Electrical Power and Energy Systems 83 (2016) 485–494

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

A developed control strategy for mitigating wind power generation transients using superconducting magnetic energy storage with reactive power support

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ARTICLE INFO

Article history:
Received 7 August 2015
Received in revised form 6 April 2016
Accepted 11 April 2016
Available online 29 April 2016

Keywords:
Wind energy conversion system (WECS)
Superconducting magnetic energy storage (SMES)
Squirrel cage induction generator (SCIG)
Fuzzy logic controller (FLC)
Wind gust

ABSTRACT

The fast variations of wind speed during extreme wind gusts result in fluctuations in both generated power and the voltage of power systems connected to wind energy conversion system (WECS). This paper presents a control strategy which has been tested out using two scenarios of wind gusts. The strategy is based on active and reactive powers controls of superconducting magnetic energy storage (SMES). The WECS includes squirrel cage induction generator (SCIG) with shunt connected capacitor bank to improve the power factor. The SMES system consists of step down transformer, power conditioning unit, DC–DC chopper, and large inductance superconducting coil. The WECS and SMES are connected at the point of common coupling (PCC). Fuzzy logic controller (FLC) is used with the DC–DC chopper to control the power transfer between the grid and SMES coil. The FLC is designed so that the SMES can absorb/deliver active power from/to the power system. Moreover, reactive power is controlled to regulate the voltage profile of PCC. Two inputs are applied to the FLC; the wind speed and SMES current to control the amount active and reactive power generated by SMES. The proposed strategy is simulated in MATLAB/Simulink®. The proposed control strategy of SMES is robust, as it successfully controlled the PCC voltage, active and reactive powers during normal wind speeds and for different scenarios of wind gusts. The PCC voltage was regulated at 1.0 pu for the two studied scenarios of wind gusts. The fluctuation ranges of real power delivered to the grid were decreased by 53.1% for Scenario #1 and 56.53% for Scenario #2. The average reactive power supplied by the grid to the wind farm were decreased by 27.45% for Scenario #1 and 31.13% for Scenario #2.

Introduction

Solar and wind energy resources are considered the most popular renewable energy resources. They are environmental-friendly and sufficiently available naturally, so their utilization continues to show a significant growth worldwide [1]. Wind power's total installed capacity in 2010 was estimated at around 340 TW h. This indicates that about 1.6% of the total electricity generation worldwide is supplied by wind power generation [2]. Wind energy was used in both of distribution and transmission power systems to improve the voltage stability problem [3]. Fixed-speed squirrel cage induction generators (SCIGs) are the most popular wind turbine generators (WTGs) because induction generators are the simplest, most cost-effective and robust machine for energy conversion [4]. However, because induction generator absorbs reactive power from the network, it is equipped with parallel capacitors to improve power factor [5].

Wind energy is considered intermittent (and therefore unpredictable) because its electrical output is difficult to predict and subject to factors outside the control of the operating company, which can make matching electricity supply to consumer demand problematic. Controlling the output of wind generation and its potential impacts on the electric grid is different from the traditional energy sources. At high penetration levels, an extra fast response reserve capacity is needed to cover the shortfall of generation when a sudden deficit of wind takes place [6,7]. One method to mitigate power fluctuations is to use storage batteries [8] and superconducting magnetic energy storage (SMES) [9,10].

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http://dx.doi.org/10.1016/j.ijepes.2016.04.037
0142-0615/

Nomenclature

P_m	mechanical output power of the wind turbine (W)
C_p	performance coefficient of the wind turbine
ρ	air density (kg/m^3)
A	turbine swept area (m^2)
v_{wind}	wind speed (m/s)
λ	tip speed ratio of the rotor
β	blade pitch angle (rad)
E	SMES energy (J)
L	SMES coil inductance (H)
I	SMES coil current (A)
V	SMES coil voltage (V)
V_{DC}	DC link voltage (V)
V_{G}	grid voltage at point of common coupling (V)
θ	phase angle (rad)
dI_{sm}	change of SMES current (A)
dv_w	change of wind speed (m/s)
λ_{ds}	stator direct flux (Weber-turn)
λ_{qs}	stator quadrature flux (Weber-turn)
λ_{dr}	rotor direct flux (Weber-turn)
λ_{qr}	rotor quadrature flux (Weber-turn)
R_s	stator resistance (Ω)
L_s	stator leakage inductance (H)
R_r	rotor resistance (Ω)
L_r	rotor leakage inductance (H)
L_m	magnetizing inductance (H)
ω_r	rotor angular velocity (rad/s)
θ_r	rotor angular position (rad)
T_e	electromagnetic torque (N m)
T_m	shaft mechanical torque (N m)
H	combined rotor and load inertia constant (kg m^2)
σ	variable that determine the center of the peak
c	width of the bell curve
$\mu_c(z)$	membership function of the output
z_o	output of defuzzification process of FLC

An SMES system consists of superconductor coil, power-conditioning system, cryogenic refrigerator, and cryostat/vacuum vessel to keep the coil in the superconducting state. SMES can absorb or deliver active and reactive powers [5]. SMES stores energy within a magnetic field created by the flow of direct current in the coil and it is the only storage system known to store electrical energy directly based on electric current [11]. An SMES unit is highly efficient due to its lower power loss. The overall efficiency of SMES depends on the coil material and the configuration used, which typically exhibits a range of 90–98% [12,13]. The other advantages of SMES over other storage systems include the SMES's short and quick time delay during the charge and discharge process [14,15]. The SMES can make power available almost immediately, and can provide very high power output for a short period. Moreover, SMES system has unlimited number of charging and discharging cycles [16–18]. These features can increase the effectiveness of the control and enhance system reliability and availability. The major drawback of SMES is its high cost of implementation as well as the environmental issues associated with strong magnetic fields [19]. However, with the use of appropriate high temperature superconductors (HTS) materials, designers may overcome these drawbacks and thus encourage a market niche for SMES in the near future [20].

Independent control of real and reactive powers of SMES is possible [15,21,22]. Although the output of real power from an SMES device is limited to the amount of energy stored in the coil, an SMES can continuously operate throughout its range of reactive power to regulate the voltage at the point of common coupling (PCC). The control domains of the active and reactive power can be achieved by controlling the converter firing angles [22].

Many papers investigated the application of SMES to WECSs. Some of these studies focused on the use of SMES to enhance the transient stability of multi-machines system connected to DFIG [21,22], the frequency regulation of interconnected restructured power systems with dynamic participation from DFIG based wind farm [23]. The application of SMES to minimize frequency fluctuations of a small scale isolated power system with wind farm is reported in [24]. Other studies focused on the use of the SMES to improve the performance of a wind turbine during voltage sag and voltage swell at the grid side [15,25]. The applications of SMES to enhance the transient stability of wind generators are presented in [9,10,26]. Using SMES to improve the low-voltage-ride-through (LVRT) capability of variable speed wind turbine generators is presented in [27].

Controlling the output power of wind farms by SMES is presented in [28] for normal wind speeds and in [29] for small and slow power fluctuations. However, smoothing power fluctuation of wind farm during extreme wind speed gusts did not appear in the literature. Also, voltage mitigation of PCC of a grid based wind farm by controlling the real and reactive power between wind farm and grid has not been addressed. These two points are the subject of the current work.

This paper presents a fuzzy-logic-controlled SMES strategy to improve the performance of a grid connected to fixed-speed WECS during extreme wind gust scenarios by controlling both active and reactive powers of SMES, and this is the contribution of the paper. The control scheme of SMES is based on pulse width modulation (PWM), voltage source converter (VSC), and two-quadrant DC–DC chopper using insulated-gate bipolar transistor (IGBT). Charging and discharging of SMES are determined by the chopper duty cycle, which is controlled by fuzzy logic controller (FLC) where two inputs are used: wind speed and SMES current. A combination of the active and reactive power control is achieved by determining the active power generated by the WECS and using it to control the charging/discharging of active power and the delivering/absorbing of reactive power of SMES to the power system that maintains the voltage of PCC at preset specified value.

The studied power system is a wind farm connected to the grid at PCC. The MATLAB/Simulink® is used to simulate the wind turbine, the SMES unit, and the model under study. The simulation results show the effectiveness of SMES in mitigating the voltage by controlling the active and reactive powers injected to the grid during extreme wind gust scenarios.

The organization of this paper is as follows: Section 'Modeling of wind turbine generator' describes the modeling of the wind turbine. Section 'Modeling of SMES and FLC' describes the modeling of SMES and FLC. Section 'Simulation results and discussions' analyzes the simulation results. Finally, Section 'Conclusion' provides conclusions regarding this work.

Modeling of wind turbine generator

Aerodynamics

The aerodynamics model is based on the steady-state power characteristics of the turbine. The output power of the turbine is given by (1) [30].