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Original Research Article

Low voltage ride-through enhancement of fixed-speed wind farms using series FACTS controllers

Hossein Ali Mohammadpour *, Amin Ghaderi, Hassan Mohammadpour, Mohd. Hasan Ali

Department of Electrical Engineering, University of South Carolina, Columbia, SC 29208, USA

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ABSTRACT

This paper studies the application and control of three series flexible AC transmission system (FACTS) devices namely, the gate-controlled series capacitor (GCSC), the thyristor controlled series capacitor (TCSC), and series braking resistor (SBR), in order to enhance the low voltage ride-through (LVRT) in fixed-speed wind turbine generator systems (FSWTGS). Modeling and simulations are carried out in order to investigate and compare the performance of these devices, considering (1) successful reclosing of circuit breakers (CBs), (2) unsuccessful reclosing of CBs, and (3) connection of a dynamic load to the point of common coupling (PCC). Simulation results exhibit significantly enhanced transient stability of FSWTGS due to the employment of the GCSC. Furthermore, the GCSC is competitive with the TCSC and the SBR, and it requires less power rating to stabilize the wind generator system. Therefore, the proposed GCSC can be considered an effective tool to improve the LVRT of FSWTGS.

1. Introduction

Environmental pollution and possible shortage of conventional fossil fuels are two of the most important energy-related issues facing the world today. These issues have led to increasing interests in electric power generation by renewable energy sources. Among the variety of renewable energy sources, wind energy is one of the most attractive and is rapidly being adopted around the world [1]. However, increasing interest and use of wind energy will inevitably lead to the connection of large wind turbine generator systems to the existing utility power grids. Although fixed-speed wind turbine generator systems (FSWTGS) are diminishing, they are still a substantial part of the fast-growing wind energy market [2].

The FSWTGS employ squirrel cage induction generators (IGs) and are directly connected to the utility power grid. However, the grid-connected IGs can cause stability problems since the IGs are not equipped with direct electrical control of torque or speed [3]. With increasing wind power penetration, the grid codes demand the wind farms to remain connected to the grid in the case of voltage drop, for a certain period of time. Low-voltage ride-through (LVRT) capability is one of the most important issues among grid codes [4,5].

A common technology employed to stabilize the FSWTGS and enhance the LVRT of FSWTGS is the pitch control system [6]. In addition, flexible ac transmission system (FACTS) devices, such as static synchronous compensator (STATCOM) [3,7], static var compensator (SVC) [4], thyristor controlled series capacitor (TCSC) [8], series braking resistor (SBR), and super-conductive magnetic energy storage (SMES) [9–12] systems are investigated as effective tools for stabilization of the FSWTGS. The gate-controlled series capacitor (GCSC) is a series FACTS device, which was initially proposed for series compensation of a transmission line to control power flow [13,14]. The benefits presented by the GCSC in the control of power flow in power systems have already been studied in the literature [15,16]. Moreover, the application of the GCSC has been studied for sub-synchronous resonance (SSR) damping in power systems by de Jesus, et al., in [17] and the corresponding author of the current work in [18–21].

This paper proposes application and control of the GCSC for transient stability enhancement of FSWTGS. In order to justify the effectiveness of the proposed GCSC, its performance is compared with the TCSC and SBR, in terms of point of common coupling (PCC) voltage, the IG real power, and the synchronous generator (SG) load angle. The studied power system in this paper consists of one SG and one fixed-speed wind turbine IG, delivering electrical power to an infinite bus via double-circuit transmission lines. The simulations are carried out using the electromagnetic simulation program EMTDC/PSCAD [22], considering both

* Corresponding author. Tel.: +1 803 569 0156.
E-mail address: mohammah@email.sc.edu (H.A. Mohammadpour).

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temporary and permanent balanced three-phase-to-ground (3LG) faults on the transmission line [23].

The structure of the paper is as follows: in Section 2, we describe the studied power system; in Section B, we present the modeling of the studied power system; in Section 3, we present the dynamic performance of the system without any compensation; in Section 4, we briefly present the structure and control system of the GCSC, the TCSC, and the SBR. In Section 5, we analyze and discuss the simulation results. In this section, we consider three events to investigate the effectiveness of each series FACTS controllers, namely, (1) a 3LG temperately fault, (2) a 3LG permanent fault, and (3) a dynamic load connection to the system. In Section 6, we conclude this work based on the simulation results.

2. Power system description

The power system studied in this paper is shown in Fig. 1. This system consists of a 100 MVA synchronous generator (SG) and a 50 MW fixed-speed wind turbine-based wind farm, delivering power to an infinite bus through a transmission line with two circuits. The 50 MW wind farm is an aggregated model of 25 wind turbine units, where each unit has the power rating of 2 MW. In fact, a 2 MW wind turbine is scaled up to represent a 50 MW wind farm. This assumption of wind farms is supported by several studies [24,25], suggesting that the dynamic behavior of an aggregated wind farm is sufficient for power system dynamics studies.

As shown in Fig. 1, there exists a local transmission line, which connects the wind farm to the main transmission line through a transformer. A fixed-capacitor is connected to the terminal of the induction generator to compensate demand of the generator's reactive power at steady state condition, and its value is chosen in a way that the power factor of the wind farm is unity, when the rated power and voltage are generated [3]. The system data and modeling are given in the Appendix A and B, respectively.

Moreover, Fig. 1 shows that the GCSC, TCSC, or SBR are inserted in series at the wind generator terminal bus. In this paper, the performance of these three series FACTS devices on transient stability improvement of the system is studied.

3. Simulation of the system without series FACTS

In this section, the simulations are presented, for the case that no FACTS device is installed in the system. Two different scenarios for the simulation are considered. In the first scenario (Scenario I), a balanced temporary 3LG fault occurs at point F1 near the synchronous generator, as shown in Fig. 1. In this scenario, the fault occurs at $t = 0.2$ s, and the CBs on the faulted lines are opened at $t = 0.3$ s, and they are closed again at $t = 1.2$ s, while the fault is cleared.

In the second scenario (Scenario II), a permanent 3LG fault occurs at the same point F1, making an unsuccessful re-closer of CBs. In this scenario, it is assumed that the reclosing of the CBs is not successful, because of the permanent fault. The CBs are reopened after 0.1 s of the reclosing time.

The RMS value of the PCC voltage is depicted for both scenarios in Fig. 2, including the LVRT profile. Note that the LVRT profile shown in Fig. 2 is adopted from the Nordel grid code for the Nordic countries including Norway, Denmark, and Sweden [4]. As seen in Fig. 2, the wind turbine is not capable of maintaining the stability after fault, and the peak of the PCC voltage drops from 1 p.u. to about 0.5 p.u. in both scenarios.

4. Overview of the series FACTS controllers used in this work

4.1. The gate-controlled series capacitor (GCSC)

The GCSC consists of a fixed capacitor in parallel with a bidirectional switch with a pair of gate turn-off (GTO) thyristors (g_1 and g_2), as shown in Fig. 3. The current and voltage waveforms of the GCSC are shown in Fig. 4. The principle of GCSC operation is based on the variation of the turn-off angle (β) of the gate-controlled switches. By controlling the turn-off angle (β), the series compensation level of the transmission line can be determined. The turn-off angles of the GTOs are measured from the zero crossing of the line current, and the compensation level of the GCSC is determined by the fundamental component of the voltage ($v_{CG}(t)$) across the GCSC. The effective reactance of the GCSC is determined by the following equation [19]:

$$X(\beta) = \frac{X_{CG}}{\pi}(2\beta - 2\pi - \sin(2\beta)) \quad (1)$$

where X_{CG} is the reactance of the GCSC capacitor.

Fig. 5 shows typical impedance characteristic of the GCSC as a function of the turn-off angle. As shown in this figure, as β varies from 90 to 180 degrees, $X(\beta)$ varies from $-X_{max}$ ($-X_{CG}$) to 0 [19].

A generic block diagram of the basic control structure of a GCSC device is depicted in Fig. 6. This controller is based on a proportional-integral (PI) regulator. In this figure, T_{mG} is the time constant of first order low pass filter associated with the measurement of the line power. In this controller, the measured line power P_m is compared to the reference current P^*_{Line}, and the error ΔP_e is passed through a PI regulator. The output of the PI regulator, X_{Gdes}, is the input signal to the linearization block, which computes β_{order}, based on Eq. (1). The turn-off pulse generator, which is synchronized with the transmission line current, produces the GCSC's input turn-off pulse.

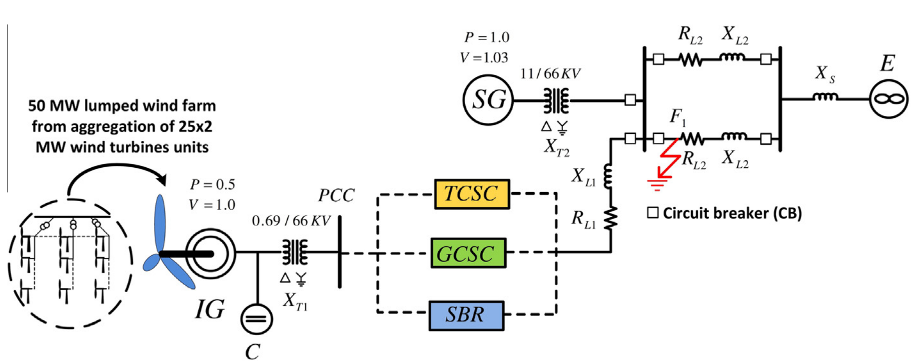

Fig. 1. Schematic of power system with a fixed speed wind turbine for modeling and simulation.