

# DAMPING OF POWER SYSTEM OSCILLATIONS WITH FUZZY BASED DPFC

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**ABSTRACT**--A new control scheme to improve the stability of a system by optimal design of distributed power flow controller (DPFC) based stabilizer is presented in this paper. The paper demonstrates the basic module, steady state operation, mathematical analysis, and current injection modeling of the DPFC. The purpose of the work reported in this paper is to design an oscillation damping controller for DPFC to damp low frequency electromechanical oscillations. The optimal design problem is formulated as an optimization problem, and particle swarm optimization (PSO) is employed to search for the damping controller parameters. Results demonstrate that DPFC with the proposed model can more effectively improve the dynamic stability and enhance the transient stability of power system compared to the genetic algorithm based damping controllers. The  $r$  and  $\phi$  are relative magnitude and phase angle of DPFC controller. Moreover, the results show that the  $r$  based controller is superior to the  $\phi$  based controller.

## INTRODUCTION

Because of the power demand grows dramatically, and extension in transmission and generation is restricted with the rigid environmental constraints and the limited availability of resource. However, this causes the power systems to be operated near their stability limits. Moreover, interconnection between remotely power systems results rise to low frequency oscillations in the range of 0.2–3 Hz. These oscillations may keep growing in magnitude until loss of synchronism results, if not well damped [1]. In order to minimize this problem, power system stabilizers (PSSs) have been successfully used to damp these low frequency oscillations. However, PSSs may unfavorably affect on the voltage profile, may result in leading power factor, and may be unable to control oscillations cause by large disturbances [2]. The idea of FACTS technology is to increase controllability and to optimize the utilization of the existing power system capacities using the reliable and

power electronic devices instead of mechanical controllers [3].

The opportunities arise through the ability of FACTS devices to control the parameters of transmission systems, which includes the series/shunt impedances, phase angle and damping of oscillations at various frequencies below the rated frequency. These constraints cannot be overcome otherwise, while maintaining the required system stability, by mechanical means without decreasing the transmission capacity [4]. By providing added flexibility, FACTS controllers can enable a line to carry power closer to its ratings. The DPFC recently presented in [5,6] is a powerful device within the FACTS family, which provides much lower cost and higher reliability than conventional FACTS devices. It is derived from the UPFC [7] and has the same capability of simultaneously adjusting all the parameters of the power system: line impedance, transmission angle, and bus voltage magnitude.

The DPFC eliminates the common DC link between the shunt and series converters, instead of one large three-phase converter, the DPFC employs multiple singlephase converters (distributed-FACTS concept) as the series compensator, as shown in Fig. 1. This concept reduces the rating of the components and provides a high reliability because of the redundancy [5]. Since the DPFC can instantaneously control the active and reactive power flow and the voltage magnitude, it implies a great potential for power oscillation damping. Ref. [8] presents the capability of the DPFC for damping the low frequency oscillations and the power oscillation damping controller parameters also are calculated by using the residue method. The contribution of this work is that a novel current injection model and dynamic simulation of the DPFC for studying the low frequency oscillations and incorporated in the transmission system model. A new approach for the optimal design of the DPFC damping controller is investigated in this paper, for

high-speed first time. The problem of damping controller design for DPFC is formulated as an optimization problem, and PSO technique is used to solve it. A problem of interest in the power industry is the mitigation of power system oscillations. These oscillations are related to the dynamics of system power transfer and often exhibit poor damping. Various types of FACTS controller's first and second generations, particularly SVC, TCSC, STATCOM, SSSC, UPFC, and IPFC are being used in literature in order to damp of the power system oscillations. The main motivation of this work is to damp out the electromechanical oscillations using the (new) distributed power flow controller with proposed injection model in a simple power system.

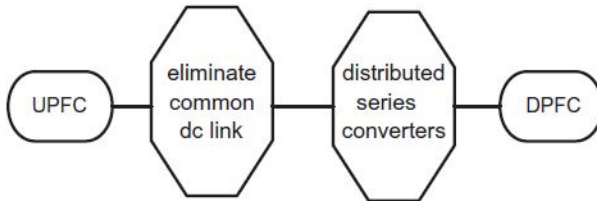


Figure 1 Transformation from the UPFC to the DPFC

**BASIC MODULE OF DPFC**

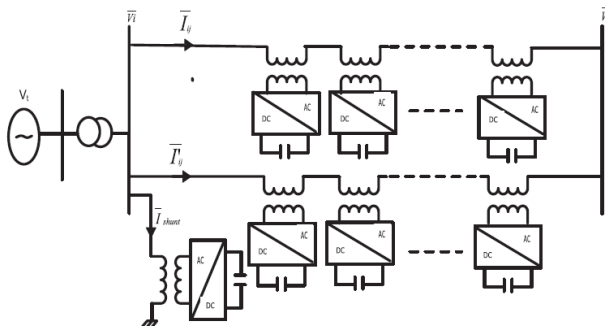


Figure 2 Power System of the case study equipped with DPFC.

The DPFC consists of one shunt and several series connected converters. The shunt converter is similar as a STATCOM, while the series converters employ the D-FACTS concept. Each converter within the DPFC is independent and has a separate DC link capacitor to provide the required DC voltage. Fig. 2 shows the structure of DPFC that is used in a transformation system with two parallel lines. The control capability of the UPFC is given by the back-to-back connection between the shunt and the series converters with DC link, which allows the active power to exchange freely. To ensure that the DPFC has the same control capability as the UPFC device, a method that allows the exchange of active power between converters without DC link is the prerequisite. In the DPFC, there is a common connection between the AC terminals of the shunt and the series converters, which is the transmission line. Therefore, it is allows to exchange the active power

terminals of the converters [5].

**DPFC current injection model**

In order to investigate the impact of shunt-series converters on power systems effectively, appropriate models of these devices are very important. In this study, we propose current injection model of DPFC to study the effects of it on low frequency oscillations. The installation of DPFC changes the system bus admittance matrix  $Y_{bus}$  to an unsymmetrical matrix [8]. When the DPFC is used for time-domain simulations of power systems, the modification of  $Y_{bus}$  is required at each stage. For this reason, a current injection model of DPFC is developed to avoid using the modification of  $Y_{bus}$  at each stage. By using equivalent injected currents at terminal buses to simulate a DPFC, no modification of  $Y_{bus}$  is required at each stage [9]. The synchronous generator in Fig. 2 is delivering power to the infinite bus through a double circuit transmission line and a DPFC. Fig. 3 shows the equivalent circuit of DPFC converters in the test power system. The idea of the current injection model is to use current sources, which are connected as shunt, instead of the series voltage sources. The test power system in this paper includes two parallel transmission lines, and series converters are distributed in lines at different distances. In Fig. 3, the shunt converter current,  $I_{shunt}$ , can be written as:

$$I_{shunt} = I + \alpha \quad (1)$$

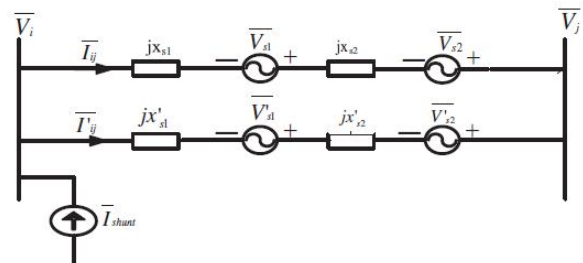


Figure 3 Electrical circuits in DPFC converts of case study transformation system.

Where  $I$  is in phase with  $V_i$  and  $I_q$  is in quadrature to  $V_i$ . The voltage sources  $V_{s1}; V_{s2}; V_{0s1}; V_{0s2}$  have been replaced instead of series converters. The  $X_{s1}; X_{s2}; X_{0s1}; X_{0s2}$  are reactance of transmission lines. The magnitudes and phase angle of series converters are controllable. In this paper we assume that they have same value. Therefore we have:

$$s_1 = s_2 = s_1' = s_2' = r \quad (2)$$

where  $0 < r < r_{max}$  and  $0 < k < 2p$ . The  $r$  and  $k$  are relative magnitude and phase angle respect to  $V_i$ , respectively. The injection model is obtained by

$$(15)$$

through the AC

replacing the voltage sources with the current sources as shown in Fig. 4 and we have [10]:

$$s_{s1} = \frac{V_{s1}}{jX_{s1}} = -j \frac{r_{s1}}{X_{s1}} \quad (3)$$

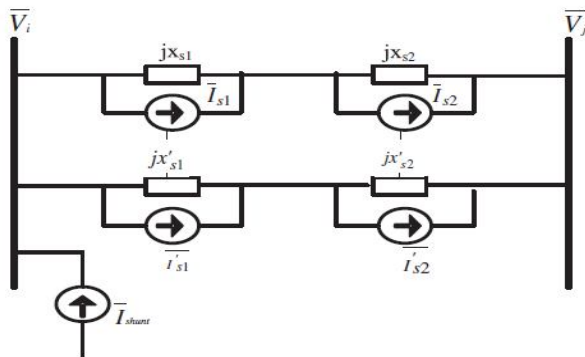
$$s_{s2} = \frac{V_{s2}}{jX_{s2}} = -j \frac{r_{s2}}{X_{s2}} \quad (4)$$

$$s_{s1} = \frac{V_{s1}}{jX_{s1}} = -j \frac{r_{s1}}{X_{s1}} \quad (5)$$

Where  $b_{s1} = \frac{1}{X_{s1}}$ ;  $b_{s2} = \frac{1}{X_{s2}}$ ;  $b_{s1} = \frac{1}{X_{s1}}$  and  $b_{s2} = \frac{1}{X_{s2}}$ . The active power supplied by the shunt current source can be calculated as follows:

$$(7)$$

With the neglected DPFC losses we have:



**Figure 4 Representation of series voltage sources by current sources.**

The apparent power supplied by the series converter  $V_{s1}$  can be calculated as:

$$S_{s1} = \frac{V_{s1}^2}{jX_{s1}} \quad (9)$$

From (9) and (10) the exchanged active and reactive power by converter  $V_{s1}$  are distinguished as:

$$(11)$$

$$(12)$$

With attention the above equations, the exchanged active and reactive power by converters  $V_{s2}$ ;  $V_{s1}$  and  $V_{s2}$  are calculated as:

$$(13)$$

$$(14)$$

$$(28)$$

$$(29)$$

$$(30)$$

$$(16)$$

$$(17)$$

$$(18)$$

Substitution of (7), (11), (13), (15) and (17) into (8) gives:

$$(19)$$

Finally, the shunt converter current can be obtained as

$$(20)$$

$$(21)$$

$E_q$  is the equivalent susceptance used to control  $I_q$ .

Thus, the current injection model of DPFC is obtained as follows:

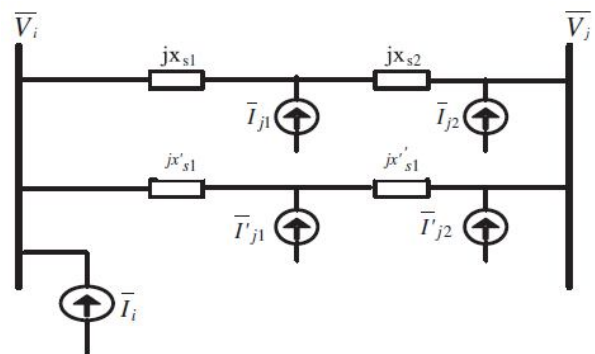
$$(22)$$

$$(23)$$

$$(24)$$

$$(25)$$

$$(26)$$



**Figure 5 Current injection model of DPFC**

Substituting (4), (5), (6), (7) and (21) into (22)–(26) gives the current injection model parameters as follows:

$$(27)$$

(31)

Fig. 5 shows the current injection model of DPFC.

### DPFC based damping controller

The three control parameters of the DPFC ( $r$ ,  $k$ , and  $Bq$ ) can be modulated in order to produce the damping torque. In this paper,  $r$  and  $k$  are modulated in order to design of the damping controller. The speed deviation is considered as the input to the controller. The structure of DPFC based damping controller is shown in Fig. 6. This controller may be considered as a lead lag compensator [11]. The parameters of the damping controller are obtained using PSO algorithm.

### Design of DPFC damping controller using PSO technique

It is worth mentioning that the designed controller with proposed model is tuned to damp power system oscillations with minimum control effort following a disturbance. An Integral of Time multiplied Absolute value of the Error is considered as the fitness function, in this study. The objective function is defined as follows [1]:

(32)

(33)

In Eqs. (32) and (33),  $t_{sim}$  is the time range of simulation, and  $N_p$  is the total number of operating points for which the optimization is carried out. The design problem can be formulated as the following constrained optimization problem, where the constraints are the controller parameters bounds:

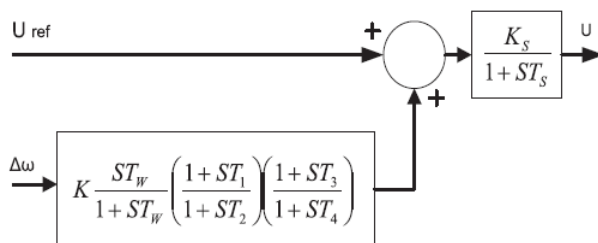


Figure 6 DPFC with lead-lag controller.

In our implementation, in order to acquire better

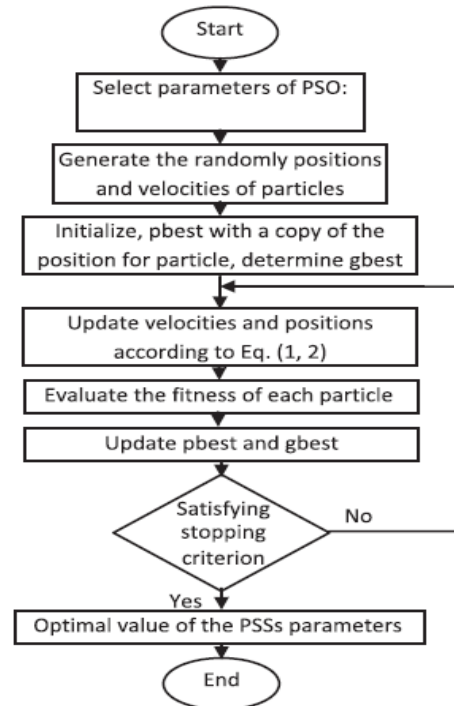


Figure 7 Flowchart of the PSO technique.

Minimize  $J$  subject to

(34)

(35)

(36)

The PSO algorithm and its improvement methods have been described in the several published literatures. Also, application of PSO algorithm in power systems has been reported in several papers, and its effectiveness has been proven [12–14]. Fig. 7 shows the flowchart of the PSO algorithm. In this flowchart, the update velocities and positions of particles are done by (35) and (36) [12].

The optimization of DPFC controller parameters is carried out by evaluating the objective cost function as given in Eq. (33), which considers a multiple of operating conditions. The operating conditions are considered as:

- Base case:  $P = 0.75$  pu and  $Q = +0.17$  pu (Nominal loading)
- Case 1:  $P = 0.6$  pu and  $Q = +0.2025$  pu (Light loading)
- Case 2:  $P = 0.95$  pu and  $Q = +0.07$  pu (Heavy loading)

#### 4.1. Scenario 1:

performance, number of particle, particle size, number of iteration,  $c_1$  and  $c_2$  are chosen as 30, 5, 50, and 2, respectively. Also, the inertia weight,  $w$ , is linearly decreasing from 0.9 to 0.4. These parameters are selected through the dimension of the optimization problem. Results of the controller parameter set values using both the PSO and the GA methods are given in Table 1.

**MATLAB MODELING OF CASE STUDY AND RESULTS**

The proposed control scheme for DPFC is evaluated by computer simulation in MATLAB/Simulink. The details of simulation model are depicted in Fig. 8. The parameters of test power system are listed, in Table 2. In Table 2, the machine parameters including nominal voltage and power, impedance and phase angle of sending and receiving ends are presented. In order to assess the robustness of the designed damping controller, simulation studies are carried out for three scenarios occurred as demonstrated below.

In this scenario, it is considered a 6-cycle three-phase fault occurred at  $t = 1$  s at the middle of the one transmission line' cleared by permanent tripping of the faulted line. The speed deviation of generator at nominal, light, and heavy loading conditions due to designed controller for  $k$  and  $r$  by PSO algorithm are shown in Fig. 9. Also, Fig. 10 shows the generator output power, internal voltage variations, and excitation voltage deviation with  $k$  and  $r$  based controllers for nominal loading conditions, respectively. These figures obviously show the good damping effect of the supplementary controller.

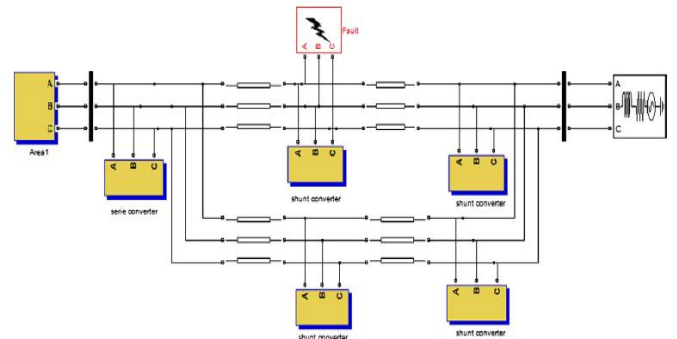
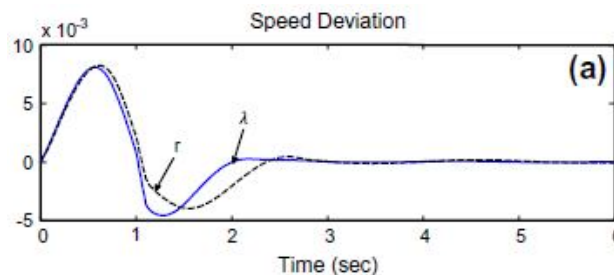


Figure 8 SMIB with DPFC built with MATLAB/Simulink.

Table 2 Parameters of test power system

Parameter	(kv)	(kv)	F (Hz)	S MVA	Deg	Deg	Line length (km)
Value	230	230	60	900	10	0	220





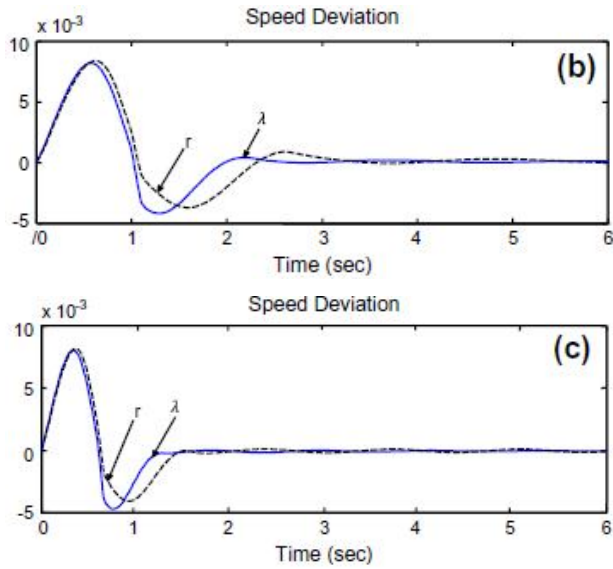


Figure 9 Dynamic responses for Dx in scenario 1 at: (a) nominal, (b) light, (c) heavy loading conditions.

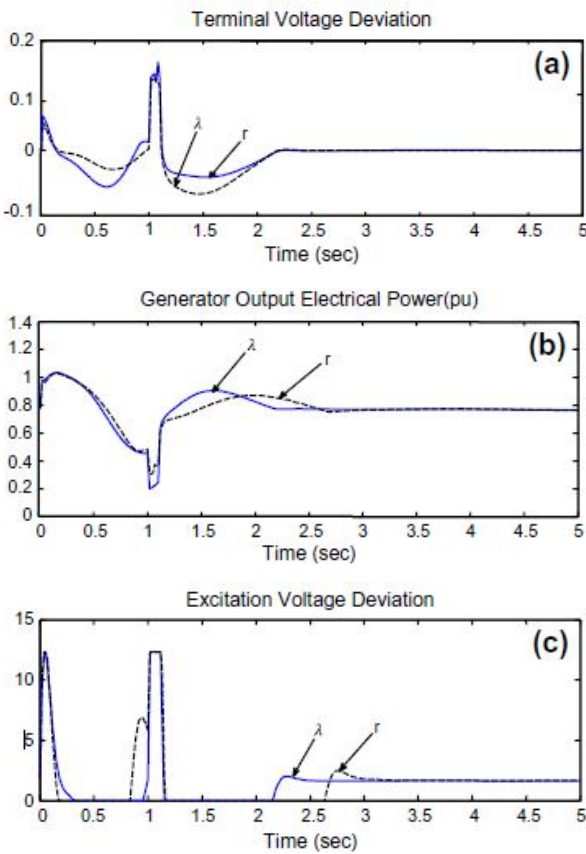


Figure 10 Dynamic responses at nominal loading: (a) terminal voltage deviation, (b) output electrical power (pu), (c) excitation

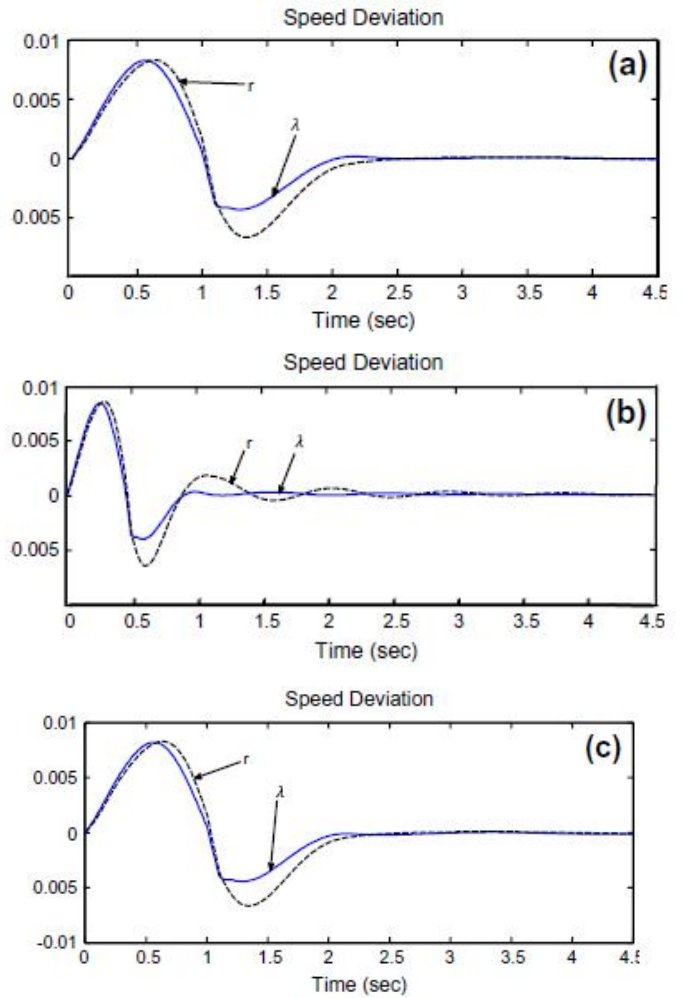


Figure 11 Dynamic responses for Dx in scenario 2 at: (a) nominal, (b) light, (c) heavy loading conditions.

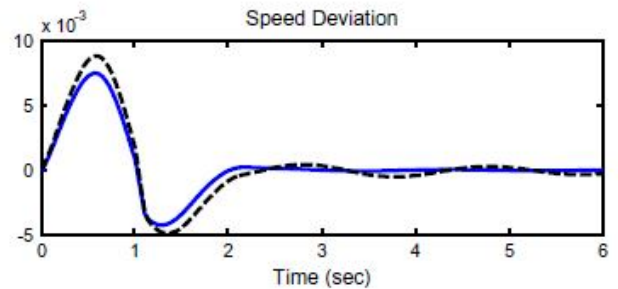
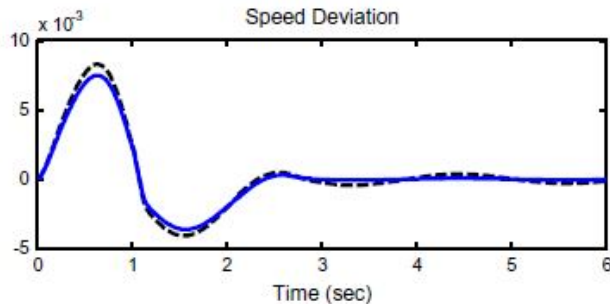


Figure 12 Dynamic responses for Dx at (a) nominal loading condition; solid (PSO based k controller) and dashed (GA based k controller).

#### 4.2. Scenario 2:

A 6-cycle three-phase fault occurred at  $t=1$  s at the middle of one of the transmission line is considered. The fault is cleared

voltage.  
without line tripping, and the original system is restored upon the clearance of the fault. The system response to this disturbance is shown in Fig. 11. It can be seen that the proposed model based optimized DPFC damping controller has good performance in damping low frequency oscillations and stabilizes the system quickly. From the above conducted tests, it can be concluded that the k based damping controller is superior to the r based damping controller tuned by PSO algorithm.



**Figure 13** Dynamic responses for Dx at (a) nominal loading condition; solid (PSO based r controller) and dashed (GA based r controller).

#### 4.3. Scenario 3:

A 6-cycle signal-phase fault occurred at  $t = 1$  s at the middle of one of the transmission line is considered. The fault is cleared without line tripping, and the original system is restored upon the clearance of the fault. The speed deviation of generator at base nominal loading condition with control parameters of the k and r is shown in Figs. 12 and 13, respectively. The performance of the PSO based damping controller is quite prominent in comparison with the GA based damping controller, and the overshoots and settling time are significantly improved for the proposed controller. It can be seen that the system response with the PSO based damping controller settles faster and provides superior damping. To demonstrate performance robustness of the proposed method, two performance indices: ITAE and FD based on the system performance characteristics are defined as [1]:

$$(37)$$

$$(38)$$

Where speed deviation (Dx), Overshoot (OS), Undershoot (US), and settling time of speed deviation of the machine are considered for evaluation of the ITAE and FD indices. It is worth mentioning that the lower the value of these indices is, the better the system response in terms of time-domain characteristics. Numerical results of performance robustness for all system loading cases are listed in Table 3. This demonstrates that the overshoot, undershoot, settling time, and speed deviations of the machine are

greatly reduced by applying the proposed PSO based tuned controller.

#### CONCLUSION

In this study, the DPFC as new FACTS device that can regulate line active and reactive power flow of the transmission line and provide enough damping to system oscillation modes. The initiatives of the presented work are given as follows:

- The mathematical analysis and current injection modeling of a new FACTS device based on distributed power flow controller are presented.
- A novel current injection model of the DPFC for studying on the low frequency oscillations is proposed for the first time.
- The proposed model of the DPFC is explained mathematically, and it can be implemented in MATLAB/SIMULINK environment and further can be extended for different applications in example power system.
- The design problem of the DPFC damping controller parameters is converted into an optimization problem which is solved by a PSO technique that has a strong ability to find the most optimistic results.
- The results have shown that the proposed model can effectively damp power system oscillations following large disturbances.

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