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A Sensitivity Based Approach to Study the Stability of the Power Systems Integrated with Wind Farm and Superconducting Magnetic Energy Storage

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Abstract: The transient stability of a multi-machine power system integrated with a wind farm and superconducting magnetic energy storage (SMES) unit is studied here using a sensitivity based index. Doubly-fed induction generator (DFIG) based wind farm is considered for the study. The index is based on the terminal voltage of the wind farm. The study is carried out with variable speed wind profiles of different penetration level in MATLAB platform.

Keywords: Transient stability, sensitivity index, DFIG, SMES.

1. INTRODUCTION

Wind power is the cheapest of the major renewable sources available. Since wind is a variable and intermittent source of energy, the integration of wind power to the grid is a very important issue. A variable speed wind generator is needed for extracting the maximum power from wind. Doubly fed induction generator (DFIG) is used in this study. It can operate in both sub-synchronous and super-synchronous speed regimes due the presence of power electronic interface in the machine rotor circuit [Nunes et al. 2004]. Studies are carried out on the impacts of increased wind penetration on the system stability [Gautam, Vittal and Harbour, 2009; Mitra and Chatterjee, 2015]. Energy storage unit can be used to reduce the fluctuation in the injected wind power to the system grid. Superconducting magnetic energy storage (SMES) is one such unit which has high efficiency and capacity with a long life time [Gupta et al. 2011]. SMES is a large superconducting coil through which DC current is flowing to generate magnetic field where energy is stored [Buckles and Hassenzahl, 2000]. SMES is used for transient stability improvement of squirrel cage induction generator (SCIG) based wind farm connected power system [Ali et al. 2009]. Application of SMES for improvement of voltage stability is discussed in [Yunus, Masoum and Abu-Siada, 2012].

Trajectory sensitivity (TS) can be used as a tool for assessing the power system stability [Laufenberg and Pai, 1998; Hiskens and Pai, 2000]. Here a new index [Mitra and Chatterjee, 2013] is used to assess the transient stability of the power system integrated with a DFIG based wind farm and SMES. The sensitivity index is based on the DFIG terminal voltage magnitude. First the index is verified to study the transient stability of a power system integrated with a DFIG based wind farm in the absence of SMES with variable speed wind profiles of different penetration levels. The effectiveness of the new index is then verified for the study of the power system stability with SMES. The study is carried out in MATLAB. System used for the study is WSCC 3-machine 9-bus system.

2. MODEL OF POWER SYSTEM, DFIG AND SMES

2.1 Model of Power System

The flux decay model of the synchronous generator is considered in the in the study along with a static exciter of one gain and one time constant [Sauer and Pai, 2002; Kundur, 1994] as described by the following equations,

$$\frac{d\delta_i}{dt} = \omega_s \Delta\omega_{r_i} \tag{1}$$

$$2H_i \frac{d_i \Delta\omega_{r_i}}{dt} = P_{m_i} - P_{e_i} - k_{D_i}\Delta\omega_{r_i} \tag{2}$$

$$T'_{do_i}\frac{dE'_{q_i}}{dt} = -\frac{x_{d_i}}{x'_{d_i}}E'_{q_i} + \left(\frac{x_{d_i}}{x'_{d_i}} - 1\right)V_i\cos(\delta_i - \theta_i) + E_{fd_i} \tag{3}$$

$$T_{A_i}\frac{dE_{fd_i}}{dt} = -E_{fd_i} + \left(V_{ref_i} - V_i\right)K_{A_i} \tag{4}$$

where $i = 1, \ldots, m$, m is the number of machines, δ is the angular position of the rotor, ω_s is the synchronous speed, $\Delta\omega_r$ is the per unit speed deviation of the rotor, P_m and P_e are the mechanical and electrical power, H is the inertia constant, k_D is damping coefficient, x_d and x_q are d-axis and q-axis synchronous reactance, x'_d is d-axis transient reactance, E'_q is the q-axis voltage behind 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, V is per unit terminal voltage of the machine and θ is its angle. The dynamics of the networks are neglected and they are represented by a set of algebraic equations. The loads are considered to be as constant impedance type.

2.2 Model of DFIG

The wind farm is represented by an aggregated wind turbine driving an aggregated DFIG. A two mass model the wind turbine and the DFIG rotating mass [Pal and Mei, 2008] described by the following equations is used.

$$\frac{d\omega_r}{dt} = \frac{1}{2H_g}\left[k_{sh}\theta_{tw} + C_{sh}\omega_{elB}(\omega_t - \omega_r) - T_e\right] \tag{5}$$

$$\frac{d\theta_{tw}}{dt} = \omega_{elB}(\omega_t - \omega_r) \tag{6}$$

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$$\frac{d\omega_t}{dt} = \frac{1}{2H_t}\left[T_m - k_{sh}\theta_{tw} - C_{sh}\omega_{elB}\left(\omega_t - \omega_r\right)\right] \quad (7)$$

where ω_{elB} is the electrical base speed, ω_r and ω_t are the rotor electrical and mechanical speeds respectively, θ_{tw} is the shaft torsional angle, H_t and H_g are the turbine and the generator inertia respectively, k_{sh} and C_{sh} are the shaft stiffness and damping coefficient respectively. T_m is the mechanical torque of the wind turbine which is a function of wind velocity (V_w) [Pal and Mei, 2008]. T_e is the electromagnetic torque. The stator and the rotor circuits of the DFIG are represented by [Pal and Mei, 2008]

$$\frac{di_{ds}}{dt} = \frac{\omega_{elB}}{L'_s}\left[\begin{array}{l} -\left(R_s + \frac{\left(L_{ss} - L'_s\right)}{T_r}\right)i_{ds} + L'_s i_{qs} - \frac{e'_q}{T_r} \\ \quad + \omega_r e'_d + K_{mrr}V_{dr} - V_{ds} \end{array}\right] \quad (8)$$

$$\frac{di_{qs}}{dt} = \frac{\omega_{elB}}{L'_s}\left[\begin{array}{l} -\left(R_s + \frac{\left(L_{ss} - L'_s\right)}{T_r}\right)i_{qs} - L'_s i_{ds} + \frac{e'_d}{T_r} \\ \quad + \omega_r e'_q + K_{mrr}V_{qr} - V_{qs} \end{array}\right] \quad (9)$$

$$\frac{de'_d}{dt} = \omega_{elB}\left[\begin{array}{l} \omega_s\frac{\left(L_{ss} - L'_s\right)}{T_r}i_{qs} - \frac{e'_d}{T_r} + \omega_s\left(\omega_s - \omega_r\right)e'_q \\ \quad - \omega_s K_{mrr}V_{qr} \end{array}\right] \quad (10)$$

$$\frac{de'_q}{dt} = \omega_{elB}\left[\begin{array}{l} -\omega_s\frac{\left(L_{ss} - L'_s\right)}{T_r}i_{ds} - \frac{e'_q}{T_r} - \omega_s\left(\omega_s - \omega_r\right)e'_d \\ \quad + \omega_s K_{mrr}V_{dr} \end{array}\right] \quad (11)$$

where V_{ds} and V_{qs} are the stator d-axis and q-axis voltages, V_{dr}, and V_{qr} are the rotor d-axis and q-axis voltages respectively, i_{ds} and i_{qs} are the stator d-axis and q-axis currents respectively, R_s and R_r are the stator and rotor resistance, L_{ss} and L_{rr} are stator and rotor inductance and $T_r = L_{rr}/R_r$. Also, e'_d and e'_q are the equivalent d-axis and q-axis source voltage behind transient impedance.

$$e'_d = \omega_s L_m\left(i_{qr} + K_{mrr}i_{qs}\right) \quad (12)$$

$$e'_q = -\omega_s L_m\left(i_{dr} + K_{mrr}i_{ds}\right) \quad (13)$$

where i_{dr}, and i_{qr} are the rotor d-axis and q-axis currents respectively, $K_{mrr} = L_m/L_{rr}$ and L_m is the mutual inductance.

Also, $L'_s = L_{ss} - L_m^2/L_{rr}$ (14)

The electromagnetic torque is

$$T_e = (e'_q i_{qs} + e'_d i_{ds})/\omega_s \quad (15)$$

In this work, d-axis is considered to be oriented along the stator voltage V_i (DFIG connected to i^{th} bus) with the q-axis is leading to d-axis. Hence the bus voltage at which DFIG is connected is given as

$V_{ds} = V_i$ and $V_{qs} = 0$ (16)

In this study the DFIG is considered to be operated in an open loop condition without considering the controller dynamics. To include the effect of current control, it is assumed that the rotor current is fixed at its pre-fault value until the rotor voltage hits its predefined limit [Mitra and Chatterjee, 2013]. The limit is decided on the basis of the voltage rating of the rotor side converter (RSC). If the rotor voltage hits the limit then the rotor current is varied keeping the rotor voltage at its limiting value. During fault ride through (FRT) operation the rotor is short circuited through an external resistance (crowbar) thus bypassing the converters [Hansen and Michalke, 2007]. Under this condition, the rotor dynamics is considered. The stator dynamics is also considered during fault ride-through operation. Though under normal operating condition, the stator and rotor dynamics are neglected which is the usual practice for transient stability study of power systems. The stator and rotor are then represented by their corresponding algebraic equations obtained by putting zero in the left hand side of the equations (8)-(11).

2.3 Model of SMES

The SMES is connected to the grid through a current source converter (CSC) [Ali, Wu and Dougal, 2010; Shi et al. 2008]. The DC side of CSC is directly connected with the SMES inductor and its ac side is connected to the power line through a transformer (Fig. 1). Besides filtering the higher order harmonics of the ac line current, the capacitor bank at the CSC terminal is used to buffer the energy stored in line inductances during the process of commutating direction of ac line current. The SMES is inherently a current source, so the transfer of active and reactive powers is very fast between the CSC and the power network. The d-axis and q-axis components of the voltage across c_g (v_g) are [Shi et al. 2008]

$$v_{dg} = V_{ds} + r_g i_{dg} + l_g\frac{d}{dt}i_{dg} - l_g\omega_{elB}i_{qg} \quad (17)$$

$$v_{qg} = r_g i_{qg} + l_g\frac{d}{dt}i_{qg} + l_g\omega_{elB}i_{dg} \quad (18)$$

Here c_g is the per phase capacitance of the capacitor bank, r_g and l_g are the resistance and inductance respectively of the connecting path between CSC and the transformer, i_{dg} and i_{qg} are the d-axis and q-axis components of the current injected to the grid by the SMES. The d-axis and q-axis components of the current output of the CSC (i_{ct}) are [Shi et al. 2008]

$$i_{dct} = i_{dg} + c_g\frac{d}{dt}v_{dg} - c_g\omega_{elB}v_{qg} \quad (19)$$

$$i_{qct} = i_{qg} + c_g\frac{d}{dt}v_{qg} + c_g\omega_{elB}v_{dg} \quad (20)$$

The d-axis current reference I_{dgref} is obtained from the SMES active power reference P_{ref} using

$$I_{dgref} = \left(\frac{2}{3V_{ds}}\right)P_{ref} \quad (21)$$

A reduced order model of the SMES may be considered treating the SMES unit as an ideal current source ($i_{dg} = I_{dgref}$) by neglecting all the dynamics of its controllers and the associated capacitors. The charging and discharging of SMES takes place up to a limit determined by the rating of the SMES.

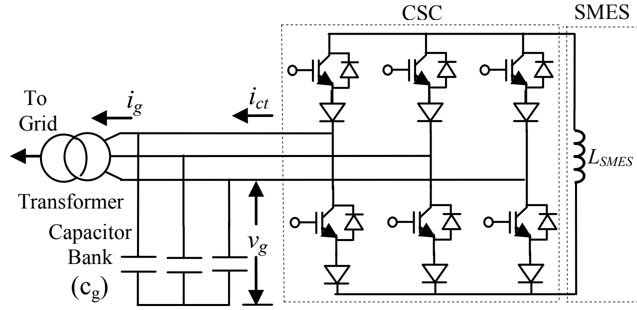

Fig. 1. CSC based SMES connected to grid