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Stability Enhancement of Multi Machine system using a Unified Power Flow Controller

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ABSTRACT:A Unified Power Flow Controller (UPFC) in Multi machine system is proposed. The UPFC model is having a voltage source. The magnitude and angle of this voltage source depends on the UPFC control parameters. For the analysis of Eigen value, power system with linearized model was developed. Poorly damped electromechanical mode is controlled by stabilizing signal. The superior stabilizing signal is selected by approach based singular value decomposition. The UPFC with voltage source model incorporated into the generator output power equation simplifies the dynamic analysis of the system and this incorporation into the generators output power equation can be easily done. This proposed model will be used to compare and determine a simple system's dynamic behavior, equipped with an adaptive UPFC.

I.INTRODUCTION

Present-day multi-machine power system or interconnected power systems consists of many SG's having the different inertia constants, connected with heavily loaded and weakly connected large transmission network are vast and highly complex systems to control. Under steady state or dynamic state of the system, generally they may be ignored. But, as they play vital role during the transient state of the system they cannot be ignored. As the nonlinearities in the power system model are inherent by nature, the dynamic behavior of the system should be studied by using nonlinear model as the basis in described[1,2].Nonlinear equation studied by standard form of linearization technique .This technique has been well used to find out the system matrix then analyze a dynamics behavior of multi machine power system by using Eigen value analysis. Now day's stability is improved by FACTS device. One of advanced FACTS device is UPFC [6,7].In this paper, the linearized Phillips-Heffronmodel[2,10] of a power system installed with an UPFC is first established.

II.MATHEMATICAL MODEL

To formulate multi-machine small-signal model, without loss of generality the following assumptions are made, and studied in [5] the stator and the network transient are neglected. The turbine governor dynamics are neglected resulting in constant mechanical TM_i the damping torque $TF_i = DF_i(W_i - W_s)$ s assumed linear.

Reduced-order flux-decay model

If the damper winding constants are very small, then we can set them to zero, then
The DAEs of generator with static exciter with linearization

$$\delta_i = \Delta W_i$$

$$\Delta W_i = \left(\frac{1}{M_i}\right)(\Delta TM_I - Eq_i^1 \Delta Iq_i - \Delta Eq_i^1 Iq_i - (Xq_i^1 - Xd_i^1)Id_i \Delta Iq_i - (Xq_i^1 - Xd_i^1)Iq_i \Delta Id_i$$

$$\Delta Eq_i^1 = \left(\frac{1}{Td_i^1}\right)(-\Delta Eq_i^1 - (Xq_i^1 - Xd_i^1)\Delta Id_i + \Delta Efd_i$$

$$\Delta Efd_i = \left(\frac{1}{TA_i}\right)(-\Delta Efd_i + KAVref_i - KA_i$$

The above 4 equations are written in matrix form

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$$\begin{bmatrix}\begin{bmatrix}\Delta\delta i\\ \Delta Wi\\ \Delta Eqi\\ \Delta Efdi\end{bmatrix}\end{bmatrix}=\begin{bmatrix}0 & 1 & 0 & 0\\ 0 & 0 & -Iq_i/Mi & 0\\ 0 & 0 & -1/Td_i^1 & 1/Td_i^1\\ 0 & 0 & 0 & -1/TAi\end{bmatrix}\begin{bmatrix}\Delta\delta i\\ \Delta Wi\\ \Delta Eqi\\ \Delta Efdi\end{bmatrix}+\begin{bmatrix}0 & 0\\ m & n\\ p & 0\\ 0 & 0\end{bmatrix}\begin{bmatrix}\Delta Idi\\ \Delta Iqi\end{bmatrix}+\begin{bmatrix}0 & 0\\ 0 & 0\\ 0 & 0\\ 0 & -KAi/TAi\end{bmatrix}\begin{bmatrix}\Delta\theta i\\ \Delta Vi\end{bmatrix}+$$

$$\begin{bmatrix}0 & 0\\ 1/Mi & 0\\ 0 & 0\\ 0 & -KAi/TAi\end{bmatrix}\begin{bmatrix}\Delta TMi\\ \Delta Vref\end{bmatrix}$$

Where

m= $-(Xq_i^1-Xd_i^1)Iqi$ /Min= (- $(Xq_i^1-Xd_i^1)Id_i$ /Mi)+(-Eqi/Mi) p= $(Xq_i^1-Xd_i^1)/Tdi$

Now write in simple form

$$\Delta X_i = A1\Delta X + B1\Delta Ig + B2\Delta Vg + E1\Delta U$$

For the m-machine system, the order of matrix $A1_{4m*4m}$, $B1_{4m*2m}$, $B2_{4m*2m}$ and $E1_{4m*2m}$ Each machine system matrix is diagonal elements of overall matrix

The stator algebraic equations: The stator algebraic equations of synchronous machine written in [2]

$$V_i \sin(\partial i - \theta i) - Xq_i Iq_i = 0$$

$$V_i \cos(\partial i - \theta i) + Xd_i Id_i - Eq_i^1 = 0$$

Now linearization of stator algebraic equations writes in matrix form

$$\begin{bmatrix}V_i\cos(\delta i-\theta i) & 0 & 0 & 0\\ V_i\cos(\delta i-\theta i) & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}\Delta\delta i\\ \Delta Wi\\ \Delta Eqi\\ \Delta Efdi\end{bmatrix}+\begin{bmatrix}0 & -Xq_i\\ -Xd_i & 0\end{bmatrix}\begin{bmatrix}\Delta Idi\\ \Delta Iqi\end{bmatrix}+\begin{bmatrix}-vi\cos(\delta i-\theta i) & \sin(\delta i-\theta i)\\ -vi\sin(\delta i-\theta i) & -\cos(\delta i-\theta i)\end{bmatrix}\begin{bmatrix}\Delta\theta i\\ \Delta Vi\end{bmatrix}$$

Now write in simple form

$$0 = C1\Delta X + D1\Delta Ig + D2\Delta Vg$$

for the m-machine system, the order of matrix $C1_{2m*4m}$, $D1_{2m*2m}$, and $D2_{2m*2m}$

Each machine matrix is diagonal elements of overall matrix

III.POWER NETWORK MODEL

The power networks interconnect the synchronous machine with transmission and distribution nodes along with rest of the system components. The equivalent circuit of the power system networks together with stator networks of the synchronous machines and the active and imaginary power loads is presented in figure1. The network equations for an n number of bus systems were written in complex form studied in [10]

The network equations for the generator buses are given by

$$V_i e^{J\theta}(Id_i - Iq_i)e^{-j\left(\partial i-\frac{\Pi}{2}\right)} + PL_i(V_i) + jQL_i(V_i) = \varepsilon V_i V_k V_{ik} e^{j(\theta i-\theta k-\alpha ik)}$$

for i=1, 2, 3, . . ., m (number of generator buses).

The network equation for the load buses is

$$PL_i(V_i) + jQL_i(V_i) = \varepsilon V_i V_k V_{ik} e^{j(\theta i-\theta k-\alpha ik)}$$

for i=m+1, m+2, m+3, . . ., n (number of load buses).

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Here

$$V_i e^{J\theta}(Id_i - Iq_i)e^{-j\left(\partial i - \frac{\Pi}{2}\right)} = PG(V_i) + jQG_i(V_i)$$

QG_i is the complex power "injected" into bus i due to the generator.
For the generator buses network equations are separated into real and imaginary parts and are represented in power balance form as

$$Id_i V_i cos(\delta i - \theta i) - Id_i V_i sin(\delta i - \theta i) + QL_i(V_i) - \sum V_i V_k V_{ik}\, e^{j(\theta i - \theta k - \alpha ik)} = 0$$

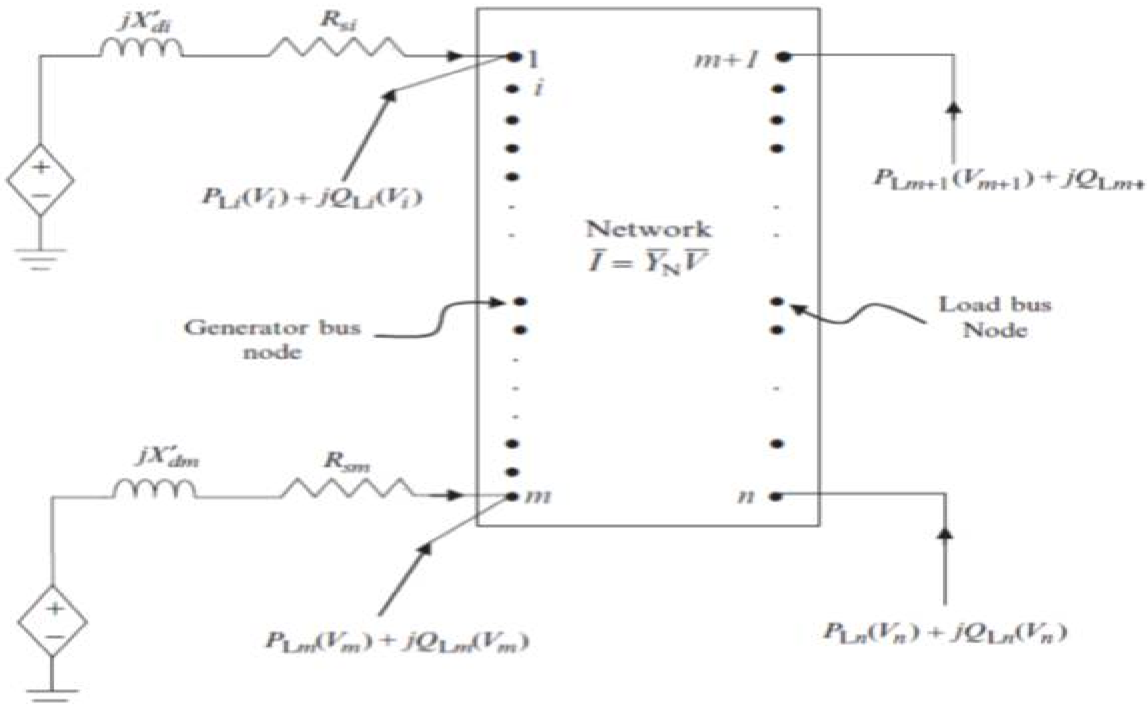

Figure 1: Synchronous machine dynamic circuit with power networks

where i=1, 2, 3, . . ., m for generator buses.m+1,m+2…….n are load buses now Linearization of the network equations that pertain to generator buses (PV buses) gives write in matrix form

$$\begin{bmatrix} (Id_i V_i cos(\delta i - \theta i) - Id_i V_i sin(\delta i - \theta i)) & 0 & 0 & 0 \\ -Id_i V_i cos(\delta i - \theta i) + -Iq_i V_i cos(\delta i - \theta i) & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta X \\ \Delta w \\ Eq_i^1 \\ Efd_i \end{bmatrix} + \begin{bmatrix} V_i sin(\delta i - \theta i) & -V_i cos(\delta i - \theta i) \\ V_i cos(\delta i - \theta i) & -V_i sin(\delta i - \theta i) \end{bmatrix} \begin{bmatrix} \Delta Idi \\ \Delta Iqi \end{bmatrix} +$$

$$D4(i,k)\Delta Vg + D5(i,k)\Delta V$$

Here
D4(i, k), k=1, 2. . . m (for generator buses) : D5(i, k), k=m+1, m+2, . ,n (for non-generator buses).
$[\Delta\theta i \quad \Delta Vi] = \Delta Vg_i$ Here i=1, 2...m (for generator buses) and $[\Delta\theta i \quad \Delta Vi] = \Delta V1_i$ Here $\Delta V1_i$ i=m+1, m+2. . .n (for non-generator buses),

Now above equation in simple form for number of m machines

$$C2\Delta X + D3\Delta Ig + D4(i,k)\Delta Vg + D5(i,k)\Delta V1 = 0$$

for the m-machine system, the order of matrix$C1_{2m*4m}, D3_{2m*2m}$, Each machine matrix is diagonal elements of overall matrix$D4_{2m*2m}, and\ D5_{2m*2m}$ are obtained linearization the PV Bus equation with respect generator and loads.D4

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matrix obtain linearization PV Bus equation with respect to all PV bus voltage and angle . D5 matrix obtains linearization PV Bus equation with respect to all PQ bus voltage and angle.
Linearization of the network equations that pertain to load buses (PQ buses)

$$PL_i(V_i) - \sum V_i V_k V_{ik} \cos(\delta i - \delta j - \alpha ik) = 0$$

$$QL_i(V_i) - \sum V_i V_k V_{ik} \sin(\delta i - \delta j - \alpha ik) = 0$$

Write in simple form

$$D6(i,k)\Delta Vg + D7(i,k)\Delta V1 = 0$$

Here order of $D6_{2m*2m}, D7_{2n*2n}$ are full matrices
D6 matrix obtain linearization PQ Load equation with respect to all PV bus voltage and angle
D7 matrix obtain linearization PQ Load equation with respect to all PQ bus voltage and angle
Write all equation together

$$\Delta X_i = A1\Delta X + B1\Delta Ig + B2\Delta Vg + E1\Delta U$$

$$0 = C1\Delta X + D1\Delta Ig + D2\Delta Vg$$

$$0 = C2\Delta X + D3\Delta Ig + D4\Delta Vg + D5\Delta V1$$

$$0 = D6\Delta Vg + D7\Delta V1$$

Where

$$X = [X_1^T .. X_2^T .. X_3^T ... X_M^T]$$

$$Xi = [\delta i, Wi, Edi, Efdi]$$

$$Vg = [\theta 1, V1, \theta 2, V2 .... \theta m, Vm]$$

$$V1 = [\theta_{m+1}, V_{m+1}, \theta_{m+2}, V_{m+2} .... \theta n, Vn]$$

Rearrange the above equation.
Write as $I = -(D_1^{-1}C_1)\Delta X - D_1^{-1}D_2\Delta Vg$ into above equations

$$\Delta X_i = (A1 - B_1 D_1^{-1}C_1)\Delta X + (B2 - B_1 D_1^{-1}D_2)\Delta Vg + E1\Delta U$$

$$0 = (D4 - D_3 D_1^{-1}D_2)\Delta X + (C2 - D_3 D_1^{-1}C_1)\Delta Vg + D5\Delta V1$$

$$0 = D6\Delta Vg + D7\Delta V1$$

Writing Equations Above in state-space representation

$$\begin{bmatrix}\Delta X_i \\ 0 \\ 0\end{bmatrix} = \begin{bmatrix} A1 - B_1 D_1^{-1}C_1 & B2 - B_1 D_1^{-1}D_2 & 0 \\ D4 - D_3 D_1^{-1}D_2 & C2 - D_3 D_1^{-1}C_1 & D5 \\ 0 & D6 & D7 \end{bmatrix} \begin{bmatrix}\Delta X \\ \Delta Vg \\ \Delta V1\end{bmatrix} + \begin{bmatrix} E1 \\ 0 \\ 0\end{bmatrix}\Delta U$$

This in more compact form written as

$$\begin{bmatrix}\Delta X_i \\ 0\end{bmatrix} = \begin{bmatrix} A^1 & B^1 \\ C^1 & D^1\end{bmatrix}\begin{bmatrix}\Delta X_i \\ \Delta VN\end{bmatrix} + \begin{bmatrix}E1 \\ 0\end{bmatrix}\Delta U$$

$$A^1 = A1 - B_1 D_1^{-1}C_1$$

$$B^1 = B2 - B_1 D_1^{-1}D_2$$

$$C^1 = \begin{bmatrix} C2 - D_3 D_1^{-1}C_1 \\ 0 \end{bmatrix}$$

$$D^1 = \begin{bmatrix} D4 - D_3 D_1^{-1}D_2 & D5 \\ D6 & D7 \end{bmatrix}$$

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Now

$$[ASYS]4m*4m = A^1 - [B_1^1 B_2^1][D_1^1]^{-1}\begin{bmatrix} C1^1 \\ C2^1 \end{bmatrix}$$

This model can be used to examine the effect of small-signal disturbance on the Eigen values of the multi-machine power system. When a PSS or any FACTS devices are installed at any machine, the extra state variables corresponding to these controllers will be added with the system matrix.

IV.UPFC MODEL

Unified power flow controller (UPFC) is one of the most advanced FACTS devices and is a combination of STATCOM and a SSSC[3]. UPFC was designed with two VSCs sharing a mutual capacitor on their dc side and a unified control system. The two devices are coupled through the dc link and the combination allows exchange of real power between the series SSSC and the shunt STATCOM. This controller (UPFC) has the facility to provide concurrent real and reactive series line compensation without any external electric energy source. Thus, UPFC is able to control real power flow, reactive power flow in a line, and the voltage magnitude at the UPFC terminals and may also be used as independently for shunt reactive compensation studied in[3,8].

The flow of active power for the series unit (SSSC) is obtained from the line itself through the shunt unit (STATCOM). STATCOM is used for voltage (or reactive power) control, while SSSC is utilized for real power control. UPFC is a complete FACTS controller for both active and reactive power flow controls in a line. The real power required for the series converter is drawn by the shunt converter from the ac bus (i) and supplied to bus j by the dc link. The inverted ac voltage (V_{ser}) at the output of SSSC is added to the sending end node voltage V_i at line side to boost the nodal voltage at the j^{th} bus. It may be noted here that the voltage magnitude of the output voltage $|V_{ser}|$ provides voltage regulation, while the phase angle d_{ser} determines the power flow controlmode [11]. Additional

storage device through an electronic interface would provide the enhancement in capability of UPFC in active power flow control. In addition by providing a support in the real power exchange that takes place between the series converter and the ac system, the shunt converter may also generate or absorb reactive power in order to provide independent voltage regulation at its point of connection with the ac system[8,9].

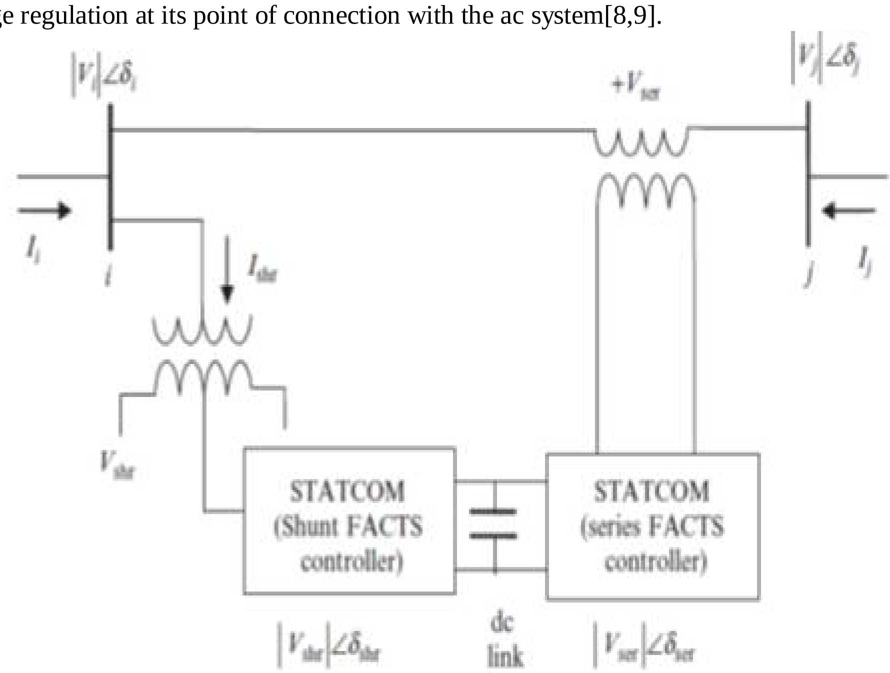

Figure 2: Schematic of a UPFC

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The UPFC equivalent circuit shown in figure2 consists of a shunt-connected voltage source and a series-connected voltage source. The active power constraint equation links the two voltage sources[3]. The two voltage sources are connected tothe ac system through inductive reactance representing the VSC transformers. The expressions for the two voltage sources and the constraint equation would be

$$V_{shr} = | V_{shr} | (cos\delta_{shr} + jsin\delta_{shr})$$

$$V_{ser} = | V_{ser} | (cos\delta_{ser} + jsin\delta_{ser})$$

$$RE(-V_{Shr}I_{shr} + V_{ser}I_{ser})$$

Here, V_{shr} and dshr are the controllable magnitude and the voltage source phase representing the shunt converter. The magnitude $V_{ser}$and phase angled_{ser} of the voltage source represent the series converter. Similar to the shunt and series voltage sources used to represent the STATCOM and the SSSC, respectively, the voltage sources used in the UPFC application would also have control limits, i.e., $V_{shrmin} < V_{shr} < V_{shrmax}$,0< d_{shr} <2pi and $V_{sermin} < V_{ser} < V_{sermax}$, 0<d_{ser}<2pi, respectively. The phase angle of the series-injected voltage determines the mode of power flow control.

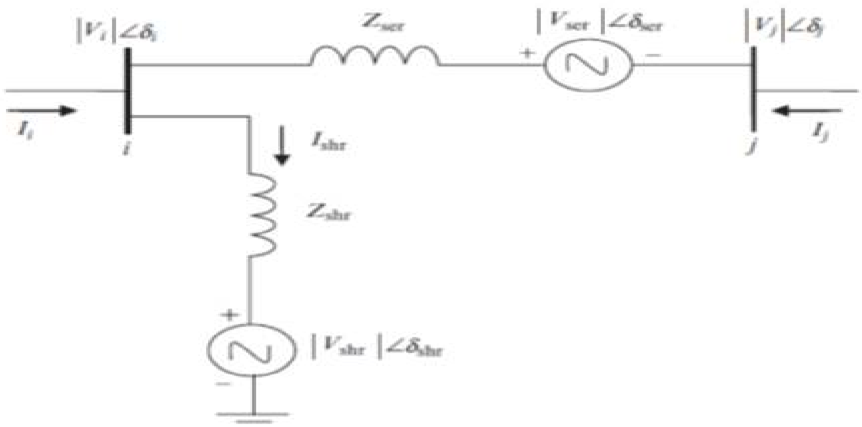

Figure 3: Equivalent circuit of a UPFC between two buses i and j.

Based on equivalent circuit from figure 3

$$I_i = (V_i - V_j - V_{ser})Y_{ser} + (V_i - V_{ser})Y_{shr}$$

$$I_i = (-V_i + V_j + V_{ser})Y_{ser}$$

$$\begin{bmatrix} S_i \\ S_j \end{bmatrix} = \begin{bmatrix} Vi & 0 \\ 0 & Vj \end{bmatrix} \begin{bmatrix} I_i^* \\ I_j^* \end{bmatrix}$$ HereS_i=P_i+j$Q_i$simply the equation

The real and imaginary ati^{th} and j^{th} end

$$P_i = V_i^2 G_{ii} + V_i V_j \left(G_{ij}cos(\delta i - \delta j) + B_{ij}sin(\delta i - \delta j)\right) + \left(V_i V_{ser}\left(G_{ij}cos(\delta i - \delta ser) + B_{ij}sin(\delta i - \delta ser)\right) + V_i V_{shr}(G_{io}cos(\delta i - \delta shr) + B_{io}sin(\delta i - \delta shr)\right)$$

$$P_j = V_j^2 G_{jj} + V_i V_j \left(G_{ij}cos(\delta j - \delta i) + B_{ij}sin(\delta j - \delta i)\right) + \left(V_i V_{ser}\left(G_{ij}cos(\delta j - \delta ser) + B_{ij}sin(\delta j - \delta ser)\right)\right)$$

$$Q_i = -V_i^2 B_{ii} + V_i V_j \left(G_{ij}sin(\delta i - \delta j) - B_{ij}sin(\delta i - \delta j)\right) + \left(V_i V_{ser}\left(G_{ij}sin(\delta i - \delta ser) - B_{ij}cos(\delta i - \delta ser)\right) + V_i V_{shr}(G_{io}sin(\delta i - \delta shr) - B_{io}sin(\delta i - \delta shr)\right)$$

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$$Q_j = -V_j^2 B_{jj} + V_i V_j \left(G_{ij} sin(\delta j - \delta i) + B_{ij} cos(\delta j - \delta i)\right) + \left(V_i V_{ser}\left(G_{ij} sin(\delta j - \delta ser) - B_{ij} cos(\delta j - \delta ser)\right)\right.$$

The UPFC power equations, in liberalized form, are combined with those of the ac network. In order to get the linearized model of the system using power mismatch form, let us assume UPFC is connected to node i and the power system is connected to node j. UPFC is required to control voltage at the shunt converter terminal, node i, and active power flows from node j to node i. The non-linear dynamic model of the system using UPFC is given below. IEEE-ST1static excitation system is considered studied in [9]

$$V_{dc} = \left(\frac{0.75}{C}\right)\left(Mcos(\delta sh) * (Ishd)\right) + (\sin(\delta sh) * Ishq)) + m(cos\delta sr) * Isrd) + (\sin(\delta sh) * Isrq))$$

V.MATHMATICAL ANAYLSIS: WSCC TYPE 3-MACHINE, 9-BUS SYSTEM

Participation factor is a tool for identifying the state variables that have significant participation in a selected mode among many modes in a multi generator power system [5].

The standard IEEE 3 Machine 9 Bus system taken from literature[4]

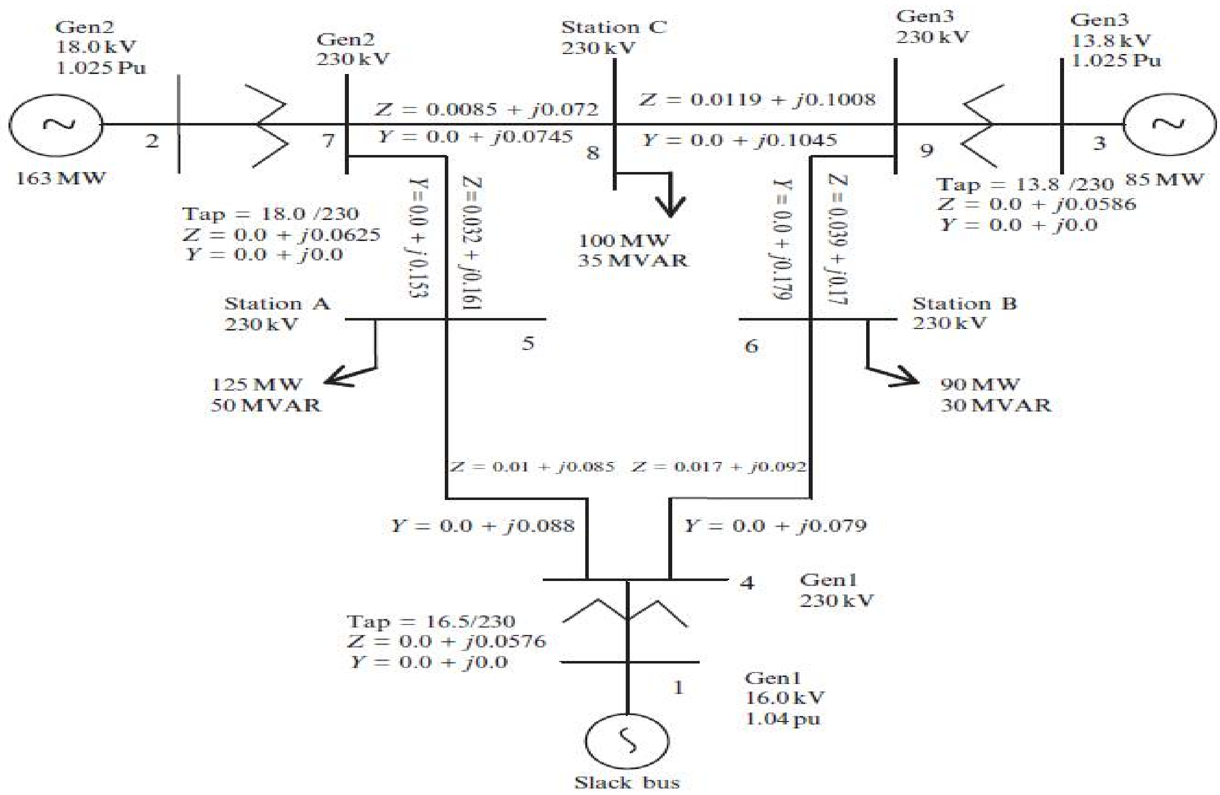

Figure 4: WSCC Type 3-Machine, 9-Bus System

It is natural to say that the significant state variables for an Eigen value I_p are those that correspond to large entries in the corresponding eigenvector fp. But the problem of using right and left eigenvector entries individually for identifying the relationship between the states and the modes is that the elements of the eigenvectors are dependent on

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dimension and scaling associated with the state variables. As a solution of this problem, a matrix called the participation matrix (P) is suggested in which the right and left eigenvectors entries are combined, and it is used as a measure of the association between the state variables and the modes
Here

$$P = [P1, P2 \ldots . Pr] = \begin{bmatrix} P1 \\ P2 \\ . \\ . \\ P3 \end{bmatrix} = \begin{bmatrix} \emptyset 1p\emptyset p1 \\ \emptyset 2p\emptyset p2 \\ . \\ . \\ \emptyset 3p\emptyset p3 \end{bmatrix}$$

ϕkp is the element on the k^{th} row and p^{th} column of the modal matrix, ϕ is the k^{th} entry of the right eigenvector $\phi p, \varphi pk$ is the element on the p^{th} row andk^{th} column of the modal matrix, and C is the k^{th} entry of the left Eigen vector. The element $Pkp = \phi kp\varphi pk$ is termed the participation factor[12].

From Participation factor it was found that at the generator 2 had a lowest damping ratio,so the controller (UPFC) placed in between at generator 2 to line 7.Now UPFC effects on PV bus (2) and PQ bus (7). That on multi machine it effects on D4, D5, D6, D7,B1, B2 matrixes and A12.Now linearization the static excitation of UPFC equation. The systematic matrix includes UPFC static excitation equation then order is increased by one .now order is (4m+1)*(4m+1). For 3 machine 9 bus system new order of system matrix is 13×13 the linearization of UPFC process seen in appendix.

From the UPFC power load flow equation(both Active and Reactive power equation) put i=2 j=7 and linearization done with respect $\theta i, Vi$

Load flow at bus 2 linearization done with respect Θ_2, V_2include in D4 matrix.
Load flow at bus 2 linearization done with respect Θ_7, V_7include in D5 matrix
Load flow at bus 7 linearization done with respect Θ_2, V_2include in D6 matrix
Load flow at bus 7 linearization done with respect Θ_7, V_7include in D7 matrix
All these equation includes, and measurement the UPFC parameter now new Eigen value include UPFC

VI.RESULT AND DISCUSSION

In this paper discuss analysis of Multi machine system by linearization process which including two axis model of synchronous generator ,stator algebraic equation, generator equation and PQ equations and the analysis of UPFC on power system load flows. Stability had done by using state matrix representation form. By forcibly the system is under driven in to unstable, and then by using participation factor location of lowest damping factor is found. Then UPFC are to be fixed at machine then observe the stability increase from unstable to stable region.

EIGEN. VALUE WITH OUT UPFC	EIGEN VALUE WITH UPFC
-0.9699 +18.5135i	-6.4138 + 0.0000i
-0.9699 -18.5135i	-5.9255 - 0.0000i
-1.0405 + 9.1857i	-1.9529 + 0.0000i
-1.0405 - 9.1857i	-1.3287 - 0.0000i
-1.5762 + 3.4923i	-0.0297 - 0.8268i
-1.5762 - 3.4923i	-0.0297 + 0.8268i
1.4374	-0.0008 - 0.2685i
-1.6759 + 1.9202i	-0.0008 + 0.2685i
-1.6759 - 1.9202i	-1.9579 -13.8156i
-1.4293 + 0.1750i	-1.5618 +13.8475i
-1.4293 - 0.1750i	-11.7080 + 0.0801i
-1.0292	-12.1966 - 0.1117i
	-0.0071 - 0.0003i

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APPENDIX

MACHINE DATA

Parameters	Machine #1	Machine #2	Machine #3
R_s(pu)	0.089	0.089	0.089
H (s)	23.64	6.4	3.01
D (pu)	0.2	0.2	0.2
X_d (pu)	0.269	0.8958	1.998
X_{d1}(pu)	0.0608	0.1198	0.1813
X_q (pu)	0.0969	0.8645	1.2578
X_{q1}(pu)	0.0969	0.8645	1.2578
T_{d0} (s)	8.96	6.0	5.89
T_{q0}(s)	0.31	0.535	0.6

Exciter Data

Parameters	Machine #1	Machine #2	Machine #3
KA	20	20	20
TA	0.2	0.2	0.2
TE(S)	0.314	0.314	0.314
KE(S)	1	1	1

UPFC PARAMETER:
DC LINK:V_{dc}=10;M_{sr}=0.0;C_{dc}=2
D_{elsr}=131.5,m_{sh}=0.193 D_{elsh}:52.76

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