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Optimal Tuning of Unified Power Flow Controller Using Firefly Algorithm to Improve Damping of Inter-Area Oscillations in Multi-Machine System

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***Abstract*— The interconnection system faces inter-area oscillation challenges that affect power system stability. Conventional Power System Stabilizer (PSS) cannot provide effective damping to the inter-area oscillations. This paper deals with a Proportional Integral (PI) controller as a damping control scheme of the Unified Power Flow Controller (UPFC) to improve the damping of inter-area oscillation in a multi-machine system. The proposed PI Controller-based UPFC is tuned using the Firefly Algorithm (FA), and the performance is compared with PSS. Simulation results show that the proposed PI Controller-based UPFC provides a better stability margin than PSS under the different conditions and effectively reduces the overshoot by 53%, accelerating the settling time by 74%, and minimizing the area graph by 85%.**

Keywords*— *inter-area oscillation, UPFC, PI controller, firefly algorithm, eigenvalue

I. INTRODUCTION

Interconnection systems continue to grow and present challenges in maintaining synchronization between various parts of the power system. Large interconnected systems and weak transmission lines are subjected to inter-area oscillations [1]. For low-frequency oscillations, Power System Stabilizer (PSS) has been widely used as the most potent damping controller. However, in large multi-machine systems, the PSS controller does not provide maximal results in reducing inter-area oscillations [2]. In this case, the use of other Flexible AC Transmission System (FACTS) devices is essential [3]. Unified Power Flow Controller (UPFC) is the most effective FACTS device which provides unconstrained series voltage to control power flow in transmission lines [4]. The lead-lag controller is already known as an additional damping controller and is commonly used for UPFC. The performance also has been compared with PSS [5]. Another controller for the UPFC damping control scheme is Proportional Integral (PI) controller, which will be presented in this paper [6].

UPFC cannot be installed on all transmission lines due to the high installation cost. That is why, for planning studies, it is a big challenge to design and present a UPFC controller model. Therefore, to simplify the problem, the efficient optimization methods are used to identify the best placement of UPFC along with its control parameters. Firefly Algorithm (FA) provides better performance in terms of speed and accuracy compared with other optimization algorithms[7],[8]. There are two main advantages of the FA compared to other algorithms. First, the working principle of the FA is based on attractiveness, which will decrease with increasing distance. The population is automatically divided into several subgroups that are clustered in each mode or local optimal. Thus, the best global solutions can be found. Second, this automatic subdivision allows the discovery of all optima simultaneously. Therefore, the FA is very suitable for multimodal optimization problems that are very nonlinear. Besides, the acceleration of convergence can also be done by setting parameters in the FA [9].

In this paper, the proposed parameters of the PI Controller-based UPFC are tuned using Firefly Algorithm, and the result of damping inter-area oscillations in a multi-machine system is compared with PSS whose parameters have also been optimized using the same algorithm. Results are presented using eigenvalue along with time-domain analysis. For time-domain analysis, area graph calculation is conducted beside maximum overshoot and settling time.

II. INTER-AREA OSCILLATIONS

Inter-area oscillations can be defined as the oscillations associated with many generators in one part of the system against generators in other regions where a weak tie line connects them. The frequency range of inter-area oscillations is about 0.2 to 0.8 Hz. If these oscillations are not effectively damped, it will turn into more significant oscillations and cause the system to lose synchronization, resulting in partial or complete power outages. The nonlinear and non-deterministic behavior of large interconnected systems makes damping control difficult. These oscillations can result from small or large disturbances, such as changes in interconnected system operating points or line faults [1].

III. EIGENVALUE ANALYSIS

Small signal stability or steady-state stability from the system's equilibrium point can be analyzed by looking at the eigenvalue A or the reduced system status matrix. The eigenvalue of matrix A is given by (1) [10].

$$(A - \lambda I)\phi = 0 \tag{1}$$

For non-trivial solutions, the determinant $(A - \lambda I)$ is equal to zero, and eigenvalues can be calculated. The n solution of $\lambda = \lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_n$ are eigenvalues of A, and ϕ represents the right eigenvector.

$$\lambda = \sigma + j\omega \tag{2}$$

Where σ is the real part, and $j\omega$ is the imaginer part. For complex eigenvalues (2), the frequency of oscillation in Hz and the damping ratio, are given by,

$$f = \frac{\omega}{2\pi} \tag{3}$$

$$\xi = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{4}$$

For the system to be stable or free of oscillations, all eigenvalues must be placed in the left half-plane. This means that the actual part of the eigenvalues must be negative, and the damping ratio must be positive.

IV. UNIFIED POWER FLOW CONTROLLER

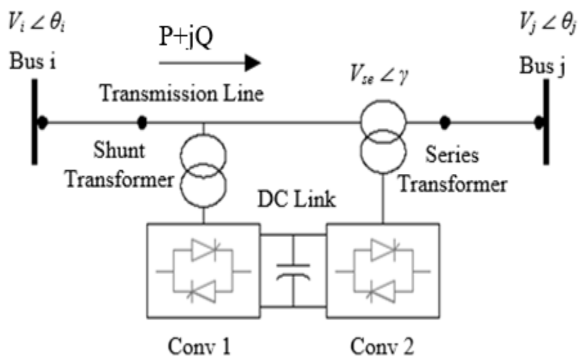


Fig. 1 UPFC Model

UPFC, as shown in Fig. 1, has two converters, each installed in series and shunt to the system via an insertion transformer. Both converters are connected through a DC link and capacitor bank as a support for the common DC voltage [11]. UPFC can control the voltage, impedance, and phase angle of the transmission line simultaneously or selectively.

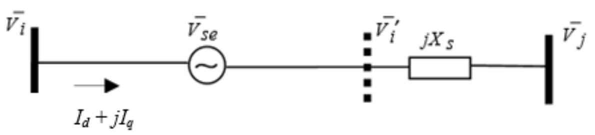


Fig. 2 Representation of the series-connected voltage source

The injection model of the UPFC is conducted by optimizing the series parts, as shown in Fig. 2. If the UPFC is assumed to be ideal, where losses are neglected, $P_{sh}=P_{se}$, and Q_{sh}=0; then, the UPFC injection model is given by Fig. 3 below [12].

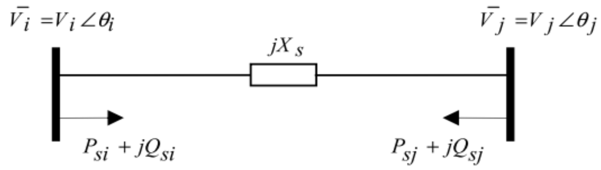


Fig. 3 Injection Model of UPFC

$$P_{si} = rb_sV_iV_j\sin(\theta_{ij} + \gamma) \tag{5}$$

$$Q_{si} = rb_sV_i^2\cos\gamma \tag{6}$$

$$P_{sj} = -rb_sV_iV_j\sin(\theta_{ij} + \gamma) \tag{7}$$

$$Q_{sj} = -rb_sV_iV_j\cos(\theta_{ij} + \gamma) \tag{8}$$

where $\theta_{ij} = \theta_i - \theta_j$ and $b_s = 1/X_s$

V. FIREFLY ALGORITHM

The firefly's lights that are flickering in nature inspire this algorithm. Flashing is the main characteristic of fireflies that can be idealized into the three rules. The fireflies will be attracted to one another regardless of gender because they are unisex; the brightness level is proportional to the attraction, it will increase with the distance ratio; and the brightness determines the objective function [13]. The flowchart of FA, as shown in Fig. 4.

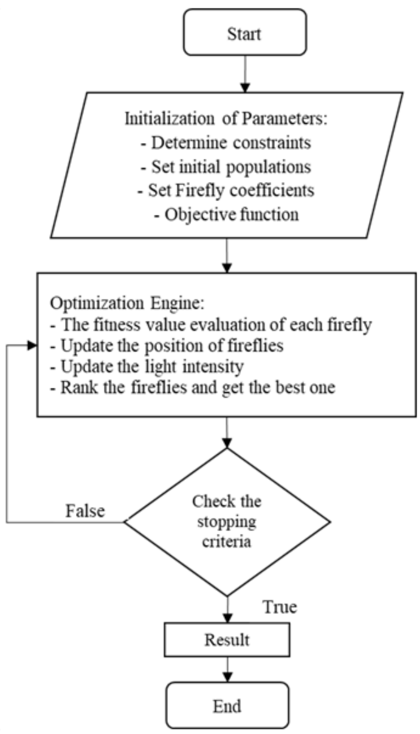


Fig. 4 The Flowchart of Firefly Algorithm

VI. PROPOSED METHODOLOGY

A. System Understudy

This paper uses a 500 kV interconnection system consists of 8 generators and 20 buses, as shown in Fig. 5 as a model. Bus 1 is a slack bus that is connected to a generator with the highest capacity in the system. The proposed UPFC is installed on the line connecting bus 1 and 19 with the highest power transfer line, while PSS is connected to all generators. The case study was simulated under Matrix Laboratory (MATLAB) environment.

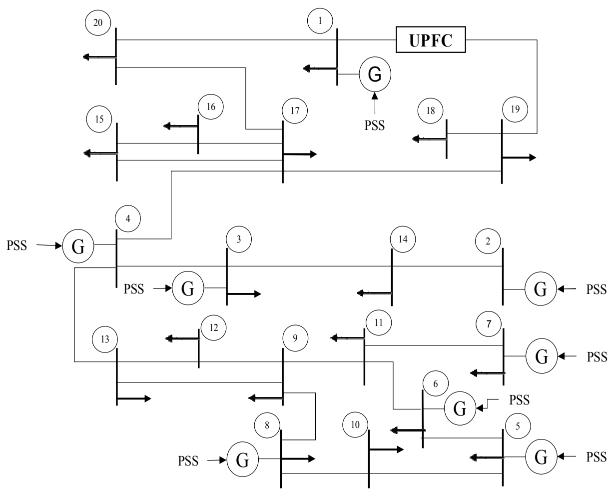


Fig. 5 Single Line Diagram of System Model

B. Control Scheme of UPFC

For effective oscillation damping, the injected series voltage (V_{se}) should be properly controlled. V_{se} consists of v_p and v_q, which are in-phase and quadrature components in the UPFC control system. V_{se} can be calculated as follows [6], [12].

$$\bar{V}_{se} = r\bar{V}_i e^{j\gamma} \tag{9}$$

Where r is the relative magnitude of V_{se} with a control range of $0 \le r \le r_{max}$, and γ is the angle of V_{se} with a control range $0 \le \gamma \le 2\pi$.

$$r = \sqrt{v_p^2 + v_q^2} \tag{10}$$

$$\gamma = arctan\left(\frac{v_q}{v_p}\right) \tag{11}$$

To improve the damping controller, another feedback signal, the generator rotor speed deviation, is added to the control scheme. The overall control scheme of the proposed PI controller-based UPFC, as shown in Fig. 6.

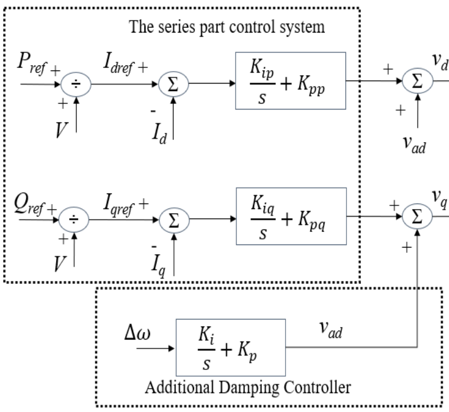


Fig. 6 Control Scheme of UPFC

C. Optimization Process

FA optimizes the parameter of PI Controller-based UPFC, and the objective function is the Comprehensive Damping Index (CDI).

$$CDI = \sum_{i=1}^{n} 1 - \xi_i \tag{12}$$

Based on the literature [14], the optimal parameters of FA to get the appropriate results are as shown in Table I.

TABLE I. FA PARAMETERS

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

The parameters of the PSS consist of K_{pss}, T_1, T_2, T_3, and T_4, while T_w is set at 10 seconds. The parameters of UPFC consists of K_{pp}, K_{ip}, K_{pq}, and K_{iq} for the series controller along with K_p and K_i for the additional damping controller. Table II shows the optimized PSS parameters, and Table III shows the optimized UPFC parameters.

TABLE II. PSS PARAMETERS

Generator	PSS Parameters				
	K_{pss}	T_1	T_2	T_3	T_4
Lower Limit	0.1	0	0	0	0
Upper Limit	5	1	1	1	1
Result					
1	5	0.8117	0.3347	0.8332	0.7584
2	2.945	0.1216	0.5072	0.3286	0.329
3	1.1314	0.0744	0.4754	0.0429	0.2562
4	3.9548	0.5289	0.8263	0.5153	0.9387
5	3.441	0.8677	0.9161	0.0756	0.5415
6	1.5067	0.0632	0.2856	0.2317	0.5746
7	4.2803	0.6204	0.6255	0.141	0.3157
8	2.4251	0.621	0.6264	0.1304	0.3388

TABLE III. UPFC PARAMETERS

Parameter	K_{pp}	K_{ip}	K_{pq}	K_{iq}	K_p	K_i
Lower Limit	0.1	0.001	0.1	0.001	0	0
Upper Limit	3	0.01	3	0.01	50	1
FA Result	1.6457	0.0043	1.5305	0.007	21.2348	0.4096

VII. SIMULATION RESULTS AND ANALYSIS

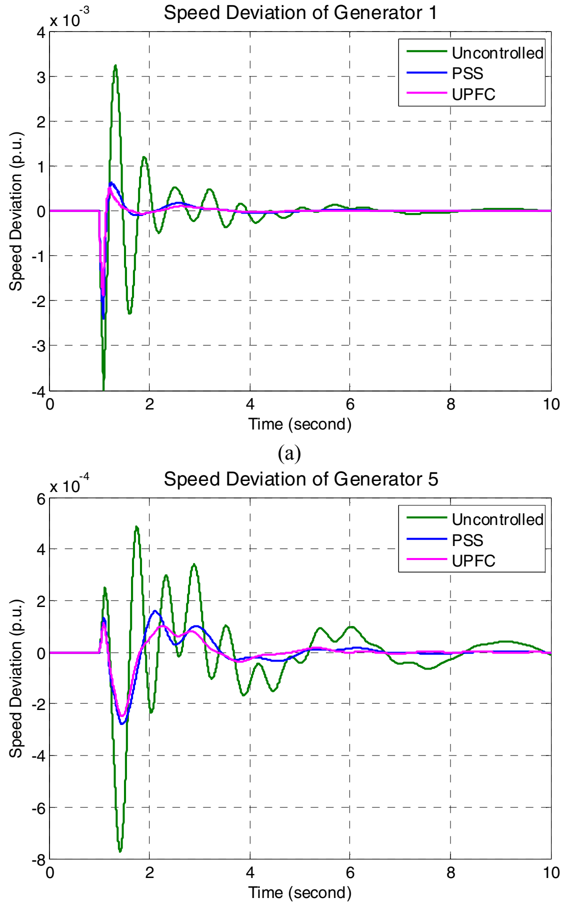
The simulation is carried out in two cases. The first case is a ramping change of 0.05 p.u is assumed in generator 1 at t = 1 second for five cycles, and the second is a three-phase fault on the line connecting bus 15 and 16 at t = 1 second for five cycles. In this paper, it is sufficient to make observations only on generators 1 and 5 to represent eight generators to analyze the inter-area oscillations, because generator 1 is a slack bus and generator 5 is a generator with the furthest position from a slack bus.

A. *Case 1: A Ramping Change of 0.05 p.u.*

Table IV presents the eigenvalues of inter-area mode without and with the proposed controllers. It can be observed that PI Controller-based UPFC provides maximum damping ratio in the inter-area mode from 0.10 to 0.33.

TABLE IV. THE EIGENVALUE OF INTER-AREA MODE CASE 1

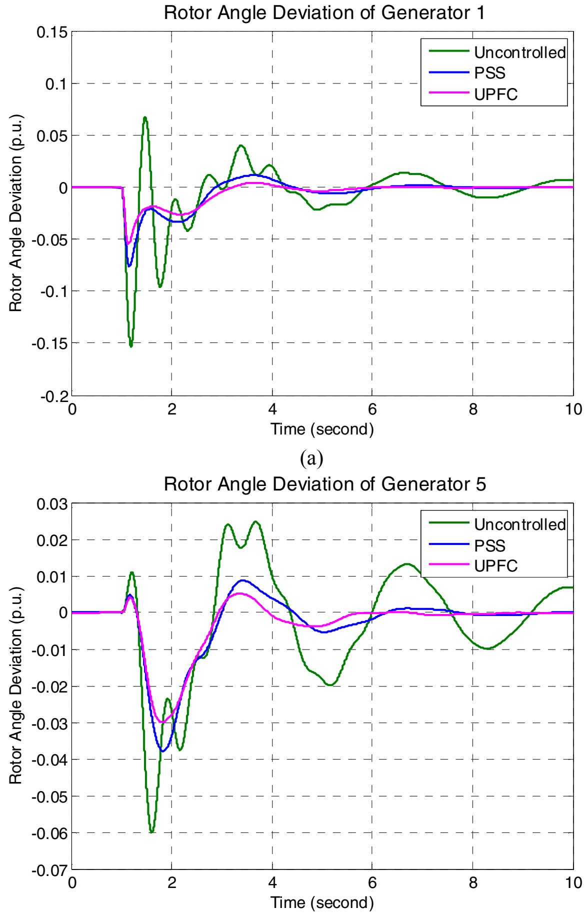
SYSTEM	EIGENVALUE	DAMPING RATIO	FREQUENCY (Hz)
Uncontrolled	-0.2023 + 1.9526i	0.10	0.31
PSS	-0.5331 + 1.8796i	0.27	0.30
UPFC	-0.7794 + 2.2458i	0.33	0.36



(b)

Fig. 7 Speed Deviation of Case 1. (a) Generator 1; (b) Generator 5

Fig. 7 shows that due to the assumed generation ramping change, the speed decreases because electrical power (P_e) is getting higher than the mechanical power (P_m). The inappropriate response of the generator will affect the overall stability of the system and leads the rotor speed to deviate from the normal operating condition. Results in Fig. 7 reveal that the PI Controller-based UPFC provides a better result in reducing the maximum overshooting than PSS; it also can reduce the settling time.



(b)

Fig. 8 Rotor Angle Deviation of Case 1. (a) Generator 1; (b) Generator 5

Fig. 8 shows the angle response of the rotor, which becomes negative because the rotor moves slowly. The higher deviation will have an impact on the generation. Therefore, it is expected that the rotor angle can return to a steady-state position immediately so that the power produced remains stable. PI Controller-based UPFC can reduce the rotor angle deviation better than PSS with faster settling time.

The overall response of generator 1 and generator 5 without and with the investigated controller are summarized in Table V.

TABLE V. TIME-DOMAIN PARAMETERS ON GENERATOR 1 AND GENERATOR 5 OF CASE 1

Time-domain Analysis	System	CASE 1			
		Generator 1		Generator 5	
		Speed Deviation	Rotor Angle Deviation	Speed Deviation	Rotor Angle Deviation
Maximum Overshoot (p.u)	Uncontrolled	0.0040	0.1535	0.0008	0.0601
	PSS	0.0024	0.0758	0.0003	0.0400
	UPFC	0.0019	0.0538	0.0002	0.0297
Settling Time (second)	Uncontrolled	12.8900	18.6600	12.5300	18.6200
	PSS	4.7210	7.5910	4.9370	7.6510
	UPFC	3.2350	5.7980	3.1140	5.4760
Area Graph (area)	Uncontrolled	1.6379	112.3407	0.6178	85.4159
	PSS	0.3874	49.3165	0.2132	32.9163
	UPFC	0.2412	34.6739	0.1462	23.9677

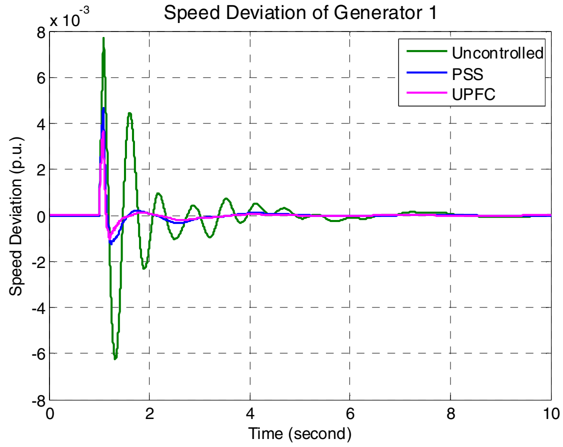
B. Case 2: A Three-Phase Fault on the Line Connecting Bus 15 and 16

Table VI presents the eigenvalues of inter-area mode without and with the proposed controllers. It can be observed that PI controller-based UPFC provides maximum damping ratio in the inter-area mode from 0.10 to 0.33.

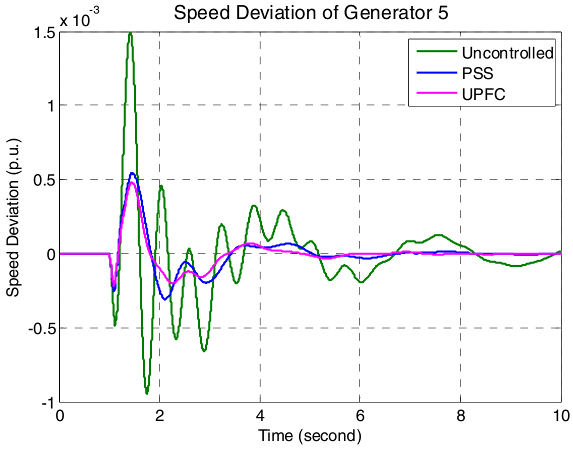
TABLE VI. THE EIGENVALUE OF INTER-AREA MODE CASE 2

SYSTEM	EIGENVALUE	DAMPING RATIO	FREQUENCY (Hz)
Uncontrolled	-0.2026 + 1.9502i	0.10	0.31
PSS	-0.5334 + 1.8773i	0.27	0.30
UPFC	-0.7805 + 2.2435i	0.33	0.36

Fig. 9 shows that a three-phase fault leads to an increase in speed. PSS can reduce the oscillation that occurs in the generators, but the PI Controller-based UPFC provides the best reduction with faster settling time.



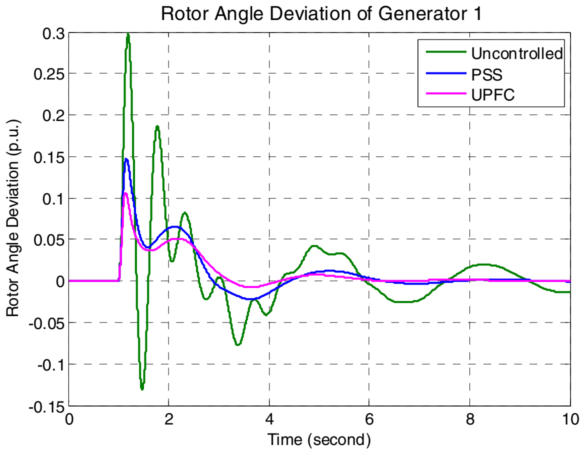
(a)



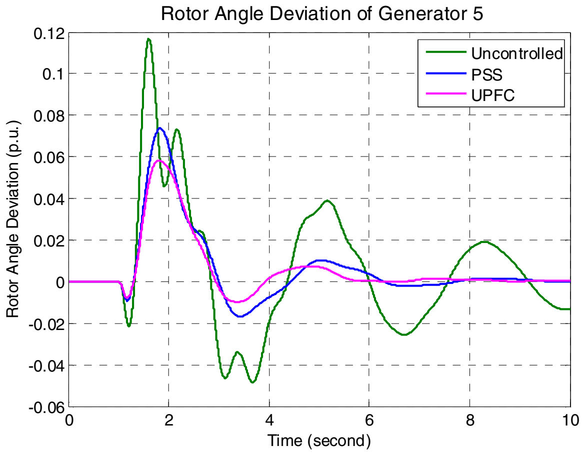
(b)

Fig. 9 Speed Deviation of Case 2. (a) Generator 1; (b) Generator 5

On the other hand, Fig. 10 shows that the rotor moves faster with a positive angular response because the load to be released from the system during a fault. The rotor angle should be kept in a reasonable condition for generating stable power. The graphs show that the PI Controller-based UPFC can reduce the maximum overshoot better than PSS and achieve an acceleration in settling time.



(a)



(b)

Fig. 10 Rotor Angle Deviation of Case 2. (a) Generator 1; (b) Generator 5

The overall response of generator 1 and generator 5 for case 2 are summarized in Table VII.

TABLE VII. TIME-DOMAIN PARAMETERS ON GENERATOR 1 AND GENERATOR 5 OF CASE 2

Time-domain Analysis	System	CASE 2			
		Generator 1		Generator 5	
		Speed Deviation	Rotor Angle Deviation	Speed Deviation	Rotor Angle Deviation
Maximum Overshoot (p.u)	Uncontrolled	0.0077	0.2976	0.0015	0.1167
	PSS	0.0046	0.1471	0.0006	0.0777
	UPFC	0.0036	0.1043	0.0005	0.0576
Settling Time (second)	Uncontrolled	12.9500	18.7600	12.7300	18.8600
	PSS	5.1360	7.7670	5.0360	7.6670
	UPFC	3.4320	5.9820	3.2300	5.5290
Area Graph (area)	Uncontrolled	3.1725	218.0596	1.1987	165.9942
	PSS	0.7495	95.6635	0.4129	63.9317
	UPFC	0.4694	67.1766	0.2832	46.3885

C. Discussion

Based on the eigenvalue analysis for both cases, the damping ratio of inter-area oscillations for the system with PI Controller-based UPFC shows a better damping ratio than the system with PSS. Fig. 11 below shows the comparison of the damping ratio between PSS, the PI Controller-based UPFC, and the uncontrolled system.

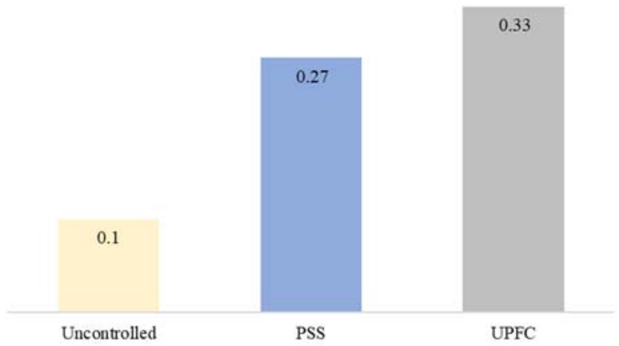


Fig. 11 Comparison of Damping Ratio between PSS, PI Controller-based UPFC, and The Uncontrolled System

The results of the speed deviation graph on generator 1 for both cases will be used as a reference to analyze the damping performance of a PI Controller-based UPFC in a time-domain analysis. Fig. 12 shows the comparison of damping performance for speed deviation between PSS and the PI Controller-based UPFC against the uncontrolled system in both cases for generator 1 based on the average percentage of maximum overshooting, settling time, and graph area.

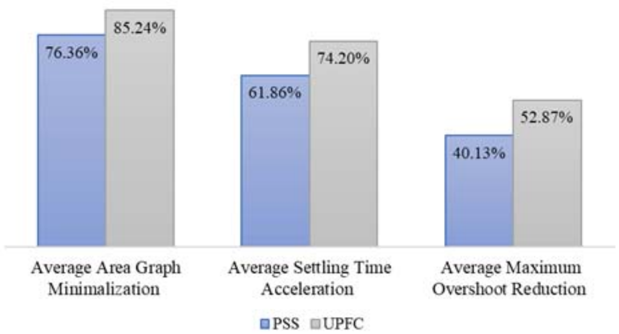


Fig. 12 Comparison of Damping Performance in Time-Domain Analysis for Speed Deviation between PSS and PI Controller-based UPFC against Uncontrolled System on Generator 1

Based on the eigenvalue and time-domain analysis above, it appears that the installation of PI Controller-based UPFC provides better damping than PSS. Although the PI Controller-based UPFC is designed at a specific operating point, it still can provide a good damping effect under other different conditions.

VIII. CONCLUSIONS

The proposed parameters of PI Controller-based UPFC, which are optimized by the Firefly Algorithm, provide better damping performance in inter-area oscillation than PSS under different conditions. Testing the effectiveness of the controller is conducted by simulating a ramping generation change of 0.05 p.u. and a three-phase fault on the transmission line. Based on the simulation results, PSS can increase the damping ratio from 0.10 to 0.27, while PI Controller-based UPFC can expand the damping ratio to 0.33. The time-domain analysis also shows that PI controller-based UPFC provides better damping performance compared to PSS. The maximum overshooting can be minimized by 53%, while PSS reduces it to only 40%. The implementation of PI Controller-based UPFC also reduces the settling time by 74%, while PSS reduces it by only 62%. In terms of area graph, PI Controller-based UPFC can reduce the area graph by 85% while PSS provides a 76% reduction only.

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