Electrical Power and Energy Systems 78 (2016) 414–421

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Transient modeling and analysis of a DFIG based wind farm with supercapacitor energy storage

M. Kenan Döşoğlu [a,*], Ayşen Basa Arsoy [b]

[a] Duzce University, Technology Faculty, Electrical-Electronics Engineering Department, 81620 Konuralp, Duzce, Turkey
[b] Kocaeli University, Engineering Faculty, Electric Engineering Department, 41380 Umuttepe, Kocaeli, Turkey

ARTICLE INFO

Article history:
Received 2 February 2015
Received in revised form 26 November 2015
Accepted 9 December 2015
Available online 22 December 2015

Keywords:
Energy storage
Supercapacitor
Low voltage ride through (LVRT)
Double Fed Induction Generator (DFIG)
Reduced order model
Transient Stability

ABSTRACT

Energy storage system (ESS) coupled to a wind generator has been recommended in improving the stability of the power system to which the wind farm is connected. ESS is particularly preferred in enhancing low voltage ride through (LVRT) capability owing to its fast charging and efficiency for high power applications. In the present study, a supercapacitor type ESS is used in transient state analysis of a grid connected wind turbine. The ESS consisting of a supercapacitor and a voltage buck-boost converter circuit is mathematically modeled in the grid side converter circuit of a doubly fed induction generator (DFIG) used as a wind generator. Moreover, reduced order model (ROM) for the DFIG is used in simulating stator dynamics. All modeling study has been carried out in MATLAB/SIMULINK environment. Three phase faults and having static loads for a short period of time are considered as transient cases. The effectiveness of the ESS on LVRT are shown by observing the responses of several system parameters. The study results show that utilizing a nonlinear supercapacitor type ESS in a ROM based DFIG removes oscillations in a short time during transient states, therefore enhances LVRT.

Introduction

There has been a tendency towards renewable energy sources due to the rising cost and limited use of fossil fuels in recent years. One of the most important renewable energy sources is wind energy. Grid-connected wind farms are adversely affected by transient states in converting wind energy to electrical energy. The generator of wind farm should be selected to compensate grid disturbances within certain limits. Therefore, DFIG is preferred as it provides active power and torque control. Various methods have been developed with a view to reducing the effects of transient states on DFIG. One of these methods is referred to as low voltage ride through (LVRT) capability enhancement through ESS. Among ESS components, a supercapacitor is particularly suitable for wind power applications due to its high power density, wide temperature range and long life.

The modeling of a grid integrated wind generator has also been important issue for transient stability analyses. There are tendencies using simplified models to avoid the computation burden without giving up accuracy. Among them, the third order model has been accepted as a sufficient model for power system disturbance studies since it is a good compromise between simplicity and accuracy [1–4].

Integration of a supercapacitor type energy storage system into a doubly fed induction generator (DFIG) in a wind farm has been received an attention by some researchers. It has been recommended for LVRT and output power smoothening during a disturbance [5–11]. By using a supercapacitor, the effects of frequency fluctuation and deviation on system during fault condition can be minimized. Moreover, supercapacitor regulates electrical torque and inertia of DFIG by supporting frequency [12,13]. Design and control techniques for the energy storage device have been developed for this purpose. The study presented in [8] proposes a two layer control scheme where the first one is to have the supercapacitor acting as a flywheel to eliminate wind power fluctuations while the second one is to optimize the reference output power using the wind forecast data. All of these studies employ MATLAB/SIMULINK and PSCAD to show the effectiveness of their proposed control scheme, but they do not give the details of DFIG and ESS models.

Design procedures of a supercapacitor for wind turbine pitch systems are given in [14] for enhancing LVRT, after evaluation and comparison of possible ESS types for a wind turbine. On the other hand, some researchers have proposed the hybrid ESS usage (Battery-supercapacitor) coupled to a DC bus of a wind turbine for several applications [15–18]. The topology of the hybrid ESS is

* Corresponding author. Tel.: +90 380 5421133 2178; fax: +90 380 5421134.
E-mail addresses: kenandosoglu@duzce.edu.tr (M. Kenan Döşoğlu), aba@kocaeli.edu.tr (A.B. Arsoy).

http://dx.doi.org/10.1016/j.ijepes.2015.12.020
0142-0615/

covered in [15], while the effectiveness of the hybrid usage is shown in [17] through a real time simulator. Charge–discharge duration in the ESS can be made more effectively with the energy management algorithm as given in [16–18]. Hybrid wind (micro-hydro) system application is used with a supercapacitor energy storage device. In hybrid system, the relationship between slip-powers at different rates has been examined [19]. Battery-Supercapacitor energy storage is used in energy management of a doubly fed induction generator. With Battery-Supercapacitor, the system exacts its effect on load model operating in power systems [20,21].

A supercapacitor type ESS can also be integrated into a wind turbine through an interface of STATCOM. Refs. [22–25] show that an enhanced LVRT can be achieved through a proper control of this integration.

This paper differs from other papers in literature by the way of modeling of a supercapacitor type ESS and a wind turbine generator for LVRT applications. Nonlinear modeling of a supercapacitor which is based on a voltage–capacity relationship is conducted in this study. Thanks to using look-up table in voltage-capacity relationship, supercapacitor provides a better dynamic response than various papers in literature. Due to its computationally simple but sufficiently accurate features, the reduced order model for DFIG is preferred. Mathematical equations for modeling are presented and implemented on a test system using MATLAB/SIMULINK. A comparison is drawn between the states having a DFIG with/without a supercapacitor both in 3 phase fault analysis and activation or deactivation of static loads. The study results show that the system becomes stable in a short time and power oscillations decreases when a supercapacitor ESS is coupled to a DFIG during transient states.

Doubly fed induction generator (DFIG) Modeling

A doubly fed induction generator (DFIG) of a wind turbine is basically a wound rotor induction machine with the stator windings directly connected to the three phase grid and with the rotor windings connected to a back-to-back converter, consisting of grid-side converter and rotor-side converter connected to a common DC bus. The behavior of the DFIG is governed by these converters and their controllers in both steady-state and transient conditions. The converters control the rotor voltage in magnitude and phase angle, and therefore, they are used for active and reactive power control [26,27].

The full order DFIG model is represented by five equations, considering the generator's variables in the d–q synchronous reference frame. The equations for the stator and rotor windings with the torque equations can be given in (1)–(5) as follows:

$$v_{ds} = R_s i_{ds} - w_s \lambda_{qs} + \frac{d}{dt}\lambda_{ds} \tag{1}$$

$$v_{qs} = R_s i_{qs} + w_s \lambda_{ds} + \frac{d}{dt}\lambda_{qs} \tag{2}$$

$$v_{dr} = R_r i_{dr} - s w_s \lambda_{qr} + \frac{d}{dt}\lambda_{dr} \tag{3}$$

$$v_{qr} = R_r i_{qr} + s w_s \lambda_{dr} + \frac{d}{dt}\lambda_{qr} \tag{4}$$

$$M = \lambda_{ds} i_{qs} - \lambda_{qs} i_{ds} \tag{5}$$

Flux-inductance equations can be expressed in d–q coordinates as follows:

$$\lambda_{ds} = (L_s + L_m) i_{ds} + L_m i_{dr} \tag{6}$$

$$\lambda_{qs} = (L_s + L_m) i_{qs} + L_m i_{qr} \tag{7}$$

$$\lambda_{dr} = (L_r + L_m) i_{dr} + L_m i_{ds} \tag{8}$$

$$\lambda_{qr} = (L_r + L_m) i_{qr} + L_m i_{qs} \tag{9}$$

Reduced order DFIG models are employed to ease computation for transient analyses. In this model, a stator is represented by a transient voltage source behind a transient reactance where stator fluxes derivation is neglected. The main idea is that the dc component is omitted from the stator transient current [28,29]. Related equations are given in (10)–(16) as follows:

$$v_{ds} = R_s i_{ds} - X' i_{qs} + e_{d_s} \tag{10}$$

$$v_{qs} = R_s i_{qs} + X' i_{ds} - e_{qs} \tag{11}$$

$$\frac{de_{ds}}{dt} = -\frac{1}{T_0}[e_{ds} - (X - X') \times I_{qs}] + s \times w_s \times e_{qs} - w_s \times \frac{L_m}{L_m + L_s} \times v_{dr} \tag{12}$$

$$\frac{de_{qs}}{dt} = -\frac{1}{T_0}[e_{qs} + (X - X') \times I_{ds}] - s \times w_s \times e_{ds} + w_s \times \frac{L_m}{L_m + L_s} \times v_{qr} \tag{13}$$

$$v_{dr} = R_r i_{dr} + s w_s \lambda_{qr} + \frac{d}{dt}\lambda_{dr} \tag{14}$$

$$v_{qr} = R_r i_{qr} - s w_s \lambda_{dr} + \frac{d}{dt}\lambda_{qr} \tag{15}$$

$$M = e_{ds} i_{qs} + e_{qs} i_{ds} \tag{16}$$

In these equations; v_{ds}, v_{dr}, v_{qs}, v_{qr}: d and q axis voltages of stator and rotor, i_{ds}, i_{dr}, i_{qs}, i_{qr}: d and q axis of currents of stator and rotor, λ_{ds}, λ_{qs}, λ_{dr}, λ_{qr}: d and q axis magnetic fluxes of stator and rotor, E_{ds} and E_{qs}: d axis and q axis source voltages of stator, w_s: angular speed of stator, s: slip R_s and R_r: resistance of stator and rotor, X: stator reactance, X' transient reactance, L_s and L_r: inductance of stator and rotor, L_m: magnetic inductance and M: torque. Transient reactance of the model is expressed in (17), while transient open circuit time constant is given in (18) [30].

$$X' = w_s\left((L_m + L_s) - \frac{L_m^2}{L_m + L_r}\right) \tag{17}$$

$$T_0 = \frac{L_r + L_m}{R_r} \tag{18}$$

Wind energy and energy storage

The addition of storage to wind farm based on DFIG is applied in various operations, but it is ignored in the industry owing to its high cost. Energy storage system devices should be made more commercially viable for the operation of the generator because storage system is important both for grid and wind farm based on DFIG during transient cases [22,31,32]. In addition, storage should be preferred in power control as well as power dispatch, energy management, and power quality.

Wind farm can be used in storage and suboptimal power points for power dispatch. These two ways ensure a reliable operation of DFIG. Whereas storage systems can influence any operation points, suboptimal power point can influence only certain operation points. While storage systems can increase efficiency, they can also improve LVRT capability during transient cases.

Storage systems cannot be used in wind farm for some conditions particularly when there is a difference between set power point and the terminal generator. The operating point of DFIG