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Nonlinear maximum power point tracking control and modal analysis of DFIG based wind turbine

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ABSTRACT

The doubly fed induction generator based wind turbine (DFIG-WT) has strong nonlinearities originated from the aerodynamics of the wind turbine and the coupled dynamic of the DFIG, and can operate under a time-varying and wide operation region. This paper investigates a feedback linearisation controller based on the detailed model of the DFIG-WT, the control objective is to maximize energy conversion for this system. The original nonlinear system is partially linearized to a third-order linear system and a remained second-order internal nonlinear system. Fully decoupled control of the external dynamics is achieved, and the stability of the remained internal dynamics is analyzed via Lyapunov stability method. Moreover, modal analysis is applied for the nonlinear system controlled by the proposed nonlinear controller to verify its global optimal performance and low-voltage ride-through (LVRT) capability over various wind operation range. Simulation studies verify that more accurate tracking and better LVRT capability can be achieved in comparison with conventional vector control (VC).

Introduction

Nowadays, the doubly fed induction generator based wind turbine (DFIG-WT) has been one of popular wind power generation systems and widely installed in industry due to its merits of high energy conversion efficiency from variable speed operation and relative low-cost of power electronic converter [1]. The performance of DFIG-WT fully depends upon control systems applied on turbine side and generator side, which are generally designed via a cascade structure way including a fast inner-loop for power control of the DFIG and a slow outer-loop for speed control of the drive-train. In addition, wind turbine also utilizes pitch angle control to adjust the output power for wind speed above the rated speed. Below the rated wind speed, one of the crucial control task is to maximize the captured wind energy via variable speed operation, which requires the DFIG-WT must be fully controllable and operated at an optimal rotor speed according to time-varying wind speed, simultaneously minimizing the driven-train mechanical load [2].

In the past decade, modelling and control of DFIG-WT have attracted extensive research efforts [3]. Among those results, vector control (VC) with proportional-integral (PI) loops is the most usual control algorithm for the power regulation of the DFIG, due to the capability of decoupling control of active/reactive power and simple structure [4]. This approach is generally derived based on two basic assumptions, namely the constant stator flux or stator voltage, and negligible stator resistance [5–7]. However, the stator flux and stator voltage is no longer constant under grid faults or load variations. Moreover, the presence of small stator resistance will result in a poorly damped dynamics of stator flux. On the other hand, the dynamic of VC relies on the fine tuning of gains of PI controllers. Although the suitable range can be found via the observation of each mode loci using modal analysis [8–10], unsuitable control gains may result in Hopf bifurcation [12]. Their optimal parameters can be determined by other methods such as particle swarm optimization or genetic algorithm [13,11]. However, the parameter optimization is highly dynamic and requires a learning period until the optimal parameters found, which cannot provide consistent optimal performance with fast time-varying wind power inputs.

In fact, the DFIG-WT has strong nonlinearities originated from the aerodynamics of wind turbine and the coupled dynamic of the DFIG and operates under a time-varying and wide operation region according to turbulent wind power inputs. To tackle system

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nonlinearities, nonlinear control methodologies have been applied, such as a sliding mode controller for power extraction and improve the low voltage ride through capacity [14], a nonlinear backstepping approach for achieving optimal reference tracking and globally asymptotically stable in the context of Lyapunov theory [15], a passivity-based controller to maintain the beneficial system nonlinearities to improve the system transient responses [18], and several feedback linearisation controllers (FLC) including a decentralized FLC for improving the transient stability of power systems [16,17], and an adaptive FLC equipped with a disturbance observer for estimating parameter uncertainties [19]. These FLCs compensate system nonlinearities through exact linearisation and controlling of the equivalent linear system in order to provide a global optimal control performance across the whole operation region. Moreover, comparing with the cascade-structure used by VC, they are designed in an integrated way and the load of tuning PI loops gains is reduced as well. However, to achieve the fully linearisation, some works ignored the stator dynamic and used a third-order system model [16]. Due to this model simplification, the stator dynamics were ignored and not considered. In fact, the system relative degree is less than system order when the full-order model is used, and the stability of the remained internal dynamics should be addressed. Otherwise, the unstable internal dynamics will lead to an unbounded output [22].

This paper designs a FLC based on the detailed fifth-order DFIG-WT model to achieve maximum power point tracking (MPPT). Since the system nonlinearity is fully considered, including the stator dynamics, a global optimal control can be achieved under time-varying wind speed conditions. By choosing the tracking error of rotation speed and reactive power as outputs, the original nonlinear system has only been partially linearized to a third-order equivalent linear system and a remained second-order nonlinear internal dynamic system. The zero dynamics of the remained internal dynamics have been proven to be stable in the sense of Lyapunov such that the stability of the FLC is guaranteed. Moreover, the modal analysis is applied to the DFIG-WT equipped with FLC to investigate the consist and global optimal performance against different wind speeds and the improvement of LVRT capacity under voltage sags and drops. Simulation studies have been done to verify the effectiveness of the FLC-based MPPT.

The remainder of the paper is organized as follows. Section 'Dynamic model of DFIG-WT' is devoted to the basic development of DFIG-WT model. Section 'FLC of DFIG-WT' presents the nonlinear control design via rotor side converter (RSC), which includes input/output linearisation of the external dynamics. Section 'The stability of internal dynamics' proves the stability of internal dynamics in the sense of Lyapunov method. In Section 'Modal analysis and simulation study', the modal analysis is carried out to the DFIG-WT equipped with FLC at different operation points to evaluate the consist global optimal performance and the LVRT capability, whose effectiveness is verified by simulation studies. Section 'Conclusion' gives the conclusions.

Dynamic model of DFIG-WT

A schematic diagram of DFIG-WT is shown in Fig. 1. The wind turbine is connected to the induction generator through a mechanical shaft system, while the stator is directly connected to grid while rotor is fed through a back-to-back converter [3].

Wind turbine aerodynamic model

The aerodynamic model of a wind turbine can be characterized by the power coefficient $C_p(\lambda, \beta)$, which is a function of both tip-speed-ratio λ and blade pitch angle β, in which λ is defined by

$$\lambda = \frac{w_m R}{v_{wind}} \tag{1}$$

where R is the blade radius, ω_m is the wind turbine rotational speed and v_{wind} is the wind speed. Based on the wind turbine characteristics, a generic equation used to model $C_p(\lambda, \beta)$ is [8]

$$C_p(\lambda, \beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{-\frac{c_5}{\lambda_i}} + c_6\lambda \tag{2}$$

with

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

The coefficients c_1 to c_6 are: $c_1 = 0.5176$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = 21$ and $c_6 = 0.0068$ [23–25].

The mechanical power that wind turbine extracts from the wind is calculated as

$$P_m = \frac{1}{2}\rho\pi R^2 C_p(\lambda, \beta) v_{wind}^3 \tag{4}$$

where ρ is the air density. We consider the wind turbine operates in the sub-rated speed range hence its pitch control is deactivated such that $\beta \equiv 0$.

Generator model

The generator dynamics are described as followed [8]:

$$\frac{di_{qs}}{dt} = \frac{\omega_b}{L_s'}\left(-R_1 i_{qs} + \omega_s L_s' i_{ds} + \frac{\omega_r}{\omega_s}e_{qs}' - \frac{1}{T_r\omega_s}e_{ds}' - v_{qs} + \frac{L_m}{L_{rr}}v_{qr}\right) \tag{5}$$

$$\frac{di_{ds}}{dt} = \frac{\omega_b}{L_s'}\left(-\omega_s L_s' i_{qs} - R_1 i_{ds} + \frac{1}{T_r\omega_s}e_{qs}' + \frac{\omega_r}{\omega_s}e_{ds}' - v_{ds} + \frac{L_m}{L_{rr}}v_{dr}\right) \tag{6}$$

$$\frac{de_{qs}'}{dt} = \omega_b\omega_s\left[R_2 i_{ds} - \frac{1}{T_r\omega_s}e_{qs}' + \left(1 - \frac{\omega_r}{\omega_s}\right)e_{ds}' - \frac{L_m}{L_{rr}}v_{dr}\right] \tag{7}$$

$$\frac{de_{ds}'}{dt} = \omega_b\omega_s\left[-R_2 i_{qs} - \left(1 - \frac{\omega_r}{\omega_s}\right)e_{qs}' - \frac{1}{T_r\omega_s}e_{ds}' + \frac{L_m}{L_{rr}}v_{qr}\right] \tag{8}$$

where ω_b is the electrical base speed and ω_s is the synchronous angle speed; e_{ds}' and e_{qs}' are equivalent d-axis and q-axis (dq-) internal voltages; i_{ds} and i_{qs} are dq-stator currents; v_{ds} and v_{qs} are dq- stator terminal voltages; v_{dr} and v_{qr} are rotor voltages. The remained parameters can be found in Appendix A.

The electromagnetic torque T_e produced by the generator is obtained as

$$T_e = (e_{qs}'/\omega_s)i_{qs} + (e_{ds}'/\omega_s)i_{ds} \tag{9}$$

We align the q-axis with stator voltage and the d-axis leading the q-axis, hence, $v_{ds} \equiv 0$ and v_{qs} equals to the magnitude of the terminal voltage. Thus the reactive power Q_s can be obtained as

$$Q_s = v_{qs}i_{ds} - v_{ds}i_{qs} = v_{qs}i_{ds} \tag{10}$$

Shaft system model

The shaft system is simply modeled as a single lumped-mass system with the lumped inertia constant H_m, calculated by [23].

$$H_m = H_t + H_g \tag{11}$$

where H_t and H_g are the inertia constants of the turbine and the generator, respectively.

The electromechanical dynamic equation is then given by

$$\frac{d\omega_m}{dt} = \frac{1}{2H_m}(T_m - T_e - D\omega_m) \tag{12}$$

where ω_m is the rotational speed of the lumped-mass system and is equal to the generator rotor speed ω_r when both of them given in