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Designed damping controller for SSSC to improve stability of a hybrid offshore wind farms considering time delay

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A R T I C L E I N F O

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A B S T R A C T

This paper presents the stability improvement results of hybrid doubly fed induction generator (DFIG)-based and permanent magnet generator (PMG)-based offshore wind farms (OWFs) using a static synchronous series compensator (SSSC). An adaptive-network-based fuzzy inference system (ANFIS) controller of the proposed SSSC is designed to render adequate damping characteristics to the studied system. A frequency-domain approach based on a linearized system model using eigenvalue technique analysis is performed. A time-domain scheme based on a nonlinear system model subject to a three-phase short circuit fault at infinite bus with variations in the signal transmission delays has also been investigated to compare the damping of the studied system in cases of with and without controller. The simulation results with MATLAB/SIMULINK toolbox have been presented. It can be concluded from the simulation results that the proposed SSSC joined with the designed ANFIS damping controller can offer adequate damping performance to the studied hybrid DFIG-based and PMG-based OWFs under severe disturbance.

Introduction

Nowadays, with the fast increasing of the offshore wind farm (OWF) systems, besides many large OWF projects with several hundred MW of capacity in Europe such as 576-MW Gwynt y Môr OWF in United Kingdom, 400-MW Anholt OWF in Denmark, or 325-MW Thorntonbank OWF in Belgium... by the end of 2012, 76-GW have been installed in China [1]. When connecting such these large capacity systems to power grid low-frequency oscillations (LFOs) can be happened. It is shown that LFOs are resulted from the lack of damping of mechanical mode of the interconnected power systems [2,3]. Different control schemes to improve damping of power systems have been extensively proposed and presented. One of the countermeasures to improve damping of power systems is by means of using flexible ac transmission system (FACTS) devices.

FACTS devices have become more important in recent years because high-power power-electronics converters with inherent high-speed response can effectively control the amount of power flow of power systems. FACTS devices can also effectively enhance the stability of power systems and allow more efficient uses of existing transmission lines [4,5]. FACTS devices based on voltage-sourced converters (VSCs) can be used for improving power transfer limits, for congestion management in the network, for damping oscillatory modes [6], etc. The static synchronous series compensator (SSSC) is a series FACTS device and it can effectively control the power flow of transmission lines [7]. An auxiliary stabilizing signal of a SSSC can also be superimposed on its power flow control function to enhance the damping of power-system oscillations [8,9]. To achieve these important goals, the damping function of a SSSC was presented in [8] while the fundamental principles, performance and advantages of a SSSC were depicted in [7,10]. Besides that, SSSC was employed in power systems with high penetration of renewable energy units to achieve low voltage ride through capability in abnormal operation in addition to power enhancement in normal operation [9]. Electromagnetic Transients Program (EMTP) was used to simulate the operating characteristics of an inverter-based SSSC [10] while the control and modeling of an inverter-based SSSC were explained in [11]. The impacts of SSSC control modes on small-signal stability and transient stability of an OMIB power system were studied and discussed in [12]. The SSSC can be combined with the static synchronous compensator (STATCOM) to constitute a unified power flow controller (UPFC) while the dc-link capacitor of the UPFC is the common capacitor used for both SSSC and STATCOM [13,14].

In [15], a fuzzy logic controller (FLC) was designed to analyze the effect of coordinated fuzzy logic (FL) based SSSC on real power flow, damping of first swing and the transient stability margin enhancement of a single machine infinite bus system. Also in [16], a comparative evaluation of PI controller and FLC based SSSC

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has been presented for a generator bus with a local load connected in series with the transmission line. However, the drawbacks of fuzzy inference system were completely based on the knowledge and experience of the designer.

Since both FL and artificial neural network (ANN) have their advantages, therefore, the idea of combining them together for producing a powerful processing tool that has both ANN and FL advantages is proposed. In [17], the architecture and learning procedure underlying adaptive-network-based fuzzy inference system (ANFIS) have been proposed. In which, ANFIS incorporates the self-learning ability of ANN with the linguistic expression function of fuzzy inference. Applications to power system, controller parameters for STATCOM were adjusted by ANFIS technology to achieve a better performance of power system [18].

In recent years, with the fast development of communication technology, various communication links makes it possible to provide the control center with the real time signals from remote areas. However, the use of centralized controller entails inputs that may arrive after a certain time delay. Time delays can make the control system have less damping features. In order to satisfy specifications for remote control systems, the design of a controller should take into account this time delay in order to provide a controller that is robust. Since the studied hybrid OWFs locates far from the onshore substation, this paper investigates the design of an ANFIS damping controller for the proposed SSSC considering the potential time delays.

This paper is organized as below. System configuration and mathematical models of the studied hybrid DFIG-based and PMG-based OWFs system and the proposed SSSC are depicted in Section 'System configuration and mathematical models'. Frequency-domain analysis is presented in Section 'Frequency-domain analysis'. The design ANFIS damping controller for SSSC is explained in Section 'Design of an ANFIS damping controller for the SSSC'. Comparative dynamic and transient responses of the studied system subject to a severe disturbance are studied in Section 'Time-domain simulations'. Finally, specific important conclusions of this paper are drawn in Section 'Conclusion'.

System configuration and mathematical models

Fig. 1 plots the configuration of the studied system. The hybrid DFIG-based and PMG-based OWFs with capacity of 200-MW is connected to an infinite bus through a 33/150-kV step-up transformer and two parallel transmission lines [19]. The proposed ±50-MVAR SSSC is located near the point of common coupling (PCC). The 100-MW DFIG-based OWF (OWF_1) is represented by an equivalent aggregated variable-speed wind turbine (VSWT) with an equivalent gearbox driven an equivalent aggregated DFIG that is fed to offshore common bus through a step-up transformer of 4/33-kV and an undersea cable. The 100-MW PMG-based OWF (OWF_2) is represented by an equivalent aggregated VSWT driven an equivalent aggregated PMG. The employed mathematical models of the studied system are explained as follows.

Wind turbine model

The captured mechanical power (in *W*) by a WT can be written by

$$P_{mw} = \frac{1}{2}\rho_w A_{rw} V_W^3 C_{pw}(\lambda_w, \beta_w) \tag{1}$$

where ρ_w is the air density (kg/m^3), A_{rw} is the blade impact area (m^2), V_W is the wind speed (m/s), and C_{pw} is the dimensionless power coefficient of the WT. The power coefficient of the WT C_{pw} is given by

$$C_{pw}(\psi_{kw}, \beta_w) = c_1\left(\frac{c_2}{\psi_{kw}} - c_3\beta_w - c_4\beta_w^{c_5} - c_6\right)\exp\left(-\frac{c_7}{\psi_{kw}}\right) \tag{2}$$

in which

$$\frac{1}{\psi_{kw}} = \frac{1}{\lambda_w + c_8\beta_w} - \frac{c_9}{\beta_w^3 + 1} \tag{3}$$

$$\lambda_w = \frac{R_{bw}\omega_{bw}}{V_W} \tag{4}$$

where ω_{bw} is the blade angular speed (rad/s), R_{bw} is the blade radius (m), λ_w is the tip speed ratio, β_w is blade pitch angle (degrees), and c_1–c_9 are the constant coefficients for power coefficient C_{pw} of the studied WT.

DFIG-based OWF model

Fig. 2 shows diagram of single wind DFIG driven by a WT. The stator windings of the DFIG are directly connected to the low-voltage side of the 4/33-kV step-up transformer (TR2) while the rotor windings of the DFIG are connected to 4-kV through a rotor-side converter (RSC), a dc-link, a grid-side converter (GSC), and TR1, respectively. For normal operation of a DFIG, the input ac-side voltages of the RSC and the GSC can be effectively controlled to achieve the aims of simultaneous output active-power and reactive-power control. The detailed operation of the RSC and GSC can be referred to [20].

PMG-based OWF model

Fig. 3 illustrates the *qd*-axis equivalent-circuit model of a PMG.

The input *dq*-axis pu voltages of the VSC-based converter of the PMG can be expressed by, respectively [21]

$$v_{cond} = km_{cond}V_{dcp} \tag{5}$$

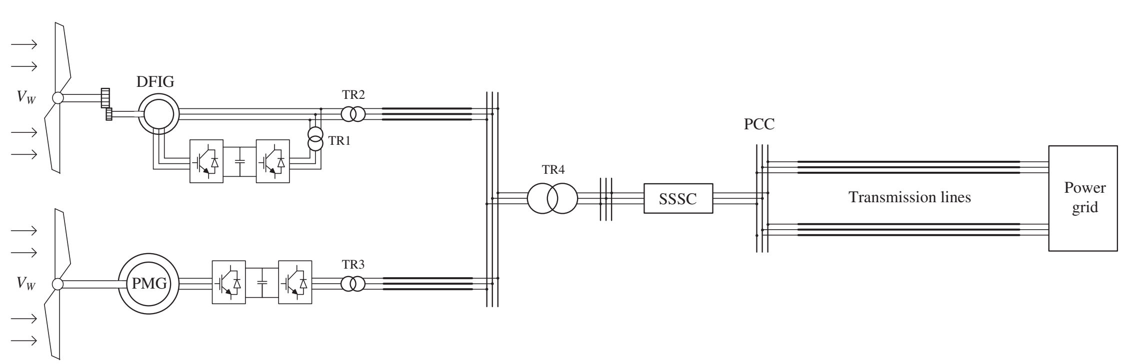

Fig. 1. One-line diagram of the studied hybrid DFIG-based and PMG-based OWFs and the proposed SSSC.