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Power Regulation and Pitch Control of Wind Turbines using Actuator Fault Tolerant Adaptive Control

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Abstract—High performance, reliability and power maximization are required for the wind turbines to compensate unbalanced loads caused by the unpredictable wind speed and turbulences. This paper studies the control methodology for optimal power capture in a variable speed variable pitch wind turbine. The pitch actuator faults can affect the pitching performance with slow dynamics and results in generator power instability. The dynamic change in the pitch actuator, effectiveness loss and bias are considered as uncertainties and augmented into the pitch dynamic model. The nonlinear model of the wind turbine is presented and a model based non-linear controller is designed considering the effects of non-linear system dynamics, actuator fault uncertainties and unknown external disturbances. The adaptive controller is designed to be robust against unexpected actuator faults, model uncertainties, unknown control direction and disturbances including wind speed and model noises. The simulations are performed to confirm the effectiveness of the proposed control strategy and the simulation results shows that the performance of the adaptive controller to be superior to that of a conventional controller.

Keywords—Wind Energy Conversion System; Adaptive PID controller; fault-tolerant; pitch control;self-tuning gains; unknown control direction; wind turbine power regulation

I. INTRODUCTION

Wind Power generation has widely grown during the recent years and nowadays is one of the promising type of renewable energy capable of supplying world's power demand. However, fluctuations in the output power caused by the uncontrollable and stochastic wind severely affects the stabilities of the grid. In this paper, a pitch angle controller is designed so as to produce rated power via blade pitch angle control to avoid probable catastrophic operation.

As analyzed from [1], the control of pitch angle is not easy because the system behaviour is highly nonlinear. Many studies have been reported about the wind turbine pitch control. Advanced fault detection, accommodation schemes are necessary for reliable operation of wind power system. A passive and active fault tolerant scheme is proposed in [2]. However, detection of sensor faults are not considered. In [3], proposed fuzzy controller shows better robustness feature than the conventional controller but actuator fault detection and diagnosis schemes are not considered in this paper. Moreover, reducing mechanical stress of the actuator is important for efficient operation. The controller which has been designed for the linearized wind turbine model may not render the expected performance on the non linear model [4].

The main objective of this paper is to design a suitable pitch controller robust against wind speed variation. Moreover, the controller should be robust to pitch actuator faults and model uncertainties. The proposed adaptive controller ensures auto tuning of the gains, functions satisfactorily and provides acceptable performance for industrial applications.

II. SYSTEM MODELLING

In this section, the mathematical modelling of the Variable Speed Wind Turbine (VSWT) is described. A variable speed wind turbine consists of following components i.e. aerodynamics which converts kinetic energy into mechanical energy, a drive train, which allows increasing the speed and decreasing the torque, a tower model, a pitch system, a converter and a generator, which transfers mechanical energy into electrical energy.

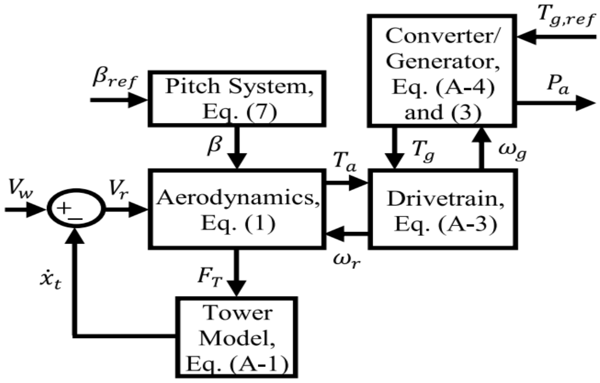

Fig. 1. Combined schematic model of wind turbine.

A. *Wind Turbine Modelling*

The aerodynamic power captured by the turbine blades is given by the following nonlinear equation.

$$P_a = \frac{1}{2}\rho_a \pi R^2 C_P(\lambda,\beta) V_r^{\,3} \tag{1}$$

where ρ_a and R are the air density and blade length respectively. C_p, the power coefficient depends on the blade pitch angle β and tip speed ratio, λ which is stated as in (2).

$$C_P(\lambda,\beta) = B_1\left[\frac{B_2}{\lambda_i} - B_3\beta - B_4\right].\exp\left[\frac{-B_5}{\lambda_i}\right] + B_6\lambda \tag{2}$$

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where;

$$\frac{1}{\lambda_i}=\frac{1}{\lambda+0.08\beta}-\frac{0.035}{\beta^2+1} \tag{3}$$

where the parameters B_i are known constants without units. The rotor speed, ω_r is defined as;

$$\lambda=\frac{R\omega_r}{v_r} \tag{4}$$

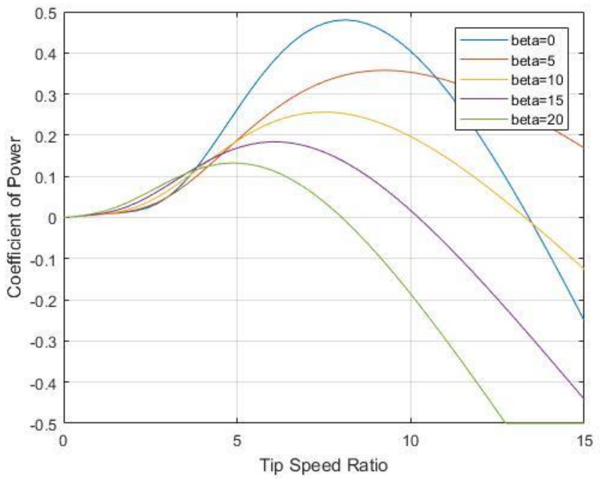

Fig. 2. Wind turbine Power Coefficient Curve.

The aerodynamic torque is expressed as;

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

The aerodynamic thrust is stated as;

$$F_t=\frac{1}{2}\rho\pi R^2 C_T(\lambda,\beta)V^3 \tag{6}$$

where the torque coefficient, C_q and thrust coefficient, C_T is given by the following equations.

$$C_q(\lambda,\beta)=\frac{C_p(\lambda,\beta)}{\lambda} \tag{7}$$

$$C_T=0.5\tilde{C}_T\left(1+sign(\tilde{C}_T)\right)$$

$$\tilde{C}_T=A_1+A_2(\lambda-A_3\beta).\exp(-A_4\beta)+ A_5\lambda^2.\exp(-A_6\beta)+A_7\lambda^3.\exp(-A_8\beta) \tag{8}$$

where the parameters A_i are known constants without units.

B. Tower Model

This nacelle motion is modeled as the following equation.

$$M_t\ddot{x}_t=F_t-B_t\dot{x}_t-K_t x_t \tag{9}$$

where x_t is the nacelle displacement, measured from its equilibrium point, M_t is the nacelle mass, B_t is the damping ratio and K_t is the elasticity coefficient of the tower.

C. Drive Train Model

Fig.3 shows the two mass model of the wind turbine.

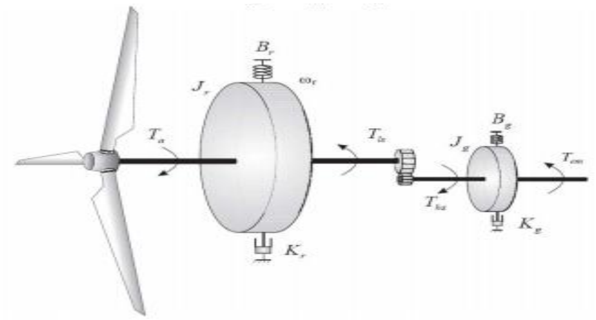

Fig. 3. Two mass model of wind turbine.

The dynamics of the rotor is modeled by the following differential equation.

$$J_r\dot{\omega}_r=T_a-K_{dt}.\theta-(B_r+B_{dt})\omega_r+\frac{B_{dt}}{N_g}\omega_g \tag{10}$$

$$J_g\dot{\omega}_g=\frac{\eta_{dt}}{N_g}K_{dt}\theta+\frac{\eta_{dt}.B_{dt}}{N_g}\omega_r-\left[B_g+\frac{\eta_{dt}B_{dt}}{N_g{}^2}\right]\omega_g-T_g \tag{11}$$

where J_r and J_g are inertia of the rotor and generator shaft respectively, which are rotating at speeds w_r and w_g respectively. N_g is the drive train ratio, K_{dt} is the torsion stiffness and B_{dt} is the torsion damping. B_r and B_g are viscous frictions of rotor and generator respectively. $\theta_\wedge$ is the drive train torsional angle which is defined as;

$$\theta=\theta_r-\frac{\theta_g}{N_g} \tag{12}$$

where θ_r and θ_g are rotation angles of rotor and generator respectively. η_{dt} is the drive train efficiency.

D. Converter Model

A converter is located in between the generator and the grid to adjust the generated power frequency. The converter is modeled as a first order system with a time delay as;

$$\dot{T}_g=-a_g T_g+a_g T_{g,ref} \tag{13}$$

E. Generator Model

The power, P_g produced in the generator is given by;

$$P_g=\eta_g\omega_g T_g \tag{14}$$

where T_g is the generator shaft torque and η_g is the generator efficiency.

F. Pitch Actuator Model

The considered wind turbine has a hydraulic pitch system to rotate the blades and adjust the pitch angle to reference pitch angle, which is commanded by the pitch controller. It is modeled as second order dynamic system.

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$$\ddot{\beta} = -\omega_n^2 \beta - 2\omega_n \xi_d \dot{\beta} + \omega_n^2 \beta_{ref} \tag{15}$$

The three major pitch actuator dynamic changes are pump wear, high air content in the oil and hydraulic leakage. These leads to slower response speeds and consequently, poor power regulation.

The dynamic changes can be considered as an uncertainty and augmented into the dynamic model, and the rewritten pitch actuator model is stated as the given equation.

$$\ddot{\beta} = -\omega_{n,N}^2 \beta - 2\omega_{n,N} \xi_N \dot{\beta} + \omega_{n,N}^2 \beta_{ref} + \Delta\tilde{f}_{PAD} \tag{16}$$

$$\Delta\tilde{f}_{PAD} = -\alpha_{f1} \Delta(\bar{\omega}_n^2) \beta - 2\alpha_{f2} \Delta(\tilde{\omega}_n \tilde{\xi}) \dot{\beta} + \alpha_{f1} \Delta(\bar{\omega}_n^2) \beta_{ref}$$

$$\Delta(\bar{\omega}_n^2) = \omega_{n,HL}^2 - \omega_{n,N}^2$$

$$\Delta(\tilde{\omega}_n \tilde{\xi}) = \omega_{n,HAC} \xi_{HAC} - \omega_{n,N} \xi_N \tag{17}$$

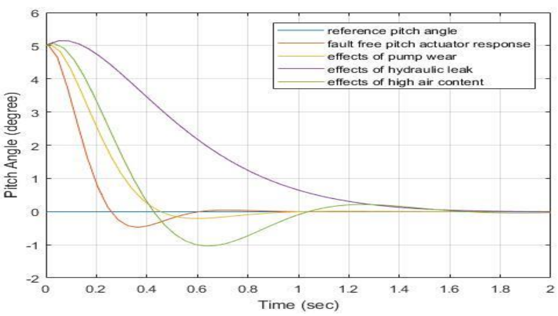

Fig. 4. Dynamic Change Effects on Pitch Actuator

N, HAC, PW, HL represent normal, high air content, pump wear and hydraulic leakage respectively. The effectiveness loss and bias can be modeled as,

$$\ddot{\beta} = -\omega_{n,N}^2 \beta - 2\omega_{n,N} \xi_N \dot{\beta} + \omega_{n,N}^2 \big(p(t)\beta_{ref}(t) + \phi(t)\big) + \Delta\tilde{f}_{PAD} \tag{18}$$

where $\phi(t)$ is the unknown pitch actuator bias that causes unbalanced rotor rotation and p(t) represents the unknown pitch actuator effectiveness.

III. WIND TURBINE DYNAMICS

It is desirable to keep the drive train torsion angle variation as small as possible, which, consequently leads to reduction in the drive train stress. The desirable operational dynamic equation of the wind turbine with reduced drive train stress can be stated as,

$$\ddot{\omega}_r = c_1 \omega_r + c_2 \omega_g + c_3 T_a + c_4 T_g + a_3 \dot{T}_a \tag{19}$$

Assumption 1: T_a (V_r, w_r, β^*) and β^* for any given pair (V_r,w_r) are constant through time.

Assumption 2: It can be stated that $-L \le \delta T_a / \delta\beta \le -U < 0$, where $0 < U < L$, which implies that with increasing pitch angle, the aerodynamic torque will decrease.

Considering Assumption 1,

$$\dot{T}_a(V_w, \omega_r, \beta) = \dot{\beta} \frac{\partial T_a}{\partial \beta} = \dot{\beta} T_a)_\beta \tag{20}$$

Considering (18), (19) and (20),

$$\ddot{\omega}_r = F(x,t) + G(x,t)\big(p(t)\beta_{ref} + \phi(t)\big) + D(x,t) \tag{21}$$

where,

$$F(x,t) = c_1 \omega_r + c_2 \omega_g + c_3 T_a + c_4 T_g - \frac{\omega_{n,N} a_3 T_a)_\beta \beta}{2\xi_N} - \frac{a_3 T_a)_\beta \ddot{\beta}}{2\omega_{n,N} \xi_N}$$

$$G(x,t) = \frac{\omega_{n,N} a_3 T_a)_\beta}{2\xi_N}$$

$$D(x,t) = \frac{a_3 T_a)_\beta \Delta\tilde{f}_{PAD}}{2\omega_{n,N} \xi_N} \tag{22}$$

Assumption 3: There is an unknown non negative constant, a_f and non negative function ψ_f such that

$$|F(x,t) + \phi(t)G(x,t) + D(x,t)| \le a_f \varphi_f(x) \tag{23}$$

IV. FAULT TOLERANT ADAPTIVE CONTROLLER

The proposed fault tolerant controller is designed to regulate the pitch angle in the presence of wind speed variation, model uncertainty and unexpected actuator faults. It is aimed to provide automatic adaptive gain tuning without trial and error processes. The tracking error and its derivative is defined as,

$$e_r(t) = \omega_r(t) - \omega_{r,rated} \tag{24}$$

$$\dot{e}_r(t) = \dot{\omega}_r(t) - \dot{\omega}_{r,rated}$$

Second time derivative of error considering dynamic model,

$$\ddot{e}_r = F(x,t) + G(x,t)\big(p(t)\beta_{ref} + \phi(t)\big) + D(x,t) \tag{25}$$

The tracking error filter is defined as,

$$Z(t) = 2\lambda e_r(t) + \lambda^2 \int_0^t e_r(\tau) d\tau + \dot{e}_r(t) \tag{26}$$

The filtered error, Z(t) is formed by combination of proportional, integral and derivative terms of the tracking error, $e_r(t)$. Combining (18) and (26),

$$\dot{Z} = H(x,t) + B(x,t)\beta_{ref} \tag{27}$$

where,

$$B(x,t) = p(t)G(x,t)$$

$$H(x,t) = 2\lambda \dot{e}_r(t) + \lambda^2 e_r(t) + F(x,t) + \phi(t)G(x,t) + D(x,t) \quad (28)$$

The adaptive controller is defined as,

$$\beta_{ref} = (\lambda_{DO} + \lambda_D) N(\xi) Z(t) \quad (29)$$

The controller gain is obtained via the following adaptive gains.,

$$\lambda_D = \hat{a}\varphi^2$$
$$\dot{\xi} = (\lambda_{DO} + \lambda_D) Z^2 \quad (30)$$
$$\dot{\hat{a}} = -\sigma_0 \hat{a} + \sigma_1 \varphi^2 Z^2$$

where,

$$\psi_f = |c_1\omega_r| + |c_2\omega_g| + c_3\left(\frac{N_g T_{g,\max}}{\eta_{dt}}\right) + |c_4 T_g| + \left|\frac{\omega_{n,N} a_3 U\beta}{2\xi_N}\right| + \left|\frac{a_3 U \dot{\beta}}{2\omega_{n,N}\xi_N}\right| + \left|\frac{\omega_{n,N} a_3 U}{2\xi_N}\right| + \left|\frac{a_3 U \Delta(\tilde{\omega}_n \tilde{\xi})\dot{\beta}}{\omega_{n,N}\xi_N}\right| + \left|\frac{a_3 U \Delta(\omega_n)(\beta_{\max} - \beta_{\min})^{-2}}{2\omega_{n,N}\xi_N}\right| \quad (31)$$

$$\varphi(x) = \varphi_f(x) + |\dot{e}_r| + |e_r| + 1 \quad (32)$$

The Nussbaum - type function is defined as,

$$N(\xi) = \xi^2 Cos(\xi) \quad (33)$$

V. SIMULATION RESULTS

A. *Normal Actuation Mode*

The performance of the wind turbine in normal actuation mode using the proposed controller and a conventional PID controller, under the wind profile shown in Fig.5 are demonstrated and compared in Fig.6 and Fig.7.

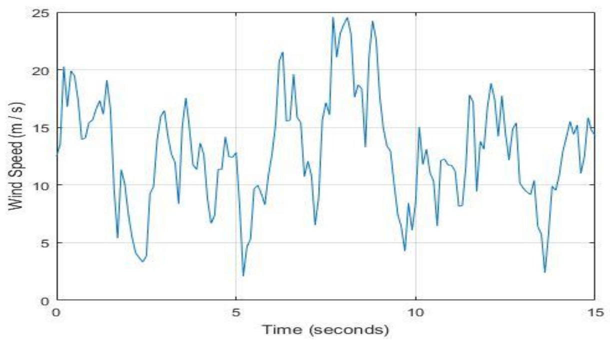

Fig. 5. Wind Speed Profile

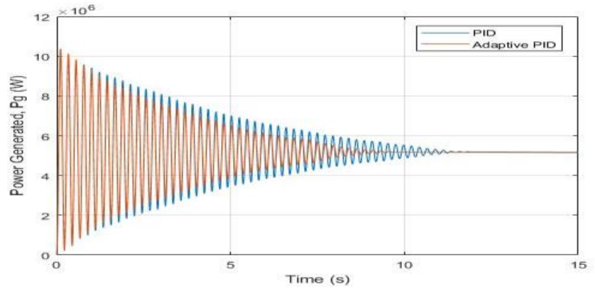

Fig. 6. Generated Power using Adaptive and PID controller

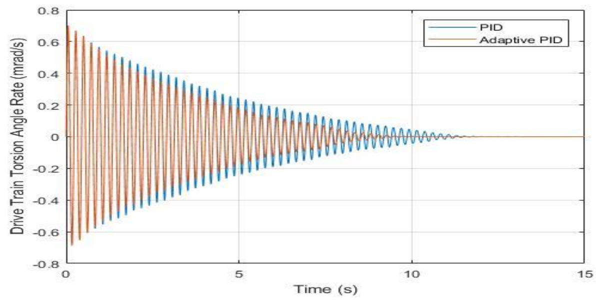

Fig. 7. Drive train torsion angle variation using Adaptive and PID controller

B. *Faulty Actuation Mode*

Case1: Pitch Actuator Bias, ϕ(t) = 15

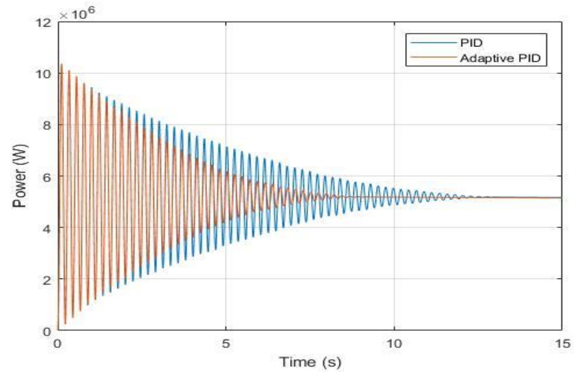

Fig. 8. Generated Power using Adaptive and PID controller during pitch actuator bias

Case2: Effectiveness loss, p(t) = 0.4

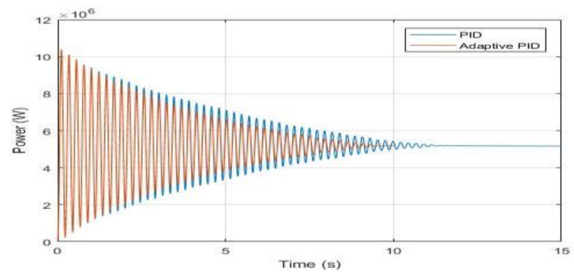

Fig. 9. Generated Power using Adaptive and PID controller during effectiveness loss

Case3:Dynamic Change Effect; High Air Content

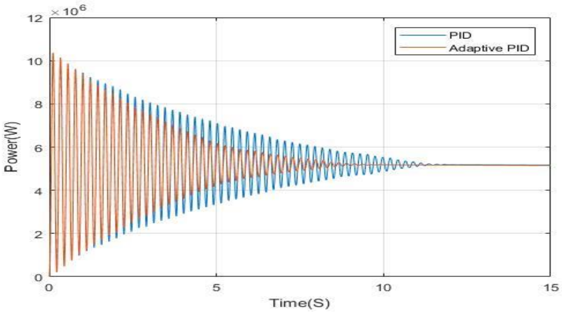

Fig. 10. Generated Power using Adaptive and PID controller during high air content in the oil

Case4: Pitch Actuator Bias = 10, Pump Wear

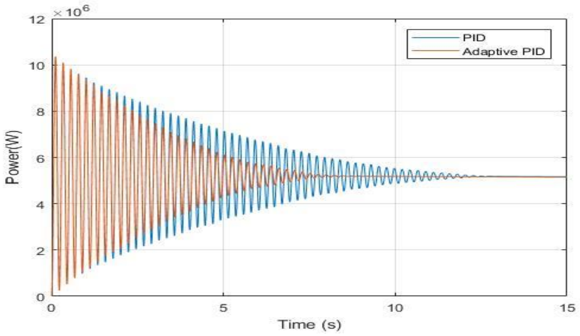

Fig. 11. Generated Power using Adaptive and PID controller during pitch actuator bias and pump wear

VI. CONCLUSION

In this paper, an adaptive fault tolerant controller with adaptive gain adjustment for non linear wind turbines is designed and simulated. The simulation results shows that the adaptive controller shows better robustness than a conventional PID controller, with less overshoot and shorter settling time, during both faulty and fault free cases. The proposed controller is robust against model uncertainties, unpredictable wind speed variations, unknown control direction and unexpected pitch actuator faults. Future studies may include the integration of controller for both operational regions considering the generator faults.

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