Optimized Control of DFIG-Based Wind Generation Using Sensitivity Analysis and Particle Swarm Optimization

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***Abstract*—Optimal control of large-scale wind farm has become a critical issue for the development of renewable energy systems and their integration into the power grid to provide reliable, secure, and efficient electricity. Among many enabling technologies, the latest research results from both the power and energy community and computational intelligence (CI) community have demonstrated that CI research could provide key technical innovations into this challenging problem. In this paper, we propose a sensitivity analysis approach based on both trajectory and frequency domain information integrated with evolutionary algorithm to achieve the optimal control of doubly-fed induction generators (DFIG) based wind generation. Instead of optimizing all the control parameters, our key idea is to use the sensitivity analysis to first identify the critical parameters, the unified dominate control parameters (UDCP), to reduce the optimization complexity. Based on such selected parameters, we then use particle swarm optimization (PSO) to find the optimal values to achieve the control objective. Simulation analysis and comparative studies demonstrate the effectiveness of our approach.**

***Index Terms*—Computational intelligence, DFIG, optimized control, particle swarm optimization, sensitivity analysis, smart grid.**

I. INTRODUCTION

WITH THE continuous increase of energy demand and environment concerns, the development of a smart electric power grid has become a critical research topic world widely [1], [2]. To tackle the critical challenges and develop a truly smart grid, extensive efforts have been devoted into this area at different levels, ranging from academic research, industrial research and development (R&D), to government policy makers [1]–[4]. While the entire smart grid system is an extremely complicated integrative technology and social system, in this paper we focus on one of the critical components to the whole picture, optimal control of wind turbine (WT) with doubly-fed induction generators (DFIG) based on sensitivity analysis and particle swarm optimization (PSO).

DFIG is widely used in the wind power system for its advantages over other wind turbine generators, such as squirrel-cage induction generator and permanent magnet synchronous generator [5]. The characteristics of DFIG are high efficiency, flexible control and low investment. The stator of DFIG is directly connected to the power grid while the rotor is connected to the power grid through a back-to-back converter, which only takes about 20%–30% of the DFIG rated capacity for the reason that the converter only supplies the exciting current of the DFIG. The back-to-back converter consists of three part: rotor side converter (RSC), grid side converter (GSC), and dc link capacitor. The controllers of the converter have significant effect on the stability of grid-connected DFIG [6].

In previous research, the stability analysis and optimal control of WT with DFIG had been studied by many researchers [7], [8], [25], [26], [28]–[30]. One of the key challenges for DFIG based wind farm optimization is the involvement of a large number of parameters need to be optimized to ensure a good interaction of the wind power with the power grid at the common coupling point (CCP). For instance, in [7], the authors presented an approach to use PSO to optimize all the control parameters in a DFIG simultaneously. This method can improve the performance of the DFIG in the power grid, however, when the number of the DFIG in a wind farm increases, the number of the control parameters will increase significantly. Therefore, advanced coordinated control approaches such as adaptive dynamic programming (ADP) based methods have showed great success and promising for such a challenging problem [9]–[12].

Sensitivity analysis has widely applications in power system analysis and modeling [13]–[16]. Eigenvalue sensitivity analysis [17] and voltage sensitivity analysis [19] based on DFIG system was also investigated by other researchers. In [17], the author applied eigenvalue sensitivity analysis on a DFIG system and found that the impact of different DFIG parameters on different critical eigenvalue pairs at different rotor speeds was different. One of the key questions for this is how to identify a uniformed dominate control parameters (UDCP) which can be used in the control optimization and reduce the optimization complexity for large-scale wind farms.

In this work, we propose a sensitivity analysis based optimal control of WT with DFIG using the PSO technique motivated from our previous work [7]. Through sensitivity analysis with both trajectory sensitivity analysis and eigenvalue sensitivity analysis, the UDCP can be obtained. Then we propose to use PSO to optimize these UDCP to improve the dynamic performance of the wind generation system. Simulation studies are

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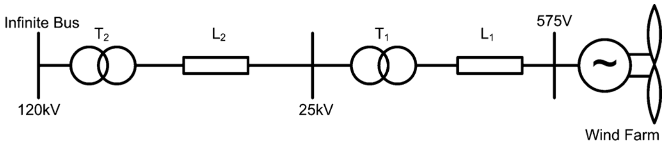

Fig. 1. Single-line diagram of the benchmark power system that includes a DFIG-based wind farm.

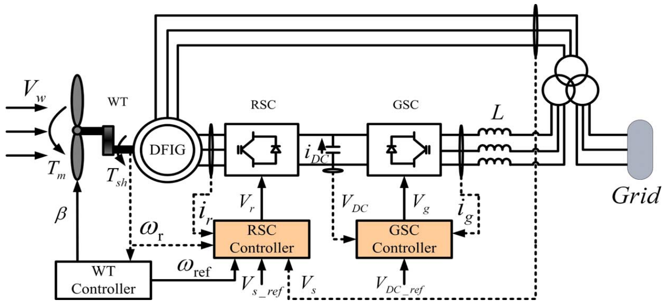

Fig. 2. Schematic diagram of DFIG wind turbine system [17], [18].

carried out in MATLAB/SIMULINK to verify the effectiveness of proposed method.

II. POWER SYSTEM MODEL

Normally, there are tens to hundreds wind turbines in a large wind farm. From previous research, if the controller of the wind turbines are well-tuned, there will be no mutual interaction between wind turbines on a wind farm [20]. Therefore, in this paper, the wind farm will be represented by one WT with DFIG system. Fig. 1 shows the diagram of the simulated single wind farm infinite bus system in MATLAB/SIMULINK. A 36 MW wind farm consisting of twenty-four 1.5 MW wind turbines connected to a 25 kV distribution system exports power to a 120 kV grid through a 30 km, 25 kV feeder. This 120 kV grid represents an infinite bus to the wind farm. Wind turbines use a DFIG consisting of a wound rotor induction generator and an ac/dc/ac insulated-gate bipolar transistor (IGBT) based pulse width modulation (PWM) converters. The stator winding is connected directly to the 60 Hz grid while the rotor is fed at variable frequency through the ac/dc/ac converter. The detailed model of the DFIG wind turbine system is introduced in this paper.

III. DFIG WIND TURBINE SYSTEM MODEL

The wind turbine model studied in this paper is illustrated in Fig. 2 [17], [18]. In this system, the wind turbine is connected to the DFIG through a drive train system, which consist of a low and a high speed shaft with a gearbox in between. The DFIG system is an induction type generator in which the stator windings are directly connected to the three-phase grid and the rotor windings are fed through three-phase back-to-back IGBT based PWM converters. The back-to-back PWM converter consist of three parts: a rotor side converter (RSC), a grid side converter (GSC) and a dc link capacitor placed between the two converters. There controller also consist of three parts: rotor side controller, grid side controller and wind turbine controller. The function of these controllers are to produce smooth electrical power with constant voltage and frequency to the power grid whenever the wind system is working at sub-synchronous speed or super-synchronous speed, depending on the velocity of the wind. Vector control strategy is employed for both the RSC and GSC to achieve decoupled control of active and reactive power.

A. Model of Generator

As DFIG is an induction machine, the $d-q-0$ reference frame based model of DFIG can be represented as follows [7]:

$$\begin{aligned}\frac{X_s'}{\omega_s}\frac{di_{ds}}{dt} &= v_{ds} - \left[R_s + \frac{(X_s - X_s')}{\omega_s T_0'}\right] * i_{ds}\\ &\quad - (1-s_r)E_d' - \frac{L_m}{L_{rr}}v_{dr}\\ &\quad \times -\frac{1}{\omega_s T_0'}E_q' - X_s' i_{qs} \end{aligned} \tag{1}$$

$$\begin{aligned}\frac{X_s'}{\omega_s}\frac{di_{qs}}{dt} &= v_{qs} - \left[R_s + \frac{(X_s - X_s')}{\omega_s T_0'}\right] * i_{qs}\\ &\quad - (1-s_r)E_q' - \frac{L_m}{L_{rr}}v_{qr}\\ &\quad \times -\frac{1}{\omega_s T_0'}E_d' - X_s' i_{ds} \end{aligned} \tag{2}$$

$$\begin{aligned}\frac{dE_d'}{dt} &= s_r\omega_s E_q' - \omega_s\frac{L_m}{L_{rr}}v_{qr}\\ &\quad - \frac{1}{T_0'}\times[E_d' + (X_s - X_s')i_{qs}] \end{aligned} \tag{3}$$

$$\begin{aligned}\frac{dE_q'}{dt} &= s_r\omega_s E_d' - \omega_s\frac{L_m}{L_{rr}}v_{dr}\\ &\quad - \frac{1}{T_0'}\times[E_q' + (X_s - X_s')i_{ds}] \end{aligned} \tag{4}$$

where $E_d' = -(\omega_s * L_m/L_{rr} * \psi_{qr})$, $E_q' = -(\omega_s * L_m/L_{rr} * \psi_{dr})$, $X_s = \omega_s * L_{ss}$, $X_s' = \omega_s * [L_{ss} - (L_m^2/L_{rr})]$ and $T_0' = L_{rr}/R_r$.

The parameters used in above equations are defined as follows:

ψ_{dr}	the d axis rotor flux linkages;
ψ_{qr}	the q axis rotor flux linkages;
L_{ss}	the stator self-inductance;
L_{rr}	the rotor self-inductance;
L_m	the mutual inductance;
R_r	the rotor resistance;
ω_s	the synchronous angle speed;
s_r	the rotor slip;
X_s	the stator reactance;
X_s'	the stator transient reactance;
E_d'	the d axis voltage behind the transient reactance;
E_q'	the q axis voltage behind the transient reactance;
T_0'	the rotor circuit time constant;
i_{ds}	the d axis stator current;