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RESEARCH ARTICLE OPEN ACCESS

Transient Stability Enhancement of a Multi-Machine System using Particle Swarm Optimization based Unified Power Flow Controller

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Abstract

In this paper an attempt has beenmade to investigate the transient stability enhancement of both SMIB and Multi-machine system using UPFC controller tuned by Particle Swarm Optimization. Power injection modelfor a series voltage source of UPFC has been implemented to replace UPFC by equivalent admittance. The admittance matrix of the power system is then modified according to the power injection model of UPFC. To mitigate the power oscillations in the system, the required amount of series voltage injected by UPFC controller has been computed in order to damp inter area & local mode of oscillations in multi-machine system.

Keywords:UPFC, Transient Stability, Converters, SMIB, Multi-machine modeling, Capacitor Dynamics,UPFC(Unified Power Flow Controller), FACTS (Flexible AC Transmission System), Power injection model. Particle Swarm Optimization.

I. INTRODUCTION

Modern interconnected power system comprise a number of generators, a large electrical power network & a variety of loads& such a complex system is vulnerable to sudden faults, load changes & uncertain nature resulting in instability & so the designing of such a large interconnected power systems to ensure secure & stable operation is a complicated problem. The power transmission network is an important element of the power system which is responsible for causing instability, sudden voltage collapse during transient conditions. In recent years, technologically developments in Flexible AC Transmission Systems or FACTS devices [1] provided better performance in enhancing power system. The FACTS envisage the use of a solid state power converter technology to achieve fast & reliable control of power flow in transmission line. The greatest advantage of using a FACTS device in a power transmission network is to enhance the transient stability performance by controlling the real & reactive power flow during fault conditions. The FACTS devices are classified into two categories; the shunt type comprises of SVC [21]&STATCOM while the series comprises of TCSC & TCPST. UPFC is the most versatile belong to FACTS family which combines both shunt & series features. It is capable of instantaneous control of transmission line parameters [5].The UPFC can provide simultaneous control of all or selectively basic parameters of power system [6, 7, 20] (transmission voltage, line impedance and phase angle) and dynamic compensation of AC power system. In this paper UPFC is used to inject thevariable voltage in series with the line, whose magnitude can varies from 0 to Maximumvalue (depends on rating) and phase angle can differ from 0 to 2π which modulates the line reactance to control power flow in transmission line. By regulating the power flow in a transmission line, the speed of oscillations of the generator can be damped effectively.

II. UPFC DESCRIPTION

The UPFC constitute of two voltage source converters linked with common DC link. One of the converters is connected in series (known as series converter or SSSC) with the line via injection transformer and provides the series voltage and other converter (called shunt converter or STATCOM) is connected in parallel via shunt transformer to inject the shunt current and also supply or absorb the real power demand by series converter at common dc link. The reactive power exchanged at the ac terminal of series transformer is generated internally by voltage source converter connected in series. The voltage source converter connected in shunt can also generate or absorb controllable reactive power, thus providing shunt compensation for the line independent of the reactive power exchange by the converter connected in series. The UPFC, thus, can be summarize as an ideal ac to ac power converter in which real power can flow freely in either direction between the ac terminal of the two converters and reactive power can be generated or absorbed by the two converters independently at their own ac terminals. Figure 1 shows the equivalent circuit of the UPFC in which the UPFC can be represented as a two port device with controllable voltage source V_{se} in series with line and controllable shunt current source I_{sh}. The voltage across the dc capacitor is maintained constant because the UPFC as a whole does not generate or absorb any real power. In this paper, the UPFC is used to damp the power oscillations and thus improves the transient stability of both SMIB and multi-machine power system.UPFC parameters have been optimized using Bacterial Foraging in paper [16]. Particle Swarm Optimization technique, another heuristic technique based on bird and fish flock movement behavior is implemented for optimizing the parameters of UPFC efficiently and effectively in real time.

In this paper, section II describes about the UPFC. Section III explains the brief description of the SMIB test systemtaken whereas section IV explains the mathematical modeling of the SMIB system equipped with UPFC Controller. Section V briefly describes the multi-machine power system under study. Section VI illustrates the modeling ofmulti-machine power system. Modeling of unified power flow controller for load flow is illustrated in Section VII. Section VIII illustrates the simulation results ofboth SMIB system and multi-machine system without and with UPFC controller based on PSO and section IX concludes and expresses the future scope of work.

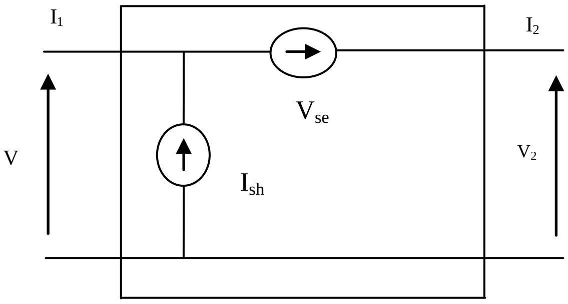


Fig. 1.Equivalent Circuit of UPFC

III. SMIB SYSTEM UNDER STUDY

For analysis of the UPFC for damping the power swings, parameters of the system like generator rotor angle, theta, terminal voltage, active power and reactive power are considered. A 200MVA, 13.8KV, 50Hz generator supplying power to an infinite bus through two transmission circuits as shown in fig(2) is considered. The network reactance shown in fig. is in p.u. at 100 MVA base. Resistances are assumed to be negligible. The system is analyzed with different initial operating condition, with quantities expressed in p.u. on 100MVA, 13.8 KV base. P=0.4p.u, 0.8p.u, 1.2p.u and 1.4p.u are different operating conditions considered. The other generator parameters in p.u. are given in appendix. The three phase fault at infinite bus bar is created for 100msec duration & simulation is carried out for 10sec. to examine the transient stability of the study system.

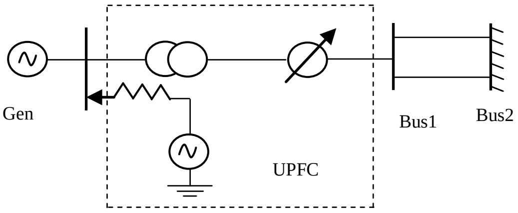


Fig 2.

IV. MATHEMATICAL MODELING

a. Synchronous Machine Model

Mathematical models of synchronous machine vary from elementary classical model to more detailed one. Here, the synchronous generator is represented by third order machine model [2,4]. Different equations for stator, rotor, excitation system etc. are as follows:

Stator:

$$V_q = E_q^{'} - r_s i_q - x_d^{'} i_d$$

$$V_d = E_d^{'} - r_s i_d - x_q^{'} i_q$$

$$V_1 = v_d + jv_q \qquad I = i_d + ji_q$$

$$S = V_1 I^*$$

$$P = v_d i_d + v_q i_q$$

$$Q = v_q i_d - v_d i_q$$

Where,

$$\omega = \omega_o + \frac{d\delta}{dt}$$

$$\frac{\delta\omega}{dt} = \frac{P_m - P_e}{M}$$

Let D and K=0

r_s is rotor winding resistance

$x_d^{'}$ is d-axis transient reactance

$x_q^{'}$ is q-axis transient reactance

$E_d^{'}$ is d-axis transient voltage

$E_q^{'}$ is q-axis transient voltage

Rotor:

$$T_{do}^{'} \frac{dE_q^{'}}{dt} + E_q^{'} = E_f - \left(x_d - x_d^{'}\right) i_d$$

$$\frac{dE_q^{'}}{dt} = \frac{E_f - E_q^{'} - \left(x_d - x_d^{'}\right) i_d}{T_{do}^{'}}$$

Where, $T_{do}^{'}$ is d-axis open-circuit transient time constant $T_{qo}^{'}$ is q-axis open-circuit transient time constant E_f is field voltage

Torque Equation

$$T_e = E_q^{'} i_q + E_d^{'} i_d + \left(x_q^{'} - x_d^{'}\right) i_d i_q$$

Excitation System

$$\frac{d(\Delta E_{fd})}{dt} = \frac{K_e(V_{ref} - V_t)}{T_e} - \frac{\Delta E_{fd}}{T_e}$$

Where $-0.6 \leq E_{fd} \leq 0.6$

b. UPFC Controller Structure in PQ Mode

P-Q demand on load side is met by controlling series voltage injection. In order to achieve the system stability, it is required to control the in phase & quadrature component of the series injected voltage after fault near infinite bus-bar.

1. Series Converter

Let the voltage injected by the series converter is V_L. In d-q frame of reference, V_L can be written as

$$V_{Ld} = V_L \sin(\theta - \varphi), \qquad V_{Lq} = V_L \cos(\theta - \varphi)$$

$$V_L = \sqrt{(V_{Ld})^2 + (V_{Lq})^2}$$

Where, $\theta = \tan^{-1} \frac{v_d}{v_q}$

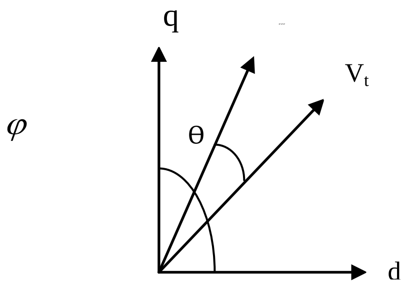


Fig. 3.d-q representation of series converter

In phase and quadrature components of V_L are responsible forreactive and active power flow in line.

$$V_{Lp} = V_{Lpo} + \Delta V_p$$
$$V_{Lq} = V_{Lqo} + \Delta V_q$$
$$V_{bd} = V_{Ld} + (X_d^{'} + X_1) i_q - X_1 i_{sq}$$
$$V_{bq} = V_{Lq} + e_q^{'} - (X_d^{'} + X_1) i_d - X_1 i_{sd}$$
$$V_b = \sqrt{V_{bd}^2 + V_{bq}^2} \tag{6}$$
$$P_{ref} = (V_d + V_{Ld})(i_d - i_{sd}) + (V_q + V_{Lq})(i_q - i_{sq})$$
$$Q_{ref} = (V_q + V_{Lq})(i_d - i_{sd}) - (V_d + V_{Ld})(i_q - i_{sq})$$

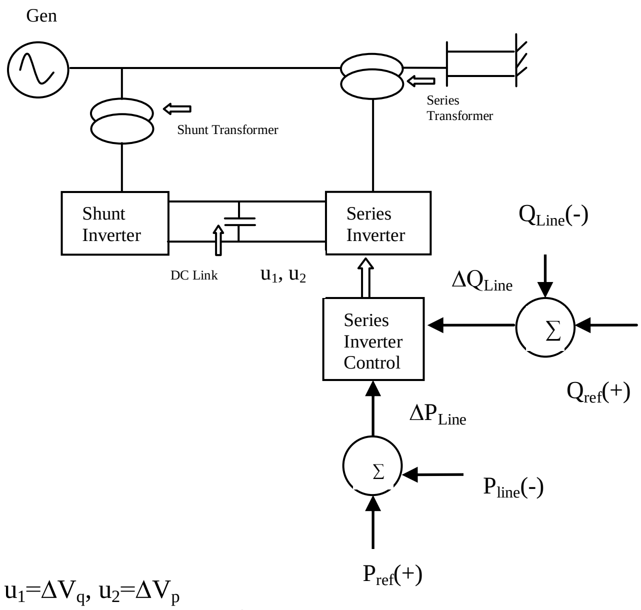
Where,

$$V_{Lpo} = V_{Ld} \sin\left(\tan^{-1} \frac{i_d - i_{sd}}{i_q - i_{sq}} \right) + V_{Lq} \cos\left(\tan^{-1} \frac{i_d - i_{sd}}{i_q - i_{sq}} \right)$$

$$V_{Lqo} = V_{Lq} \sin\left(\tan^{-1} \frac{i_d - i_{sd}}{i_q - i_{sq}} \right) + V_{Ld} \cos\left(\tan^{-1} \frac{i_d - i_{sd}}{i_q - i_{sq}} \right)$$

$$\Delta V_q = k_{p1} \Delta P + k_{i1} \int_0^T \Delta P \qquad \Delta V_p = k_{p2} \Delta Q + k_{i2} \int_0^T \Delta Q$$

$$\Delta P = P_{ref} - P \qquad \Delta Q = Q_{ref} - Q$$



$u_1 = \Delta V_q$, $u_2 = \Delta V_p$

Fig.4 PI controller of the study system in PQ Mode

2. Shunt Converter

Let i_{sh} be the current injected by shunt voltage source converter which is in same phase as that of generator terminal voltage, hence it will not supply or absorb reactive power & its aim is to provide the real power demand of series power voltage source converter.

Let lossless UPFC device is considered, then

$$R\left(\overline{V_1} \overline{I_1^*} - \overline{V_2} \overline{I_2^*}\right) = 0$$

And with losses, to maintain the voltage across the capacitor, shunt power should be equal to sum of series power and capacitor power.

$$V_t i_{sh} = V_{Ld}(i_d - i_{sd}) + V_{Lq}(i_q - i_{sq}) + V_{dc} C \frac{dV_{dc}}{dt}$$

From the above equation, i_{sh} can be obtained.

Where,

$$i_{shd} = i_{sh} \sin\theta, \qquad i_{shq} = i_{sh} \cos\theta$$

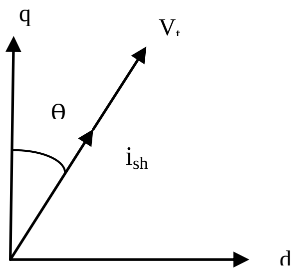


Fig.5. d-q representation of shunt converter

c. Transmission Line currents

The transmission line current i_t is split into d-q components represented as i_{td} hand i_{tq}.

$$i_{td} = i_d - i_{shd}, \qquad i_{tq} = i_q - i_{shq}$$

d. Capacitor Dynamics

The difference between the shunt power and series power is the capacitor power.

Mathematically,

Capacitor power=Shunt power– Series power

$$\left(C\frac{dV_{dc}}{dt}\right)V_{dc} = P_{sh} - P_{se}$$

$$P_{sh} = V_t i_{sh}$$

$$P_{se} = V_{Ld} i_{td} + V_{Lq} i_{tq}$$

$$\left(C\frac{dV_{dc}}{dt}\right)V_{dc} = V_t i_{sh} - \left(V_{Lp} i_{td} + V_{Lq} t_{tq}\right)$$

i_{sh} then can be computed from the above equation

V. DESCRIPTION OF MULTI-MACHINE SYSTEM

A multi-machine power system (8 bus system) with twoUPFC's connected are considered as shown in fig 2. Three generators are connected at buses 1, 2 and 3.Generator 1 is hydro & G2 & G3 are Thermalgenerators.The parameters of all the generators are given in appendix. Bus number 1 is taken as slack bus. The transmission line parameters are also given in appendix.UPFC1 is connected between bus number 4 and 5, while UPFC2 is connected between bus number 7 and 8. Loads are connected at bus number 1, 2 and 3. They are represented in terms of admittances Y_{L1}, Y_{L2}, Y_{L3} and Y_{L4}& are computed from load bus data. Using power Injection model[19] of UPFC1 and UPFC2, they are represented by equivalent admittances and the admittance matrix of the power network is then modified. Simple AVR are connected to each generator. The operating conditions taken are: p1=4.5, q1=1.5, p2=1.3, q2=0.6,p3= 1.0,q3=0.5. Fault is created at the Centre of line3-4at 0.5 sec & cleared at 0.6 sec which results in power deviation in the transmission line. The real power deviation in the transmission line generates the component V_{SEQ} of series voltage injection in quadrature with line current and the reactive power deviation in line generates the in phase component V_{SEP}. kp and ki relates these components to power deviations. These PI controller parameters are then tuned by PSO technique to damp the inter area and local area oscillations effectively.

VI. MATHEMATICAL MODELING

A. *Synchronous Machine Model*

Mathematical models of synchronous machine vary from elementary classical model to more detailed one.

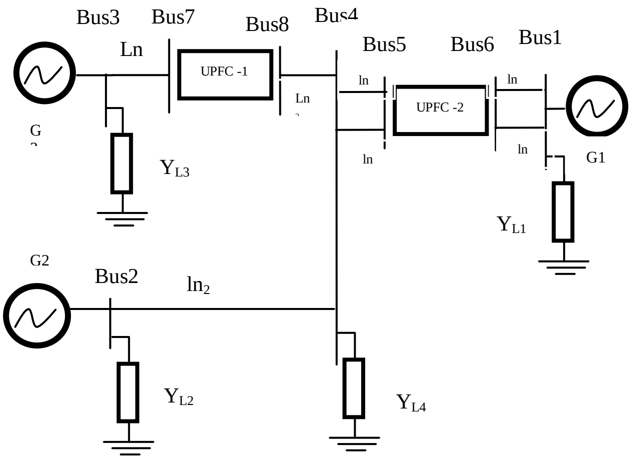


Fig. 6

Here, the synchronous generator is represented by third order machine model. The differential equations governing the dynamics of each machine (1,2 and3) are same as for SMIB system modeling given above.

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B. *Power Injection Model of UPFC*

Two voltage source model of UPFC shown in fig. (1) is converted into two power injections in rectangular form for power flow studies [3, 27]. The advantage is that it maintains the symmetric characteristics of the admittance matrix.

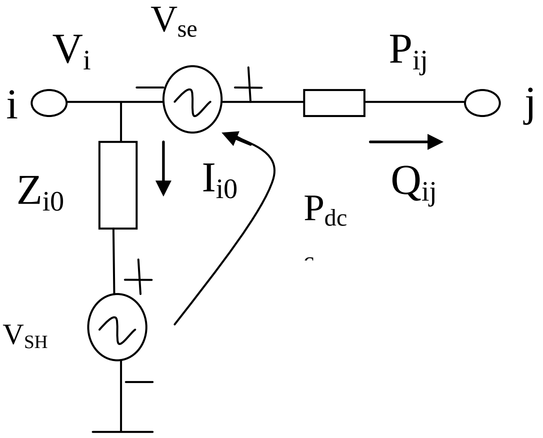


Fig. 7

1. *Shunt Converter:*

Let the current injected by the shunt converter is I_{i0} & voltage source is V_{SH} Shown in fig.(7). The shunt side of UPFC is converted into power injection at bus bar i only.

$$S_{i0} = P_{io} + jQ_{io} = V_i\left(\frac{V_i - V_{SH}}{Z_{io}}\right)^*$$

Where $Z_{io} = R_{io} + jX_{io}$

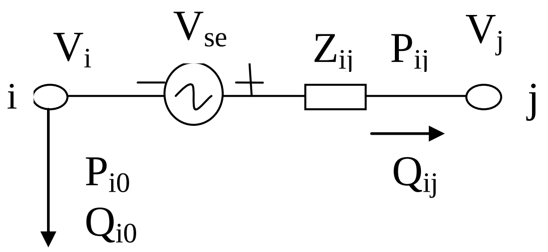


Fig.8

Since the shunt reactive compensation capability of UPFC is not utilized that is the UPFC shunt converter is assumed to be operating at unity power factor [20].Its main function is to transfer the real power demand of series converter through the dc link, so

$P_{io} = V_i I_{SH}$ and $Q_{io} = 0$

1. *Series Converter:*

Let the ideal voltage injected by the series converter is V_{se} and reactance X_{ij} be present between two buses (i,j) in the power system shown below[26]. The series side of UPFC is then converted into two power injections at buses i& j.

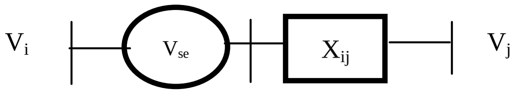


Fig. 9

The Norton equivalent of the above circuit is shown as:

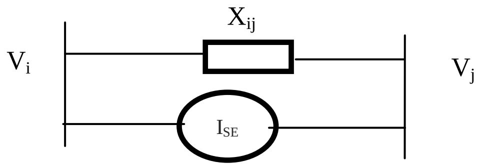


Fig.10

$I_{SE} = \frac{-V_{SE}}{Z_{ij}}$ in parallel with the line

Where,

$Z_{ij} = 0 + jX_{ij}$, $B_{ij} = 1/X_{ij}$

$$S_i = P_i + jQ_i = V_i\left(\frac{-V_{SE}}{X_{ij}}\right)^* = V_i\left(-V_{SE}B_{ij}\right)$$

Since $V_{SE} = \rho V_i e^{j\beta}$ and

$$\beta = \tan^{-1}\left(\frac{V_{SEQ}}{V_{SEP}}\right) + \tan^{-1}\left(\frac{I_{ijd}}{I_{ijq}}\right) - \tan^{-1}\left(\frac{V_{id}}{V_{iq}}\right)$$

$$S_i = V_i\left(jB_{ij}\rho \mathrm{V_i}\, \mathrm{e}^{j\beta}\right)^* = -B_{ij}\rho|V_i|^2\sin(\beta) - jB_{ij}\rho|V_S|^2\cos(\beta)$$

$P_i(inj) = -B_{ij}\rho|V_i|^2\sin(\beta)$ and $Q_i(inj) = -B_{ij}\rho|V_i|^2\cos(\beta)$

Similarly,

$$S_j = V_j\left(I_{SE}\right)^* = V_j\left(V_{SE}B_{ij}\right)^*$$

$$S_j = V_j\left(-jB_{ij}\rho \mathrm{V_i}\, \mathrm{e}^{j\beta}\right)^* = B_{ij}\rho|V_i||V_j|\sin(\theta_{ij}+\beta) + jB_{ij}\rho|V_i||V_j|\cos(\theta_{ij}+\beta)$$

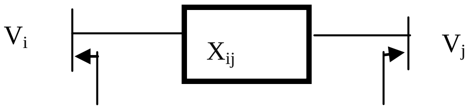
$$P_j(inj) = B_{ij}\rho|V_i||V_j|\sin(\theta_{ij}+\beta)$$

$$Q_j(inj) = B_{ij}\rho|V_i||V_j|\cos(\theta_{ij}+\beta)$$

Where

$$\theta_{ij} = \theta_i - \theta_j$$

Based on the explanation above, the injection model of a series connected voltage source can be represented by two independent loads [3] as shown in fig (27).



$P_i = -B_{ij}\rho|V_i|^2\sin(\beta)$ $P_j = B_{ij}\rho|V_i||V_j|\sin(\theta_{ij}+\beta)$

$Q_i = -B_{ij}\rho|V_i|^2\cos(\beta)$ $Q_j = B_{ij}\rho|V_i||V_j|\cos(\theta_{ij}+\beta)$

Fig. 11

Further the real power associated with converter-1 can be written as

$P_{io} = |V_i| I_{SH}$

Where I_{SH} is in phase current with the bus voltage V_i

P_{dc} is the power transfer from shunt side to series side.

$$P_{dc} = \mathrm{Re}\left[V_{SE}\left(\frac{V_i + V_{SE} - V_j}{X_{ij}}\right)\right]^* = \mathrm{Re}\left[\rho V_i e^{j\beta}\left(\frac{V_i + V_{se} - V_j}{X_{ij}}\right)\right]^*$$

On solving,

$$P_{dc} = B_{ij}\rho|V_i||V_j|\sin(\theta_{ij}+\beta) - B_{ij}\rho|V_i|^2\sin(\beta)$$

When power loss inside the UPFC is neglected, than P_{io}=$P_{dc}$and modified injection model is formulated as shown in fig.(11)

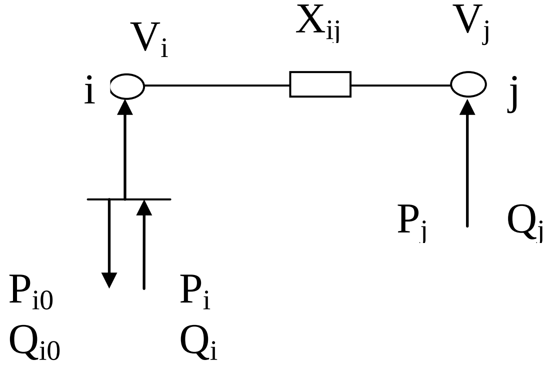
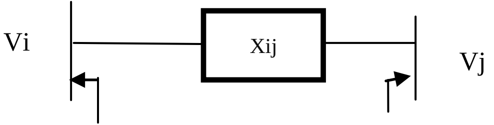


Fig.12

$$S_i(inj) = S_i - S_{io} = P_i - P_{io} + jQ_i$$
$$S_j(inj) = S_j = P_j + jQ_j$$



$$P_i = -B_{ij}\rho|V_i|^2\sin(\beta) - |V_i|I_{SH} \qquad P_j = B_{ij}\rho|V_i||V_j|\sin(\theta_{ij}+\beta)$$
$$Q_i = -B_{ij}\rho|V_i|^2\cos(\beta) \qquad Q_j = B_{ij}\rho|V_i||V_j|\cos(\theta_{ij}+\beta)$$

Fig. 13

I_{ijd} and I_{ijq} are d-q axis transmission line currents. V_{id} and V_{iq} are d-q axis voltage of ith bus of UPFC.

The component in phase and quadrature component of $V_{se}$is responsible for real and reactive power flow in line & hence finally mitigate the power oscillations.

$$\Delta P_1 = P_{ref1} - P_1, \qquad \Delta Q_1 = Q_{ref1} - Q_1$$
$$\Delta P_2 = P_{ref2} - P_2, \qquad \Delta Q_2 = Q_{ref2} - Q_2$$

For Machine 1,

$$V_{SEP1} = kp1\Delta Q_1 + ki1\int \Delta Q_1, \; V_{SEQ1} = kp2\Delta P_1 + ki2\int \Delta P_1$$

For Machine 2,

$$V_{SEP2} = kpp1\Delta Q_2 + kii1\int \Delta Q_2,$$
$$V_{SEQ2} = kpp2\Delta P_2 + kii2\int \Delta P_2$$

2. *Dynamics of Capacitor*

The dynamics of the D.C voltage neglecting losses can be represented by

$$CV_{dc}\frac{dV_{dc}}{dt} = [P_{io} - P_{dc}]$$

By putting the values of P_{io} and P_{dc}, in above equation,the dynamics of the D.C link is represented as:

$$\frac{dV_{dc}}{dt} = \frac{1}{C\,V_{dc}}\left[|V_i|I_{SH} - B_{ij}\rho|V_i||V_j|\sin(\theta_{ij}+\beta) + B_{ij}\rho|V_i|^2\sin(\beta)\right]$$

Above equation will be written for both UPFC's.

VII. PROCEDURE FOR MULTI-MACHINE POWER SYSTEM SIMULATION

The digital simulation reads the initial nodes specifications and generates the steady state load flow solution assuming the reference bus voltage in p.u as $1\angle 0^0$, corresponding to a common reference frame rotating at synchronous speed thus representing Q axis. The common reference frame & the reference frame of the ith machine are related by the transformation [4].

$$\begin{bmatrix} V_{Di} \\ V_{Qi} \end{bmatrix} = \begin{bmatrix} \cos(\delta_i) - \sin(\delta_i) \\ \sin(\delta_i)\cos(\delta_i) \end{bmatrix} \begin{bmatrix} V_{di} \\ V_{qi} \end{bmatrix}$$
$$\begin{bmatrix} I_{Di} \\ I_{Qi} \end{bmatrix} = \begin{bmatrix} \cos(\delta_i) - \sin(\delta_i) \\ \sin(\delta_i)\cos(\delta_i) \end{bmatrix} \begin{bmatrix} I_{di} \\ I_{qi} \end{bmatrix}$$

Where δ_i is the angle between the machine reference axes (d_i, q_i) and the common reference axes (D,Q) as shown:

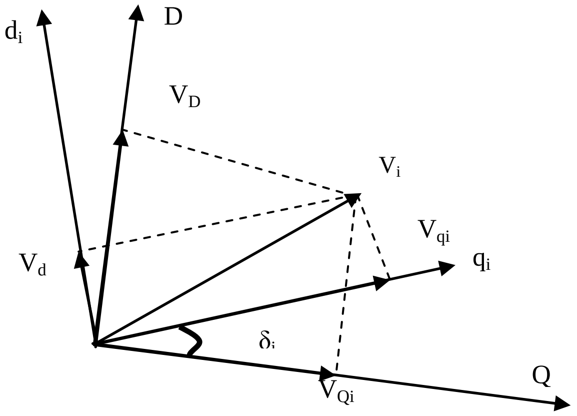


Fig. 14

Further the voltage behind the transient reactance ($E_q^{'}$), transient reactance ($x_{di}^{'}$), quadrature axis reactance (x_{qi}) of the ith machine are related to its terminal voltage components in the common reference frame as

$$\begin{bmatrix} 0 \\ E_{qi}^{'} \end{bmatrix} = \begin{bmatrix} 0 & x_{qi} \\ -x_{di}^{'} & 0 \end{bmatrix} \begin{bmatrix} \cos(\delta_i) & \sin(\delta_i) \\ -\sin(\delta_i) & \cos(\delta_i) \end{bmatrix} \begin{bmatrix} I_{Di} \\ I_{Qi} \end{bmatrix} = \begin{bmatrix} \cos(\delta_i) & \sin(\delta_i) \\ -\sin(\delta_i) & \cos(\delta_i) \end{bmatrix} \begin{bmatrix} V_{Di} \\ V_{Qi} \end{bmatrix}$$

Hence machine angle δ_i can be computed as

$$\tan(\delta_i) = \frac{x_{qi}I_{Qi} - V_{Di}}{x_{qi}I_{Di} = V_{Qi}}$$

This voltage is then utilized in the 3rd order machine model and the differential equations are solved. Using this machine angle, the voltage behind the transient reactance of machine are solved. Moreover for an 'n' number of machines & 'm' number of load buses in a power network, the algebraic equations are written in compact form:

$$E_m + x_m T_{mn}^{-1} I = T_{mn}^{-1} V$$
$$I = Y_m V$$
$$E_m + x_m T_{mn}^{-1} Y_m V = T_{mn}^{-1} V$$

Hence the generator terminal voltage components in the common reference frame and the machine internal voltages are related by

$$V = \left[U - T_{mn} x_m T_{mn}^{-1} Y_m\right]^{-1} T_{mn} E_m$$

Where U is the unity matrix.

Both UPFC's are represented by an equivalent admittances derived from their power injection models :

$$Y_{Li} = \frac{P_i - jQ_j}{V_i^2}$$

$$Y_{Lj} = \frac{P_j - jQ_j}{V_j^2}$$

Where

$$P_i = B_{ij}\rho|V_i|^2 \sin(\beta) + |V_i|\, I_{SH} \qquad P_j = B_{ij}\rho|V_i||V_j|\sin(\theta_{ij} + \beta)$$

$$Q_i = B_{ij}\rho|V_i|^2 \cos(\beta) \qquad Q_j = -B_{ij}\rho|V_i||V_j|\cos(\theta_{ij} + \beta)$$

When fault is created in any line, the admittance matrix is then modified according to position of fault& taking into account of UPFC admittances. All system equations are converted into common frame of reference which is rotating at synchronous speed.

VIII. PARTICLE SWARM OPTIMIZATION BASICS

PSO was introduced by Eberhart and kennedy in1995 [22]. It is a heuristic & stochastic based optimization technique. PSO can be used on optimization problem that are partially irregular, noisy, change over time, etc. It is developed from swarm intelligence and is based on the research of bird and fish flock movement behavior .The particle swarm optimization consists of swarm of particles which are initialized with a population of random candidate solution in the multidimensional search space. During their flying movement they follow the trajectory according to their own best flying experience (pbest) & best flying experience of the group (gbest). During this process, each particle modify its position & velocity according to shared information to follow the best trajectory leads to optimum solution & this technique is simple & very few parameters need to be determined. The choice of PSO parameters can have a large impact on optimization performance. Selecting PSO parameters that yield good performance has therefore been the subject of much research.

A. Algorithm

```
Step 1: Initialize the number of particles,minimum and maximum limits for the d-dimension search space $m_{\max}$, $m_{\min}$ andi$_{tmax}$.
Step2: Set initial position of particles $x_i^k$
Where,
$x_i^k = m_{\min} + (m_{\max} - m_{\min}) * rand(\ )$
Step 3: Set initial velocity $v_i$ of particles
$v_{id}^k = v_{\min} + (v_{\max} - v_{\min}) * rand(\ )$
Where,
$v_{\max} = 0.1 * (m_{\max} - m_{\min})$
$v_{\min} = -0.1 * (m_{\max} - m_{\min})$
Step 4: Select initial $p_{ibest}^k$, $g_{best}^k$
Step5: calculate cost function f ($x_i$) taking initial position into consideration.
Step 6:    If
    f ($x_i$) >  f($p_{ibest}^k$)
    Then
        Update the value of $x_i^k$ by $p_{ibest}^k$
    Else
        retain the $p_{ibest}^k$ as $p_{ibest}^k$
    end if;
Step 7:    If
    f($p_{ibest}^k$) > f($g_{best}^k$)
    Then
        Update value of $p_{ibest}^k \rightarrow g_{best}^k$
    Else
    go to step 8.
step 8:  If
    maximum number of iterations has been done
    then
        store$g_{best}^k$ as best position value.
    Else
    Increase order of iteration by one.
    Update particle velocity &position:
$v_i^{k+1} = v_i^k + c1 * rand1\left(pbest_i^k - x_i^k\right) + c2 * rand2\left(gbest^k - x_{id}^k\right)$
$x_i^{k+1} = x_i^k + v_i^{k+1}$
```

Where, $c1$ and $c2$ represents the acceleration factors, $rand1$ and $rand2$ represents distributed random numbers between (0,1).First part of equation (1) depicts the previous velocity of the particle, the second part is a positive cognitive component & third part is a positive social component as described in [23].

```
Repeat Step 4 to step 7
Else if,
End.
```

IX. FORMULATION OF AN OBJECTIVE FUNCTION

Objective function formulated is based on the optimization parameters.

It is worth mentioning that the PIparameters of UPFC are tuned using PSO to minimize the power system oscillations after a disturbance so as to improve the transient stability. These oscillations are reflected in the deviations in the generator rotor speed Δw_1,Δw_2 andΔw_3 in the present study. The objective function J for SMIB system is formulated as the minimization of

$$J = \int_0^t \left[t(\Delta\omega\,(t,x))^2\right]dt$$

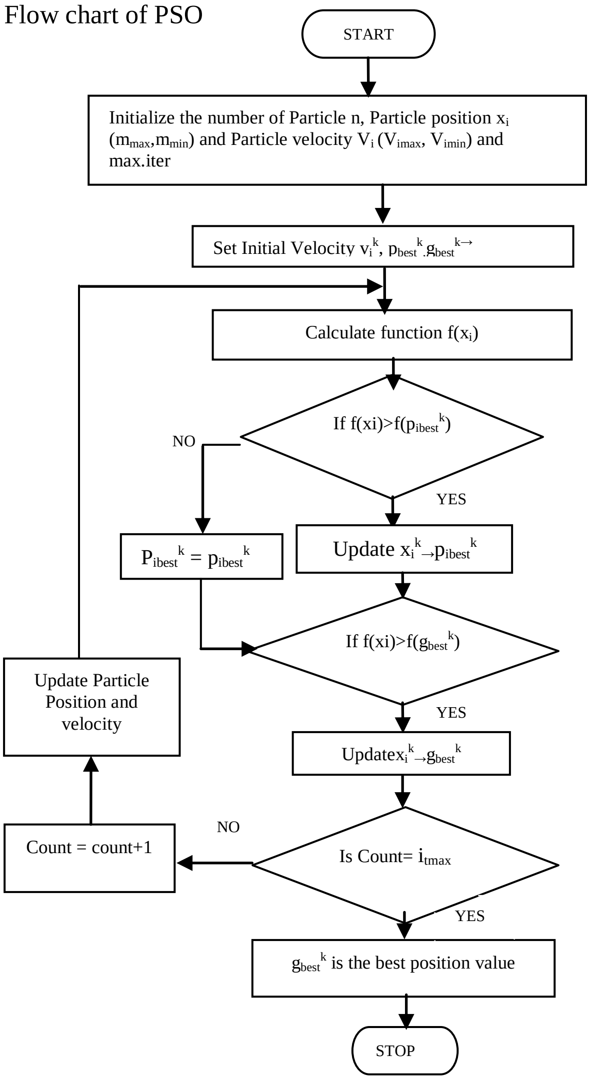
where $\Delta\omega\,(t,x)$ denotes the rotor speed deviation.

And for multi-machine system,

$$J = \int_0^t \left[t(\Delta\omega_1(t,x))^2 + (\Delta\omega_2(t,x))^2 + (\Delta\omega_3(t,x))^2\right]dt$$

In the above equations, Δw_1 (t,x), Δw_2 (t,x) and Δw_3 (t,x) denotes the rotor speed deviations of generator 1,2& 3 for a set of controller parameters x and (note that, here x represents the parameters to be optimized i.ek_p&k_i, the parameters of PI controller) and t is the time range of the simulation. For objective function calculation, the time-domain simulation of the power system model is carried out for the simulation period. It is aimed to minimize this objective function in order to improve the system response in terms of the settling time and overshoots.

Flow chart of PSO



X. Simulation

The SMIB system with UPFC is simulated using PSO technique in MATLABenvironment. The number of parameters to be optimized are four (k_{p1}, k_{p2} , k_{i1}& k_{i2}). The analysis is carried out with 3 phase fault at Infinite bus for 0.1 sec& system is run for 10 sec. The result have been shown with controller parameters tuned by PSO (each particle is assigned with a set of 4 variables to be optimized and assigned with random value within the universe of disclosure).

The following are the simulation results of the system without controller and with PSO based UPFC controller for different operating conditions.

Case 1: P=0.4p.u, Q=0.6p.u

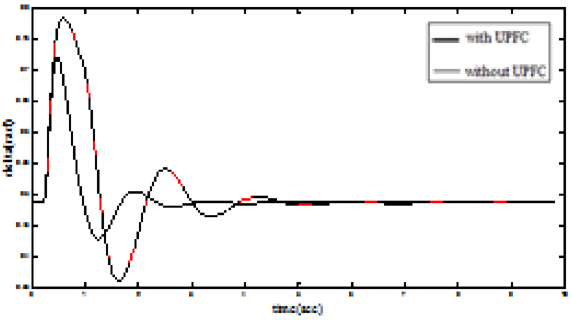


Fig.15 (i)

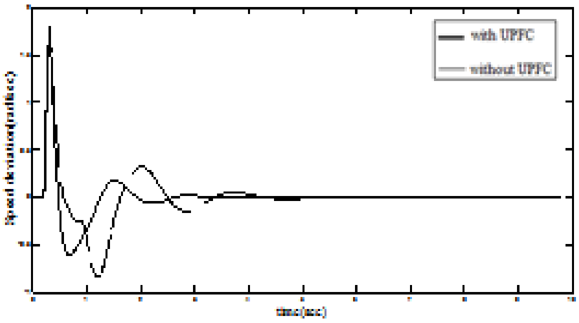


Fig. 15 (ii)

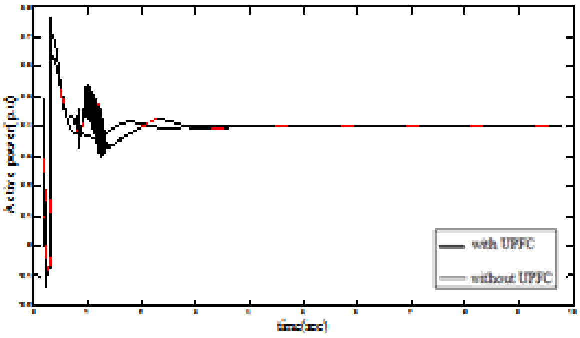


Fig. 15 (iii)

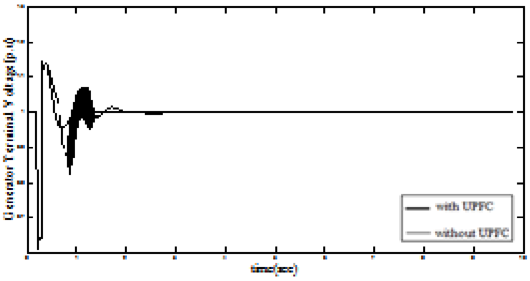


Fig. 15 (iv)

Case 2: P=1.2p.u, Q=0.6p.u

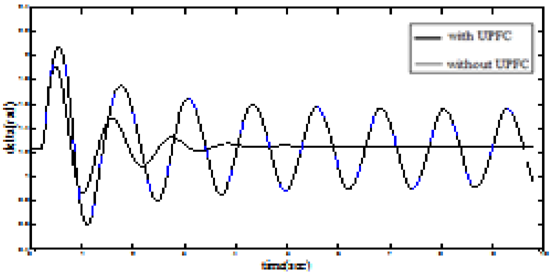


Fig.16(i)

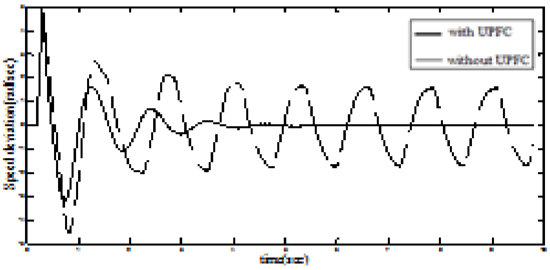


Fig. 16(ii)

Case 3: P=1.4p.u, Q=0.6p.u, PSO based UPFC controller provides the power system stability as shown in fig.18 while without UPFC, system becomes unstable as shown in fig.17

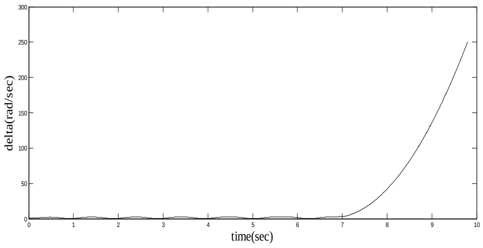


Fig.17

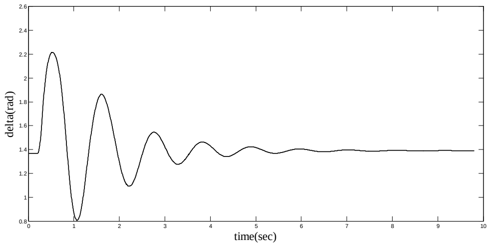


Fig.18 (i)

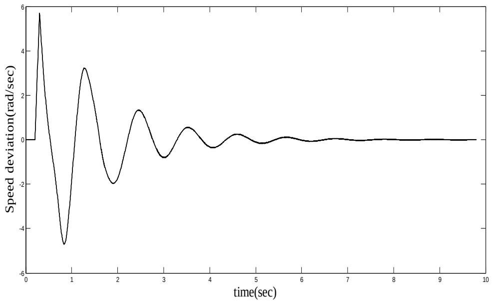


Fig. 18(ii)

In case of multi-machine power system simulation, bus 1 is taken as a slack bus.A fault is created at the centre of the transmission line connecting bus numbers 3 and 7 & simulation is carried out without and with PSO based UPFC Controller foroperating conditions P_1=4.5p.u, Q_1=1.5p.u, P_2=1.3p.u, Q_2=0.6p.u, P_3=1.0p.u, Q_3=0.5p.u. Both inter area & local mode of oscillations are shown below.

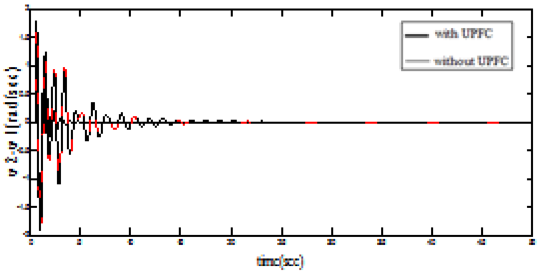


Fig. 19(i)

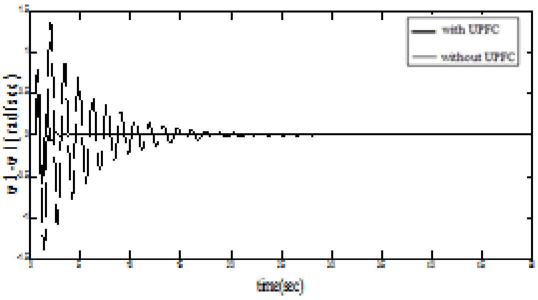


Fig. 19 (ii)

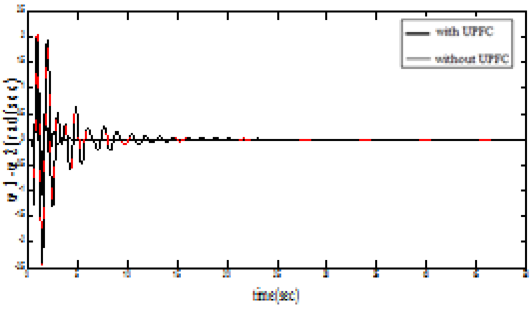


Fig. 19 (iii)

z

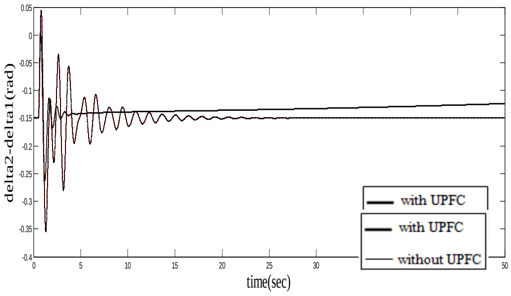


Fig. 19 (iv)

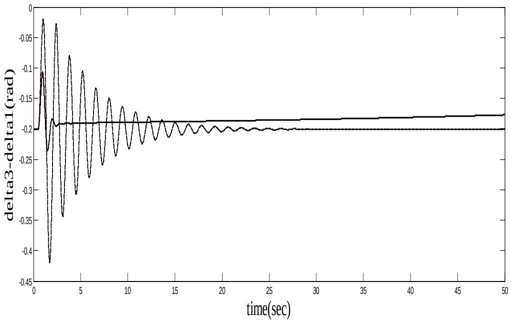


Fig. 19 (v)

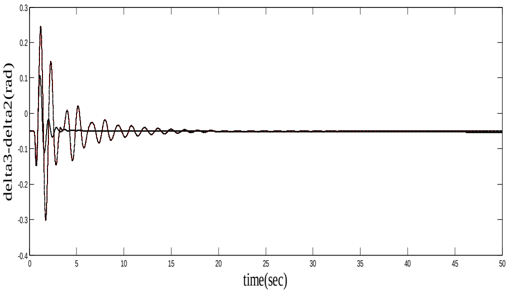


Fig. 19 (vi)

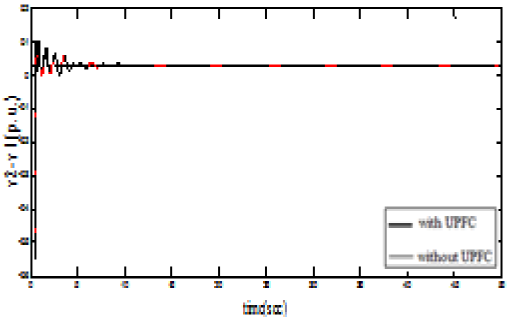


Fig. 19 (vii)

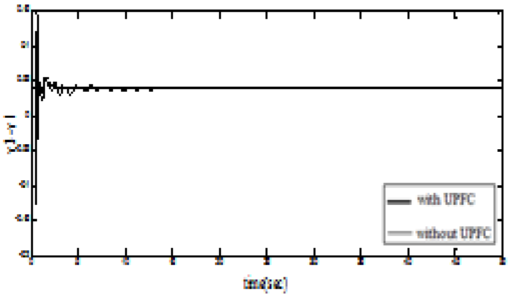


Fig.19 (viii)

with UPFC
without UPFC

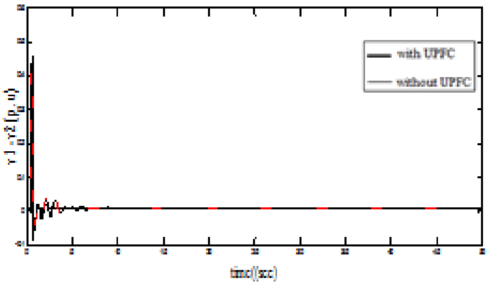


Fig. 19 (ix)

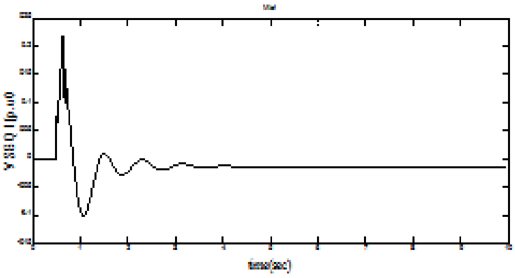


Fig.19 (x)

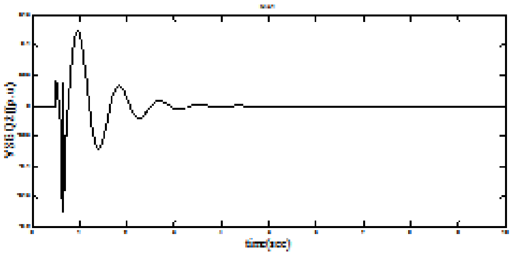
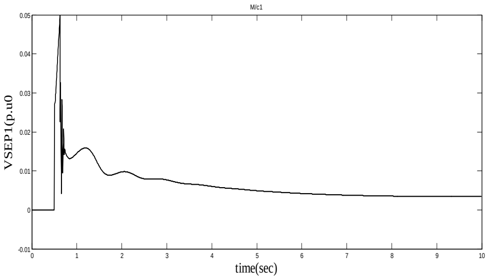
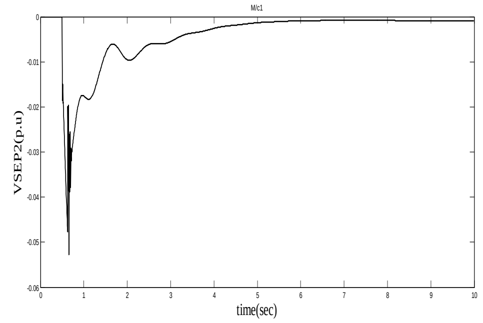


Fig.19 (xi)





XI. CONCLUSION

The UPFC controller parameters (kp1, ki1, kp2, ki2) of UPFC Controller in an SMIB system and (kp1, kp2, kpp1, kpp2 ki1, ki2, kii1, kii2) in multi-machine system are tuned effectively for transient stability enhancement. The response curve shows that the speed deviation, machine angle, generator terminal voltage, active power and reactive power are settled down quickly after the disturbance in an SMIB system and angular speed deviation, rotor angle, & voltage oscillations for inter area (m/c 2 vs. m/c 1 and m/c 3 vs. m/c1) and local area (m/c 3 vs. m/c 2) are damped out effectively during fault in line 3-7 in multi-machine power system. This paper has a vital scope for future studies. Artificial Intelligence Methods like genetic algorithm, Fuzzy Logic technique, ant colony optimization technique and Hybrid BFO-Particle Swarm optimization technique can be used to tune the UPFC controller parameters for better transient stability enhancement. Moreover additional auxiliary signals can be added as a supplementary signals for better transient stability enhancement.

APPENDIX

Generator Data(All reactance are on 100 MVA base) for SMIB system:

Generator Data

$x_d' = 0.17\text{p.}u,\ x_q' = 0.3\text{p.u},\ x_{do}' = 0.15\text{ p.u},$

$x_d = 1.9$ p.u, $x_q = 1.6$,T_{do}' = 6.314 p.u, H= 5s

Exciter data:

K_E=50, T_E= 0.1s

Generator Data (All reactance are on 100 MVA base) for Multi-machine system:

Generator 1

x_{d1} = 0.1468p.u , x_{d1}' = 0.0608p.u , x_{q1}= 0.0969p.u ,x_q'=0.0969,T_{do1}' = 8.96, H_1=5

Generator 2

x_{d1} = 0.8958p.u , x_{d1}' = 0.1198p.u , x_{q1}= 0.8645p.u,x_q'=0.1969, T_{do1}' = 0.1969, H_2=4

Generator 3

x_{d1} =1.3125p.u, x_{d1}' = 0.1813p.u, xq1=1.2578 p.u,x_q'=0.25, T_{do1}' = 0.25, H_3=4

Exciter Data:

K_{E1}= 25,T_{E1}= 0.05sec,K_{E2}=25, T_{E2}=0.02sec, K_{E3}=25, T_{E3}= 0.06sec

Transmission line Data:

z24=j0.068, z37=j0.068, z84=jz37, z78=0.1*z37, z45=j0.07, z56=0.1*z45, z61=j0.07

Equivalent Load Reactance:

Y_{L5}=0, Y_{L6}=0, Y_{L7}=0, Y_{L8}=0, Y_{L1}=6.261-j1.044, Y_{L2}=0.0877-j0.029, Y_{L3}=0.0877-j0.0292, Y_{L4}=0.9690-j0.3391

UPFC Data:

C = 3500 µF, B_{SE}=142.85siemens, $V_{\text{dc base}}$=31.5 kV

PSO based Controller Data for SMIB system:

kp1=0.3145, ki1=2.7387, kp2=0.5297, ki2=1.9115

PSO based Controller Data for Multi-machine system:

kp1 = 0.045, ki1 =0.3245, kpp1 =0.0511, kii1 =0.2211 kp2=0.015,ki2=0.1021, kpp2=0.0115, kii2=0.3101

PSO Parameters:

c1=0.2,c2=0.4, Number of Particles=30,w_{max}=0.5, w_{min}=-0.5

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