Damping Control through STATCOM Using Adaptive Pole-shift Method

A.H.M.A.Rahim, *SeniorMember, IEEE,* M.Baber Abbas and S.F.Faisal

***Abstract*—Synchronous static compensator (STATCOM) can be used to improve the dynamic performance of a power system. This article presents an online adaptive pole-shift method for stabilization of a single machine system. An adaptive linear plant parameter model is used to derive the pole-shift control strategy. The controller performance has been tested for various disturbances. From a number of simulation studies on a single machine infinite bus power system it was observed that the adaptive algorithm converges very quickly and also provides robust damping profiles over a range of operation.**

***Index Terms* -- Power system stability, STATCOM, damping control, online adaptive control, pole - shifting method.**

I. NOMENCLATURE

δ	Generator rotor angle
ω	Rotor speed
ω_o	Base (synchronous) speed
P_m	Mechanical power input
P_e	Electrical power output
M	Inertia constant
D	Damping coefficient of generator
e_q'	Quadrature (q) axis internal voltage
T_{do}'	Open circuit field time constant
E_{fd}	Field voltage
x_d, x_d'	Synchronous, transient direct (d) axis reactance
I_d	d-component of armature current
K_A, T_A	Exciter gain, time constant
V_t	Generator terminal voltage
V_L	STATCOM bus voltage
V_b	Network bus voltage
E_{fdo}, V_{to}	Nominal field, terminal voltage
V_{dc},I_{dc}	dc capacitor voltage, current of STATCOM
C_{dc}	Capacitance of dc capacitor
I_{Lo}	Steady ac STATCOM current
m, ψ	Modulation index, phase of STATCOM voltage
θ	Parameter vector
φ	Measurement Vector
λ	Forgetting Factor

A.H.M.A. is with the King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia (email: ahrahim@kfupm.edu.sa).

M. Baber Abbas is with Saudi Electricity Company, Dammam, Saudi Arabia (email: mbaber@sec.com.sa).

S.F.Faisal is with the Petoleum Institute, Abu Dhabi, UAE (email: sfaisal@pi.ac.ae).

II. INTRODUCTION

The static synchronous compensator (STATCOM) is a power electronic based synchronous voltage generator that generates a three-phase voltage from a dc capacitor. By controlling the magnitude of the STATCOM voltage, the reactive power exchange between the STATCOM and the transmission line and hence the amount of shunt compensation in the power system can be controlled [1]. In addition to reactive power exchange, properly controlled STATCOM can also improve damping of a power system [2,3].

While most of the control designs are carried out with linearized models, nonlinear control strategies for STATCOM have also been reported recently [4]. STATCOM controls for stabilization have been attempted through complex Lyapunov procedures for simple power system models [5]. Applications of fuzzy logic and neural network based controls have also been reported [6-8]. 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. In order to yield satisfactory control performance, it is desirable to develop a controller which has the ability to adjust its parameters from on-line determination of system structure or model according to the environment in which it works. Application of adaptive control theory to excitation control and reactive power control problems are reported in the literature [9-11]. STATCOM is relatively new power electronics based device, and its control studies have generally been limited in this regard.

This article investigates the stability enhancement problem of a single machine power system installed with STATCOM. The adaptive control strategy developed has been tested for its robustness over wide ranges of operation.

III. THE SYSTEM MODEL

A single machine infinite bus system with a STATCOM installed at the mid-point of the transmission line is shown in Fig.1. The STATCOM consists of a step down transformer, a three phase GTO–based voltage source converter, and a DC capacitor. The STATCOM is modeled as a voltage sourced converter (VSC) behind a step down transformer. Depending on the magnitude the VSC voltage, the STATCOM current can be made to lead or lag the bus voltage. Generally, the STATCOM voltage is in phase with the bus voltage. However, some active power control may be possible through a limited control of phase angle. This would necessitate a power source behind the capacitor voltage.

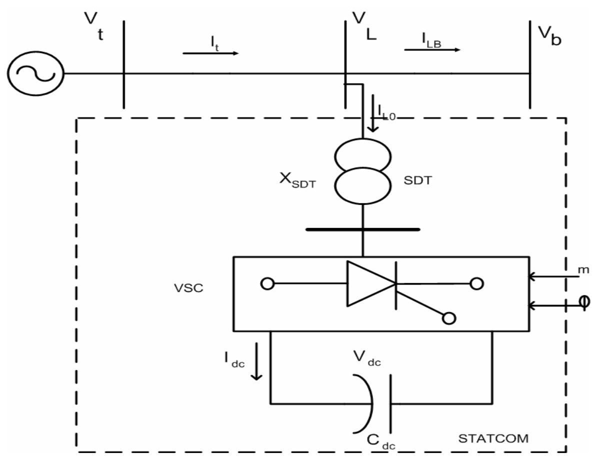

Fig. 1. A single machine system with STATCOM

The dynamic equations of the generator-excitation system is,

$$\dot{\delta} = \omega_o \Delta\omega$$
$$\dot{\omega} = -\frac{1}{M}[P_m - P_e - D\Delta\omega]$$
$$\dot{e}_q' = \frac{1}{T_{do}'}[E_{fd} - e_q' - (x_d - x_d')I_d] \tag{1}$$
$$\dot{E}_{fd} = -\frac{1}{T_A}(E_{fd} - E_{fdo}) + \frac{K_A}{T_A}(V_{to} - V_t)$$

The STATCOM capacitor voltage equation is,

$$\frac{dV_{dc}}{dt} = \frac{I_{dc}}{C_{dc}} = \frac{m}{C_{dc}}\left(I_{Lod}\cos\psi + I_{Loq}\sin\psi\right) \tag{2}$$

Combining (1) and (2), the dynamics of the single machine system is written as a 5^{th} order state model as,

$$\dot{x} = f(x, u) \tag{3}$$

The state and the control vectors are given as, $[\delta\ \ \omega\ \ \Delta e_q'\ \ E_{fd}\ \ V_{dc}]^T$ and $[m\ \psi]^T$, respectively.

IV. SELF-TUNING ADAPTIVE REGULATOR

Self-tuning control is one form of adaptive control which has the ability of self-adjusting its control parameters according to system conditions. Fig.2 shows the structure of an adaptive regulator. The self-tuning strategy is composed of two processes - the system identifier and the controller. The identifier determines the parameters of the mathematical model of the system from input-output measurement of the plant. The parameters of the identifier are updated at each sampling instant so that it can track the changes in the controlled plant. The control for the plant is then calculated based on this recursively updated system model.

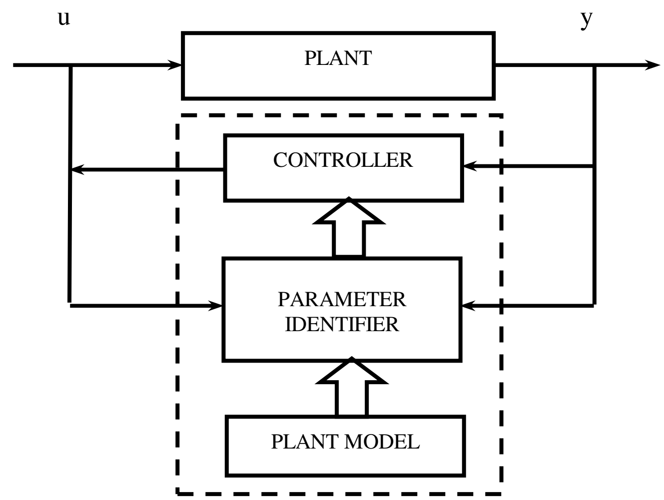

Fig. 2. Block diagram of self-tuning controller

The plant model is assumed to be of the form,

$$A(z^{-1})y(t) = B(z^{-1})u(t) + e(t) \tag{4}$$

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:

$$A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3} + a_4 z^{-4} + \ldots\ldots\ldots\ldots \tag{5}$$

$$B(z^{-1}) = 1 + b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3} + b_4 z^{-4} + \ldots\ldots\ldots\ldots \tag{6}$$

The vector of parameters $\theta(t) = [a_1\ a_2 \ldots\ldots;\ b_1\ b_2 \ldots\ldots]^T$ are calculated recursively on-line through the recursive least square [9] technique using,

$$\theta(t+1) = \theta(t) + K(t)\,[y(t) - \theta^T(t)\,\varphi(t)] \tag{7}$$

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

$$\varphi(t) = [-y(t-1)\ y(t-2) \ldots\ldots y(t-n_a)\ u(t-1)\ u(t-2) \ldots\ldots u(t-n_b)]^T$$
$$K(t) = \frac{P(t)\varphi(t)}{\lambda(t) + \varphi^T(t)P(t)\varphi(t)}$$
(8)
$$P(t+1) = \frac{1}{\lambda(t)}[P(t) - K^T(t)P(t)\varphi(t)]$$

λ(t) is the forgetting factor; n_a and n_b denote the order of the polynomials A and B, respectively. The identified parameters in (7) depend on all the past records of input and output samples.

V. POLE-SHIFT CONTROL

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 [12] is given below.

Assume that the feedback loop has the form,

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

where,

$$F(z^{-1}) = 1 + f_1 z^{-1} + f_2 z^{-2} + f_3 z^{-3} + f_4 z^{-4} + \ldots\ldots\ldots\ldots\ldots + f_{nf} z^{-nf}$$

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

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

From (4) and (9) the characteristic polynomial can be derived as,

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

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.

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

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,

$$MZ(\alpha) = L(\alpha) \qquad (12)$$

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,

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

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

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:

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

It can be shown that the change in α which minimizes J can be expressed as,

$$\Delta\alpha = \frac{\varepsilon_1 - f_1 f_2}{\varepsilon_2 + \frac{1}{2}[f_1 f_3 + 2b_1^2 f_2^2]} \qquad (15)$$

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 the updates of 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,

$$\alpha(t) = \alpha(t-1) + \Delta\alpha \qquad (16)$$

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.

VI. CONTROLLER EVALUATION

For the power system considered in Fig.1, the input and output of the plant were considered to be the control of the modulation index (m) in the STATCOM circuit and the generator speed variation (Δω), respectively. In order to excite the plant, a sequence voltage steps and torque pulses in the regulator-exciter and generator shaft, respectively were applied. The diagonal elements of the initial covariance matrix P is assumed be 2×10^5; the initial pole shift factor 0 and the forgetting factor of 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.

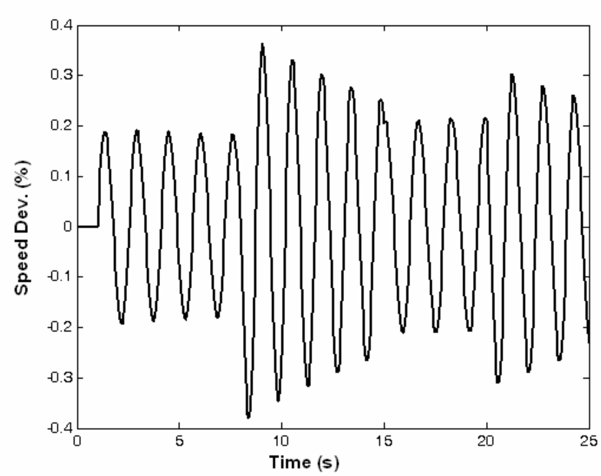

Fig. 3. Generator speed deviation when excited with alternate torque steps

Fig.3 shows the generator speed deviation with no control when excited by a sequence of toque steps of +5%, -5%, +5%

and -5%. The nominal loading is 0.9 pu at 0.9pf lagging. Fig.4 shows the variation of the generator speed with the pole-shift control applied to the identified process.

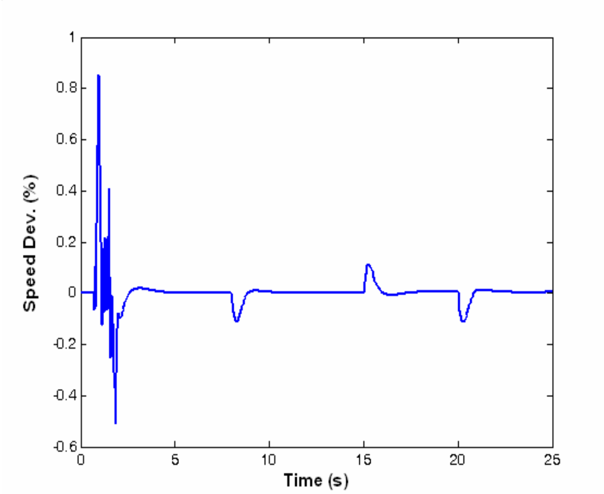

Fig. 4. Speed deviation of the generator with adaptive pole-shift control

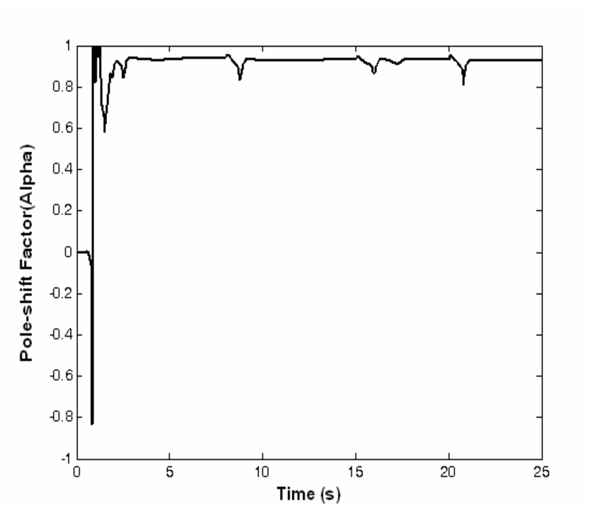

Fig. 5. The variation of the pole-shift factor with the progression of the adaptive process

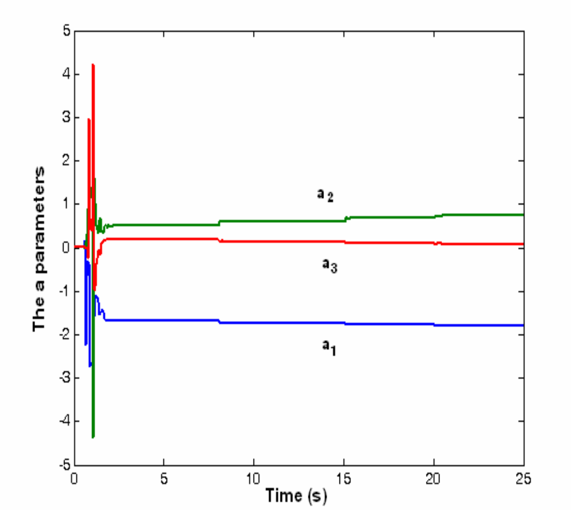

Fig. 6. The variation of the a-parameters of the adaptively identified plant function

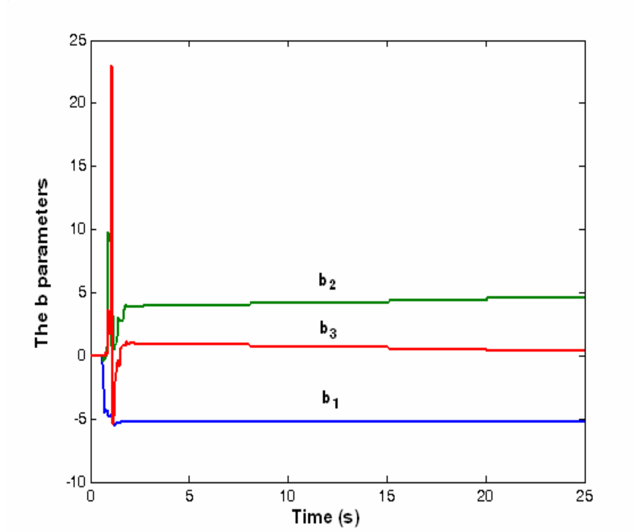

Fig. 7. The variation of the b-parameters of the adaptively identified plant function

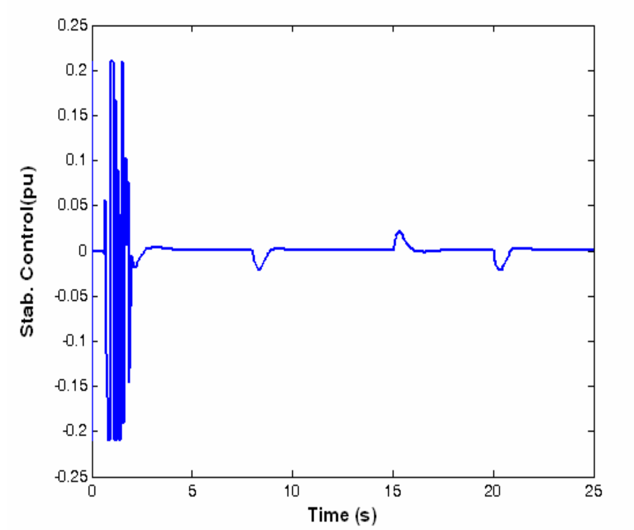

Fig. 8. Control signal produced by the adaptive process

From Figs 3 and 4, 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 giving rise to very large overshoots. However, as the identification process progresses, the plant parameters are estimated more and more accurately to yield better updates of the pole shift factor, and hence providing better damping profiles.

Fig. 5 shows the convergence of the pole shift factor as the estimation process progresses. The convergence of the {a} and {b} parameters of the estimated plant function are shown in Figs. 6 and 7, respectively. The control generated by the adaptive pole-shift algorithm is shown in Fig. 8. It can be observed that 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.

VII. TESTING CONTROLLER ROBUSTNESS

A number of case studies were performed with the adapted system model and the pole shift parameters arrived at in the previous section. For a 50% input torque pulse on the generator for 0.1s, the rotor angle variations recorded for 3 operating conditions are shown in Fig.9. These are for generator outputs of a) 1.2 pu , b) 0.9 pu , and c) 0.5pu. 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 three loadings. It is to be noted that without control the system is under damped, in general, and unstable in some cases.

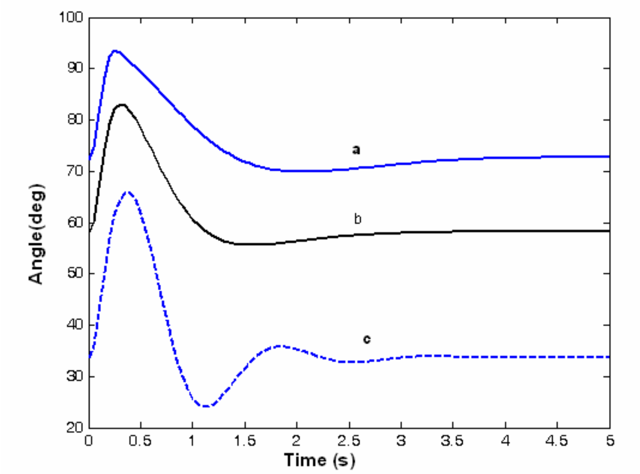

Fig. 9. Generator rotor angle variations with the proposed pole-shift control for the loadings of a)1.2 pu, b) 0.9 pu, and c) 0.5 pu. The disturbance considered is a 50% torque pulse for 0.1s

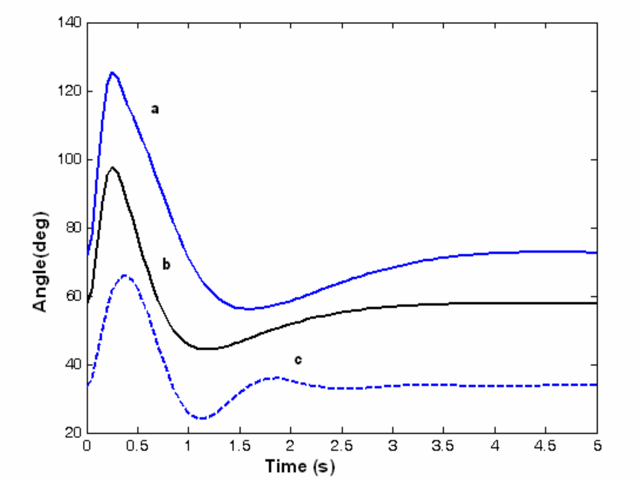

Fig. 10. Generator rotor angle variations following a three-phase fault for 0.1s with the proposed pole-shift control. The loadings are: a) 1.2 pu, b) 0.9 pu, and c) 0.5 pu.

VIII. CONCLUSIONS

An adaptive control technique has been used to enhance the dynamic performance of a power system installed with synchronous static compensator. The control employed is in the modulation index of the converter voltage. The proposed technique generates a stabilizing control on the basis of shifting the poles of the closed loop system towards the center of the unit circle in z-domain, thus providing more damping to the not so stable modes. 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 electromechanical modes. The robustness of the control strategy was tested by simulating different types of disturbances including three phase faults covering a number of operating states.

IX. ACKNOWLEDGMENT

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