Adaptive Stabilizing Control of Power System through Series Voltage Control of a Unified Power Flow Controller

A.H.M.A. Rahim S.A. Al-Baiyat
Department of Electrical Engineering
King Fahd University of Petroleum & Minerals
Dhahran, Saudi Arabia.
E-mail: ahrahim@kfupm.edu.sa

Keywords: Power system stability, UPFC, damping control, adaptive control, pole-shifting control.

Abstract
The unified power flow controller (UPFC) is a FACTS device, which is used to control the` power flow on a transmission line. The dynamic and transient behavior of a power system can be improved by controlling the voltage magnitude and phase angle of the converter voltages in the UPFC. Self-tuning adaptive control of the voltage magnitude of the series converter for power system stability is presented in this article. The control is derived through a pole-shifting technique employing the predicted plant model. The controller has been tested for ranges of operating conditions and for various disturbances. From a number of simulation studies on a simple power system it was observed that the adaptive algorithm converges very quickly and also provides robust damping profiles.

INTRODUCTION
The unified power flow controller (UPFC) is normally located on a transmission network requiring reactive support. The usual form of a UPFC consists of two voltage source converters, which are connected through a common DC link capacitor. The first voltage source converter known as static synchronous compensator (STATCOM) injects an almost sinusoidal current of variable magnitude at the point of connection. The second voltage source converter known as static synchronous series compensator (SSSC) injects a sinusoidal voltage of variable magnitude in series with the transmission line. The real power exchange between the converters is affected through the common DC link capacitor. UPFC can be used for power flow control, loop flow control, load sharing among parallel corridors, providing voltage support, enhancement of transient stability, mitigation of system oscillations, etc. [1,2]. The stability and damping control aspect of an UPFC has been investigated by a number of researchers [3-7]. The additional damping control circuits can be installed in normal power flow controllers. Most of the control studies in power systems are based on linearized models of the nonlinear power system dynamics. The methods include exact linearization, linear quadratic regulator theory, direct feedback linearization, etc. Stabilizers based on conventional linear control theory with fixed parameters can be very well tuned to an operating condition and provide excellent damping under that condition, but they cannot provide effective control over a wide operating range for systems that are nonlinear, time varying and subject to uncertainty. It is desirable to develop a controller which has the ability to adjust its own parameters, finding the system structure or model on-line according to the environment in which it works to yield satisfactory control performance. Application of adaptive control theory to excitation control problems is well documented in the literature [8, 9]. Adaptive control of SVC systems has also been reported in the literature [10, 11]. UPFC is relatively new power electronics based device, and its control studies have generally been limited in this regard.

This article considers a stabilizing control design procedure of the voltage magnitude of the series converter of the UPFC. The design is carried out through a variable pole shifting method employing the identified plant model parameters which are tuned adaptively.

POWER SYSTEM MODEL WITH UPFC
Fig. 1 shows a single machine system connected to a large power system bus through a transmission line installed with UPFC. The UPFC is composed of an excitation transformer (ET), a boosting transformer (BT), two three-phase GTO based voltage source converters (VSC), and a DC link capacitor [1, 3]. m and α refer to amplitude modulation index and phase angle of the control signal of the two voltage source converters (E and B), respectively which can be adjusted through their own control loops.

Representing the synchronous generator-exciter system through a 4 differential equations, including the series and parallel transformer line dynamics, and one differential equation to represent the DC link, the composite model of a synchronous generator UPEC system can be expressed through the 9th order dynamic relationship,

$$\dot{x} = f[x,u] \qquad (1)$$

Here, the state vector $x = [I_{Ed}\ \ I_{Eq}\ \ I_{Ld}\ \ I_{Lq}\ \ V_c\ \ \delta\ \ \omega\ \ e_q'\ \ E_{fd}]^T$ and $u=[m_E\ \ \alpha_E\ \ \ m_B\ \ \alpha_B]^T$. The first 4 states are the d-q components of the shunt and series (line) currents respectively; V_c is the DC capacitor voltage, and the last 4 are those for the generator-exciter system. The control vector comprises of the magnitude and phase angles of the converter voltages.

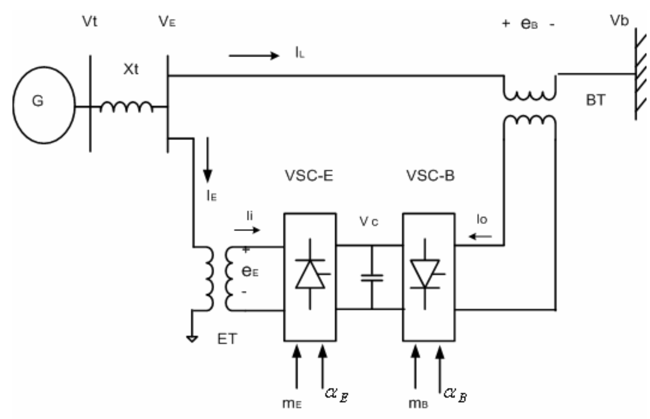

Figure 1 A single machine infinite bus system with UPFC

SELF-TUNING ADAPTIVE REGULATOR

Self tuning control employs a feedback controller loop in which the controller parameters are modified depending on the error between the real plant output and estimated outputs, as shown in Fig.2. The control for the plant is designed using a linear plant model, parameters of which are estimated and updated recursively.

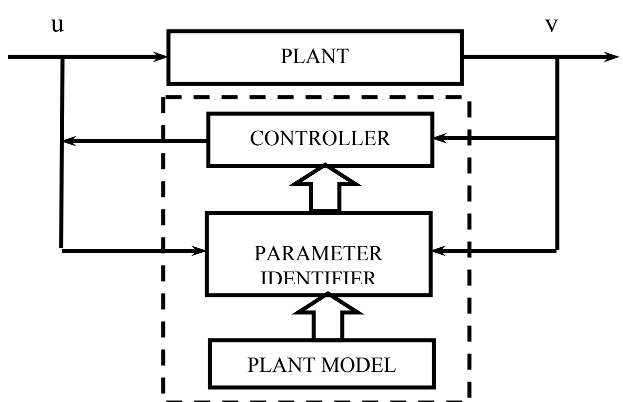

Figure 2 Block diagram of self-tuning controller

The plant model is assumed to be of the form,

$$A(z^{-1})y(t)=B(z^{-1})u(t)+e(t) \tag{2}$$

where, y(t),u(t) and e(t) are system output, input and the white noise, respectively; z^{-1} is the delay operator. The polynomial A and B are defined as,

$$A(z^{-1}) = 1+ a_1z^{-1} + a_2z^{-2} + a_3z^{-3} + a_4z^{-4} + \text{...........} \tag{3}$$

$$B(z^{-1}) = 1+ b_1z^{-1} + b_2z^{-2} + b_3z^{-3} + b_4z^{-4} + \text{............} \tag{4}$$

The vector of parameters $\theta(t)= [a_1\ a_2\ \text{........},b_1\ b_2\ \text{..........}]^T$ are calculated recursively on-line through the recursive least square [8] technique using,

$$\theta(t+1) = \theta(t) +K(t)\ [y(t) - \theta^T(t)\psi(t)] \tag{5}$$

The measurement vector, modifying gain vector, and the covariance matrix, respectively are,

$$\psi(t)= [-y(t-1)\ y(t-2)\text{......}y(t-n_a)\ u(t-1)\ u(t-2)\text{........}u(t-n_b)]^T$$

$$K(t) = \frac{P(t)\psi(t)}{\lambda(t)+\psi^T(t)P(t)\psi(t)} \tag{6}$$

$$P(t+1) = \frac{1}{\lambda(t)}[P(t) - K^T(t)P(t)\psi(t)]$$

$\lambda(t)$ is the forgetting factor; n_a and n_b denote the order of the polynomials A and B, respectively. The identified parameters in (5) can be considered as the weighted sum of the previously identified parameters and those derived from the present signals. For systems with constant parameters $\lambda = 1$ produces convergence of the algorithm while for systems with time-varying parameter a variable forgetting factor given by [12],

$$\lambda(t)=\mathrm{trace}[P(t) - K(t)\ \psi^T(t)P(t)]/\mathrm{trace}(P_0) \tag{7}$$

is required to maintain the trace of the error covariance matrix constant. In the above, P_0 is the initial error covariance matrix and P(t) is the matrix at the iteration before discounted by λ. Using the forgetting factor, the error covariance matrix is updated at each sampling instant by,

$$P(t)=P(t-1)/\ \lambda(t) \tag{8}$$

THE CONTROL STRATEGY

Using the parameters obtained from the real time parameter identification method, a self-tuning controller based on pole assignment is computed on-line and fed to the plant. Under the pole shifting control strategy, the poles of the closed loop system are shifted radially towards the centre of the unit circle in the z-domain by a factor α, which is less than one. The procedure for deriving the pole–shifting algorithm [13] is given below.
Assume that the feedback loop has the form,

$$\frac{u(t)}{y(t)} = -\frac{G(z^{-1})}{F(z^{-1})} \tag{9}$$

where,

$$F(z^{-1}) = 1+ f_1z^{-1} + f_2z^{-2} + f_3z^{-3} + f_4z^{-4} + \text{................}+f_{nf}z^{-nf}$$

$$G(z^{-1}) = g_0 + g_1 z^{-1} + f_2 z^{-2} + f_3 z^{-3} + f_4 z^{-4} + \ldots\ldots\ldots\ldots + f_{ng} z^{-ng}$$

$n_f = n_b - 1,\ n_g = n_a - 1$

From (2) and (9) the characteristic polynomial can be derived as,

$$T(z^{-1}) = A(z^{-1})F(z^{-1}) + B(z^{-1})G(z^{-1}) \tag{10}$$

The pole-shifting algorithm makes $T(z^{-1})$ take the form of $A(z^{-1})$ but the pole locations are shifted by a factor α, i.e.

$$A(z^{-1})F(z^{-1}) + B(z^{-1})G(z^{-1}) = A(\alpha z^{-1}) \tag{11}$$

Expanding both sides of (11) and comparing the coefficients give,

$$\begin{bmatrix} 1 & 0 & . & 0 & b_1 & 0 & . & 0 \\ a_1 & 1 & . & 0 & b_2 & b_1 & . & 0 \\ . & a_1 & . & . & . & b_2 & . & 0 \\ a_{n_a} & . & . & 1 & b_{n_b} & . & . & b_b \\ 0 & a_{n_a} & . & a_1 & 0 & b_{n_b} & . & b_2 \\ . & 0 & . & . & . & 0 & . & . \\ . & . & . & . & . & . & . & . \\ 0 & 0 & . & a_{n_a} & 0 & 0 & . & b_{n_b} \end{bmatrix} \begin{bmatrix} f_1 \\ . \\ . \\ f_{nf} \\ g_0 \\ . \\ . \\ g_{n_g} \end{bmatrix} = \begin{bmatrix} a_1(\alpha - 1) \\ a_2(\alpha^2 - 1) \\ . \\ . \\ a_{n_a}(\alpha^{n_a} - 1) \\ 0 \\ . \\ 0 \end{bmatrix}$$

The above is written in the form,

$$MZ(\alpha) = L(\alpha) \tag{12}$$

If parameters $[\{a_i\}, \{b_i\}]$ are identified at every sampling period and pole-shift factor α is known, the control parameters $Z=[\{f_i\},\{g_i\}]$ solved from (12) when substituted in (9) will give,

$$u(t, \alpha) = X^T(t)Z = X^T(t)M^{-1}L(\alpha) \tag{13}$$

In the above, $X(t)=[-u(t-1)\ -u(t-2).....u(t-n_f)\ -y(t)\ -y(t-1)\ -y(t-2)..........y(t-n_g)]$

The controller objective is to force the system output y(t) to follow the reference output $y_r(t)$. The objective function can then be expressed as,

$$J = \min_{\alpha}[y(t) - y_r(t)]^2 \tag{14}$$

In the above, $y(t)=b_1u(t) + X^T\beta$; $\beta=[-b_2\ \ -b_3\ \ \ldots\ldots.\ a_1\ \ a_2\ \ldots\ldots.]$.

If the variation of J with respect to α can be made smaller than a predetermined error bound ε_1, it can be shown that a minimum will occur when,

$$\Delta\alpha = \frac{\varepsilon_1 - \dfrac{\partial J}{\partial \alpha}}{\varepsilon_2 + \dfrac{1}{2}\dfrac{\partial^2 J}{\partial \alpha^2}} \tag{15}$$

where, ε_2 is a small number chosen to avoid the singularity. This can then be expressed as,

$$\Delta\alpha = \frac{\varepsilon_1 - f_1 f_2}{\varepsilon_2 + \dfrac{1}{2}[f_1 f_3 + 2b_1^2 f_2^2]} \tag{16}$$

In the above,

$$f_1 = \frac{\partial J}{\partial u};\quad f_2 = \frac{\partial u}{\partial \alpha};\quad f_3 = \frac{\partial^2 u}{\partial \alpha^2}$$

The partial derivatives are evaluated from (13) and (14), and updates of the control is obtained considering first few significant terms of the Taylor series expansion of $u(t,\alpha)$.The algorithm can be started by selecting an initial value of α and updating it at every sample through the relationship,

$$\alpha(t) = \alpha(t-1) + \Delta\alpha \tag{17}$$

The control function is limited by the upper and lower limits and the pole shift factor should be such that it should be bounded by the reciprocal of the largest value of characteristic root of A (z^{-1}). The latter requirement is satisfied by constraining the magnitude of α to unity.

PERFORMANCE OF THE CONTROLLER

The input and output of the plant were considered to be the series converter voltage magnitude of the UPFC and the generator speed variation, respectively. In order to excite the plant for the identification and control process, a sequence of torque step disturbances to the generator shaft are simulated. The diagonal elements of the initial covariance matrix P is assumed be $2x10^5$, the initial pole shift factor 0 and the forgetting factor 1 were used. The starting values of all the parameters were considered to be 0.001 in all the simulations for consistency. The model order to be estimated was assumed to be 3. Fig.3 shows the generator speed deviation with no control when excited by the sequence of torque steps of +5%, -5%, +5% and -5%. The nominal loading is 0.85 pu at 0.9pf lagging. The generator terminal voltage at this load is 1.07 pu and the bus voltage is 1 pu.

The response of the system with the online control strategy and convergence of the parameters is shown in Figs 4-8. Fig.4 shows the variation of the generator speed with the pole-shift control applied to the identified process. It is apparent that the electromechanical transients are damped very well by the adaptive controller. The plant parameters are unknown at the start of the estimation process which gives the poorer response in the early part of the transients. Fig. 5 shows the variation of the pole shift factor as the estimation procedure progresses. The convergence of the {a} and {b} parameters in the in the adaptive algorithm are shown in Figs. 6 and 7, respectively. The estimation algorithm converges to the desired values rapidly. The convergence of the algorithm is independent of the initial choice of the pole shift factor α. The variation of the control function is depicted in Fig.8; it can be observed that very good damping can be provided with minimum control effort.

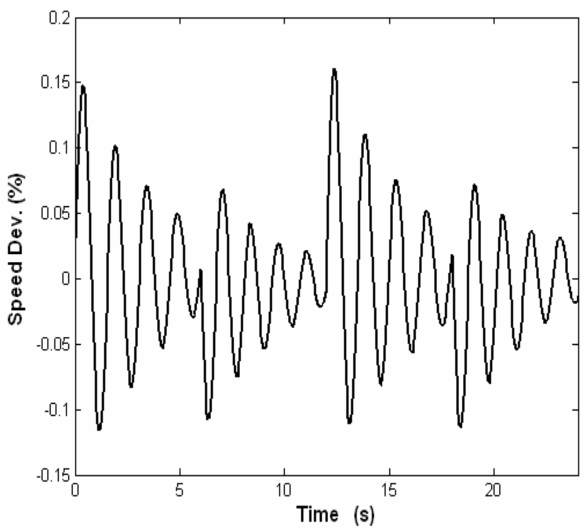

Figure 3 Generator speed variation with no control

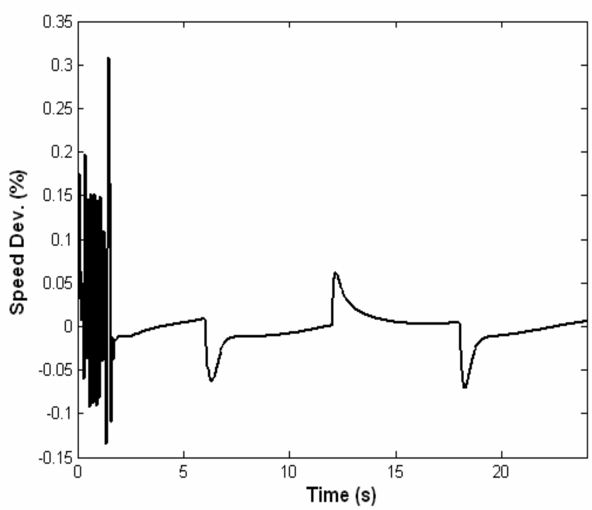

Figure 4 Generator speed deviation with the online adaptive stabilizing control

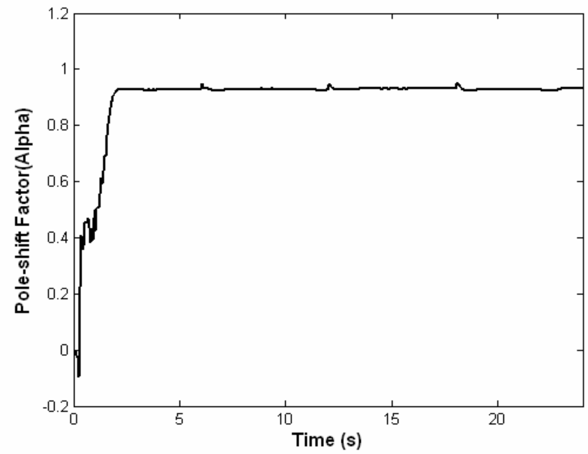

Figure 5 Online adaptation of the pole shift factor

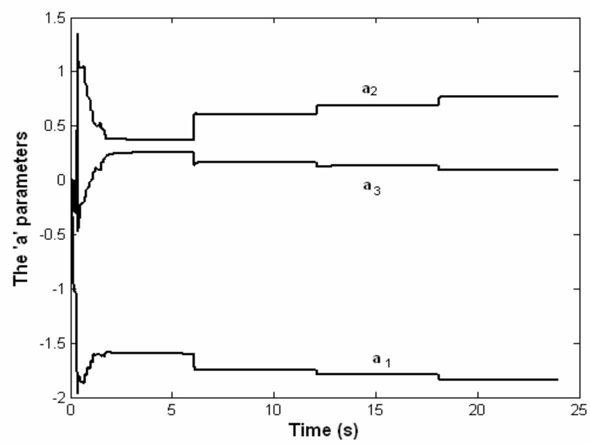

Figure 6 Online adaptation of the ‘a’ parameters in the model function

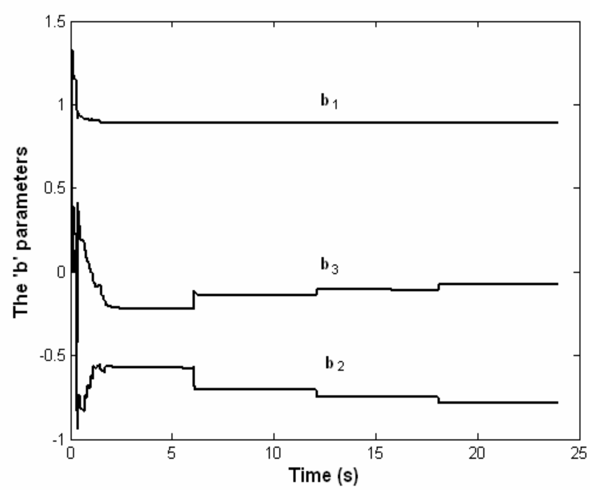

Figure 7 Online adaptation of the ‘b’ parameters

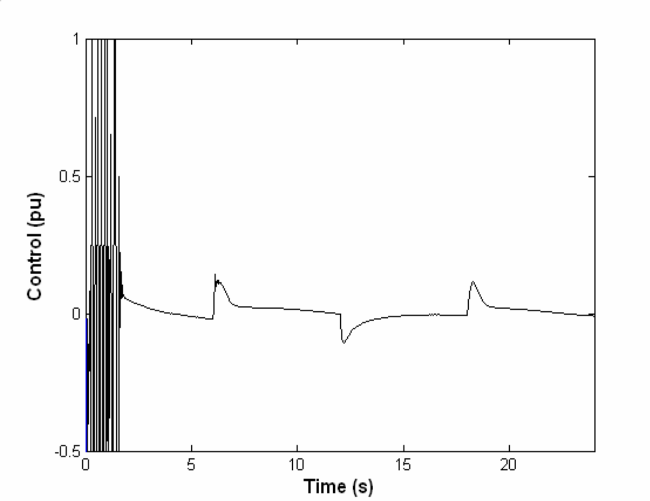

Figure 8 The control signal using the pole-shift method

TESTING THE ADAPTIVE CONTROLLER

A number of case studies were performed with the adapted system parameters and the pole shift parameters arrived at in the previous section. For a 50% input torque pulse on the generator, the rotor angle variations recorded for 5 operating conditions are shown in Fig.9. These are for generator outputs of a)1.1 pu , b)1.02 pu , c) 0.85pu , d)0.78 pu, and e)0.6pu. It can be observed that the damping properties are very good for the whole range of operation considered. Fig. 10 shows the transient angle variations of the generator with the proposed adaptive control strategy for severe three-phase fault of 0.1s duration for the loadings considered in Fig.9. It is to be noted that without control the system is under damped, in general, and unstable in some cases. Fig. 11 shows the response without control (p) and with control (q) for the three phase fault condition at 1.1 pu loading.

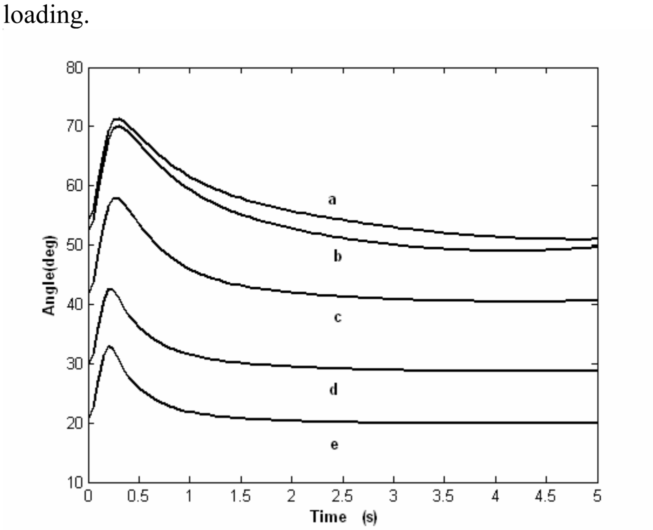

Figure 9 Generator rotor angle variations following 50% torque pulse for 5 loading conditions.

Fig.12 shows the variations of the generator terminal voltage for three loading conditions (a) 1.1pu, (b) 1.02 and (c) 0.85 pu. It can be seen that that the control strategy restores the voltage very quickly from a total collapse. These simulations were carried out with the converged plant model and pole-shift factor as obtained in the nominal loading considered in Figs. 3-10. In real applications, the models as well as the controls will be tuned on-line and is, hence, expected to provide better performance. All these simulation results indicate good dynamic behavior of the power system with the adaptive UPFC controller.

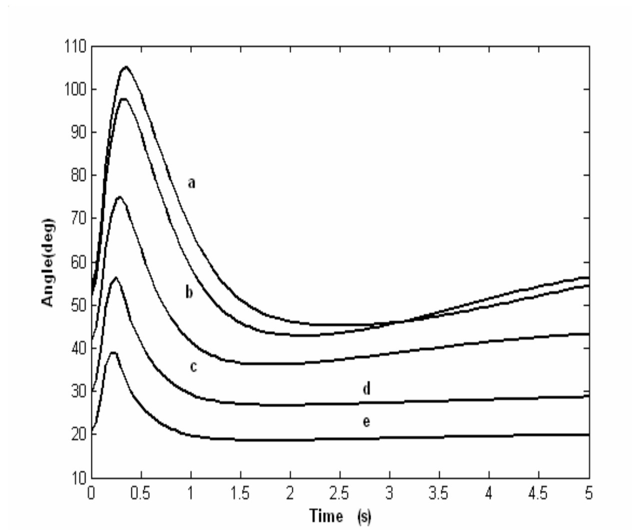

Figure 10 Generator rotor angle following a three-phase fault for the loadings as in Fig. 9

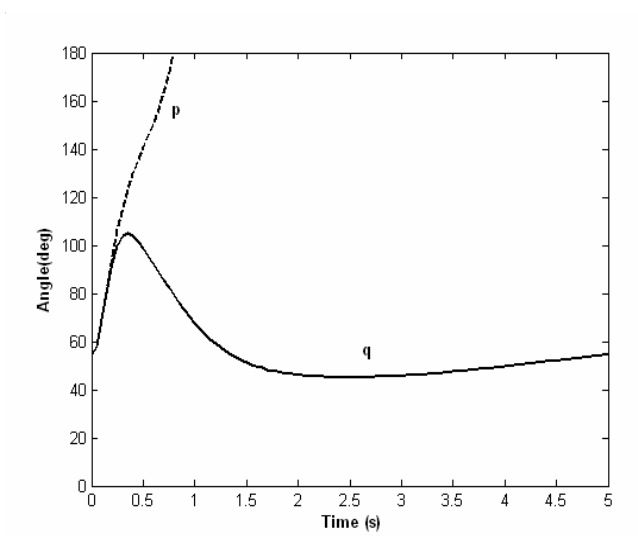

Figure 11 Comparison of response without control (p) and the proposed adaptive control (q) following three-phase fault at 1.1 pu loading

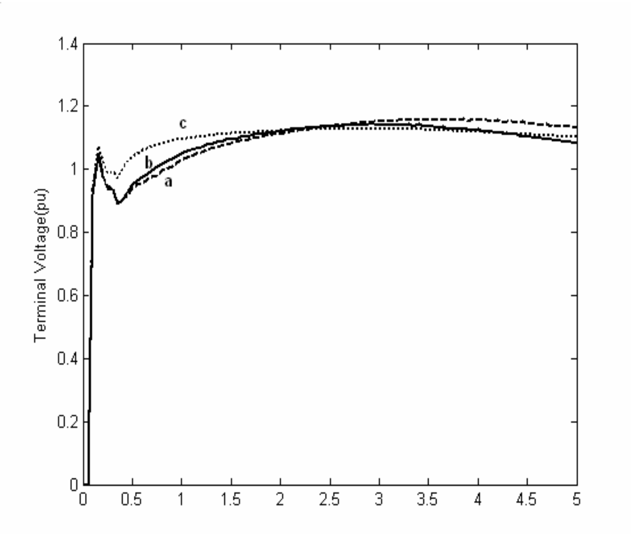

Figure 12 Terminal voltage variation of generator following three-phase fault for different loading conditions

CONCLUSIONS

An adaptive control technique has been used to enhance the dynamic performance of a power system installed with unified power flow controller. The control employed is the magnitude of the series converter voltage. The proposed stabilizing technique identifies the plant model on-line and generates a control to stabilize the closed-loop system employing a pole shift technique. The algorithm has been shown to converge to estimated parameter model rapidly. The on-line controller has demonstrated to provide very good damping to the system transients. The robustness of the control strategy was tested by considering the converged values obtained from the test phase. It was observed that the control provided robust performance over a wide range of power system operation.

ACKNOWLEDGEMENT

The authors wish to acknowledge the facilities provided by the King Fahd University of Petroleum and Minerals towards this research. This work is funded by KFUPM under Project FT-2005-09.

REFERENCES

[1] Nabavi-Niaki, A., and Irvani, M.R., "Steady State and Dynamic Models of Unified Power Flow Controller (UPFC) for Power System Studies", *IEEE Trans. on Power Systems*, 1996, 11(4), pp.1937- 1943.

[2] Dong, L.Y., Zhang, L., and Crow, M.L., "A New Control Strategy for Unified Power Flow Controller", *IEEE PES Winter Meeting*, 2002, Vol. 1, pp.562-566.

[3] Seo, J., Moon, S., Park, J. and Choe, J., "Design of a Robust UPFC Controller for Enhancing the Small Signal Stability in the Multi-machine Power Systems", *IEEE Power Engineering Society Winter Meeting,* 2001, Vol. 3, pp.1197-1202.

[4] Wang, H.F., "Damping Function of Unified Power Flow Controller", *IEE Proc.-Gener. Transm. Distrib.*, 1999, 146(1), pp.81-87.

[5] Tambey, N. and Kothari, M.L., "Damping of Power System Oscillations with Unified Power Flow Controller (UPFC)", *IEE Proc.-Gener. Transm. Distrib.,* 2003, 150(2), pp.129-140.

[6] Wu, X., Qu, Z., and Mohapatra, R.N., "Stability Constrained Operation of UPFC Devices", *IEEE Transmission& Distribution Conference & Exposition*, 2001, Vol. 1, pp.31-36.

[7] Wang, H.F., "Applications of Modeling UPFC into Multi-machine Power Systems", *IEE Proc.-Gener. Transm. Distrib.*, 1999, 146(3), pp.306-312.

[8]W.M.Hussein and O.P.Malik, "Study of System Performance with Duplicate Adaptive Power System Stabilizer", Electric Power Components and Systems, 2003, 31, 899-912.

[9] A. Soos and O.P.Malik, "An H_2 Optimal Adaptive Power System Stabilizer", IEEE Trans. on Energy Conversion, 2002, 17(1), 143-149.

[10] J.R. Smith, D.A. Pierre , D.A.Rudberg, I. Sadhigi, A.P.Johnson and J.F.Hauer, An Enhanced LQ Adaptive VAr Unit Controller for Power System Damping, IEEE Trans. on Power Systems, 1989, 4(2), 443-451.

[11]P.K.Dash, P.C.Panda, A.M.Sharaf and E.F.Hill, Adaptive Controller for Static Reactive Power Compensation in Power Systems, Proc. IEE, 1987, 134(3), 256-284.

[12] R.Lozano-Leal and C. Goodwin-Graham, "A Globally Covergent Adaptive Pole-placement Algorithm with Persistency of Excitation Requirements", IEEE Trans. on Automatic Control, 1985, AC 30(8), 795-798.

[13] O.P.Malik, G.P.Chen, G.S. Hope, Q.H.Qin and G.Y.Xu, "Adaptive Self-optimizing Pole Shifting Control Algorithm", IEE Proc.-D, 1992, 139(5), 429-438.