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Article

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Efficacious pitch angle control of variable-speed wind turbine using fuzzy based predictive controller

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Abstract

The Wind energy is more reliable and speedier growing, among the renewable energy resources, due to the world environment challenges as well as increasing demand for energy. The wind turbine system's stability is cumbersome due to the uneven distribution of wind. Centrifugal and gravitational loads on the blades of a wind turbine creates weariness, resultantly decreases the power output along with the life of the equipment. Therefore, the need for a pitch angle control that can reduce the loading effect in addition to provide maximal power output. This paper proposes the fuzzy based model-predictive controller of pitch angle control to minimize the loading effect on wind turbine by limiting power output and rotor speed to its rated value as well as to maximize the extracted power output as compared to other techniques. The fuzzy logic controller works very efficiently by encountering the system's non-linearity while model predictive controller helps the system to become more stable and efficient. The superiority of prescribed controller is verified by comparing it with PI controller. The proposed model has been tested in MATLAB/Simulink using a 3MW wind turbine system.

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Keywords: Wind turbine; Pitch-angle control; PMC fuzzy controller; Power output

1. Introduction

Rapidly increase in energy consumption is causing a shortage of conventional energy resources. The earth's pollution in addition to its global warming is rising at a much higher pace. So, the need of exploring and utilizing alternate resources, which abets to keep the environment green and clean. Renewable energy, specifically wind energy, is getting more popular day by day due to its abundant nature [1]. Frequency and voltage stability are

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the prominent problems of wind turbine connected to the power grid [2]. Subsequently, power control techniques apropos of grid integration are getting more importance.

Normally, the wind turbine system is comprising of three operating regions depending upon wind speed. The wind speed in the first region is less than the cut-in value and utilized for the rotor to accelerate [3]. The wind speed in the second region is in between the cut-in and the rated value, which is called the normal operation zone. In this area, the turbine speed and pitch angle are adjusted in a specific way to maximize power output [4]. In the third region, wind speed exceeds from the nominal value; output power is adjusted to its nominal by using the pitch angle to protect the equipment from damaging out [5]. It is also called full load operating region [6]. To limit the power output, attained from region III, various pitch angle control methodologies are adopted [7]. Normally, the output power is regulated through PI and PID controller [8]. By the changing of operating points, the effectiveness of the controller is compromised in this method, as these are designed based on system linearity. Linear matrix inequality method is suggested by implementing the H_∞ controller [9]. This technique provides quite effective results, but it is bit complex because the change of weighting functions by the constraints, different values for model and controller needs to be reconsidered. Another technique, linear quadratic Gaussian (LQG), for pitch angle control has been implemented [10]. This controller is quite effective in phase and gain margins but nonlinear features of wind turbine impede it to work efficiently. The gain scheduling control was presented to rectify the issue of the system's nonlinearity, with the varying system operating states, controller gains are also updated [11]. The disadvantage of this technique is that, it works on the wind turbine linearization at particular points and hence not easy to design and update the controller gains at the various operating point. Another technique, which implements sliding mode control method is also used for the pitch angle control [12], which entirely dependent upon the wind turbine's mathematical model. However, if control variables change abruptly and in large number, it leads to increase in stress of the wind turbine. Some fuzzy logic techniques are implemented to control the pitch angle [13]. These controllers are quite effective and robust for the nonlinear characteristics of wind speed but the drawback is that, it uses the information of wind speed. It requires anemometer and hence increasing the price, in addition to it degrading the reliability of the system. This research paper puts forth a control methodology which is quite different from other fuzzy controllers. The proposed fuzzy controller along with model predictive controller uses rotor speed along with output power as input instead of wind speed and hence, independent of the anemometer. Moreover, Model predictive control is also being used thus making the controller more effective as well as robust. The output of the two controllers combines and directs the actuator to adjust the pitch angle control, and limits the power output; so as to keep the wind turbine in the normal operating region and extract the maximum power output.

2. Wind turbine system

2.1. Modeling of wind turbine

The wind turbine should operate at maximum efficiency in the ideal scenario, i.e. to draw utmost power output through wind speed. Wind turbine's efficiency is mainly reliant on the coefficient of power C_p the maximum achievable C_p ranges from 0.4 to 0.5. Theoretically, the determined value of the coefficient of power is 0.59 and termed as the Betz limit.

$$P_m = \frac{1}{2} \rho A C_p (\lambda, \beta) v^3 \quad (1)$$

Here, ρ denotes air density which is measured in (kg/m^3), A represents turbine swept area and calculated (m^2) while V specifies the wind speed and quantified in (m/s). Furthermore, the wind turbine torque is given as:

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

Here, R symbolizes the radius of blades, measured in meters.

2.2. Pitch actuator

Pitch angle is utilized to control the power output within the nominal value. The pitch actuator is utilized to move the blades to its longitudinal axis. It is nonlinear actuator and normally moves the blades completely or their part

according to requirement. In closed loop, the pitch actuator is designed as a first-order delay system or integrator having a time constant (τ_c). Pitch actuator’s dynamic behavior is as follows [1].

$$\frac{d\beta}{dt} = -\frac{1}{\tau_c}\beta + \frac{1}{\tau_c}\beta_{ref} \tag{3}$$

$$\beta_{max} \leq \beta \leq \beta_{min}, \left(\frac{d\beta}{dt}\right)_{max} \leq \frac{d\beta}{dt} \geq \left(\frac{d\beta}{dt}\right)_{min}$$

Here, β_{max} is maximum pitch angle while β_{min} is minimum pitch angle.

3. Controller design

3.1. PI controller

Conventionally, this controller is utilized to regulate the pitch angle as well as to confine the yielded power of wind turbine. It is designed on some specific operating point at which nonlinear dynamics are linearized, assuming the value of torque for generator and turbine is the same. It is entirely dependent on the values of K_p and K_i . These values are calculated by different techniques, in this controller values are computed by using the Ziegler Nichols method. Values of K_p and K_i are 15.876 and 30.498 respectively. The schematic diagram of PI-controller is displayed in Fig. 1(a).

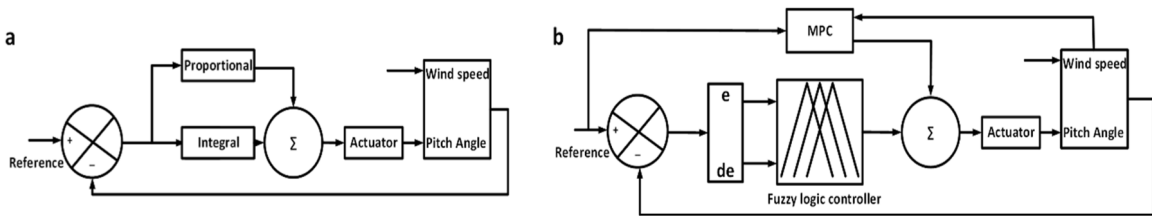


Fig. 1. (a) PI controller; (b) Proposed controller.

3.2. Proposed fuzzy based model predictive controller

Schematic illustration of the controller is presented in Fig. 1(b). ω_r is fed to the fuzzy controller as well as to the model predictive controller (PMC). The PMC has two input variables i.e. ω_r in addition to power output and one output variable which is feeding to the actuator where it combines with the instruction from fuzzy and helps in regulating the pitch angle. PMC mainly uses power output to predict the wind turbine systems behavior and acts accordingly. The predictive controller is described as,

$$x(k+1) = A(k)x(k) + B(k)u(k) \tag{4}$$

$$y(k) = C(k)x(k) \tag{5}$$

Here, x is state, u is input, and y is output. For input, the rotor speed is used; wind speed is disturbance while the pitch angle is acquired as output. U defined as; $U = [U^T(0) U^T(1) \dots U^T(N-1)]^T$ and X can be defined as $X = [X^T(1) X^T(2) \dots X^T(N-1) X^T(N)]^T$, so the predicted model equation is;

$$X = SU + TX(0) \tag{6}$$

$$S = \begin{bmatrix} B & 0 & 0 & 0 \\ AB & B & 0 & 0 \\ \dots & \dots & \dots & \dots \\ A^{N-1}B & A^{N-2}B & \dots & B \end{bmatrix}, T = \begin{bmatrix} A \\ A^2 \\ \dots \\ A^N \end{bmatrix} \tag{7}$$

The objective function is defined as, and Optimal solution for the control function is $\partial j / \partial \Delta U = 0$

$$J = (R_s - Y)(R_s - Y) + \Delta U^T \bar{R} \Delta U \tag{8}$$

Here, $R_s^T = [1 \ 1 \ \dots \ 1]$ and, $k = 1, 2, 3, \dots, n$

$$\Delta U = (S^T S + \bar{R})^{-1} S^T (\bar{R}_S r(k_i) - Fx(k_i)) \tag{9}$$

To design the fuzzy controller, the Mamdani’s inference method is used with the combination of minimum, maximum and probabilistic; 49 rules are constructed to design the controller.

4. Simulation results

The proposed controller is implemented in MATLAB/Simulink to prove its effectiveness. Horizontal-axis 3 MW wind turbine is used and parameters are given in Table 1. Real time wind data is extracted from GH-bladed software and different wind profiles will be used to test the behavior of the proposed controller at variable wind speed.

Table 1. Simulation parameters for wind turbine.

Rated power	3 MW
Air density	1.225 kg/m ³
Base wind speed	12 m/s
Cut-in wind speed	3 m/s
Cut-off wind speed	25 m/s
Maximum pitch angle	25°
Maximum rate of change of pitch angle	2°/s
Base rotational speed (p.u. of base generator speed)	1.2

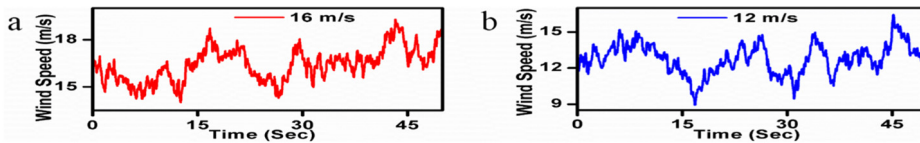


Fig. 2. (a) Wind speed at 16 m/s; (b) wind speed at 12 m/s.

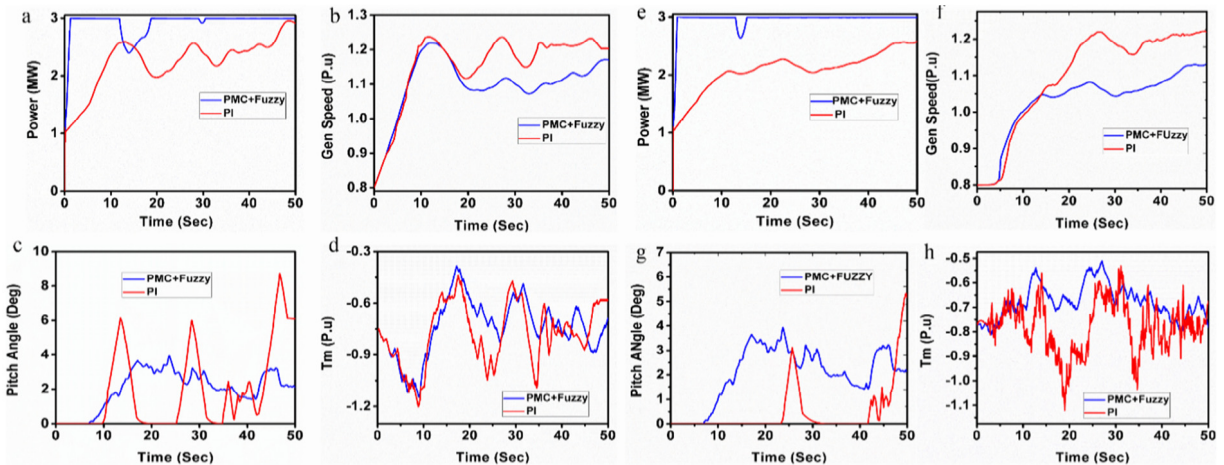


Fig. 3. At wind speed 12 m/s (a) Power output; (b) generator speed; (c) Pitch angle; (d) Mechanical torque: at wind speed 16 m/s (e) Power output; (f) generator speed; (g) Pitch angle; (h) Mechanical torque.

In the first scenario, variable wind speed at about 12 m/s is provided to the WT as given in Fig. 2(b). The results for output-power, rotor speed as well as pitch angle are given in Fig. 3. Analyzing Fig. 3(a), it is summarized that, the proposed controller is effective in extracting the maximal output power through regulating the pitch angle better than the PI. The mean output-power obtained from the proposed method is 2.726 MW, the mean rotor speed is 1.061 Pu with a peak of 1.143 Pu while from PI is 1.842 MW, 1.127 Pu and 1.230 Pu respectively. In Fig. 3(b), rotor speed obtained from the proposed methodology is less than the PI which shows that this technique is keeping the rotor speed in its limit. From Fig. 3(c), pitch angle movement according to the requirement of rotor speed and

power, the output can be seen which proves its effective and efficient regulation. Fig. 3(d) denotes the mechanical torque.

In the second scenario, different wind speed at 16 m/s is provided to the wind turbine which is given in Fig. 2(a). From Fig. 3(e), it is shown that power output for the proposed controller is greater than the PI. In Fig. 3(f), the rotor speed is much lesser by using the proposed controller as compared to PI, which reduces loading effect and increases the life of the equipment. Fig. 3(g) shows the effective working of pitch angle to maintain higher power output as well as lower rotor speed. Fig. 3(h) depicts that the mechanical torque obtained from the proposed controller is less as compared to PI, which tends to decrease the loading effect and improves the working of the equipment. The mean power output attained from the proposed technique is 2.761 MW; mean rotor speed is 1.031 Pu with the peak of 1.132 Pu while from PI is 1.818 MW, 1.123 Pu and 1.220 Pu respectively.

5. Conclusion

In this research, proposed control methodology is implemented with the combination of fuzzy logic with the predictive controller on a 3 MW wind turbine. The main aim was to limit the power output as well as the speed of the rotor to its nominal value, thus reducing the loading effect. The rotor speed is provided as input to the fuzzy controller while power output to the predictive controller, thus preventing from any other wind turbine dynamics and wind speed. Simulation results obtained from the proposed method are illustrated, which proves its superiority over other controllers. The statistical data examined from the output results also indicate the efficacy of the proposed methodology. The proposed pitch angle control can limit as well as regulate the power output and rotor speed to its rated value. Power output extracted from the proposed controller is greater than from the PI-controller, which makes it more effective and efficient.

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