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Design of UPFC Controller Using Modified Bilinear Equation for Improving Transient Stability

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Abstract: Based on the use of the modified bilinear equation for the unified power flow controller (UPFC), this paper proposes a new control strategy to improve the transient stability of power system. This control strategy is applied to shunt and series inverters of UPFC as the modulating signals at the operating point. This input signals are such that the derivative of Liapunov energy function is negative definite. Simulation results show that the transient stability of power system has improved more effectively than the conventional PI controllers. Moreover, the coordination between series and shunt controllers of UPFC via one control law is considered as the main advantages of the designed controllers.

Key words: Unified Power Flow Controller (UPFC), Bilinear system, liapunov energy function, power oscillation damping

INTRODUCTION

A Unified Power Controller (UPFC) is a versatile FACTS device that is used to regulate the active and reactive power flow and the line voltage at it's both sides. It can also improve the dynamic or transient stability of power system[1,2].

For the safe and good operation of PWM inverters of UPFC, the DC capacitor voltage of inverters should be constant[3]. For this aim, a PI controller is used to balance the input and output power of dc capacitor via determining the d-axis current reference in shunt inverter. In deed, since the speed of d-axis current tracking of shunt inverter from it's reference is high, the interaction between series and shunt inverters via dc link capacitor is not considered and therefore, the series and shunt controller in UPFC are designed individually[4,5].

For example, in[6] in order to improve transient stability, the series controller is designed by setting the variation of line power equal to zero and two conventional PI controllers is used for the shunt controller. In that paper, the shunt inverter is connected to a voltage regulated bus and it does not control the bus voltage and the interaction of shunt and series inverter via dc link is not considered.

In spite of individually design of shunt and series controllers, under certain condition and operating point, the interaction between series and shunt inverters may be cause to instability as discussed in[6,7].

For better performance of UPFC in transient state, It is required that the variation of dc capacitor voltage to be considered in UPFC modeling. Design of simultaneous shunt and series controllers under one control law with considering the variation of dc capacitor voltage is the main aim of this paper. In this design, the output voltage of each inverter is considered as the dc capacitor voltage multiplying by input controller (Eq. 2). So, similar the bilinear equation, we have bilinear term that is exposed by the multiplying the state variable and input in the state equation.

If the variation of dc capacitor voltage is ignored, these nonlinear terms are considered as the constant inputs.

In this research, based on bilinear equation, the structure and mathematical model of UPFC is derived. Using this model, the controllers of shunt and series inverters are designed simultaneously. To reduce the total energy of system, an adaptive scheme for gain-scheduling is used under supervisory control.

UPFC STRUCTURE AND MODELING

Figure 1 shows the block diagram of a UPFC and equivalent circuit of its shunt and series inverter. The dc sides of these inverters are connected to a dc link capacitor. The ac side of series inverter is in series with the power line network via a three phase transformer. The ac side of shunt inverter is also connected to the input bus of UPFC through a three phase transformer.

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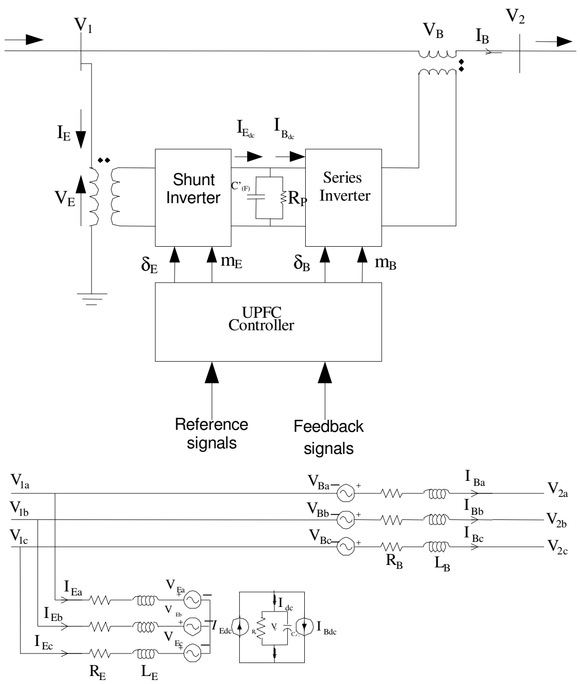

Fig. 1: block diagram of a UPFC and equivalent circuit

The series inverter voltage can regulate the active and reactive power of transmission line in dynamic and steady state conditions. The shunt inverter regulates the dc bus voltage required for series inverter via the balance of input and output active power of capacitor. It can also regulate the input line voltage by generation or consumption of reactive power[8].

According to Fig. 1, there are the following equations:

$$V_{1d} = -V_{Bd} + R_B I_{Bd} + L_B \frac{dI_{Bd}}{dt} - \omega I_{Bq} + V_{2d}$$
$$V_{1q} = -V_{Bq} + R_B I_{Bq} + L_B \frac{dI_{Bq}}{dt} + \omega I_{Bd} + V_{2q}$$
$$V_{1d} = R_E I_{Ed} + L_E \frac{dI_{Ed}}{dt} - \omega I_{Eq} + V_{Ed}$$
$$V_{1q} = R_E I_{Eq} + L_E \frac{dI_{Eq}}{dt} + \omega I_{Ed} + V_{Eq} \qquad (1)$$

$$V_1 = |V_1|\cos\delta_1 + J|V_1|\sin\delta_1 = V_{1d} + JV_{1q}$$

$$V_B = V_{Bd} + JV_{Bq}$$
$$V_{Bd} = V_c K_B m_B \cos\delta_B$$
$$V_{Bq} = V_c K_B m_B \sin\delta_B$$

$$V_E = V_{Ed} + JV_{Eq}$$
$$V_{Ed} = V_c K_E m_E \cos\delta_E$$
$$V_{Eq} = V_c K_E m_E \sin\delta_E \qquad (2)$$

In above equation V_E and V_B are the voltages of shunt and series inverter outputs, (m_E,δ_E) and (m_B,δ_B)are modulation index and phase angle of shunt and series inverters respectively. K_E and K_B are the coefficients including transformers ratios and relating the dc to ac voltage of the shunt and series inverter respectively. These coefficients are usually greater than one.

The input and output current of dc capacitor is:

$$I_{Edc} = \frac{3}{2}\frac{V_{Ed}I_{Ed} + V_{Eq}I_{Eq}}{V_c}$$
$$= \frac{3}{2}K_E m_E \left(I_{Ed}\cos\delta_E + I_{Eq}\sin\delta_E\right)$$
$$I_{Bdc} = \frac{3}{2}\frac{V_{Bd}I_{Bd} + V_{Bq}I_{Bq}}{V_c} \qquad (3)$$
$$= \frac{3}{2}K_B m_B \left(I_{Bd}\cos\delta_B + I_{Bq}\sin\delta_B\right)$$
$$I_{dc} = I_{Edc} - I_{Bdc}$$

After some manipulations, the state equations of the UPFC in per- unit will be represented as:

$$\begin{bmatrix}\dot{X}_1\\ \dot{X}_2\\ \dot{X}_3\\ \dot{X}_4\\ \dot{X}_5\end{bmatrix} = \omega_b \begin{bmatrix} \frac{-R_B}{L_B} & \frac{\omega}{\omega_b} & 0 & 0 & \frac{U_1}{L_B} \\ -\omega & \frac{-R_B}{L_B} & 0 & 0 & \frac{U_2}{L_B} \\ 0 & 0 & \frac{-R_E}{L_E} & \frac{\omega}{\omega_b} & \frac{-U_3}{L_E} \\ 0 & 0 & \frac{-\omega}{\omega_b} & \frac{-R_E}{L_E} & \frac{-U_4}{L_E} \\ -1.5U_1C & -1.5U_2C & +1.5U_3C & +1.5U_4C & \frac{-C}{R_p} \end{bmatrix} \qquad (4)$$
$$\begin{bmatrix}X_1\\ X_2\\ X_3\\ X_4\\ X_5\end{bmatrix} + \omega_b \begin{bmatrix} \frac{1}{L_B} & 0 & \frac{-1}{L_B} & 0 & 0 \\ 0 & \frac{1}{L_B} & 0 & \frac{-1}{L_B} & 0 \\ \frac{1}{L_E} & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{L_E} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_{1d} \\ V_{1q} \\ V_{2d} \\ V_{2q} \\ 0 \end{bmatrix}$$

The state variables and the inputs of the UPFC are:

$$X = [I_{Bd} \quad I_{Bq} \quad I_{Ed} \quad I_{Eq} \quad V_C]$$
$$U_1 = K_B m_B \cos\delta_B$$
$$U_2 = K_B m_B \sin\delta_B$$
$$U_3 = K_E m_E \cos\delta_E$$
$$U_4 = K_E m_E \sin\delta_E \qquad (5)$$

Equation (4) can be rewritten in the bilinear form of (6) as:

$$
\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \\ \dot{X}_4 \\ \dot{X}_5 \end{bmatrix} = \begin{bmatrix} \frac{\omega_b}{L_B}(V_{1d} - V_{2d}) \\ \frac{\omega_b}{L_B}(V_{1q} - V_{2q}) \\ \frac{\omega_b}{L_E}(V_{1d}) \\ \frac{\omega_b}{L_E}(V_{1q}) \\ 0 \end{bmatrix} + \begin{bmatrix} \frac{-R_B\omega_b}{L_B} & \omega & 0 & 0 & 0 \\ -\omega & \frac{-R_B\omega_b}{L_B} & 0 & 0 & 0 \\ 0 & 0 & \frac{-R_E\omega_b}{L_E} & \omega & 0 \\ 0 & 0 & -\omega & \frac{-R_E\omega_b}{L_E} & 0 \\ 0 & 0 & 0 & 0 & \frac{-C\omega_b}{R_P} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{bmatrix}
$$

$$
+ \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{\omega_b}{L_B} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ -1.5C\omega_b & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{bmatrix} U_1 + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{\omega_b}{L_B} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & -1.5C\omega_b & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{bmatrix} U_2
$$

$$
+ \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-\omega_b}{L_E} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1.5C\omega_b & 0 & 0 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{bmatrix} U_3 + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-\omega_b}{L_E} \\ 0 & 0 & 0 & 1.5C\omega_b & 0 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{bmatrix} U_4 \tag{6}
$$

$$
= AX + P_1U_1X + P_2U_2X + P_3U_3X + P_4U_4X + D = AX + \sum_{K=1}^{4} P_K U_K X + D
$$

The above state equation is represented in global d-q components. In design of controller, first we assume the input bus voltage of UPFC as the reference:

$$
\begin{aligned} & V_{1D} + jV_{1Q} = |V_1|\angle 0 \\ & (V_1 = |V_1|\angle\delta_1) \end{aligned} \tag{7}
$$

Then the other states and voltages are represented in new local D-Q components as:

$$
\begin{bmatrix} X_D \\ X_Q \end{bmatrix} = \begin{bmatrix} \cos\delta_1 & \sin\delta_1 \\ -\sin\delta_1 & \cos\delta_1 \end{bmatrix} \begin{bmatrix} X_d \\ X_q \end{bmatrix} \tag{8}
$$

So, the controller is designed in local D-Q components and then the variables are converted to global d-q components and are inserted to inverters.

UPFC CONTROLLER DESIGN USING LIAPUNOV ENERGY FUNCTION

The design of control law by Liapunov method is carried out in two stages. In the first stage a positive definite function should be selected. In the second stage, to keep the system in asymptotically stable, the control law is designed such that the total energy of the system reduces[9].

Considering of (6), the positive definite matrix Q and Liapunov function are selected as:

$$
\begin{aligned} & Q = diag(q_1 \quad q_1 \quad q_2 \quad q_2 \quad q_3) \\ & V = X^T Q X \end{aligned} \tag{9}
$$

The derivative of Liapunov function is:

$$
\begin{aligned} & \dot{V} = \dot{X}^T QX + X^T Q\dot{X} = (AX + \sum_{K=0}^{4} P_K U_K X + D)^T QX \\ & + X^T Q(AX + \sum_{K=1}^{4} P_K U_K X + D) \\ & = X^T (A^T Q + QA)X + X^T \left\{ (\sum_{K=1}^{4} P_K U_K)^T Q + Q(\sum_{K=1}^{4} P_K U_K) \right\} \\ & X + D^T QX + X^T QD \end{aligned} \tag{10}
$$

After some manipulation:

$$
\begin{aligned} & X^T(A^T Q + QA)X = -2q_1 \frac{R_B \omega_b}{L_B}(X_1^2 + X_2^2) \\ & -2q_2 \frac{R_E \omega_b}{L_E}(X_3^2 + X_4^2) - 2q_3 \frac{C\omega_b}{R_P} X_5^2 \end{aligned} \tag{11}
$$

And:

$$
\begin{aligned} & X^T((\sum P_K U_K)^T Q + Q(\sum_{K=1}^{4} P_K U_K))X = \\ & 2(\frac{\omega_b}{L_B} q_1 - 1.5C\omega_b q_3) X_1 X_5 U_1 \\ & +2(\frac{\omega_b}{L_B} q_1 - 1.5C\omega_b q_3) X_2 X_5 U_2 \\ & -2(\frac{\omega_b}{L_E} q_2 - 1.5C\omega_b q_3) X_3 X_5 U_3 \\ & -2(\frac{\omega_b}{L_E} q_2 - 1.5C\omega_b q_3) X_4 X_5 U_4 \end{aligned} \tag{12}
$$

And:

$$
\begin{aligned} & X^T QD + D^T QX = 2X^T QD = \frac{2q_1\omega_b}{L_B}((V_{1d} - V_{2d})X_1 \\ & +(V_{1q} - V_{2q})X_2) + \frac{2q_2\omega_b}{L_E}(V_{1d}X_3 + V_{1q}X_4) \end{aligned} \tag{13}
$$

From (4):

$$V_{1d} - V_{2d} = \frac{L_B}{\omega_b}(-A_{11}X_1 - A_{12}X_2 + \dot{X}_1) - V_{Bd}$$
$$V_{1q} - V_{2q} = \frac{L_B}{\omega_b}(-A_{21}X_1 - A_{22}X_2 + \dot{X}_2) - V_{Bq}$$
$$V_{1d} = \frac{L_E}{\omega_b}(-A_{33}X_3 - A_{34}X_4 + \dot{X}_3) + V_{Ed}$$
$$V_{1q} = \frac{L_E}{\omega_b}(-A_{43}X_3 - A_{44}X_4 + \dot{X}_4) + V_{Eq} \tag{14}$$

And from (13) and (14):

$$\begin{aligned} &X^T Q D + D^T Q X = \frac{2q_1\omega_b}{L_B} R_B (X_1^2 + X_2^2) \\ &+ 2q_1(X_1^2 + X_2^2)' - \frac{2q_1\omega_b}{L_B}\frac{2}{3}P_B \\ &+ \frac{2q_2\omega_b}{L_E} R_E (X_3^2 + X_4^2) + 2q_2(X_3^2 + X_4^2)' \\ &+ \frac{2q_2\omega_b}{L_E}\frac{2}{3}P_E P_B = \frac{3}{2}(X_1 V_{Bd} + X_2 V_{Bq}), \\ &P_E = \frac{3}{2}(X_3 V_{Ed} + X_4 V_{Eq}) \end{aligned} \tag{15}$$

Where P_E and P_B are the input power to shunt inverter and the output power of series inverter respectively.

So, from (11) and (12) and (15), the derivative of Liapunov function will:

$$\begin{aligned} \dot{V} &= -3C\omega_b q_3 X_1 X_5 U_1 - 3C\omega_b q_3 X_2 X_5 U_2 \\ &+ 3C\omega_b q_3 X_3 X_5 U_3 + 3C\omega_b q_3 X_4 X_5 U_4 \\ &+ 2q_1(X_1^2 + X_2^2)' + 2q_2(X_3^2 + X_4^2)' - \frac{2q_3 C\omega_b}{R_P} X_5^2 \end{aligned} \tag{16}$$

With respect of:

$$\begin{aligned} V_{Bd} &= X_5 U_1 \quad , \quad V_{Bq} = X_5 U_2 \\ V_{Ed} &= X_5 U_3 \quad , \quad V_{Eq} = X_5 U_4 \end{aligned} \tag{17}$$

The (16) can be rewritten as:

$$\begin{aligned} \dot{V} &= 3C\omega_b q_3 \{X_3 V_{Ed} + X_4 V_{Eq} - X_1 V_{Bd} - X_2 V_{Bq} \\ &+ \frac{2q_1}{3C\omega_b q_3}(X_1^2 + X_2^2)' + \frac{2q_2}{3C\omega_b q_3}(X_3^2 + X_4^2)'\} \end{aligned} \tag{18}$$

The aim of UPFC control strategy is to enforce the system as quickly as possible to the pre- disturbance equilibrium point. For this propose the control low is selected such that the derivative of V is negative as possible.

If the control low is defined as:

$$\begin{aligned} V_{Bd} &= 2K_1\dot{X}_1 \operatorname{sgn}((X_1^2 + X_2^2)') \\ V_{Bq} &= 2K_1\dot{X}_2 \operatorname{sgn}((X_1^2 + X_2^2)') \\ V_{Ed} &= 2K_2\dot{X}_3 \operatorname{sgn}((X_3^2 + X_4^2)') \\ V_{Eq} &= 2K_2\dot{X}_4 \operatorname{sgn}((X_3^2 + X_4^2)') \end{aligned} \tag{19}$$

Then (18) will be:

$$\begin{aligned} \dot{V} = 3C\omega_b q_3(&-K_1 \operatorname{sgn} P + a_1)X_a \\ &+ (K_2 \operatorname{sgn} P + b_1)X_b \end{aligned} \tag{20}$$

That:

$$\begin{aligned} &X_a = (X_1^2 + X_2^2)',\ X_b = (X_3^2 + X_4^2)' \\ &a_1 = \frac{2q_1}{3C\omega_b q_3}\rangle 0,\ \ b_1 = \frac{2q_2}{3C\omega_b q_3}\rangle 0 \\ &P = a_1 X_a + b_1 X_b \end{aligned} \tag{21}$$

To obtain the asymptotic stability criteria $(\dot{V}\langle 0)$, four different cases are considered:

$$\begin{aligned} &1.\ \text{if}: X_a\rangle 0, X_b\rangle 0, P\rangle 0 \text{ then}: K_1\rangle a_1, K_2\langle -a_2 \\ &2.\ \text{if}: X_a\langle 0, X_b\langle 0, P\langle 0 \text{ then}: K_1\rangle -a_1, K_2\langle a_2 \\ &3.\ \text{if}: X_a\rangle 0, X_b\langle 0 \text{ and} \\ &\text{a) if}: P\rangle 0 \text{ then}: K_1\rangle a_1, K_2\langle -a_2 \\ &\text{b) if}: P\langle 0 \text{ then}: K_1\langle -a_1, K_2\langle a_2 \\ &4.\ \text{if}: X_a\langle 0, X_b\rangle 0 \text{ and} \\ &\text{a) if}: P\rangle 0 \text{ then}: K_1\langle a_1, K_2\langle -a_2 \\ &\text{b) if}: P\langle 0 \text{ then}: K_1\rangle -a_1, K_2\rangle a_2 \end{aligned} \tag{22}$$

In order to have the better balance between the input and output power of DC capacitor and with respect of:

$$\begin{aligned} P_E - P_B &= +K_2 X_b \operatorname{sgn} P - K_1 X_a \operatorname{sgn} P \\ &= C V_C \frac{dV_C}{dt} \end{aligned} \tag{23}$$

it is required that:

In case 2: ($K_2\rangle 0$ and $K_1\rangle 0$) or ($K_1\rangle 0$ and $K_2\rangle 0$)

In case 3: for $P\langle 0$: $K_2\rangle 0$

In case 4: for $P\langle 0$: $K_1\rangle 0$ and for $P\langle 0$: $K_1\rangle 0$

RESULTS

The procedure of UPFC simulation in power system is shown in Fig. 2. To evaluate the performance of proposed controller, a four machine, two area system is selected (Fig. 3). All generators are fourth-order two-axis models and equipped with the first order fast exciters. The data of this system is summarized in Appendix. The operating point of this system is selected such that the power transfer from area 1 to area 2 is about 650 MW and near the surge Impedance loading of lines without UPFC. Therefore the system is somewhat stressed in steady state. This system has one inter-area-mode between area 1 and area 2 with $\eta = 0.026$, $f_n = 0.64$ HZ and a local mode of area 1 with $f_n = 1.12$, $\eta = 0.08$ and a local mode of area 2 with $f_n = 1.16$, $\eta = 0.08$

Figure 4-6 shows the simulation results of UPFC with proposed controllers and PI controllers in two case of with PSS and without PSS of generators. To have better performance of the PI controllers in UPFC to damping power swing, the integrator gains are increased as possible and to avoid the saturation of these controllers during transient state, the integrators have nonwindup limit[10].

At t = 1 sec. a temporary three phase fault with a duration of 0.1 Sec. is inserted at bus 6. Figure 4 shows the response of active power at output bus of UPFC to this fault. Plot-1 of Fig. 4 reveal the effectiveness of proposed controller compare with PI controller without PSS. The same result with PSS is shown in plot-2 of this figure. The proposed controller has co-ordination with PSS and so the response of power will be better damped (plot-3 of Fig. 3). These figures reveal that immediately after fault, the proposed controller reduces the peak of power swing in both cases of with/without PSS.

Figure 5 shows the power angle oscillation of generators of G_1, G_2 and G_3 and with respect of G_4. These oscillations are well damped after about 3 sec.

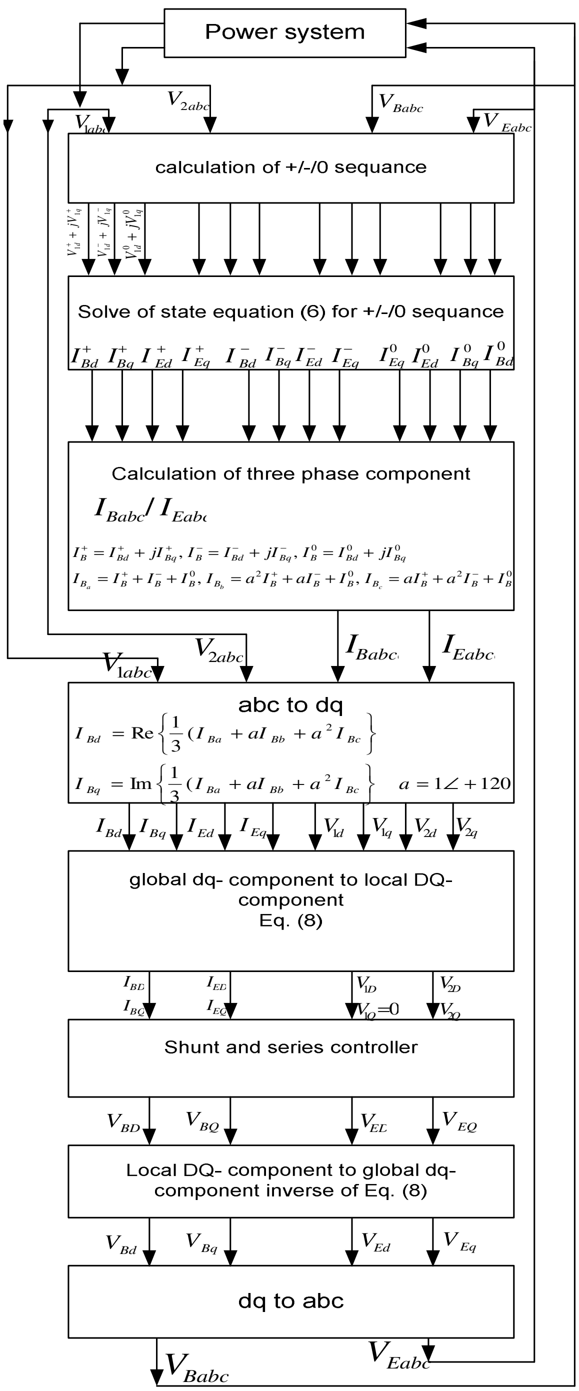

Fig.2: simulation algorithm of UPFC in power system

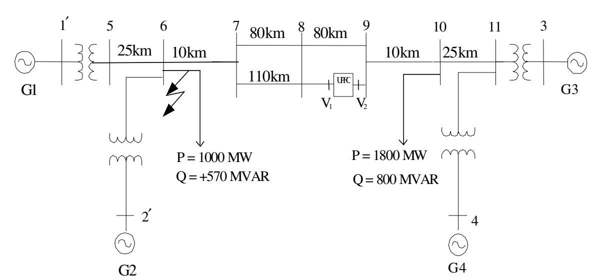

Fig.3: Block diagram of test system

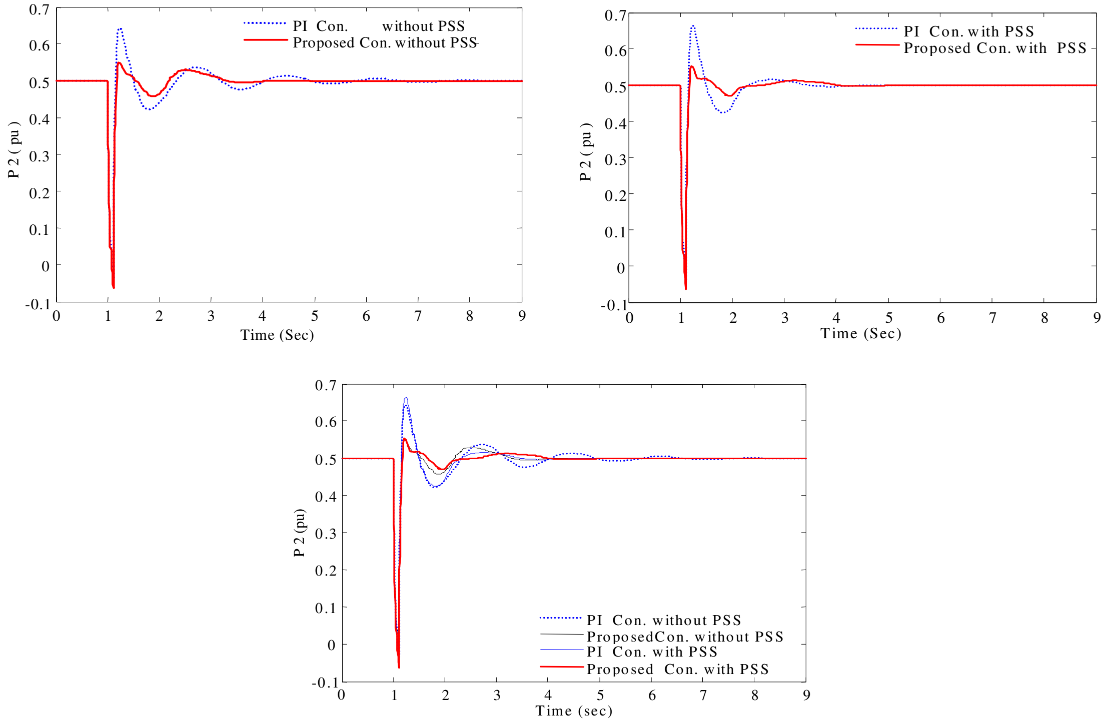

Fig. 4: Active and reactive power at output bus of UPFC

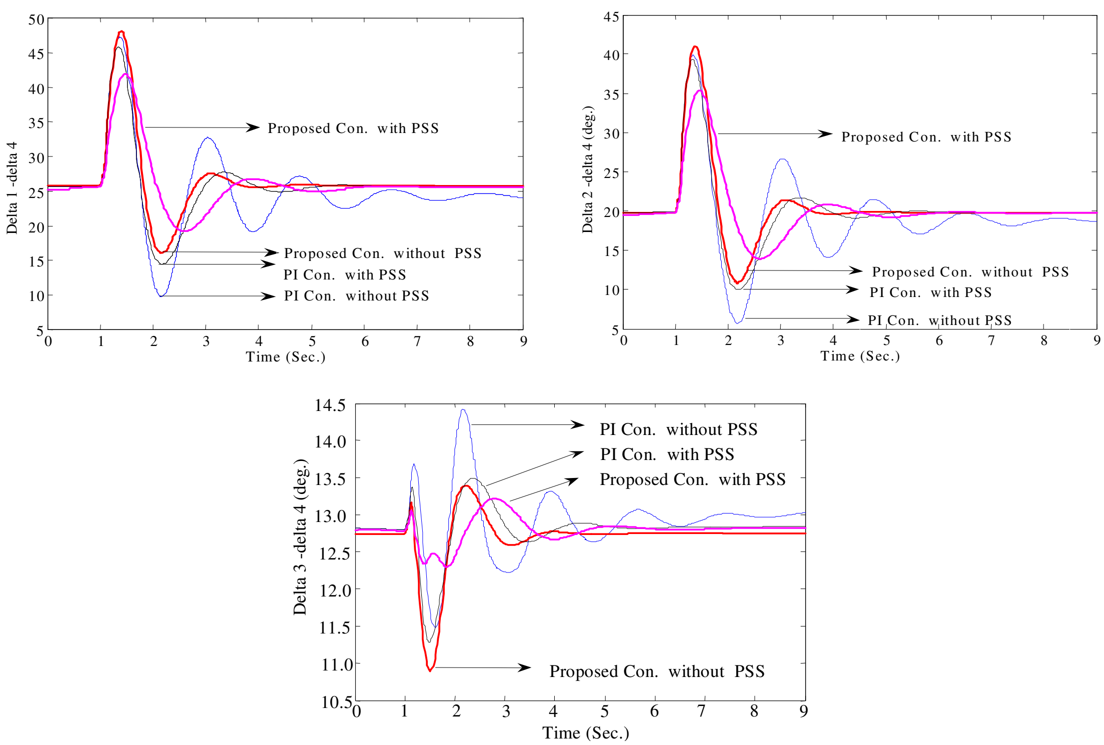

Fig. 5: Power angles of G1, G2 and G3 with respect of G4

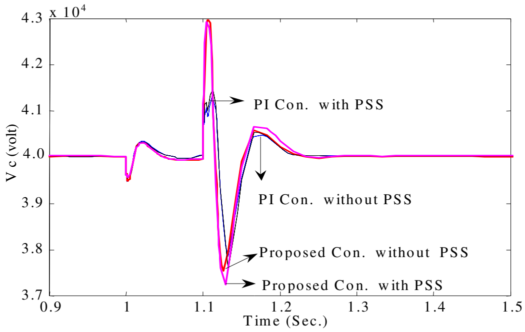

Fig. 6: The DC capacitor bus voltage

The DC capacitor voltage is shown in Fig. 6. because the proposed controller use the variation of DC capacitor voltage in output voltage of inverters, this model is more accurate than other conventional method and this variation will be greater than the case of with PI controller.

CONCLUSION

This research proposes an application of modified bilinear equations to UPFC controllers. The nonlinear control strategy is designed for series and shunt inverter based on Liapunov second method and energy function under one control low for shunt and series inverters. The output of controllers is yield such that the derivative of positive definite energy function is negative definite. So, the system will be asymptotically stable.

Simulation results indicate that amplitude of power oscillation immediately after fault clearance, is reduced considerably compared with conventional PI controller and so transient stability of power system will be improved. Reduction of first swing peak immediately after fault clearance is the main result of proposed controller. Because the effect of DC voltage variation of capacitor is considered in output voltage of inverter, this model is more accurate compare with other models and so the variation of dc voltage capacitor is greater than other model.

APPENDIX

The data of Generators are:

$1000\text{MVA},\ 20\text{KV},\ 50\text{HZ}, R_a = 0.0025\text{pu}, 4\text{Pole}$

$X_d = 1.8,\ X'_d = 0.3,\ X''_d = 0.25$

$X_q = 1.7,\ X'_q = 0.55,\ X''_q = 0.25,\ X_l = 0.2$

$T'_{do} = 8,\ T''_{do} = 0.03,\ T'_{qo} = 0.4,\ T''_{qo} = 0.05$

$H_2 = H_1 = 6\text{ Sec. } H_3 = H_4 = 5.8\text{ Sec}$

$T_l : 1000\text{MVA},\ 20/230\text{KV}$

Line parameters are:

$\text{Lines}: R = 0.001\Omega/\text{Km},\ K = 0.002\text{H}/\text{Km}$

UPFC parameters are:

$R_E = 0.0005\text{ pu},\quad L_E = 0.01\text{ pu}$

$R_B = 0.0005\text{ pu},\quad L_B = 0.01\text{ pu}$

$C = 10\mu\text{F},\quad V_C = 40000\text{V}$

$S_b = 1000\text{MVA}$

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