Power System Stabilizers as Undergraduate Control Design Projects

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***Abstract*—The use of power system stabilizers (PSS) to damp power system swing mode oscillations is of practical importance. The design of PSS is taught in graduate level courses on power system dynamics and control, and has been the topic of numerous M.S. and Ph.D. theses. This paper discusses the experience in assigning PSS projects in an undergraduate control design course to provide students with a challenging design problem using three different techniques and to expose them to power system engineering. The details of the PSS design projects using root-locus, frequency-domain, and state-space methods are provided.**

***Index Terms*—Frequency-domain compensation, power system stabilizers, root-locus techniques, state-space methods, undergraduate design projects.**

I. Introduction

THE undergraduate level control systems engineering (CSE) course at Rensselaer Polytechnic Institute and many other universities covers the root-locus technique, frequency-response compensation, and state-space methods for control design [1]. The prerequisite of the course is the signals and systems course [2]. A course in modeling of dynamic systems [3] is helpful but not required. In the Rensselear CSE course, the students are required to do a sequence of design projects, each corresponding to a different design technique. Past projects included a ball-and-beam system and an inverted pendulum system [4], which are challenging but tend to be more of textbook- and laboratory-type problems. To introduce the students to real-world design problems, in the Fall 2002 semester, three power system stabilizer (PSS) design problems were assigned to about 40 students. As part of the projects, the students were also required to design the voltage regulator (VR). The MATLAB package, with the Control System Toolbox and Simulink, was used for the design [5].

In assigning these problems, we needed to distill the PSS design methodologies into steps that the students could accomplish with basic design knowledge. Most of the CSE students had not taken an introductory power system analysis course, but did have notions of dynamic systems. In each project, the same single-machine, infinite-bus system model in state-space form, presented in Section II, was used. The VR was obtained first using basic design guidelines offered in textbooks [1], [6], [7]. Then with the VR loop closed, more specialized techniques were used to design the PSS to add damping to the swing mode. In both the VR and PSS designs, realistic control specifications such as the rise time and the overshoot of step responses were given. The PSS structure and the lead-lag compensator formulas were provided to allow students to concentrate on selecting the PSS parameters. The final designs were verified by time simulation using Simulink. These design projects are described in Sections III–V. Some observations on the projects are provided in Section VI.

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II. Power System Model

A single-machine infinite-bus system (Fig. 1) was used as the design model. The machine, modeled with subtransient effects, delivers the electrical power P_e to the infinite bus. The voltage regulator controls the input u to a solid-state rectifier excitation system [8], which provides the field voltage to maintain the generator terminal voltage $V_{\rm term}$ at a desired value $V_{\rm ref}$. The states for the machine are its rotor angle δ, its speed ω, and its direct- and quadrature-axis fluxes E'_q, ψ_d, E'_d, and ψ_q. The exciter is modeled with the voltage state V_R. All of the variables are normalized on a per-unit (p.u.) basis, except for δ which is in radians.

The power system model is linearized at a particular equilibrium point to obtain the linearized system model given in the state-space form

$$\Delta\dot{x} = A\Delta x + B\Delta u, \quad \Delta y = C\Delta x \tag{1}$$

where Δ denotes the perturbation of the states, input, and outputs from their equilibrium values, with

$$x = \begin{bmatrix}\delta & \omega & E'_q & \psi_d & E'_d & \psi_q & V_R\end{bmatrix}^T \tag{2}$$

$$y = [V_{\rm term} \quad \omega \quad P_e]^T. \tag{3}$$

The matrices for (1) derived from typical machine parameters are given in Appendix A. In the sequel, the Δ symbol will be dropped to simplify notations. The dominant poles of (1) are the real pole $s = -0.105$ associated with the field voltage response, and the electromechanical (swing) mode $s = -0.479 \pm j9.33$ with a small damping ratio $\zeta = 0.0513$, representing the oscillation of machine against the infinite bus.

Starting from (1), the students were required to first use the terminal bus voltage signal $V_{\rm term}$ to design a high-gain VR $K_V(s)$. Because the VR destabilized the swing mode, a PSS $K_d(s)$ using the machine speed signal ω was used to add damping to the swing mode. The feedback control system block diagram implemented in Simulink is shown in Fig. 2. Note that the gain N is set to 1 for the root-locus and frequency-response designs. The input signal to a speed-input PSS is derived from

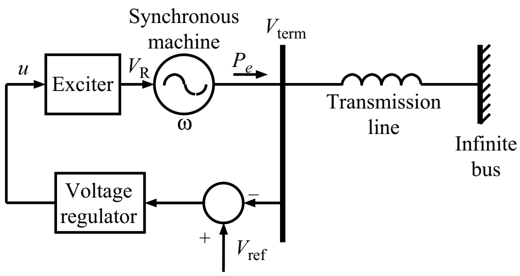

Fig. 1. Single-machine infinite-bus system.

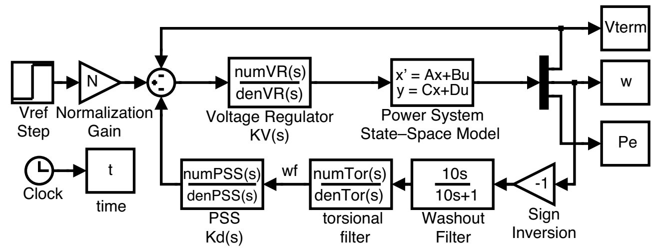

Fig. 2. Control structure of the single-machine infinite-bus system.

the machine speed passed through a washout filter and several banks of torsional filters [9]. The washout (derivative) filter $10s/(10s+1)$ is a high-pass filter having a dc gain of 0, such that in steady state, the PSS path is not active. The aggregate phase lag effect of the torsional filters is represented by

$$G_{\rm tor}(s) = \frac{1}{1 + 0.061s + 0.0017s^2}. \quad (4)$$

Note that the conventional PSS path comes into the $V_{\rm ref}$ summing junction with a positive sign. Here, we use a negative sign, balanced by a sign inversion in the feedback path, because the MATLAB root-locus function assumes negative feedback. The open- and closed-loop transfer functions required in various design stages are generated from the Simulink diagram by opening appropriate connections.

The P_e output was not used in the projects. It can be used if an instructor wants to extend the designs to a dual-input PSS with both the machine speed and the output power as the input signals [10]–[12].

Detailed discussions of PSS design techniques based on the synchronizing and damping torque concept can be found in many excellent references such as [13]–[15]. In the PSS projects, these ideas were translated into procedures that could be followed by students with basic control system design skills.

III. Root-Locus Design

A. Design Tasks

The first project in the sequence was the design of the VR and the PSS using root-locus techniques, which are usually taught first in a control systems course. The process was specified in several tasks:

(R1) For a 0.1-p.u. step in $V_{\rm ref}$, simulate the $V_{\rm term}$ response of the open-loop system (1) up to 10 s. Then with the PSS-loop open, repeat the simulation for (1) controlled by a proportional VR $K_V(s) = K_p$ with $K_p = 10, 20, \ldots, 50$.

(R2) Make a root-locus plot of the voltage regulation loop using the proportional controller and find the gain K_u when the lightly damped swing mode becomes unstable.

(R3) Apply a PI controller for the VR

$$K_V(s) = K_{\rm PI}(s) = K_p\left(1 + \frac{K_I}{s}\right) \quad (5)$$

and plot the closed-loop $V_{\rm term}$ response to a 0.1-p.u. $V_{\rm ref}$ step input. Select the parameters from $0 < K_p < K_u$ and $0.1 < K_I < 10$ such that the rise time t_r is less than 0.5 s and the overshoot M_p is about 10%. These specifications reflect the requirements of modern high-gain VRs.

(R4) Close the voltage regulation loop with $K_{\rm PI}(s)$ and perform a root-locus analysis of the PSS loop using the transfer function from $V_{\rm ref}$ to ω_f, the output of the torsional filter, assuming $K_d(s)$ to be a proportional gain control. Find the angle of departure $\phi_{\rm dep}$ of the root-locus branch leaving the swing mode with the positive imaginary part.

(R5) Based on $\phi_{\rm dep}$, design a second-order phase-lead compensator

$$K_d(s) = K_{\rm ld}\left[\alpha_{\rm ld1}\frac{s - z_{\rm ld1}}{s - p_{\rm ld1}}\right]\left[\alpha_{\rm ld2}\frac{s - z_{\rm ld2}}{s - p_{\rm ld2}}\right] \quad (6)$$

$$p_{{\rm ld}i} = \alpha_{{\rm ld}i} z_{{\rm ld}i}, \quad \alpha_{{\rm ld}i} > 1, \quad i = 1, 2 \quad (7)$$

using the phase-lead properties described in Appendix B, such that the angle of departure of the compensated system is about 180°. Perform another root-locus analysis for (6) and select $K_{\rm ld}$ to achieve a damping ratio $\zeta \geq 15\%$ for the swing mode.

(R6) Implement $K_d(s)$ in the Simulink diagram and simulate the closed-loop $V_{\rm term}$ response to a 0.1-p.u. $V_{\rm ref}$ step input. Check if $t_r \leq 0.5$ s and $M_p \leq 10\%$ have been satisfied.

B. Discussion of Design

Tasks R1 and R2 reveal important properties of the system and the proportional control. Fig. 3 shows the open-loop step response and the responses for the different K_p values. Note the slow open-loop response which settles to 0.0747 p.u., yielding a 25% steady-state error. As K_p increases, the closed-loop step response becomes faster and the steady-state error smaller, but the oscillation due to the swing mode becomes less damped. At $K_p = 50$, the feedback system is unstable with a growing oscillation. The instability can be studied with a root-locus plot, as shown in Fig. 4. As K_p increases, the voltage mode moves left from $s = -0.105$, thus improving t_r. The swing mode, however, is destabilized, and crosses the imaginary axis at $K_u \approx 47$. Although the system becomes stable again as K_p is increased beyond 1260, such a high gain is nonrobust because any reduction in the system gain due to changing operating condition would pull the swing mode back into the right half-plane. Thus, the proportional gain has to be kept below 47.

A good way to approach task R3 is to set up a grid of K_p and K_I values and simulate the step response by sweeping through