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Effects of operational limits of DFIG wind turbines on long-term voltage stability studies

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ABSTRACT

This paper investigates the effects of doubly fed induction generators (DFIGs) operational limits on long-term voltage stability. DFIG operational limits are defined based on wind generator's capability curve in terms of the actual terminal voltage and wind speed. Also, the limitations of the converter, machine and wind turbine are considered in DFIG control schemes. The evolution of different variables is examined using two models for DFIG operational limits: fixed limits and variable limits. Time domain simulations have been performed in three different cases: constant wind speed, ramp up event, and ramp down event. This study also considers the dynamic models of over excitation limiter (OEL) and on-load tap changers (OLTC) combined with static and dynamic loads. Some important conclusions can be extracted from the simulation results, which can help in choosing the appropriate model to represent the DFIG operational limits in long-term voltage stability studies.

1. Introduction

Nowadays, wind power capacity is increasing in power systems, and doubly fed induction generator (DFIG) is one of the most common wind turbine technologies installed in wind farm projects. As penetration level of wind farms increases, ancillary services provided by the wind turbines becomes more relevant, such as voltage control. The DFIG capability of varying the reactive power depends on the power electronic converters rating [1]. However, in many studies, the DFIG operating limits are assumed fixed in their control schemes. Consequently, the proper modeling of DFIG operating limits is of crucial importance for voltage stability analysis, in particular long-term voltage stability, mainly due to the variable nature of wind power.

Long-term voltage stability has been an increasing concern in power industry [2]. This phenomenon involves slower acting equipment such as on load tap changer (OLTC) transformers and over-excitation limiters (OEL) of synchronous generator. The study period of interest may extend to several or many minutes, and long-term simulations are required for analysis of system dynamic performance [3].

Researchers in the past have investigated the effect of OEL of conventional synchronous generators on long-term voltage stability using time domain simulation [4,5]. The voltage stability margin is significantly reduced when the field current of the synchronous generator becomes limited [6]. However, the effect of operational limits of DFIG-based wind turbines on long-term voltage stability has not been extensively studied.

Ref. [7] investigates the long-term voltage stability aspects of variable speed wind turbines, but do not consider the voltage dependent reactive power limits of the DFIG. In [8], reactive power control strategies applied to DFIG are proposed to contribute to terminal voltage support. Operational limits are taken into account, but reactive power limits are modeled as simple fixed limits (e.g., ±1 p.u.). Besides, long-term voltage stability phenomenon is not accessed. Ref. [9] analyzes the impact of utilizing the capability curve of a DFIG based wind park on dynamic power system operation. DFIG reactive power limits are calculated from the capability curve, but the long-term voltage stability is not considered. A capability curve based reactive power control strategy for the DFIG is proposed in [10] to improve network stability. The authors accomplish long-term simulations considering DFIG reactive power limitations. However, the system does not contain the main elements that influence long-term voltage stability, such as OEL and OLTC. Finally, in [11], the impact of DFIG on long-term voltage stability is analyzed, considering their operational limits

Abbreviations: DFIG, doubly fed induction generator; GSC, grid side converter; OLTC, on load tap changer; OEL, over-excitation limiter; PV, power voltage; RSC, rotor side converter.

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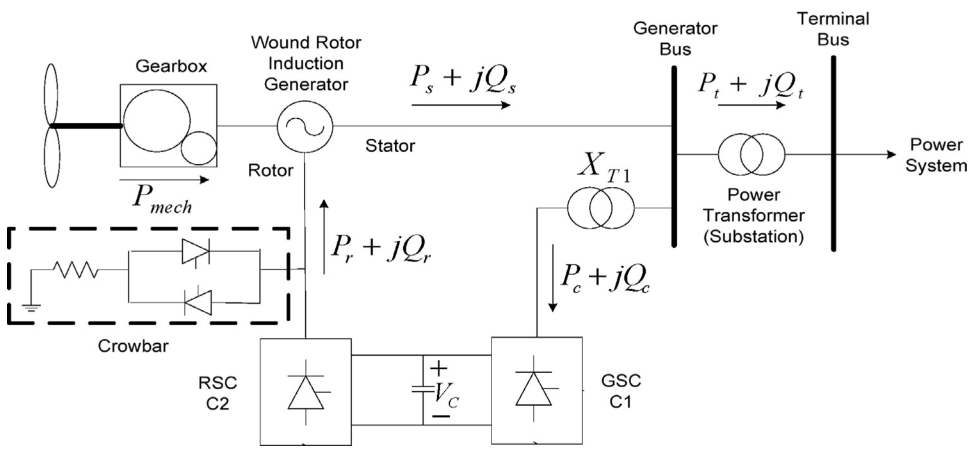

Fig. 1. A schematic diagram of doubly fed induction generator.

modeled as variable limits obtained from capability curve. However, no discussions or comparisons on the effects of this modeling on long-term voltage stability are presented. Moreover, only a wind speed regime was considered in all simulation results presented in [11], which can be difficult to conduct a detailed comparative analysis of the effects of reactive power limits of DFIG wind turbines on long-term voltage stability.

Based on the aforementioned shortcomings identified in the existing literature, this paper is a continuation of the preliminary investigation presented in [11], and examines the influence of DFIG operational limits on long-term voltage stability. Two models are tested: DFIG with fixed limits (independent of wind speed and voltage variations) and variable limits (dependent of wind speed and voltage variations). To analyze the effect of wind speed regime, time domain simulations are performed considering three different scenarios: constant wind speed, wind speed increase, and wind speed decrease. Dynamic aspects of the generator OEL and OLTC transformer, combined with static and dynamic load are properly considered. The simulations were conducted using the software ANAREDE for power flow analysis and ANATEM for dynamic analysis [12,13].

The main contribution of this paper is to provide a clear understanding of how simplifications on DFIG operational limits affect long-term voltage stability of power system, and discuss possible simplifications in the model, considering different wind speed scenarios, in order to obtain reliable results from power system simulations.

This paper is organized as follows. Section 2 presents the concept of DFIG operation and its control loops. Section 3 presents DFIG operational limits. Section 4 presents the test system used. The simulations results and analysis are discussed in Section 5. Finally, Section 6 presents the main conclusions.

2. Doubly fed induction generator

The doubly fed induction generator is a variable speed machine where the stator terminals are directly connected to the grid, while the rotor winding is connected via slip-rings to a three-phase converter as shown in Fig. 1.

The rotor side converter (RSC) can use either a torque controller, speed controller, or active power controller to regulate the output power of the DFIG. This output power is controlled to follow the wind turbine's power-speed characteristic curve. The grid side converter (GSC) is used to regulate the voltage of the DC link between the two converters and interchange reactive power with the grid, allowing the production/consumption of reactive power. Then, DFIG has reactive power controllability and can operate on power factor control mode or voltage control mode. The voltage control mode is adopted in this paper since it is more effective for voltage stability problems [14]. Also, GSC is operated at unity power factor (zero reactive power injection) as usually adopted.

DFIG is represented by simplified third-order model where electromagnetic transients of the stator are neglected [15] and its converters are modeled by vector control strategy. The control strategy adopted in the rotor side converter (RSC) is to align the stator flux with *d*-axis, and the terminal voltage is aligned with *q*-axis. Fig. 2 shows the RSC control loop.

The control strategy adopted in GSC is to align the terminal voltage with *q*-axis, and the DC-link voltage is controlled by converter active power. The GSC loop control used in this paper is the same employed in [11].

3. DFIG operational limits

The DFIG wind turbines are able to control active and reactive power independently. However, reactive power capability of these generators is limited by rotor current, stator current, and rotor voltage [16]. This section shows only the maximum reactive power equations associated with the rotor current, since it is typically the limiting factor regarding reactive power production. The reactive power limits associated with the stator current and rotor voltage are stated mathematically in [11].

The rotor current limits depend on the generator design and the rotor converter capacity, which is 30% of the nominal generator power. Eq. (1) represents maximum reactive power injected limited by rotor current.

$$Q_{s\,\max} = \sqrt{{S_{Ir\,\max}}^2 - P_s^2} + Q_{0s} \tag{1}$$

$$S_{Ir\,\max} = |I_{r\,\max}|.|V_s|.\left|\frac{X_m}{X_m + X_s}\right| \tag{2}$$

$$Q_{0s} = -\frac{|V_s|^2}{X_m + X_s} \tag{3}$$

where $Q_{s\,\max}$, stator reactive power limit (p.u.); $S_{Ir\,\max}$, stator apparent power limit as a function of the rotor current (p.u.); Q_{0s}, reactive power absorbed by the machine due to rotor current (p.u.); P_s, active power injected at the stator (p.u.); $I_{r\,\max}$, maximum rotor current (p.u.); V_s, stator voltage (p.u.); X_m, magnetizing reactance (p.u.); X_s, stator leakage reactance (p.u.).

Fig. 3(a) presents the DFIG reactive power capability curve considering GSC operating at unity power factor. The combination of all limiting factors mentioned above is considered: rotor current, stator current and rotor voltage. This final curve is obtained by the most restrictive of the three limitations. Since Q_{0s} is negative, the