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Self Tuning Adaptive Pole-Shift STATCOM Control for Single and Multi Machine Power Systems

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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 which is then extended to a multi-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. Responses for the single machine system were also compared with optimized PI control and robustness of the proposed adaptive algorithms was tested. From a number of simulation studies on the single machine as well as the multi-machine power system it was observed that the adaptive algorithm converges very quickly and also provides robust damping profiles to the under damped power system.

Keywords
Power system stabilizing control, STATCOM, on-line identification, adaptive control, pole - shifting control

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 Bus admittance matrix of system excluding generator and STATCOM

1. 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 provide damping to a power system [2, 3].
The modeling, operation and control fundamentals of the STATCOM have been extensively discussed in the literature [1, 4-7]. While most of the control designs are carried out with linearized models, nonlinear control strategies for STATCOM have also been reported recently [8]. STATCOM controls for stabilization have been attempted through complex Lyapunov procedures for simple power system models [8]. Applications of fuzzy logic and neural network based controls have also been reported [9, 10]. 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 methods to power system excitation control systems and static VAR systems has been reported [11, 12]; however, its application to FACTS devices has been very limited.

This article investigates the stability enhancement problem of power systems installed with STATCOM through adaptive online control of converter voltage magnitude. The adaptive control strategy developed has been tested for its robustness over wide ranges of operation for a single machine as well as a multi-machine system.

The organization of the article is as follows: Section 2 gives the model of the power system including STATCOM; the theory of self-tuning adaptive regulator is included in section 3, and section 4 presents the pole-shift control algorithm used in conjunction with adaptive control. Sections 5, 6, and 7 devote on the simulation results for single machine case, while sections 8 and 9 give simulation results on the multi-machine system. At the end the conclusions of the study are presented in section 9.

2. Single Machine System with STATCOM

A single machine infinite bus system with a STATCOM installed at the mid-point of the transmission line is shown in figure 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. The dynamic equations of the generator-excitation system are [13],

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

The state variables [δ ω e_q' E_{fd}] are the generator rotor angle, speed, internal voltage and field voltage respectively. The STATCOM capacitor voltage equation is,

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

Here, m and ψ are the magnitude and phase angle of the STATCOM ac side voltage. Combining (1) and (2), the dynamics of the single machine system is written as a 5^{th} order state model as,

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

Here, the control is considered to be the vector comprising of m and ψ, respectively.

3. 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. Figure 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.

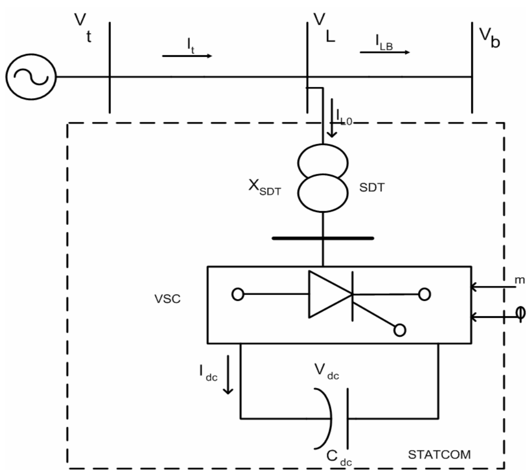

Figure 1 A single machine system with STATCOM

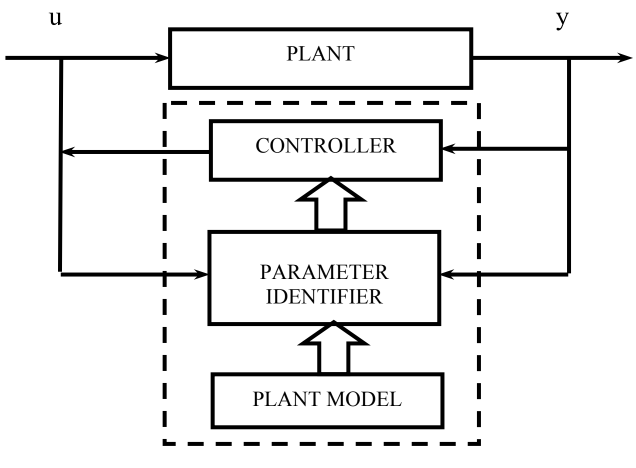

Figure 2 Block diagram of self-tuning controller

The plant model is assumed to be of the form,

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

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,

$$A(z^{-1}) = 1+ a_1z^{-1} + a_2z^{-2} + a_3z^{-3} + a_4z^{-4} + ... \quad (5)$$

$$B(z^{-1}) = 1+ b_1z^{-1} + b_2z^{-2} + b_3z^{-3} + b_4z^{-4} + ... \quad (6)$$

The vector of parameters $\theta(t)= [a_1\ a_2\ ....,b_1\ b_2\ ....]^T$ are calculated recursively on-line through the recursive least square [11] technique using,

$$\theta(t+1) = \theta(t) + K(t)\,[y(t) - \theta^T(t)\psi(t)] \quad (7)$$

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

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

$$K(t) = \frac{P(t)\psi(t)}{\lambda(t) + \psi^T(t)P(t)\psi(t)} \quad (8)$$

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

$\lambda(t)$ is the forgetting factor; n_a and n_b denote the order of the polynomials A and B, respectively. The identified parameters in (7) can be considered as the weighted sum of the previously identified parameters and those derived from the present signals.

4. The Control Strategy

Using the parameters obtained from the real time parameter identification method, a self-tuning controller based on pole shift 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 [14] is given below.

Assume that the feedback loop has the form,

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

where,

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

$G(z^{-1}) = g_0+ g_1z^{-1} + f_2z^{-2} + f_3z^{-3} + f_4z^{-4} + ...+f_{ng}z^{-ng}$

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

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

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

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.

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

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,

$$M\,Z(\alpha) = L(\alpha) \quad (12)$$

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 (7) will give,

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

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,

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

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

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 of J will occur when,

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

where, ε_2 is a small number chosen to avoid the singularity. 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,

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

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.

5. STATCOM Controller Performance for Single Machine System

For the power system considered in figure 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 $2x10^5$; 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. For solution of differential equations ode54 function from MATLAB 6.5 was used. The adaptive algorithm was developed by the authors.

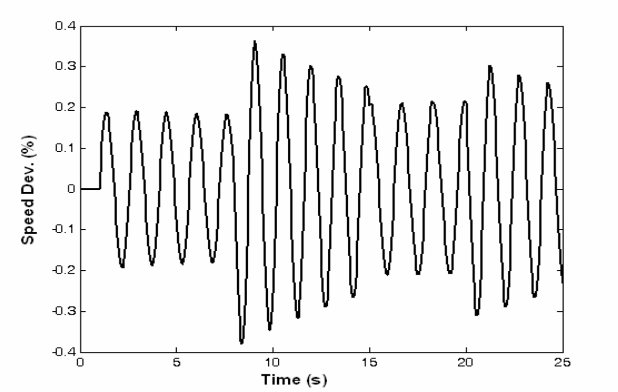

Figure 3. Generator speed deviation when excited with alternate torque steps

Figure 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. Figure 4 shows the variation of the generator speed with the pole-shift control applied to the identified process.

From figures 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.

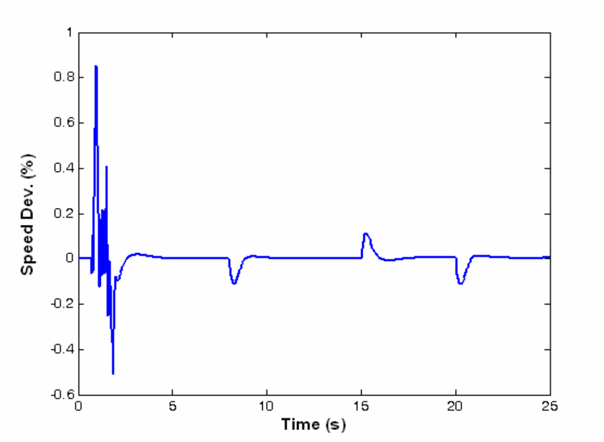

Figure 4 Speed deviation of the generator with adaptive pole-shift control

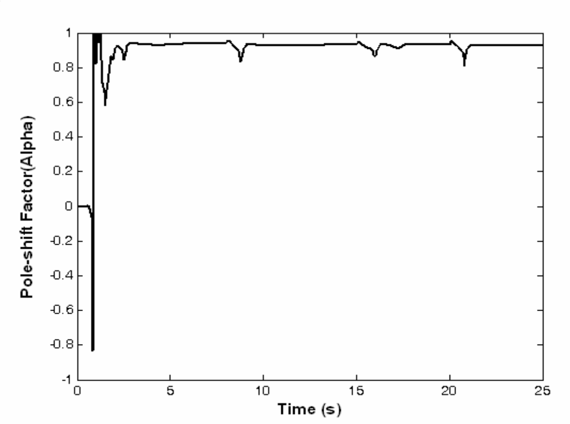

Figure 5 The variation of the pole-shift factor with the progression of the adaptive process

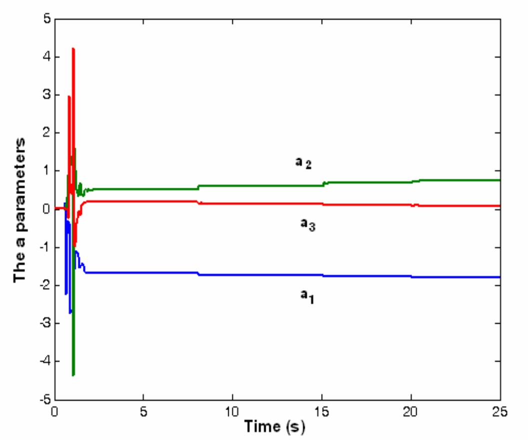

Figure 6 The variation of the a-parameters of the adaptively identified plant function

Figure 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 figures 6 and 7, respectively. 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.

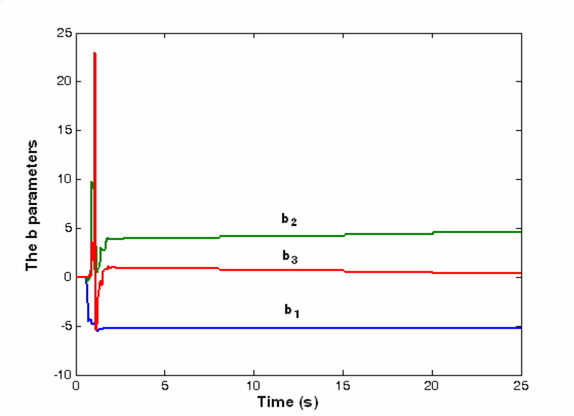

Figure 7 The variation of the b-parameters of the adaptively identified plant function

6. Testing the STATCOM Controller

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 figure 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. Figure 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.

7. Evaluation through PI Control

The damping properties of the proposed coordinated robust controller were compared with a conventional PI controller in the STATCOM voltage magnitude control loop. The PI (or PID) controllers are normally installed in the feedback path. An additional washout is included in cascade with the controller to eliminate any unwanted signal in the steady state. The controller function in the feedback loop is written as,

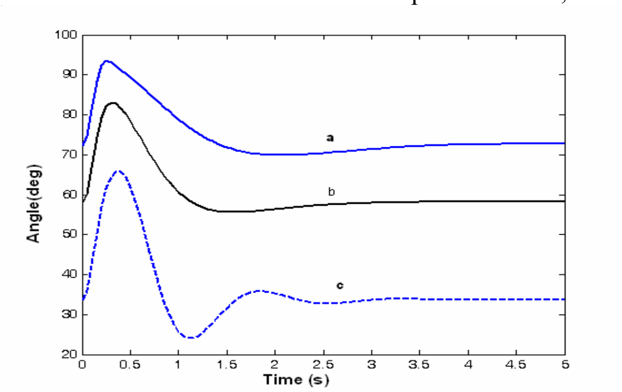

Figure 8 Generator rotor angle variations with the proposed pole-shift control for the loadings of a) 1.2 pu, b) 0.9 pu, and c) 0.5 pu. The disturbance considered is a 50% torque pulse for 0.1s

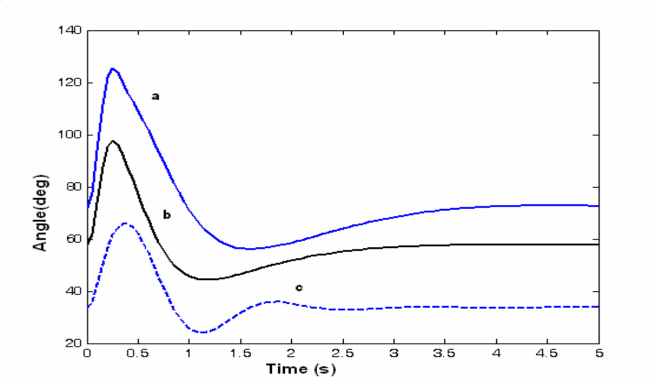

Figure 9 Generator rotor angle variations following a three-phase fault for 0.1s with the proposed pole-shift control. The loadings are: a) 1.2 pu, b) 0.9 pu, and c) 0.5 pu.

A pole–placement technique was used to determine the optimum gain settings (K_P and K_I) of the controller. For a desired location of the dominant closed-loop eigen value λ, the following equation is solved for K_P and K_I,

$$H(\lambda)= [C(\lambda I-A)^{-1}B]^{-1} \qquad (18)$$

H(λ) is obtained from (17) for the desired λ .

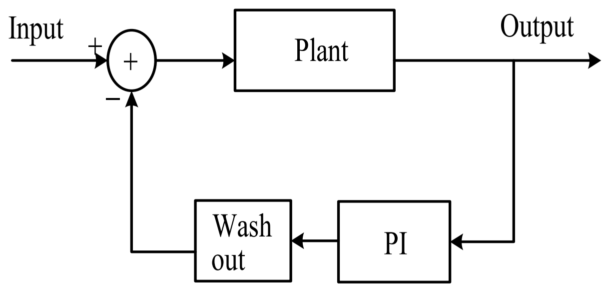

Figure 10 PI controller configuration

$$H(s) = [K_P + \frac{K_I}{s}]\left[\frac{sT_w}{1+sT_w}\right] \qquad (17)$$

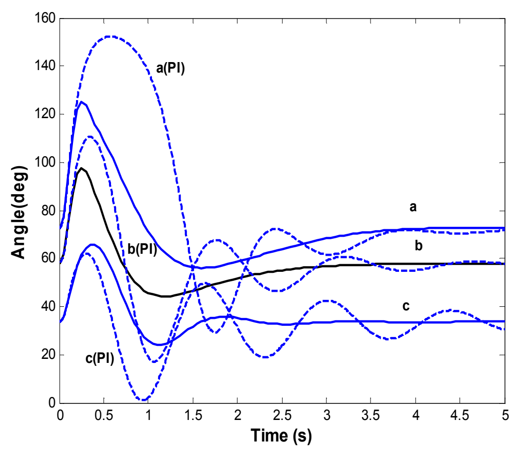

Figure 11 Generator rotor angle characteristics following a three-phase fault for 0.1s

Figure 11 shows the rotor angle variations of the synchronous generator following a three-phase fault with and without PI control for the 3 loading conditions considered in figures 8 and 9. The nominal loading is 1.01 pu. The values of K_P and K_I, respectively are 5.957 and 10.892 for closed-loop system damping ratio of 0.3. The responses with dotted lines are with PI control. The figure shows comparison of the responses of the PI control with the pole-shift adaptive control of STATCOM voltage magnitude. While the PI control provides reasonable response for the nominal operating condition (curve b), for loadings farther away from nominal it is not satisfactory. The pole-shift adaptive control, on the other hand, provides very well damped stable response for all the 3 operating conditions considered.

8. STATCOM Performance on a Multi-machine System

A 4-machine power system with STATCOMs located at the middle of the transmission lines connecting each generator to the rest of the grid is shown in figure 12. The system dynamics involves a set of equations similar to (3) for each generator in addition to the network voltage-current relationships. The network quantities are transformed to individual machine d-q frames and a closed form state model for the multi-machine system is arrived at.

The variable pole-shift adaptive control strategy was tested on the 4-machine power system given in figure 12. The output was considered to be the change in power of generator #2 which is connected to the system through bus 9. The input signal is the modulation index of the STATCOM converter voltage. In order to excite the plant, a sequence of torque pulses was applied on the shaft of generator #2.

Figure 13 shows the relative speed deviations of the generators with no control when excited by a sequence of toque steps of +5%, -5%, +5% and -5%. Figure 15 shows the variation of the generator speed with the adaptive variable pole-shift control applied to the identified process. The initial parameters of the adaptive algorithm were selected as in the single machine case.

From figure 14, 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 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.

Figure 15 shows the convergence of the pole shift factor as the estimation process progresses. The convergence of the {a} parameters of the estimated plant function is shown in figures 16. It can be observed that the estimation algorithm converges to the desired values rapidly with minimum subsequent control expenditure. The convergence of the algorithm is independent of the initial choice of the pole shift factor α

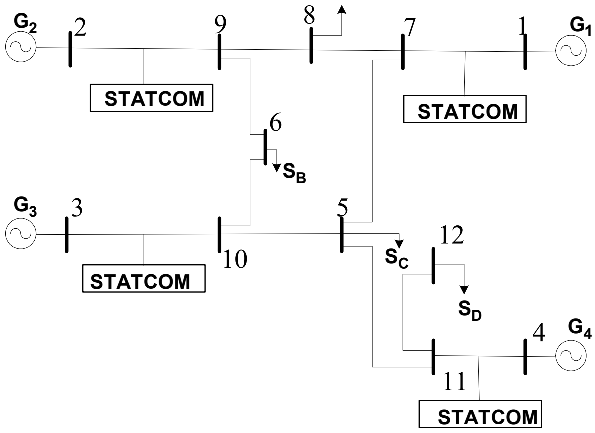

Figure 12 The multi-machine power system configuration

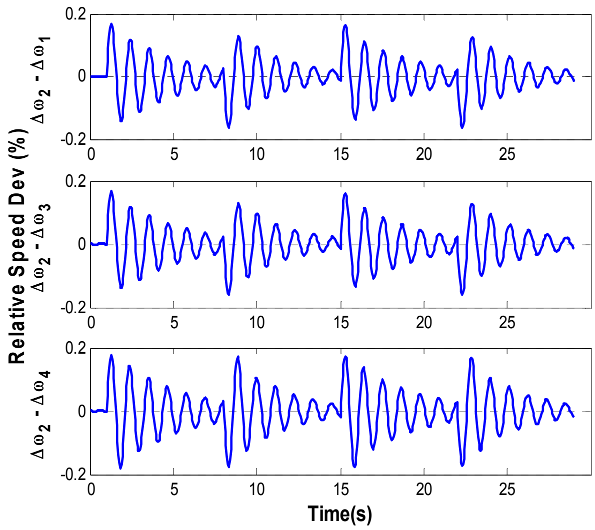

Figure 13 Generator speed deviation when excited with alternate torque steps

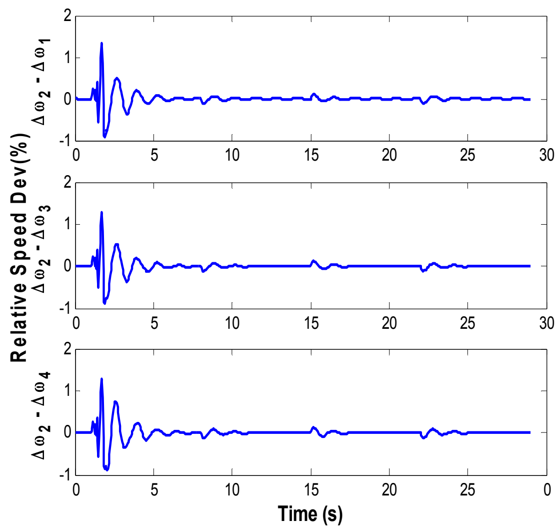

Figure 14 Speed deviation of the generator with adaptive pole-shift control

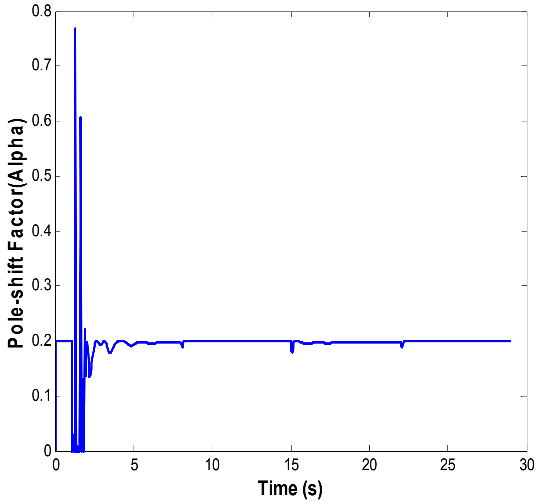

Figure 15 The variation of the pole-shift factor with the progression of the adaptive process

9. Testing the Multi-machine System Adaptive Controller

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 generator #2 for 0.1s, the rotor angle variations recorded for 2 operating conditions are shown in figure 17.The loadings are quite apart from each other. It can be observed that the damping properties are very good for the whole range of operation considered. It is to be noted that without control the system is very much under damped, and for this disturbance is on the verge of instability.

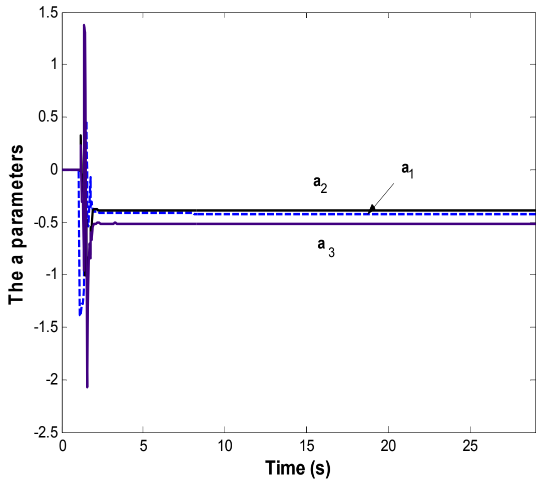

Figure 16 The variation of the a-parameters of the adaptively identified plant function

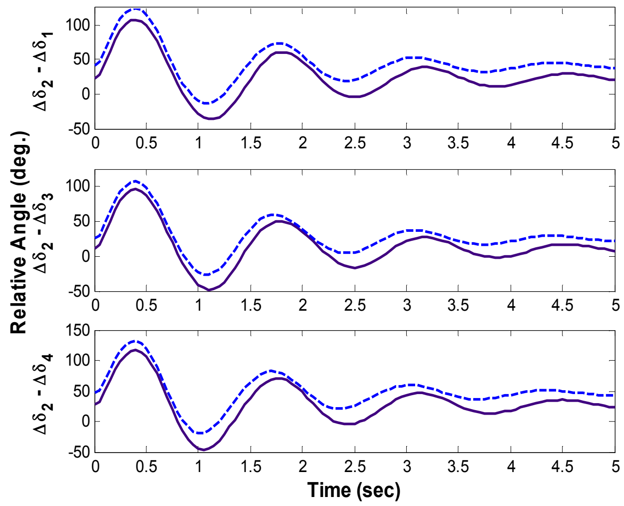

Figure 17 Relative rotor angle variations of the generators with the proposed pole-shift control for two loading conditions. The disturbance considered is a 100% torque pulse for 0.1s on generator 2.

10. Conclusions

An adaptive stabilizing control technique has been used to enhance the dynamic performance of a single machine as well as a multi-machine power system installed with synchronous static compensators. The control employed is the modulation index of one of the converter voltages. 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 for both the single machine as well as the multi-machine system. 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. The adaptive strategy was also compared with optimized PI control response for a single machine system and was observed to provide much superior performance

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