Design of a Static VAR Compensator Using Model Reference Adaptive Control

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SUMMARY

A novel approach for the design of a static VAR compensator (SVC) is proposed. The SVC, which comprises a fixed capacitor and a thyristor-controlled inductor, can be used to improve generator damping without deterioration in the voltage profile under severe disturbance conditions. In order to achieve better dynamic performance, a supplementary proportional-integral (PI) controller, of which the parameters are determined by eigenvalue assignment, is incorporated in the static VAR compensator. To further improve the damping characteristics over a wide range of operating conditions, an adaptive controller using model reference adaptive control (MRAC) is also developed. Results from the digital simulation of the system subject to a three-phase fault indicate that the MRAC can provide better dynamic performance than the fixed-gain PI controllers.

1. INTRODUCTION

During the past two decades, various damping schemes such as power system stabilizers [1 - 7] and static VAR compensators (SVCs) [8 - 14] have been developed to improve power system dynamic stability which has deteriorated by the widespread use of long transmission lines and static excitation systems. Among the supplementary controllers presented so far, the SVC will be examined in this paper.

In the literature, SVCs have been applied successfully to suppress arc furnace flicker [15], to regulate the voltage of transmission systems [16, 17], to improve transmission capacity [18], and to improve the transient stability of the synchronous machine [19 - 21]. The applications of static VAR systems

to damp out machine oscillations are rather limited [8 - 14].

The purpose of this paper is to present a new approach for the design of an SVC to improve the damping characteristics of a synchronous machine. The proposed technique makes use of a proportional-integral (PI) controller which is the most commonly used control algorithm in the process industry. In order to achieve good dynamic performance over a wide range of operating conditions, the fixed-gain PI controller is further extended by an adaptive control algorithm called the model reference adaptive control (MRAC). For purposes of comparison, the dynamic responses following a major disturbance achieved by employing the proposed PI static VAR controller are compared with those obtained by using an MRAC SVC. It is found that the MRAC SVC can produce better dynamic responses than the fixed-gain PI SVC.

2. MATHEMATICAL MODEL

Figure 1 shows the schematic diagram for a synchronous generator equipped with an SVC. By adjusting the firing angles of thyristors

Fig. 1. Schematic diagram of a synchronous generator equipped with a static VAR compensator.

$$M = \begin{bmatrix} L_d + L_e & kM_F & kM_D & 0 & 0 & 0 & 0 & 0 & 0 & -L_e & 0 & 0 \\ kM_F & L_F & M_R & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ kM_D & M_R & L_D & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & L_q + L_e & kM_Q & 0 & 0 & 0 & 0 & 0 & -L_e & 0 \\ 0 & 0 & 0 & kM_Q & L_Q & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \tau_j & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{T_A}{K_A} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_F & -K_F & 0 & 0 & 0 \\ L_d & kM_F & kM_D & 0 & 0 & 0 & 0 & 0 & 0 & L_B & 0 & 0 \\ 0 & 0 & 0 & L_q & kM_Q & 0 & 0 & 0 & 0 & 0 & L_B & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{T_r}{K_r} \end{bmatrix}$$

and

$$V_t = [(\nu_d^2 + \nu_q^2)/3]^{1/2}$$

$$L_B = X_T - \frac{1}{B_C + B_L}$$

$$B_L = B_{L0} + \Delta B_L$$

In the design of the PI static VAR controller using the eigenvalue assignment method, the nonlinear differential equations have to be first linearized around a nominal operating condition of the synchronous machine to obtain the desired state equations:

$$\dot{X}(t) = AX(t) + BU(t) + \Gamma z(t) \quad (1)$$

$$Y(t) = CX(t) \quad (2)$$

where

$$X = [\Delta i_d \quad \Delta i_F \quad \Delta i_D \quad \Delta i_q \quad \Delta i_Q \quad \Delta \omega \quad \Delta \delta \quad \Delta V_{ST} \quad \Delta E_{FD} \quad \Delta i_{Bd} \quad \Delta i_{Bq} \quad \Delta B_L]^T$$

is the state vector

$$z = [V_{REF} \quad T_m]^T$$

is the disturbance vector,

$$B = M^{-1}B' \quad \text{and} \quad \Gamma = M^{-1}\Gamma'$$

$$B' = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1]^T$$

$$\Gamma' = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$$C = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]$$

$$A = -M^{-1}K$$

K =

$r + R_e$	0	0	$\omega_0(L_q + L_e)$	$\omega_0 k M_Q$	$\lambda_{q0} + L_e(i_{q0} - i_{Bq0})$	$-\sqrt{3}V_\infty \cos \delta_0$	0	0	$-R_e$	$-\omega_0 L_e$	0
0	r_F	0	0	0	0	0	0	$-\frac{\sqrt{3}V_F}{kM_F}$	0	0	0
0	0	r	0	0	0	0	0	0	0	0	0
$-\omega_0(L_d + L_e)$	$-\omega_0 k M_F$	$-\omega_0 k M_D$	$r + R_e$	0	$-\lambda_{d0} - L_e(i_{d0} - i_{Bd0})$	$-\sqrt{3}V_\infty \sin \delta_0$	0	0	$\omega_0 L_e$	$-R_e$	0
0	0	0	0	r_Q	0	0	0	0	0	0	0
$\frac{\lambda_{p0} - L_d i_{q0}}{3}$	$\frac{-kM_F i_{q0}}{3}$	$\frac{-kM_D i_{q0}}{3}$	$\frac{-\lambda_{d0} + L_q i_{d0}}{3}$	$\frac{kM_Q i_{d0}}{3}$	$-D$	0	0	0	0	0	0
0	0	0	0	0	-1	0	0	0	0	0	0
z_1	z_2	z_3	z_4	z_5	z_6	0	1	$\frac{1}{K_A}$	0	0	0
0	0	0	0	0	0	0	1	0	0	0	0
r	0	0	$\omega_0 L_q$	$\omega_0 k M_Q$	$\lambda_{q0} + L_{B_0} i_{Bq0}$	0	0	0	0	$\omega_0 L_{B_0}$	$\frac{\omega_0 i_{Bq0}}{B_0^2}$
$-\omega_0 L_d$	$-\omega_0 k M_F$	$-\omega_0 k M_D$	r	0	$-(\lambda_{d0} + L_{B_0} i_{Bd0})$	0	0	0	$-\omega_0 L_{B_0}$	0	$-\frac{\omega_0 i_{Bd0}}{B_0^2}$
z_1	z_2	z_3	z_4	z_5	z_6	0	0	0	0	0	$\frac{1}{K_r}$

$$\mathbf{M} = \begin{bmatrix} L_d + L_e & kM_F & kM_D & 0 & 0 & 0 & 0 & 0 & 0 & -L_e & 0 & 0 \\ kM_F & L_F & M_R & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ kM_D & M_R & L_D & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & L_q + L_e & kM_Q & 0 & 0 & 0 & 0 & 0 & -L_e & 0 \\ 0 & 0 & 0 & kM_Q & L_Q & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\tau_j & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ w_1 & w_2 & w_3 & w_4 & w_5 & 0 & 0 & 0 & \frac{T_A}{K_A} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_F & -K_F & 0 & 0 & 0 \\ L_d & kM_F & kM_D & 0 & 0 & 0 & 0 & 0 & 0 & L_{B_0} & 0 & 0 \\ 0 & 0 & 0 & L_q & kM_Q & 0 & 0 & 0 & 0 & 0 & L_{B_0} & 0 \\ w_1 & w_2 & w_3 & w_4 & w_5 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{T_r}{K_r} \end{bmatrix}$$

$$z_1 = -k_d r + k_q \omega_0 L_d$$

$$z_2 = k_q \omega_0 kM_F$$

$$z_3 = k_q \omega_0 kM_D$$

$$z_4 = k_d \omega_0 L_q + K_q r$$

$$z_5 = k_d \omega_0 kM_Q$$

$$z_6 = -k_d \lambda_{qo} + k_q \lambda_{do}$$

$$w_1 = k_d L_d$$

$$w_2 = k_d kM_F$$

$$w_3 = k_d kM_D$$

$$w_4 = k_q L_q$$

$$w_5 = k_q kM_Q$$

$$k_d = \frac{\sqrt{3}v_{do}}{(v_{do}^2 + v_{qo}^2)^{1/2}}$$

$$k_q = \frac{\sqrt{3}v_{qo}}{(v_{do}^2 + v_{qo}^2)^{1/2}}$$

$$L_B = X_T - \frac{1}{B_C + B_L}$$

$$B_L = B_{L_0} + \Delta B_L$$

$$B_0 = B_C + B_{L_0}$$

$$L_{B_0} = X_T - \frac{1}{B_0}$$

where $y = \Delta\omega$ is the output signal, and $u = V_s$ is the control signal which can be expressed in the frequency domain as

$$U(s) = H(s) Y(s)$$

$$= K_P + \frac{K_I}{s} Y(s) \quad (3)$$

with K_P and K_I the gains of the PI static VAR controller. The main purpose here is to find a proper pair of parameters K_P and K_I to improve the damping of machine oscillations.

3. DESIGN OF A FIXED-GAIN STATIC VAR CONTROLLER USING THE EIGENVALUE ASSIGNMENT METHOD

In this section, the eigenvalue assignment method is employed for the design of a PI static VAR controller. In other words, the two parameters K_P and K_I are determined by shifting to more desirable locations a pair of eigenvalues associated with the oscillation mode with worst damping. The state equations in the frequency domain are first

written by taking the Laplace transform of (1) and (2):

$$sX(s) = AX(s) + BU(s) \quad (4)$$

$$Y(s) = CX(s) \quad (5)$$

Equation (4) can be rearranged as follows:

$$X(s) = (sI - A)^{-1}BU(s) \quad (6)$$

Combining eqns. (3), (5) and (6), we have

$$X(s) = (sI - A)^{-1}BH(s)CX(s) \quad (7)$$

or

$$[I - (sI - A)^{-1}BH(s)C]X(s) = 0 \quad (8)$$

If λ is the assigned eigenvalue of the closed-loop system equipped with the PI static VAR controller, then

$$\det[I - (\lambda I - A)^{-1}BH(\lambda)C] = 0 \quad (9)$$

Using the identity [22]

$$\det[I - E \cdot F] = \det[I - F \cdot E] \quad (10)$$

eqn. (9) can be written as

$$1 - C(\lambda I - A)^{-1}BH(\lambda) = 0 \quad (11)$$

or

$$H(\lambda) = \frac{1}{C(\lambda I - A)^{-1}B} \quad (12)$$

Therefore, a pair of simultaneous algebraic equations with the two unknown variables K_P and K_I can be obtained by substituting two prespecified eigenvalues $S = \lambda_1$ and $S = \lambda_2$ into (12). The two parameters of the PI static VAR controller are then computed from the solution of these two algebraic equations.

4. DESIGN OF A MODEL REFERENCE ADAPTIVE CONTROLLER

Consider a model reference adaptive controller (MRAC) as shown in Fig. 3. The reference model, which specifies the desired response characteristic for the system, and the plant are described by the equations

$$\dot{X}_{M1} = A_{M1}X_{M1} + B_{M1}U_{M1} \quad (13)$$

$$\dot{X}_{P1} = A_{P1}X_{P1} + B_{P1}U_{P1} + B_{P1}U_{P2} \quad (14)$$

The function of the adaptation mechanism is to generate the control signals

Fig. 3. Model reference adaptive control system.

$$U_{P1} = -K_{P1}X_{P1} + K_{M1}X_{M1} + K_{U1}U_{M1} \quad (15)$$

$$U_{P2} = \Delta K_P(t, e_1)X_{P1} + \Delta K_U(t, e_1)U_{M1} \quad (16)$$

in order to assure that the error signal

$$e_1 = X_{M1} - X_{P1} \quad (17)$$

would finally vanish in the steady state. In other words, the following condition must be met:

$$\lim_{t \rightarrow \infty} e_1(t) = 0$$

under disturbance conditions.

One must first verify that the linear model following control system ($U_{P2} = 0$) satisfies the 'perfect model following' conditions

$$(I - B_{P1}B_{P1}^+)B_{M1} = 0$$

$$(I - B_{P1}B_{P1}^+)(A_{M1} - A_{P1}) = 0$$

where B_{P1}^+ is the Penrose pseudo-inverse of B_{P1} :

$$B_{P1}^+ = (B_{P1}^T B_{P1})^{-1} B_{P1}^T$$

The MRAC is a generalization of a fixed-gain PI controller in which a 'proportional plus integral' adaptation law for $\Delta K_P(t, e)$ and $\Delta K_U(t, e)$ is employed. Thus we have [11]

$$\begin{aligned} \Delta K_P(t, e_1) = & \int_0^t \tilde{L}v(QX_{P1})^T d\tau + Lv(QX_{P1})^T \\ & + \Delta K_P(0) \end{aligned} \quad (18)$$

$$\begin{aligned} \Delta K_U(t, e) = & \int_0^t \tilde{M}v(RU_{M1})^T d\tau + Mv(RU_{M1})^T \\ & + \Delta K_U(0) \end{aligned} \quad (19)$$

where

$$v = D_1 e_1 \quad (20)$$

is a generalized error and $L, \tilde{L}, M, \tilde{M}, Q$ and R are positive definite matrices of appropriate dimension.

In order that the system be asymptotically hyperstable, the transfer matrix

$$Z(s) = D_1(sI - A_{M1} + B_{P1}K_{M1})^{-1}B_{P1} \quad (21)$$

must be strictly positive real. This implies that $(A_{M1} - B_{P1}K_{M1})$ must be a Hurwitz matrix and that D_1 is given by

$$D_1 = B_{P1}^T P \quad (22)$$

where P is a positive definite matrix solution of the Lyapunov equation

$$(A_{M1} - B_{P1}K_{M1})^T P + P(A_{M1} - B_{P1}K_{M1}) = -H \quad (23)$$

H being an arbitrary positive definite (or semidefinite) matrix. For the particular cases in which K_{M1} is given by

$$K_{M1} = B_{P1}^T \tilde{P} \quad (24)$$

where $\tilde{P}$ is the solution of the algebraic Ricatti equation

$$\tilde{P}A_{M1} + A_{M1}^T \tilde{P} - \tilde{P}B_{P1}B_{P1}^T \tilde{P} + \tilde{H} = 0 \quad (25)$$

the gains K_{P1} and K_{U1} are determined by

$$K_{P1} = B_{P1}^+ (A_{P1} - A_{M1} + B_{P1}K_{M1}) \quad (26)$$

$$K_{U1} = B_{P1}^+ B_{M1} \quad (27)$$

5. EXAMPLE

Consider a synchronous generator connected to a large power system through a double-circuit transmission line as shown in Fig. 1. The parameters of the system are as follows [1, 13].

Synchronous generator

$$\omega_R = 377 \text{ rad s}^{-1}$$

$$L_d = 1.7 \text{ p.u.}, \quad L_q = 1.64 \text{ p.u.}$$

$$L_F = 1.65 \text{ p.u.}$$

$$L_D = 1.605 \text{ p.u.}, \quad L_Q = 1.526 \text{ p.u.}$$

$$kM_F = kM_D = M_R = 1.55 \text{ p.u.}$$

$$kM_Q = 1.49 \text{ p.u.}$$

$$l_d = l_q = 0.15 \text{ p.u.}$$

$$r = 0.001096 \text{ p.u.}, \quad r_F = 0.000742 \text{ p.u.}$$

$$r_D = 0.0131 \text{ p.u.}, \quad r_Q = 0.054 \text{ p.u.}$$

$$H = 2.37 \text{ s}, \quad D = 0$$

$$R_e = 0.02 \text{ p.u.}, \quad L_e = 0.4 \text{ p.u.}$$

Voltage regulator and exciter

$$T_A = 0.05 \text{ s}, \quad K_A = 400$$

$$T_F = 1 \text{ s}, \quad K_F = 0.025$$

Static VAR compensator

$$X_T = 0.08 \text{ p.u.}$$

$$K_r = 50, \quad T_r = 0.15 \text{ s}$$

$$V_{s\max} = 0.12 \text{ p.u.}, \quad V_{s\min} = -0.12 \text{ p.u.}$$

$$\Delta B_{L\max} = 0.375 \text{ p.u.}, \quad \Delta B_{L\min} = -0.4 \text{ p.u.}$$

$$B_C = 0.625 \text{ p.u.}, \quad B_{L_0} = -0.6 \text{ p.u.}$$

The eigenvalues of the system under the generator loading condition of $P = 1.0 \text{ p.u.}$ and $Q = 0.62 \text{ p.u.}$ are listed in Table 1 and it can be observed from the Table that, for the system without a PI controller, the damping of the electromechanical mode, which is described by the eigenvalues $-0.161 \pm j9.476$, is very poor. Therefore, a supplementary PI controller is required if better damping characteristics for this mode are to be achieved. With a damping ratio of 0.32, two prespecified eigenvalues, $-2.578 \pm j8.103$, were assigned for the mechanical mode. With these eigenvalues substituted into (12), the desired PI controller parameters $K_P = 3.8$ and $K_I = 0.055$ are obtained.

For the model reference adaptive SVC, the linearized model at the nominal operating point of $P = 1.0 \text{ p.u.}$ and $Q = 0.62 \text{ p.u.}$ is chosen as the reference.

TABLE 1

System eigenvalues at $P = 1.0 \text{ p.u.}$ and $Q = 0.62 \text{ p.u.}$

Open-loop system (without PI controller)	Closed-loop system (with PI controller)
$-0.161 \pm j9.476$	$-2.578 \pm j8.103^a$
$-6.194 \pm j377.389$	$-6.986 \pm j377.411$
$-10.890 \pm j376.112$	$-10.360 \pm j376.008$
$-39.884 \pm j42.303$	$-39.617 \pm j42.594$
$-32.530 \pm j4.825$	-28.027
-2.547	-34.611
-1.007	-0.982
	-0.166

^aExactly assigned eigenvalues.

Fig. 4. Angular speed variations for loading condition of $P = 0.5$ p.u.: (a) PI controller; (b) MRAC.

Fig. 5. Angular speed variations for loading condition of $P = 1.0$ p.u.: (a) PI controller; (b) MRAC.

The weighting matrices H , Q , L and $\tilde{L}$ used in the simulation are

$$H = \text{diag}[1 \ 1 \ 1 \ 1 \ 1 \ 10^3 \ 10^3 \ 1 \ 1 \ 1 \ 1 \ 10^3]$$

$$Q = \text{diag}[1 \ 1 \ 1 \ 1 \ 1 \ 10^2 \ 10^2 \ 1 \ 1 \ 1 \ 1 \ 10^2]$$

$$\tilde{L} = 5 \times 10^{20}$$

$$L = 8 \times 10^{25}$$

In order to demonstrate the effectiveness of the proposed MRAC SVC over a wide range of operating conditions, digital simula-

Fig. 6. Angular speed variations for loading condition of $P = 1.5$ p.u.: (a) PI controller; (b) MRAC.

Fig. 7. Terminal voltage variations for loading condition of $P = 0.5$ p.u.: (a) PI controller; (b) MRAC.

tions were performed for the generator subject to a four-cycle three-phase fault at the midpoint of one of the two transmission lines. Three different loading conditions, $P = 0.5$ p.u., $P = 1.0$ p.u., and $P = 1.5$ p.u., were considered in the simulation. The generator angular speed variations $\Delta\omega$ obtained by using the fixed-gain PI and MRAC static VAR compensators are compared in Figs. 4 - 6 while the terminal voltage variations ΔV_t are compared in Figs. 7 - 9, respectively.

Fig. 8. Terminal voltage variations for loading condition of $P = 1.0$ p.u.: (a) PI controller; (b) MRAC.

Fig. 9. Terminal voltage variations for loading condition of $P = 1.5$ p.u.: (a) PI controller; (b) MRAC.

On comparing these Figures, it is observed that the MRAC SVC can provide better dynamic performance than the fixed-gain PI SVC. Only minor deviations in the terminal voltage have been experienced by both static VAR compensators. Moreover, the stability margin can be expanded by the MRAC since the generator with the MRAC SVC can remain stable at the loading condition of $P = 1.5$ p.u., while that with the fixed-gain PI SVC can not.

6. CONCLUSIONS

The design of a static VAR compensator for the damping of a synchronous generator has been examined by using a fixed-gain PI controller and a model reference adaptive controller. It is found that the MRAC SVC can offer better dynamic responses than the PI SVC over a wide range of loading conditions. Moreover, the MRAC SVC can provide a larger transient stability margin than the PI SVC. Both controllers can maintain a smooth voltage profile during disturbance conditions.

NOMENCLATURE

A, B, C, Γ	system matrices
B_C	capacitive susceptance of SVC
B_L	inductive susceptance of SVC
D	damping coefficient
E_{FD}	exciter field voltage
H	inertia constant
i_B	SVC current
i_d, i_q	stator d-axis and q-axis currents
i_D, i_Q	d-axis and q-axis damper winding currents
i_F	field winding current
$kM_F = kM_D = M_R$	$= L_d - l_d$
kM_Q	$= L_q - l_q$
K_A	regulator gain
K_F	stabilizing transformer gain
K_P, K_I	PI controller gain
K_r	SVC gain
l_d, l_q	d-axis and q-axis stator winding leakage inductances
L_d, L_q	d-axis and q-axis stator winding inductances
L_D, L_Q	d-axis and q-axis damper winding inductances
L_e	external inductance
L_F	field winding inductance
r	stator resistance
r_D, r_Q	d-axis and q-axis damper winding resistances
r_F	field resistance
R_e	external resistance
T_A	regulator time constant
T_F	stabilizing transformer time constant

T_m	mechanical input
T_r	SVC time constant
T_w	washout time constant
v_d, v_q	d-axis and q-axis stator voltages
V_{REF}	reference voltage for generator
V_s	SVC output
V_{ST}	stabilizing transformer output
V_t	generator terminal voltage
V_∞	infinite bus voltage
X_T	transformer reactance of SVC
δ	torque angle
ω	angular speed
ω_R	rated angular speed

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