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Application of UPFC-based Adaptive Controller for Damping Inter-Area Oscillations

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Abstract: **-** In this paper a UPFC-based non-linear adaptive controller is proposed and designed to damp the tie line power oscillations. The adaptive controller design is based on determination of control signal using a new linear quadratic pole placement control law and identification of power system parameters using recursive least squares method with variable forgetting factor. A new model of UPFC has been introduced too. The simulation results show that the adaptive controller can damp tie line power oscillation more effective than the conventional PID controller and it is not sensitive to the loading conditions and the changes in power system topology.

Key-Words: **-** UPFC, Adaptive Controller, Power Oscillation Damping, Recursive Least squares.

1 Introduction

The main application of Unified Power Flow Controller (UPFC) is independent control of active and reactive power of transmission line and regulation of bus voltage by injection or absorption of reactive power. This device can be used to improve transient stability margin or to damp low frequency oscillations [1-3]. However coordination of multiple control loops of UPFC is one of the most important problems in UPFC controllers design. The power oscillations can occur on tie lines after large or small disturbances. Sometimes the power system stabilizer (PSS) installed on a specific generator can not provide effective damping for tie line power oscillations. It has been shown that the addition of supplementary control signal to the UPFC controllers can effectively solve the problem [4-7]. But conventional PID controller is designed based on a linearized model of the system and can not provide satisfactory performance for a wide range of operating conditions or network topology changes. Therefore the main problem of this design is the system nonlinearities and the validity of design only for a particular operating condition. Changing in loading condition or the topology of the network results in changes in the system parameters, but the structure of the designed controllers remains constant. It can not be expected that the interaction between system and its controllers is the same as before in the new operating condition. In [8] and [9] application of adaptive control algorithms for SVC, TCSC is explained, and the desired characteristics of the control system is achieved for a wide range of operating conditions. In this paper a UPFC-based adaptive stabilizer has been used for damping of tie line low frequency oscillations. The design algorithm is based on a new linear quadratic pole placement control law and recursive least squares identification method with variable forgetting factor. A new simplified model of UPFC has been presented, too.

2 Modeling of UPFC and its Controllers

Detailed model of UPFC, including dynamics of switching, can be used for dynamic studies of the network [10]. As a result the simulation time in low frequency and multi machine power systems studies is very long. As an approximation, in some researches it is assumed that all currents and voltages are sinusoidal and the electrical modes of network have been neglected. In this paper all electrical and mechanical modes of system have been considered and only the dynamics of switching has been omitted.

Fig.1 shows the two machine system. In order to control the active and reactive power of the transmission line and to regulate the voltage of bus B_2, a UPFC has been used. The control signals of shunt inverter are m_1 (modulation index) and angle of injected shunt voltage with respect to phase angle of bus B_2 voltage, i.e. α. Reactive power or bus voltage can be regulated by m_1; α can control active power absorption or DC bus voltage. The control system of shunt inverter is shown in Fig.2. The gain K_V is the reciprocal of the slope setting of shunt inverter reactive current versus bus voltage. For the series inverter, the series injected voltage, i.e. e_{sery}, can be decomposed to $e_{dse.}$ and $e_{qse.}$ as shown in Fig.3.

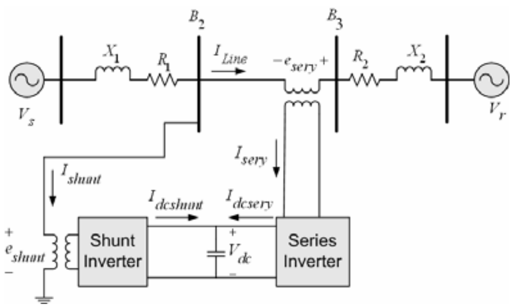

Fig.1. Single line diagram of case study.

The amplitude of the series injected voltage is controlled by m_2. Changing of β with respect to angle of V_{B_2} results in the series injected voltage angle changes. The control signals are generated by PI controllers shown in Fig.4. Using the voltage of bus B_2 as the reference, the injected voltages of series and shunt inverters for phase (a) can be written in the form of equations (1) and (2).

$$e_{sha} = k_1 * m_1 * V_{dc} * \sin(\omega t + \alpha) \tag{1}$$

$$e_{sea} = k_2 * V_{dc} * m_2 * \sin(\omega t + \beta) \tag{2}$$

The coefficients of K_1 and K_2 depend on the type of inverters. Neglecting the switching dynamics and for lossless inverters the main equations can be written as follows:

$$\begin{aligned} &P_{dc} = P_{ac} = (P_{ac})_{shunt} + (P_{ac})_{sery} \\ &V_{dc} * (I_{dc})_{shunt} + V_{dc} * (I_{dc})_{sery} = (e_{ash} i_{ash} + e_{bsh} i_{bsh} \\ &+ e_{csh} i_{csh}) + (e_{ase} i_{ase} + e_{bse} i_{bse} + e_{cse} i_{cse}) \\ &I_{dc} = \frac{P_{ac}}{V_{dc}},\ V_{dc} = \frac{1}{C}\int i_{dc}dt + V_c(0) \end{aligned} \tag{3}$$

The block diagram of Fig.5 is based on the equations (3). As it can be seen in this figure, using the instantaneous voltages and currents of shunt and series inverters, the DC voltage can be determined in time domain. The control signals α, β, m_1 and m_2 are also obtained by controllers and then according to equations (1) and (2), the series and shunt injected voltages can be determined.

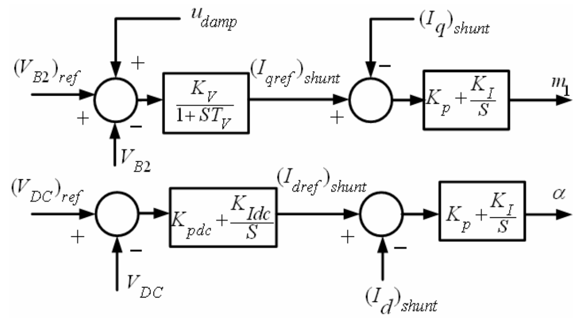

Fig.2. Control system of shunt inverter.

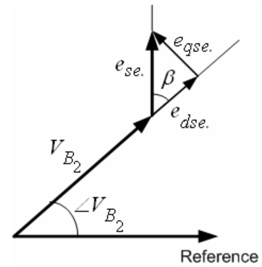

Fig.3. Control of series injected voltage with constant DC bus voltage.

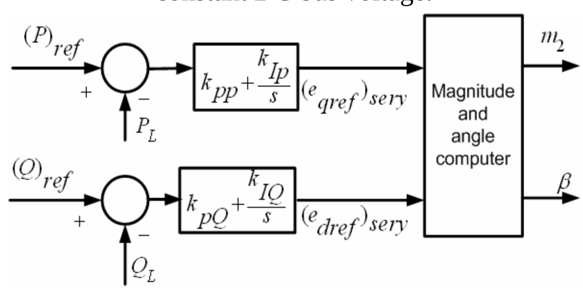

Fig.4. Control system of series inverter.

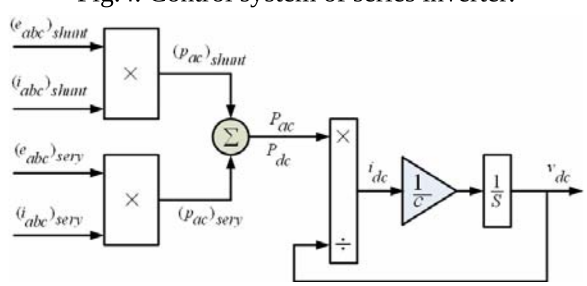

Fig.5. Determination of DC bus voltage.

3 Designing Linear Damping Controller

Fig.6 shows a two area 4-machine interconnected system with 2 parallel tie lines [11]. A UPFC has been used, to control the active and reactive power of the tie line and regulating the voltage of bus 101. The non linear differential and algebraic equations of generators, exciters and network can be written as follows [12].

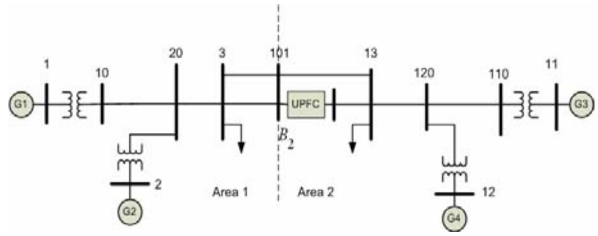

Fig.6. Two area 4-machine power system with 2 parallel tie lines.

$$p\omega_{ri} = \frac{1}{2H_i}\left[P_{mi} - P_{ei} - D_i\Delta\omega_{ri}\right] \quad (4)$$

$$p\delta_i = \omega_0\Delta\omega_{ri} \quad (5)$$

$$E_{fdi} = \frac{1}{T_{Ai}}[\text{-E}_{\text{fdi}} + \text{K}_{\text{Ai}}(\text{V}_{\text{refi}} - \text{V}_{\text{ti}})] \quad (6)$$

$$P_{ei} = V_{tdi}I_{di} + V_{tqi}I_{qi} \quad (7)$$

$$\text{V}_{\text{tdi}} = X_{qi}I_{qi} \quad (8)$$

$$\text{V}_{\text{tqi}} = E'_{qi} - X'_{di}I_{di} \quad (9)$$

$$\text{V}_{\text{ti}} = \sqrt{V_{tdi}^2 + V_{tqi}^2} \qquad \text{i} = 1,2,3,4 \quad (10)$$

$$pV_{dc} = \frac{3m_2}{4C}(\cos\beta.I_{serd} + \sin\beta.I_{serq}) + \frac{3m_1}{4C}(\cos\alpha.I_{shd} + \sin\alpha.I_{shq}) \quad (11)$$

The linear state space representation of the system is obtained by linearization of the non-linear model and presented by the following equations:

$$\dot{X} = AX + Bu \quad (12)$$

$$y = CX + Du \quad (13)$$

$$X = [\Delta\delta, \Delta\omega_r, \Delta E'_q, \Delta E_{fd}, \Delta V_{dc}] \quad (14)$$

$$u = [\Delta\alpha, \Delta m_1, \Delta\beta, \Delta m_2]^T \quad (15)$$

$$\Delta\delta = [\Delta\delta_1, \Delta\delta_2, \Delta\delta_3, \Delta\delta_4]^{\text{T}} \quad (16)$$

$$\Delta\omega_{\text{r}} = [\Delta\omega_{\text{r1}}, \Delta\omega_{\text{r2}}, \Delta\omega_{\text{r3}}, \Delta\omega_{\text{r4}}]^{\text{T}} \quad (17)$$

$$\Delta E_{\text{fd}} = [\Delta E_{\text{fd1}}, \Delta E_{\text{fd2}}, \Delta E_{\text{fd3}}, \Delta E_{\text{fd4}}]^{\text{T}} \quad (18)$$

$$\Delta\text{E}'_{\text{q}} = [\Delta\text{E}'_{\text{q1}}, \Delta\text{E}'_{\text{q2}}, \Delta\text{E}'_{\text{q3}}, \Delta\text{E}'_{\text{q4}}]^{\text{T}} \quad (19)$$

Where u is the control signal vector. The necessary equations for $\Delta\alpha, \Delta m_1, \Delta\beta$ and Δm_2 can be written considering the control systems shown in Fig.2 and Fig.4. Therefore the closed loop state space representation of the system with its all controllers can be written as follows:

$$\dot{X}_m = A_m X_m + Bu_{damp} + \Gamma_m \text{P} \quad (20)$$

$$y = C_m X_m + D_m u_{damp} \quad (21)$$

$$P = [\Delta V_{101ref}, \Delta V_{Dc}, \Delta P_{Lref}, \Delta Q_{Lref}]^T \quad (22)$$

Where P is the disturbance vector and A_m, B_m, C_m, D_m and Γ_m are function of system parameters and operating point. u_{damp} is damping signal which is obtained from damping controller and is added to the reference signal of AC voltage controller. H(s) is the transfer function between controller and system out put as given in the following:

$$H(s) = K_G\frac{sT_w}{1+sT_w} \times \frac{1+sT_1}{1+sT_2} \times \frac{1+sT_3}{1+sT_4} \quad (23)$$

To obtain the optimal parameters of UPFC, the gradient Newton type algorithm can be used [3], [13]. The optimal gain settings of all PI controllers have been given in the appendix.

In the steady state condition, about 700 MW power is generated by each generator. The loads on bus 3 and 13 of Fig.6 are 967 MW and 1767 MW, respectively. 413MW is transmitted from area 1 to area 2 through parallel tie lines. The dominant modes of this system without considering any PSS and UPFC are:

a) The inter-area mode which is clearly observable in the tie line power and is unstable $(f_n = 0.65Hz, \xi = -0.026)$

b) Local mode of area 1 $(f_n = 1.12Hz, \xi = 0.08)$ involving area 1 machines against each other.

c) Local mode of area 2 $(f_n = 1.16Hz, \xi = 0.08)$ involving area 2 machines against each other.

Using UPFC in the tie line with its optimized parameters, the electromechanical inter-area mode, shifts to new location $(f_n = 0.56Hz, \xi = 0.08)$ which is stable but has a poor damping. In order to improve system damping, a supplementary PID controller has been used. The tie line power fluctuations and u_{damp} are selected as input and output of this controller. The lead lag compensator, H(s), results in a pure damping torque [4] and proper selection of H(s) parameters can shift the inter-area electromechanical mode to a new location $(f_n = 0.56Hz, \xi = 0.5)$ which has enough damping. The parameters of the controller are listed in the appendix. This controller will act effectively for the operating point but if the loading condition or topology of the network changes, designer can not be sure about the results of interactions between controllers and system.

4 Adaptive Damping Controller Design

In the previous section the pole placement method has been used. An adaptive power oscillation damping controller based on a new linear quadratic pole placement algorithm will be presented in this section. The case study is the same system shown in Fig.6. The reference signals of UPFC are disturbances of the system and *u* is the control signal. The active power fluctuation of tie line is selected as output (*y*). The relationship between *u* and *y* can be written in descretized form:

$$y(k)+a_1 y(k-1)+a_2 y(k-2)= b_1 u(k-1)+b_2 u(k-2) \quad (24)$$

Where *k* is the number of sampling. The coefficients of equation (24) will be estimated online. Linear Quadratic Gaussian design method can be used for designing adaptive damping controller [14]. In this method the cost function of equation (25) is minimized.

$$J=\sum_{k=0}^{\infty}\{[u_c(k)-y(k)]^2+\rho.[u(k)]^2\} \quad (25)$$

In equation (25) ρ is penalization of controller output and u_c is the reference signal. The optimal control law for minimizing the cost function of (25) is obtained by solving Especial Factorization Problem. The discretized control law of this system can be written as follows:

$$u(k)=\frac{1}{p_0}[r_0 u_c + r_1 u_c(k-1)-q_0 y(k)- q_1 y(k-1)-p_1 u(k-1)] \quad (26)$$

The parameters of controller are determined by solving following two Diophantine equations:

$$A(z^{-1})P(z^{-1})+B(z^{-1})Q(z^{-1})=D(z^{-1}) \quad (27)$$

$$B(z^{-1})R(z^{-1})+F(z^{-1})S(z^{-1})=D(z^{-1}) \quad (28)$$

$$D(z^{-1})=d_0+d_1 z^{-1}+d_2 z^{-2} \quad (29)$$

Where we have:

$$A(z^{-1})=1+a_1 z^{-1}+a_2 z^{-2} \quad (30)$$

$$B(z^{-1})=b_1 z^{-1}+b_2 z^{-2} \quad (31)$$

$$P(z^{-1})= p_0+p_1 z^{-1} \quad (32)$$

$$Q(z^{-1})=q_0+q_1 z^{-1} \quad (33)$$

$$R(z^{-1})=r_0+r_1 z^{-1} \quad (34)$$

$$F(z^{-1})=1+z^{-1} \quad (35)$$

In equation (28), $S(z^{-1})$ is an appropriate polynomial but with minimum degree of one. The identification algorithm is recursive least squares method using variable forgetting factor [15]. Equation (24) can be written in vector form of (36).

$$\hat{y}_k=\theta_{k-1}^T.\phi_k \quad (36)$$

$$\theta_{k-1}=[\hat{a}_1,\hat{a}_2,\hat{b}_1,\hat{b}_2] \quad (37)$$

$$\phi_k=[-y_{k-1},-y_{k-2},-u_{k-1},-u_{k-2}] \quad (38)$$

The elements of vector θ_{k-1} are the estimated parameters computed in the previous step and the elements of the vector ϕ_k are output and input values which must be used for the computation of the output current y_k. Parameter estimations are determined according to the following equations using output estimation $\hat{y}_k$ in step *k*.

$$\theta_k=\theta_{k-1}+\frac{C_{k-1}.\phi_k}{\varphi+\phi_k^T.C_{k-1}.\phi_k}.(y_k-\theta_{k-1}^T.\phi_k) \quad (39)$$

$$C_k=\frac{1}{\varphi}[C_{k-1}-\frac{C_{k-1}.\phi_k.\phi_k^T.C_{k-1}}{\varphi+\phi_k^T.C_{k-1}.\phi_k}] \quad (40)$$

Where φ is exponential forgetting factor. In each sampling period, the estimated parameters of the system are determined, then the characteristic polynomial $D(z^{-1})$ is specified and the control signal is obtained by solving Diophantine equations (27), (28). The block diagram of the adaptive controller is shown in Fig.7.

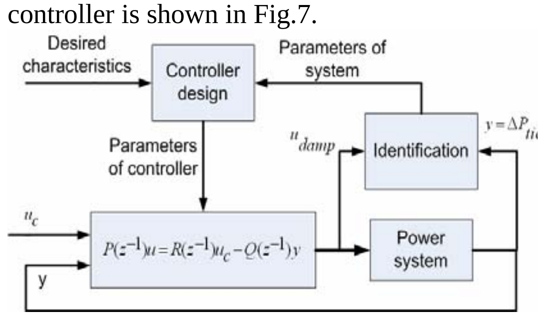

Fig. 7 Block diagram of adaptive controller

5 Simulation Results

To present the merits of the proposed adaptive controller, the system shown in Fig.6 has been simulated for four cases:

a) Without UPFC.
b) With UPFC and without PID damping controller.
c) With UPFC and with PID damping controller.
d) With UPFC and with adaptive damping controller.

In all cases the generators have not any PSS. The operating point of the system is the same as [11] except that voltage profile has been improved by installing 187 MVAr more capacitors in each area (Bus 3 and Bus 13). Generators are equipped with fast static exciters with a gain of 200. The loads are

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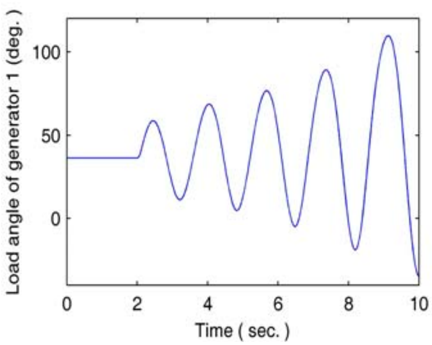
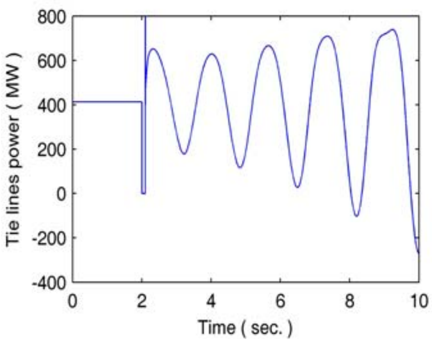
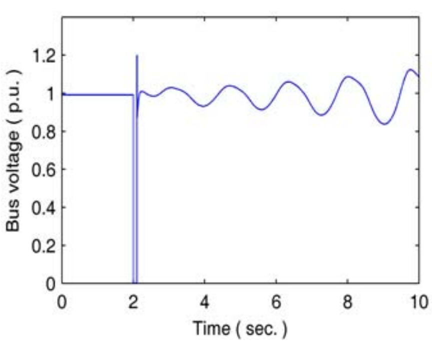
represented as constant impedances and split between two areas in such a way that area 1 is exporting 413 MW to area 2. The parameters of system and the UPFC can be found in [11] and the appendix, respectively. A three phase fault has been simulated in bus 101 and it is cleared in 0.1 s without disconnecting the line. The system responses for case (a) are shown in Fig.8. The results of this figure show that the system is unstable with respect to unstable inter area mode. Fig.9 shows the same results when a UPFC with optimized parameters has been used. It can be seen that the system is stable but the damping of the system is very poor. Fig.10 shows simulation results for case (c). It is obvious that the addition of the PID damping controller can increase the system damping significantly and reduce the first swing peak angle slightly. Long term simulations show that the machines speeds oscillate with a low frequency of 0.076 Hz. The results for case (d) are presented in Fig.11. The results illustrate that the adaptive damping controller is more effective in damping the rotor angle oscillation than PID damping controller. Comparing Fig.10-c and Fig.11-c it can be seen that adaptive controller has been damped low frequency oscillation of generator speeds, too. The control signal of adaptive controller and tie lines power are presented in Fig.11-b and Fig.11-d, respectively.



(8-a)

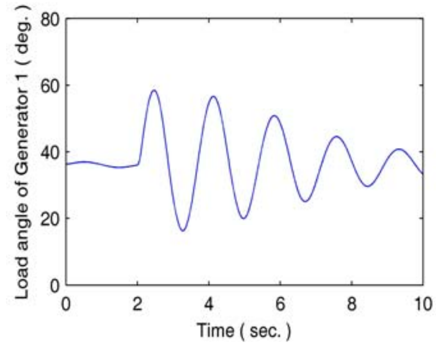


(8-b)

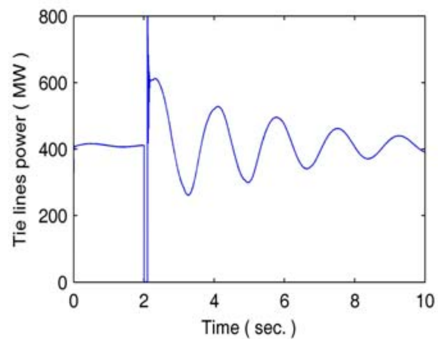


(8-c)

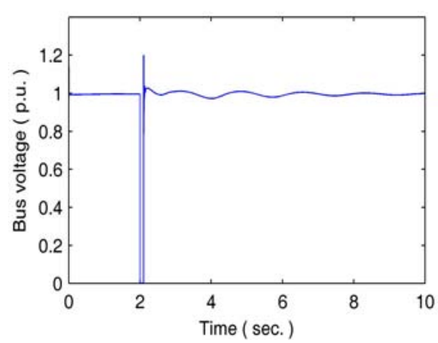
Fig.8 Responses for a three phase fault without UPFC a) Load angle of generator 1. b) Tie lines power. c) The voltage of bus 101.



(9-a)

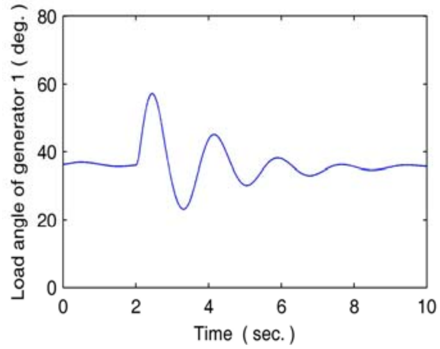


(9-b)

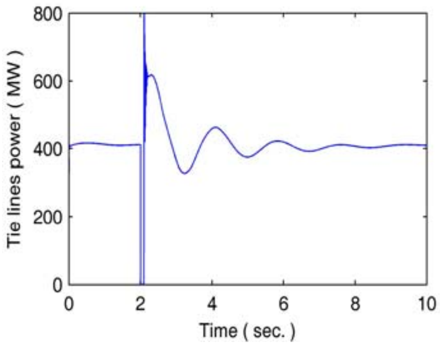


(9-c)

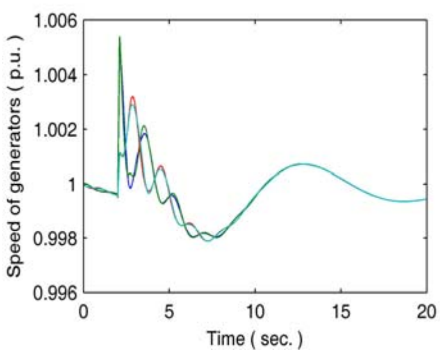
Fig.9 Responses for a three phase fault with UPFC and without any power oscillation damping controller. a) Load angle of generator 1. b) Tie lines power. c) The voltage of bus 101.



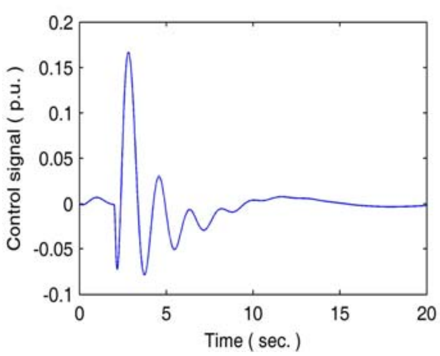
(10-a)



(10-b)

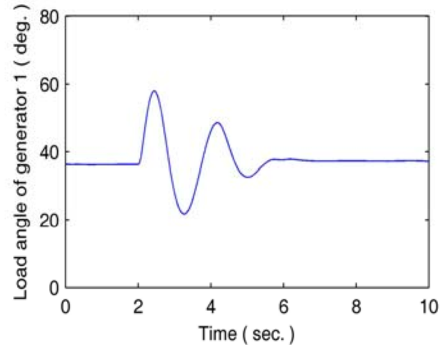


(10-c)

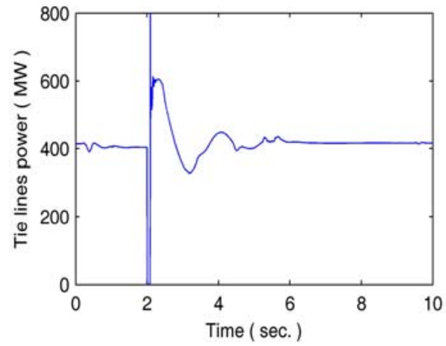


(10-d)

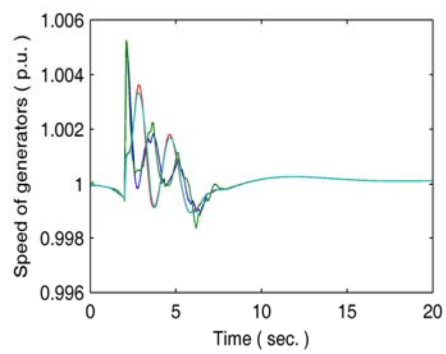
Fig.10 Simulation results for a three phase fault with UPFC and with PID damping controller. a) Load angle of generator 1. b) Tie lines power. c) Speed of generators. d) Control signal of PID controller.



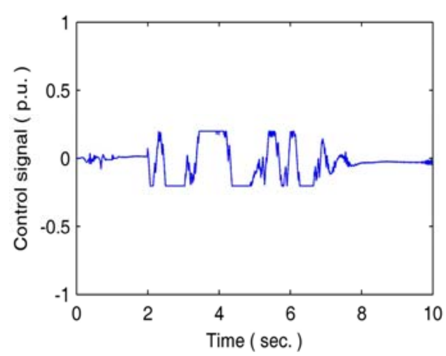
(11-a)



(11-b)



(11-c)



(11-d)

Fig.11 Simulation results for a three phase fault with UPFC and with adaptive damping controller. a) Load angle of generator 1. b) Tie lines power. c) Speed of generators. d) Control signal of adaptive controller.

6 Conclusion

In this paper a new model of UPFC for dynamic studies is proposed. Using this model, an adaptive damping controller has been designed for an interconnected system. It is shown that the proposed designed controller can damp power system oscillations more effective than PID controller. The simulation results show that the PID controller is sensitive to load conditions and system topology but the adaptive damping controller is not sensitive to these changes. For adaptive controller design, a new Linear Quadratic Gaussian pole placement algorithm based on recursive least squares method using variable forgetting factor is introduced, too.

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Appendix

Parameters of UPFC:

$k_v = 33, k_{pdc} = 0.008, k_{pp} = 0.1, k_{pQ} = 0.1,$

$T_v = 0.05, k_{Idc} = 0.15, k_{Ip} = 1.5 , k_{IQ} = 1.5$

$k_p = 0.15$ and $k_I = 6.5$

Parameters of PID controller, H(s):

$T_w = 5\sec.,\ T_1 = T_3 = 0.025\sec.,$

$T_2 = T_4 = 0.33\sec.$ and $K_G = 0.92\,p.u.$