Energy Conversion and Management 59 (2012) 96–102

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Supercapacitor energy storage system for fault ride-through of a DFIG wind generation system

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ARTICLE INFO

Article history:
Received 26 November 2011
Received in revised form 7 February 2012
Accepted 5 March 2012
Available online 5 April 2012

Keywords:
Wind energy system
DFIG
Supercapacitor energy storage
STATCOM
Wind energy grid integration

ABSTRACT

The doubly fed induction generators (DFIGs) are preferred over other variable speed generators because of their advantages in terms of economy and control. One of the problems associated with high wind power penetration DFIG systems, however, is the inability of their converters to work properly under extreme low voltage conditions. This article presents a decoupled *P*–*Q* control strategy of a supercapacitor energy storage system, interfaced through a STATCOM, for low voltage ride through as well as damping enhancement of the DFIG system. The STATCOM meets the reactive power need under the depressed voltage condition, while the supercapacitor caters to the real power unbalance. An extensive dynamic model of the DFIG system including a supercapacitor DC–DC buck–boost converter and the STATCOM circuit has been developed. The fault ride-thorough capability of the generator has been investigated for a severe symmetrical three-phase to ground fault on the grid bus. Simulation results suggest that the proposed decoupled control of the supercapacitor STATCOM control strategy can help the DFIG ride through extreme low voltage conditions for significant duration. The proposed control strategy also damps the electromechanical transients, and thus quickly restores normal operation of the converters.

1. Introduction

Among several fast growing wind turbine technologies, variable speed wind turbines utilizing doubly fed induction generators (DFIGs) are gaining popularity because of their higher energy transfer capability from wind, reduction of flicker by adjusting the shaft speed and flexible controls [1–3]. With such drive system wide range of variable speed constant frequency operation is possible with independent control capabilities of real and reactive power [4]. The stator of a wind turbine driven DFIG is directly connected to the grid while the rotor is connected through a back-to-back converter and a DC link capacitor. The frequency of the rotor injected voltage is adjusted depending on the turbine speed change to obtain constant frequency at the stator terminals [5,6]. Since the DFIG stator is directly connected to the grid via a step-up transformer and the rating of the grid-side and rotor-side converters is limited, the DFIG is quite sensitive to any grid disturbance [7]. Also, the existence of a sophisticated, multi-loop control structure of the converters makes the DFIG based wind power system prone to undesirable dynamic interaction with the grid [8].

Low voltage ride-through (LVRT) capability is of special interest in a wind power generator system that employs a doubly fed induction generator. LVRT grid code standards of power utilities specify a minimum voltage profile that a wind farm should be able to ride-through. Although the operation of a DFIG wind turbine is satisfactory under balanced grid voltage conditions, there exists potential for a significant reduction in power output due to a low network voltage during grid disturbances. Under such conditions, the electromagnetic transients of the DFIG give rise to high over-currents to avoid disconnection in the semiconductors [9–11]. Different authors have reported solutions oriented to enhance fault ride-through capabilities. Many of these are based on implementing controllers in the rotor and grid side converters [11]. Some deal with reduction of high rotor inrush current observed during grid faults while others are based on limiting electromagnetic torque oscillations when a generator is subjected to a voltage dip [12]. The application of energy storage devices such as flywheel energy storage [13], superconducting magnetic energy storage [14,15] and battery energy storage [16] to smoothen wind power fluctuations have been reported. Capacitor energy storage for variable speed permanent magnet synchronous generators has been considered to damp out power oscillations [17]. Capacitor energy storage has also been reported to improve the voltage profile for fixed speed cage generators [18]. Storage of the excess energy of the generator during a low voltage condition and its utilization in the post-disturbance regime is suggested to improve the voltage profile [19]. Low voltage ride-through of permanent magnet synchronous generators with a current controlled voltage source converter was proposed in [20]. With increased wind penetration a variety of problems including voltage instability may require coordinated study on voltage control

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0196-8904/$ - see front matter
http://dx.doi.org/10.1016/j.enconman.2012.03.003

Nomenclature

P_m	power output of wind turbine
V_w	wind speed
β	pitch angle
λ	tip speed ratio
d–q	subscripts for direct–quadrature axes
r, s	subscript to represent rotor and stator quantities
R_s, x_s	resistance and reactance of the DFIG stator
R_r, x_r	resistance and reactance of the DFIG rotor
R_a, L_a	stator side filter resistance and reactance
C, V_c	DFIG converter capacitance and voltage
m_1, m_2	modulation indices
α_1, α_2	converter voltage phase angles
s	slip of DFIG
ω_o, ω_e	base and electrical angular frequency
ω_r, ω_t	generator rotor, turbine angular speeds
ω_e	generator voltage angular frequency
V_{st}, I_{st}	STATCOM voltage and injected current
R_{st}, L_{st}	resistance and inductance of STATCOM circuit
V_{dcs}, C_{dcs}	DC link voltage and capacitance of STATCOM
V_{sc}, I_{sc}	supercapacitor voltage and current
L_{sc}, C_{sc}	supercapacitor inductance and capacitance
P_{st}, Q_{st}	real and reactive power of STATCOM
x_d, x_q	synchronous reactance (d axis, q axis)
x_m	DFIG stator–rotor mutual reactance
I_{st}	STATCOM current
R, X	transmission line resistance and reactance
H_g, H_t	inertia constant of generator and turbine
D_g, D_t	damping coefficient of generator and turbine

and reactive power planning [21]. Since the power ratings of DFIG converters are generally not very large, and also because low voltage conditions may not allow the controllers located in the feedback circuit to act properly, additional short-duty energy storage devices installed at the DFIG terminals would be helpful.

Enhancement of DFIG system performance under low voltage conditions with additional real and reactive power support is considered in this article. A supercapacitor energy storage system interfaced through a STATCOM is used for this purpose. The organization of the article is as follows: Section 2 describes the model of the DFIG wind system. The STATCOM supercapacitor model is given in Section 3 followed by supercapacitor energy storage control design procedure in Section 4. Section 5 presents the simulation results and conclusions are drawn in Section 6.

2. DFIG wind turbine system model

Fig. 1 illustrates the DFIG wind power generation system connected to the grid through a step-up transformer and its transmission network. A back-to-back converter, consisting of two sub-converters VSC-1 and VSC-2, is connected in the rotor circuit. VSC-1, the grid-side converter, is connected to the generator stator through a transformer and filter circuit having resistance R_t and inductance L_t. The rotor side converter, VSC-2, is employed to control rotor voltage V_r whose frequency is adjusted according to the turbine speed so as to produce stator voltage V_s at the desired grid frequency. The supercapacitor controller is connected to the generator end of the transmission line. The models for the different components are given in the following [22].

2.1. The doubly fed induction generator

From the Park's transformation of the voltage–current–flux relationships of an induction machine operating under generator mode, the d–q components of stator and rotor currents can be expressed as,

$$\begin{bmatrix} \dot{i}_{sd} \\ \dot{i}_{rd} \end{bmatrix} = Z \begin{bmatrix} \omega_o R_s & 0 & \omega_e x_s & -\omega_e x_m \\ 0 & \omega_o R_r & -s\omega_o x_m & -s\omega_o x_m \end{bmatrix} [i_g] + \begin{bmatrix} \omega_o v_{sd} \\ \omega_o v_{rd} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} \dot{i}_{sq} \\ \dot{i}_{rq} \end{bmatrix} = Z \begin{bmatrix} \omega_e x_s & \omega_e x_m & \omega_0 R_s & 0 \\ s\omega_0 x_m & s\omega_o x_r & 0 & \omega_o R_r \end{bmatrix} [i_g] + \begin{bmatrix} \omega_o v_{sq} \\ \omega_o v_{rq} \end{bmatrix} \quad (2)$$

Here the subscripts s and r stand for stator and rotor voltages (v) and currents (i) along the d–q axes. The state vector comprises of the d–q components of stator and rotor currents arranged as, $i_g = [i_{sd}\ i_{rd}\ i_{sq}\ i_{rq}]'$. The matrix Z and slip s in the above, respectively, are given as,

$$Z = \begin{bmatrix} -x_s & -x_m \\ -x_m & -x_r \end{bmatrix}^{-1}, \quad s = \frac{\omega_o - \omega_r}{\omega_o} \quad (3)$$

The DFIG stator terminals always supply real power to the grid at sub-synchronous as well as super-synchronous speed. The rotor circuit delivers power to the grid at super-synchronous speed, while the grid supplies the rotor under sub-synchronous conditions. A list of symbols is given in the Nomenclature.

2.2. The electromechanical system

A two-mass model for the turbine generator system is adopted since a high inertia wind turbine is connected to a low inertia DFIG rotor with a relatively soft shaft. The dynamic equations of the two-mass representation are expressed as,

$$2H_t \frac{d\omega_t}{dt} = P_m - K_s\theta_s - D_t\Delta\omega_t \quad (4)$$

$$2H_g \frac{d\omega_r}{dt} = K_s\theta_s - P_e - D_g\Delta\omega_r \quad (5)$$

$$\frac{d\theta_s}{dt} = \omega_o(\omega_t - \omega_r) \quad (6)$$

In the above, θ_s is the shaft torsion angle, K_s is the shaft stiffness, H and D are the inertia and damping coefficients, respectively of turbine and generator; subscripts t and g refer to the turbine and generator quantities, respectively. The generator electrical output P_e is given as,

$$P_e = x_m i_{rq} i_{sd} - x_m i_{rd} i_{sq} \quad (7)$$

The mechanical power input to the generator supplied by the turbine is,

$$P_m = \frac{1}{2}\rho A C_p(\lambda, \beta) V_\omega^3 \quad (8)$$

Here ρ is the air density and A is the swept area by the turbine blades. The power coefficient C_p is expressed as a function of tip speed ratio λ and the blade pitch angle β [23],

$$C_p(\lambda, \beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-21}{\lambda_i}} + 0.0068\lambda$$
$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (9)$$