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Damping of Generator Oscillations Using an Adaptive UPFC-based Controller

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Abstract: In this study a UPFC-based non-linear adaptive controller is proposed and designed to damp generator 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 with recursive least squares method with adaptive directional forgetting factor. A new model of UPFC has been introduced too. The simulation results show that the adaptive controller can damp 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

INTRODUCTION

The main function 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 devise can be used to improve transient stability margin or to damp low frequency oscillations[1-3]. In recent years many researches are focused on the modeling of UPFC and its interactions with the power system. But most of these researches use a steady state model of the electrical network and disregard network dynamics. However coordination of multiple control loops of UPFC is one of the most important problems in UPFC controllers design. In[4] Hefron-Phillips model of UPFC, is presented and its controllers design with gradient-type optimization method is discussed. In[5] selecting control signals, controllability and observability indexes are discussed. Papic and et al. in[6] and[7] introduce a new control system for decoupling multiple control loops of UPFC. In that research the parameters of UPFC and transmission line must be known and as a result the main problem of these methods 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 and state space matrixes of linearized system, but the structure of the designed controllers remains constant. It can not be expected that the effectiveness of coordination between system and its controllers is the same as before in the new operating condition. In[8] and[9] multi-variable control design methods for solving the problems of coupling between multiple control systems of UPFC has been presented. But these methods are based on linearized model of system, too. In [10] and[11] 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 study an adaptive UPFC-based stabilizer is used for damping of low frequency oscillations. The design algorithm is based on a new linear quadratic pole placement control law and recursive least squares identification method with adaptive directional forgetting factor. A new model of UPFC as an average model has been presented and simulated in a power system. In the presented model all electrical and mechanical modes of system has been considered and only the dynamics of switching is neglected. The simulation results show that the new model has enough accuracy for low frequency studies.

Proposed model of UPFC: A detailed model of UPFC, including dynamics of switching, can be used for dynamic studies of the network. 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[3]. In the proposed model of this study, all electrical and mechanical modes of system have been considered and only the dynamics of switching has been omitted.

Figure 1 shows a 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 shunt converter is a three level PWM inverter with carrier frequency of 1.6 KHz. The control signals of this inverter are m (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; 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

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reactive current versus bus bar voltage which is assumed to be 3% in this study. The other parameters are given in appendix. The series inverter consists of four three level inverters which are connected by two zigzag-delta and two zigzag-star transformers to the AC bus. The primaries of transformers are connected in series and form a 48 pulse inverter[1]. The amplitude of series injected voltage is controlled by overlap angle σ shown in Fig. 3. Changing of ß with respect to angle of voltage B_2 results in the series injected voltage angle changes. PI controllers shown in Fig. 4 generate the control signals. Using the voltage of bus B2 as the reference, the injected voltages of series and shunt inverters for phase (a) can be written as equations (1) and (2).

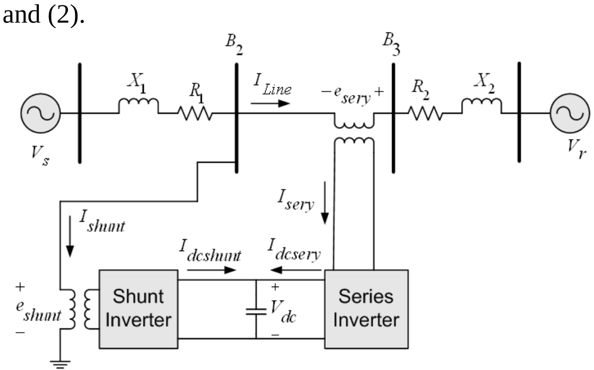


Fig.1: Single line diagram of case study

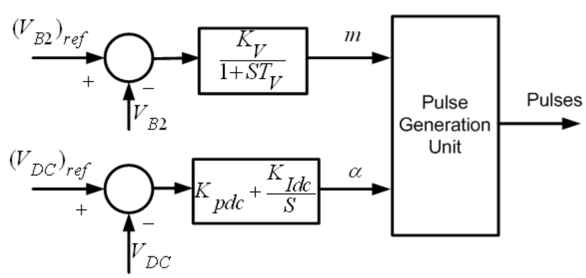


Fig. 2: Control system of shunt inverter

$$e_{ash.} = k_1 * m * V_{dc} * \sin(\omega t + \alpha) \qquad (1)$$

$$e_{ase.} = k_2 * V_{dc} * \sin\frac{\sigma}{2} * \sin(\omega t + \beta) \qquad (2)$$

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

$$P_{dc} = P_{ac} = (P_{ac})_{shunt} + (P_{ac})_{sery} \qquad (3)$$

$$V_{dc} * (I_{dc})_{shunt} + V_{dc} * (I_{dc})_{sery} = (e_{ash.} i_{ash.} + e_{bsh.} i_{bsh.} + e_{csh.} i_{csh.}) + (e_{ase.} i_{ase.} + e_{bse.} i_{bse.} + e_{cse.} i_{cse.}) \qquad (4)$$

$$I_{dc} = \frac{P_{ac}}{V_{dc}} \qquad (5)$$

$$V_{dc} = \frac{1}{C}\int i_{dc}\,dt + V_c(0) \qquad (6)$$

The block diagram of Fig. 5 is based on the equations (3-6). 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, σ *and* m are also obtained by controllers and then according to equations (1) and (2), the series and shunt-injected voltages can be determined.

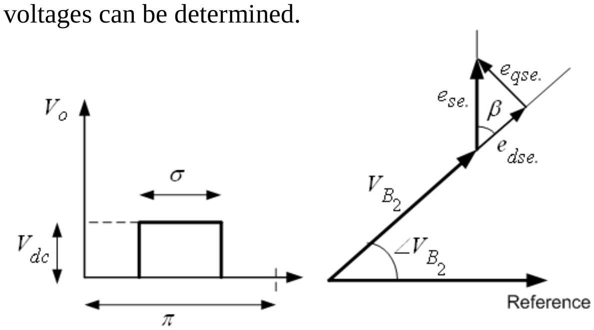


Fig. 3: Control of series injected voltage with constant DC bus voltage

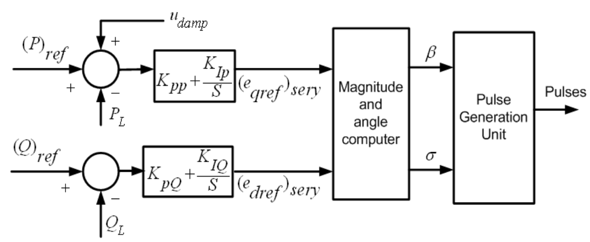


Fig. 4: Control system of series inverter

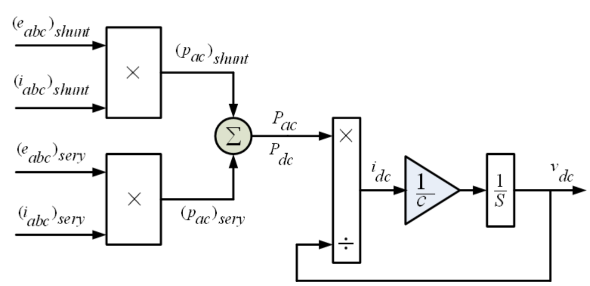
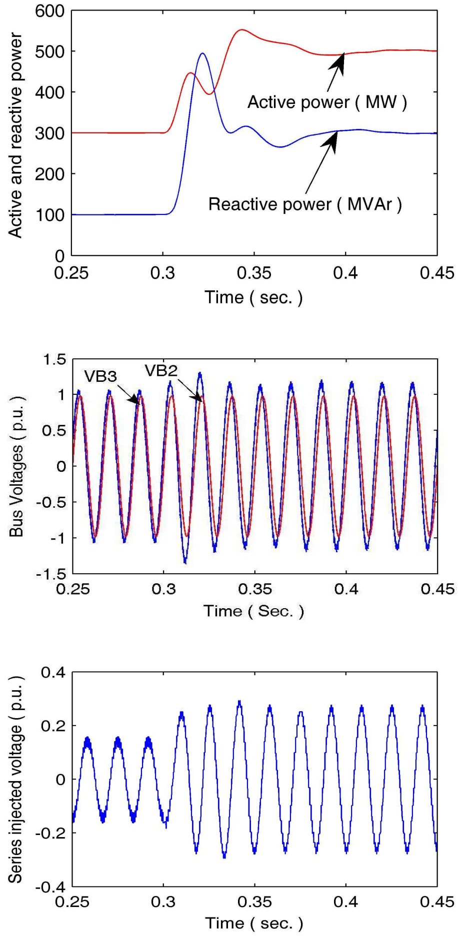


Fig. 5: Determination of DC bus voltage

In UPFC, the control signals obtained from different controllers are transmitted to the pulse generation unit. This unit generates pulses for all switches, so that the desired series and shunt voltages are produced to achieve the specified control objectives. Each switch opening and closing changes the topology of the system and as a result the new set of algebraic and differential equations must be solved for the new topology. Considering the high frequency of switching, the process needs long simulation time and enough memory. For low frequency studies we can neglect the switching dynamics and the proposed model can be used.

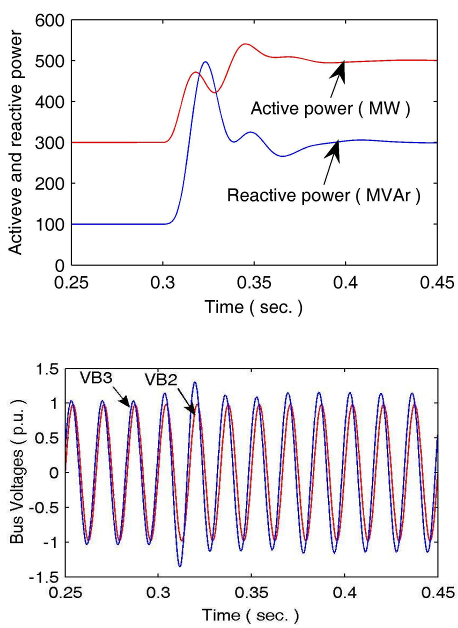


(a)

(b)

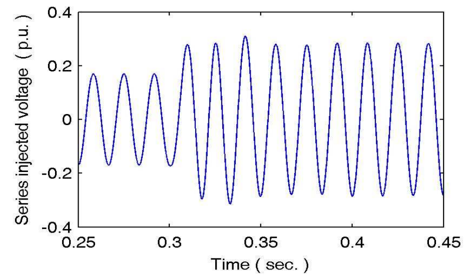
(c)

Fig. 6: Simulation results of detailed model. a) Active and reactive power of line. b) Bus B_2 and B_3 voltages. c) Series injected voltage



(a)

(b)



(c)

Fig. 7: Simulation results of the proposed model. a) Active and reactive power of line. b) Bus B_2 and B_3 voltages. c) Series injected voltage

To show the validity of proposed model, the system shown in Fig. 1 has been modeled with its all details, including switching dynamics. In the study, this model is named the detailed model. The same power system has been modeled based on the proposed method, too. It is assumed that at the start of simulation, the set points of line power flow are 300MW and 100MVAr and the phasors V_s and V_r are equal. At t = 0.3 sec., the set points have been changed to 500 MW and 300 MVAr. Figure 6 and 7 show the simulation results of the detailed and proposed models, respectively. A good agreement between the results can be seen in these figures. The simulation time of the proposed model, is about ten times faster than the detailed model and all electrical modes of network have been detected, too.

In order to improve system damping, a supplementary damping controller can be added with its output u_{damp} used to modulate the reference of active power flow controller (Fig. 4) to provide damping effects. The damping controller can be a conventional PID controller[13] (Fig. 8) or an adaptive damping controller suggested in the next section. H(s) is the transfer function between controller and system out put as shown in Fig. 8 and given in the following equation.

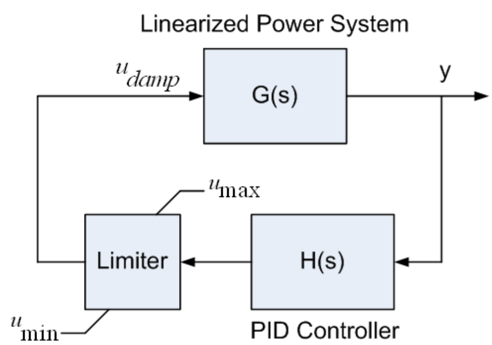


Fig. 8: Linear (PID) power oscillation damping controller

$$H(s) = K_G \frac{sT_w}{1+sT_w} \times \frac{1+sT_1}{1+sT_2} \quad (7)$$

This controller can be designed with linear control methods for the linearized system, around an operating condition[12,13]. It 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 result of interaction between controller and system.

Designing Adaptive Damping Controller: In this section, an adaptive power oscillation-damping controller based on a new linear quadratic pole placement algorithm will be presented. Fig. 9 shows a power system with parallel lines. A UPFC has been installed in one of these lines, to control the active and reactive power of the line and regulating the AC bus voltage. The reference signals of UPFC are the disturbances of the system and u is the control signal. The system output (y) can be $\Delta\omega_r$ or line active power fluctuations. The relationship between u and y can be written in descretized form:

$$y(k)+a_1y(k-1)+a_2y(k-2)= b_1u(k-1)+b_2u(k-2) \qquad (8)$$

Where k is the number of sampling. The coefficients of the equation (8) will be estimated online, using recursive least squares (RLS) identification method considering adaptive directional forgetting factor[14]. Equation (8) can be written in z domain as follows:

$$G(z)=\frac{b_1z^{-1}+b_2z^{-2}}{1+a_1z^{-1}+a_2z^{-2}}=\frac{B(z^{-1})}{A(z^{-1})} \qquad (9)$$

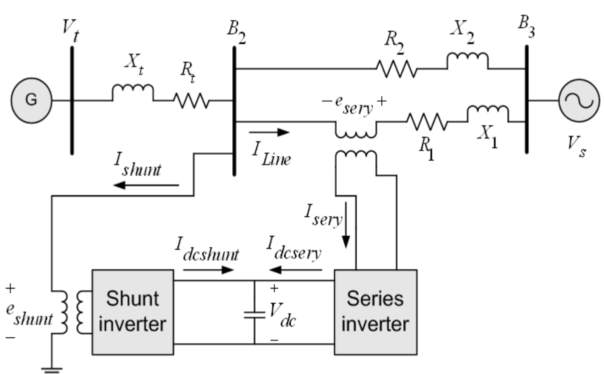


Fig. 9: Power system with parallel lines

Linear Quadratic Gaussian design method can be used for designing adaptive damping controller. In this method the cost function of equation (10) is minimized.

$$J=\sum_{k=0}^{\infty}\{[u_c(k)-y(k)]^2+\varphi.[u(k)]^2\} \qquad (10)$$

In equation (10) φ is penalization of controller output and u_c is reference signal. The optimal control law for minimizing the cost function of (10) is obtained by solving Especial Factorization Problem. The necessary equations have been given by (11)-(17).

$$m_0=\varphi.(1+a_1^2+a_2^2)+(b_1^2+b_2^2) \qquad (11)$$

$$m_1=\varphi.(a_1+a_1a_2)+b_1b_2 \qquad (12)$$

$$m_2=\varphi.a_2 \qquad (13)$$

$$\lambda=\frac{m_0}{2}-m_2+\sqrt{(\frac{m_0}{2}+m_2)^2-m_1^2} \qquad (14)$$

$$\delta=\frac{\lambda+\sqrt{\lambda^2-4m_2^2}}{2} \qquad (15)$$

$$d_2=\frac{m_2}{\delta} \qquad (16)$$

$$d_1=\frac{m_1}{\delta+m_2} \qquad (17)$$

The discretized control law of this system can be written as follows:

$$u(k)=\frac{1}{p_0}[r_0u_c+r_1u_c(k-1) -q_0y(k)-q_1y(k-1)-p_1u(k-1)] \qquad (18)$$

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

$$A(z^{-1})P(z^{-1})+B(z^{-1})Q(z^{-1})=D(z^{-1}) \qquad (19)$$

$$B(z^{-1})R(z^{-1})+F(z^{-1})S(z^{-1})=D(z^{-1}) \qquad (20)$$

Where we have:

$$D(z^{-1})=1+d_1z^{-1}+d_2z^{-2} \qquad (21)$$

$$A(z^{-1})=1+a_1z^{-1}+a_2z^{-2} \qquad (22)$$

$$B(z^{-1})=b_1z^{-1}+b_2z^{-2} \qquad (23)$$

$$P(z^{-1})=p_0+p_1z^{-1} \qquad (24)$$

$$Q(z^{-1})=q_0+q_1z^{-1} \qquad (25)$$

$$R(z^{-1})=r_0+r_1z^{-1} \qquad (26)$$

$$F(z^{-1})=1-z^{-1} \qquad (27)$$

In equation (20), $S(z^{-1})$ is an appropriate polynomial but with minimum degree of one. The parameters of system must be estimated in each sampling period. The identification algorithm is recursive least squares method using adaptive directional forgetting factor.

$$\hat{y}_k=\theta_{k-1}^T.\phi_k \qquad (28)$$

$$\theta_{k-1}=[\hat{a}_1,\hat{a}_2,\hat{b}_1,\hat{b}_2,] \qquad (29)$$

$$\phi_k=[-y_{k-1},-y_{k-2},,-u_{k-1},-u_{k-2}] \qquad (30)$$

The elements of vector θ_{k-1} are the estimated parameters computed in 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. The exponential forgetting method can be further improved by adaptive directional forgetting which changes forgetting coefficient with respect to changes of input and output signal. Process parameters are updated using recursive equation:

$$\theta_k=\theta_{k-1}+\frac{C_{k-1}.\phi_k}{1+\xi}.(y_k-\theta_{k-1}^T.\phi_k) \qquad (31)$$

$$\xi=\phi_k^T.C_{k-1}.\ \phi_k \qquad (32)$$

The covariance matrix C is updated in each step according to equation (33):

$$C_k = C_{k-1} - \frac{C_{k-1}.\phi_k.\phi_k^T.C_{k-1}}{\varepsilon^{-1}+\xi} \qquad (33)$$

where

$$\varepsilon = \varphi_{k-1} - \frac{1-\varphi_{k-1}}{\xi} \qquad (34)$$

Forgetting coefficient is updated as follows:

$$\varphi_k = \frac{1}{1+(1+\rho)\{\ln(1+\xi)+[\frac{(v_k+1)\eta}{1+\xi+\eta}-1]\frac{\xi}{1+\xi}\}} \qquad (35)$$

Where:

$$v_k = \varphi_{k-1}(v_{k-1}+1) \qquad (36)$$

$$\eta = \frac{(y_k - \theta_{k-1}^T\phi_k)^2}{\lambda_k} \qquad (37)$$

$$\lambda_k = \varphi_{k-1}[\lambda_{k-1} + \frac{(y_k-\theta_{k-1}^T\phi_k)^2}{1+\xi}] \qquad (38)$$

In each sampling period, the estimated parameters of the system are determined. With the help of these parameters and solving especial factorization problem, desired characteristic polynomial $D(z^{-1})$ is specified and then, the control signal is obtained by solving two Diophantine equations. The block diagram of the adaptive controller is shown in Fig. 10. The control signal and the active power reference can be seen in Fig. 11.

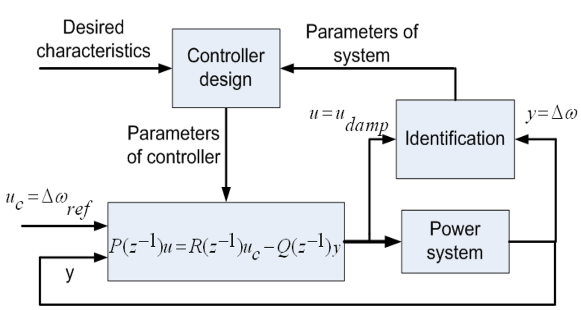


Fig. 10: Block diagram of adaptive controller

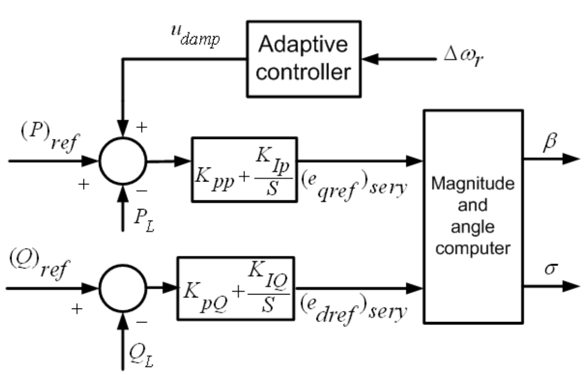
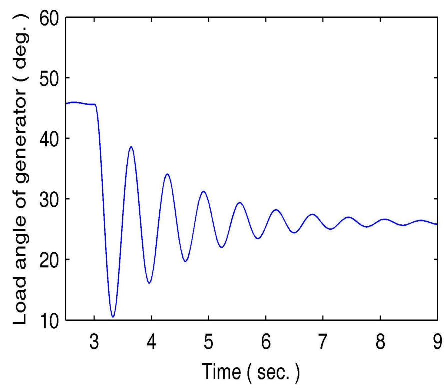


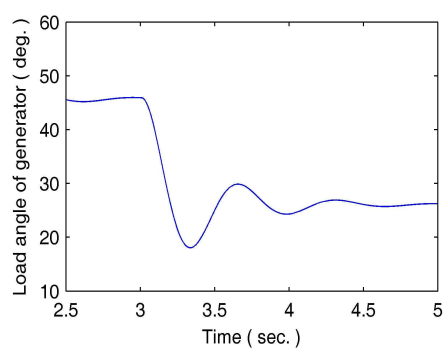
Fig. 11: Adaptive damping controller

RESULTS

To present the merits of the proposed adaptive controller, the system shown in Fig. 9 has been simulated in three cases, a) without any damping controller, b) with a PID controller and c) with an adaptive controller. The set point of active power flow in the line with UPFC is 0.5 p.u.. At t= 3 sec., the set point has been changed to 0.75 p.u.. The load angle of generator for the three cases are presented in Fig. 12a-c, respectively. Load angle of generator without any damping controller has poor damping (with the mechanical mode of $\lambda_0 = -0.47 \pm j8.37$). Considering the parameters of H(s) given in appendix, the mechanical mode is shifted to new location ($\lambda_1 = -4.84 \pm j8.25$). Considering the Fig. 12b and c it can be seen that the adaptive controller can damp the oscillations better than the PID controller for a changes in the operating conditions. Figure 12d and e show the active power of generator and control signal of adaptive controller, respectively. The second simulation is a three phase fault simulation for three cycles in the bus near the generator. The generator load angle for the system with PID and adaptive damping controller are presented in Fig. 13a and b, respectively. It is clear that the adaptive controller damps the system oscillations better. Figure 13c shows the control signal of adaptive controller.



(a)



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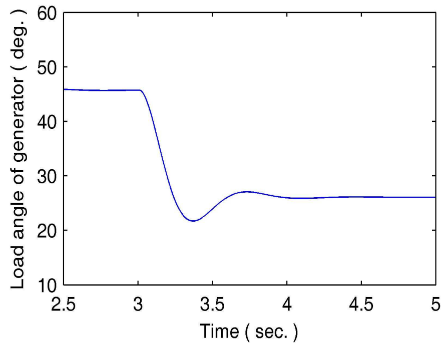

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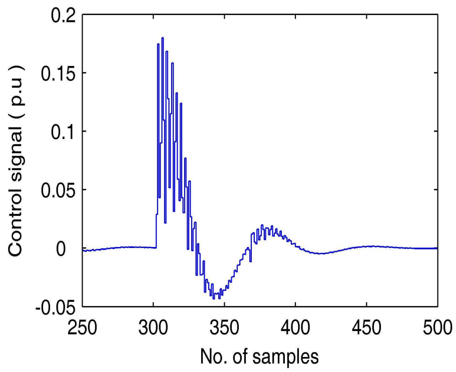
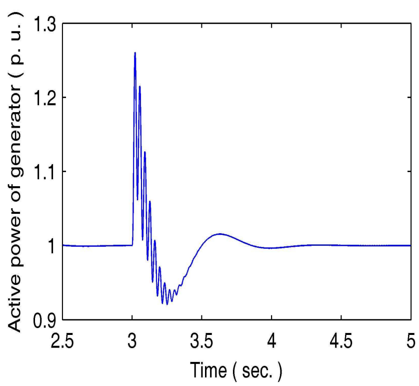
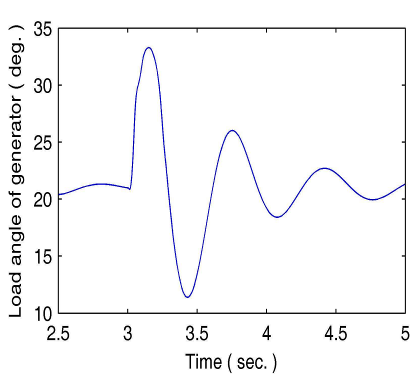


(d)

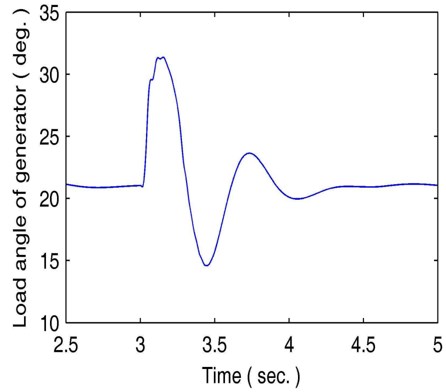


(e)

Fig. 12: Operating point and generator load angle changes, a) without any damping controller, b) with PID controller, c) with adaptive controller, d) Control signal of adaptive controller, e) Active power of generator



(a)



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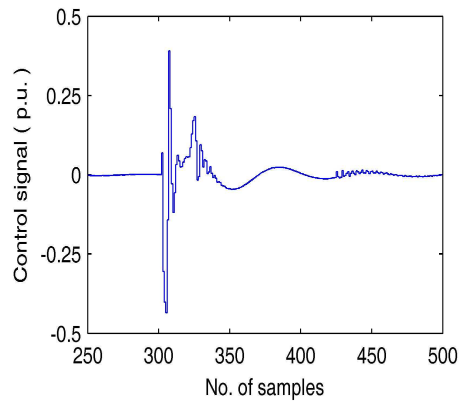

(c)

Fig. 13: Three phase fault and the generator load angle changes, a) PID controller, b) Adaptive controller, c) Control signal of adaptive damping controller

CONCLUSION

In this study a new model of UPFC for dynamic studies is proposed. Using this model, an adaptive damping controller has been designed. It is shown that the proposed designed controller can damp power system oscillations better than PID controller. Considering the simulation results, it can be seen that the adaptive damping controller is not sensitive to load condition and system topology changes. In the adaptive controller phase, a new Linear Quadratic Gaussian pole placement algorithm based on recursive least squares method using adaptive directional forgetting factor is introduced, too. In this algorithm control signal is obtained by solving two Diophantine equations and minimizing an objective function.

Appendix

The parameters of Fig. 1:

$R_1 = R_2 = 0.05\,p.u.$, $X_1 = X_2 = 0.85$ p.u.,

$V_s = V_r = 1$ p.u.,

$V_B = 400$ kV, $S_B = 400$ MVA and $C = 75$ mF

The parameters of Fig. 9:

$R_t = 0.01 p.u.$, $X_t = 0.12 p.u.$, $V_s = 1 p.u.$,
$R_1 = R_2 = 0.05 p.u.$ and $X_1 = X_2 = 0.85$ p.u.
Generator:
$X'_d = 0.3 p.u.$, $X_q = 0.9 p.u.$, $p_{mech} = 1 p.u.$,
$H = 3.5$ sec and $D = 0.05$ p.u.
Excitation:
$K_A = 200$ and $T_A = 0.05$ sec.
The parameters of UPFC:
$K_V = 33, k_{pdc} = 0.15, k_{pp} = 0.1, k_{pQ} = 0.1,$
$T_V = 0.05, k_{Idc} = 3, k_{Ip} = 70$ and $k_{IQ} = 70$
The parameters of PID controller, H(s):
$T_w = 5 \sec.$, $T_1 = 0.1 \sec.$,
$T_2 = 0.5 \sec.$ and $K_G = 26 p.u.$
Series and shunt inverter transformers:
$X_{tshunt} = 0.1 p.u.$, $R_{tshunt} = 0.01 p.u.$,
$X_{tsery} = 0.1 p.u.$ and $R_{tsery} = 0.01 p.u.$

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