2021 3rd International Conference on High Voltage Engineering and Power Systems (ICHVEPS)

An Effective Damping Control Scheme to Improve Inter-Area Power System Stability

A. Abu-Siada
Electrical and Computer Engineering Department
Curtin University
Perth, Australia
A.AbuSiada@curtin.edu.au

Suwarno
School of Electrical Engineering and Informatics
Institut Teknologi Bandung
Bandung, Indonesia
suwarno@stei.itb.ac.id

Nanang Hariyanto
School of Electrical Engineering and Informatics
Institut Teknologi Bandung
Bandung, Indonesia
nanang.hariyanto@stei.itb.ac.id

Fathin Saifur Rahman
School of Electrical Engineering and Informatics
Institut Teknologi Bandung
Bandung, Indonesia
fathinsr@stei.itb.ac.id

Muhammad Ruswandi Djalal
Department of Energy Engineering
Politeknik Negeri Ujung Pandang
Makassar, Indonesia
wandi@poliupg.ac.id

Joko Hartono
Transmission and Distribution Department
PT PLN Research Institute
Jakarta, Indonesia
joko.hartono@pln.co.id

Rathy Shinta Utami
School of Electrical Engineering and Informatics
Institut Teknologi Bandung
Bandung, Indonesia
rathyshintautami@gmail.com

Luky Handayani
School of Electrical Engineering and Informatics
Institut Teknologi Bandung
Bandung, Indonesia
lukyhandayani@yahoo.com

2021 3rd International Conference on High Voltage Engineering and Power Systems (ICHVEPS) | 978-1-6654-4354-8/21/$31.00 ©2021 IEEE | DOI: 10.1109/ICHVEPS53178.2021.9600970

***Abstract*— In a large and complex interconnected power system with long transmission lines, the inadequate damping scheme for the inter-area oscillations may lead to system instability. This issue is commonly solved by employing a power system stabilizer (PSS) to increase the system damping. However, the use of PSS encounters some limitations that include voltage fluctuation and poor performance in damping significant oscillations that result due to three-phase faults. To improve the damping of the inter-area oscillation modes, a unified power flow controller (UPFC) along with the PSS is proposed in this paper. Simultaneous utilization of PSS and UPFC calls for proper coordination to attain an optimal damping performance. Hence, a method to obtain optimal coordination between the PSS and UPFC by employing the Firefly algorithm is proposed. To verify the effectiveness of the proposed method, the performance of the proposed damping scheme is analyzed through simulation analysis. Simulation results show the effectiveness of the proposed method in damping low as well as large oscillations in the power systems.**

Keywords*— *inter-area oscillation, power system stabilizer, unified power flow controller, PI-controller, firefly algorithm

I. INTRODUCTION

The development of large interconnected electric power systems makes it more prone to interarea oscillations, particularly on weak tie-lines which affects system stability and reliability [1]. Small-signal instability is attributed to the insufficient damping of the oscillation modes in the power systems. These oscillations are classified into a local mode with a frequency range of 0.8 Hz to 2.0 Hz or inter-area modes which involve several generators with a frequency range of 0.1 to 0.8 Hz. If not effectively damped, these oscillation modes may result in synchronization loss of the generators and a partial outage or a total blackout [2].

To overcome stability problems that may occur due to the insufficient damping of the oscillation modes, a power system stabilizer (PSS) has been widely proposed. PSS working principle is based on providing an electric torque component that matches the deviation of the rotor speed. However, the use of PSS exhibits some drawbacks such as it may cause variations to the voltage profile and it has poor performance in suppressing oscillations resulting from three-phase faults and inter-area oscillation [3], [4]. Hence, various flexible AC transmission system (FACTS) devices have been proposed to enhance system stability and suppress inter-area oscillations [5]–[8]. Out of the several FACTS devices suggested in the literature, the unified power flow controller (UPFC) shows superior performance [9].

Thus, the simultaneous utilization of PSS and UPFC could result in a further improvement in the system damping. To improve the damping performance of the UPFC, additional controller such as proportional integral (PI), controller has been proposed in the literature [4], [9]–[13]. However, to simultaneously utilize both PSS and UPFC along with the PI controller, a proper coordination scheme should be adopted to avoid any unstable response [14].

To achieve optimal coordination of the PSS and UPFC, various optimization techniques such as the firefly algorithm (FA) can be employed. FA has been widely used to solve various optimization problems and has resulted in faster and better results than other optimization techniques [15]–[17].

In this paper, a new coordination scheme for the PSS and UPFC using FA is presented. The performance of the UPFC is further improved using a PI-controller.

II. FUNDAMENTAL THEORY

A. Inter-Area Oscillations

The inter-area oscillation modes are of typical frequency range 0.2 to 0.8 Hz. This type of oscillations involves two or more groups of generators connected by weak tie-lines. In the past, this type of oscillations was insignificant due to the short distance between generators and load center. However, due to the necessity of interconnecting large power systems over long distances, inter-area oscillation has become one of the prominent issues to be addressed in modern power systems. In large and complex interconnected power systems, non-linear and non-deterministic behaviour of the system result in the difficulty to properly control and maintain sufficient damping to power systems. Inadequate system damping could lead to system blackout. Therefore, ensuring sufficient system damping, especially for inter-area modes, is essential for reliable power system operation [18], [19].

B. Power System Stabilizer

PSS has been widely used to suppress various oscillation modes of power systems. The input to the PSS is the generator shaft speed deviation $\Delta\omega$, and the output is an additional voltage signal V_s to the exciter that is expressed as below and is shown schematically in Fig. 1 [18].

$$V_s = \left[K_{PSS} \frac{T_w s(1+T_1 s)(1+T_3 s)}{(1+T_w s)(1+T_2 s)(1+T_4 s)} \right] \Delta\omega \qquad (1)$$

The PSS model shown in Fig. 1, consists of gain block (K_{pss}); washout block with time constant T_w to act as a high-pass filter; lead-lag blocks of time constants T_1, T_2, T_3, and T_4 that act as a compensator. The output signal is limited within specific operational range.

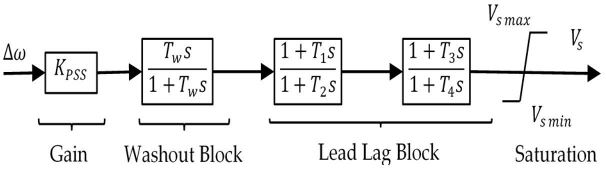

Fig. 1 The structure of PSS and lead-lag Controller [19]

C. Proportional Integral Derivative Controller

The proportional integral derivative (PID) shown in Fig. 2 can be considered as a form of phase lead-lag compensator with one pole in its origin and the other is at infinity. Likewise, PI and PD controller can also be considered as modified forms of phase-lag and phase-lead compensators, respectively. The standard PID controller has the following transfer function [20].

$$\begin{aligned} G(s) &= K_P + K_I \frac{1}{s} + K_D s \\ &= K_P \left(1 + \frac{1}{T_I s} + T_D s\right) \end{aligned} \qquad (2)$$

where K_P, K_I and K_D are respectively the proportional, integral and derivative gains, T_I and T_D are the integral and derivative time constants, respectively.

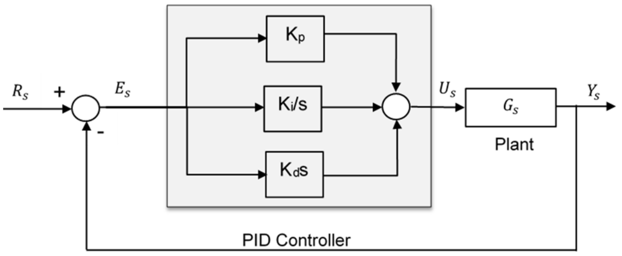

Fig. 2 PID controller block diagram [20]

D. Unified Power Flow Controller

The UPFC is designed to facilitate a simultaneous control of the voltage magnitude, phase angle, and impedance of the transmission line [21]. As shown in Fig. 3, the UPFC consists of two converters connected through a dc-link capacitor and is interfaced to the system through series and shunt transformers. The series converter provides direct voltage control and phase shifting. On the other hand, active power modulation is performed through the shunt converter [22]. The equivalent model of the UPFC is shown in Fig. 4. Assuming bus i as the sending-end and bus j as the receiving-end, the synchronous voltage source is used to replace each converter in series with associated transformer leakage reactance [23].

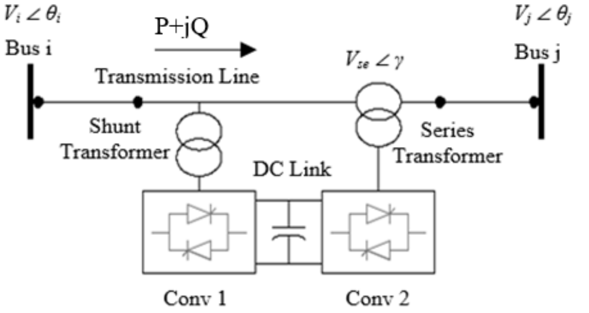

Fig. 3 UPFC Model

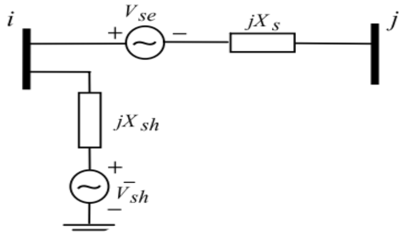

Fig. 4 Equivalent model of UPFC [23]

E. Damping Control Scheme of UPFC

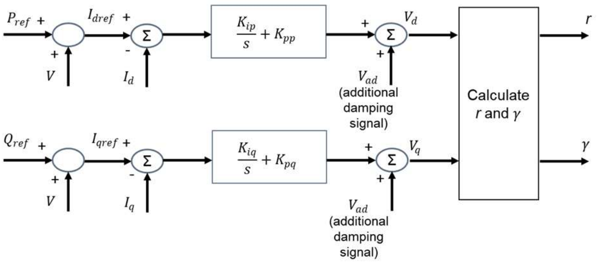

Fig. 5 The control system of the series part of the UPFC[23]

The effectiveness of oscillation damping can be achieved by optimizing the voltage injected by the series part of the UPFC, V_{se}, using a PI controller [23], as shown in Fig. 5. The control system of the UPFC consists of in phase, V_p, and quadrature voltage components, V_q. r and γ are the magnitude and angle of the injected voltage, V_{se}, where r is $0 \le r \le r_{max}$, and γ is $0 \le \gamma \le 2\pi$ [24].

$$r = \sqrt{v_p^2 + v_q^2} \qquad (3)$$

$$\gamma = arctan\left(\frac{v_q}{v_p}\right) \qquad (4)$$

The control scheme of the UPFC is also equipped with an additional damping controller to improve its ability to damp the inter-area oscillations. The input for the additional damping controller is the rotor speed deviation. In this paper, the considered additional damping controllers are PI, PID, and lead-lag controller as shown in Fig. 6.

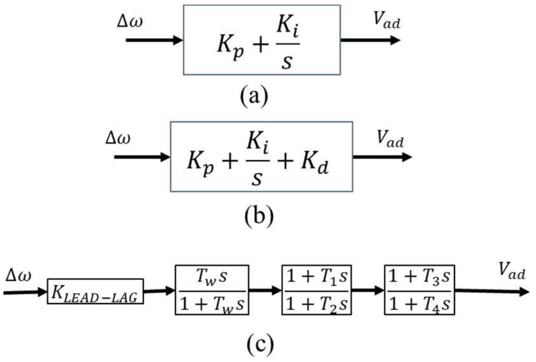

Figure 6 Additional Damping Controllers (a) PI; (b) PID; (c) Lead-lag

F. *Firefly Algorithm*

Firefly Algorithm as shown in the flowchart of Fig. 7 is one of the swarm intelligence methods developed by Yang in 2008 [15]. It is a kind of meta-heuristic algorithm which is aimed at finding solutions through trial and error and stochastic analysis using randomization methods [25]. In FA, the entire population is divided into several subgroups to facilitate obtaining the best possible global solution rapidly which makes FA ideal candidate for multimodal highly non-linear optimization problems [26], [27].

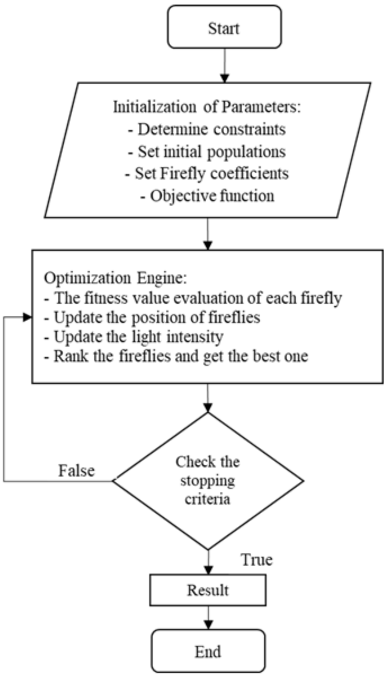

Fig. 7 The Flowchart of Firefly Algorithm[28]

III. PROPOSED METHODOLOGY

The proposed methodology consists of three parts: power system modelling, optimization process to tune the PSS and UPFC parameters to obtain the best damping performance and validating the performance of the proposed control system through simulation analysis.

A. *Test System*

The 500 kV interconnection system under study consists of 8 generators and 20 buses as shown in Fig. 8 with all data presented in [29]. PSS is assumed to be installed with each generator while one UPFC is connected at the middle of the line connecting buses 1 and 19. The system is simulated using MATLAB/Simulink software.

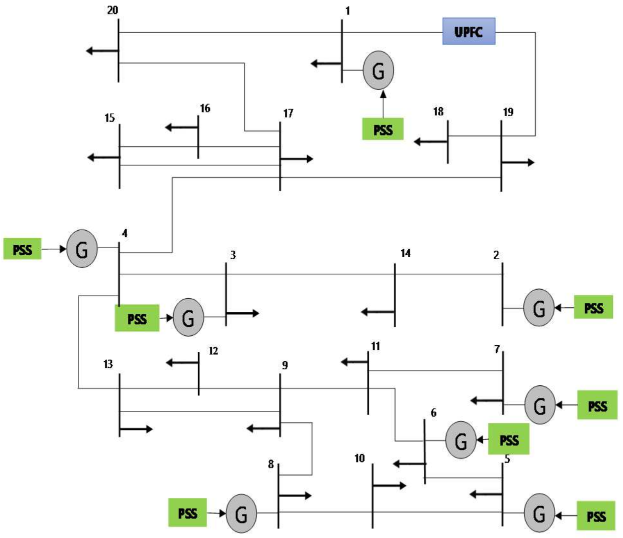

Fig. 8 Single line diagram of the system under study [29]

B. *Optimization Process*

Firefly Algorithm is used to optimize the control parameters of the PSS and UPFC when they are connected individually and simultaneously. The comprehensive damping index (CDI) given by (9) is employed as the objective function to optimize.

$$CDI = \sum_{i=1}^{n} 1 - \xi_i \tag{9}$$

Table 1 lists the FA parameters, used in the optimization process [30].

Table 1
Parameters of Firefly Algorithm [30]

FA Parameters	Value
α (Randomization)	0.2
β (Attractiveness)	0.2
γ (Absorption)	1
Number of Fireflies	20
Number of Iterations	50

For PSS, the parameters to be optimized are K_{pss}, T_1, T_2, T_3, and T_4. K_{iss} value is limited in the range 0.1-5 to get maximum damping effect. T_w is set at 10 s, based on [31]. The value of T_1, T_2, T_3, and T_4 varies between 0.1-1 s. UPFC parameters include K_{pp}, K_{ip}, K_{pq}, and K_{iq} for the series controller. The boundaries of K_{pp} and K_{pq} is 0.1-3, while K_{ip} and K_{iq} are in the range 0.001-0.01. For the additional PID damping controllers, the parameters include K_p, K_i, and K_d that are assumed to be in the ranges 0-50, 0-1, and 0-0.01; respectively. The control parameters of the lead-lag controller have the same boundaries as the PSS, except for the $K_{lead\text{-}lag}$, which varies between 0 and 50. The parameters obtained from the optimization process are listed in Tables 2 through 6.

IV. SIMULATION RESULTS AND ANALYSIS

Two disturbances are assumed to test the robustness of the proposed controllers: a load change of 0.05 p.u. and a three-phase fault in one of the transmission lines.

A. Case study-1: A Load Change of 0.05 p.u.

In this case, a load change of +0.05 p.u. is assumed on generator 1 at t = 1 s for a period of five cycles. In this case, the electrical power (P_e) becomes higher than the mechanical power (P_m) to meet the load demand. If the generator does not provide a proper response, there will be a deviation in the rotor speed from the normal conditions which may have an adverse impact on system stability.

Table 2
Parameters of PSS

Generator	PSS Parameters					
	Kpss	Tw	T1	T2	T3	T4
1	5	10	0.8117	0.3347	0.8332	0.7584
2	2.945	10	0.1216	0.5072	0.3286	0.329
3	1.1314	10	0.0744	0.4754	0.0429	0.2562
4	3.9548	10	0.5289	0.8263	0.5153	0.9387
5	3.441	10	0.8677	0.9161	0.0756	0.5415
6	1.5067	10	0.0632	0.2856	0.2317	0.5746
7	4.2803	10	0.6204	0.6255	0.141	0.3157
8	2.4251	10	0.621	0.6264	0.1304	0.3388

Table 3
Parameters of Damping Control Scheme-based UPFC

Parameter	PI Controller-based UPFC Parameters	PID Controller-based UPFC Parameters	Lead-Lag Controller-based UPFC Parameters
Kpp	1.6457	1.2977	1.3225
Kip	0.0043	0.0055	0.0049
Kpq	1.5305	1.4676	1.1576
Kiq	0.007	0.0054	0.006
Kp	21.2348	20.6359	
Ki	0.4096	0.5554	
Kd		0.004	
Klead-lag			36.7677
Tw			10.0000
T1			0.5751
T2			0.4675
T3			0.6843
T4			0.5863

Table 4
Coordinated Parameters of PSS with PI Controller- based UPFC

Generator	COORDINATED					
	PSS Parameters					
	Kpss	Tw	T1	T2	T3	T4
1	2.5751	10	0.8272	0.3271	0.8437	0.7829
2	2.4234	10	0.1238	0.5157	0.3219	0.33
3	1.3603	10	0.0744	0.4298	0.0457	0.2535
4	2.6914	10	0.5253	0.8195	0.5247	0.9145
5	3.0177	10	0.8815	0.9276	0.076	0.5228
6	3.7741	10	0.0663	0.2575	0.2288	0.573
7	2.9003	10	0.6135	0.6117	0.1291	0.3229
8	1.6405	10	0.6181	0.6245	0.1298	0.3298
	UPFC Parameters					
	Kpp	Kip	Kpq	Kiq	Kp	Ki
	2.1805	0.0066	1.2543	0.005	46.9758	0.6711

Fig. 9 shows that the rotor of generator 1 will exhibit a significant oscillations if no additional damping scheme is employed. With the connection of a damping controller, both maximum overshooting and settling time will be significantly reduced and the oscillations will be suppressed. As can be seen from Fig. 9, the best damping performance is provided by a combination of UPFC-PI and PSS. This can be also noticed from the numerical analysis in Table 7. A similar observation can be made when the used UPFC is equipped with PID or lead-lag controller as shown in Figs. 10, 11 and Tables 8 and 9; respectively.

Table 5
Coordinated Parameters of PSS with PID Controller- based UPFC

Generator	COORDINATED TUNING					
	PSS Parameters					
	Kpss	Tw	T1	T2	T3	T4
1	4.0239	10	0.8244	0.3238	0.8357	0.7782
2	2.8325	10	0.1181	0.5136	0.3225	0.3304
3	2.8033	10	0.0722	0.4477	0.0446	0.2561
4	3.0679	10	0.5231	0.8338	0.5136	0.9217
5	1.5276	10	0.8796	0.9345	0.075	0.5347
6	2.2108	10	0.064	0.2737	0.222	0.58
7	3.8067	10	0.6177	0.6367	0.1247	0.3291
8	1.8937	10	0.6162	0.6119	0.1362	0.3321
PID Controller-based UPFC Parameters						
Kpp	Kip	Kpq	Kiq	Kp	Ki	Kd
1.5726	0.0053	2.0988	0.0062	41.2178	0.5863	0.0032

Table 6
Coordinated Parameters of PSS with Lead-lag Controller- based UPFC

Generator	COORDINATED TUNING					
	PSS Parameters					
	Kpss	Tw	T1	T2	T3	T4
1	2.2981	10	0.8275	0.3317	0.8275	0.7813
2	1.9063	10	0.1241	0.5302	0.3272	0.3116
3	2.8586	10	0.0752	0.4433	0.0448	0.2542
4	1.977	10	0.5344	0.822	0.5199	0.9291
5	2.3876	10	0.8698	0.9311	0.0755	0.524
6	2.2291	10	0.0647	0.2806	0.2335	0.5754
7	2.0288	10	0.6161	0.6268	0.1197	0.327
8	3.0348	10	0.6238	0.6238	0.1266	0.3229
Lead-lag Controller-based UPFC Parameters						
		Kpp	Kip	Kpq	Kiq	
		1.3597	0.0055	1.2016	0.0043	
	Klead-lag	Tw	T1	T2	T3	T4
	38.6722	10	0.4053	0.6639	0.6045	0.3042

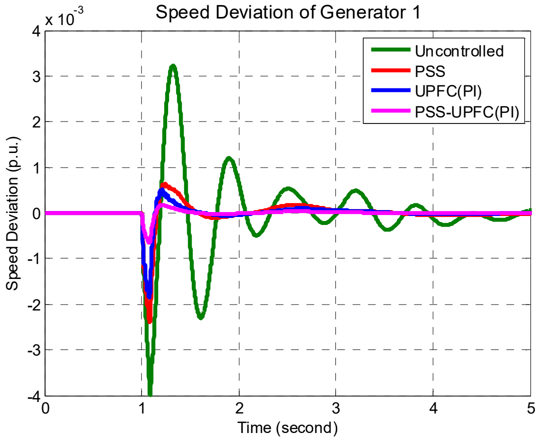

Fig. 9 Speed deviation of Case 1 under different controllers including UPFC-PI controller

Table 7

The Parameters of Inter-Area Mode PSS-UPFC (PI) Case1

System	Damping Ratio	Maximum Overshoot (p.u)	Settling Time (second)
Uncontrolled	0.103	3.98E-03	12.890
PSS	0.273	2.40E-03	4.721
UPFC(PI)	0.328	1.86E-03	3.235
PSS-UPFC(PI)	0.365	6.53E-04	1.621

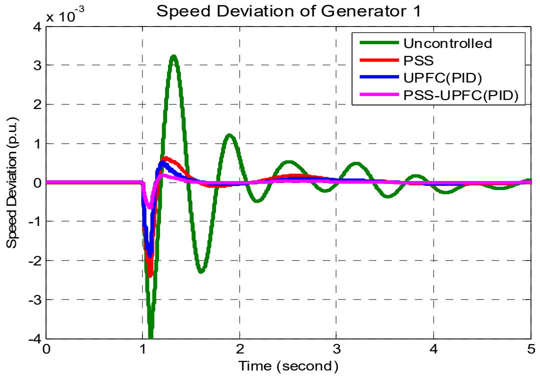

Fig. 50 Speed deviation of Case 1 Speed deviation of Case 1 under different controllers including UPFC-PID controller

Table 8
The Parameters of Inter-Area Mode PSS-UPFC (PID) Case 1

System	Damping Ratio	Maximum Overshoot (p.u)	Settling Time (second)
Uncontrolled	0.103	3.98E-03	12.890
PSS	0.273	2.40E-03	4.721
UPFC(PID)	0.325	1.89E-03	3.337
PSS-UPFC(PID)	0.360	6.66E-04	1.630

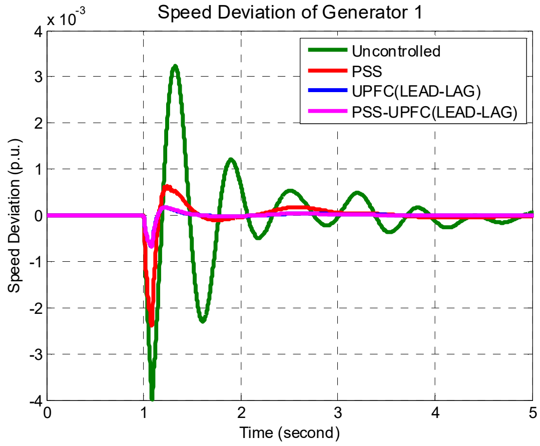

Fig. 61 Speed deviation of Case 1 under different controllers including UPFC-lead-lag controller

Table 9
The Parameters of Inter-Area Mode PSS-UPFC (Lead-lag) Case 1

System	Damping Ratio	Maximum Overshoot (p.u)	Settling Time (second)
Uncontrolled	0.103	3.98E-03	12.890
PSS	0.273	2.40E-03	4.721
UPFC(LEAD-LAG)	0.345	6.69E-04	1.636
PSS-UPFC(LEAD-LAG)	0.359	6.68E-04	1.634

B. Case study-2: Three-phase Fault at line 15-16

In this case, a three-phase fault is assumed to take place within the middle of the transmission line connecting buses 15 and 16 at t = 1 s and lasts for five cycles.

Fig. 12 shows that with no control scheme, a significant maximum overshooting occurs at the instant of fault occurrence and the generator shaft exhibits significant oscillations with substantial settling time. While the individual PSS and UPFC can provide a sufficient damping, best damping performance is observed when a combination of the two devices is adopted. This can be obviously seen from the numerical analysis in Table 10. Similar to the previous case study, same trend can be observed when a UPFC along with PID or lead-lag controller is used as can be seen in Figs. 13, 14 and Tables 11 and 12; respectively.

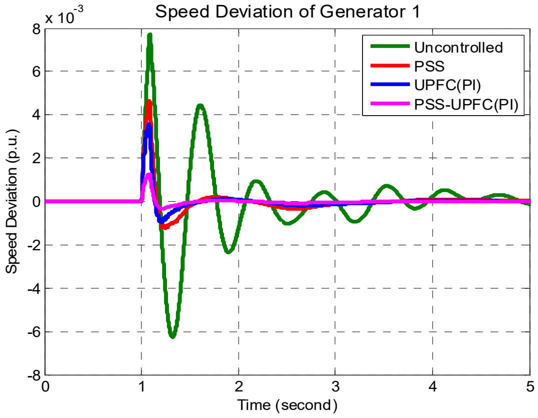

Fig. 12 Speed deviation of Case 2 under different controllers including UPFC-PI controller

Table 10
The Parameters of Inter-Area Mode PSS-UPFC (PI) Case 2

System	Damping Ratio	Maximum Overshoot (p.u)	Settling Time (second)
Uncontrolled	0.103	7.72E-03	12.950
PSS	0.273	4.60E-03	5.136
UPFC(PI)	0.329	3.60E-03	3.432
PSS-UPFC(PI)	0.366	1.27E-03	2.001

Table 11
The Parameters of Inter-Area Mode PSS-UPFC (PID) Case 2

System	Damping Ratio	Maximum Overshoot (p.u)	Settling Time (second)
Uncontrolled	0.103	7.72E-03	12.950
PSS	0.273	4.60E-03	5.136
UPFC(PID)	0.326	3.66E-03	3.454
PSS-UPFC(PID)	0.360	1.29E-03	2.025

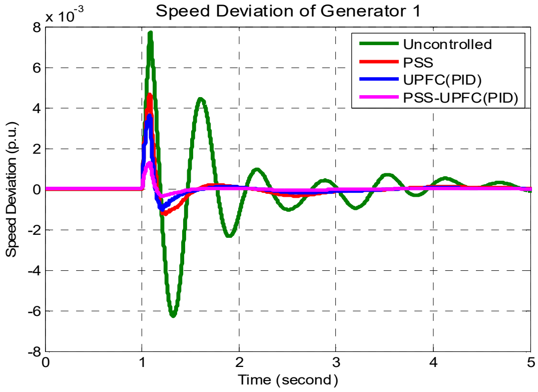

Fig. 73 Speed deviation of Case 1 Speed deviation of Case 2 under different controllers including UPFC-PID controller

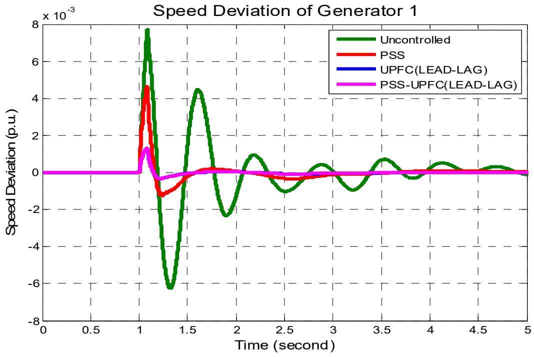

Fig. 8 Speed deviation of Case 2 under different controllers including UPFC-lead-lag controller

Table 12
The Parameters of Inter-Area Mode PSS-UPFC (Lead-lag) Case 2

System	**Damping Ratio**	**Maximum Overshoot (p.u)**	**Settling Time (second)**
Uncontrolled	0.103	7.72E-03	12.950
PSS	0.273	4.60E-03	5.136
UPFC(LEAD-LAG)	0.346	1.30E-03	2.039
PSS-UPFC(LEAD-LAG)	0.360	1.30E-03	2.037

Results show that the UPFC-based damping scheme is of better damping performance of the inter-area oscillations in the power systems than the PSS. It is to be noted that, PSSs are assumed to be installed at all generators in the system while one UPFC connected at a proper location can achieve acceptable damping performance. Additional PI, PID or lead-lag controller with the UPFC can reduce the maximum overshooting by 53.3%, 52.6%, and 83.2%; respectively, while the PSS can reduce it by 40.1%. In terms of settling time, the UPFC with PI, PID and lead-lag controller UPFC can reduce the settling time by 74.2%, 73.7%, and 85.8%; respectively, while the PSS is reducing it by 61.9%.

Results also show that, when PSS and UPFC are simultaneously adopted, the damping performance will be even better. Numerical analysis show that combination of UPFC-PI with PSS can reduce the maximum overshooting by 83.6%, while it is reduced by 83.3% when a combination of PID-UPFC with PSS is used. When a lead-lag-UPFC with PSS is used, the maximum overshooting is reduced by 83.2%. Also the settling time for the three combination schemes is respectively reduced by 87.4%, 87.4%, and 87.3%.

It is to be noticed that, other FACTS devices such as superconducting magnetic energy storage can provide the same performance as UPFC [32-37].

V. CONCLUSIONS

Various damping schemes for the inter-area oscillations in power systems are investigated in this paper. Results show that with a proper coordination of the PSS and UPFC along with additional PI, PID or lead-lag controller, the oscillations due sudden load change or severe three phase short circuit faults can be effectively damped. While PSS is widely used to damp such oscillations, it has to be installed with each generator in the system. On the other hand, a proper location for UPFC in the system may be enough to damp the oscillations within the entire system to avoid any dynamic or transient stability issues. A combination of PSS and UPFC provides the best damping performance however, the control parameters should be coordinated properly through an effective optimization technique.

ACKNOWLEDGMENT

This paper is supported by PT Perusahaan Listrik Negara (Persero).

REFERENCES

[1] J. J. Grainger and W. D. Stevenson Jr, *Power System Analysis*. McGraw-Hill, 1994.

[2] P. Kundur, *Power System Stability and Control*. McGraw-Hill, 1993.

[3] M. W. Mustafa, J. Usman, and N. A. Arzeha, “Application of PSS and FACTS Devices for Damping Low Frequency Oscillations in Power Systems,” *Arch. Des Sci. J.*, vol. 66, no. 2, pp. 254–264, 2013.

[4] A. N. Hussain and S. H. Shri, “Optimal Coordinated Design of PSS and UPFC-PID Controller Using Dolphin Echolocation Optimization Algorithm for Damping Oscillation,” *J. Eng. Appl. Sci.*, vol. 14, no. 15, pp. 5051–5059, 2019, doi: 10.36478/jeasci.2019.5051.5059.

[5] A. F. Abdou, A. Abu-Siada, and H. R. Pota, “Application of a STATCOM for Damping Subsynchronous Oscillations and Transient Stability Improvement”, presented at AUPEC conference Brisbane, Australia, September 2011..

[6] A. F. Abdou, A. Abu-Siada, and H. R. Pota, “Damping of Subsynchronous Oscillations and Improve Transient Stability for Wind farms” proceeding of the IEEE Innovation Smart Grid Technologies conference, WA, November 2011..

[7] A. Abu-Siada, “Damping of Large Turbo-Generator Subsyncronous Resonance using Superconducting Magnetic Energy Storage unit”, proceeding of AUPEC’10, December, 2010, Christchurch, New Zealand.

[8] A. M. Shiddiq Yunus, A. Abu-Siada, M. R. Djalal and J. X. Jin, "Optimal Design of SMES and PSS for Power System Stability based on Ant Colony Optimization," 2020 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD), Tianjin, 2020.

[9] Yasser M. Alharbi, A. M. Shiddiq Yunus, A. Abu-Siada “Application of UPFC to Improve the LVRT Capability of Wind Turbine Generator”, proceeding of AUPEC conference, Bali, Indonesia, September 2012.

[10] Yasser Alharbi, A. Abu-Siada, “Application of UPFC to Improve the Low-Voltage-Ride-Through Capability of DFIG” presented at the 24th IEEE International Symposium on Industrial Electronics, Búzios, Rio De Janeiro, Brazil, June 03-05, 2015..

[11] Yasser Alharbi , A. Abu-Siada and A. Abdou, “Application of UPFC on Stabilizing Torsional Oscillations and Improving Transient Stability”, proceeding of the Australasian Universities Power Engineering Conference , AUPEC’13, Hobart, 29 Sep.-3 Oct., 2013.

[12] G. Kannayeram, P. S. Manoharan, and N. B. Prakash, “PI-tuned UPFC damping controllers design for multi-machine power system,” *J. Meas. Eng.*, vol. 6, no. 2, pp. 81–92, 2018, doi: 10.21595/jme.2018.19898.

13] M. I. Mosaad, A. Alenany and A. Abu-Siada, "Enhancing the performance of wind energy conversion systems using unified power flow controller," IET Generation, Transmission & Distribution, vol. 14, no. 10, pp. 1922-1929, 22 5 2020.

[14] A. Najafi, M; Kazemi, “Coordination of PSS and FACTS Damping Controllers in Large Power Systems for Dynamic Stability Improvement,” *Int. Conf. Power Syst. Technol.*, 2006, doi: 10.1109/ICPST.2006.321541.

[15] N. F. Johari, A. M. Zain, N. H. Mustaffa, and A. Udin, “Firefly Algorithm for Optimization Problem,” *Appl. Mech. Mater.*, vol. 421, pp. 512–517, 2013, doi: 10.4028/www.scientific.net/AMM.421.512.

[16] B. Vijay Kumar and N. V. Srikanth, “Bat Algorithm and Firefly Algorithm for Improving Dynamic Stability of Power Systems Using UPFC,” *Int. J. Electr. Eng. Informatics*, vol. 8, no. 1, pp. 164–187, 2016, doi: 10.15676/ijeei.2016.8.1.12.

[17] M. Klein, G. . Rogers, and P. Kundur, “A Fundamental Study of Inter-Area Oscillation in Power System,” *IEEE Trans. Power Syst.*, vol. 6, no. 3, pp. 914–921, 1991, doi: 10.1109/59.119229.

[18] K. Prasertwong, M. Nadarajah, and D. Thakur, “Understanding Low-Frequency Oscillation in Power Systems,” *Int. J. Electr. Eng. Educ.*, vol. 47, no. 3, pp. 248–262, 2010, doi: 10.7227/IJEEE.47.3.2.

[19] A. N. Hussain, “Damping Improvement of Multiple Damping Controllers by Using Optimal Coordinated Design Based on PSS and FACTS-PID in a Multi-Machine Power System,” J. Babylon Univ. Sci., vol. 24, no. 3, 2016.

[20] K. H. Ang, G. Chong, and Y. Li, “PID Control System Analysis , Design , and Technology,” *IEEE Trans. Control Syst. Technol.*, vol. 13, no. 4, pp. 559–576, 2005, doi: 10.1109/TCST.2005.847331.

[21] A. Abu-Siada et al, “Application of FACTS in Renewable Energy Systems”, Bentham Science Publishers, ISBN: 978-1-68108-543-2,

September 2017.

[22] L. Gyugyi, “A Unified Power Flow Control Concept for Flexible AC Transmission Systems,” *IEE Proc. C - Gener. Transm. Distrib.*, vol. 139, no. 4, pp. 323–331, 1992, doi: 10.1049/ip-c.1992.0048.

[23] A. Kazemi and M. R. Shadmesgaran, “Extended Supplementary Controller of UPFC to Improve Damping Inter-Area Oscillations Considering Inertia Coefficient,” Int. J. Energy, vol. 2, no. 1, pp. 1–8, 2008.

[24] A. Kazemi and M. V. Sohrforouzani, “Power System Damping Using Fuzzy Controlled FACTS Devices,” *Int. J. Electr. Power Energy Syst.*, vol. 28, no. 5, pp. 349–357, 2006, doi: 10.1016/j.ijepes.2005.09.008.

[25] I. Fister, I. Fister, X. Yang, and J. Brest, “A comprehensive review of firefly algorithms,” *Swarm Evol. Comput.*, vol. 13, no. 1, pp. 34–46, 2013, doi: 10.1016/j.swevo.2013.06.001.

[26] X. Yang and X. He, “Firefly Algorithm : Recent Advances and Applications,” *Int. J. Swarm Intell.*, vol. 1, no. 1, pp. 36–50, 2013, doi: 10.1504/IJSI.2013.055801.

[27] X. Yang, “Firefly Algorithm, Stochastic Test Functions and Design Optimisation,” *Int. J. Bio-Inspired Comput.*, vol. 2, no. 2, pp. 78–84, 2010, doi: 10.1504/IJBIC.2010.032124.

[28] Y. Eren and I. B. Ku, *Optimization in Renewable Energy System, Chapter 2: Introduction to optimization*. 2017.

[29] R. M. Bamatraf, “Optimal Design of Power System Stabilizer (PSS) and Flexible AC Transmission System (FACTS) using Craziness Particle Swarm Optimization (CRPSO) in the Java Bali 500 kV Interconnection System,” Institut Teknologi Sepuluh November, 2010.

[30] Y. Bin Mo, Y. Z. Ma, and Q. Y. Zheng, “Optimal Choice of Parameters for Firefly Algorithm,” in *4th International Conference on Digital Manufacturing and Automation, ICDMA*, 2013, pp. 887–892, doi: 10.1109/ICDMA.2013.210.

[31] K. R. Pradiyar, *Power System Dynamics*. BS Publications, 2008.

[32] A. M. S. Yunus et al, "Enhancement of DFIG LVRT Capability During Extreme Short-Wind Gust Events Using SMES Technology," IEEE Access, vol. 8, pp. 47264-47271, 2020.

[33] A. M. Shiddiq Yunus, et al, “Impact of SMES Unit on DC-Link Voltage of DFIG during Various Types and Level of Faults”, Przegląd Elektrotechniczny Poland, Vol. 95, August 2019, pp.121-126.

[34] A. M. Shiddiq Yunus, A. Abu-Siada, and M. A. S. Masoum, "Application of SMES Unit to Improve DFIG Power Dispatch and Dynamic Performance During Intermittent Misfire and Fire-Through Faults," IEEE Transactions on Applied Superconductivity, vol. 23, No. 4, pp. 5701712-5701712, August 2013.

[35] A. M. Shiddiq Yunus, M. A. S. Masoum, A. Abu-Siada, “Application of SMES Unit to Enhance the Dynamic Performance of DFIG during Voltage Sag and Swell”, IEEE transaction on applied superconductivity, Vol. 22, No. 4, August 2012.

[36] A. M. Shiddiq Yunus, A. Abu-Siada, M. A. S. Masoum, “Improving Dynamic Performance of Wind Energy Conversion System using Fuzzy-Based Hysteresis Current Controlled SMES”, IET Power Electronic, Vol. 5, No. 8, pp. 1305-1314, November 2012.

[37] A. Abu-Siada, S. Islam, “Application of SMES unit in Improving the Performance of an AC/DC Power System”, IEEE Transactions on Sustainable Energy, Vol. 2, No. 2, pp. 109-121, 2011.