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Modeling and control of DFIG-based variable-speed wind-turbine

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ABSTRACT

This paper presents a modeling and a control of doubly fed induction-generator (DFIG)-based variable-speed wind-turbine. A detail dynamic model of a DFIG-based wind-turbine grid-connected system is presented in the *dq*-synchronous reference frame. Along with conventional control schemes for wind turbine, an innovative voltage control scheme is proposed that manipulates dynamically the reactive power from the voltage-source converter (VSC) with taking into account its operating state and limits.

1. Introduction

Increased wind power generation has influenced the overall power system operation and planning in terms of power quality, security, stability, and voltage control [1–6]. The local power flow pattern and the system's dynamic characteristics change when large wind turbines (WTs) are connected to the utility grid [7].

Both fixed-speed and variable-speed WTs are presently used in Europe and North America. To achieve the required voltage regulation, fixed-speed WTs are often complemented by additional equipment and/or compensating devices that may be installed in close proximity or at a remote location [8–11]. Doubly fed induction generators (DFIGs) are also becoming popular for variable-speed WTs, particularly in North America, with the modern units often exceeding the 3 MW level [12]. Variable-speed WTs utilize power electronic converter technology that in addition to accommodating variable-speed operation also enables rapid control of real and reactive power [13].

In many WT applications, variable-speed operation is achieved by appropriately controlling the back-to-back voltage-source converters (VSC). There have been a great number of publications proposing various control solutions to achieve desirable dynamic performance and decoupled control of active and reactive power. Although different in implementation, most commonly used converters enable the WTs to maintain the required power factor (power factor control, PFC) or voltage (local voltage control, LVC) at the terminals [14–17]. The rotor-side converter provides the active and the reactive power necessary to attain the control objectives for either the PFC or the LVC modes. The grid-side converter is connected to electric utility through a filter. Its main objective is to maintain the DC-link capacitor voltage by exchanging the active power with the grid. Consequently, PFC-mode is often used for maximum active power exchange with the grid.

Mostly, undesirable interferences with the protection circuitry and/or the trip of WTs are caused when DC-voltage in DC-link reaches its limit. From this point of view, it is desirable to minimize and/or suppress the voltage swings at the terminal of WT. To achieve this objective, an innovative reactive power control methodology is presented in the rotor-side converter and the grid-side converter.

Without loss of generality, in this paper, a dynamic model of wind power system composed of typical industrial DFIG-based WT is developed to demonstrate and validate the proposed control methodology. Since the focus of this paper is on the wind-energy-system, the detailed PWM switching of converters is not represented, and instead the converters are modeled using controllable voltage sources assuming linear modulation region as it is commonly done in literature [13–18]. However, the transient studies are conducted using full-order models of machines and other relevant components of the system. The performance of various controllers is evaluated in the presence of noise. Overall, computer studies demonstrate potential improvements that can be achieved with the proposed supervisory control scheme.

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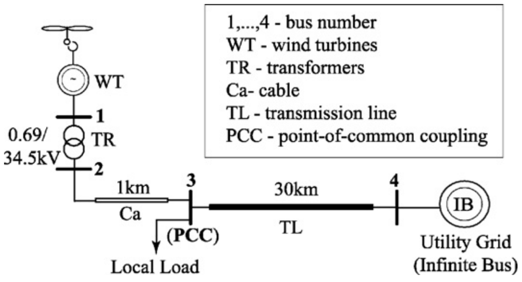

Fig. 1. Grid-connected wind-turbine system.

This paper is organized as follows: The study system is described in Section 2; in Section 3, the VSC control design is presented; the reactive power control scheme and the control design is proposed in Section 4 and Section 5, respectively; the case studies are carried out in Section 6; and conclusions are drawn in Section 7.

2. Study system of grid-connected DFIG-based variable-speed wind-turbine

Fig. 1 shows a simplified diagram of system considered in this paper. Here, the WT is equipped with a step-up 0.69 kV/34.5 kV transformer (TR). The WT is connected to the point-of-common coupling (PCC, bus 3) by 1 km cable. The WT and the utility grid are connected through the 132 kV transmission line (TL, 30 km). Here, the utility grid is represented by an infinite-bus. The details of the WT considered in the model are shown in Fig. 2. The data for a 2 MW wind turbine considered in this analysis is given in Appendix A [19]. The WT consists of a three-bladed rotor with the corresponding pitch controller, a mechanical gearbox, a DFIG with two converters, a DC-link capacitor, and a grid filter.

Including the DFIG, the individual components of electrical subsystem including a transformer, a cable, and a transmission line are modeled using the *dq*-synchronous reference frame [20]. Wherein, *d*-axis is assumed to be aligned to stator flux, and the current coming out of the generator is considered positive. The DFIG controllers utilize the concept of disconnection of the active and reactive power controls by transformation of the machine parameters into the *dq*-reference frame and by separating forming of the rotor voltages. Then, the active power can be controlled by influencing the *d*-axis component of the rotor current while the reactive power can be controlled by influencing the *q*-axis components of the rotor current.

The system parameters, operating conditions, controller gains, etc., are given in Appendix A and also more details can be found in [21]. The mathematical models for the electrical components and the mechanical components are as follows:

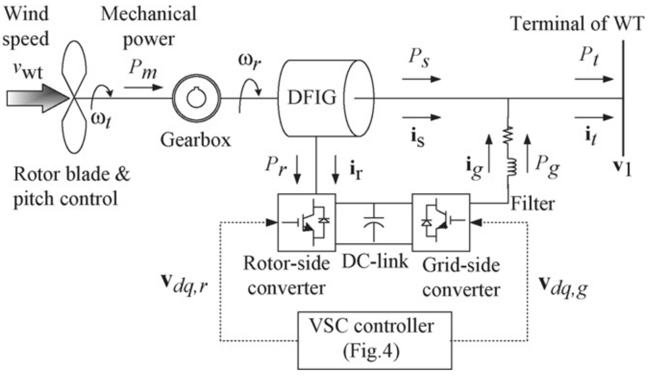

Fig. 2. Doubly fed induction-generator wind-turbine.

2.1. Double-fed induction generator

The DFIG was represented by the following equations

$$\begin{aligned}
\frac{1}{\omega_b}\frac{d\psi_{ds}}{dt} &= R_s i_{ds} + \omega_e \psi_{qs} + v_{ds}\\
\frac{1}{\omega_b}\frac{d\psi_{qs}}{dt} &= v_{qs} + R_s i_{qs} - \omega_e \psi_{ds}\\
\frac{1}{\omega_b}\frac{d\psi_{dr}}{dt} &= v_{dr} + R_r i_{dr} + \omega_s \psi_{qr}\\
\frac{1}{\omega_b}\frac{d\psi_{qr}}{dt} &= v_{qr} + R_r i_{qr} - \omega_s \psi_{dr}
\end{aligned} \tag{1}$$

with

$$\begin{aligned}
\psi_{ds} &= -(L_s + L_m) i_{ds} - L_m i_{dr}, & \psi_{qs} &= -(L_s + L_m) i_{qs} - L_m i_{qr}\\
\psi_{dr} &= -(L_r + L_m) i_{dr} - L_m i_{ds}, & \psi_{qr} &= -(L_r + L_m) i_{qr} - L_m i_{qs}
\end{aligned} \tag{2}$$

where v is the voltage, R is the resistance, i is the current, ω_e and $\omega_s = \omega_e - \omega_r$ are the stator and slip electrical angular speed, respectively, ω_r is the rotor electrical angular speed, ω_b is the base angular speed in rad/s, L_m is the mutual inductance, L_s and L_r are the stator and rotor leakage inductance, respectively, and ψ is the flux linkage. The subscripts *d* and *q* indicate the direct and quadrature axis components, respectively. The subscripts s and r indicate stator and rotor quantities, respectively. The electrical active and reactive power delivered by the stator are given by

$$P_s = v_{ds} i_{ds} + v_{qs} i_{qs}, \qquad Q_s = v_{ds} i_{qs} - v_{qs} i_{ds} \tag{3}$$

2.2. Dynamic model of transmission line, transformer, cable, and load

The mathematical model of a TL, a TR, a cable, and a load can be found from the description of the R, L, C segment into the *dq*-synchronous reference frame [19]. The equations of the TL, the TR, the cable, the RL-filter on the grid-side converter, and the load are given in (4)–(8). For the formulation of the TR and the load, for the numerical purpose, small capacitors ($C_o = 1\,e^{-6}$ pu) are used to the sending-end with removing two capacitors, and the sending-end capacitors are only considered in the case of formulating the cable since its capacitance contributes to the reactive power (Fig. 3).

Transmission line (TL)

$$\begin{aligned}
&\frac{L_{TL}}{\omega_b}\frac{di_{dl}}{dt} = v_{d2} - v_{d1} - R_{TL} i_{dl} + \omega_e L_{TL} i_{ql}\\
&\frac{L_{TL}}{\omega_b}\frac{di_{ql}}{dt} = v_{q2} - v_{q1} - R_{TL} i_{ql} - \omega_e L_{TL} i_{dl}\\
&\frac{C_{TL}}{\omega_b}\frac{dv_{d1}}{dt} = i_{dc1} + \omega_e C_{TL} v_{q1}, \qquad \frac{C_{TL}}{\omega_b}\frac{dv_{q1}}{dt} = i_{qc1} - \omega_e C_{TL} v_{d1}\\
&\frac{C_{TL}}{\omega_b}\frac{dv_{d2}}{dt} = i_{dc2} + \omega_e C_{TL} v_{q2}, \qquad \frac{C_{TL}}{\omega_b}\frac{dv_{q2}}{dt} = i_{qc2} - \omega_e C_{TL} v_{d2}
\end{aligned} \tag{4}$$

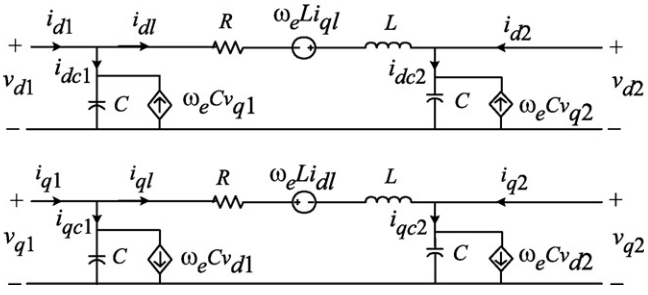

Fig. 3. Lumped TL description in the *dq*-domain.