Adaptive power system stabiliser based on pole-shifting technique

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Abstract: The design of a self-tuning power system stabiliser (PSS) using the pole-shifting technique is presented. The controller uses a state-feedback law, whose gains are evaluated from the pole-shifting factor. The proposed method is simple and computationally efficient. The dynamic performance of the proposed PSS is quite satisfactory and the PSS adapts extremely quickly to varying operating conditions.

List of symbols

- $T_{m}$, $T_{e}$ = mechanical/electrical torque, p.u.
- $I_{d}$, $I_{q}$ = direct and quadrature axis components of armature current
- $V_{d}$, $V_{q}$ = direct and quadrature axis components of terminal voltage
- $h^{g}$ = voltage proportional to direct axis flux linkages
- $E_{j}$ = exciter output voltage (applied to generator field), p.u.
- $V_{t}$ = terminal voltage of synchronous machine, p.u.
- $V_{b}$ = infinite bus voltage
- $\delta$ = angle between quadrature axis and infinite bus
- $\omega$ = angular velocity, p.u.
- $u$ = stabilising signal, p.u.
- $Y_{t}$, $x_{t}$ = transmission line resistance and reactance, p.u.
- $T_{A}$ = regulator-amplifier time constant, s
- $K_{A}$ = regulator gain, p.u.
- $H$ = inertia constant, s
- $T_{d}$ = direct axis transient open-circuit time constant, s
- $x_{d}$, $x_{q}$ = direct and quadrature axis components of synchronous machine reactance, p.u.
- $x'_{d}$ = direct axis transient reactance of synchronous machine, p.u.

1 Introduction

The application of power system stabilisers (PSS) for enhancing overall system stability has been extensively studied in the literature. The conventional fixed structure PSS provides optimum performance for a nominal set of operating parameters. However, under large variations in operating conditions, researchers have found that self-tuning PSS perform better. Various PSS design methods based on self-tuning control techniques have been proposed. The original self-tuning control concept [1, 2] employed the minimum variance control strategy. However, there exists a certain class of stochastic control problems for which the application of minimum variance strategy is inappropriate. An example of such a class is the non-minimum phase plant where unstable poles are used to cancel zeros that exist outside the unit circle. Self-tuning controllers based on pole-assignment have the advantages of overcoming the drawbacks of minimum variance control and incorporating comparatively simple control calculations. In addition, they always produce a smoother control action which is more acceptable. Pole-shifting control algorithms further simplify the calculation while retaining the basic advantages. Instead of considering both the poles and the zeros of the system, pole-shifting control considers only the poles of the system and allows the zeros to be configured according to the design algorithm. This simplification is very significant for on-line computer control. Linear quadratic control strategies also eliminate the problems associated with minimum variance control.

Mao et al. [3] have applied the linear quadratic control strategy to design an adaptive PSS. The formulation suggested, from the identified model, ensures a phase-canonical structure. A major contribution is that no state observers are required because of this, since the output of the controlled plant is directly used for deriving the feedback control signal. Hence the controller can rapidly track any change in the output. This feature has been used in this work together with a pole-shifting technique which simplifies the control calculations. The feedback gains here are simple linear functions of the pole-shifting factor and identified system parameters and hence their evaluation is easy. Unlike the linear quadratic control strategy, in the proposed method, solution of discrete-Riccati equation is not required. A synchronous generator equipped with an IEEE-type ST1 excitation system and connected to an infinite-bus through a double-circuit transmission line has been considered for the studies. The nominal sys-
2 Pole-shifting self-tuning PSS

For power system control, a third-order identification model has been generally used. In the z-domain, this can be described as
\[
y(z) = \frac{z^{-1}B(z^{-1})}{A(z^{-1})} u(z)
\]
where
\[
A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3}
\]
\[
B(z^{-1}) = b_0 + b_1 z^{-1} + b_2 z^{-2}
\]
y(z) and U(Z) are the z-transforms of the output y(k) and control signal U(\theta), respectively. From eqn. 1
\[
x(k+1) = A(x(k)) y(k) = B(z^{-1}) u(z)
\]
y(k + 1) + a_1 y(k - 1) + a_2 y(k - 2) + b_0 u(k) + b_1 u(k - 1) + b_2 u(k - 2)

The parameters a to b, are identified using an RLS identification algorithm every sampling period. Define a new control signal u(k) such that
\[
u(k) = b_0 u(k) + b_1 u(k - 1) + b_2 u(k - 2)
\]
The discrete-time dynamic model in state-space form is obtained as
\[
x(k + 1) = Gx(k) + Hu'(k)
\]
by defining the state-variables as in [3]:
\[
2i(k)y(k - 2); \quad z_1(k) = y(k - 1); \quad z_2(k) = y(k)
\]

The discrete-time dynamic model (eqn. 5), is in phase-canonical form which is needed for realizing the pole-shifting algorithm. A state-feedback control law is considered, i.e.
\[
-\dot{x}(k) = -Kx(k) = -K_{b1}(k) - K_{b2}(k) - K_{b3}(k)
\]
The feedback gain vector K is evaluated every sampling interval. Using eqns. 5 and 7 the stabilising signal u(k) is obtained as
\[
u(k) = \left[ -K_{b1}(k) - K_{b2}(k) - K_{b3}(k) \right] - b_{1d}(k - 1) - b_{2d}(k - 2) / b_{1o}
\]

3 Simulation studies

The nonlinear dynamic model of the machine-infinite bus system considering the IEEE Type-ST1 excitation system is given below. The notation is explained in the List of symbols.
\[
\theta = (T_x - T_y)/2H
\]
\[
\delta = 2n f (\omega - U)
\]
\[
E = [E_{id} - (E + (x_d - x_q) f_d)]/T_{s},
\]
\[
\dot{E}_{id} = [K_d (V_{df} - V_t + U) - B_{id}/T_{s}]
\]
\[
V_{df} = x_{qf}
\]
\[
V_t = (V + V^*) V^*
\]
\[
I_d = [t_e + x_{q}(E - V, \cos S) - v_0 r, \sin S]/r^2
\]
\[
I_i = [r(E - V, \cos S) + (z^2 + x_{e}) x_{q}/r^2, \sin S]/r^2
\]
\[
K = V_q + X_{ LF}
\]
\[
Z_{ce}^2 = \frac{\dot{z}_e^2 + z_0^2 + Z_{ce} x_{q} + \dot{x}_e}{\dot{x}_e^2 + x_{ce}^2}
\]
\[
V_e = [k - f_{de} + f_{de} x_{e}] / (l_{de}, f_{de} x_{e})^2
\]
The limits imposed on the AVR output, i.e. field voltage Efd and on the stabilising signal U (PSS output), are:
\[
E_{max} = 7.0 \text{ p.u.; } E_{min} = -7.0 \text{ p.u.}
\]
\[
t_{W} = 0.2 \text{ p.u. ; } u_{min} = 0.1 \text{ p.u.}
\]
The dynamic performance of the proposed self-tuning PSS is examined by simulating a balanced three-phase fault at the sending end of one of the transmission lines. The fault is cleared by removing the faulted line after 0.1s. Such a fault would result in large deviations from normal operating conditions. The output signal y(k) used for the identification model of the self-tuning PSS is,\[
y(k) = K_{ai} w(k), \text{ which is proportional to speed deviation. A sampling period of 40ms has been considered for simulation. Satisfactory dynamic performance}
\]
has been achieved for a pole-shifting factor of $p = 0.58$ and a high value of $K_c = -4000$.

![Fig. 1 Dynamic response for a large disturbance](image)

Fig. 1 shows the dynamic responses of the system with the proposed PSS following the three-phase fault. The settling time with the proposed pole-shifting self-tuning PSS is significantly less. Fig. 2 shows the variation of the state-feedback gains $K_1$, $K_2$ and $K_3$ with the proposed adaptive PSS. It is seen that, the state-feedback gains as expected, attain their steady-state values in a very short time. Dynamic performance of the system was also obtained considering a large step increase in mechanical torque $T_m$, i.e. $AT_m = 0.25 \text{ p.u.}$ (Fig. 3). It is seen that the proposed PSS has a fast settling time. Two different output signals $AV_1 + K_1 Aw$ and $K_2 Aw$, with $K = -4000$ were considered in the identification model. The dynamic responses with the two different output signals were, however, very close to each other. It is seen that the strength of the stabilising signal $u(k)$ (eqn. 15) decreases with increase in $b_0$. A sensitivity study carried out to investigate into the effect of variation of $b_0$ shows that the performance is very less affected on decreasing $b_0$. However, the system becomes unstable if $b_0$ is increased beyond 40% of nominal (i.e. for $b_0 > 7.0$). Hence, the choice of $b_0$ is quite critical and should be made judiciously.

![Fig. 2 Adaptation of state-feedback gains](image)

![Fig. 3 Dynamic responses for $AT_m = 0.25 \text{ p.u.}$](image)

4 Conclusions

The design of a state-feedback self-tuning PSS using pole-shifting technique has been proposed. The method uses a model formulation which obviates the need for state observers and the output is directly used to derive the feedback control signal. It combines this with a simple pole-shifting control technique in this framework to achieve quite satisfactory dynamic performances. The control calculations are simple and require less computational effort.

5 References


6 Appendix: Nominal system parameters

Nominal parameters of the sample system investigated are given below. All data are in per unit of value, except that $H$ and time constants are in seconds.

Generator: $H = 5.0s$; $T_{do} = 6.0s$; $x_d = 1.6$; $X' = 0.32$; $x_q = 1.55$.

IEEE Type-ST1 excitation system: $K_A = 50.0$; $T_A = 0.05s$.

Transmission line: $x_e = 0.4$; $r_e = 0.0$. 