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Dynamic modeling and optimal control of DFIG wind energy systems using DFT and NSGA-II

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ABSTRACT

Once a doubly-fed induction generator (DFIG) is subjected to a disturbance by a change in the wind speed, the stator flux cannot change instantly. Under this condition, rotor back-EMF voltages reflect the effects of stator dynamics on rotor current dynamics, and have an important role on the oscillations of the rotor current. These oscillations decrease the DFIG system reliability and gear lifetime. Moreover, by focusing only on small signal analysis, the dynamic damping performance immediately following such disturbances is often degraded. Additional improvement in performance will be achieved if discrete Fourier transform (DFT) is used to quantify damping characteristic of the rotor current during changes of the operating points. This paper introduces an optimization technique based on non-dominated sorting genetic algorithm-II (NSGA-II) incorporating DFT analysis to achieve better control performance for DFIG system stability. Considering small signal stability, the main purpose of the control system in the present paper is to increase the system damping ratio as well as to guarantee enough stability margin. Eigenvalue analysis and time-domain simulations have been presented to demonstrate that the proposed optimizing method yields better control performance in comparison with one designed using mere eigenvalue relocation.

1. Introduction

In the development of wind turbine (WT) technologies, doubly-fed induction generators (DFIGs) are becoming the dominant type due to their advantages of variable speed operation, four-quadrant active and reactive power capabilities, independent control of their active and reactive output powers, high energy efficiency, and low size converters [1–4]. A diagram of a grid-connected DFIG-based wind energy generation system is shown in Fig. 1, which is composed of a wind turbine and gear-box, a wound rotor induction generator, a rotor-side converter (RSC) and a grid-side converter (GSC). Grid-side converter works at the grid frequency, leading or lagging in order to produce more or less reactive power while RSC works at different frequencies, depending on the blades speed [5,6]. Consequently, the speed can be varied while the operating frequency on the stator side remains constant. Rotor-side converter is used to control the generator speed and reactive power, whereas the GSC is connected to the grid through a grid-side filter and is used to control the DC-link voltage.

Due to the popularity of DFIG systems for wind energy generation, control systems suitable for this application have been extensively investigated [7–12]. However, the most popular and practical control scheme of DFIGs is still field-oriented control (FOC) based on proportional-integral (PI) controllers, which enables decoupled control of real and reactive powers [13–15]. FOC has been implemented in two ways. One way is to control the DFIG with stator flux orientation, and the other is with air gap flux orientation. This paper deals with the analysis and improvement of transient performance in the DFIG modeled with the stator flux orientation. In this control scheme, the nonlinear cross coupling is eliminated with feed-forward compensation, after which the machine model becomes linear and PI control techniques can be applied. Thus, the active and reactive powers can be controlled by the quadrature and the direct rotor current components, respectively. Appropriate controller parameters are needed to achieve better control performance for DFIG system stability. For this purpose, evolution algorithms have been used as optimization tools in the DFIG controller parameters design procedure [16–20]. For instance, in Ref. [17], genetic algorithm has been applied to optimize the controller parameters of the RSC, and hence, larger oscillations of the DC-link voltage cannot be avoided. Particle swarm optimization has been also employed to find the optimal control parameters in order to achieve optimal control of DFIG

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$\omega_b, \omega_s, \omega_r, \omega_t, \omega_2$ base, synchronous, rotor, turbine and rotor slip angular frequency
$V_{dqs}, V_{dqr}, V_{dqg}, e_{dq}$ stator, rotor, grid-side filter and back-EMF dq-axis voltages
$i_{dqs}, i_{dqr}, i_{dqg}$ stator, rotor and grid-side filter dq-axis currents
L_s, L_r, L_m stator and rotor self-inductances and mutual inductance
R_s, R_r stator and rotor resistance
R_g, L_g grid-side filter resistance and inductance
ψ_{dqs}, ψ_{dqr} stator and rotor dq-axis fluxes
H_r, H_t inertia constants of generator and turbine
D, K_s, β damping and shaft stiffness coefficient, and shaft twist angle
ρ, R, V_ω, β_p air density, wind turbine blade radius, wind speed, and pitch angle

multiple controllers in [18,19]. Another early algorithm uses bacteria foraging optimization to improve the damping of oscillatory modes in the DFIG wind turbine [20]. However, single objective and single operating point conditions have been considered in most of the algorithms. Therefore, robust damping performance for changed operating conditions cannot be obtained.

This paper introduces a new procedure for optimal controller design of DFIG based on both eigenvalue analysis and DFT to quantify the oscillations damping of DFIG transient response. Non-dominated sorting genetic algorithm-II (NSGA-II) is used to obtain the optimal controller parameters so as to obtain well damping performance as well as sufficient stability margin under variations of operating points. It is found that the proposed optimizing method yields a better control performance in comparison with a design merely based on eigenvalue relocation.

2. DFIG model

The global rotating reference frame of the DFIG system by a d_1- and q_1-axis rotating at the angular frequency of ω_s is shown in Fig. 2. The global reference frame is defined on infinite bus bar with the d_1-axis in the direction of the voltage space vector of V_{inf}. The local reference frame of the stator flux is depicted by d_2- and q_2-axis rotating at dynamic speed ω, in which the position of the d_2-axis coincides with the maximum of the stator flux (i.e., $\psi_{ds} = \psi_s$ and $\psi_{qs} = 0$). Using the motor convention, the following set of equations modeling the DFIG generator can be derived [21]:

$$\dot{\psi}_{ds} = \omega_b(V_{ds} - R_s i_{ds} + \omega\psi_{qs}) \tag{1a}$$

$$\dot{\psi}_{qs} = \omega_b(V_{qs} - R_s i_{qs} - \omega\psi_{ds}) \tag{1b}$$

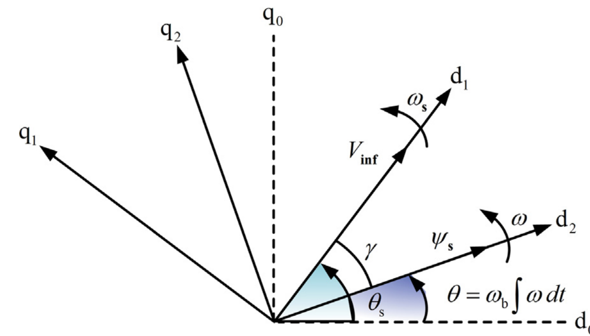

Fig. 2. Phasor diagram of field-oriented DFIG system.

$$\dot{\psi}_{dr} = \omega_b(V_{dr} - R_r i_{dr} + \omega_2\psi_{qr}) \tag{1c}$$

$$\dot{\psi}_{qr} = \omega_b(V_{qr} - R_r i_{qr} - \omega_2\psi_{dr}) \tag{1d}$$

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr}, \quad \psi_{qs} = L_s i_{qs} + L_m i_{qr} \tag{1e}$$

$$\psi_{dr} = L_m i_{ds} + L_r i_{dr}, \quad \psi_{qr} = L_m i_{qs} + L_r i_{qr} \tag{1f}$$

$$T_e = \frac{L_m(\psi_{qs} i_{dr} - \psi_{ds} i_{qr})}{L_s} \tag{1g}$$

$$P_s = V_{dr} i_{dr} + V_{qr} i_{qr}, \quad P_r = V_{dr} i_{dr} + V_{qr} i_{qr} \tag{1h}$$

$$Q_s = V_{ds} i_{qs} - V_{qs} i_{ds} \tag{1i}$$

2.1. Rotor modeling

From (1a)–(1f), the rotor dynamics are given by:

$$\dot{i}_{dr} = \omega_b \frac{-R'_r i_{dr} + \omega_2 L'_r i_{qr} - e_d + V_{dr}}{L'_r} \tag{2a}$$

$$\dot{i}_{qr} = \omega_b \frac{-R'_r i_{qr} - \omega_2 L'_r i_{dr} - e_q + V_{qr}}{L'_r} \tag{2b}$$

$$e_d = L_m \frac{V_{ds} + \omega_r\psi_{qs} - R_s\psi_{ds}/L_s}{L_s} \tag{2c}$$

$$e_q = L_m \frac{V_{qs} - \omega_r\psi_{ds} - R_s\psi_{qs}/L_s}{L_s} \tag{2d}$$

where $L'_r = L_r - (L_m^2/L_s)$, $R'_r = R_r + (L_m/L_s)^2 R_s$ and $\omega_r = \omega - \omega_2$. The configuration of the controllers for the DFIG system is shown in Fig. 3. As it can be seen, the actual d–q current signals i_{dqr} are compared with their reference signals i_{dqr}^{ref} to generate the error signals, which are passed through two PI controllers and these signals

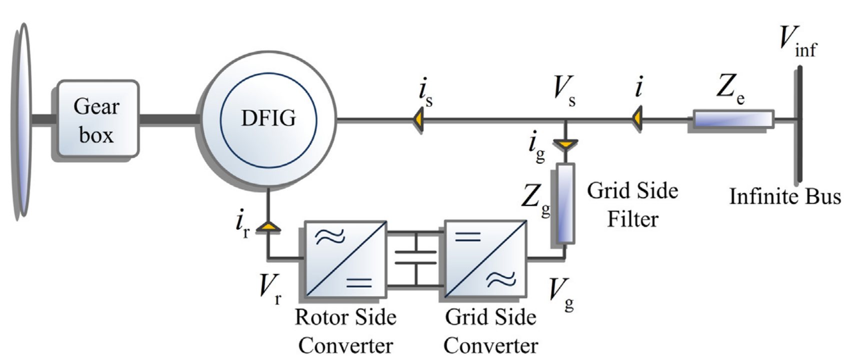

Fig. 1. Schematic diagram of DFIG system.