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Modeling and enhanced control of DFIG under unbalanced grid voltage conditions

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ABSTRACT

This paper presents a mathematical model of a doubly fed induction generator (DFIG) based on stator voltage orientation (SVO) in the positive and negative synchronous reference frames under unbalanced grid voltage conditions. The oscillations of the DFIG electromagnetic torque and the stator active and reactive powers are fully described during grid voltage unbalance. A new rotor current controller implemented in the positive synchronous reference frame is proposed. The controller consists of a proportional integral (PI) regulator and a harmonic resonant (R) compensator tuned at twice the grid frequency. Thus, the positive and negative sequence components of DFIG rotor currents are directly regulated by the PI + R controller without the need of involving positive and negative sequence decomposition, which indeed improves the dynamic performance of DFIG-based wind power generation system during small steady-state and relatively larger transient network unbalances. The theoretical analysis and the feasibility of the proposed unbalanced control scheme are validated by simulation studies on a 1.5-MW wind-turbine driven DFIG system. Compared with conventional single PI current control design, the proposed control scheme results in significant elimination of either DFIG power or torque oscillation under unbalanced grid voltage conditions.

1. Introduction

Wind energy has become one of the subjects of much recent research and development all over the world. Among the various types of wind turbines, the variable-speed wind turbines based on the doubly fed induction generator (DFIG), which have many advantages over the fixed-speed generators, including variable-speed constant frequency (VSCF) operation, reduced flicker and independent control capabilities for active and reactive powers, have attracted particular attention [1]. These excellent merits are primarily achieved via the control of a rotor-connected back-to-back PWM voltage source converter, which is typically rated at around 30% of the generator rating for a given rotor speed range of 0.75–1.25 pu under normal operation conditions. Thus, the converter cost becomes relatively lower than other types of wind power generation systems.

The steady-state and transient response of DFIG-based wind power generation system under symmetrical supply voltage have been well understood [1–4]. Practically, both transmissions and distribution networks can experience voltage unbalance. If this is not taken into account by the DFIG control system, the wind turbines might have to be disconnected from the network under unbalanced grid voltage conditions [5] due to the excessive stator current imbalances and power and torque oscillations. Whereas, the emerging grid codes require wind turbines to withstand a maximum value of 2% steady-state phase-voltage unbalance without disconnection [6].

The system control and operation of wind-turbine driven DFIG under unbalanced grid voltage conditions were studied in [5,7–11]. In [7,8] the focus was purely on compensating torque pulsation during grid voltage unbalance. The compensated rotor voltage was generated directly from the double-frequency oscillating terms of either the torque [7] or the calculated current compensation [8]. As a result, the PI current controller must be carefully tuned at twice the grid frequency to provide the required system response. While in [5,9], the grid-side converter was controlled to behave as a STATCOM. In [10], an extended vector control of doubly fed machine under unbalanced network conditions was proposed, which was implemented in the positive and negative synchronous reference frames, respectively. Ref. [11] presented an investigation into the impact of unbalanced stator voltage on the pulsations of stator and rotor currents, electromagnetic torque, and stator active and reactive powers. Similar to [10], a dual rotor current PI controller based on stator flux orientation (SFO) was employed, which necessitated

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the decomposing of positive and negative sequence rotor currents. Since the decomposing process of positive and negative sequence components involves considerable time delay and leads to errors in amplitude and phase with respect to the original signals, the systems cannot be fully decoupled during the transient conditions. As a result, the system performance and stability are degraded. Furthermore, even when the grid voltage is perfectly balanced, the control system still has to perform the decomposition process and to implement the regulation of the positive and negative sequence currents, respectively, which unnecessarily affects the transient performance of the whole control system.

This paper firstly presents a DFIG mathematical model, in the positive and negative synchronous reference frames, which is based on stator voltage orientation (SVO). To provide enhanced control and operation of DFIG-based wind turbine systems during network unbalance, four alternative control targets are introduced to verify the DFIG model. A new rotor current controller, which consists of a proportional integral (PI) regulator plus a harmonic resonant (R) compensator tuned at twice the grid frequency is proposed. The controller is implemented in the positive synchronously rotating reference frame without involving the decomposition of positive and negative sequence rotor currents. Finally, simulation studies on a 1.5-MW DFIG system during small steady-state and relatively larger transient network unbalance are provided to demonstrate the feasibility and performance of the proposed control scheme.

2. Dynamic DFIG model based on SVO

An investigation on DFIG model and system behavior based on SFO under unbalanced grid voltage conditions has been provided in [11]. As indicated in [12], in contrast to SFO, SVO results in the system stability and damping being independent of the rotor current. Thus in this section a modified DFIG model based on SVO is presented.

2.1. DFIG model

Fig. 1 shows the spatial relationships between the stationary $(\alpha\beta)_s$ reference frame, the rotor $(\alpha\beta)_r$ reference frame rotating at the speed of ω_r, and the dq^+ and dq^- reference frames rotating at the angular speed of ω_s and $-\omega_s$, respectively. As shown, the d^+-axis of the dq^+ reference frame is fixed to the positive sequence stator voltage V^+_{sd+}. According to Fig. 1, the transformations between $(\alpha\beta)_s$, $(\alpha\beta)_r$ and dq^+ and dq^- reference frames are given by

$$\boldsymbol{F}^+_{dq} = \boldsymbol{F}_{(\alpha\beta)_s}\,\mathrm{e}^{-j\omega_s t} \quad \boldsymbol{F}^-_{dq} = \boldsymbol{F}_{(\alpha\beta)_s}\,\mathrm{e}^{j\omega_s t}, \tag{1a}$$

$$\boldsymbol{F}^+_{dq} = \boldsymbol{F}^-_{dq}\,\mathrm{e}^{-2j\omega_s t} \quad \boldsymbol{F}^-_{dq} = \boldsymbol{F}^+_{dq}\,\mathrm{e}^{2j\omega_s t}, \tag{1b}$$

$$\boldsymbol{F}^+_{dq} = \boldsymbol{F}_{(\alpha\beta)_r}\,\mathrm{e}^{-j2\omega_{\mathrm{slip}+}t} \quad \boldsymbol{F}^-_{dq} = \boldsymbol{F}_{(\alpha\beta)_r}\,\mathrm{e}^{j2\omega_{\mathrm{slip}-}t}. \tag{1c}$$

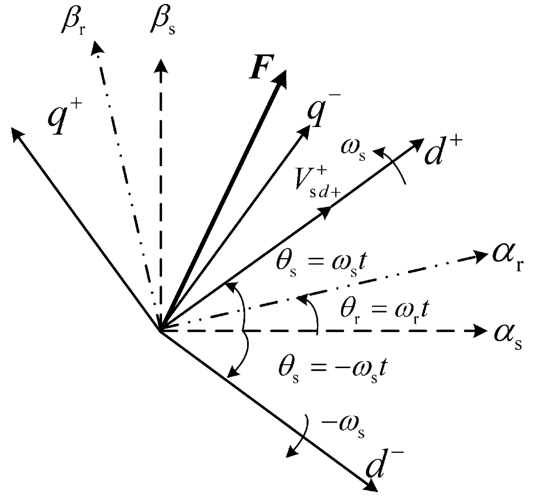

Fig. 1. Relationships between $(\alpha\beta)_s$, $(\alpha\beta)_r$ and dq^+ and dq^- reference frames.

where $\boldsymbol{F}$ represents the voltage, current and flux and superscripts +,− represent the positive and negative synchronously rotating reference frames, respectively, $\omega_{\mathrm{slip}+} = \omega_s - \omega_r$ and $\omega_{\mathrm{slip}-} = -\omega_s - \omega_r$.

The equivalent circuit of a DFIG in the dq^+ reference frame is shown in Fig. 2.

According to Fig. 2, the stator and rotor voltages and fluxes are given, respectively, by

$$\boldsymbol{V}^+_{sdq} = R_s\boldsymbol{I}^+_{sdq} + \frac{\mathrm{d}\boldsymbol{\psi}^+_{sdq}}{\mathrm{d}t} + j\omega_s\boldsymbol{\psi}^+_{sdq}, \tag{2}$$

$$\boldsymbol{V}^+_{rdq} = R_r\boldsymbol{I}^+_{rdq} + \frac{\mathrm{d}\boldsymbol{\psi}^+_{rdq}}{\mathrm{d}t} + j\omega_{\mathrm{slip}+}\boldsymbol{\psi}^+_{rdq}, \tag{3}$$

$$\boldsymbol{\psi}^+_{sdq} = \boldsymbol{L}_s\boldsymbol{I}^+_{sdq} + \boldsymbol{L}_m\boldsymbol{I}^+_{rdq} \qquad \boldsymbol{\psi}^+_{rdq} = \boldsymbol{L}_m\boldsymbol{I}^+_{sdq} + \boldsymbol{L}_r\boldsymbol{I}^+_{rdq}, \tag{4}$$

where, $L_s = L_{\sigma s} + L_{\mathrm{m}}$ and $L_r = L_{\sigma r} + L_m$ are the total stator and rotor self-inductances, respectively.

According to (1) and Fig. 1, the stator and rotor current, voltage and flux vectors can be expressed in terms of their respective positive and negative sequence components in the positive and negative synchronous reference frames as

$$\boldsymbol{F}^+_{sdq} = \boldsymbol{F}^+_{sdq+} + \boldsymbol{F}^+_{sdq-} = \boldsymbol{F}^+_{sdq+} + \boldsymbol{F}^-_{sdq-}\,\mathrm{e}^{-j2\omega_s t}, \tag{5}$$

where subscripts +,− represent positive and negative sequence components.

According to (4), the rotor flux and stator current can be calculated as

$$\boldsymbol{\psi}^+_{rdq} = \frac{L_m\boldsymbol{\psi}^+_{sdq}}{L_s} + \sigma L_r\boldsymbol{I}^+_{rdq}, \tag{6}$$

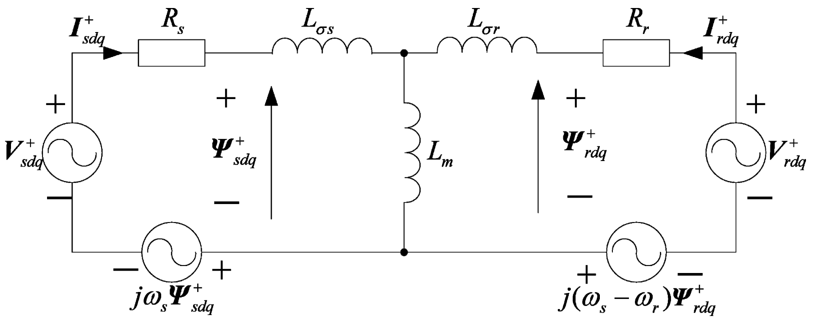

Fig. 2. DFIG equivalent circuit in the positive synchronous reference frame rotating at ω_s.