



A didactic procedure for designing power oscillation dampers of FACTS devices ☆

H.M. Ayres^a, I. Kopcak^{b,*}, M.S. Castro^a, F. Milano^c, V.F. da Costa^a

^a University of Campinas, UNICAMP/FEEC/DSEE, Av. Albert Einstein, 400, 13083-852, C.P. 6101, Campinas-SP, Brazil

^b Federal University of Goiás, UFG/EEEC, Av. Universitaria, 1488, Quadra 86, Bloco A, 74605-010, Goiânia-GO, Brazil

^c University of Castilla-La Mancha, Electrical Engineering Department, Campus Universitario, s/n, 13071, Ciudad Real, Spain

ARTICLE INFO

Article history:

Received 26 October 2009

Received in revised form 29 January 2010

Accepted 12 February 2010

Available online 19 February 2010

Keywords:

Flexible ac transmission system (FACTS) devices

Power oscillation damper (POD)

Power systems engineering education

Nyquist plot

MATLAB

PSAT

ABSTRACT

An important issue related to power system stability is to properly damp low frequency oscillations. Traditionally, these oscillations have been damped by means of power system stabilizers. In recent years, FACTS devices equipped with a power oscillation damper have been also efficiently used for damping oscillations. This paper is a tutorial for designing such power oscillation damper. The paper presents design projects suitable for students in the power system control area at the M.Sc. and Ph.D. levels. For educational purposes, the procedure is based on MATLAB and on two specific toolboxes, namely the Power System Analysis Toolbox and the Control System Toolbox. A single-machine infinite bus and a two-area test systems, with a thyristor controlled series compensator and an unified power flow controller, respectively, are used as examples for the POD design. Classroom experience has shown that the procedure helps in consolidating a better understanding of power system stability and control.

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1. Introduction

The benefits of Flexible AC Transmission Systems (FACTS) devices are widely recognized by power system practitioners and the T&D community for enhancing both steady-state and dynamic performances of power systems [1–3]. The advent of these devices has required additional efforts in modeling and analysis, requiring engineers to have a wider background for a complete understanding of power systems dynamic behavior.

From the students' viewpoint, the challenge is to combine the knowledge of fields formally studied separately, such as electric machines, linear analysis, and control theory. This traditional organization allows the student focusing on each field independently, for a deeper understanding of the specific mathematical tools or the solution algorithms. Although this approach is well established, it does not facilitate merging mathematical tools and models of different areas in a wider and more complex context. As a consequence, students hardly get familiar with power system dynamics and interactions, even when having an adequate background.

Power systems analysis textbooks take the advantage of simplified test systems and models for consolidating the understanding of the “physical behavior” of power systems [4–7]. Nowadays, the most popular approach consists in using research-oriented Matlab-based software tools [8–10]. Both textbook and software-based approaches usually illustrate

☆ This work was supported by FAPESP and CNPq.

* Corresponding author. Tel.: +55 62 3209 6292; fax: +55 62 3209 6292.

E-mail addresses: hmayres@dsee.fee.unicamp.br (H.M. Ayres), ikopcak@eee.ufg.br (I. Kopcak), marcelo.castro@eletrobras.com (M.S. Castro), Federico.Milano@uclm.es (F. Milano), vivaldo@dsee.fee.unicamp.br (V.F. da Costa).

power system behavior through the single-machine infinite bus (SMIB) system. In particular, reference [8] presents an interesting discussion about control design projects using the SMIB system at the undergraduate level.

The aim of this paper is to present a procedure to design power oscillation dampers (PODs) for FACTS devices in order to contextualize some concepts of control theory into power system stability. A variety of design methods can be used for tuning POD parameters. The most common techniques are based on frequency response [11], pole placement [12], eigenvalues sensitivities [13,12], and residue method [14]. Recently, researchers have investigated robust control techniques for designing power system stabilizers [15,12]. However, the classical phase compensation method is the most adequate as an educational tool. In addition, comparisons of performance have shown that controllers based on classical techniques can be as good as robust ones [15]. In this paper, the POD controller is designed using the frequency response method through Nyquist plots of a given Open Loop Transfer Function (OLTF).

The proposed procedure has been successfully used in assignments of the graduate course “Low Frequency Electromechanical Oscillations in Power Systems” at the University of Campinas (Unicamp), Brazil. Students’ feedback has shown that the simulations helped not only in learning about POD controller design, but also provided a better understanding of the dynamic behavior of power systems.

It is worth to note that the proposed procedure makes use of PSAT [16], an open source MATLAB-based package. The advantage of this package lies in its flexibility and scalability. Using a simple interface, the student can set up both the conventional SMIB test system as well as more complex systems of “any” size. This is an advantage because FACTS devices and controllers perform better in meshed grids [17].

The structure of the paper is as follows. Section 2 presents a brief overview of the graduate course at Unicamp. Section 3 describes the power system model and its representation in state-space form. Section 4 presents the procedure for POD design. Sections 5 and 6 discuss two examples of assignments where students have to design PODs for different FACTS devices. Finally, Section 7 provides final remarks and draws conclusions.

2. Overview of the graduate course

The graduate course “Low Frequency Electromechanical Oscillations in Power Systems” is a semester long course offered at Unicamp. The problem of electromechanical oscillations is an issue of short-term power system angle stability [18]. The course covers the main topics in this area focusing on the concepts of synchronizing and damping torque [19]. The first part of the course covers load-frequency control and synchronous machine representation in stability studies. The second part introduces FACTS devices modeling and POD design techniques.

Students are evaluated by completing assignments. In addition, a final project is required at the end of the course. Two suggested design projects are presented in Sections 5 and 6. Some static and dynamic analyses such as power flow, small-signal stability analysis and time-domain simulation, must be performed in order to complete the projects and assignments. All of these studies can be performed using PSAT. Thus, students are encouraged to use it, so that they can focus only in the analyses and simulations.

Analysis of the SMIB system is the key starting point for a better understanding of stability phenomena. In multi machine systems, students can also face challenging problems. All test systems used in the projects are built using the PSAT-Simulink one-line diagram editor and can be found in the PSAT test repository. Thus, the interested reader can easily reproduce all simulations presented in this paper.

3. Power system model

An electric power system can be represented by a set of non-linear differential-algebraic equations (DAE), as follows [5,7]:

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{f}(\mathbf{x}, \mathbf{y}, \mathbf{u}) \\ \mathbf{0} &= \mathbf{g}(\mathbf{x}, \mathbf{y}, \mathbf{u}) \\ \mathbf{w} &= \mathbf{h}(\mathbf{x}, \mathbf{y}, \mathbf{u})\end{aligned}\tag{1}$$

where

- $\mathbf{x} \in \mathbb{R}^n$ is the vector of the state variables;
- $\mathbf{y} \in \mathbb{R}^m$ is the vector of algebraic variables (e.g., bus voltage magnitudes and phase angles);
- $\mathbf{u} \in \mathbb{R}^\ell$ is a set of controllable parameters (e.g., controller reference signals);
- $\mathbf{w} \in \mathbb{R}^k$ is a set of output variables (e.g., line current flows);
- \mathbf{f} is a set of differential equations that represents system and controller dynamics ($\mathbf{f} : \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R}^\ell \mapsto \mathbb{R}^n$);
- \mathbf{g} is a set of algebraic equations that represents the transmission network power flows ($\mathbf{g} : \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R}^\ell \mapsto \mathbb{R}^m$);
- \mathbf{h} is a set of equations that represents output variables (e.g., measurements), such as line power flows and rotor angle speeds ($\mathbf{h} : \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R}^\ell \mapsto \mathbb{R}^k$).

3.1. Modal analysis

The design of POD controllers is based on linear system techniques. After solving the power flow problem (enforcing $\dot{\mathbf{x}} = 0$ in (1)), a modal analysis is carried out by computing the eigenvalues and the participation factors of the state matrix of the system. It is worth pointing out that PSAT includes all algorithms needed for this type of study (such as power flow and small-signal stability analysis [20]). Thus, the students can concentrate on the power system behavior and on the controller design, rather than on programming their own software.

Linearizing (1) at an equilibrium point $(\mathbf{x}_0, \mathbf{y}_0, \mathbf{u}_0)$, yields:

$$\begin{bmatrix} \Delta \dot{\mathbf{x}} \\ 0 \\ \Delta \mathbf{w} \end{bmatrix} = \begin{bmatrix} \mathbf{F}_x & \mathbf{F}_y & \mathbf{F}_u \\ \mathbf{G}_x & \mathbf{G}_y & \mathbf{G}_u \\ \mathbf{H}_x & \mathbf{H}_y & \mathbf{H}_u \end{bmatrix} \begin{bmatrix} \Delta \mathbf{x} \\ \Delta \mathbf{y} \\ \Delta \mathbf{u} \end{bmatrix} \quad (2)$$

where $\mathbf{F}_x = \nabla_{\mathbf{x}}^T \mathbf{f}$, $\mathbf{F}_y = \nabla_{\mathbf{y}}^T \mathbf{f}$, $\mathbf{F}_u = \nabla_{\mathbf{u}}^T \mathbf{f}$, $\mathbf{G}_x = \nabla_{\mathbf{x}}^T \mathbf{g}$, $\mathbf{G}_y = \nabla_{\mathbf{y}}^T \mathbf{g}$, $\mathbf{G}_u = \nabla_{\mathbf{u}}^T \mathbf{g}$, $\mathbf{H}_x = \nabla_{\mathbf{x}}^T \mathbf{h}$, $\mathbf{H}_y = \nabla_{\mathbf{y}}^T \mathbf{h}$, and $\mathbf{H}_u = \nabla_{\mathbf{u}}^T \mathbf{h}$.

Eliminating $\Delta \mathbf{y}$, and assuming that power flow Jacobian \mathbf{G}_y is non-singular (i.e., the system does not show a singularity-induced bifurcation), the state matrix \mathcal{A} of the system is given by

$$\mathcal{A} = \mathbf{F}_x - \mathbf{F}_y \mathbf{G}_y^{-1} \mathbf{G}_x \quad (3)$$

and the state-space representation of (2) is

$$\begin{aligned} \Delta \dot{\mathbf{x}} &= \mathcal{A} \Delta \mathbf{x} + \mathcal{B} \Delta \mathbf{u} \\ \Delta \mathbf{w} &= \mathcal{C} \Delta \mathbf{x} + \mathcal{D} \Delta \mathbf{u} \end{aligned} \quad (4)$$

where the input matrix $\mathcal{B} = (\mathbf{F}_u - \mathbf{F}_y \mathbf{G}_y^{-1} \mathbf{G}_u)$; the output matrix $\mathcal{C} = (\mathbf{H}_x - \mathbf{H}_y \mathbf{G}_y^{-1} \mathbf{G}_x)$; and the feedforward matrix $\mathcal{D} = (\mathbf{H}_u - \mathbf{H}_y \mathbf{G}_y^{-1} \mathbf{G}_u)$ [21].

The state-space representation is the base for controller design. Observe that, even if the test system devices, topology, and/or the \mathcal{A} , \mathcal{B} , \mathcal{C} , and \mathcal{D} matrices elements and sizes change, the POD design procedure remains the same. This procedure is discussed in the next section.

4. POD design

The POD controller is designed using the frequency response method through Nyquist plots of a given OLTF. The general control diagram is depicted in Fig. 1. The Nyquist criterion allows to assess the closed-loop stability of a feedback system by checking the OLTF poles and plotting its frequency response [22,23]. Closed-loop stability of the open-loop unstable system is obtained by ensuring an anti-clockwise encirclement of the -1 point of the complex plane in the Nyquist plot of the OLTF after applying feedback compensation [24,25].

The structure of the POD controller is similar to the classical power system stabilizer (PSS), as shown in Fig. 2. The controller consists of a stabilizer gain, a washout filter, and phase compensator blocks. The washout signal ensures that the POD output is zero in steady-state. The output signal v_{POD} is subjected to an anti-windup limiter and its dynamic is given by a small time constant (in this paper we use $T_r = 0.001$ s). The gain K_ω determines the amount of damping introduced by the POD and the phase compensator blocks provide the appropriate phase lead-lag compensation of the input signal.

A fundamental issue concerning the design of an effective and “robust” POD is the selection of an appropriate input signal. To improve the effectiveness of the POD and to avoid additional costs/delays associated with communication systems, only local signals have been chosen as input signals for all PODs. Students are encouraged to design PODs considering several input signals. Students are also requested to discuss about local and remote signals, variables coupling/decoupling, and the relationship between controllability and observability of the “physical” system.

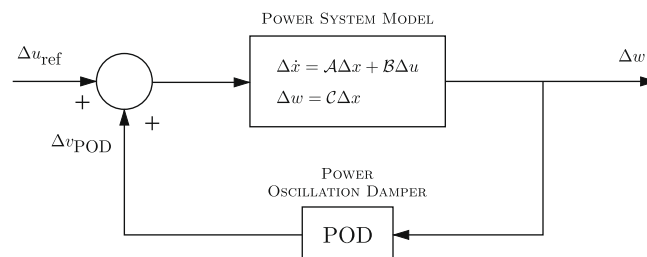


Fig. 1. General feedback control system.

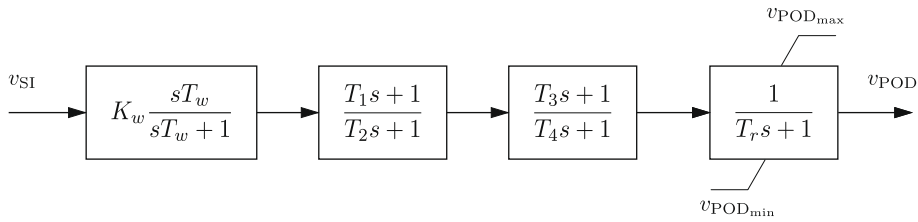


Fig. 2. Scheme of the POD controller.

4.1. Design procedure

The main steps of the procedure for POD design are as follows:

4.1.1. Eigenvalue analysis

Once the power flow problem has been solved, the eigenvalues and the participation factors of the state matrix (3) are computed in order to identify the critical modes of the system (4). Note that the analysis of the system has to be carried out without the POD. MATLAB allows computing a reduced number of eigenvalues based on sparse matrix properties and eigenvalue values. The participation factors of the state variables to each eigenvalue are computed by using right and left eigenvectors.

4.1.2. State-space form

The next step consists in computing all output and input matrices (\mathcal{A} , \mathcal{B} , \mathcal{C} , and \mathcal{D}). In a SISO (single-input/single-output) system of dimension n , \mathcal{A} is a $(n \times n)$ square matrix, \mathcal{B} is a $(n \times 1)$ column vector, \mathcal{C} is a $(1 \times n)$ row vector, and \mathcal{D} is an (1×1) element. Thus, one must conveniently handle these matrices to ensure modal controllability and observability requirements [21,25]. The most common input and output matrices of interest in power systems are available in PSAT: \mathcal{B} matrices for all FACTS devices, and \mathcal{C} matrices that have as outputs bus voltage magnitudes, bus voltage angles, line current flows, line active power flows, and line reactive power flows. Moreover, the user can define any other input and output variables implementing new \mathcal{B} and \mathcal{C} matrices in PSAT.

4.1.3. Nyquist analysis

Fig. 3 shows an illustrative Nyquist plots of the OLFs $\Delta\omega(s)/\Delta u_{ref}(s)$ (uncompensated loop) and $\Delta v_{POD}(s)/\Delta u_{ref}(s)$ (compensated loop) regarding the control diagram of Fig. 1. The variable ω_n on these polar plots indicates the critical frequency of

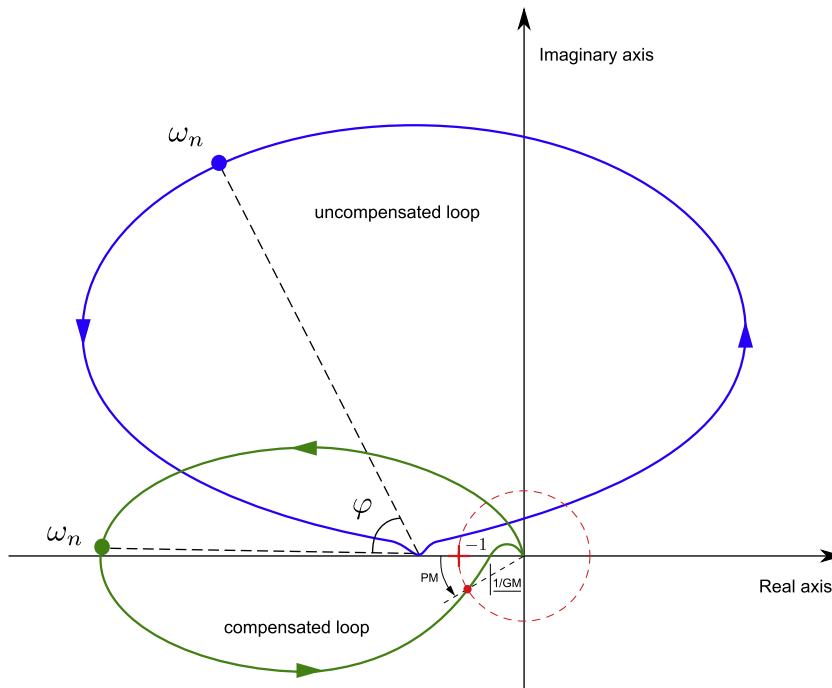


Fig. 3. Nyquist plot of $\Delta\omega(s)/\Delta u_{ref}(s)$ and $\Delta v_{POD}(s)/\Delta u_{ref}(s)$.

the applied input signal (Δu_{ref}). The necessary phase compensation φ , required by the POD to obtain a good phase margin (PM), can be determined based on the critical frequency ω_n . The polar plot encircling the $(-1,0)$ point should be approximately symmetrical with respect to the real axis to yield a good PM [11]. Nyquist plots can be verified only for positive frequencies, and thus, the number of anti-clockwise encirclements of the -1 point will be half. The washout filter is taken into account in these computations. The value of time constant T_ω can be in the range of 1–20 s [5].

4.1.4. Compensator blocks tuning

Having determined φ , the parameters of the phase compensator blocks can be obtained as follows:

$$\alpha = \frac{1 - \sin(\varphi/n)}{1 + \sin(\varphi/n)} \tag{5}$$

$$T_2 = \frac{1}{\omega_n \sqrt{\alpha}} \tag{6}$$

$$T_1 = \alpha T_2 \tag{7}$$

where n is the number of the lead-lag blocks and ω_n is the frequency of the critical mode to be damped. Usually, one or two lead-lag blocks are sufficient to properly compensate the input signal. In PSAT the POD structure is fixed and limited to two blocks ($n = 2$).

4.1.5. Damping ratio adjustment

The POD gain K_ω has to be determined in order to provide the desired damping for the closed-loop system. A gain margin (GM) indicates how much K_ω can be raised before instability results (see Fig. 3). This step completes the POD design.

Students can also use some classical time-response indices to improve or check the performance of controllers. In fact, for practical applications, one has to carefully choose and specify the parameters and check the performance of controllers to be implemented. Such parameters are, for example, the maximum rise time (t_r), the maximum overshoot (M_p), the desired damping ratio (ζ), and the settling time (t_s) [23–25]. However, observe that the damping ratio is the main specification in power system control design [5,21] and, for large power systems, 10% of damping is considered sufficient for POD controllers [5,17,21,22].

5. Example 1: Project with TCSC

The test system for this case study is depicted in Fig. 4, and is taken from [5]. It comprises a thermal generation station consisting of four 555 MVA, 24 kV, 60 Hz units connected to an infinite bus through a step-up transformer followed by two transmission circuits. The four generators of the plant are represented by an equivalent one-axis model generator equipped

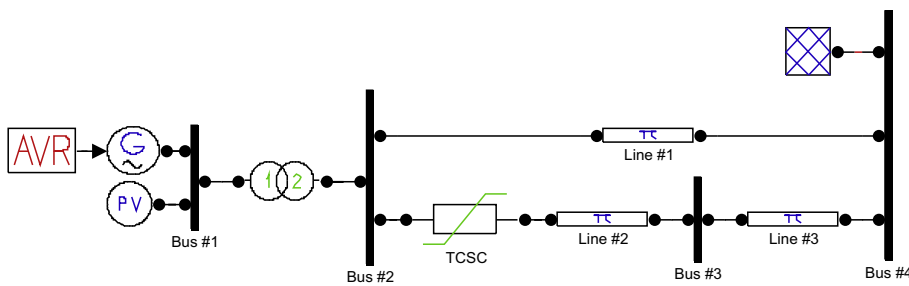


Fig. 4. SMIB with TCSC built with PSAT-Simulink one-line diagram editor.

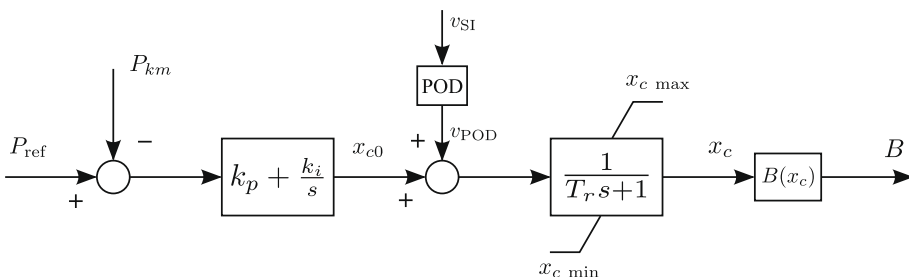


Fig. 5. TCSC control scheme.

with an automatic voltage regulator. The operating point corresponds to a heavy load condition in which the generators are delivering 1998 MW to the infinite bus. For this condition, the TCSC (in series with Line #2) makes the effective impedance of Line #2 plus Line #3 to be the same of Line #1.

Fig. 5 depicts the TCSC control scheme, and its differential equations are

$$\begin{aligned}\dot{x}_c &= \frac{1}{T_r} (k_p(P_{\text{ref}} - P_{km}) + v_{\text{POD}} + x_1 - x_c) \\ \dot{x}_1 &= k_i(P_{\text{ref}} - P_{km})\end{aligned}\quad (8)$$

The requirements for the first assignment are given by:

5.1. Assignment #1

The first assignment consists in designing a POD for the system depicted in Fig. 4 in order to modulate the x_c parameter of TCSC to achieve at least a 10% of damping ratio for the electromechanical mode following the instructions below:

- Set T_ω parameter as 10 s.
- Choose the current across transformer (I_{2-1}) as the stabilizer signal (or feedback signal).
- Check the performance of the POD controller by applying 10% step in the mechanical power of the Machine (P_m).

5.2. Discussion of the design

As indicated by the first step of the design procedure, the eigenvalue analysis for the system with TCSC and without POD controller is solved. Table 1 shows the eigenvalue of the electromechanical mode that requires damping. The eigenvalue analysis and the step response allow verifying the effect of the TCSC on damping and synchronizing generator torques, which are related to the real and imaginary parts of the electromechanical mode, respectively.

The next step is to build the SISO system by computing the input and output matrices (Appendix A provides the MATLAB commands for an example of POD design). Then, the Nyquist analysis can be performed.

Choosing the transmission line current I_{2-1} as input signal, the transfer function to be analyzed is $\Delta I_{2-1}(s)/\Delta v_{\text{POD}}(s)$. Fig. 6 shows the Nyquist plot (only the positive frequencies) of the uncompensated OLF (pre-design) and the compensated one (post-design). The OLF for the system is stable, but presents poorly damped poles. In this case, the polar plot should encircle the (+1,0) point of the Nyquist plot. For a good POD design, the resulting polar plot should be approximately symmetric with respect to the real axis of the complex plane [11], such as the compensated loop shown in Fig. 6. The lead-lag compensator parameters are calculated in order to relocate the angle φ of the critical frequency $\omega_n = 8.49$ rad/s (through a lead of 95.2°).

The last step of the procedure consists in defining the POD gain K_ω by launching the root-locus editor of the MATLAB Control System Toolbox (see Fig. 7) and by dragging the critical mode to the desired damping (12%).

The resulting POD transfer function is as follows:

$$\text{POD}_1(s) = 0.0661 \left(\frac{10s}{10s + 1} \right) \left(\frac{0.3037s + 1}{0.0457s + 1} \right)^2 \quad (9)$$

5.3. Assessment of POD controller

The TCSC control strategy acts in order to keep the active power flow in Line #2 at a specified value ($P_{2-3} = 999$ MW). The PI controller design is based on the pole placement technique. The gains k_p and k_i are selected in order to achieve the minimal impact on the electromechanical mode. The parameters for the PI controller in all simulations with TCSC are $k_p = 0.005$ and $k_i = 0.5$.

Fig. 8 shows the response of the TCSC without POD. In this case, Line #1 absorbs the whole active power generation increase (Appendix B provides the MATLAB commands for a 10% step in the P_m). The power flow in Line #2 regains its scheduled pre-disturbance value through the PI controller action. Note that the PI has a comparatively slow response and thus the power line scheduling is accomplished over a settling time of about 15 s. The effectiveness of the POD controller is shown in Fig. 9. Using the POD controller and for the same 10% step in the P_m , power oscillations are fully damped in about 5.0 s.

Table 1
Electromechanical mode of SMIB system with TCSC and without POD.

Mode	Eigenvalue ($\lambda = \sigma \pm j\omega_n$)	Frequency (f_n) (Hz)	Damping ratio (ζ) (%)
Local	$-0.37 \pm j8.48$	1.35	4.40

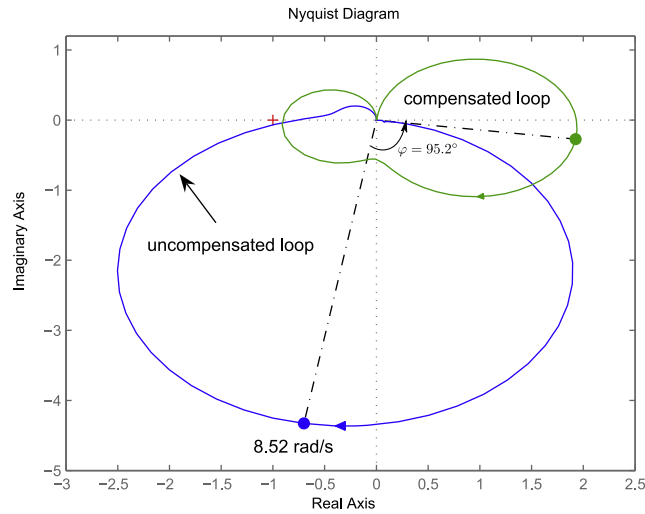


Fig. 6. Nyquist plots of SMIB system with and without POD.

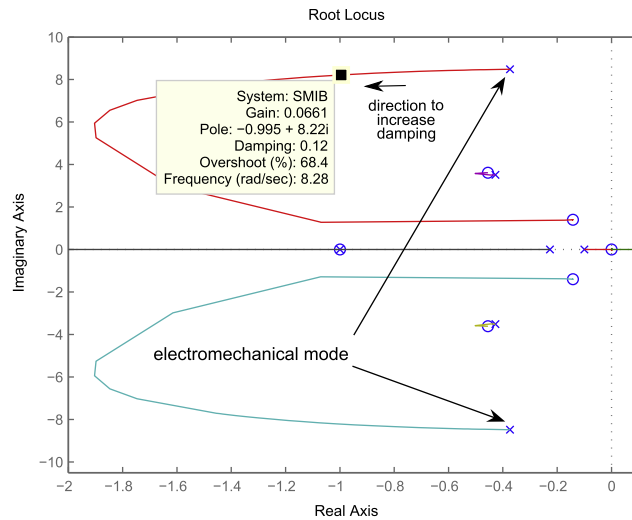


Fig. 7. Electromechanical mode dragged in the root-locus editor.

Note that the poles associated with electromechanical modes (related to the machine inertia constants) are typically characterized by a low frequency (0.1–2.0 Hz). Therefore, system variables show a slow dynamic response, specially for system disturbances that affect directly the mechanical power. For large generators (as in the SMIB test system of Fig. 4), the overshoot related to electromechanical modes has typically a high value (40–60%), as shown in Figs. 8 and 9. Reference [8] shows overshoot design specification for all controllers of about 5–15%. However, this overshoot range concerns automatic voltage regulators and not FACTS devices. The dynamic performance of excitation control systems allows reducing the overshooting [26]. On the other hand, [27] shows a real-case study with TCSC for damping interarea oscillations. The performance of three POD designed shows high overshoot, due to the inherent characteristic of the mechanical power step perturbation acting directly on the electromechanical modes.

6. Example 2: Project with UPFC

Fig. 10 shows a test system with an UPFC installed in series to one of the branches that connects Bus #8 to Bus #9. This two-area four-machine system is taken from [5]. The UPFC provides a series compensation of the line reactance and regulates the voltage at Bus #8. Fig. 10 also shows the POD controller. However, it has to be noted that POD should be included in the system only after the POD design procedure is completed.

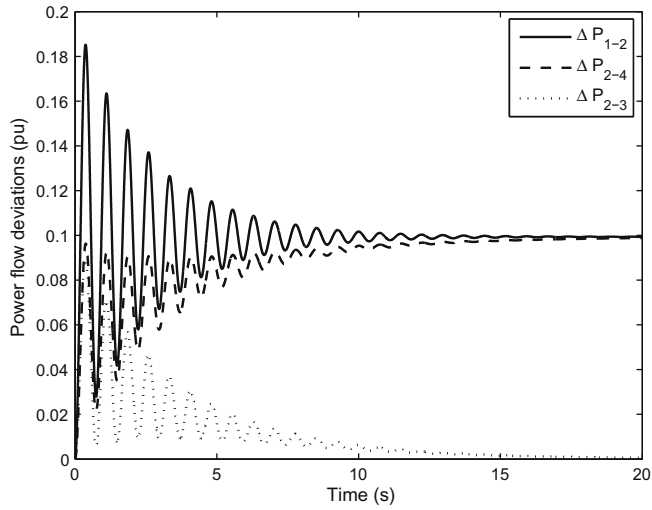


Fig. 8. Power flow response for a 10% step in the P_m without POD.

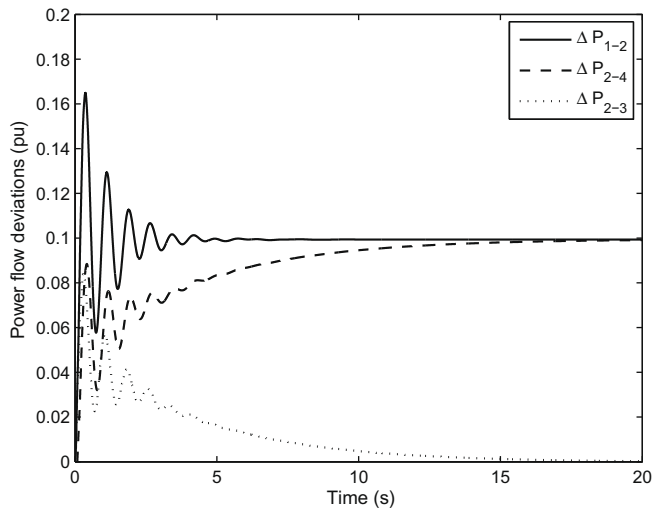


Fig. 9. Power flow response for a 10% step in the P_m with POD.

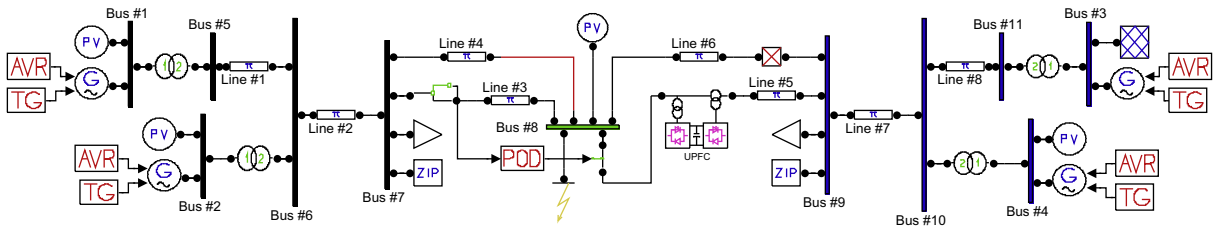


Fig. 10. Two-area system with UPFC built with the PSAT-Simulink one-line diagram editor.

The UPFC is represented by one series voltage source \bar{v}_S and by one shunt current source \bar{i}_{SH} [28,29,20]. The voltage and current sources are modeled as

$$\begin{aligned} \bar{v}_S &= (v_p + jv_q)e^{i\phi} = r\bar{V}_k e^{j\gamma} \\ \bar{i}_{SH} &= (i_p - ji_q)e^{i\theta_k} \end{aligned} \tag{10}$$

Fig. 11 depicts the UPFC dynamic model, which has three state variables. Observe that the POD can be used to modulate any UPFC parameters (v_p, v_q, i_q). The set of UPFC differential equations is

$$\begin{aligned} \dot{v}_p &= \frac{1}{T_r} [v_{p0} + v_{\text{POD}} - v_p] \\ \dot{v}_q &= \frac{1}{T_r} [v_{q0} - v_q] \\ \dot{i}_q &= \frac{1}{T_r} [K_r(V_{\text{ref}} - V_k) - i_q] \end{aligned} \tag{11}$$

The design requirements for the second project are as follows.

6.1. Assignment #2

The second assignment consists in designing a POD for the system of Fig. 10, that modulates the v_p state variable of the UPFC in order to achieve a 25% damping ratio for the critical oscillation mode. We consider two perturbations:

- A 5% step in the AVR voltage reference of Machine #1 with a desired overshoot lower than 20%.
- A three-phase short-circuit of 50 ms of duration at Bus #8 cleared by tripping Line #6 (refer to Fig. 10).

Finally, we assume that the active power of transmission Line #3 (P_{7-8}) is the stabilizer signal (or feedback signal) and that $T_\omega = 5$ s.

6.2. Discussion of the design

According to the first step of the design procedure, the eigenvalue analysis is carried out for the system with UPFC and without POD controller. The system exhibits three electromechanical modes: two local modes and one interarea mode. We focus on the interarea mode, which is poorly damped, as shown in Table 2.

The Nyquist plot of the OLTF to be analyzed is $(\Delta P_{7-8}(s)/\Delta v_{p0}(s))$. Fig. 12 shows the Nyquist plots of both the uncompensated loop (pre-design) and the compensated loop (post-design). As indicated in Table 2, the interarea mode frequency is $\omega_n = 4.00$ rad/s. At this frequency, the lead-lag block parameters are calculated to compensate the angle φ with respect to real axis through a lead of 33.2° . By launching the root-locus editor of the MATLAB Control Design Toolbox, the POD gain K_ω can be adjusted by dragging the interarea mode until it reaches the desired damping (see Fig. 13) for a damping of 25%.

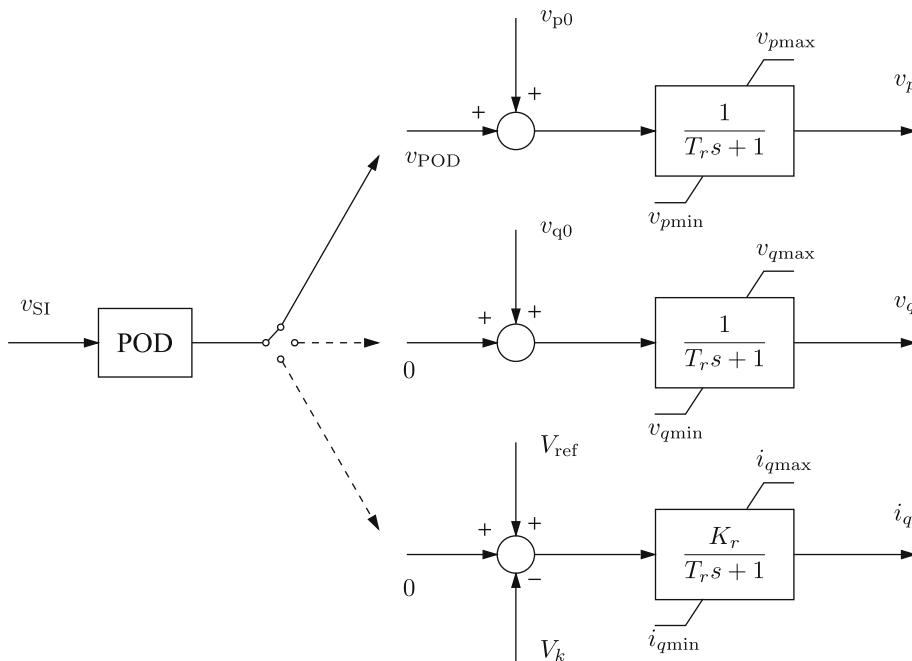


Fig. 11. UPFC control block diagrams.

Table 2
Electromechanical modes of Two-area system with UPFC and without POD.

Mode	Eigenvalues ($\lambda = \sigma \pm j\omega_n$)	Frequency (f_n) (Hz)	Damping ratio (ζ) (%)
Local 1	$-1.2902 \pm j8.1367$	1.29	15.7
Local 2	$-1.3085 \pm j8.4668$	1.35	15.3
Interarea	$-0.13347 \pm j4.0009$	0.64	3.3

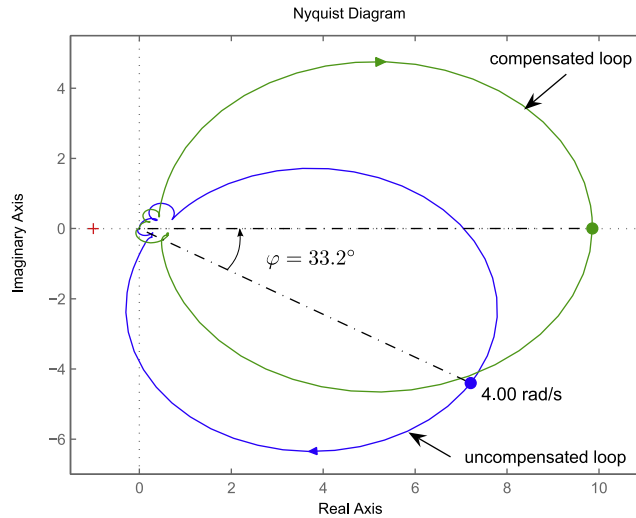


Fig. 12. Nyquist plots of two-area system with and without POD.

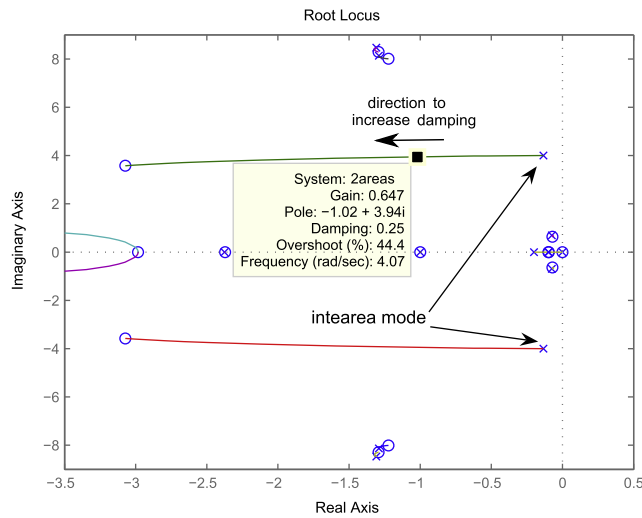


Fig. 13. Interearea mode dragged in the root-locus editor.

The resulting POD transfer function is:

$$POD_2(s) = -0.675 \left(\frac{5s}{5s + 1} \right) \left(\frac{0.3411s + 1}{0.1829s + 1} \right)^2 \tag{12}$$

Note that, according to Fig. 1, the K_ω gain must be negative in this case.

6.3. Assessment of POD controller

Fig. 14 shows the voltage of Bus #7 for a 5% step applied to the AVR #1 reference voltage (Appendix C shows the MATLAB commands for such step disturbance). The voltage magnitude increases since Bus #7 is in the same area of Synchronous Machine #1. As expected, system oscillations are well-damped if the POD controller is included and M_p is about 17%.

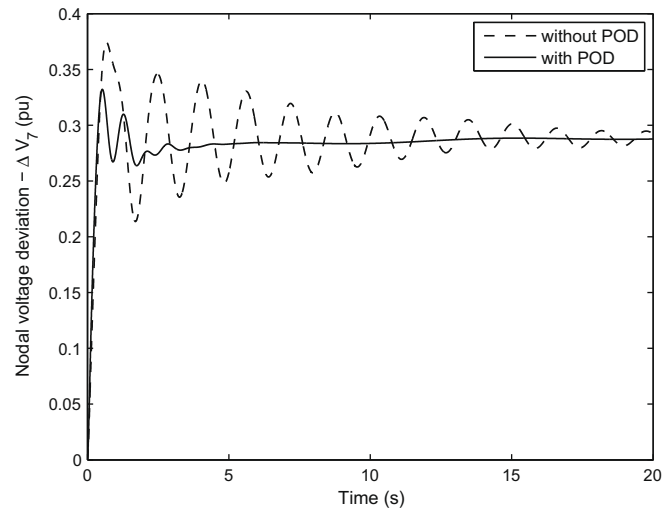


Fig. 14. Bus #7 voltage trajectory following a step of 5% in AVR #1 reference voltage.

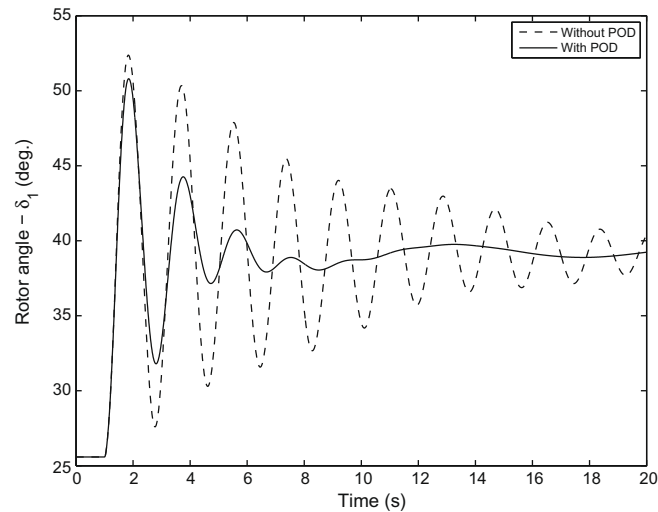


Fig. 15. Rotor angle of machine #1 after a fault at Bus #8.

Although the proposed procedure is carried out for a linearized system, it is common practice to check POD robustness by means of a transient stability study. Fig. 15 depicts the Machine #1 rotor angle trajectory following a fault at Bus #8. The fault consists in a three-phase short-circuit occurring at $t = 1$ s and cleared at $t = 1.05$ s by tripping Line #6 (refer to Fig. 10). Even after this severe disturbance, the POD improves the system performance by damping out interarea oscillations.

7. Concluding remarks

The paper presents a didactic procedure for designing POD controllers of FACTS devices. The procedure is specially suited for solving assignments in a graduate course on power system stability and control. It can help students in learning both power system electromechanical oscillations and feedback control. For instance, a course that places emphasis on power systems behavior could approach optimal FACTS siting (the compromise between the best place for steady-state operation, and the best place for improving system stability). On the other hand, a course with emphasis on control techniques could approach the concepts of observability and controllability, or use the design methodology presented in the paper as benchmark for comparing different design techniques. The advantages of the proposed procedure are twofold: the usage of the MATLAB environment and the usage of an open source software package for power system analysis (PSAT). Both tools are typically well-known by power engineering students.

At University of Campinas, the students feedback on carrying out assignments with PSAT/MATLAB environment have been very positive. Further work will concentrate on improving the POD controller scheme and on incorporating robust control techniques in this didactic procedure.

Appendix A. Matlab commands for POD designs

The basic background of the didactic procedure is described based on the PSAT environment and few MATLAB functions provided by the Control System Toolbox [30]. Hereinafter, any text preceded by \gg means a command typed at MATLAB prompt. We assume a power system with a Static Var Compensator (SVC) used for damping power oscillations (refer to PSAT manual [20] for the SVC dynamic model). Choosing the SVC reference voltage (ΔV_{ref}) as the input signal Δu , and the fictitious Line #5 current flow (ΔI_{sent}) as the output Δw , the procedure for the POD design is as follows:

Step 0: Run PSAT power flow routine.

Step 1: Identify the electromechanical mode to be damped (ω_n in rad/s) and set a value for T_ω .

Step 2: Compute \mathcal{A} , \mathcal{B} , \mathcal{C} , and \mathcal{D} matrices, and build the system in state-space model.

```
 $\gg$  fm_abcd
```

```
 $\gg$  a = LA.a
```

```
 $\gg$  b = LA.b_svc(:,1)
```

Note: index 1 refers to the fictitious SVC #1;

```
 $\gg$  C = LA.h_is*LA.c_y
```

Note: $\mathcal{C} = (\mathbf{H}_x - \mathbf{H}_y \mathbf{G}_y^{-1} \mathbf{G}_x)$, where $\mathbf{H}_x = \mathbf{0}$; $\mathbf{H}_y = \text{LA.h_is}$; and $-\mathbf{G}_y^{-1} \mathbf{G}_x = \text{LA.c_y}$;

```
 $\gg$  c = C(5,:)
```

Note: index 5 refers to the fictitious Line #5;

```
 $\gg$  d = 0
```

```
 $\gg$  sys = ss(a,b,c,d)
```

Step 3: Analyze of the OLTF ($\Delta I_{sent}(s)/\Delta V_{ref}(s)$)

```
 $\gg$  wsh = tf([Tw 0],[Tw 1])
```

```
 $\gg$  nyquist( $\pm$ sys*wsh)
```

```
 $\gg$  [x,y] = nyquist( $\pm$ sys*wsh,wn)
```

```
 $\gg$  phi = angle(x+j*y)
```

Step 4: Set the lead-lag parameters

```
 $\gg$  alpha = (1-sin(phi/n))/(1+sin(phi/n))
```

```
 $\gg$  T2 = 1/(wn*sqrt(alpha))
```

```
 $\gg$  T1 = alpha*T2
```

```
 $\gg$  leadlag = tf([T1 1],[T2 1])2
```

Step 5: Adjust the damping ratio

```
 $\gg$  rlocus( $\pm$ sys*wsh*leadlag)
```

Note: Drag the critical mode as desired;

Appendix B. Matlab commands for step disturbance in the mechanical power P_m

Run PSAT power flow routine and type:

```
 $\gg$  fm_abcd
```

```
 $\gg$  a = LA.a
```

```
 $\gg$  Gu = zeros(DAE.m,1)
```

Note: DAE.m is the number of algebraic variables.

```
 $\gg$  Gu(Syn.pm) = 1
```

```
 $\gg$  b = full(-DAE.Fy*(DAE.Gy\Gu))
```

```
 $\gg$  c = LA.c_y
```

Note: LA.c_y is the output for all algebraic variables.

```
 $\gg$  d = zeros(DAE.m,Syn.n)
```

Note: Syn.n is the number of synchronous machines.

```
 $\gg$  sys = ss(a,b*0.1,c,d)
```

Note: the 0.1 factor is used to apply a 10% step disturbance in the input matrix.

```
>>[Y,T,X] = step(sys,[0:0.001:30])
```

where $Y = \Delta w = \Delta y$ contains all algebraic variables; T is the time vector; and $X = \Delta x$ contains all state variables.

```
>>figure; plot(T,X(:,Syn.delta))
```

Note: the last command will plot the machines rotor angles response.

Appendix C. Matlab commands for step disturbance in the AVR voltage reference

Run PSAT power flow routine and type:

```
>>fm_abcd
>>a = LA.a
>>b = LA.b_avr
>>c = LA.c_y
```

Note: `LA.c_y` is the output for all algebraic variables.

```
>>d = zeros(DAE.m,Exc.n)
```

Note: `DAE.m` and `Exc.n` are the number of algebraic variables and the number of AVR, respectively.

```
>>sys = ss(a,b*0.05,c,d)
```

Note: the 0.05 factor is used to apply a 5% step disturbance in the input matrix.

```
>>[Y,T,X] = step(sys,[0:0.001:20])
```

where $Y = \Delta w = \Delta y$ contains all algebraic variables; T is the time vector; and $X = \Delta x$ contains all state variables.

```
>>figure; plot(T,Y(:,Bus.v))
```

Note: the last command plots the response of all voltage magnitudes.

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