DAMPING ENHANCEMENT OF A MULTI-MACHINE SYSTEM USING A GENERALIZED UNIFIED POWER FLOW CONTROLLER (GUPFC)

Nguyen Thi Ha*, Le Thanh Bac**

The University of Danang, University of Science and Technology

*nthadht@gmail.com; **lethanhbac2012@yahoo.com

Abstract - This paper presents the design procedures of two proportional-integral-derivative (PID) damping controllers for a generalized unified power flow controller (GUPFC) to achieve damping improvement of a four-machine system. Two PID damping controllers of the proposed GUPFC are designed to contribute adequate damping characteristics to the dominant modes of the system under various operating conditions. A frequency-domain approach based on a linearized system using eigenvalue analysis anda time-domain method based on nonlinear-model simulations subject to a three-phase short-circuit fault at the transmission line is systematically performed to examine the effectiveness of the proposed control schemes. It can be concluded from the comparative simulated results that the proposed GUPFC joined with the designed PID scan improve the stability of the system subject to a severe disturbance.

Key words - Multi-machine system; generalized unified power flow controller (GUPFC); PID controller; damping controller; flexible AC transmission system (FACTS).

1. Introduction

With the development of high-voltage semiconductor devices and high-speed power-electronics control technology, flexible AC transmission systems (FACTS) devices are found to be very effective in improving both stability and damping of a power system by dynamically controlling the power-angle curve of the connected systems [1]. Due to their fast response, these devices are used to dynamically adjust the network configuration to enhance steady-state performance as well as dynamic stability [2]. There are various forms of FACTS devices, some of which are connected in series with a line and the others are connected in shunt or a combination of series and shunt. The detailed description of various FACTS devices including their operating principles can be found in [3].

An innovative approach to utilize FACTS controllers for providing multifunctional power flow management was proposed in [4]. There are several possibilities of operating configurations by combing two or more converter blocks with flexibility. Among them, there are two novel operating configurations, namely the interline power-flow controller (IPFC) and the generalized unified power flow controller (GUPFC) [5], 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 (UPFC) or static synchronous series compensator (SSSC). GUPFC has been widely studied in the technical literature and has been shown to significantly enhance system stability.

Different control methods of FACTS device have been proposed for power oscillation damping and transient stability improvement. One popular damping control method used a washout filter followed by an *m*th order lead-lag controller [6]. In general, the parameters of a lead-lag controller were designed using the pole-zero location method [7].

In this paper, two PID damping controllers of the proposed GUPFC are designed to contribute adequate damping characteristics to the dominant modes of the system under various operating conditions. The linearized model is derived with confirmation from simulation of the non-linear model to investigate the impact of various GUPFC control functions on power system oscillation damping. The results demonstrate that a satisfactory damping of power system oscillations can be achieved.

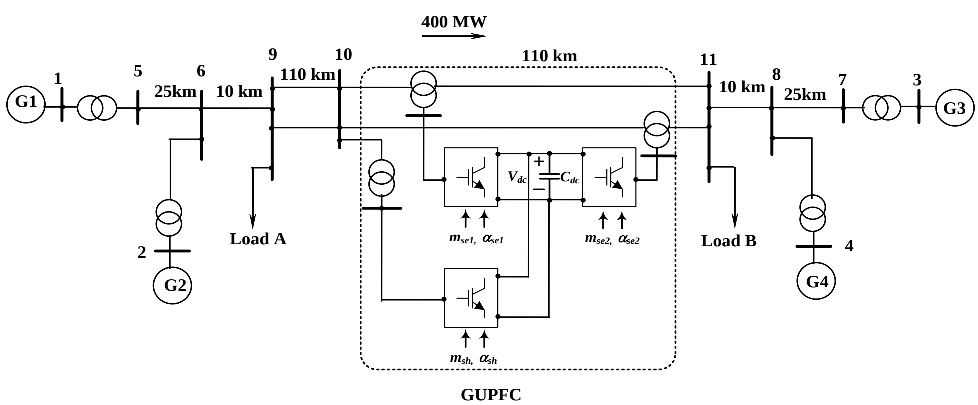


Figure 1. *The configuration of studied system*

2. System configuration and mathematical models

The multi-machine system consisting of two fully symmetrical areas linked together by two 230-kV lines of 220-km length installed with the GUPFC is shown in Figure 1. This system is specifically designed to study low-frequency electromechanical oscillations in large-scale interconnected power systems. Each area is equipped with two identical round-rotor synchronous generators rated 20kV/900MVA. Thermal plants having identical speed governors are further assumed at all locations, in addition to the fast static exciters. Each generator produces the active power of about 700 MW. The loads are represented by constant impedances and split between the two areas in such a way that there is a power transfer of 400 MW from area 1 to area 2. The GUPFC is the combination of three converters. Two of three converters are connected in series with the parallel lines from bus 10 to 11 and one converter is connected in shunt with the line at bus 10. All three converters are connected via DC link.

2.1. Multi-machine system

The well-known four-machine system which is widely used in power system stability studies. The completeparameters of this system can be referred to [8]. In this system, each synchronous generator is represented by a two-axis model whose block diagramis shown in Figure 2. In this model, the transient effects are accounted for while the sub-transient effects are neglected. The additional assumptions made in this model are that the transformer-voltage terms in the stator voltage equations are negligible compared to the speed-voltage terms. The pudifferential equations for the *i*-th synchronous generator aredescribed as below.

$$\tau'_{qoi}\, p(E'_{di}) = -E'_{di} - (X_{qi} - X'_{qi}) I_{qi} \qquad (1)$$

$$\tau'_{doi}\, p(E'_{qi}) = -E'_{qi} + E_{FDi} + (X_{di} - X'_{di}) I_{di} \qquad (2)$$

$$\tau_{ji}\, p(\omega_i) = T_{mi} - [I_{di}E'_{di} + I_{qi}E'_{qi} - (L'_{qi} - L'_{di}) I_{di} I_{qi}] - D_i\omega_i \qquad (3)$$

$$p(\delta_i) = \omega_b (\omega_i - 1) \qquad (4)$$

2.2. GUPFC model [3]

The GUPFC is the latest generation of FACTS devices which can be used to control power flows of multiple transmission lines, increase loadability of the power system and improved stability, etc. [3]. The simplest form of the GUPFC is the combination of three converters, two of them are connected in series with two transmission lines and one is connected in shunt with the line. All three converters are connected via DC link. The GUPFC is capable of providing voltage control at a bus as well as independent real and reactive power flow control on two transmission lines therefore controlling a total of five power system quantities. Two-converter applications each provide control capability for three power system quantities. The addition of the third converter provides two more degrees of freedom in control of power systems. The remaining capacity of the shunt converter is utilized for providing voltage support at the bus via reactivepower exchange. The reactive power is exchanged between the two series converters and the power system to meet the real power flow control objectives. GUPFC is more complex than other FACTS devices.

Three converters of GUPFC provide a total of six control variables. A simplified control system block diagram for the GUPFC isshown in Figure 3. 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}.

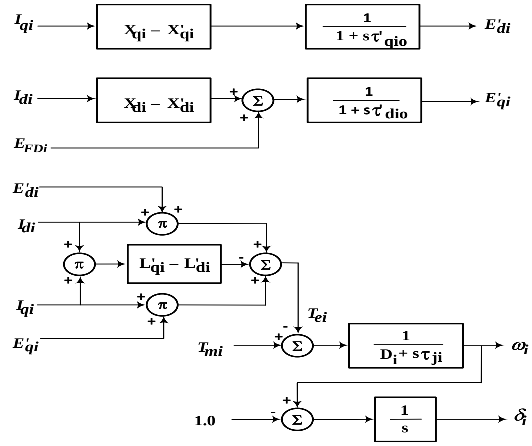
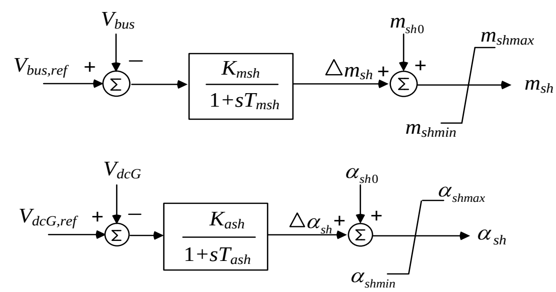
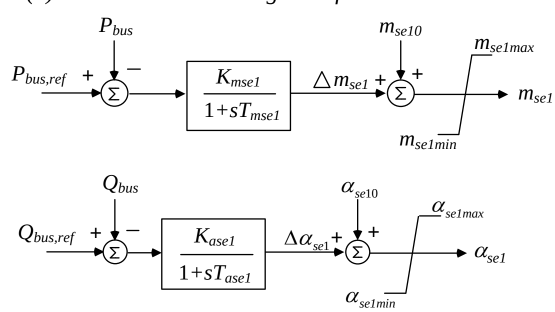


Figure 2. *Block diagram representation of the two-axis model of the studied SG*



(a) The control block diagram of the shunt converter



(b) The control block diagram of the series converter

Figure 3. *The control block diagram of GUPFC*

3. Design of PID damping controllers

In this section, the two PID damping controllers are designedby using pole-assignment approachfor the proposed GUPFC to achieve stability improvement of the studied system. 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 [9].

The nonlinear system equations developed in the previous section are linearized around a selected nominal operating point to acquire a set of linearized system equationsin matrix form of:

$$p\mathbf{X}=\mathbf{AX}+\mathbf{BU}+\mathbf{VW} \qquad (5)$$

$$\mathbf{Y}=\mathbf{CX}+\mathbf{DU} \qquad (6)$$

where **X** is the state vector, **Y** is the output vector, **U** is the external or compensated input vector, **W** is the disturbanc e input vector while**A**, **B**, **C**, and **D** are all constant matric es of appropriate dimensions. To design the PID damping controllers for the GUPFC, **W** in (5) and **U** in (6) can bepr operly ignoredby setting **D** = **V** = 0.

The eight eigenvalues of the studied four-machine system and the proposed GUPFC are listed in Table 1. The following pointscan be found by examining the system eigenvalues listed in Table 1.

The control block diagram of the phase angle α_{sh} of the GUPFC including the designed PID damping controllers is shown in Figure 4.

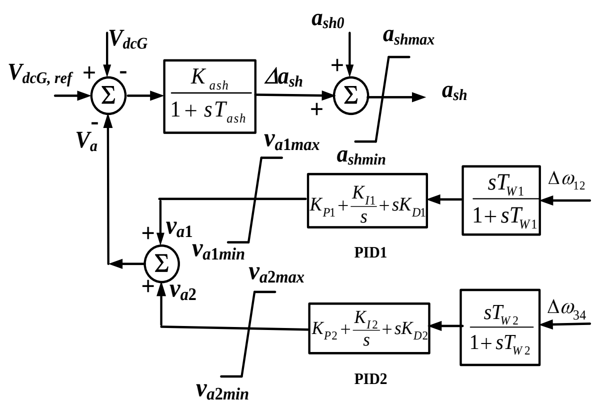


Figure 4. *The control block diagram of the phase angle* α_{sh} *of the GUPFC including two PID controllers*

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 deviation between 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 $\left(\Lambda_{1,2}, \Lambda_{3,4}, \Lambda_{5,6} \text{ and } \Lambda_{7,8}\right)$ of the studied system, as listed in Table 1. The transfer functions $H_1(s)$ and $H_2(s)$ of the two PID dampingcontrollers for the GUPFC in s domain are given by:

$$H_1(s) = \frac{\mathbf{U}_1(s)}{\mathbf{Y}_1(s)} = \frac{V_{a1}(s)}{\Delta\omega_{12}(s)} = \frac{sT_{W1}}{1+sT_{W1}}\left(K_{P1} + \frac{K_{I1}}{s} + sK_{D1}\right) \quad (7)$$

$$H_2(s) = \frac{\mathbf{U}_2(s)}{\mathbf{Y}_2(s)} = \frac{V_{a2}(s)}{\Delta\omega_{34}(s)} = \frac{sT_{W2}}{1+sT_{W2}}\left(K_{P2} + \frac{K_{I2}}{s} + sK_{D2}\right) \quad (8)$$

where T_{W1} and T_{W2} are the time constants of two wash-out terms while K_{P1}, K_{P2}, K_{I1}, K_{I2} and K_{D1}, K_{D2} are the proportional gains, integral gains, and derivative gains of the two PID damping controllers, respectively.

Substituting $G_1(s)$, $G_2(s)$ and $H_1(s)$, $H_2(s)$ into Mason's rule and extending, it yields:

$$G_1(s)\frac{sT_{W1}}{1+sT_{W1}}(K_{P1} + \frac{K_{I1}}{s} + sK_{D1}) = -1 \quad (9)$$

$$G_2(s)\frac{sT_{W2}}{1+sT_{W2}}(K_{P2} + \frac{K_{I2}}{s} + sK_{D2}) = -1 \quad (10)$$

When four pairs of the specified mechanicalmodes $\left(\Lambda_{1,2}, \Lambda_{3,4}, \Lambda_{5,6} \text{ and } \Lambda_{7,8}\right)$ are substituted into (9, 10), the eight parameters of the two PID controllers can be obtained. The design results of the two PID damping controllers for the GUPFC are given as Table 1.

Parameters of the Designed PID Damping Controllers

K_{P1} = 11.767, K_{I1} = = -54.111, K_{D1} = 5.421, T_{W1} = 0.702s,

K_{P2} = 16.572, K_{I2} = = -63.863, K_{D2} = 7.916, T_{W2} = 0.951s.

The eigenvalues of the studied four-machine system and the proposed GUPFC joined with the two designed PID damping controllers are listed in the seventh column of Table 1. It can be clearly observed that the damping ratios of $\Lambda_{1,2}, \Lambda_{3,4}, \Lambda_{5,6}$ and $\Lambda_{7,8}$ increase from 0.1230, 0.1179, 0.0790 and 0.0865 to 0.2060, 0.2081, 0.1387 and 0.1513, respectively. According to the eigenvalue results listed in the seventh column of Table 1 and the eight parameters of the two designed PID damping controllers of the GUPFC shown above, it can be concluded that the design results are appropriate to the studied system.

Table 1. *Eight eigenvalues (rad/s) of the Kundur's four-machine system without/with GUPFC and PID controllers*

No.	Dominant Modes	Without GUPFC and PID controllers		With GUPFC		With GUPFC and PID controllers	
		EVs	ζ	EVs	ζ	EVs	ζ
1, 2	$\delta_2, \omega_2, \delta_1, \omega_1$	-0.57858 ± j8.0667	0.0715	-1.1811 ± j9.5317	0.1230	**-2 ± *j*9.5***	0.2060
3, 4	$\delta_1, \omega_1, \delta_2, \omega_2$	-0.71403 ±j8.0389	0.0885	-1.1196 ± j9.4325	0.1179	**-2 ± *j*9.4***	0.2081
5, 6	$\delta_3, \omega_3, \delta_4, \omega_4$	-0.36785 ± j8.6739	0.0424	-0.79562 ±j10.037	0.0790	**-1.4 ± *j*10***	0.1387
7, 8	$\delta_4, \omega_4, \delta_3, \omega_3$	-0.79961 ± j8.7776	0.0864	-0.85834 ± j9.8844	0.0865	**-1.5 ± *j*9.8***	0.1513

ζ *denotes the damping ratioand * denotes the assigned eigenvalues*

4. Time-domain simulations

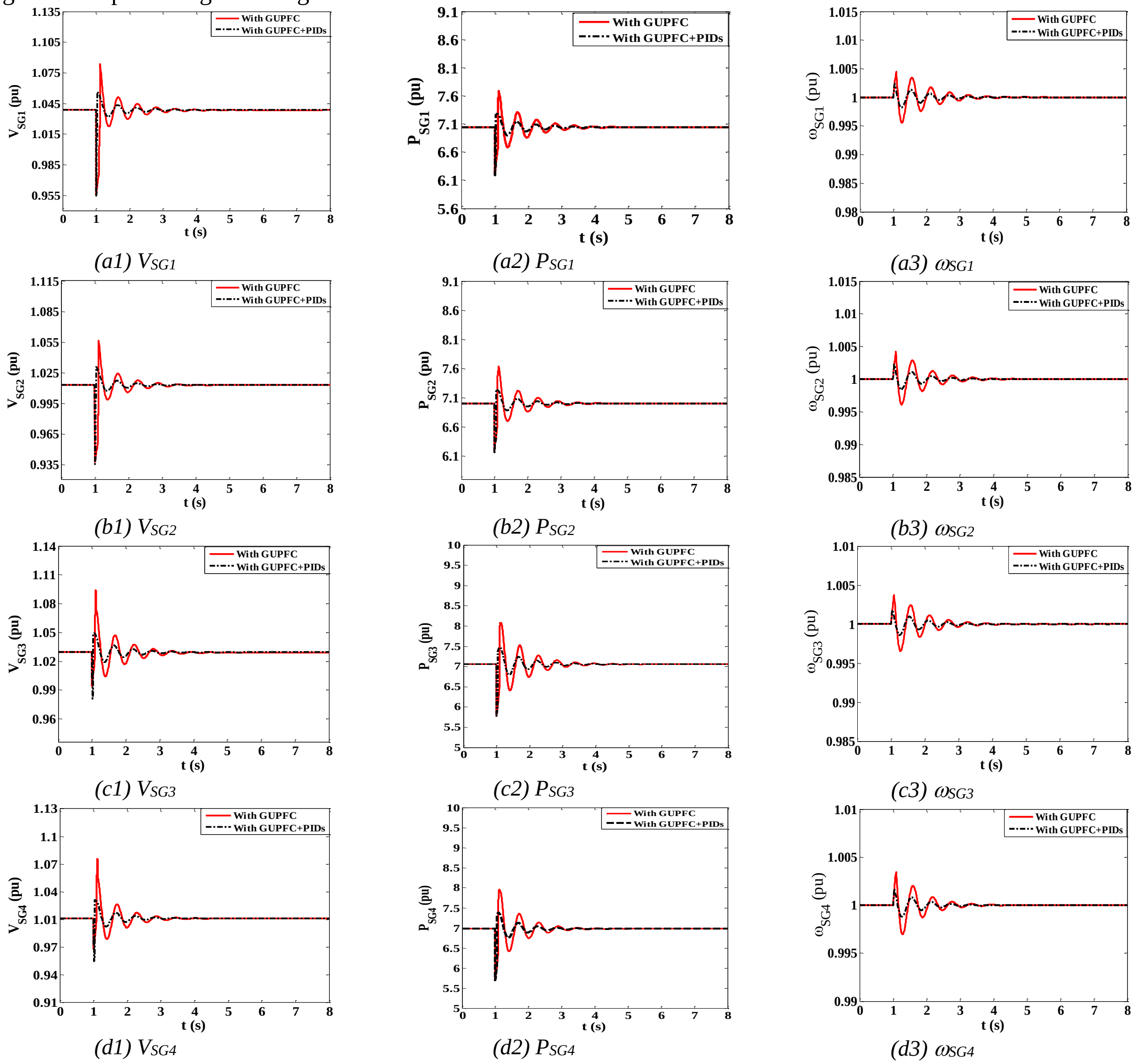
The main objective of this section is to demonstrate the effectiveness of the designed PID damping controller on enhancing dynamic stability of the studied system subject to a three-phase short-circuit fault at one of two parallel transmission lines 10-11at t = 1 s, and it is cleared at t = 1.1 s.

The simulation results of the proposed system using MATLAB/SIMULINK toolbox are presented in Figure 5. This figure plots the comparative transient responses of the studied system installed the proposed GUPFC (red lines) and the proposed GUPFC joined with the designed PID damping controllers (black lines).

It is obviously seen from the comparative transient responses shown in Figure 5 that transient responses of the studied system with the designed PIDs can offer better damping characteristics.

5. Conclusion

In this paper, the design PID controllers for damping enhancement of a Kundur's four-machine system using GUPFC subject to a severe power-system fault has been investigated. The pole-assignment algorithm has been used to find the parameters of the proposed damping controllers. The simulation results have shown that the proposed control scheme can effectively damp oscillations of the studied system under a three-phase short-circuit fault.



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

(b1) V_{SG2} *(b2) P_{SG2}* *(b3) ω_{SG2}*

(c1) V_{SG3} *(c2) P_{SG3}* *(c3) ω_{SG3}*

(d1) V_{SG4} *(d2) P_{SG4}* *(d3) ω_{SG4}*

Figure 5. *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*

REFERENCES

[1] L. Gyugyi, 'Unified power-flow control concept for flexible ACtransmission systems,", *IEE Proceedings - Generation, Transmission & Distribution*, vol. 139, no. 4, pp. 323-331, Jul. 1992.

[2] D. P. He, C. Y. Chung, and Y. Xue, "An eigenstructure-based performance index and its application to control design for damping inter-area oscillations in power systems", *IEEE Trans. Power Systems*, vol. 26, no. 4, pp. 2371-2380, Nov. 2011.

[3] X.-P. Zhang, C. Rehtanz, and B. Pal, *Flexible AC Transmission Systems: Modelling and Control*, Berlin, Germany: Springer, 2006.

[4] S. Arabi, H. Hamadanizadeh, and B. Fardanesh, "Convertible static compensator performance studies on the NY state transmission system", *IEEE Trans. Power Systems*, vol. 17, no. 3, pp. 701-706, Aug. 2002.

[5] L. Gyugyi, K. K. Sen, and C. D. Schauder, "The interline power flowcontroller: A new approach to power flow management in transmissionsystems", *IEEE Trans. Power Delivery*, vol. 14, no. 3, pp. 1115-1123, Jul. 1999.

[6] M. E. Aboul-Ela, A. A. Sallam, J. D. McCalley, and A. A. Fouad, "Damping controller design for power system oscillations using globalsignals", *IEEE Trans. Power Systems*, vol. 11, no. 2, pp. 767-773, May1996.

[7] U. P. Mhaskar and A. M. Kulkarni, "Power oscillation damping using FACTS devices: Model controllability, observability in local signals, and location of transfer function zeros", *IEEE Trans. Power Systems*, vol. 21, no. 1, pp. 285-294, Feb. 2006.

[8] P. Kundur, *Power System Stability and Control*, New York, USA: McGraw-Hill, 1994.

[9] L. Wang and Z.-Y. Tsai, "Stabilization of generator oscillations using PID STATCON damping controllers and PID power system stabilizers", in *Proc. 1999 IEEE Power Engineering Society Winter Meeting*, New York, NY, USA, Jan. 31-Feb. 4, 1999, vol. 2, pp. 616-621.

(The Board of Editors received the paper on 18/10/2014, its review was completed on 18/12/2014)