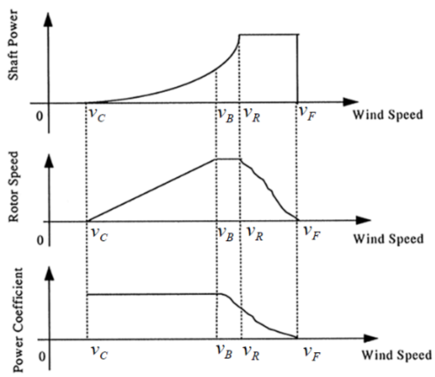

Fig. 3: The ideal operation modes of the wind turbine in terms of the (a) shaft power, (b) rotor speed and (c) power coefficient versus the wind speed [11]

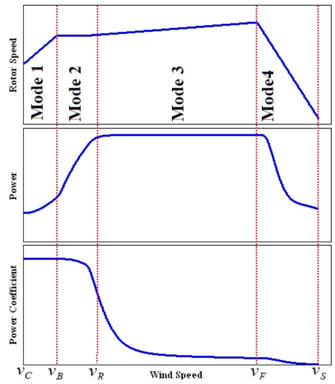

Fig. 4: Modified reference operation modes in terms of the (a) rotor angular speed, (b) power generated and (c) power coefficient versus the wind speed.

Suppose that we want to track a desired power (such that tracking error on power approaches to the zero as time goes on). So, the following sliding mode controller is designed. First, an arbitrary sliding surface as a function of the power error is defined. Then, by choosing the controller, as:

$$\dot{T}_g = \frac{(B + \frac{\lambda}{S'_p}) sign(S_P)}{\omega_r} \tag{18}$$

where $\dot{B} = |S_p||S'_p|$, $\lambda > 0$ and $S'_p = \frac{dS_p}{de_p}$, while S_p is the power sliding surface and is an arbitrary function of power error (e_p); we have

$$\dot{e}_p = \dot{P}_{ref} - T_g \dot{\omega}_r - (B + \frac{\lambda}{S'_p}) sign(S_p) \tag{19}$$

the Lyapunov function is introduced as:

$$V = \frac{1}{2} S_p^2 + \frac{1}{2}(B - B_1)^2 \tag{20}$$

Differentiating from the Lyapunov function results in:

$$\begin{aligned} \dot{V} &= S_p \dot{S}_p + \dot{B}(B - B_1) \\ &= S_p S'_p \dot{e}_p + |S_p| S'_p (B - B_1) \\ &= S_p S'_p (\dot{P}_{ref} - T_g \dot{\omega}_r - (B + \frac{\lambda}{S'_p}) sign(S_p)) + |S_p| S'_p (B - B_1) \\ &= S_p S'_p (\dot{P}_{ref} - T_g \dot{\omega}_r - \frac{\lambda}{S'_p} sign(S_p)) - |S_p| S'_p B_1 \end{aligned} \tag{21}$$

B_1 is a positive constant that satisfies

$$B_1 > |\dot{P}_{ref} - T_g \dot{\omega}_r| \tag{22}$$

Then the derivative of Lyapunov function would be negative. This controller was introduced for only one mode and with $S_p = e_p$ [10].

A. Rotor angular speed controller

The mechanical equation of the wind turbine is given by Eq. (15). So, the rotor angular speed dynamics would be:

$$\dot{\omega}_r = \frac{1}{J_t}(-B_t \omega_r + T_a - T_g) \tag{23}$$

The speed error is defined as the difference between the reference and actual speed as:

$$e_\omega = \omega_r - \omega_{ref} \tag{24}$$

By differentiation of Eq. (24) and substitution from Eq. (23), we have

$$\dot{e}_\omega = \frac{1}{J_t}(-B_t \omega_r + T_a - T_g) - \dot{\omega}_{ref} \tag{25}$$

By supposing a known value for the blade pitch angle, only one controller input exists, T_g and then the sliding mode speed controller is designed as follows. First, the sliding surface is defined as:

$$S_\omega = e_\omega \tag{26}$$

Then, a sliding mode controller on generator torque is designed as:

$$T_g = T_a - B_t \omega_{ref} - J_t \dot{\omega}_{ref} + k e_\omega + \eta sign(S_\omega) + unc \tag{27}$$

Where k>0, η>|unc| and the uncertainty as $unc = 0.1 \times B_t \omega_{ref} + 0.1 \times J_t \dot{\omega}_{ref}$.

B. Blade pitch angle controller

We also require designing another controller for the blade pitch angle. But, due to the nonlinear characteristic of the power coefficient (Eq. (3)), design of this controller for the blade pitch angle is more difficult. So, first a sliding mode controller on the power coefficient and for tracking of a desired rotor speed is designed. In fact, an initial guess for the C_p is considered. Then, by knowing the reference rotor angular speed at any time and through a numerical method, the appropriate blade pitch angle by maximum 0.1 errors is found. Thereafter, by determination of the blade pitch angle, the rotor speed can be controlled.

To design the blade pitch angle controller, the aerodynamic torque from Eq. (5) is substituted into Eq. (25). So, the error dynamics is rewritten as follows:

$$\dot{e}_\omega = \frac{1}{J_t}(-B_t e_\omega - B_t \omega_{ref} + \frac{1}{2\omega_r} \rho C_p R^2 v^3 - T_g - J_t \dot{\omega}_{ref}) \tag{28}$$

By defining the sliding surface as:

$$S_\beta = e_\omega + \frac{B_t}{J_t} \int_0^t e_\omega(\tau) d\tau \tag{29}$$

The sliding mode controller for the guess of a suitable value for the blade pitch angle to track the reference rotor angular speed is designed as:

$$C_p = \frac{2(d - \eta sign(S_\beta))\omega_r}{R^2 v^3} \tag{30}$$

where,

$$d = T_g + B_t \omega_{ref} + J_t \dot{\omega}_{ref} + unc \tag{31}$$

Where k>0, η>|unc|. The following Lyapunov function candidate is defined:

$$V = \frac{1}{2} S_\beta^2 \tag{32}$$

Its time derivative will be,

$$\begin{aligned} \dot{V} &= S_\beta \dot{S}_\beta = S_\beta [\dot{e}_\omega + \frac{B_t}{J_t} e_\omega] \\ &= S_\beta [\frac{1}{J_t}(-B_t e_\omega - B_t \omega_{ref} + \frac{1}{2\omega_r} \rho C_p R^2 v^3 - T_g - J_t \dot{\omega}_{ref}) + \frac{B_t}{J_t} e_\omega] \end{aligned} \tag{33}$$

after some math simplification, it yields to:

$$=S_{\beta}\cdot[\frac{1}{J_t}(-B_t e_{\omega}-\eta sign(S_{\beta}))+\frac{B_t}{J_t}e_{\omega}] \qquad (34)$$

$$=-\frac{\eta}{J_t}|S_{\beta}|\leq 0$$

So, the designed controller would be asymptotic stable.

The output of this controller is a good guess for the blade pitch angle value; as it is required in each tip-speed ratio. To do this, an appropriate numerical solving method is proposed. First, the rotor angular speed is approximated with its reference. Then, a table of power coefficient in terms of the blade pitch angle is formed. By knowing the output of the above controller and through a numerical method, the suitable amount of the blade pitch angle with 0.1 degree accuracy is obtained. The upper limit for the blade pitch angle is considered 35 degree. If several values for the pitch angle are obtained, the closest one to zero is selected.

V. SIMULATION RESULTS AND DISCUSSION

Characteristic parameters of the wind turbine are summarized in Table I. Simulation results for this wind turbine are carried out by using Simulink Toolbox of MATLAB. Time responses with respect to different wind velocity profiles are presented next. The properties of each mode such as their boundary velocities are given in Table II.

Figure 5 shows time response of the wind turbine to ramp wind velocity profile. It shows that these controllers have good transient and steady responses.

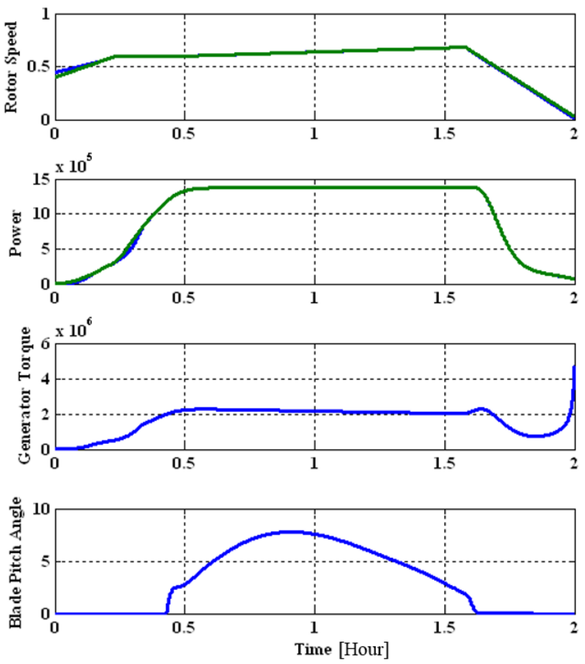

Fig. 5: Time response of the wind turbine to a ramp profile of wind velocity for $S_p=e_p$ with Sign function in various operation modes.

TABLE I. WIND TURBINE CHARACTERISTICS

Number of blades	3
Rotor diameter	70 m
Rated power	1.374 MW
Turbine total inertia	4.4532×105 kg m2
Turbine total damping	8.2384 105 kg m2/s

TABLE II. BOUNDARY VALUES FOR THE WIND VELOCITY PROFILES [11]

v_C	4 (m/s)
v_B	6 (m/s)
v_R	7.7 (m/s)
v_F	17.7 (m/s)
v_S	21.3 (m/s)

VI. CONCLUSIONS

According to the results and discussion, the following conclusions can be extracted:

- Control of a WT must be classified based on wind speed
- To shut down a WT in stormy conditions, high amount of generator torque is required.
- Type of the sliding surface affects the performance of the sliding mode controllers

REFERENCES

[1] Committee S. RenewableS 2012 Global Status Report. Technischer bericht, REN21, Renewable Energy Policy Network for the 21th Century, 2012, URL www. ren21. net; 2011.

[2] Boukhezzar B, Lupu L, Siguerdidjane H, Hand M. Multivariable control strategy for variable speed, variable pitch wind turbines. Renewable Energy. 2007;32:1273-87.

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

[4] Neugebauer, M., Sołowiej, P., Wesołowski, M., Nalepa, K., & Hałacz, J. (2020). Fuzzy Model of Wind Turbine Control. In Renewable Energy Sources: Engineering, Technology, Innovation (pp. 541-550). Springer, Cham.

[5] Wu D, Li Y. Fault diagnosis of variable pitch for wind turbines based on the multi-innovation forgetting gradient identification algorithm. Nonlinear Dynamics. 2015;79:2069-77.

[6] Hand MM. Variable-speed wind turbine controller systematic design methodology: a comparison of non-linear and linear model-based designs. National Renewable Energy Lab., Golden, CO (US); 1999.

[7] Faraji Nayeh R, Moradi H, and Vossoughi. Gh., "Multivariable robust control of a horizontal wind turbine under various operating modes and uncertainties: A comparison on sliding mode and H∞ control." International Journal of Electrical Power & Energy Systems 115 (2020): 105474.

[8] Melício R, Mendes V, Catalão J. Comparative study of power converter topologies and control strategies for the harmonic performance of variable-speed wind turbine generator systems. Energy. 2011;36:520-9.

[9] Betz A. Introduction to the theory of flow machines: Pergamon; 1966.

[10] Beltran B, Ahmed-Ali T, Benbouzid MEH. Sliding mode power control of variable-speed wind energy conversion systems. Energy Conversion, IEEE Transactions on. 2008;23:551-8.

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