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Modelling and Tuning of DPFC using Optimization Techniques

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ABSTRACT: The foremost problem of power system is low frequency fluctuations. To damp out these fluctuations, a new idea is introduced in the form of Distributed Power Flow Controller (DPFC) for the enhancement of power system stability. D-FACTS (Distributed FACTS) concept is followed by this FACTS device. It is achieved from Unified Power Flow Controller (UPFC) by excluding the common dc link. This paper presents DPFC based damping controller. Designing issues are solved by computing the optimized value of parameters of damping controller using several algorithms i.e. Particle Swarm Optimization (PSO), Differential Evolution (DE) algorithms. Results illustrate that DE algorithm gives better results to enhance the stability of system compared with PSO algorithm.

KEYWORDS: Distributed Power Flow Controller, Current Injection Model, Damping Controller, Particle Swarm Optimization Algorithm, Differential Evolution Algorithm.

I.INTRODUCTION

Power demand is growing tremendously. Because of less available sources and environmental issues, transmission systems and generation systems are limited to extend which is the main cause to operate the power system near the stability boundaries. Low frequency fluctuations (0.2-3 Hz) are caused by interconnection of systems. These fluctuations increase continuously (in magnitude) and cause the loss of synchronism, if these will not damp out properly [1]-[2]. To damp out low frequency oscillations, power system stabilizers (PSS) are used but it has some disadvantages with large disturbances point of view [2]-[3]. Hence, to overcome this problem, FACTS devices have come into the picture. These electronics based equipments are more reliable and have fast control capabilities than mechanical controllers [2]-[4].

DPFC is introduced as a powerful FCATS-device [5]-[6]. It is attained from UPFC. UPFC is a combined form of Static Synchronous Series Compensator (SSSC) and Static Compensator (STATCOM) i.e. series and shunt connected converters having a common link of DC capacitors that permits the bidirectional active power transfer between series and shunt output ports of converters [3],[7]-[8].

By excluding the common DC connection between series and shunt converters, DPFC is attained. It offers high reliability, low rating components, low price by following the D-FACTS theory concept (having numerous single phase converters) [9]-[10]. Its control capability is similar to UPFC. It also comprises independent shunt and series converters followed with D-FACTS theory, offer requisite DC voltage through their separate DC-capacitors [11].

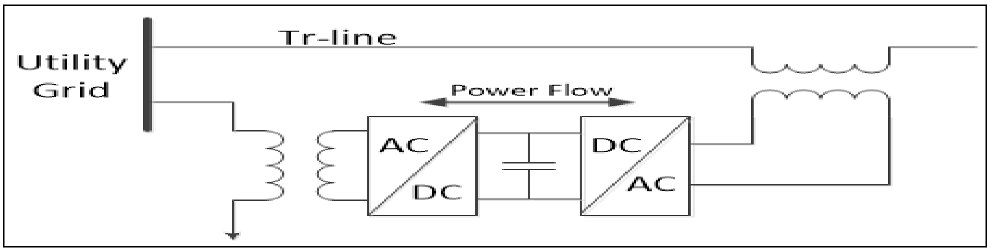

Fig. 1 UPFC structure

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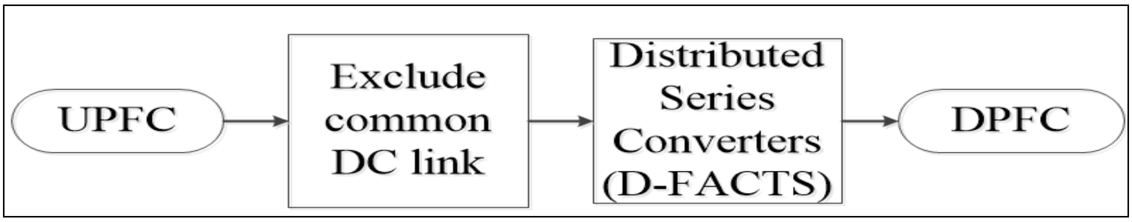

Fig. 2 Conversion of DPFC from UPFC

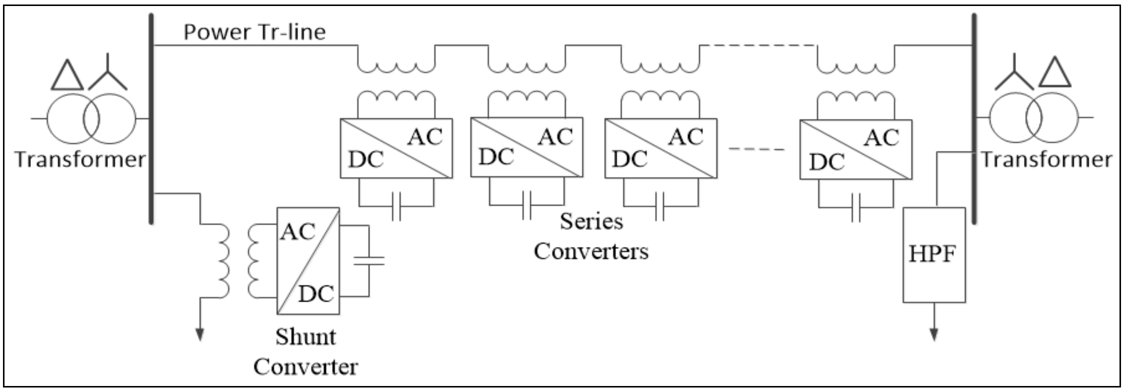

Fig. 3 Structure of DPFC

In this paper, modelling of DPFC is done by Current Injection Model. Relative magnitude (r) and phase angle (λ) related to the terminal voltage are the control parameters of DPFC for its designing. Optimization techniques are used to solve the designing problems. To compute the optimized value of controller parameters, numerous algorithms are used such as Particle Swarm Optimization (PSO) [12]-[13], Differential Evolution (DE) [14] algorithms. Response of generator is obtained under different loading conditions. Results indicate that DE algorithm offers comparatively better performance with the purpose of damping out the low frequency oscillations and improve stability.

II.PRINCIPLE OF OPERATION

There is only one common link between the series and shunt converters i.e. power transmission line. Active power is exchanged between the AC ports of the converters that is related to the power theory of non-sinusoidal theory of components [11]. Active power can be represented as below using non-sinusoidal voltage and current.

$$P = \sum V_m I_m \cos\phi_m \qquad (1)$$

Where V_m = Voltage at mth harmonic frequency, I_m = Current at mth harmonic frequency, ϕ_m = Angle between V_m and I_m.

Equation (1) demonstrates that power is not dependent at different frequencies and there is no effect of current and voltage at a frequency with power at different frequencies. Using this theory, active power absorption by shunt converter is done at fundamental frequency from grid and then at harmonic frequency, it is injected back to the line. If losses are neglected, generation and absorption at fundamental and harmonic frequency respectively, are equal.

III.CURRENT INJECTION MODEL

To understand the effect of DPFC on oscillations at low frequency, this model is developed. Whenever DPFC is directly installed in the power system, there will be modifications in admittance matrix at every step. To solve this problem, current injection method is used in which equivalent current is injected at terminal buses [15].

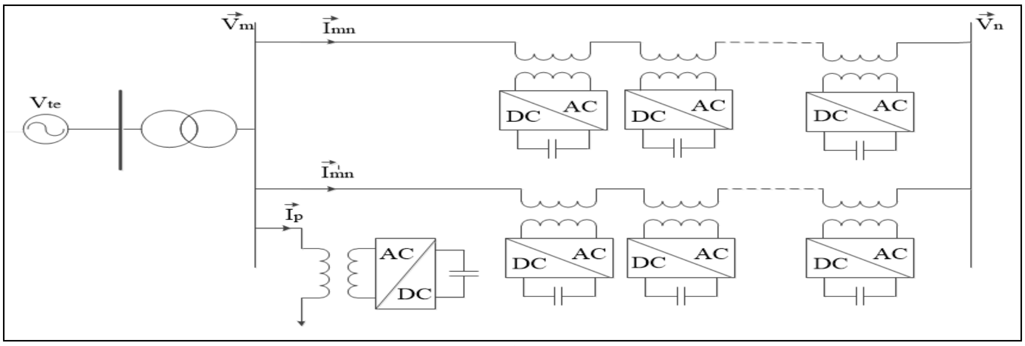

Fig. 4 Case-study model of power system with DPFC

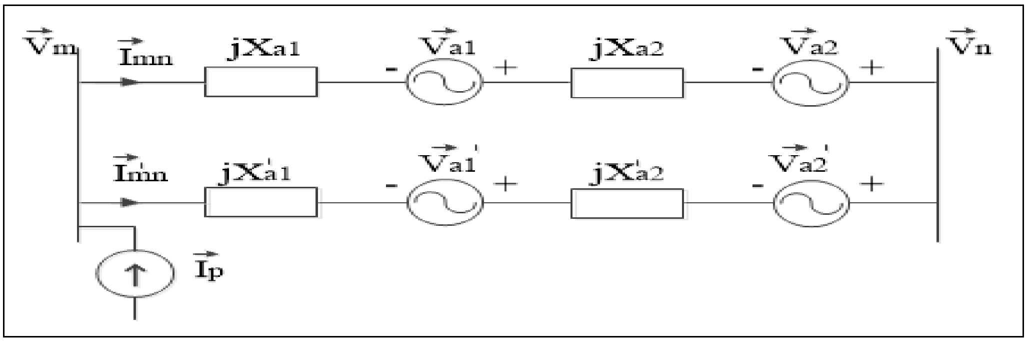

Fig. 5 Electrical equivalent system of DPFC

Using fig 4,

$$\vec{I}_p = \vec{I}_t + \vec{I}_q \tag{2}$$

Where $\vec{I}_t$ and $\vec{I}_q$ represents the phase component and quadrature component corresponding to V_m.

$\vec{V}_{a1}, \vec{V}_{a2}, \vec{V'}_{a1}, \vec{V'}_{a2}$ = Voltage sources

$\vec{X}_{a1}, \vec{X}_{a2}, \vec{X'}_{a1}, \vec{X'}_{a2}$ = Line reactances

$$\vec{V}_{a1} = \vec{V}_{a2} = \vec{V'}_{a1} = \vec{V'}_{a2} = rV_m e^{i\lambda} \tag{3}$$

Where r = Relative magnitude ($0 < r < r_{max}$) and λ = phase angle ($0 < \lambda < 2\pi$).
This model is developed by using current sources as a replacement of voltage sources as shown in fig. 6.

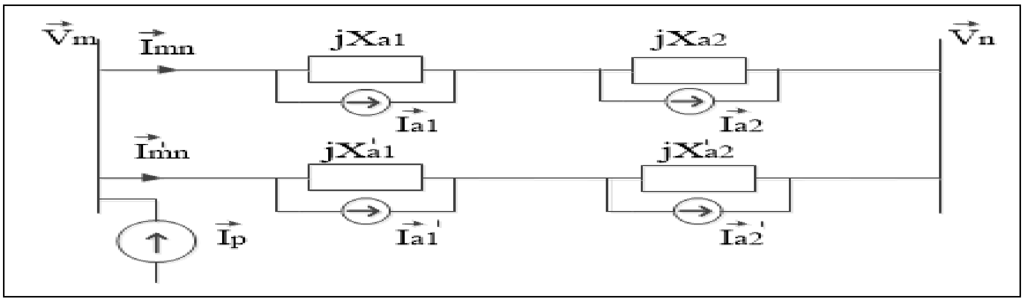

Fig. 6 Current sources representation

$$\vec{I}_{a1} = \frac{\vec{V}_{a1}}{jX_{a1}} = -jb_{a1} rV_m e^{i\lambda} \tag{4}$$

Where $b_{a1} = \dfrac{1}{X_{a1}}$

Active power drawn from shunt current source is given as-

$$P_p = \mathrm{Re}\left[\vec{V}_m\left(-\vec{I}_p^{*}\right)\right] = -V_m I_m \tag{5}$$

If losses are neglected,

$$P_{shunt} = P_{series} = P_{a1} + P_{a2} + P'_{a1} + P'_{a2} \tag{6}$$

Apparent power drawn from $\vec{V}_{a1}$ is evaluated as-

$$S_{a1} = \overrightarrow{V_{a1}}\left(\vec{I}_{mn}^{*}\right) = r\vec{V}_m e^{i\lambda}\left[\frac{\vec{V}_m + \vec{V}_{a1} + \vec{V}_{a2} - \vec{V}_n}{j\left(X_{a1} + X_{a2}\right)}\right]^{*} \tag{7}$$

$$S_{a1} = P_{a1} + jQ_{a1} \tag{8}$$

Active power and reactive power drawn from $\vec{V}_{a1}$ can calculated from equations (3), (7), (8) as-

$$P_{a1} = (b_{a1} + b_{a2})\left[rV_m V_n \sin(\theta_m - \theta_n + \lambda) - rV_m^2 \sin(\lambda)\right] \tag{9}$$

$$Q_{a1} = (b_{a1} + b_{a2})\left[rV_i^2 \cos\left(\lambda\right) + 2r^2V_i^2 - rV_iV_j \cos(\theta_i - \theta_j + \lambda)\right] \tag{10}$$

Hence, powers drawn from other sources can also be evaluated.
Shunt converter current is derived as-

$$I_p = \left(I_t + jI_q\right)e^{-j\theta_m} \tag{11}$$

Hence, Current injection model is attained as-

$$\begin{aligned}\vec{I}_m = \vec{I}_p - \vec{I}_{a1} - \vec{I}'_{a1} = \{2\left(b_{a1} + b_{a2}\right)\left[-rV_n \sin\left(\theta_m - \theta_n + \lambda\right) + rV_m \sin\left(\lambda\right)\right] \\ +2\left(b'_{a1} + b'_{a2}\right)\left[rV_n \sin\left(\theta_i - \theta_j + \lambda\right) + rV_m \sin\left(\lambda\right) + jI_q\}e^{j\theta_i} + jb_{a1}rV_m e^{j\lambda} + jb_{a2}re^{j\lambda}\right]\end{aligned} \tag{12}$$

$$\vec{I}_{n1} = \vec{I}_{a1} - \vec{I}_{a2} = -b_{a1}rV_m e^{j\lambda} + jb_{a2}re^{j\lambda} \tag{13}$$

$$\vec{I}_{n2} = \vec{I}_{a2} = -jb_{a2}rV_m e^{j\lambda} \tag{14}$$

$$\vec{I}'_{n1} = \vec{I}'_{a1} - \vec{I}'_{a2} = -jb'_{a1}rV_m e^{j\lambda} + jb'_{a2}rV_m e^{j\lambda}b'_{a1} \tag{15}$$

$$\vec{I}'_{n2} = \vec{I}'_{a1} = -jb'_{a2}rV_m e^{j\lambda} \tag{16}$$

Hence, the model is attained by using current sources as shown in fig-(7).

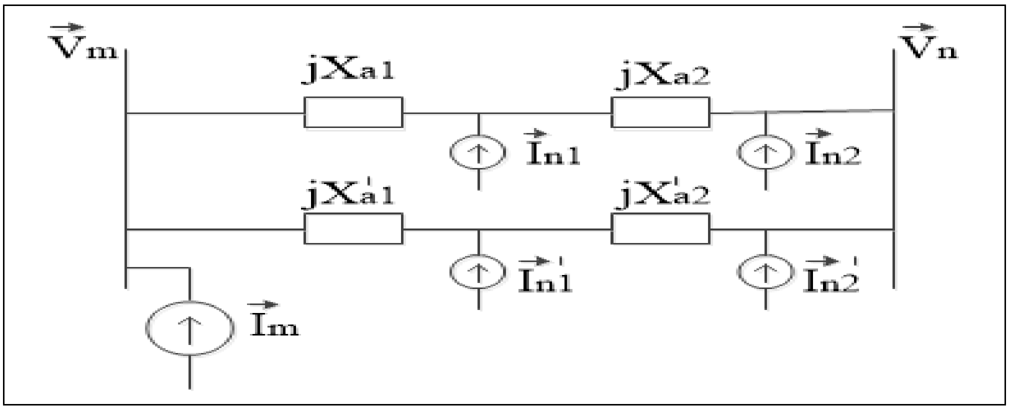

Fig. 7 DPFC representation with Current Injection Model

IV.DAMPING CONTROLLER

In this paper, damping controller is designed using r and λ as control parameters. The controller can be treated as lead-lag compensator whose input is speed deviation. Optimized value of parameters of the controller is find through PSO and DE algorithms.

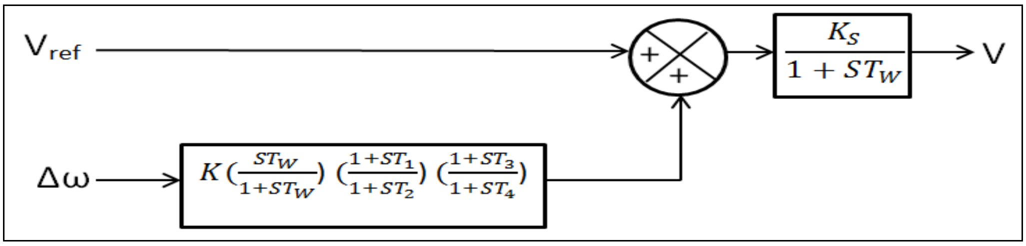

Fig. 8 DPFC Damping Controller

V.CONTROLLER STRATEGY

In this paper, a controller is designed which is tuned using the proposed model. Fitness Function is defined as Integral of Time Multiplied Absolute Error. Objective Function is considered as [1]-

$$K = \int_0^{t_{si}} t.(\Delta\omega_{i)} dt \tag{17}$$

$$f = \sum_{i=1}^{N_{ope}} K_i \tag{18}$$

Where t_{si} = Time for Simulation, N_{ope} = Total Operating Points required for optimization.

Bounds for the parameters to be optimized are as following-

$$K^{min} \le K \le K^{max}$$
$$T_1^{min} \le T_1 \le T_1^{max}$$
$$T_2^{min} \le T_2 \le T_2^{max}$$
$$T_3^{min} \le T_3 \le T_3^{max}$$
$$T_4^{min} \le T_4 \le T_4^{max} \tag{19}$$

Optimization of the parameters is done through PSO and DE algorithms, explained as following-

VI.PARTICLE SWARM OPTIMIZATION TECHNIQUE

Russell Eberhart and James Kennedy has introduced PSO technique in 1995. It is a computational technique having wide area applications. Pseudo cade for the algorithm is given as below.

```
For every particle
{
   Initialize every particle
}
Do until max iterations or min error criteria reached
{
   For every particle
   {
      Evaluate fitness function value
```

```
    If the fitness-value is better than 'pBest'
    {
        Set 'pBest' = current fitness value
    }
    If 'pBest' is better than 'gBest'
    {
        Set 'gBest' = 'pBest'
    }
}
For every particle
{
    Compute particle-Velocity
    Use 'gBest' and Velocity to update particle-Data
}
```

Velocity and position is updated by equation (20), (21) for all the particles [16].

$$V_i^{m+1} = \omega.V_i^m + C_1.rn_1.\left(pBest_i^{m+1} - X_i^m\right) + C_2.rn_2.\left(gBest_i^{m+1} - X_i^m\right) \quad (20)$$

$$X_i^{m+1} = X_i^m + V_i^{m+1} \quad (21)$$

Optimization technique parameters are set as-
Number of variables=5, Population Size=30, Iterations=100, C1=C2=2, w=0.9 to 0.4 (decreasing).

VII. DIFFERENTIAL EVOLUTION ALGORITHM

This optimization technique is proposed by Storn and Price in 1996. Mutation, crossover and selection processes are used for this technique. All the strategies executed in DE algorithm are discussed in [17].

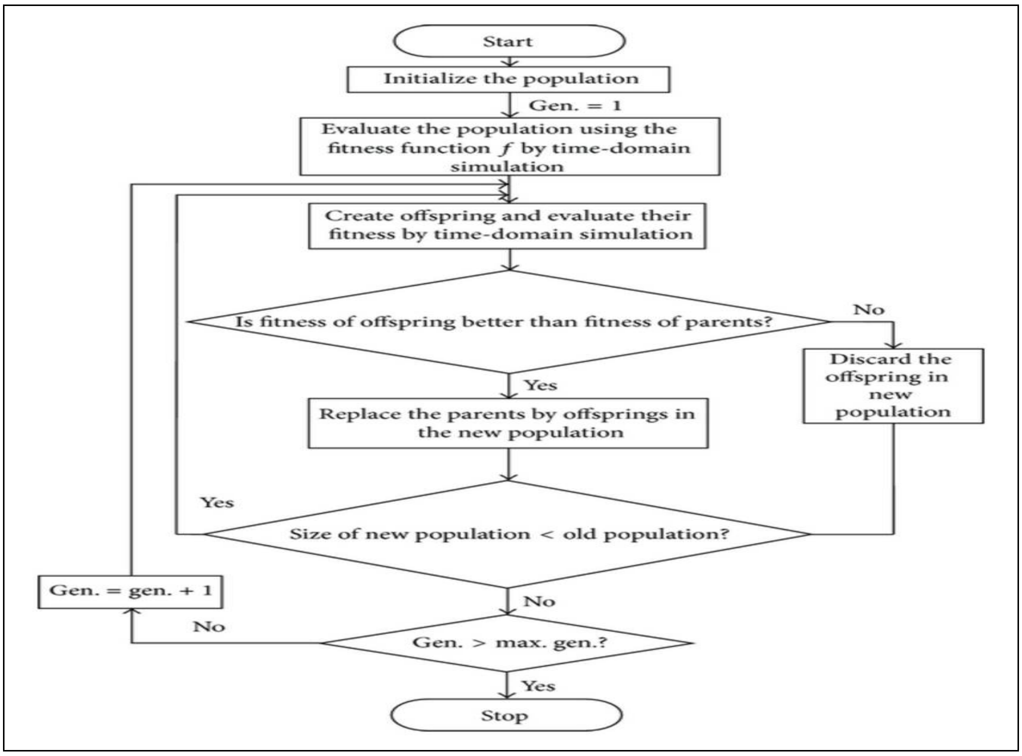

Fig. 9 Flow chart for DE algorithm

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To get the better results from optimization techniques, parameters are considered as-
Number of variables=5, Population Size=30, Iterations=100, β_{min}=0.2, β_{max}=0.8, crossover probability=0.2.

Optimized values of parameters are obtained as-

Table 1. Optimized value of Parameters

Controller Parameters Value	PSO based Controller		DE based Controller	
	Λ	r	Λ	r
K	95.56	53	98.147	62.589
T_1	0.1416	0.101	0.1359	0.0996
T_2	0.4713	2.112	0.3876	1.1270
T_1	1	0.5297	1.1134	0.4740
T_4	0.0716	1.4348	0.0669	1.7059

VIII.SIMULATION MODEL

The simulation model is used to evaluate the proposed technique, as shown in fig.10. In double-circuit line, converters are positioned at distinct locations and work independently to enhance the performance for stability point of view.

Simulation is done under distinct operating conditions, as given in table-2.

Table 2. Loading conditions for simulation study

Cases	Loading Conditions	P (Active Power)	Q (Reactive Power)
Base case	Nominal Load	0.75 (pu)	+0.17 (pu)
Case 1	Light Load	0.6 (pu)	+0.2025 (pu)
Case 2	Heavy Load	0.95 (pu)	+0.07 (pu)

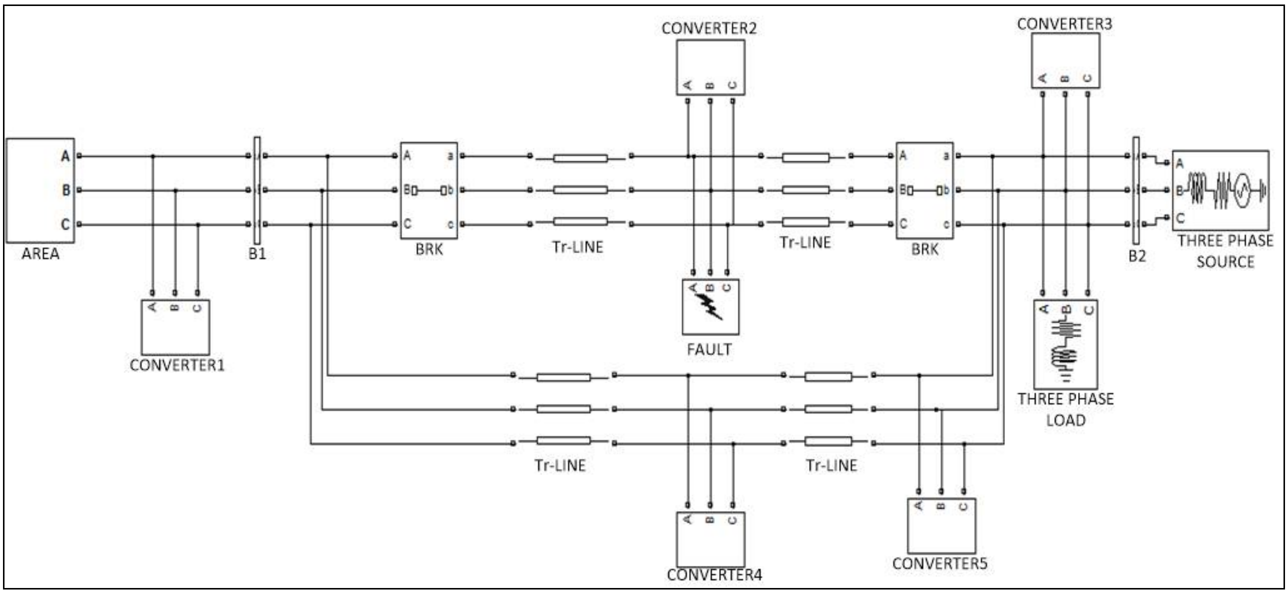

Fig. 10 Simulation model

Sending end voltage, receiving end voltage, phase angle and transmission line length are set as design parameters whose values are given in table-3.

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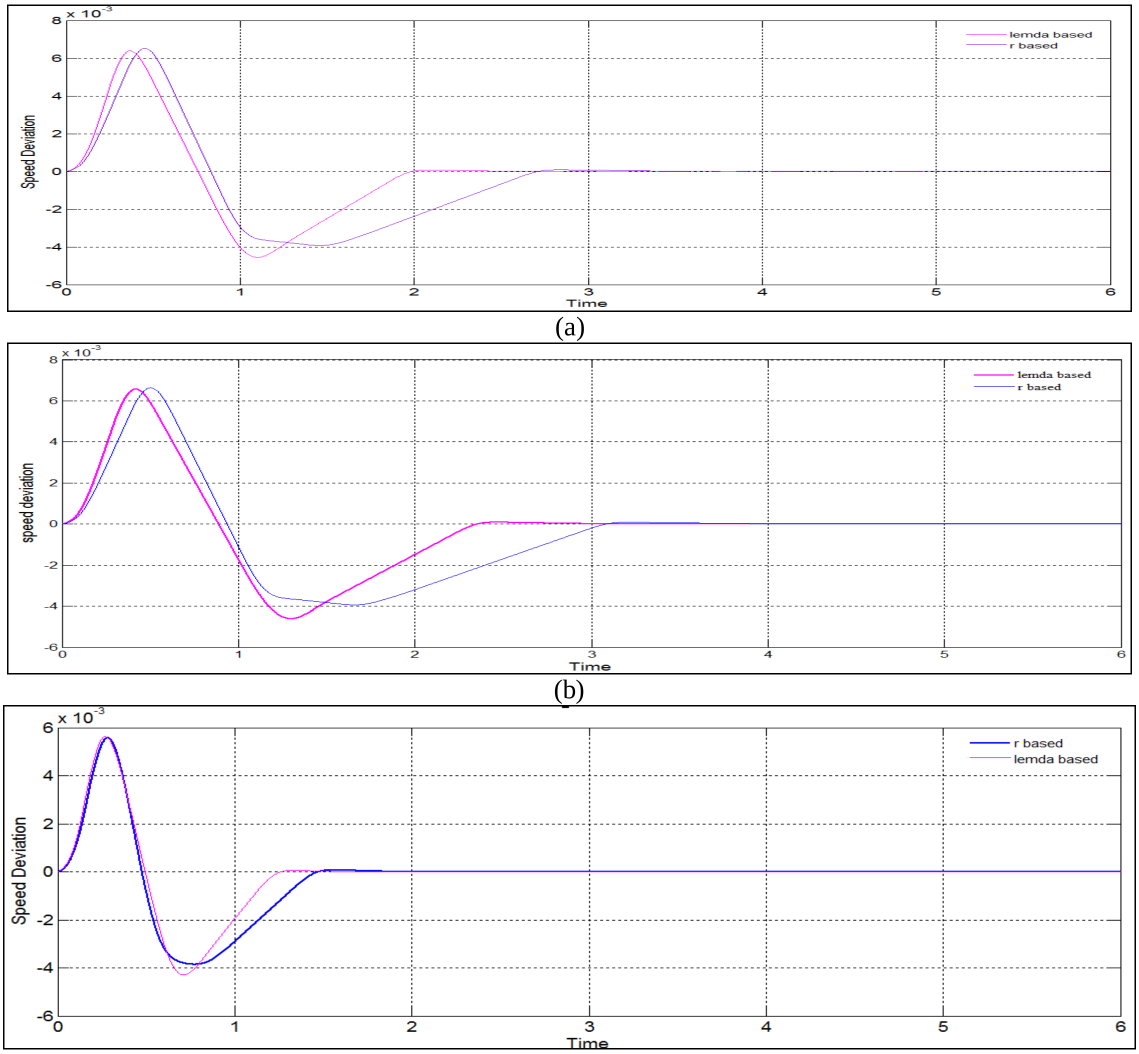
Table 3. Design parameters

Considerations	**E_s**	**δ_1**	**E_r**	**δ_2**	**S**	**Line Length**
Parameter Values	230 (KV)	10 (Deg)	230 (KV)	0 (Deg	900 (MVA)	220 (KM)

IX. SIMULATION RESULTS AND DISCUSSION

System is considered with six cycle, three phase fault at the mid of one transmission line at t = 1s. After the fault clearance, original system is achieved. Speed deviation responses of generator under distinct operating conditions are obtained using PSO and DE techniques for λ and r based damping controller.

A. By Particle Swarm Optimization technique



(a)

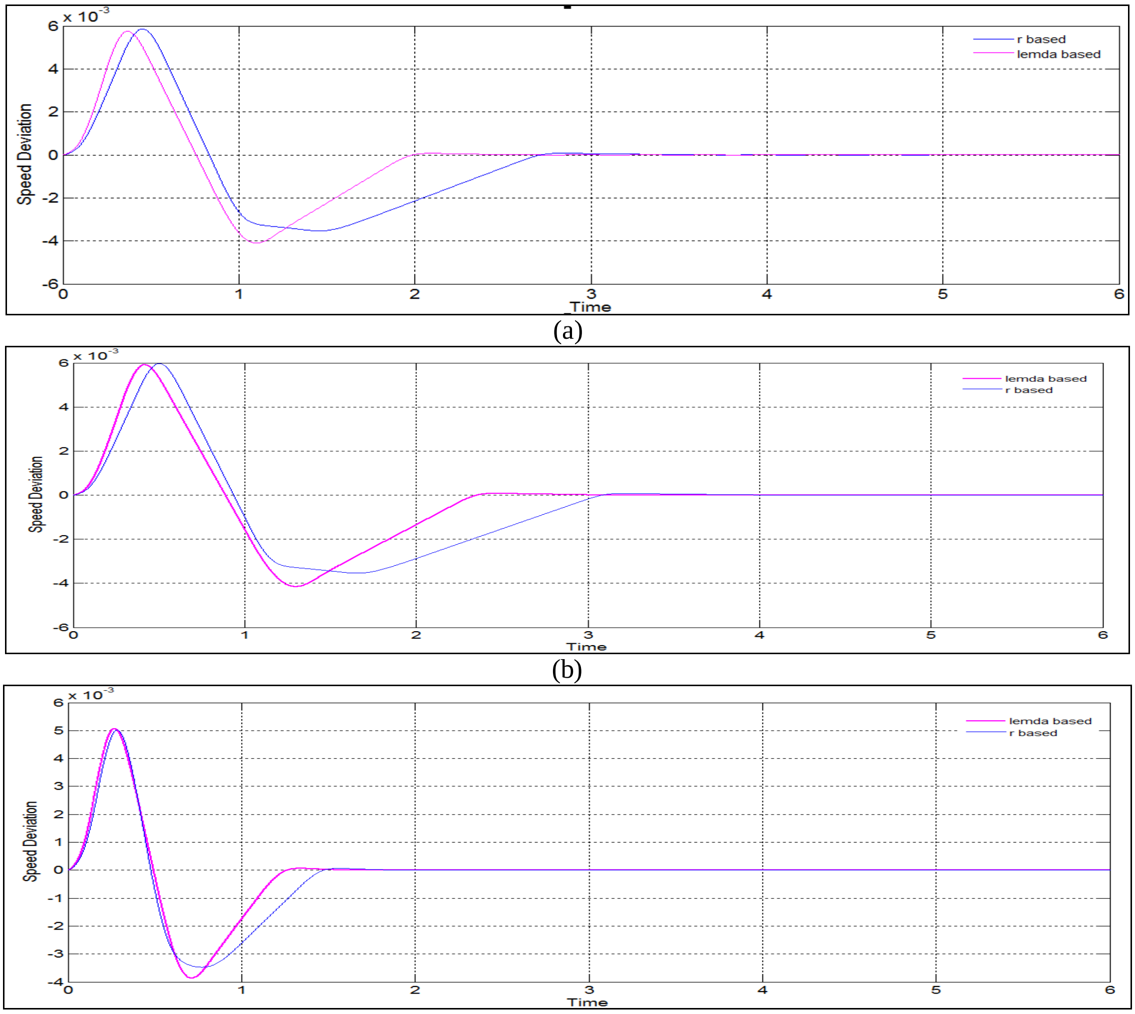
(b)

(c)

Fig. 11 Response of generator for speed deviation at (a) nominal load, (b) light load, (c) heavy load

Fig.11 shows the response of generator for speed deviation at nominal load, light load and heavy load for λ and r based controller using PSO algorithm, indicating the superiority of λ based controller over r based controller.

B. By Differential Evolution Algorithm



(a)

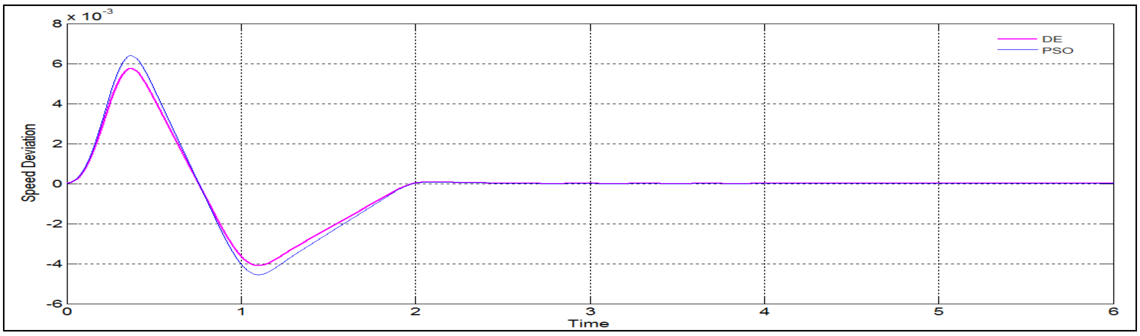
(b)

(c)

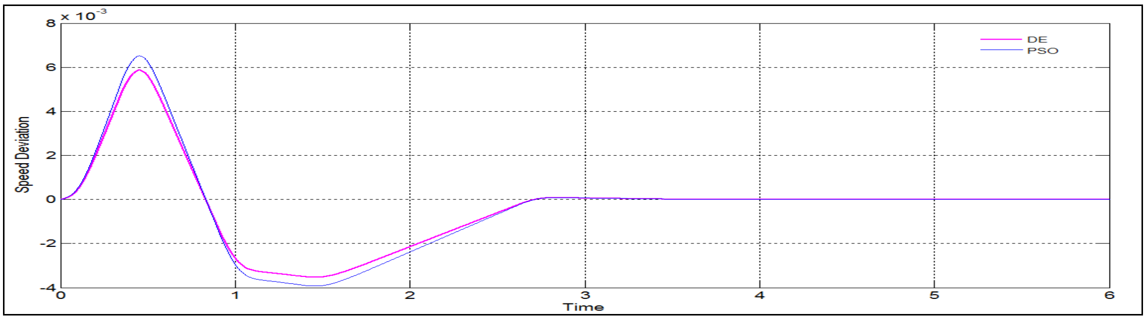
Fig. 12 Response of generator for speed deviation at (a) nominal load, (b) light load, (c) heavy load

Fig.12 shows the response of generator for speed deviation at nominal load, light load and heavy load for λ and r based controller using DE algorithm, indicating the superiority of λ based controller over r based controller.

C. Comparison of the results by PSO and DE algorithms

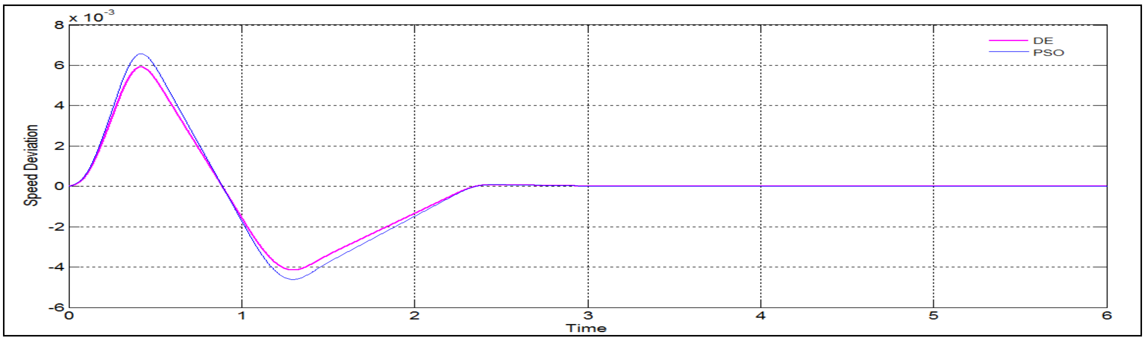


(a)

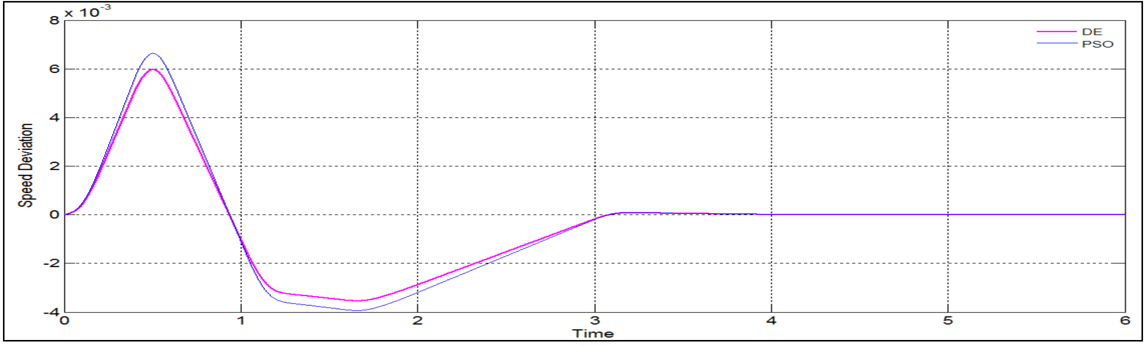


(b)

Fig. 13 Response of generator for speed deviation at nominal load (a) for λ based damping controller, (b) for r based damping controller

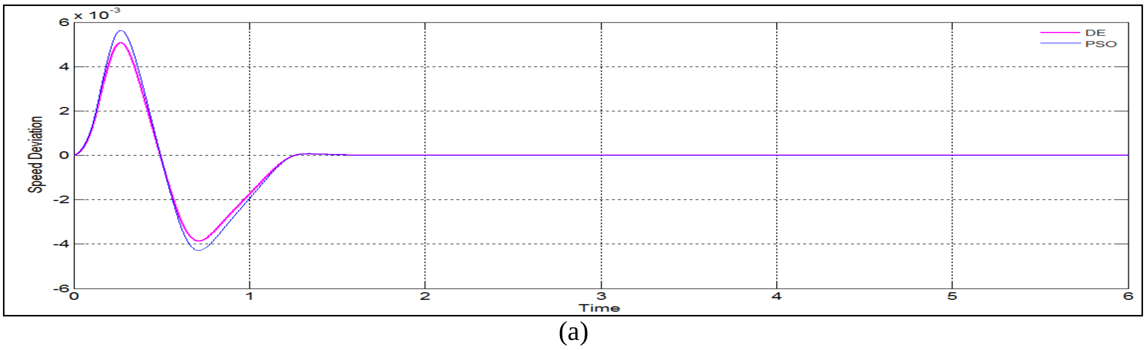


(a)

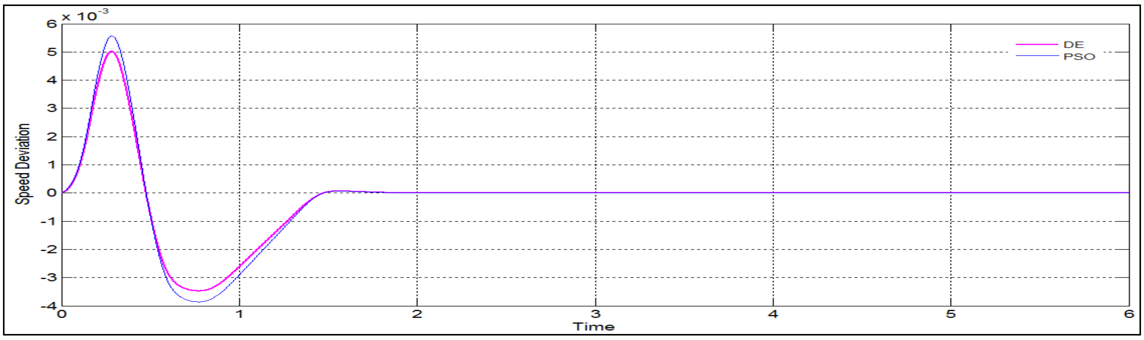


(b)

Fig. 14 Response of generator for speed deviation at light load (a) for λ based damping controller, (b) for r based damping controller



(a)



(b)

Fig. 15 Response of generator for speed deviation at heavy loading (a) for λ based damping controller, (b) for r based damping controller

Fig.13, 14, 15 shows the response of generator for speed deviation at nominal load, light load and heavy load for λ and r based controller, concluding that system response is improved by using DE algorithm as compared to PSO algorithm.

X.CONCLUSION

In this paper, mathematical analysis, modelling, simulation study of DPFC is done. It controls the line flow and provides reliable operation of system with low cost. PSO and DE optimization techniques are used to optimize the controller parameters which is designed using r and λ control parameters. Results demonstrate that DE based controller improves the system stability more effectively as compared with PSO algorithm by damping out the system oscillations more efficiently.

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