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Transient stability augmentation of PV/DFIG/SG-based hybrid power system by parallel-resonance bridge fault current limiter

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ABSTRACT

This paper proposes a parallel-resonance bridge type fault current limiter (PRBFCL) to augment the transient stability of a hybrid power system consisting of a photovoltaic (PV) power generation source, a doubly-fed induction generator (DFIG)-based wind energy system, and a synchronous generator (SG). The PRBFCL is designed such a way that it can provide sufficient damping characteristics to the studied power system. The effectiveness of the proposed PRBFCL in improving the transient stability and enhancing the dynamic performance of the hybrid power system is verified by applying both balanced and unbalanced faults in the power network. Also, its performance is compared with that of the bridge type fault current limiter (BFCL) and the fault ride through (FRT) schemes, i.e. FRT schemes of PV, DFIG, and with the AVR and governor of synchronous generator (SG). Some indexes are used to quantify the system performance. Simulation results obtained from the Matlab/Simulink software show that the proposed PRBFCL is effective in maintaining stable operation of the PV, wind generator, and synchronous generator during the grid fault. Moreover, the performance of the PRBFCL is better than that of the BFCL and the FRT methods in every aspect.

1. Introduction

Rapid depletion of the traditional sources of energy as well as the perpetual increase in energy demand in today's fast growing world has made the renewable energy as a hot research topic. The cost of the photovoltaic (PV) installation is gradually becoming low, and hence its growth is proliferating day by day. Among the renewable energy sources, the solar energy will attain the top position and fulfill almost 28% of world's total energy demand by 2040 [1]. On the other hand, the wind energy generating system (WEGS) today is an established source of renewable energy with its rapid growth. Due to their numerous advantages, such as maximum power extraction [2], more efficiency, decoupled active and reactive power control, and enhanced power quality, the variable speed wind generator (VSWG) systems are gaining more popularity over conventional induction machine-based fixed-speed wind-generators. Moreover, the simple and rugged construction, low cost, ability to capture the maximum energy from a wide range of wind velocities, and partially rated ac/dc/ac converter for generating variable frequency, make the doubly fed induction generator (DFIG) the preferred choice over other wind generating systems [3].

Transient stability is the property of a power system to regain its normal operating condition following sudden and severe faults in the system [4]. The transient stability study is extremely important for maintaining the continuity of the power flow and properly controlling the modern electrical power systems with multiple renewable energy sources integrated to it.

Compared to the wind generators with full rated inverter/converters, the DFIG systems are extremely sensitive to the grid abnormalities, as their stators are directly connected to the grid. A grid side fault causes the terminal voltage of DFIG to go very low, which results in very high current through the stator and the rotor windings may hamper the stable operation and damage the machine. Several reports on minimizing the adverse effects of grid disturbances on the DFIG-based wind farms [5–11] are available in the literature, and the issues of enhancing the stability of the power networks including both wind synchronous generators (SGs) by flexible ac transmission system (FACTS) devices are addressed in [12–15]. On the other hand, the occurrence of the grid faults causes the imbalance between the PV generated power and power inserted by the voltage source inverter (VSI) to the grid. Due to this power imbalance, there is a sharp rise in intermediate DC link voltage and also an overcurrent at the AC side of the VSI, which may result in damaging of the power electronic interfaces [16]. The

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adverse effects of large-scale penetration of PV power to the grid on the power system stability have been reported in [17].

The integration of a large scale hybrid renewable energy plant consisting of PV, wind, and marine-current to the grid is reported in [18–20]. Large scale penetration of these renewable energy sources into the power grid leads to an enhanced short-circuit power level. Moreover, the circuit breakers with their certain turn-off capability, cannot suppress the pick current. Fault current limiters (FCLs) are extensively employed in the power system networks for suppressing the fault current. In the literature, various types of fault current limiter are proposed such as resistive-type FCLs, inductive-type FCLs, superconducting FCLs (SFCLs), flux-lock-type FCLs, DC reactor-type FCL, and resonance-type FCLs [21–26]. The application of the FCLs in the power systems is not only to suppress the peak of the short-circuit current, but also for other power system applications, such as power system transient stability augmentation, fault ride through (FRT) capability enhancement of wind generator, power quality improvement, and reliability improvement. Literature shows that coordinated operation of SFCL and SMES is employed at the PCC to enhance the FRT and the power fluctuation minimization purpose of DFIG-based wind farm [27]. Switched-type FCL and high temperature superconducting fault current limiter (HTS-FCL) are employed in [28,13], respectively, for enhancing the FRT capability of the DFIG-based wind generator. Resistor-based superconducting fault current limiter (SFCL) [25,29] and HTS-FCL [30] are placed at the PCC point in order to enhance the transient stability of synchronous generator (SG)-based single-machine-infinite-bus (SMIB) power system. Dangjin power plant, operating under utility company Korean Power Exchange (KPX), has multiple thermal power generating units connected to a common bus (PCC), and SFCL is placed at the PCC to enhance the power system stability [31].

Besides the above mentioned applications of FCLs for the stability purposes, the high-voltage direct-current (HVDC) link joined with a damping controller based on adaptive-network-based fuzzy inference system (ANFIS) utilized in [18], for enhancing the transient stability of a hybrid system consisting of PV, wind, and marine current energy generator. The static synchronous series compensator (SSSC) [32], series dynamic braking resistor (SDBR) [33], static var compensator (SVC) [34], and static synchronous compensator (STATCOM) [12] are employed for enhancing the stability of the hybrid power system consisting of DFIG, permanent magnet synchronous generator (PMSG), and SG-based power systems. Applications of SMES for enhancing the dynamic performance of grid-connected wind and PV generating systems are reported in [35].

Some of the above mentioned FCLs and other auxiliary means of enhancing the stability incur additional cost due to the use of converters, coupling transformers, and filters. SFCL employs superconducting inductor and some of the bridge-FCLs use transformer for the coupling purpose incurs high manufacturing cost. Because of the high cost of SFCLs, they are not commercially available in the markets. It is important to investigate a cost-effective and new method for transient stability improvement of hybrid power systems. Due to its simplicity and low cost, the nonsuperconducting fault current limiter [26] is a promising technique for enhancing the transient stability of the power system [36] and improving the fault ride through capability of the wind generators [37]. Resonance-type FCLs suppress the fault current by exploiting various configurations of series or parallel LC resonant circuits [38]. The resonant circuits have the advantages over solid-state circuit breakers, are the simplicity of their construction and the control strategy. The disadvantage of bridge type fault current limiter (BFCL) compared to the parallel resonant circuit fault current limiter is that, it imposes less effective impedance, because of its only current limiting inductance along with the one series resistor for the power evacuation [36]. Other BFCL topology [39] employs the coupling transformer which is an expensive approach for the fault current limiting applications. However, the impedance imposed during the fault event for PRBFCL has more impact than the BFCL, because of the presence of capacitor and multiple resistors for the power evacuation.

In this work, in order to augment the transient stability and FRT capability enhancement of a hybrid power system consisting of a DFIG-based wind generator, a PV generator, and conventional synchronous generator (SG), a parallel-resonance bridge type fault current limiter (PRBFCL) is proposed. So far, the PRBFCL has not been investigated as an auxiliary means for improving the transient stability of the power systems. During the severe voltage dips, voltage source inverter (VSI) of the PV and grid side converter (GSC) of the DFIG are utilized for the reactive current injection according to the E.ON grid code [40]. FRT scheme of PV which includes DC-link voltage suppression by controlling DC/DC boost converter of the PV system is also implemented and analyzed. Also, the performance of the proposed method is compared with that of the bridge type fault current limiter (BFCL) and fault ride through (FRT) schemes i.e. FRT schemes of PV, DFIG, and with the AVR and governor of synchronous generator (SG).

The effectiveness of the proposed scheme for enhancing the transient stability is verified by considering a test system consisting of one synchronous generator-based single machine infinite-bus system, to which one DFIG-based wind farm and a PV farm are integrated through a short transmission line. By limiting the fault current and improving the voltage sag at the point of common coupling (PCC), the proposed method makes the power sources of the hybrid system stable during the grid fault. Both balanced and unbalanced faults are applied to the most vulnerable point of the network to demonstrate the effectiveness of the proposed scheme. Extensive simulations were carried by using the Matlab/Simulink software.

The next section explains the impacts of grid fault on energy sources (PV, DFIG, and SG) of hybrid power system. The modeling of the power sources of the test system is described in Section 3. In Sections 4 and 5, the constructions and control strategies of the BFCL and the proposed method are described, respectively, and simulation results are presented in Section 6. Section 7 deals with the quantification of the results by the stability indices. The responses of the injected reactive current from the PV and the DFIG are presented in Section 8 named compliance with grid-code requirement. A brief discussion about the cost of the proposed schemes is presented in Section 9. Finally, Section 10 concludes this work.

2. Impacts of grid fault on energy sources (PV, DFIG, and SG) of hybrid power system

A three-phase two-stage grid-connected PV system, shown in Fig. 1, consists of the DC/DC converter as the first stage and the DC/AC grid-connected voltage source inverter (VSI) as the second stage. The overall power flow through the PV system can be defined by:

$$P_{\mathrm{PV}} = P_{\mathrm{DC2}} + P_g, \tag{1}$$

where P_{DC2} denotes the power flow through the DC-lick capacitor C_{DC2} of the PV system, P_g is the power inserted by the inverter to the grid, and P_{PV} is the PV array output. During the normal operation, the DC power generated by the PV (P_{PV}) is equal to the AC power delivered to the grid (P_g) if the power electronic converter loss is ignored:

$$P_{\mathrm{PV}} = P_{\mathrm{g}} = 3U_{\mathrm{g}}I_{\mathrm{g}}, \tag{2}$$

where U_{g} and I_{g} are the nominal RMS value of phase voltage and phase current, respectively. The power balance makes the PV DC-link voltage constant. However, during the event of grid-fault, the