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# LOW FREQUENCY OSCILLATION DAMPING BY DISTRIBUTED POWER FLOW CONTROLLER WITH A ROBUST FUZZY SUPPLEMENTARY CONTROLLER

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**Abstract**-***In any abnormal conditions power system is under electro-mechanical oscillations. In this paper, current injection model of the DPFC is proposed to study the effects of it on power system oscillation. Supplementary damping controller is provided to enhance the damping of electro-mechanical oscillations of power system. Here, Fuzzy logic is used to design a supplementary damping controller. The advantages of the proposed the method is feasibility and robustness. To show the effectiveness of fuzzy model in damping electro-mechanical oscillations in power system, the proposed method is compared with damping controller design using particle swarm optimization (PSO) technique. The simulation is carried with the help of MATLAB for both fuzzy logic and PSO based damping controllers.***

***Key Words:*** *DPFC, FACTS, PSO, Current injection model, fuzzy, damping controller*

## 1. INTRODUCTION

Under normal operating conditions power is balanced i.e. power is generated by the system is equal to power is absorbed by the system. Under abnormal operating conditions i.e. power is generated by the system is no longer be equal to power is absorbed by the system this causes power system oscillations in the system. Concerning the low frequency oscillations which are caused due to faults, inter connection of the two power systems, tripping of the transmission line and the generator rise to low frequency range oscillations. These oscillations increases in magnitude until loss of synchronism, if not well damped [1]. In order to compensate this problem, power system stabilizers are being successfully used to damp these oscillations. However, Power system stabilizers may unfavorably affect the bus voltages, which results in leading power factor, and may be unable to modulate oscillations cause by large faults [2]. Controlling and optimizing the utilization of the power system with the use of reliable and high-speed power electronic devices called FACTS [3].FACTS devices can be able to control the line parameters, which include the series or shunt impedances, phase angle. In this paper, phase angle is considered for damping the power system oscillation. These conditions cannot be overcome otherwise, while maintaining needed stability of system, by mechanical means without decrease in transmission capacity [4]. For proving flexibility, FACTS controllers enable a line to carry power closer to its power capability. The DPFC presented in [5, 6] is a efficient device from the family of facts, which can provide much lower cost and higher reliable than other FACTS devices. It is obtained from the UPFC [7] and has the same control capability of simultaneously controlling the parameters of the power system: transmission angle, line impedance, and bus voltage. The DPFC doesn't have the common DC link between the series and shunt converters, instead of one three-phase large converter, the DPFC consists multiple single phase converters (D-FACTS) as the series compensator. This concept optimizes the rating of the components and provides reliability due redundancy [5]. DPFC can control the active and reactive power flow and the voltage magnitude instantaneously, it implies a huge potential to damp power system oscillation. The ability of the DPFC for damping the low frequency oscillations and the oscillation damping controller parameters are obtained using the residue method [8].

The contributing part of this paper is that a current injection model and the DPFC dynamic system simulation for studying the low frequency oscillations are placed in the transmission system model.

A DPFC supplementary damping controller design using a fuzzy scheme is considered to enhance damping. The objective of this work is damping low frequency oscillations using the distributed power flow controller with current injection model in power system.

## 2. DPFC

### 2.1. DPFC Basic Module

DPFC consists of multiple series and one shunt converters. Shunt converter is similar to STATCOM and series converter working is based on D-FACTS concept. Unlike UPFC, DPFC converters will have an independent capacitors instead back to back coupling capacitor. In DPFC something interesting happens i.e. the transmission line itself acts as a connection between the shunt and series converters to exchange the power between the two. How the DPFC is derived from the UPFC as shown in the figure 2.1

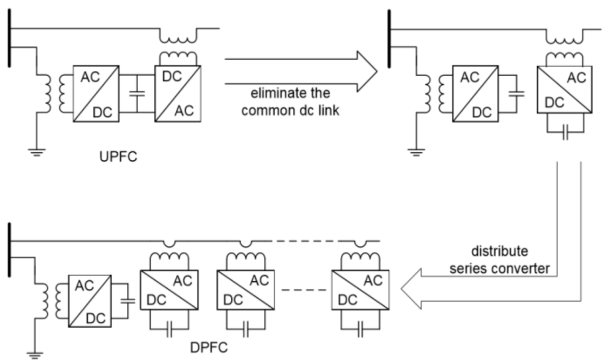



Figure 2.1 converting UPFC into DPFC

### 2.2 DPFC Current Injection Model

To study the impact of DPFC on the power system oscillations, appropriate models are required. In this paper, DPFC current injection model is presented. Installation of DPFC directly into the system changes the bus admittance matrix. So, it is necessary to modify the bus admittance at each stage. In order to avoid this current injection model of DPFC is built. At the bus to simulate a DPFC by using the current injection model, doesn't require modification of bus admittance at each stage [9].

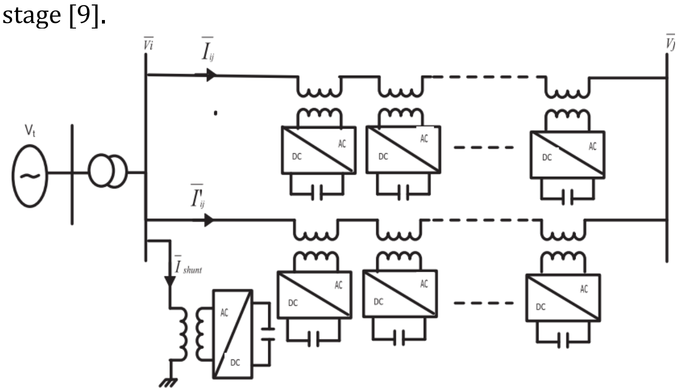


Figure 2.2 power system of the case study equipped with DPFC

Power is delivered to the infinite bus through the DPFC and transmission line. Fig 2.3 shows the test power system of equivalent circuit of DPFC. The current injection model uses current sources, which are connected a shunt, instead of sources of series voltage. In Fig 2.3 current in the shunt converter $I_{shunt}$ can be written as:

$$\overline{I}_{shunt} = \overline{I}_t + \overline{I}_q \tag{1}$$

Where $\overline{I}_t$ is in phase with $\overline{V}_i$ and $\overline{I}_q$ is in quadrature to $\overline{V}_i$

The voltage sources $\overline{V}_{s1}, \overline{V}_{s2}, \overline{V'}_{s1}, \overline{V'}_{s2}$ are replaced instead of series converters. $X_{s1}$, $X_{s2}$, $X'_{s1}$, $X'_{s2}$ are reactance of transmission lines. The phase angle and magnitudes of series converters are controllable. In this paper, it is assumed that they have same value.

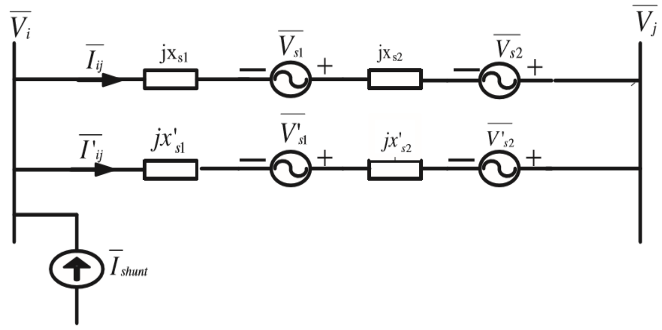



Figure 2.3 electrical circuits in DPFC converters of case study of transformation system

$$\overline{V}_{s1} = \overline{V}_{s2} = \overline{V'}_{s1} = \overline{V'}_{s2} = r\overline{V}_i e^{j\lambda} \tag{2}$$

Where $0 < r < r_{max}$ and $0 < \lambda < 2\pi$. The r and $\lambda$ are relative magnitude and phase angle respect to $\overline{V}_i$, respectively. The current injection model is obtained by replacing the voltage sources with current sources as shown in Fig. 2.4

We have [10]:

$$\overline{I}_{s1} = \frac{\overline{V}_{s1}}{jx_{s1}} = -jb_{s1} r\overline{V}_i e^{j\lambda} \tag{3}$$

$$\overline{I}_{s2} = \frac{\overline{V}_{s2}}{jx_{s2}} = -jb_{s2}\overline{rV}_i e^{j\lambda} \tag{4}$$

$$\overline{I'}_{s1} = \frac{\overline{V}_{s1}}{jx'_{s1}} = -jb'_{s1} r\overline{V}_i e^{j\lambda} \tag{5}$$

$$\overline{I'}_{s2} = \frac{\overline{V}_{s2}}{jx'_{s2}} = -jb'_{s2} r\overline{V}_i e^{j\lambda} \tag{6}$$

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:

$$P_{shunt} = Re\left[\overline{V}_i\left(-\overline{I}^*_{shunt}\right)\right] = -V_i I_i \tag{7}$$

With the neglected DPFC losses we have:

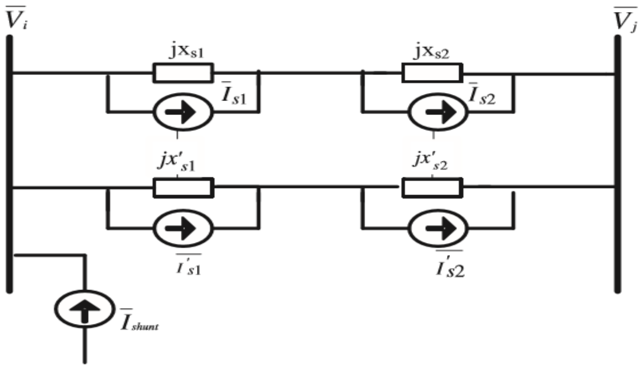



Figure 2.4 Representation of series voltage sources by current sources.

$$P_{shunt} = P_{series} = P_{s1} + P_{s2} + P'_{s1} + P'_{s2} \quad (8)$$

The apparent power supplied by the series converter $\overline{V}_{s1}$ can be calculated as:

$$S_{s1} = \overline{V}_{s1}\overline{I}^{*}_{ij} = r\overline{V}_i e^{j\lambda}\left[\frac{\overline{V}_i + \overline{V}_{s1} + \overline{V}_{s2} - \overline{V}_j}{j(x_{s1} + x_{s2})}\right]^{*}$$

$$S_{s1} = r\overline{V}_i e^{j\lambda}\left[\frac{\overline{V}_i + r\overline{V}_i e^{j\lambda} + r\overline{V}_i e^{j\lambda} - \overline{V}_j}{j(x_{s1} + x_{s2})}\right]^{*} \quad (9)$$

$$S_{s1} = P_{s1} + Q_{s1} \quad (10)$$

From (9) and (10) the exchanged active and reactive powers by converter $\overline{V'}_{s1}$ are distinguished as:

$$P_{s1} = (b_{s1} + b_{s2})[rV_iV_j \sin(\theta_i - \theta_j + \lambda) - rV^2{}_i \sin\lambda] \quad (11)$$

$$Q_{s1} = (b_{s1} + b_{s2})[rV^2{}_i \cos\lambda + 2r^2V^2{}_i - rV_iV_j \cos(\theta_i - \theta_j + \lambda)] \quad (12)$$

With attention above equation, the exchanged active and reactive power converters $\overline{V}_{s2}, \overline{V'}_{s1}$ and $\overline{V'}_{s2}$ are calculated as:

$$P_{s2} = (b_{s1} + b_{s2})[rV_iV_j \sin(\theta_i - \theta_j + \lambda) - rV^2{}_i \sin\lambda] \quad (13)$$

$$Q_{s1} = (b_{s1} + b_{s2})[rV^2{}_i \cos\lambda + 2r^2V^2{}_i - rV_iV_j \cos(\theta_i - \theta_j + \lambda)] \quad (14)$$

$$P'_{s1} = (b'_{s1} + b'_{s2})[rV_iV_j \sin(\theta_i - \theta_j + \lambda) - rV^2{}_i \sin\lambda] \quad (15)$$

$$Q'_{s1} = (b'_{s1} + b'_{s2})[rV^2{}_i \cos\lambda + 2r^2V^2{}_i - rV_iV_j \cos(\theta_i - \theta_j + \lambda)] \quad (16)$$

$$P'_{s2} = (b'_{s1} + b'_{s2})[rV_iV_j \sin(\theta_i - \theta_j + \lambda) - rV_i^2 \sin\lambda] \quad (17)$$

$$Q'_{s2} = (b'_{s1} + b'_{s2})[rV^2{}_i \cos\lambda + 2r^2V^2{}_i - rV_iV_j \cos(\theta_i - \theta_j + \lambda)] \quad (18)$$

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

$$I_t = 2(b_{s1} + b_{s2})[-rV_j \sin(\theta_i - \theta_j + \lambda) - rV_i \sin\lambda)] + 2(b'_{s1} + b'_{s2})[-rV_j \sin(\theta_i - \theta_j + \lambda) - rV_i \sin\lambda] \quad (19)$$

Finally, the shunt converter current can be obtained as:

$$\overline{I}_{shunt} = \overline{I}_t + \overline{I}_q = (I_t + jI_q)e^{j\theta_i}$$

$$\overline{I}_{shunt} = \{2(b_{s1} + b_{s2})[-rV_j \sin(\theta_i - \theta_j + \lambda) - rV_i \sin\lambda)] + 2(b'_{s1} + b'_{s2})[-rV_j \sin(\theta_i - \theta_j + \lambda) - rV_i \sin\lambda] + j\overline{I}_q\}e^{j\theta_i} \quad (20)$$

$$\overline{I}_q = jB_q\overline{V}_i \quad (21)$$

$B_q$ equivalent susceptance used to control $\overline{I}_q$.

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

$$\overline{I}_i = \overline{I}_{shunt} - \overline{I}_{s1} - \overline{I'}_{s1} \quad (22)$$

$$\overline{I}_{s1} = \overline{I}_{s1} - \overline{I}_{s2} \quad (23)$$

$$\overline{I}_{j2} = \overline{I}_{s2} \quad (24)$$

$$\overline{I'}_{j1} = \overline{I'}_{s1} - \overline{I'}_{s2} \quad (25)$$

$$\overline{I'}_{j2} = \overline{I'}_{s2} \quad (26)$$

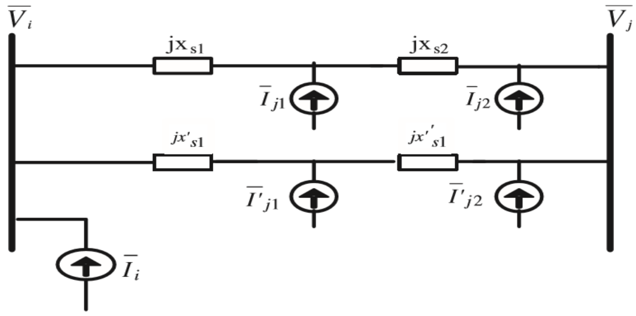



Figure 2.5 Current injection model of DPFC.

$$\overline{I}_{shunt} = \{2(b_{s1} + b_{s2})[-rV_j \sin(\theta_i - \theta_j + \lambda) - rV_i \sin\lambda)] + 2(b'_{s1} + b'_{s2})[-rV_j \sin(\theta_i - \theta_j + \lambda) - rV_i \sin\lambda] + j\overline{I}_q\}e^{j\theta_i} + -jb_{s1}r\overline{V}_i e^{j\lambda} + -jb'_{s1}r\overline{V}_i e^{j\lambda} \quad (27)$$

$$\overline{I}_{s1} = -jb_{s1}r\overline{V}_i e^{j\lambda} + jb_{s2}r\overline{V}_i e^{j\lambda} \quad (28)$$

$$\overline{I}_{j2} = -jb_{s2}r\overline{V}_i e^{j\lambda} \quad (29)$$

$$\overline{I'}_{j1} = -jb'_{s1}r\overline{V}_i e^{j\lambda} + jb'_{s2}r\overline{V}_i e^{j\lambda} \quad (30)$$

$$\overline{I'}_{j2} = -jb'_{s2}r\overline{V}_i e^{j\lambda} \quad (31)$$

Fig. 2.5 shows the current injection model of the DPFC.

## 3. DESIGN OF PSO BASED DAMPING CONTROLLER

With minimum control effort the designed controller with PSO based controller is tuned to damp low frequency oscillations. Here ITAE (Integral of Time multiplexed Absolute value of Error) is used as the fitness function. The objective function is defined as [1]:

$$J = \int_0^{t_{sim}} t.(\Delta\omega_i)dt \tag{32}$$

$$F = \sum_{i=1}^{N_p} J_i \tag{33}$$

In Eqn. (32), $t_{sim}$ is the simulation time. In Eqn. (33), $N_p$ is the total number of operating points. Damping controller with PSO technique is tune damp power system oscillations. The optimization of controller parameters is carried out by evaluating the objective function. The design problem is converted into optimization problem which is solved by the PSO, where the controller parameter bounds.

Minimize J subject to:

$$K^{min} \le K \le K^{max}$$
$$T_1^{min} \le T_1 \le T_1^{max}$$
$$T_2^{min} \le T_2 \le T_2^{max} \tag{34}$$
$$T_3^{min} \le T_3 \le T_3^{max}$$
$$T_4^{min} \le T_4 \le T_4^{max}$$

The optimization of DPFC controller parameters is obtained by evaluating the cost function as shown in Eqn. (33). Which consider multiple operating points. The operating conditions are considered as given below:

- Base scenario: P = 0.75 pu and Q = +0.17 pu (Nominal loading)
- Scenario 1: P = .06 pu and Q = +0.2025 pu (Light loading)
- Scenario 2: P=0.95 pu and Q = +0.07 pu (Heavy loading)

The structure of the DPFC with lead- lag damping controller is show Fig 3.1
Results of the controller parameter set values using the PSO method is given below

$K$ =95.56, $T_1$ = 0.1416, $T_2$ = 0.4713, $T_3$= 1, $T_4$ = 0.0716

In order to acquire the desired performance, particle size, number of particle, number of iteration, C1 and C2 are chosen as 5, 30, 50, and 2 respectively.

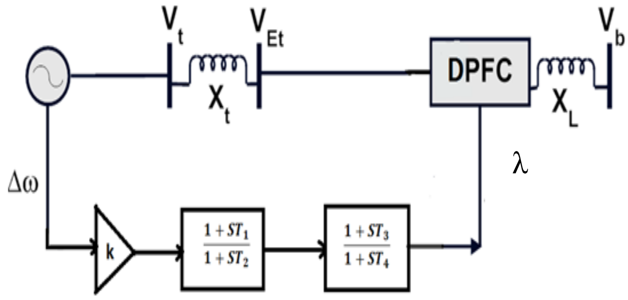



Figure 3.1 DPFC with lead-lag controller.

$$V_i^{k+1} = \omega.V_i^k + c_1.rn_1.(Pbest_i^k - X_i^k) + c_2.rn_2.(Gbest^k - X_i^k) \tag{34}$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{35}$$

In the Eqn. (34) ω is the inertia weight which is decreasing linearly from 0.9 to 0.4. These parameters are selected through the dimension of the optimization problem.

PSO easily suffers from the partial optimism, which causes the less exact at the regulation of its speed and the direction. Thus, in this paper to show the enhanced damping fuzzy logic scheme is considered.

## 4. DESIGN OF FUZZY BASED DAMPING CONTROLLER

In this paper, fuzzy controller with two inputs and one output in Fig. 4.1. The three control parameters of the DPFC ($\lambda$, $r$, $B_q$) are modulated in order to produce the damping torque. In this paper '$\lambda$' is modulated in order to design the damping controller. Speed deviation is considered as an input to controller.

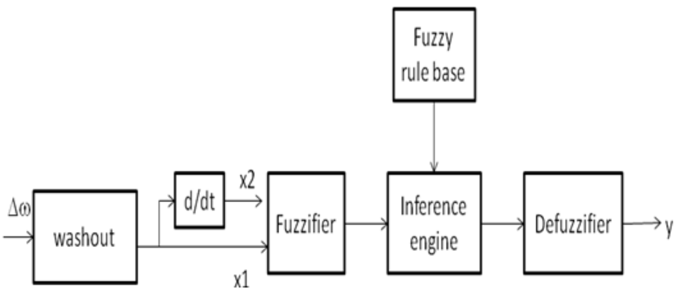



Figure **4.1** fuzzy supplementary controller

The structure of fuzzy supplementary controller is shown in Fig. 4.1. Where, the inputs are speed deviation (x1) and its rate of its change (x2), which are filtered by washout blocks to eliminate the DC content present. The output (y) is sent to main controller to modulate 'λ' is shown in Fig 3.2.

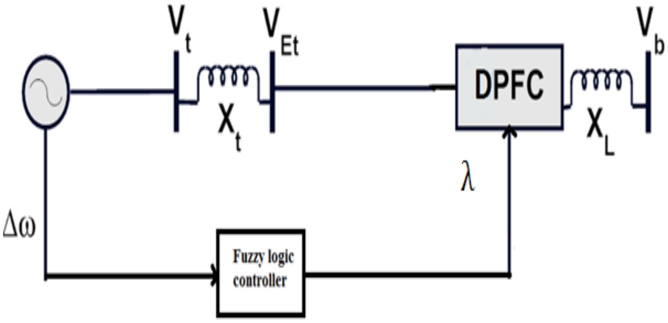



Figure 4.2 DPFC with fuzzy logic controller

Though the fuzzy controller accepts these inputs, they need to be in the fuzzified form. So, it has to convert them into fuzzified form before the rules can be evaluated. In order to get it done this is necessary to build one of the most critical and important blocks in the fuzzy controllers, the knowledge base. It consists of two blocks called the data base and the rule base.

### 4.1 Data Base

Data base consists of membership function for both input variables (x1) and (x2) and output variables (Y).
For input variables ($X_1$) and ($X_2$) described by the following linguistic variables:
For ($X_1$):
- Positive (P)
- Negative (N)

For ($X_2$):
- Negative (N)
- Near Zero (NZ)
- Positive (P)

For output variables Y (damping signal) described by the following linguistic variables:
- Positive (P)
- Positive Small (PS)
- Near Zero (NZ)
- Negative Small (NS)
- Negative (N)

In this paper, membership functions used are Gaussian membership functions" for the input variables and "triangular membership functions" for output variables

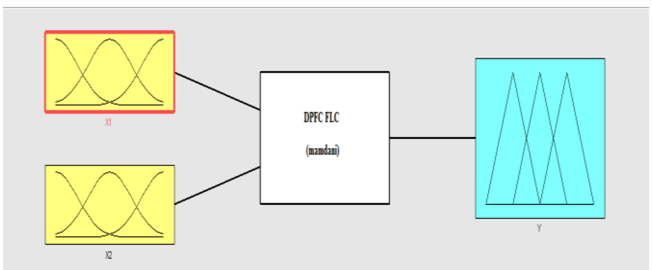



Figure: **4.3** Fuzzy(mamdani) model with two inputs and one output

Figs. 4.4-4.6 illustrates the range of all the variables.

### 4.2 Rule Base

Rule base is half of the knowledge base, which consists of rules written by the experts. To indicate the impact of a particular rule over the net fuzzified output It will have a weights, which indicate the relative importance of the rules among themselves. in this paper, fuzzy rules used in rule base are shown in table 1.

**Table 1: Fuzzy rules**

| |
|---|
| Rule 1: If ($X_2$) is NZ then (y) is NZ (1) |
| Rule 2: If ($X_2$) is P then (y) is P (1) |
| Rule 3: If ($X_2$) is N then (y) is N (1) |
| Rule 4: If ($X_2$) is NZ and ($X_1$) is P then is NS |
| Rule 5: If ($X_2$) is NZ and ($X_1$) is N then is PS |

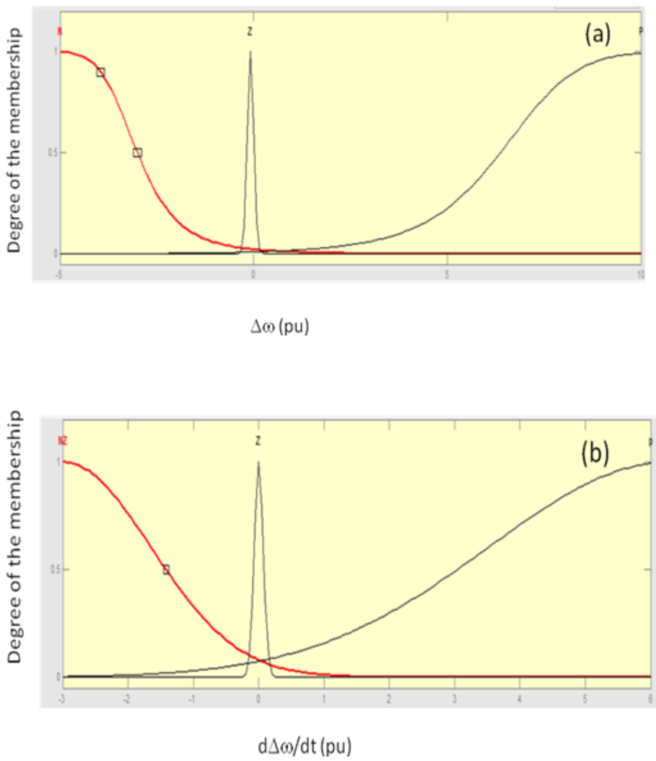



Figure: **4.4** Input membership functions of variables: (a)$X_1$ and (b) $X_2$

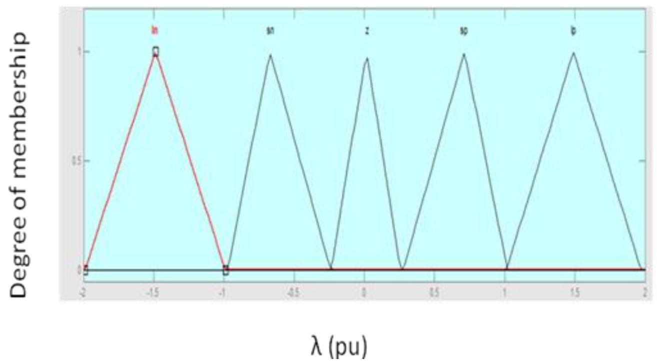



Figure: **4.5** Output membership function of variable

### 4.3 Methodologies Adopted In Fuzzy Inference Engine:

Though several methodologies is in evaluating the various expression like fuzzy union (disjunction operation), fuzzy intersection (conjunction operation), etc., with varying degree of complexity, in this paper fuzzy scheme use the most widely used methods for evaluating OR is " MAX", which is nothing but the maximum of the two operands, i.e.,

$MAX(X_1, X_2) = X_1$ if $X_1 > X_2$

$=X_2$ if $X_1 < X_2$

Similarly, the AND is evaluated using "MIN" function which is defined as the minimum of the two operands, i.e.,

$MIN(X_1, X_2) = X_1$ if $X_1 < X_2$

$= X_2$ if $X_1 > X_2$

Another highlighting point to note here is that in the present paper, it is assigned equal importance to all the rules in the rule base, i.e., all the weights are equal.

The defuzzification method followed in this paper is the "center of area method" or "gravity method".

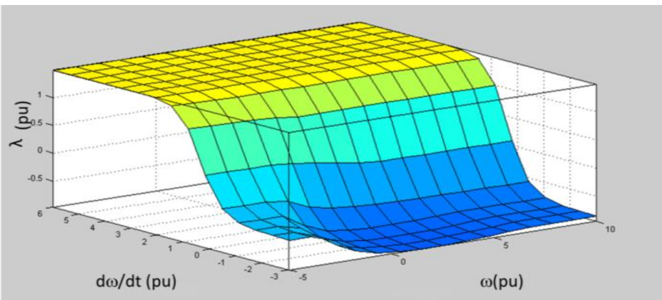



Figure: **4.6** Output coefficients versus two inputs

## 5 CASE STUDY AND SIMULATION RESULTS

### 5.1 Main Simulink Model

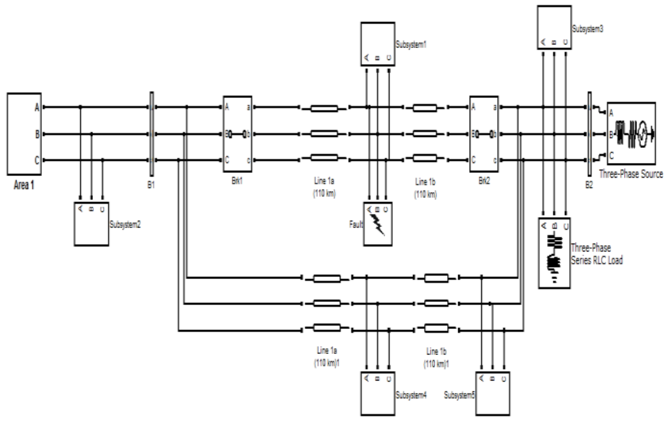


Figure 5.1 SMIB with DPFC built with MATLAB/Simulink.

### 5.2 Control Design of Fuzzy Logic Controller

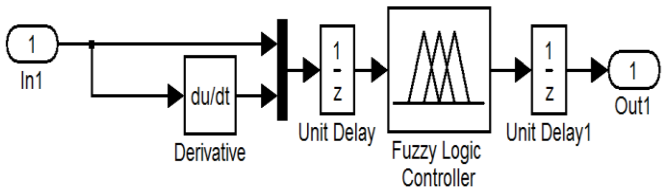



Figure 5.2 simulink control design of fuzzy logic controller

**Table 2** Parameters of test power system

| Parameter length(km ) | $E_s$(KV) | $E_r$(KV) | $F$(HZ) | $S$(MVA) | Deg | Line |
|---|---|---|---|---|---|---|
| Value | 230 | 230 | 60 | 900 | 10 | 220 |

### 5.3 Simulation in Time Domain

The control schemes for DPFC are evaluated in MATLAB or simulink by using computer simulation. The test system parameters are shown in table 2. In order to evaluate the designed controller's robustness, simulation is performed for 3 cases as explained below.

#### 5.3.1 Case 1

In this case, a 6 cycle three phase fault is occurred at middle of the transmission line at 1ms is considered. It is cleared by permanent tripping of the faulted line. The speed deviation of generator at nominal, heavy and light loading conditions due to designed controllers for λ by fuzzy and PSO are shown in fig 5.3 Also Fig. 5.4 shows the internal voltage variations, generator output power and excitation voltage deviation with λ based controllers for nominal voltage conditions. These figures show damping effect of supplementay controler.

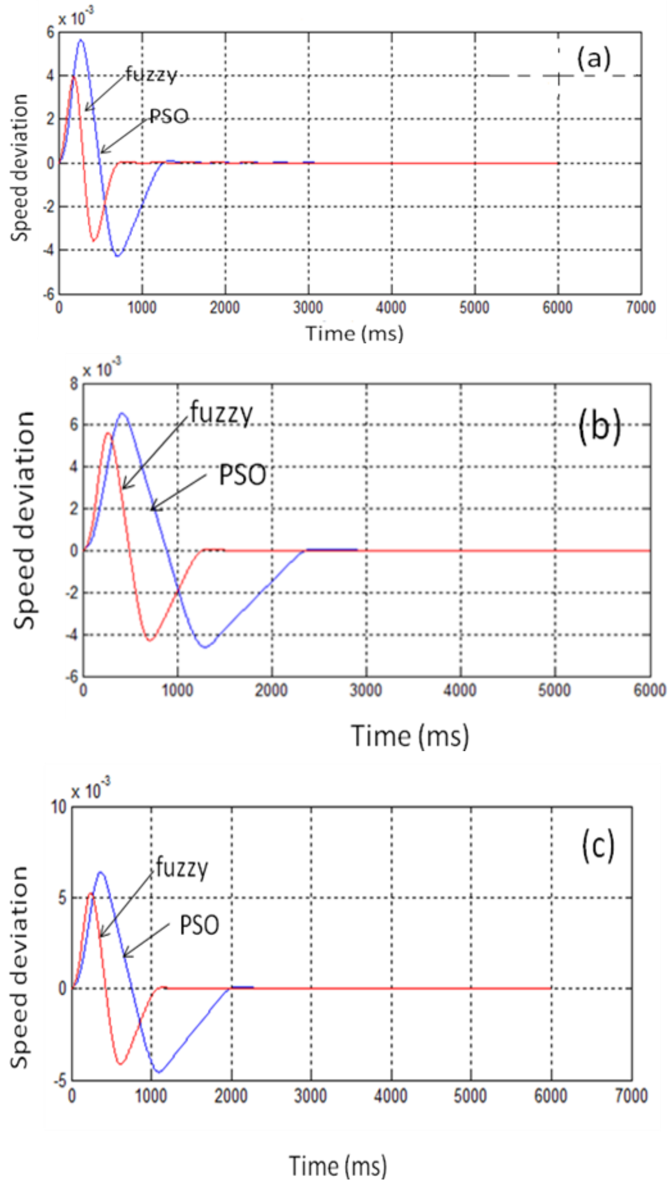
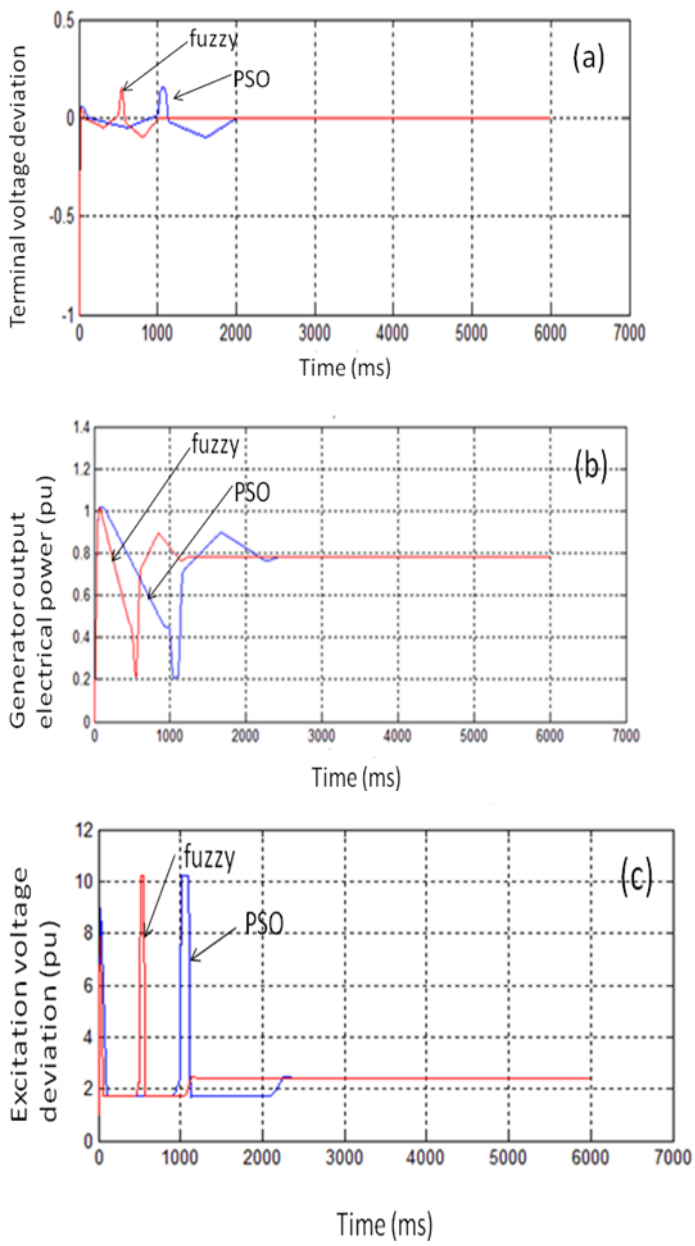



Figure 5.3 Dynamic responses for Δω in case 1 at: (a) heavy(b) light (c) nominal loading condition.




Figue 5.4 Dynamic responses at nominal loading: (a) terminal voltage deviation, (b) output electrical power, (c) excitation voltage

**5.3.2 Case 2**

In this case, it is considered a 6 cycle three phase fault occurred at middle of the transmission line at 1ms and it is cleared without line tripping and original system is restored after the clearance of the fault. The response of the system to this disturbance is shown in Fig. 5.5 it can be seen that the fuzzy based DPFC damping controller shows better performance in oscillation damping and enhances stability. From the tests it can be concluded that fuzzy based is superior to PSO based damping controller.

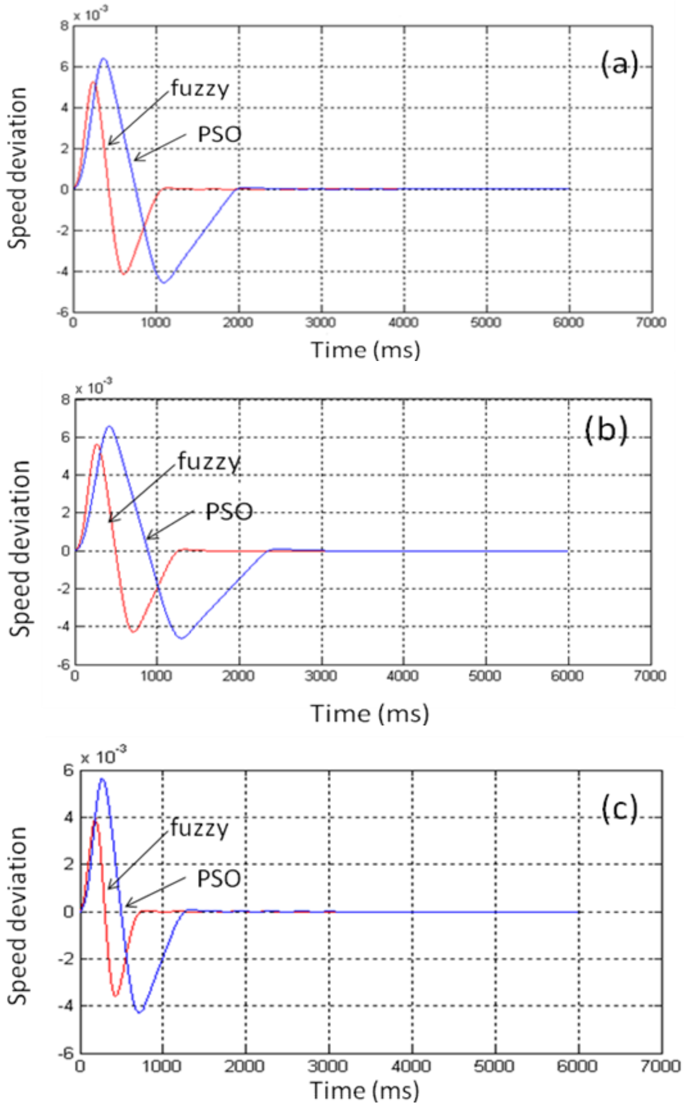



Figure 5.5 Dynamic responses for Δω in case 2 at: (a) nominal, (b) light, (c) heavy loading conditions

### 5.3.3 Case 3

In this case, it is considered a 6 cycle single phase fault occurred at middle of one of the transmission line at 1ms and it is cleared without line tripping and original system is restored after the clearance of the fault. The speed deviation of the generator at the base loading condition with control parameter λ is shown in Fig 5.6, respectively. The performance of the fuzzy based damping controller is better in comparison with the PSO based damping controller, and the performance indices are significantly improved for the fuzzy controller. It can be seen that the system response with the fuzzy based damping controller provides superior damping than that of PSO.

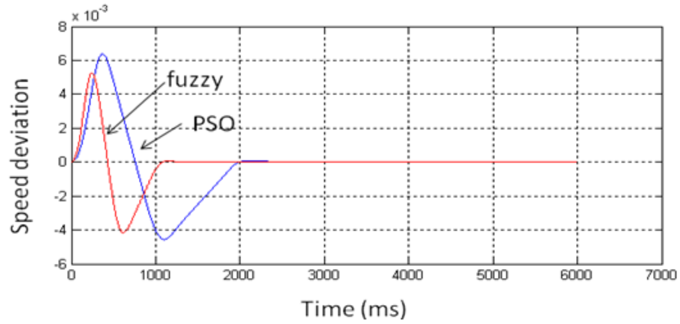



Figure 5.6 Dynamic responses for Δω at nominal loading condition: fuzzy based controller and PSO based controller

## CONCLUSION

In this paper, it has been proved that the capability of the DPFC in damping low frequency oscillations with a supplementary controller. Current injection model of the DPFC is proposed here to study the effects of it on low frequency oscillations. In this study, line parameter λ is modulated to control the power in the transmission line. It can be concluded from the above results the fuzzy based supplementary controller is superior to PSO based damping controller in damping low frequency oscillations.

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