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On power tracking and alleviation by a new controller for fulfilment of the damping and performance requisites for a variable speed wind system: An optimal approach

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A B S T R A C T

This paper addresses a new control strategy for a variable wind energy conversion system. The proposed controller aims to regulate the output power tightly in response to the desired value changes and alleviate power oscillations against the disturbances, including wind speed variation and fluctuation of the voltage magnitude, as voltage sag and swell. For the sake of straightforward analysis, an effective and reduced representation for the wind system is developed. In addition to the proper performance, the controller seeks to adequately fulfilment the damping requirements, as though both damping and performance requisites are taken into account control policy. Consequently, the proposed approach focuses on optimal tuning based upon a performance index incorporated into linear quadratic (LQ) cost function, which is subjected to the performance constraints. To validate the controller role, multiple simulation tests are carried out including set point tracking, disturbance rejection against wind speed, voltage sag and swell. Simulation results verify the proposed method features a satisfactory performance and sufficient damping, meeting both aspirations of the power regulation and disturbance suppression.

Introduction

Wind energy with a minimum environmental impact, easy availability and reasonable cost, is of great interest in recent years [1]. A variable speed system has the advantages of the suppressed mechanical load, noise reduction and high aerodynamic efficiency. Moreover more energy is captured over a wide range of the wind speed and active power and reactive power may be independently controlled [2,3]. Thus variable speed systems are preferred to fixed speed. Pitch-regulated turbines are more popular because stalled-pitch turbines attract more power and have more effective and smoother performance [4]. Recently, the full power configuration is of great attention due to the high controllability and flexibility [6]. Pulse width modulation (PWM) voltage source converter with 2-level output is considered the most common structure in full-rated wind energy conversion system (WECS); knowledge of this scheme is wide and is a matured technology [5].

Consequently, a variable speed system including the variable pitch wind turbine, the full power configuration, the back-back pulse width modulation (PWM) voltage-source converter and an induction generator is studied in this paper.

The controller objective includes the sufficient damping and tight regulation of active and reactive power against disturbances and in sympathy with set point variation. The focus of this study is to utilise a linear strategy. There are some literatures which have employed linear regulators. In [6], a linearised feedback controller was designed to regulate voltage and mechanical power for a specific operating point, and W. Chen and et al. tried to develop it, considering various disturbance conditions and pole placement technique [7]. For a variable WECS, a small signal model was dynamically represented by Tabesh et al. [8]. Some papers, such as Binachi et al. [9], utilised optimal gain scheduling technique to guarantee both the performance and the stability for a wind system. Incorporating into the damping indices, an optimal design was availed for small signal stability [10]. A damping controller was also designed using modal control theory and an eigenvalue method [11].

In this work, a state feedback controller (SFC) is designed based on a proposed method which has the following features:

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- Mechanical and electrical aspects both participate in the power control.
- A systematic approach based on LQ index is proposed to determine the weighting matrices. Another index of regulation performance is integrated into control policy. An optimisation tool allows the best response considering the predefined performance constrains.
- Augmentation representation of the system is employed to ensure sufficient damping and the tight regulation under the variable operating points; hence, the controller tracks desired signals and rejects disturbances appropriately.

This paper is organised as follows. Section 'Modelling' deals with the overall model of WECS including drive train, wind turbine, generator and power electronics converter. Section 'Controller design' is dedicated to controller design based on LQ index and the proposed approach. Finally, in Section 'Simulation results', simulation results are presented and analysed.

Modelling

Evaluation of the controller performance depends greatly on a valid model representation. Not only obtained model should be precise enough, but also it should neglect dynamics of the low participation in system performance to reduce computations and the total simulation time appropriately. Configuration of WECS under study is a single machine infinite bus (SMIB) (Fig. 1), including the variable speed wind turbine, the squirrel-cage induction generator, and a drive train. An SFC is utilised to control active and reactive power independently through the variable pitch turbine and the power electronics converter. The back-back pulse width modulation (PWM) voltage-source converter of the full power type is also employed to supply the required transferred reactive power into both generator and grid to have an acceptable power flow, as well as to decouple the generator frequency and grid frequency. Parameters of SMIB components are given in the Appendix A.

Induction generator

The dynamic equations governed by the induction machine can be written in a synchronously rotating d–q reference frame as follows [12]:

$$\dot{\Psi}_{qs} = -\omega_b \frac{r_s X_{rr}}{D} \Psi_{qs} - \omega_e \Psi_{ds} + \omega_b \frac{r_s X_M}{D} \psi_{qr} + \omega_b v_{qs} \tag{1}$$

$$\dot{\Psi}_{ds} = \omega_e \Psi_{qs} - \omega_b \frac{r_s X_{rr}}{D} \Psi_{qs} + \omega_b \frac{r_s X_M}{D} \psi_{dr} + \omega_b v_{ds} \tag{2}$$

$$\dot{\Psi}_{qr} = \omega_b \frac{r_r X_M}{D} \Psi_{qs} - \omega_b \frac{r_r X_{ss}}{D} \Psi_{qr} - (\omega_e - \omega_r)\psi_{dr}, \tag{3}$$

$$\dot{\Psi}_{qr} = \omega_b \frac{r_r X_M}{D} \Psi_{ds} + (\omega_e - \omega_r)\Psi_{qr} - \omega_b \frac{r_r X_{ss}}{D} \psi_{dr} \tag{4}$$

where v_{qs}, v_{ds} are the q-axis and d-axis of the stator voltages; Ψ_{qs}, Ψ_{ds}, Ψ_{qr}, Ψ_{dr} are the q-axis and d-axis of the stator and rotor fluxes; ω_e, ω_r, ω_b are angular speed of the synchronous reference frame, rotor angular speed and base angular speed; r_s, r_r are the stator and rotor resistances; $X_{ss} = X_{ls} + X_M$; $X_{rr} = X_{lr} + X_M$; $D = X_{ss}X_{rr} - X_M^2$, X_{ls}, X_{lr}, X_M are the stator leakage, rotor leakage and magnetising reactances, respectively.

Electromagnetic torque is described in terms of fluxes and the number of poles (p) as

$$T_e = \frac{3}{2}\frac{P}{2}\frac{X_M}{D\omega_b}(\Psi_{qs}\Psi_{dr} - \Psi_{ds}\Psi_{qr}) \tag{5}$$

Fluxes can be replaced with currents using the following coupled equation:

$$\begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} = \frac{1}{D}\begin{bmatrix} X_{rr} & 0 & -X_M & 0 \\ 0 & X_{rr} & 0 & -X_M \\ -X_M & 0 & X_{ss} & 0 \\ 0 & -X_M & 0 & X_{ss} \end{bmatrix}\begin{bmatrix} \Psi_{qs} \\ \Psi_{ds} \\ \Psi_{qr} \\ \Psi_{dr} \end{bmatrix} \tag{6}$$

Wind turbine model

Output mechanical power captured by the turbine is calculated by

$$P_t = \frac{1}{2}\rho_{air} A_r V_w^3 C_p(\lambda, \beta) \tag{7}$$

where ρ_{air} is the air density, A_r is the area swept by rotor blades, v_w is the wind speed, C_p is the power coefficient of the turbine which is a function of pitch angle (β) and $\lambda = \frac{\omega_t R}{v_w}$, the tip speed ratio, ω_t is the turbine rotor speed and R is the rotor radius. Estimation of C_p is given by Abdin and Xu [6]

$$C_p(\lambda, \beta) = (0.44 - 0.0167\beta)\sin\left(\frac{\pi(-3+\lambda)}{15 - 0.3\beta}\right) - 0.00184(-3+\lambda)\beta. \tag{8}$$

It is observed from (7) that output power is controllable by variable pitch angle. The pitch mechanism is represented as a first-order system, considering the amplitude and rate limiters of the pitch [12] (Fig. 2). A hydraulic pitch actuator with $\beta \in [-2, 30]$ and a rate limit of ±10°/s is used in this paper [13]. The dynamic of the pitch actuator in linear operating region can be written as

$$\dot{\beta} = \frac{1}{\tau_\beta}(\beta^* - \beta). \tag{9}$$

where β^* is the pitch set point and τ_β is the integral time constant.

A practical wind model is indispensable for a comprehensive evaluation of the controller performance. Wind speed model is complicated due to the intermittent nature of wind. One approach to represent wind speed, is defined by the supervision of four components: average value, a ramp component, a gust component, and turbulence component [14]. The simulation is performed in the time domain whilst the turbulence component is defined as a power spectral density in the frequency domain; thus the conversion of frequency domain value into a time sequence is complex. Another approach describes the wind speed as a random process based on a generic model, that is a power spectral density, as [15]

$$v_w = A_0 + \sum_{i=1}^{N} A_i \cos(\omega_i t + \varphi_i) \tag{10}$$

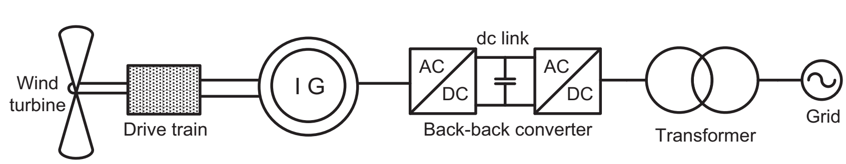

Fig. 1. System overview.