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Identification Based Control For Wind Turbine

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Abstract: The blade pitch angle control when the wind speed is above rated is considered in this paper. Finite-frequency identification approach is used to obtain the linearized model. The identification procedure can be carried out in closed loop in spite of fluctuating wind speed. PI controller coefficients determine limits for linearized model parameters for which the roots of characteristic equation of closed loop system are real-valued. If identified estimates of parameters are outside the limits maintained by previously designed PI controller then PI controller is tuned on the basis of obtained estimates. The simulation results show the high efficiency of the proposed approach.

Keywords: variable speed wind turbine, pitch control, PI control, identification, disturbance.

1. INTRODUCTION

Wind energy conversion to electric power is one of the most important problems of modern power engineering. The blade pitch angle control is considered in the paper. One of the main difficulties of this control is a significant nonlinearity of the mathematical model of the turbine rotor speed toward the pitch angle (Burton, T. et al. (2001)). Well-established PI and PID controllers are used for wind turbine control by pitch angle changing (Burton, T. et al. (2001), Leithead, W.E. et al. (2000)). More modern techniques H_2 and H_∞ are also practiced (Rocha, R. et al. (2005)). Recent papers utilised gain scheduling (Bianchi, F.D. et al. (2005)) , disturbance observer (Joo, Y. et al. (2012)), Maximum Power Point Tracking algorithm (Tilli, A. et al. (2011)), etc.

In all these techniques it is assumed that all parameters (or their limits) of the wind turbine are defined. In this paper it is assumed that controller has been obtained for known limits of the wind turbine parameters. But it is considered that blade aerodynamics can change in time and the wind turbine parameters go out of these limits. The finite-frequency identification method (Alexandrov, A.G. et al.(2011), Alexandrov, A.G. (2005),(1994)) is used in the paper for obtaining linearized model parameters. Advantages of this method are abilities to identify linearized model parameters on running turbine, in real time, in closed loop system, in spite of unknown external disturbances. Coefficients of controller can be changed based on identification results.

The case when the wind speed is above rated as operating region of pitch control is considered in the paper. In case of low wind with speed up to rated the pitch angle should be at minimum value for maximum power. This value may slightly differ from zero due to the design of wind turbine. In case of very strong wind more than 25-30 m/s the turbine is stopped for safety. Therefore the pitch controller operates in a limited range of wind speed.

2. PROBLEM STATEMENT

Control system of wind turbine is considered. It consists of the control object and the controller. The controller is blade pitch angle PI controller. The control object is considered in conditions when the wind speed is above rated and the pitch controller restricts wind turbine rotor speed while the torque controller tracks the rated power. In this case the control object is described by equation (Tilli, A. et al. (2011); Joo, Y. et al. (2012))

$$\dot{\omega} = \frac{\rho\pi}{2J\omega} R^2 V^3 C_p(\omega, \beta, V, c) - \frac{1}{J}\frac{P_R}{\omega}, \tag{1}$$

where ω is the measured turbine rotor speed, β is the controlled blade pitch angle, V is the wind speed, ρ is the air density, R is the blade rotor radius, J is the moment of inertia, P_R is rated power, $C_p(\omega, \beta, V, c)$ is the power coefficient as nonlinear function depended on turbine specifics with parameters vector c. This is a simplified model without detailed aerodynamics and mechanics and without generator and grid models.

The pitch angle β is the control value from PI controller

$$\beta = k_p(\omega - \omega_R) + z, \tag{2}$$

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$$\dot{z} = k_i(\omega - \omega_R), \quad (3)$$

where ω_R is the determined desired turbine rotor speed, z is the controller integrator output, k_p and k_i are positive PI coefficients.

Reasonable to assume that controlled blade pitch angle β is limited from 0 to 90 degrees. Although in practice these boundaries may be another.

Dinamics of pitch actuator, gear and torque controller are not considered for simplicity.

Let the right part of the equation (1) be denoted as

$$\varphi(\omega,\beta,v,c) = \frac{\rho\pi}{2J\omega}R^2V^3C_p(\omega,\beta,\mathrm{V},c) - \frac{1}{J}\frac{P_R}{\omega} \quad (4)$$

then the equation (1) takes the form

$$\dot{\omega} = \varphi(\omega,\beta,V,c). \quad (5)$$

The Taylor series for function (4) around the point $\omega_R, \beta_{st}, V_{st}$, where β_{st} provides speed ω_{ST} close to ω_R at a wind speed V_{st} is:

$$\varphi(\omega,\beta,V,c) = \varphi(\omega_R,\beta_{st},V_{st},c) + a(\omega-\omega_R) + b(\beta-\beta_{st}) + d(V-V_{st}) + \psi(\omega,R,V,c)$$

where

$$a = a(\omega_R,\beta_{st},V_{st},c) = \frac{\partial\varphi}{\partial\omega}|_{\omega_R,\beta_{st},V_{st}}, \quad (6)$$

$$b = b(\omega_R,\beta_{st},V_{st},c) = \frac{\partial\varphi}{\partial\beta}|_{\omega_R,\beta_{st},V_{st}}, \quad (7)$$

$$d = d(\omega_R,\beta_{st},V_{st},c) = \frac{\partial\varphi}{\partial V}|_{\omega_R,\beta_{st},V_{st}}, \quad (8)$$

$\psi(\omega,R,V,c)$ contains deviations in the second degree or higher.

In (6) $a < 0$ for the condition of the stability of the equation (1) therefore hereafter $-a$ where $a > 0$ will be used. Value b in (7) is always negative because rotor speed ω decreases when the β increases. Hereafter $-b$ where $b > 0$ will be used.

Let

$$y = \omega - \omega_R, \qquad u = \beta - \beta_{st}, \qquad V_d = V - V_{st} \quad (9)$$

Then linearized equation of wind turbine is

$$\dot{y} = -ay - bu + dV_d, \quad a > 0,\ b > 0 \quad (10)$$

Problem of identification: to find out estimates $\hat{a}, \hat{b}$ of parameters of the linearized model (10).

The need of identification is caused by the deformation of blades during continuous working of wind turbine which leads to undefined change of the power coefficient $C_p(\omega,\beta,V,c)$ in equation (1).

Identification is complicated by unknown variations of the wind speed V_d relatively constant V_{st}. Finite-frequency identification method (Alexandrov, A.G. (2005),(1994)) that works in spite of unknown external disturbances will be solving this problem.

The limits of parameters of the linearized model (10) a and b should be determined by coefficients k_p and k_i of PI controller (2),(3) such that the roots of the characteristic equation of closed loop system are real-valued:

$$A = [\underline{a},\ \overline{a}],\ B = [\underline{b},\ \overline{b}] \quad (11)$$

where $\underline{a}$, $\underline{b}$ are low limits and $\overline{a}$, $\overline{b}$ are high limits of the parameters.

Problem: if identified estimates $\hat{a}, \hat{b}$ are not within these limits then coefficients k_p and k_i should be tuned.

3. OPEN LOOP IDENTIFICATION

The system (1)-(3) with disabled PI controller is considered:

$$k_p = k_i = 0. \quad (12)$$

In this case pitch angle β is formed as a sum of β_{st} defined by operating point and test sine wave:

$$\beta = \beta_{st} + q\sin\gamma t \quad (13)$$

where γ is test frequency, q is amplitude of the test sine wave. The test sine wave parameters based on the finite-frequency identification method (Alexandrov, A.G. (2005)).

Then equation (10) has the form

$$\dot{y} = -ay - bq\sin\gamma t + dV_d. \quad (14)$$

A particular solution of this equation where the turbine rotor speed ω oscillates about ω_R is

$$y(t) = q\nu\sin\gamma t + q\mu\cos\gamma t + y_d, \quad (15)$$

where ν and μ are frequency parameters of object on the frequency γ; $y_d(t)$ is the output component depending on the wind speed fluctuations.

$\dot{y}(t)$ obtaining from (15) and $y(t)$ from (15) are pluged to (14). Then coefficients at sinγt and cosγt are equated. Thereby parameters a and b are expressed through frequency parameters ν and μ as

$$a = -\frac{\nu}{\mu}\gamma, \qquad b = \mu\gamma - a\nu \quad (16)$$

and conversely

$$\nu = -\frac{ba}{\gamma^2+a^2}, \qquad \mu = \frac{b\gamma}{\gamma^2+a^2} \quad (17)$$

Estimates of frequency parameters $\hat{\nu}$ and $\hat{\mu}$ are calculated as Fourier filter outputs on the frequency

$$\hat{\nu} = \nu(\tau) = \frac{2}{q\tau}\int_{t_F}^{t_F+\tau} y(t)\sin\gamma t\, dt \quad (18)$$

$$\hat{\mu} = \mu(\tau) = \frac{2}{q\tau}\int_{t_F}^{t_F+\tau} y(t)\cos\gamma t\, dt \quad (19)$$

where τ is filtering time, t_F is filtering start time. Fourier filter outputs converge for $\tau \to \infty$ to the true values if the wind speed does not contain harmonic oscillations with a frequency of γ (Alexandrov, A.G. (2005),(1994)). Implementation of frequency parameters $\hat{\nu}$ and $\hat{\mu}$ real-time calculation is acquainted (Alexandrov, A.G. et al.(2008))

Hence,

Algorithm 3.1 The open loop identification of a wind turbine consists of operations:

Step 1. To form the blades motion in accordance with the expression (13).

Step 2. To find out estimates of frequency parameters as Fourier filter outputs (18), (19).

Step 3. To calculate estimates of the object parameters by formulae (16) using estimates of frequency parameters.

4. CLOSED LOOP IDENTIFICATION

Let PI coefficients k_p and k_i be available. Then pitch angle β is formed as

$$\beta = k_p(\omega - \omega_R) + z + q \sin \gamma t \tag{20}$$

$$\dot{z} = k_i \cdot (\omega - \omega_R) \tag{21}$$

or using (9) as

$$u = k_p y + z + q \sin \gamma t, \quad \dot{z} = k_i y \tag{22}$$

Output of the system (10), (22) is

$$\bar{y}(t) = q\nu_y \sin \gamma t + q\mu_y \cos \gamma t + \bar{y}_d \tag{23}$$

and object input is

$$u(t) = q\nu_u \sin \gamma t + q\mu_u \cos \gamma t \tag{24}$$

where ν_y and μ_y are output frequency parameters which estimates can be calculated according to (18),(19), ν_u and μ_u are input frequency parameters which estimates can be calculated by formulae analogous as (18),(19) for $u(t)$ rather than $y(t)$.

Plugging (23),(24) into (10) similar as for (16),(17) ν_y and μ_y are expressed as

$$\nu_y = -b\frac{\nu_u a - \gamma\mu_u}{\gamma^2 + a^2}, \quad \mu_y = b\frac{-\mu_u a + \gamma\nu_u}{\gamma^2 + a^2} \tag{25}$$

or using (17) as

$$\nu_y = \nu_u \nu - \mu_u \mu, \qquad \mu_y = \mu_u \nu + \nu_u \mu \tag{26}$$

Frequency parameters of object ν and μ can be expressed from (26):

$$\nu = \frac{\nu_y \nu_u + \mu_y \mu_u}{\nu_u^2 + \mu_u^2} \tag{27}$$

$$\mu = \frac{\mu_y \nu_u - \nu_y \mu_u}{\nu_u^2 + \mu_u^2} \tag{28}$$

Estimates of ν_y, μ_y, ν_u, μ_u values are obtained by Fourier filter (18),(19). Hence,

Algorithm 4.1. The closed loop identification of a wind turbine consists of operations:

Step 1. To form the blades motion in accordance with the expression (20).

Step 2. To find out estimates of frequency parameters $\hat{\nu}_y$, $\hat{\mu}_y$, $\hat{\nu}_u$, $\hat{\mu}_u$ as Fourier filter outputs (18), (19) and to calculate frequency parameters of object by (27),(28).

Step 3. To calculate estimates of the object parameters by formulae (16).

In a real system it is needed to check that the torque controller should not react to our test sine wave.

5. PI COEFFICIENTS

Let estimates $\hat{a}$ and $\hat{b}$ be found. They will be used as values of the object parameters in the linearized equation (10).

PI controller formulae (2),(3) are written as

$$u = k_p y + z, \quad \dot{z} = k_i y \tag{29}$$

Differential equation obtaining after differentiating of equation (10) for $V_d = 0$ and excluding variable u is

$$\ddot{y} + (a + b\,k_p)\dot{y} + b\,k_i\,y = 0 \tag{30}$$

Then characteristic equation has the form

$$s^2 + (a + bk_p)s + bk_i = 0 \tag{31}$$

All parameters of this equation (a, b, k_p and k_i) are positive, so the roots of this characteristic equation have negative real parts. Conditions should be found so that these roots are real-valued to ensure the quality of transients. It is seen that this condition has the form

$$(a + bk_p)^2 - 4bk_i > 0 \tag{32}$$

or

$$a^2 + 2abk_p + b^2k_p^2 - 4bk_i > 0 \tag{33}$$

Sufficient conditions for validity of this inequation are

$$a > \frac{2k_i}{k_p} \tag{34}$$

or

$$b > 4\frac{k_i}{k_p{}^2} \tag{35}$$

Then low limits for parameters interval (11) for available coefficients k_p and k_i can be evaluated as

$$\underline{a} = \frac{2k_i}{k_p} \tag{36}$$

$$\underline{b} = 4\frac{k_i}{{k_p}^2} \quad (37)$$

High limits for parameters interval (11) are not evaluated because they can not violate the inequation (33) when low limits do not violate it.

Algorithm 5.1. PI coefficients correction.

Step 1. To identify estimates $\hat{a}, \hat{b}$ by Algorithm 3.1 or Algorithm 4.1.

Step 2. To check inequations (34),(35). If both of them are violated then inequation (33) is checked as condition of necessity and sufficiency.

Step 3. If inequation (33) is violated then coefficietn k_p is increased as

$$k_p > \frac{2k_i}{\hat{a}} \quad (38)$$

or

$${k_p}^2 > \frac{4k_i}{\hat{b}} \quad (39)$$

It should be considered that k_p is constrained by unmodelled dynamics of blades, gear etc. If because of that k_p can not be increased then k_i should be decreased for validity of inequation (34) or (35).

The procedure for starting the algorithm 5.1 is not discussed here. It may be started manually during maintenance or auto intermittently or as an event handling.

6. SIMULATION

The wind turbine is simulated by nonlinear model (1) where the power coefficient is approximated (Tilli, A. et al. (2011)) by

$$C_p(\omega,\beta,V,c) = c_1\left(c_2\frac{1}{L} - c_3\beta - c_4\right)e^{-\frac{c_5}{L}} - c_6\frac{\omega R}{V}, \quad (40)$$

$$\frac{1}{L} = \frac{V}{R\omega + 0.08\beta V} - \frac{0{,}035}{1+\beta^3}. \quad (41)$$

with the following parameters values (Tilli, A. et al. (2011)):

$$J = 40000\text{kg}m^2,\ \rho = 1.225\frac{kg}{m^3},\ R = 13m, \quad (42)$$

$$P_R = 200kW,\ \omega_R = 6.7\frac{rad}{s},\ V_{st} = 17\frac{m}{c},$$

$$c_1 = 0.5176,\ c_2 = 116,\quad c_3 = 0.4,\ c_4 = 5,$$

$$c_5 = 21,\ c_6 = 0.0068$$

6.1 Open loop identification simulation

Value of rotor speed $\omega_R = 6.7\frac{rad}{s}$ for $V_{st} = 17\frac{m}{c}$ is achieved by $\beta_{st} = 20.6245$ deg. The test signal for identification is formed as (13) where $q = 0.1$ and $\gamma = 0.1$. Figure 1 shows pitch angle values as the test signal and rotor speed values as the system response.

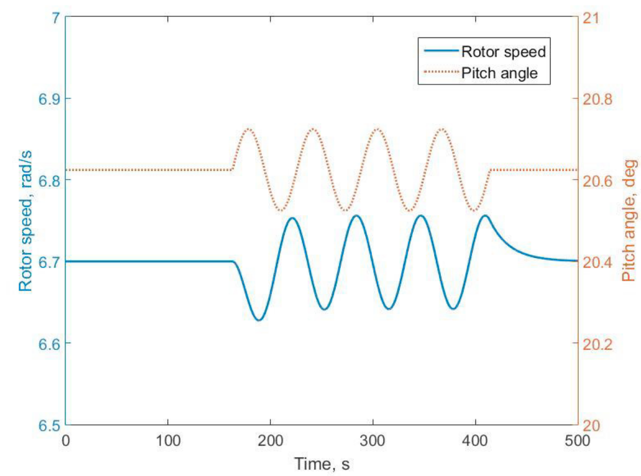

Fig.1. Object input/output during open loop identification

Algorithm 3.1 is used to obtain estimates of the object linearized model parameters from the data of this test:

$$\hat{a} = 0.04984,\ \hat{b} = 0.06414 \quad (43)$$

Simulation of nonlinear model (1),(40),(41) with parameters (42) and linearized model (10) with parameters (43) are carried out for step of β_{st} from 20.6245 deg to 20.7 deg. Figure 2 shows that outputs of these models are closely adjacent and estimates (43) are verified.

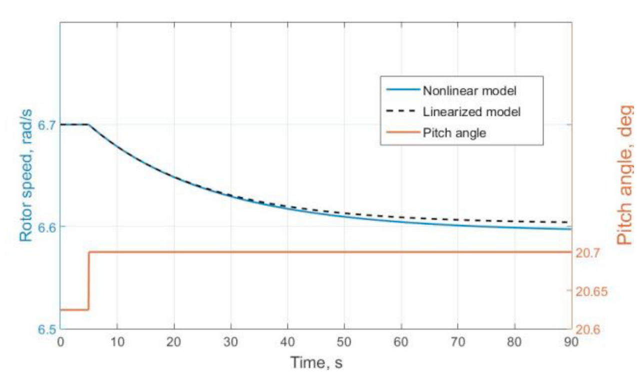

Fig 2. Step response of nonlinear and linearized models

6.2 Open loop identification for fluctuating wind speed simulation

Simulation of object (1),(40),(41) for test signal (13) with parameters $\beta_{st} = 20.6245$ deg, $q = 0.1$, $\gamma = 0.1$ when wind speed is V_{st} added by random value is shown on Figure 3.

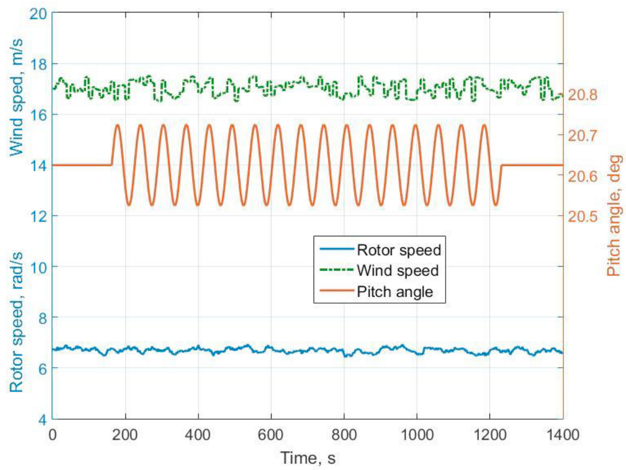

Fig.3. Object input/output during open loop identification for fluctuating wind speed

The shown wind speed is used for a simulation but identification procedure operates with the pitch angle (input) and rotor speed (output) data only.

Algorithm 3.1 returns estimates of the object linearized model parameters:

$$\hat{a} = 0.05499, \quad \hat{b} = 0.06398 \tag{44}$$

They do not differ significantly from estimates (43).

6.3 Closed loop identification simulation

The object (1) ,(40),(41) with parameters (42) with PI controller (2),(3) is simulated. Let PI coefficietns

$$k_p = 100 \text{ and } k_i = 10.$$

The pitch angle β is formed by (20),(21). Object input and output are shown on Figure 4.

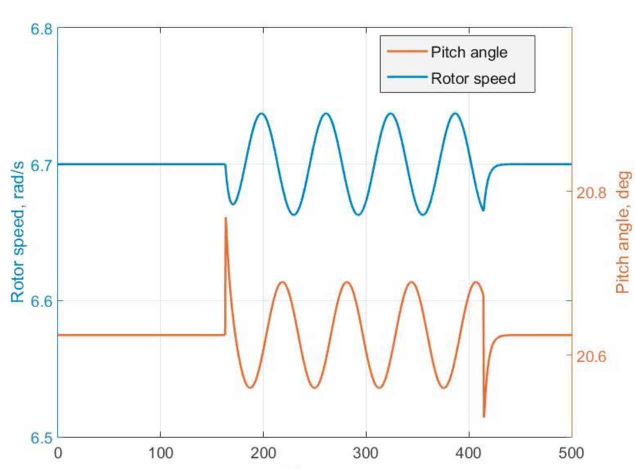

Fig.4. Object input/output during closed loop identification

Algorithm 4.1 return estimates of the object linearized model parameters:

$$\hat{a} = 0.04948, \quad \hat{b} = 0.06405 \tag{45}$$

It is practically the same values that were obtained by open loop identification.

6.4 Closed loop identification for fluctuating wind speed simulation

Closed loop identification when wind speed is V_{st} added by random value is shown on Figure 5.

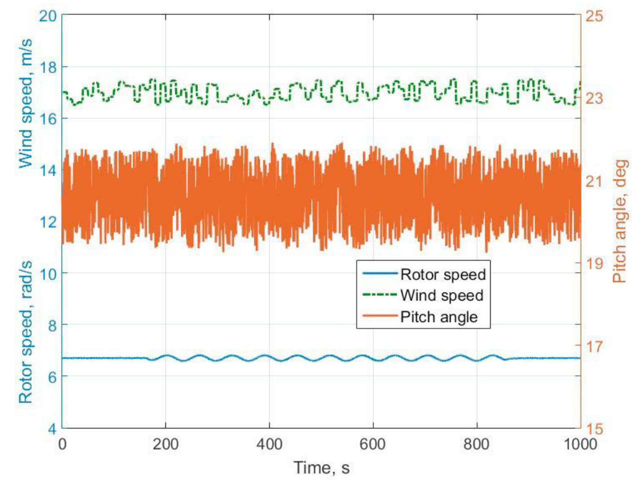

Fig.5. Object input/output during open loop identification for fluctuating wind speed

Estimates of the object linearized model parameters from the data of this test are obtained by Algorithm 4.1:

$$\hat{a} = 0.04917, \quad \hat{b} = 0.05793 \tag{46}$$

They do not differ significantly from previous estimates.

Obtained estimates obey inequations (34) and (35).

7. CONCLUSIONS

Approach to first order linearized model identification based on sine wave test signal is considered in the paper. The identification procedure can be carried out in closed loop in spite of fluctuating wind speed.

Results of first order linearized model identification can be the basis for PI controller tuning. Coefficients of PI controller are chosen from the condition that the roots of the characteristic equation of closed loop system of linearized model with PI controller are real-valued for wide limits of linearized model parameters. The simulation results show the high efficiency of the proposed approach.

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