DYNAMIC STABILITY IMPROVEMENT OF A LARGE-SCALE MACHINE POWER SYSTEM WITH A DFIG-BASED WIND FARM USING A GENERALIZED UNIFIED POWER-FLOW CONTROLLER (GUPFC)

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ABSTRACT

This research proposes the dynamic stability improvement of a large-scale power system which consists of a conventional synchronous generator (SG)-based power plant integrated with a doubly-fed induction generator (DFIG)-based wind farm by using a generalized unified power-flow controller (GUPFC). The complete dynamic mathematical equations of the studied system are established in dq-axis reference frame under three-phase balanced conditions. 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 studied system without GUPFC suffers from low-damped low-frequency oscillations due to the electromechanical mode of the SGs. The damping of these oscillations, however, is slightly increased when the GUPFC is implemented in the transmission line for controlling the power flow. The results obtained also 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: *Wind power, a large-scale power system, doubly fed induction generator (DFIG), generalized unified power-flow controller (GUPFC), stability.*

TÓM TẮT

Nghiên cứu đề xuất sự cải thiện độ ổn định động của một hệ thống điện quy mô lớn trong đó bao gồm một máy phát điện đồng bộ (SG) kết hợp với một máy phát điện gió nguồn đôi (DFIG) kết hợp với bộ GUPFC. Các phương trình toán học của hệ thống được thành lập trong hệ quy chiếu dq trong điều kiện cân bằng ba pha. Ngoài các chức năng điều khiển dòng công suất của GUPFC, bộ giảm dao dộng 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**: năng lượng gió, hệ thống điện qui mô lớn, máy phát điện gió nguồn kép , 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 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 large-scale power system which includes a conventional SG-based power plant integrated with a DFIG-based 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 illustrates a schematic diagram of the proposed integrated system consisting of a conventional SG-based power plant integrated with a DFIG-based wind farm. This system is the modification of the one-machine infinite-bus (OMIB) system shown in [6] by connecting a 200-MW DFIG-based wind farm at bus 3 via an HVAC transmission line and step-up transformers. Hence, the studied system consists of a SG and an aggregated DFIG supplying power to the utility grid (infinite bus) through two parallel transmission lines.

The SG has the rating of 2220 MVA. It represents the model of a conventional thermal power plant that has four 555-MVA units. The aggregated 200-MW DFIG is used to represent the model of a DFIG-based wind farm consisting of forty 5-MW wind-turbine generators.

A GUPFC is installed on the transmission line between bus 3 and bus 4. 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 3 to bus 4 while one power converter is connected in shunt with the transmission line at bus 3. The DC sides of the three power converters are connected via a common DC link.

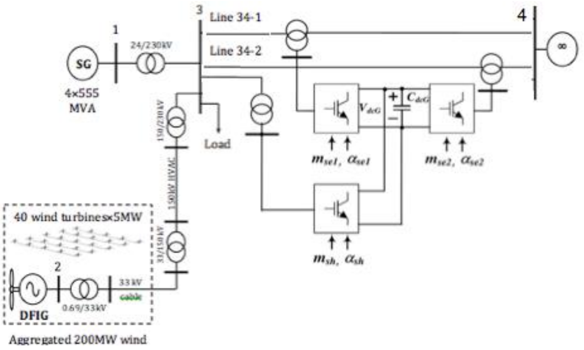


Fig.1 *Configuration of the integrated generation consisting of a conventional SG-based power plant integrated with a DFIG-based wind farm and GUPFC*

The employed mathematical models of the studied system are described as below. The equations in the following subsections are expressed in per unit (pu) except that the time variable *t* and base angular frequency ω_b are in s and rad/s, respectively.

2.1 Synchronous generator model and its subsystems

There are several mathematical models which have been used to represent the SG in power system stability studies. The degrees of simplification based on reasonable assumptions and the choices of Park's transformation as well as the choices of state variables are the main factors causing the differences among them. The order of SG models (number of differential equations) ranges from eighth order in the full model (with four rotor circuit) to second order in the classical model where only δ and ω of the SG are retained as the state variables. The SG model used in this thesis is the same as the one developed in [6].

2.2 DFIG model and Control of Power Converters

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].

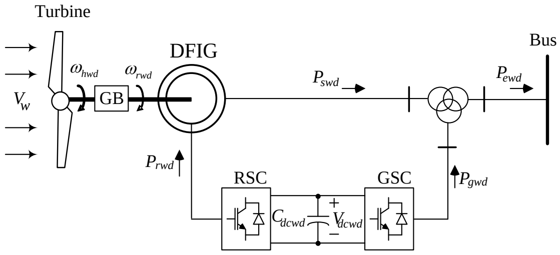


Fig. 2 *One-line diagram of wind DFIG driven by a VSWT through a GB*

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 C_{dcwd} and the DC-link voltage of V_{dcwd}, 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.

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].

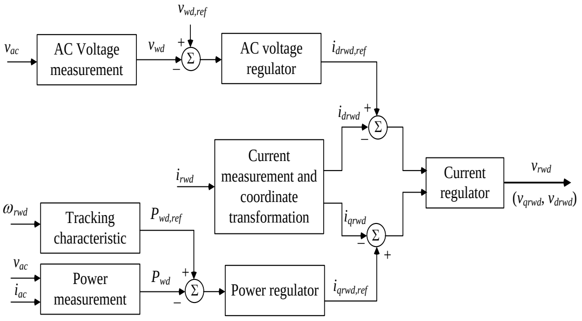


Fig. 3 *Block diagram for the control system of the RSC of the studied wind DFIG*

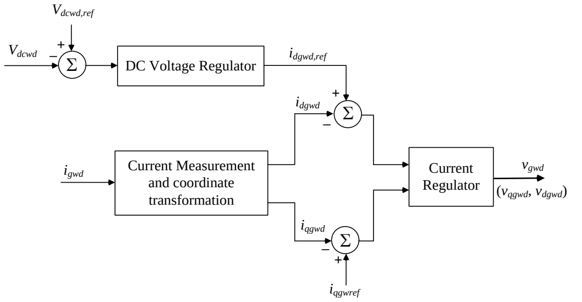


Fig. 4*. Block diagram of the control system of the GSC of the studied wind DFIG*

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 load ability 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.

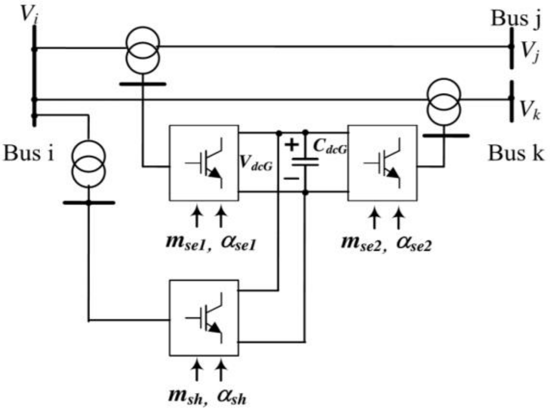


Fig.5 *Operational principle of the GUPFC with three converters*

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

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

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

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

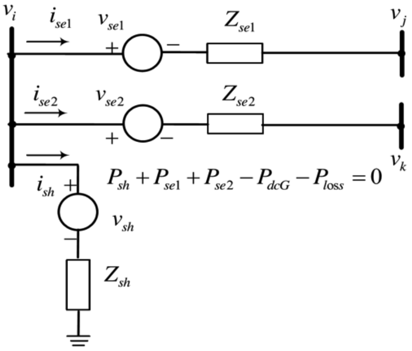


Fig. 6*. The equivalent circuit of the GUPFC*

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}, $\alpha_{se1}$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 dc 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 [17]. The proposed model is similar to the models presented in [18] 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

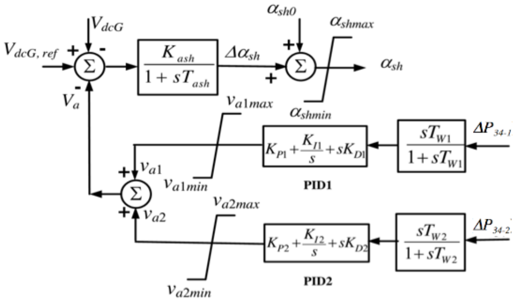


Fig. 7*. The control block diagram of the phase angle α_{sh} of the GUPFC including two PID controllers*

The two PID damping controllers are designed for this studied system. The active-power deviation through line 34-1 (ΔP_{34-1}) is sensed to generate the output signal V_{a1} of the first PID damping controller. The second one takes the active-power deviation through line 34-2 (ΔP_{34-2}) 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 ($\Lambda_{1,2}$, $\Lambda_{3,4}$, $\Lambda_{5,6}$ and $\Lambda_{7,8}$) 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 (at PSG = 0.9 p.u., VSG = 1.0 p.u., PFSG = 0.9 lagging, and VW of 13 m/s)*

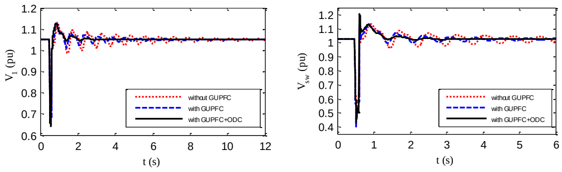
Without GUPFC		
Λ_5, Λ_6	**ζ**	**f (Hz)**
-0.211 ± j8.315	0.025	1.32
With GUPFC		
-0.372 ± j8.884	0.042	1.41
With GUPFC +ODC		
-1.20 ± j8.34*	0.142	1.33

4. TIME-DOMAIN SIMULATIONS

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.

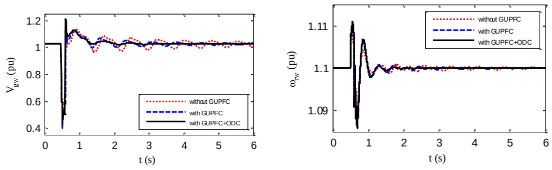
This section aims to demonstrate the effectiveness of the designed ODC on improving transient stability of the studied system when subjected to a severe three-phase short-circuit fault at the utility grid. The simulation time is 12s. The applied three-phase short-circuit fault at the grid bus (infinite bus) starts at t = 0.5 s and lasts for six cycles (0.1 s).

Fig. 8 shows the comparative transient responses of the studied system without GUPFC, with GUPFC, and with GUPFC included the designed ODC under the three-phase short-circuit fault at power grid. In this figure, the low-damped oscillations with large amplitude due to the severe three-phase short-circuit fault are very obvious when the studied system is without the designed ODC. However, it is evident that these large-amplitude low-damped oscillations can be significantly suppressed when the designed ODC is joined with the proposed GUPFC in the studied system. The oscillations in the transient responses of the studied system with the designed ODC are well-damped within only 4s. Therefore, it can be concluded that the designed ODC can effectively enhance the transient stability of the studied system under the severe three-phase short-circuit fault.



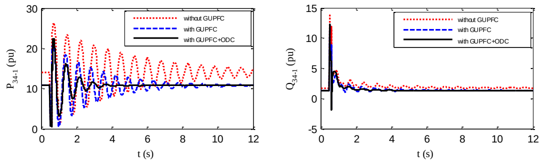
SG terminal voltage

DFIG stator voltage



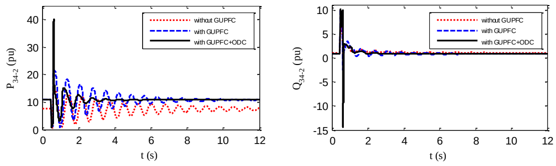
DFIG GSC voltage

DFIG rotor speed



Line 34-1 active power

Line 34-1 reactive power



Line 34-2 active power

Line 34-2 reactive power

Fig. 8. *Transient responses of the studied system under a three-phase short-circuit fault.*

5. CONCLUSIONS

This paper has proposed a GUPFC joined with the designed damping controllers to achieve dynamic stability improvement and power flow control of a large-scale machine power system connected with a large-scale offshore wind farm based on doubly-fed induction generator. The studied system is connected to the utility grid through two parallel transmission lines, one of which contains the proposed GUPFC device to control the power flow. The pole-assignment method based on modal control theory has effectively applied to the design of PID oscillation damping controller for the proposed GUPFC to exactly locate the electromechanical mode of the SG of the studied system, which is the most poor-damped mode, at desired location on the complex plane in order to achieve the dynamic stability improvement of the studied system. The steady-state analysis of the studied system under various operating conditions using the linearization technique that involves the analysis of the studied system eigenvalues has been performed. The dynamic responses of the studied system subject to a severe three-phase short-circuit fault at the power grid bus have also been carried out. From the results obtained, it can be concluded that when the GUPFC is only used as a means of power flow control it can slightly improve the damping of the studied system. When the GUPFC joined with the designed oscillation damping controller can effectively improve the damping of the electromechanical mode of the SG. Hence, the dynamic stability of the studied system can be effectively improved.

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