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A sensitivity based approach to assess the impacts of integration of variable speed wind farms on the transient stability of power systems

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ABSTRACT

The impact of large penetration of wind power on the transient stability of multi-machine power systems is discussed in this paper. Variable speed wind farms with doubly fed induction generators (DFIG) are considered. A new index based on the sensitivity of the DFIG terminal voltage is used to assess the transient stability margin of power systems, both for constant wind speed condition and during a sudden change in wind speed. Suitable locations for connecting the DFIG to an existing power system are identified with the help of this index. The effect of increase in wind power penetration on the transient stability condition of the existing power system is studied. The proposed index is also used to select the optimum crowbar resistance during fault ride-through operation.

1. Introduction

The environmental and societal impacts of the fossil fuel based and large hydro power generation have forced system planners across the globe to explore alternate sources of energy. The fast decaying reserve of fossil fuel is also continuously tilting the balance of economy towards renewable energy. Wind power is the cheapest of all the available sources of non-conventional energy technologies. Due to the variable nature of the wind speed and hence the available power, doubly fed induction machine is better suited for use as a wind generator as compared to the synchronous machine or squirrel cage induction machine. Doubly fed induction generators are variable speed machines which operate in both sub-synchronous and super synchronous speed regions extracting maximum power from wind at every point of time [1].

Different models of the DFIG and the wind turbine suitable for use in power system simulation have been studied [2–5]. The generator and the turbine rotor together form the drive train which may be represented by 1st, 2nd or 3rd order differential equations depending on whether one mass, two mass or three mass model is chosen [4,5]. These models have been compared on the basis of the accuracy of the results while studying various aspects of power system with wind generators [2,3]. The impact of the increased penetration of the distributed resources poses new questions about the stability condition of power systems [6–10]. The wind power capacity planning for an electric power system is carried out as an optimization problem in view of system operation, reliability and economic aspect in Ref. [11].

Trajectory sensitivity analysis (TSA) has been proposed as a tool for assessment of transient stability of multi-machine power systems in Ref. [12]. Use of Trajectory Sensitivity (TS) in finding critical values of parameters and dynamic rescheduling of generation has been reported in Ref. [13]. A method to reduce the number of TS calculations and to identify the suitable parameters for finding TS is discussed in Ref. [14]. The Trajectory sensitivities can be computed in a simpler way using a numerical method, which is found to be advantageous when power system consisting of power electronic devices is considered [15]. A new index based on TS is proposed in Refs. [16], which is used during short term voltage stability study to identify the suitable location of the reactive power sources.

With the increase of the share of wind power and considering its time variable nature, it becomes very much critical for the power system operators and planners to assess the stability condition of power systems. This paper discusses the application of sensitivity analysis as a tool to identify the location and suitable operating conditions of wind generators such that the power system can operate with sufficient stability margin. Normally location of a wind farm depends on the available wind speed. However, if more than one possible points of connection to the grid are available in a region having adequate wind speed, then proper choice of connecting point will be a vital issue as that may affect the stability.

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In this paper, a new stability index is proposed which uses the sensitivity of the DFIG terminal voltage. This index is easier to compute in comparison to the indices suggested before and can be useful to study system condition during sudden change in wind speed. The proposed index is used to investigate the changes of stability condition of the power system due to increase in the penetration level of wind generation. The index is also used to select the optimum crowbar resistance during fault ride-through. The study is carried out in the WSCC 3-machine 9-bus system and IEEE 16 machine 68 bus system.

2. Modeling of power system and the DFIG

2.1. Modeling of synchronous machine and the network

In this paper flux decay model of synchronous machine is considered. The exciter is represented by one gain and one time constant [17,18].

The internal voltage of the generator and its angle is given by

$$E_i\angle\phi_i = \left[\left(1-\frac{x'_{d_i}}{x'_{q_i}}\right)V_i\sin(\delta_i-\theta_i)+jE'_{q_i}\right]e^{j(\delta_i-\pi/2)} \quad i=1,\ldots,m \tag{1}$$

The generators and the exciter dynamics of an m machine system is given by

$$\frac{d\delta_i}{dt} = \omega_s\Delta\omega_{r_i}, \quad i=1,\ldots,m \tag{2}$$

$$2H_i\frac{d\Delta\omega_{r_i}}{dt} = P_{m_i}-P_{e_i}-K_{D_i}\Delta\omega_{r_i}, \quad i=1,\ldots,m \tag{3}$$

$$T'_{do_i}\frac{dE'_{q_i}}{dt} = -\frac{x_{d_i}}{x'_{d_i}}E'_{q_i}+\left(\frac{x_{d_i}}{x'_{d_i}}-1\right)V_i\cos(\delta_i-\theta_i)+E_{fd_i} \qquad i=1,\ldots,m \tag{4}$$

$$T_{A_i}\frac{dE_{fd_i}}{dt} = -E_{fd_i}+\left(V_{ref_i}-V_i\right)K_{A_i}, \quad i=1,\ldots,m \tag{5}$$

$$P_{e_i} = E'_{q_i}V_i\sin(\delta_i-\theta_i)/x'_{d_i}+0.5(1/x_q-1/x'_d)V_i^2\sin 2(\delta_i-\theta_i), \quad i=1,\ldots,m \tag{6}$$

where δ is the angular position of the rotor, $\Delta\omega_{r_i}$ is the per unit speed deviation of the rotor, ω_s is the synchronous speed, H is the inertia constant, K_D is the damping coefficient, P_m is the mechanical power input, x_d and x_q are d-axis and q-axis synchronous reactance, x'_d is the d-axis transient reactance, E'_q is the q-axis component of the voltage behind the transient reactance x'_d, T'_{do} is the d-axis open circuit time constant, E_{fd} is the exciter voltage, K_A and T_A are the gain and time constant of the exciter respectively, V is the terminal voltage of the machine in per unit and θ is the angle of this voltage.

The dynamics of the networks are neglected and they are represented by a set of algebraic equations as

$$P_{L_i} = \sum_{j=1}^{n+m}|V_i||V_j|\left[G_{ij}\cos(\theta_i-\theta_j)+B_{ij}\sin(\theta_i-\theta_j)\right] \quad i=1,2,\ldots,n \tag{7}$$

$$Q_{L_i} = \sum_{j=1}^{n+m}|V_i||V_j|\left[G_{ij}\sin(\theta_i-\theta_j)-B_{ij}\cos(\theta_i-\theta_j)\right] \quad i=1,2,\ldots,n \tag{8}$$

where n is the total number of buses of the system, m is the number of synchronous generators, G_{ij} and B_{ij} are the network transfer conductance and admittance respectively of the augmented Y_{BUS} matrix where along with the normal Y_{BUS}, the admittance corresponding to the transient reactance of the machines are included [17]. P_{L_i} and Q_{L_i} are the real and reactive power loads respectively. The loads are represented by constant impedances.

2.2. Modeling of the DFIG

The wind turbine and the DFIG rotating mass is represented by the two mass model. The equations representing the two mass model of the drive train used in this work are given as [3,4]

$$\frac{d\omega_r}{dt} = \frac{1}{2H_g}\left[k_{sh}\theta_{tw}+C_{sh}\omega_{elB}(\omega_t-\omega_r)-T_e\right] \tag{9}$$

$$\frac{d\theta_{tw}}{dt} = \omega_{elB}(\omega_t-\omega_r) \tag{10}$$

$$\frac{d\omega_t}{dt} = \frac{1}{2H_t}\left[T_m-k_{sh}\theta_{tw}-C_{sh}\omega_{elB}(\omega_t-\omega_r)\right] \tag{11}$$

For unsaturated and balanced condition, the stator and the rotor circuits can be represented by the following equations:

$$\frac{di_{ds}}{dt} = \frac{\omega_{elB}}{L'_s}\left[-\left(R_s+\frac{(L_{ss}-L'_s)}{T_r}\right)i_{ds}+L'_si_{qs}-\frac{e'_q}{T_r}+\omega_re'_d+K_{mrr}V_{dr}-V_{ds}\right] \tag{12}$$

$$\frac{di_{qs}}{dt} = \frac{\omega_{elB}}{L'_s}\left[-\left(R_s+\frac{(L_{ss}-L'_s)}{T_r}\right)i_{qs}+L'_si_{ds}-\frac{e'_d}{T_r}+\omega_re'_q+K_{mrr}V_{qr}-V_{qs}\right] \tag{13}$$

$$\frac{de'_d}{dt} = \omega_{elB}\left[\omega_s\frac{(L_{ss}-L'_s)}{T_r}i_{qs}-\frac{e'_d}{T_r}+\omega_s(\omega_s-\omega_r)e'_q-\omega_sK_{mrr}V_{qr}\right] \tag{14}$$

$$\frac{de'_q}{dt} = \omega_{elB}\left[-\omega_s\frac{(L_{ss}-L'_s)}{T_r}i_{ds}-\frac{e'_q}{T_r}-\omega_s(\omega_s-\omega_r)e'_d-\omega_sK_{mrr}V_{dr}\right] \tag{15}$$

where ω_{elB} is the electrical base speed, ω_r and ω_t are rotor electrical and mechanical speeds respectively, θ_{tw} is the shaft torsional angle (twist angle), H_t and H_g are the turbine and the generator inertia, k_{sh} is the drive train shaft stiffness, C_{sh} is the drive train damping coefficient, v_{ds}, v_{qs}, v_{dr}, and v_{qr} are the stator and the rotor d-axis and q-axis voltages respectively, i_{ds}, i_{qs}, i_{qr}, and i_{dr} are the stator and the rotor d-axis and q-axis currents, e'_d and e'_q are the equivalent d-axis and q-axis voltage sources behind transient impedance, L_m is the mutual inductance, L_{ss} and L_{rr} are stator and rotor inductances, R_s is the stator resistance.