Dynamic-Stability Improvement of A Multi-Machine Power System Connected with A Large-Scale Offshore Wind Farm Using A Generalized Unified Power Flow Controller (GUPFC)

Cải thiện ổn định động của hệ thống nhiều máy phát có kết nối với nguồn năng lượng gió qui mô lớn bằng thiết bị GUPFC

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Abstract

This paper studies the dynamic-stability improvement of a two-area four-generator system connected with a large-scale offshore wind farm based on doubly-fed induction generator (DFIG) using a generalized unified power-flow controller (GUPFC) The power flows of the studied system in steady-state conditions with and without GUPFC are calculated. A time-domain method based on nonlinear-model simulations subject to different disturbances on transmission lines and wind speed variations are both performed to examine the effectiveness of the proposed GUPFC It can be concluded from the comparative simulation results that the proposed GUPFC demonstrates better performances for improving the dynamic stability of the studied multi-machine system as well as a large-scale offshore wind farm based on DFIG subject to various severe disturbances.

Keywords: Multi-machine system, generalized unified power flow controller (GUPFC), offshore wind farm, doubly fed induction generator (DFIG); flexible AC transmission system (FACTS).

Tóm tắt

Bài báo trình bày kết quả nghiên cứu sử dụng thiết bị điều khiển dòng công suất hợp nhất (GUPFC) để cải thiện ổn định động cho hệ thống nhiều máy phát có kết nối với tổ hợp nguồn năng lượng gió quy mô lớn Dòng công suất của hệ thống được nghiên cứu, tính toán trong các điều kiện làm việc tĩnh khi có lắp đặt và khi không lắp đặt thiết bị GUPFC Thông qua phương pháp mô phỏng miền thời gian dựa trên mô hình không tuyến tính với các nhiễu loạn khác nhau trên đường dây truyền tải và khi tốc độ gió thay đổi được thực hiện để khảo sát hiệu quả của thiết bị GUPFC. Từ các kết quả mô phỏng nhận được, so sánh rút ra kết luận việc sử dụng thiết bị GUPFC cho phép cải thiện độ ổn định của hệ thống nhiều máy phát cũng như tổ hợp hệ thống năng lượng gió khi có các nhiễu loạn nguy hiểm xảy ra

Từ khóa: Hệ nhiều máy; thiết bị điều khiển dòng công suất hợp nhất; hệ thống năng lượng gió; máy phát hai nguồn kép; hệ thống truyền tải điện xoay chiều linh hoạt.

I. Introduction[1]

With the increasing concerns on energy shortage and global warming, the research and development of various renewable energies have been made significant progress for several years Among the renewable energy sources being vigorously developed, wind turbine has being undergoing a dramatic development and now has become the world's fastest growing energy source [1] From 2010 onwards, wind power annual growth rates of 20% will result in a total of 1 2 million MW being installed by the end of 2020. This will generate 2,966 Terawatt hours of electricity, equivalent to 10.85% of the expected world consumption of electricity [2] The dramatic increase in the penetration level of wind power generation into power system as a serious power source has received considerable attention. One of the major concerns related to the high level penetration of the integrated wind turbines is the impact on power system stability. As the penetration level of the wind power in power systems increases, the overall performance of the system will increasingly be affected by the inherent characteristics of wind power generators.

An innovative approach to utilize FACTS controllers for providing multifunctional power flow management was proposed in [3]. There are several possibilities of operating configurations by combing two or more converter blocks with flexibility, some

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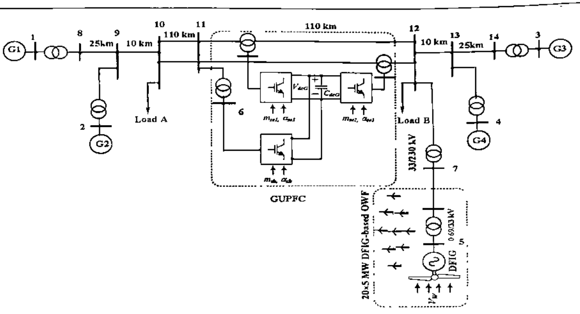


Fig 1. The configuration of studied system.

of which are connected in series with a line and the others are connected in shunt or a combination of series and shunt. Among them, there are two novel operating configurations, namely the interline power-flow controller and the generalized unified power flow controller (GUPFC) [4], which are significantly extended to control power flows of multi-lines or a sub-network rather than control power flow of single line by a unified power-flow controller or static synchronous series compensator. GUPFC has been widely studied in the technical literature and has been shown to significantly improve the dynamic stability of power systems.

In this paper, the proposed GUPFC is researched and designed to contribute adequate damping characteristics to the dominant modes of the system under various operating conditions. The power flow calculation and a time-domain simulation of the non-linear model are investigated to test the impact of various GUPFC control functions on power system oscillations. The results demonstrate that a satisfactory dynamic improvement of power system can be achieved.

2. System configuration and mathematical models

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 as shown in Fig. 1 [5]. A DFIG-based offshore wind farm (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.

2.1. Configuration of a DFIG-based wind turbine system

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_{mw} into electrical power The produced stator power P_{sw} is always positive The rotor power P_{rw} can be either positive or negative due to the presence of the back-

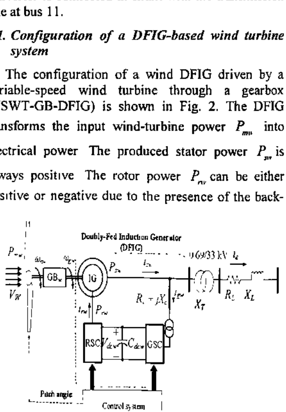


Fig. 2. One-line diagram of wind DFIG driven by a VSWT through a GB.

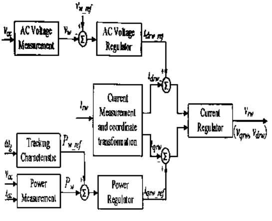


Fig. 3 Control block diagram for the RSC of the studied DFIG

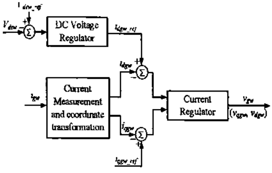


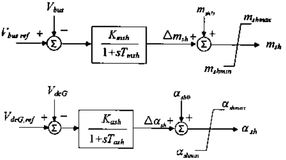
Fig. 4 Control block diagram for the GSC of the studied DFIG

to-back converter. This allows the machine to operate at either sub- or super-synchronous speed [6].

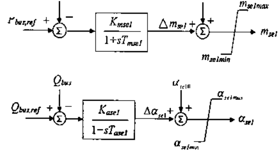
The stator windings of the DFIG are directly connected to the low-voltage side of the 0.69/33-kV step-up transformer while the rotor windings of the DFIG are connected to the same 0.69-kV side through a back-to-back converter, a step-up transformer, and a connection line. The operation of the DFIG-based wind turbine is regulated by a control system, consisting of a controller for the rotor-side converter (RSC), a controller for the grid-side converter (GSC), and a pitch angle controller.

Fig. 3 shows the control block diagram of the RSC, and the operation of the RSC requires i_{qrw} and i_{drw} to follow the varying reference points that are determined by maintaining the output active power and the stator-winding voltage at the setting values, respectively. The required voltage for the RSC (v_{rw}) is derived by controlling the pu q- and d-axis currents of the RSC.

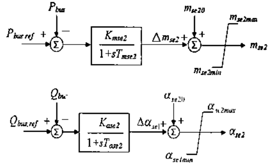
The diagram of the GSC is shown in Fig. 4. The pu *q*- and *d*- control block axis currents of the GSC, i_{qgw} and i_{dgw}, have to track the reference points that



(a) The control block diagram of the shunt converter.



(b) The control block diagram of first series converters



(c) The control block diagram of second series converter.

Fig 5 The control block diagram of GUPFC.

are maintaining the DC link voltage V_{dcw} at the setting value and keeping the output of the GSC at unity power factor, respectively. The required pu voltage of the GSC (v_{gw}) is derived by controlling the per-unit q- and d-axis currents of the GSC [7].

2.2. Wind speed Model

Wind power has characteristics of random and intermittence. The wind speed usually can be considered to consist of four terms. There are basic wind component, ramp component, gust component and turbulence or noise component [8]. The wind speed model therefore is expressed by

$$V_W = V_{WB} + V_{WG} + V_{WR} + V_{WN} \qquad (1)$$

where V_{WB} is the base wind speed in m/s, V_{WG} is the gust wind speed in m/s, V_{WR} is the ramp wind speed in m/s, and V_{WN} is the noise wind speed in m/s.

2.3. Wind turbine Model

The power generated by a wind turbine, P_{mw} comes from the kinetic energy of the wind and depends on the power coefficient, C_p, according to the following expression

$$P_{mw} = \frac{1}{2}\rho \cdot A_r \cdot V_W^3 \cdot C_p(\lambda, \beta_w) \qquad (2)$$

where ρ is the air density (kg/m^3), A_r is the blade impact area (m^2), V_W is the wind speed (m/s), and C_p is the dimensionless power coefficient of the WT. The power coefficient of the WT C_p is given by

$$C_p(\lambda, \beta_w) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta_w - c_4\beta_w^{c_5} - c_6\right)\exp\left(\frac{-c_7}{\lambda_i}\right) \qquad (3)$$

with $$\frac{1}{\lambda_i} = \frac{1}{\lambda + c_8\beta_w} - \frac{c_9}{\beta_w^3 + 1} \qquad (4)$$

The blade tip speed ratio is defined as

$$\lambda = \frac{\omega_m R_{blade}}{V_w} \qquad (5)$$

where ω_{tw} is the speed in rad/s and R_{blade} is the blade length or turbine radius in m of the WT. $c_1 \div c_9$ are the power coefficients of the WT.

2.4. GUPFC model

The GUPFC is significantly extended to control power flows of multiple lines rather than a single line The simplest form of the GUPFC is the combination of three converters, two of them are connected in series with two lines and one is connected in shunt with the line. All three converters are connected via a DC link [10]. The GUPFC is capable of providing voltage control at a bus as well as independent active and reactive power-flow control on two lines therefore controlling a total of five power-system quantities Each of the two converters provides control capability for three power system quantities. The addition of the third converter provides two more degrees of freedom in controlling power systems. The remaining capacity of the shunt converter is utilized for providing voltage support at the bus via reactive-power exchange The reactive power is exchanged between the two series converters and the power system to meet the active power control objectives [11].

Three converters of GUPFC provide a total of six control variables. A simplified control system block diagram for the GUPFC is shown in Fig. 5. In the shunt part, the constant DC link capacitor voltage control is achieved by controlling the firing angle of α_{sh} of converter 1 and the constant GUPFC terminal bus voltage control is achieved by controlling m_{sh}, of the PWM controller of converter 1. The output of the two series converters controls the active and reactive power flow of the two lines The constant active power flow control is achieved by controlling the amplitude modulation factors m_{se1} and m_{se2}, and the constant reactive power flow control is realized by controlling the phase angle factors α_{se1} and α_{se2}.

The control blocks shown in Fig 5 can be expressed by the following differential equations:

$$(T_{msh})\,p(m_{sh}) = K_{msh}\left(V_{bus\,ref} - V_{bus}\right) - m_{sh} \qquad (6)$$

$$(T_{\alpha sh})\,p(\alpha_{sh}) = K_{\alpha sh}\left(V_{dcG,ref} - V_{dcG}\right) - \alpha_{sh} \qquad (7)$$

$$(T_{mse1})\,p(m_{se1}) = K_{mse1}\left(P_{bus\,ref} - P_{bus}\right) - m_{se1} \qquad (8)$$

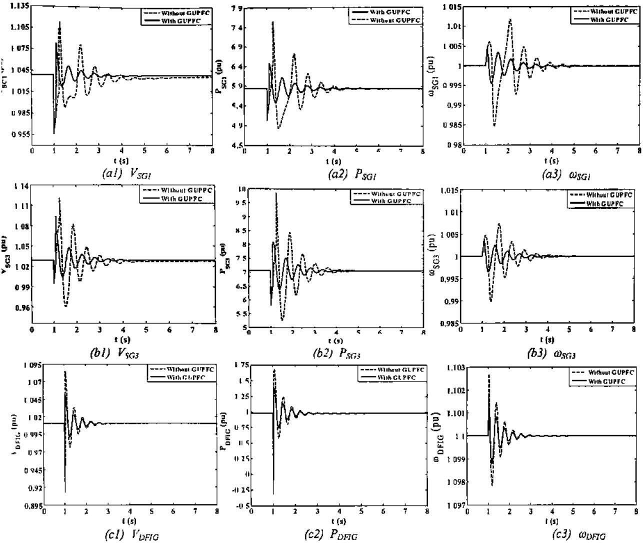
$$(T_{\alpha se1})\,p(\alpha_{se1}) = K_{\alpha se1}\left(Q_{bus\,ref} - Q_{bus}\right) - \alpha_{se1} \qquad (9)$$

Table1. Power-flow calculation results of the system without GUPFC.

Bus No.	Bus Type	Voltage (pu)	Generation		Load	
			P_G (MW)	Q_G (MVAr)	P_L (MW)	Q_L (MVAr)
1	swing	1 03	581 497	117 576	-	-
2	P-V	1 01	700	130 222	-	-
3	P-V	1 03	719	135 025	-	-
4	P-V	1 01	700	103 565	-	-
5	P-V	1 01	100	44 153	-	-
6	P-Q	1 006	-	-	-	-
7	P-Q	1 015	-	-	-	-
8	P-Q	0 995	-	-	-	-
9	P-Q	0 987	-	-	967	100
10	P-Q	0 991	-	-	-	-
11	P-Q	1 00	-	-	1767	100
12	P-Q	1 00	-	-	-	-
13	P-Q	1 015	-	-	-	-
Total:			2800 497	530.54	2734	200

Table 2. Power-flow calculation results of the system with GUPFC.

Bus No.	Bus Type	Voltage (pu)	Generation		Load	
			P_G (MW)	Q_G (MVAr)	P_L (MW)	Q_L (MVAr)
1	swing	1 03	580 817	105 276	-	-
2	P-V	1 01	700	100 55	-	-
3	P-V	1 03	719	126 759	-	-
4	P-V	1 01	700	83 678	-	-
5	P-V	1 01	100	14 569	-	-
6	P-V	1 025	-	56 23	-	-
7	P-Q	1 009	-	-	-	-
8	P-Q	1 017	-	-	-	-
9	P-Q	1 00	-	-	-	-
10	P-Q	0 996	-	-	967	100
11	P-Q	1 021	-	-	-	-
12	P-Q	1,006	-	-	1767	100
13	P-Q	1 003	-	-	-	-
14	P-Q	1 016	-	-	-	-
Total:			2799 817	487.062	2734	200



(a1) V_{SG1} (a2) P_{SG1} (a3) ω_{SG1}

(b1) V_{SG3} (b2) P_{SG3} (b3) ω_{SG3}

(c1) V_{DFIG} (c2) P_{DFIG} (c3) ω_{DFIG}

Fig. 6. Transient responses of the system subject to a three-phase short-circuit fault at one of parallel transmission lines 10-11 without and with GUPFC.

$$\left(T_{mse2}\right)p\left(m_{se2}\right)=K_{mse2}\left(P_{bus\,ref}-P_{bus}\right)-m_{se2} \quad (10)$$

$$\left(T_{ase2}\right)p\left(\alpha_{se2}\right)=K_{ase2}\left(Q_{bus,ref}-Q_{bus}\right)-\alpha_{se2} \quad (11)$$

where $T_{msh}, T_{mse1}, T_{mse2}, T_{ash}, T_{ase1}, T_{ase2}$ and $K_{msh}, K_{mse1}, K_{mse2}, K_{ash}, K_{ase1}, K_{ase2}$ are the time constants and gains of first-order lag blocks of GUPFC's shunt and two series converters.

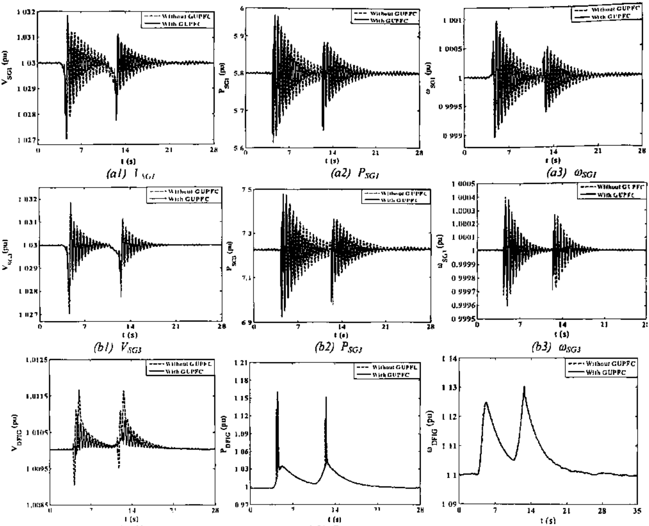
3. Power flow calculation

This part aims to perform the steady-state analysis of the studied system and to demonstrate the effectiveness of the proposed GUPFC. The power flows are calculated for the studied system in steady-state conditions with rated parameters when GUPFC is in and out service as shown in Table 1 and 2. In this performance, the generator number 1 (SG1) with bus number 1 will be worked as the slack bus.

From these tables, it can be seen clearly that with GUPFC, the quantities of the system can be significantly improved. The voltage magnitudes of buses are improved and the active power losses are minimized when the system with the proposed GUPFC. Besides, the reactive power of each generator supplies to the system can be reduced when the GUPFC is in service (from 530.54 MVAr to 487.062 MVAr in total.)

4 Time-domain simulations

The main objective of this part is to demonstrate the effectiveness of the proposed GUPFC on enhancing dynamic stability of the system under three disturbance conditions. A three-phase short-circuit fault occurs at one of two parallel transmission lines 10-11 at t = 1 s and cleared at t = 1.1 s is analyzed in Case 1 as shown in Fig. 6. It can be observed that the amplitudes of the transient responses of the SGs and DFIG can be declined



(a1) V_{SG1} (a2) P_{SG1} (a3) ω_{SG1}

(b1) V_{SG3} (b2) P_{SG3} (b3) ω_{SG3}

(c1) V_{DFIG} (c2) P_{DFIG} (c3) ω_{DFIG}

Fig. 7. Dynamic responses of the system under the variations of wind speed without and with GUPFC.

during the fault interval when the GUPFC is in service.

Case 2 illustrates the wind-speed variations on the OWF: A gust wind speed with the peak of 1 m/s is added to the base wind speed at t = 4 s and is cleared after 3 s. At t = 11 s, the wind speed is assumed to ramp up from 12 m/s to 13 m/s and drops back to 12 m/s at t = 13 s as shown in Fig. 7.

As can be seen, the effect of the noise wind speed in the system responses is negligible comparing to those of the gust and the ramp wind speeds. When the gust and the ramp wind speeds occur, they cause the corresponding fluctuations in the DFIG responses and the oscillations in the four-SG responses. However, the magnitudes of oscillations in the four-SG responses are quite small. Therefore, the wind speed variation may be regarded as the small disturbance as seen from the SGs.

The operating conditions of the studied system prior the severe disturbance are properly selected at rated conditions.

It is obviously seen from the comparative transient responses shown in Figs. 6 and 7 that transient responses of the studied system with the proposed GUPFC can offer a dynamic-stability improvement under difference disturbance conditions.

5 Conclusion

This paper has proposed a GUPFC to achieve dynamic stability improvement and power flow control of a four-machine two-area power system connected with a large-scale offshore wind farm based on doubly-fed induction generator.

The steady-state analysis of the studied system under various operating conditions that involves power-flow calculation of the system has 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 as well as the dynamic responses of the system subject to wind-speed variations have also been analyzed The analyzed results have shown that the system has a better dynamic stability improvement when the proposed GUPFC is in service.

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Ngày nhận bài:28/12/2015; Ngày phản biện:25/2/2016, Ngày duyệt đăng. 15/3/2016
Phản biện khoa học: *PGS.TS Lại Khắc Lãi – Trường Đại học Kỹ thuật Công nghiệp - ĐHTN*