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Dynamic Stability Improvement of a Multi-Machine Power System Connected with a DFIG-Based Wind Farm Using a Generalized Unified Power-Flow Controller (GUPFC)

Nghiên cứu nâng cao ổn định động của hệ thống nhiều máy phát điện nối với máy phát điện gió DFIG sử dụng thiết bị bù GUPFC

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Abstract

This paper proposes the dynamic stability improvement of a multi-machine power system which consists of conventional synchronous generators (SGs)-based power plant integrated with a doubly-fed induction generator (DFIG)-based wind farm by using a generalized unified power-flow controller (GUPFC). In addition to the power flow control function of the GUPFC, a proportional-integral-derivative (PID) type oscillation damping controller (ODC) is designed for the GUPFC to offer adequate damping for the studied system. The proposed ODC for the GUPFC is designed using the pole assignment method based on modal control theory. The steady-state analysis and time-domain simulation results show that the designed ODC for the GUPFC can significantly increase the damping and, hence, effectively improve the dynamic stability of the studied system under various disturbance conditions.

Keywords: DFIG, multi-machine, GUPFC, stability.

Tóm tắt

Bài báo đề xuất sự cải thiện độ ổn định động của một hệ thống điện nhiều máy trong đó bao gồm bốn máy phát điện đồng bộ (SG) kết hợp với một máy phát điện gió nguồn đôi (DFIG) kết hợp với bộ GUPFC. Ngoài các chức năng điều khiển dòng công suất của GUPFC, bộ giảm dao động dùng khâu vi tích phân tỷ lệ PID được thiết kế cho bộ GUPFC (ODC) để nâng cao độ ổn định cho hệ thống. Bộ ODC cho GUPFC được thiết kế bằng cách sử dụng phương pháp gán cực dựa trên lý thuyết điều khiển trạng thái. Các kết quả phân tích trong miền thời gian và miền tần số cho thấy rằng hệ thống nghiên cứu có GUPFC có độ ổn định cao hơn. Các kết quả thu được cũng cho thấy rằng ODC thiết kế cho GUPFC có thể làm tăng đáng kể độ ổn định của hệ thống do đó có thể cải thiện độ ổn định động của hệ thống trong điều kiện nhiễu loạn khác nhau.

Từ khóa: máy phát điện gió nguồn đôi, hệ thống điện nhiều máy, thiết bị bù GUPFC, độ ổn định

1. Introduction

DFIG is, currently, the most employed wind generator due to its several merits. One of the advantages is the higher efficiency compared to a direct-drive wind power generation system with full-scale power converters since only about 20% of power flowing through power converter and the rest through stator without power electronics [1]. However, by connecting stator windings directly to the power grid, a wind DFIG is extremely sensitive to grid faults. Moreover, wind energy is a kind of stochastic energy, implying that the output of OWF varies in a certain range due to unstable wind characteristic. Therefore, the operating point of the power system changes from time to time when the wind power is integrated with the power system. Especially, increase of wind-power penetration could lead to the problem of sudden disconnection of considerable amount of power generation in case of a transient fault occurred in the system, causing the system to be unstable from an otherwise harmless fault situation.

In this case, flexible alternating current transmission system (FACTS) controllers could be employed to enhance power system stability in addition to their main function of power flow control. Among them, the GUPFC has been proposed to realize the simultaneous power-flow control of several lines and enhance power-system stability [2]. Combining three or more converters working together, the GUPFC extends the concepts of voltage and power- flow control beyond what is achievable with the known two-converter UPFC controller. With

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the practical applications of the GUPFC in power systems, several research works on GUPFC have been done in recent years [3-5], most of which has been focused on the controller design for GUPFC. A fundamental-frequency model of the GUPFC consisting of one shunt converter and two series converters was proposed in [4]. While modeling the GUPFC in power flow and optimal power flow (OPF) analysis was proposed in [3]. In [5], only modelling the GUPFC in load-flow studies was considered.

In this paper, a simple four-machine two-area model of a power system connected with a DIFG-based offshore wind farm will be used to demonstrate the performance of the proposed GUPFC joined with the proportional-integral-derivative (PID) damping controllers for different contingencies and operating points. Frequency-domain approaches based on a linearized system model using eigenvalue analysis are performed while time-domain schemes based on nonlinear system models subject to disturbance are also carried out to validate the effectiveness of the proposed control schemes.

2. System Configuration

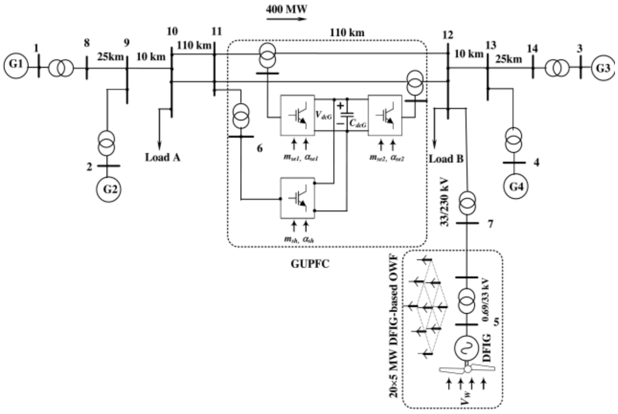


Fig. 1. Configuration of the integrated generation consisting of multi-machine system and DFIG-based wind farm and GUPFC.

Fig. 1 illustrates a schematic diagram of the proposed integrated generation consisting of multi-machine system and DFIG-based wind farm. The multi-machine system consists of two fully symmetrical areas that are linked together through two parallel 230-kV transmission lines of 220-km length [6]. A DFIG-based OWF with rated capacity of 100 MW is connected to bus 12 of the studied multi-machine system through a step-up transformer of 33/230 kV. The OWF is represented by a large equivalent aggregated wind DFIG driven by an equivalent aggregated variable-speed wind turbine (VSWT) through an equivalent aggregated gearbox. A GUPFC is installed on the transmission line between bus 11 and bus 12. In Fig. 1, the GUPFC has three power converters, where two of the three power converters are connected in series with the parallel transmission lines from bus 11 to bus 12 while one power converter is connected in shunt with the transmission line at bus 11. The DC sides of the three power converters are connected via a common DC link. The employed mathematical models of the studied system are described as follows.

2.1 Two-area four-generator system and its subsystems

The synchronous generator model, excitation system model, steam-turbine and speed-governor models are referred to [6].

2.*2 DFIG Model and Control of Power Converters*

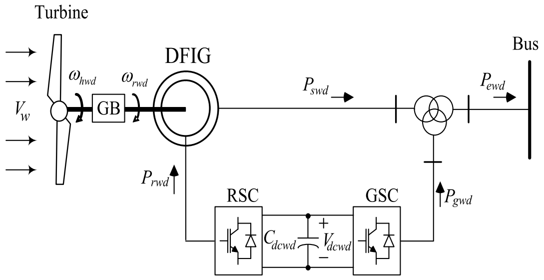


Fig. 2. One-line diagram of wind DFIG driven by a VSWT through a GB.

The configuration of a wind DFIG driven by a variable-speed wind turbine through a gearbox (VSWT-GB-DFIG) is shown in Fig. 2. The DFIG transforms the input wind-turbine power P into electrical power. The produced stator power P is always positive. The rotor power P can be either positive or negative due to the presence of the back-to-back converter. This allows the machine to operate at either sub- or super- synchronous speed [7].

The stator windings of the DFIG are directly connected to the low-voltage side of the 0.69/24-kV step-up transformer while the rotor windings of the DFIG are connected to the same 0.69-kV side through a RSC, a DC link with the DC-link capacitor of Cdcwd and the DC-link voltage of Vdcwd, a GSC, and a connection line.

For normal operation of a wind DFIG, the input AC-side voltages of the RSC and the GSC can be effectively controlled to achieve the aims of simultaneous control of output active power and reactive power [8].

In this paper, an IG model developed in a dq-axis synchronous reference frame with an assumption of neglecting the stator-winding transient effects is employed. This model can be found in [9-12]. Fig. 3

and Fig. 4 show the control block diagram of the RSC and GSC, respectively.

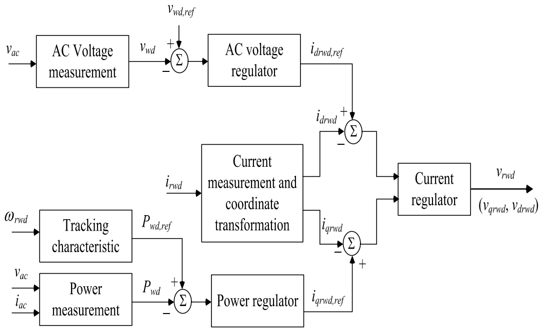


Fig. 3. Block diagram for the control system of the RSC of the studied wind DFIG

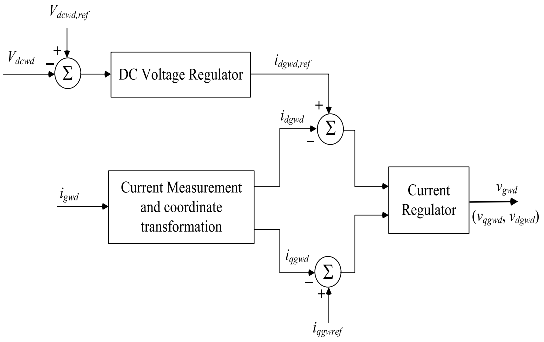


Fig. 4. Block diagram of the control system of the GSC of the studied wind DFIG.

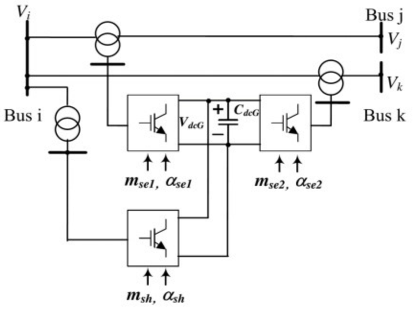


Fig. 5. Operational principle of the GUPFC with three converters.

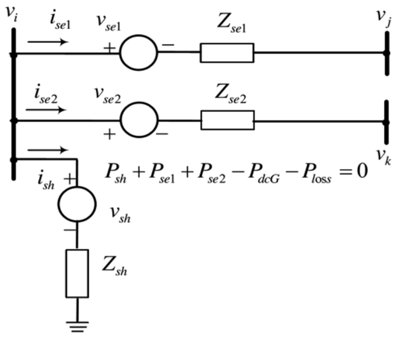


Fig. 6. The equivalent circuit of the GUPFC.

For normal operation of a wind DFIG, the input AC-side voltages of the RSC and the GSC can be effectively controlled to achieve the aims of simultaneous control of the output active power and reactive power [13-14].

2.3. GUPFC Model

The GUPFC is the latest generation of one of the FACTS devices which can be used to control power flows of multiple transmission lines, increase loadability of the power system and improved stability, etc. [15]. The basic operation principle of a GUPFC can be found in open literature [16]. The simplest GUPFC consists of three converters, one connected in shunt and the other two in series with two transmission lines via coupling transformers, respectively as shown in Fig. 5.

The GUPFC can explicitly control total five power system quantities such as the voltage magnitude of bus i and independent active and reactive power flows of the two lines. The equivalent circuit of the GUPFC including one controllable shunt injected voltage source and two controllable series injected voltage sources is shown in Fig. 6. Real power can be exchanged among the shunt and series converters via the common DC link, and the sum of the real power exchange should be zero.

In Fig. 6, Z_{sh}, Z_{se1} and Z_{se2} are the shunt and two series transformer impedances, respectively; v_{sh}, Z_{se1} and v_{se2} are the controllable shunt and two series injected voltage sources of the shunt and two series converters; P_{sh}, Z_{se1} and Z_{se2} are the active powers exchange of the shunt and two series converters via the common DC link. The controllable injected voltage sources are defined as

$$v_{sh}=\sqrt{2}V_{sh}\sin(\omega t+\theta-\alpha_{sh}) \quad (1)$$

$$v_{se1}=\sqrt{2}V_{se1}\sin(\omega t+\theta-\alpha_{se1}) \quad (2)$$

$$v_{se2}=\sqrt{2}V_{se2}\sin(\omega t+\theta-\alpha_{se2}) \quad (3)$$

It should be mentioned that six control variables are actually inputs of GUPFC. Amplitude modulation factors m_{sh}, m_{se1} and m_{se2} directly influence the voltage source magnitudes while angles α_{sh}, α_{se1} and α_{se2} influence the phase shift with respect to the voltage vi , i.e.,

$$v_j=\sqrt{2}V_i\cos(\omega t+\theta) \quad (4)$$

Amplitude modulation factors are used to calculate voltage source magnitudes as follows:

$$V_{sh} = \frac{1}{2\sqrt{2}} m_{sh} V_{dcG} \quad (5)$$

$$V_{se1} = \frac{1}{2\sqrt{2}} m_{se1} V_{dcG} \quad (6)$$

$$V_{se2} = \frac{1}{2\sqrt{2}} m_{se2} V_{dcG} \quad (7)$$

where V_{dcG} is the average DC capacitor voltage. The transformers are modeled as lossless, saturation free transformers. The converter switching losses are modeled as a resistance R in parallel to the branch loss with a capacitance C that represents DC capacitor. The variable R is not dcG loss physically included into the model. The fundamental frequency model is developed assuming that a power balance between AC and DC sides is respected according to [15]. The proposed model is similar to the models presented in [17] and accurately represents GUPFC behavior in balanced, fundamental frequency power systems studies such as a three-phase fault studies.

3. Design of two PID ODCs for GUPFC

In this section, the two PID damping controllers are designed by using pole- assignment approach. When the desired eigenvalues or poles are substituted into the closed-loop characteristic equation, the parameters of the oscillation damping controller can be easily determined [18]. The control block diagram of the phase angle α_{sh} of the GUPFC including the designed PID damping controllers is shown in Fig. 7

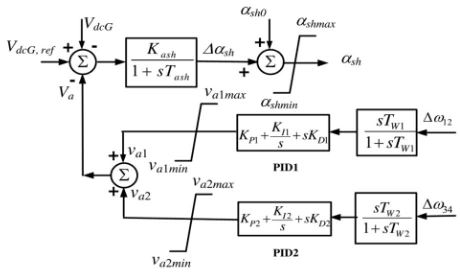


Fig. 7. The control block diagram of the phase angle α_{sh} of the GUPFC including two PID controllers.

The two PID damping controllers are designed for this studied system. The rotor speed deviation between SG1 and SG2 ($\Delta\omega_{12}$) is sensed to generate the output signal V_{a1} of the first PID damping controller. The second one takes the rotor speed deviationbetween SG3 and SG4 ($\Delta\omega_{34}$) as the input signal to generate the stabilizing signal V_{a2}. The summation of the two output signals V_{a1} and V_{a2} of two PID damping controllers is the damping signal V_a. This signal is added up to decide the phase angle signal α_{sh}, which is modulated to improve the damping ratios of modes ($\omega_{1,2}$, $\omega_{3,4}$, $\omega_{5,6}$ and $\omega_{7,8}$) of the studied system, as listed in Table 1.

The design results of the two PID damping controllers for the GUPFC are given as below.

K_{P1}=11.767, K_{I1}=-54.112, K_{D1}=5.421, T_{W1}=0.702 s

K_{P2} =16.572, K_{I2}=-63.863, K_{D2} =6.916, T_{W2}=0.951 s

The eigenvalues of the closed-loop system containing the proposed GUPFC joined with the two designed PID ODCs are listed in the ninth column of Table 1. It can be concluded that the design results are appropriate to the system.

Table 1. Eigenvalues (rad/s) of the system without GUPFC, with GUPFC, and with GUPFC and the designed PIDs.

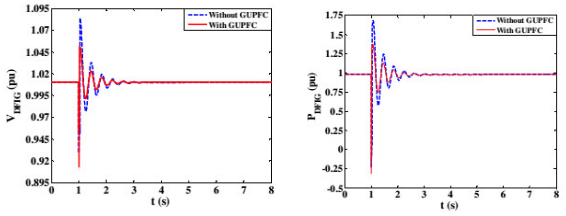
Mode		Without GUPFC		
		Eigenvalue	ζ	f (Hz)
Λ1,2	δ2, ω2, δ1, ω1	-0.7647 ± j9.0839	0.0842	1.4458
Λ3,4	δ1, ω1,δ2, ω2	-0.8108 ± j9.1659	0.0884	1.4588
Λ5,6	δ3, ω3 ,δ4ω4	-0.7619 ± j9.8936	0.0770	1.5746
Λ7,8	δ4, ω4,δ3, ω3	-0.7726 ± j9.7924	0.0789	1.5585

Mode		With GUPFC		
		Eigenvalue	ζ	f (Hz)
Λ1,2	δ2, ω2, δ1, ω1	-1.1811 ± j9.5317	0.1230	1.5147
Λ3,4	δ1, ω1,δ2, ω2	- 1.1196 ± j9.4325	0.1179	1.5012
Λ5,6	δ3, ω3 ,δ4ω4	-0.7956 ±j10.037	0.0790	1.5975
Λ7,8	δ4, ω4,δ3, ω3	-0.8583 ± j9.8844	0.0865	1.5732

Mode		With GUPFC +PIDs		
		Eigenvalue	ζ	f (Hz)
Λ1,2	δ2, ω2, δ1, ω1	**-2.0 ± j9.50***	0.20601	1.5119
Λ3,4	δ1, ω1,δ2, ω2	**-2.0 ± j9.40***	0.20811	1.4961
Λ5,6	δ3, ω3 ,δ4ω4	**-1.70 ±j10.0***	0.1676	1.5915
Λ7,8	δ4, ω4,δ3, ω3	**-1.60 ± j9.80***	0.1611	1.5597

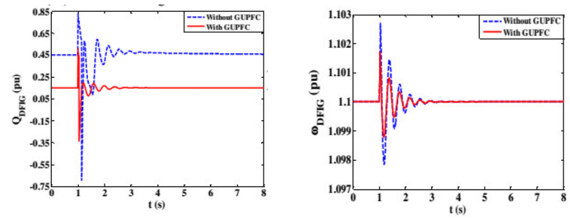
4. Time domain simulation

The main objective of this chapter is to demonstrate the effectiveness of the designed damping controllers of the proposed GUPFC on enhancing dynamic stability of the system under various disturbance conditions. This objective is achieved by performing the time-domain simulations and comparing the dynamic responses of the system without GUPFC, with GUPFC, with GUPFC joined with the designed PID controllers when subjected to disturbance. The transient responses of the system subject to a three-phase short- circuit fault occurred at one of two parallel transmission lines 10-11 at t = 1 s and cleared at t = 1.1 s without changing network structure are analyzed. Fig. 8 and Fig. 9 plot the transient responses of the system subject to a three-phase short-circuit fault under two studied cases: (a) without and with the GUPFC and (b) with the GUPFC and the GUPFC joined with PID controllers, respectively. It can be observed that the amplitudes of the transient responses of the four SGs can be declined during the fault interval when the GUPFC is in service. In addition, when the designed PID controllers are joined with the proposed GUPFC, the smaller amplitudes on different responses of the system can be effectively obtained.



(a) Terminal voltage of DFIG

(b) Active power of DFIG



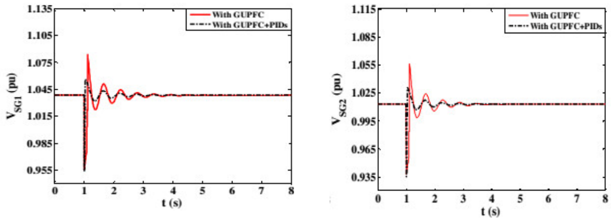
(c) Reactive power of DFIG

(d) Rotor speed of DFIG

Fig. 8. Transient responses of the system subject to a three-phase short-circuit fault at one of parallel transmission lines 10-11 without changing network structure without and with GUPFC.

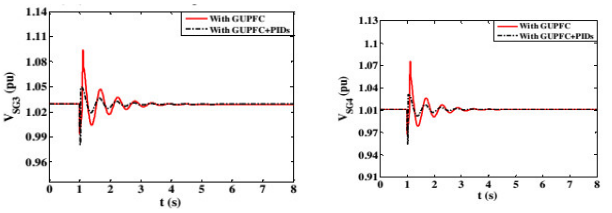
5. Conclusions

This paper has proposed a GUPFC joined with the designed damping controllers to achieve dynamic stability improvement of a four-machine two- area power system connected with a large-scale offshore wind farm based on doubly-fed induction generator. The four-machine two-area system is divided into two areas connected via two parallel transmission lines, which have installed the proposed GUPFC device to control the power flow and improve the damping oscillation. The steady-state analysis of the studied system under various operating conditions that involves power-flow calculations and eigenvalue analysis of the system have been performed. The transient responses of the studied system subject to a severe three-phase short-circuit fault at one of two parallel transmission lines have been analyzed. The analyzed results have shown that the system has a slightly damping improvement when the proposed GUPFC is in service. Moreover, when the GUPFC joined with the designed PID damping controllers, the system can have a better damping performance to mitigate the oscillations.



(a) Terminal voltage of SG1

(b) Terminal voltage of SG2



(c) Terminal voltage of SG3

(d) Terminal voltage of SG4

Fig. 9. Transient responses of the system subject to a three-phase short-circuit fault at one of parallel transmission lines 10-11 without changing network structure with GUPFC and GUPFC+PIDs.

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