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Tuning of SVC Stabilizers over a Wide Range of Load Parameters Using Pole-Placement Technique

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توليف المثبت ذو معوض الفولت الأمبير الفعال المستقر لقيم مختلفة من الاعمال باستخدام تقنية وضع الاقطاب

خالد الليثي

الخلاصة: تدرس هذه المقالة تاثير القيم المختلفة في نماذج الأحمال على ضبط المثبت (Stabilizers Tuning) الخاص بمعوض القوى الغير الفعالة الاستاتيكي. وقد تم استخدام نوعية التحكم المبني على التناسب و التكامل حيث يتم ضبط معاملاتها باختيار اماكن اقطاب النموذج (Pole Placement) في الاماكن التي تؤدي الى تحسين الاخماد في نظم القوى (Damping of Power Systems) وفي العاده تتم هذه الدراسة بفرض ان الاحمال معتمدة على الجهد. بيد انه يجب الاخذ في الاعتبار ان الاحمال تتصرف بطريقة غير محددة. مما يؤدي الى انحراف الضبط وبالتالي يسبب ضعف اداء المتحكم ذو المعاملات الثابته مع وجود أحمال ذات متغيرات اخرى بل قد يؤدي الى عدم استقرار عند بعض الاحمال. وتقدم المقالة دراسة لتاثير قيم المتغيرات في نماذج الاحمال على ضبط قيمة معاملات التحكم في معوض القوى الغير الفعالة الاستاتيكي المبني على التناسب و التكامل وتبين الدراسة ان لها تاثير كبير. وقد تم دراسة اداء النظام مع الوقت حيث تم بيان ان المتحكم ذو المعاملات الثابتة يقلل اداؤة عند تغير الاحمال كما انة قد يسبب عدم استقرار عند بعض الأحمال.

المفردات المفتاحية: قيم نماذج الاحمال، توليف مثبتات معوض القوى الغير الفعالة الاستاتيكي- وضع الاقطاب.

Abstract: This paper investigates the effect of typical load model parameters on the static var compensator (SVC) stabilizers tuning. A proportional-Integral (PI) type stabilizer is considered and its gain-settings are tuned using the pole-placement technique to improve the damping of power systems. Tuning of SVC stabilizers (damping controllers) traditionally assumes that the system loads are voltage dependent with fixed parameters. However, the load parameters are generally uncertain. This uncertain behavior of the load parameters can de-tune the gains of the stabilizer; consequently the SVC stabilizer with fixed gain-settings can be adequate for some load parameters but contrarily can reduce system damping and contribute to system instability with loads having other parameters. The effect of typical load model parameters on the tuning gains of the SVC PI stabilizer is examined and it is found the load parameters have a considerable influence on the tuning gains. The time domain simulations performed on the system show that the SVC stabilizer tuned at fixed load parameters reduce the system damping under other load parameters and could lead system instability.

Keywords: Load model parameters, SVC stabilizer, Pole-placement

1. Introduction

Studies and experience have shown that load model parameters can have a significant effect on the results of dynamic performance and voltage stability of power systems (Millanovic, *et al.* 1995; Langevin, *et al.* 1986; Ellithy, *et al.* 1989; Choudhry, *et al.* 1990; Choudhary, 1986; Ellithy, *et al.* 1997 and Craven, *et al.* 1983; Xu, *et al.*1994, Vaahedi, *el al*. 1988; Alden, *et al.* 1976; Ellithy, *et al.* 1997). Incorrect parameters of a load model could lead to a power system operating in modes that result in actual system collapse and separation (Craven, *et al.* 1983; Xu, *et al.* 1994). Accurate load model parameters are, therefore, necessary to allow more precise calculations of power system control and stability limits which are critical in the planning and operation of a power system dynamics has long been recognized, and it has become clear that assumptions regarding load model parameters can impact predicted system performance. Several efforts have been devoted to load modeling and evaluation of load parameters through field measurements (Xu, *et al.* 1997; Ohyama, *et al.* 1985). Analytical approaches to constructing accurate load models have also been considered (Xu, *et al.* 1997; Berg, *et al.* 1973). Voltage-dependent load models for composite load representation are highly recommended by the IEEE working group (IEEE Task Force for Dynamic Performance, 1995) and many utilities (Xu, *et al.* 1997; Ohyama, *et al.* 1985; Concordia, *et al*. 1982).

Flexible AC Transmission System (FACTS) controllers based on thyristor controlled reactors (TCRs), such as static var compensators (SVCs) (IEEE Special Stability Control Working group, 1994)) are being used by several

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utilities to support the voltage and to increase the capacity of their systems. SVCs with additional signals (stabilizing signals) in their voltage control loops have been used to improve the damping of power system electromechanical oscillations and to enhance system stability. The additional signals that are generally used in stabilizers (damping controllers) are rotor speed and bus frequency deviations. In recent years, many designs for SVC stabilizers have been proposed to damp out the electromechanical oscillation mode in power systems (Cheng, *et al.* 1992; Hsu, *et al.* 1988; Lee, *et al.* 1994; Hamoud, *et al.* 1987; El-Saady, *et al.* 1998; Hammad, *et al.* 1984; El-Metwally, *et al.* 2003; Fang, *et al.* 2004; Yu, *et al.* 2001; Farsangi, *et al.* 2004). The basic limitation of these designs and/or tuning of SVC stabilizers are that the influence of load model parameters has not been taken into account. Almost all of these SVC stabilizers is based on a constant impedance load (fixed load parameters). The constant impedance load representation is not accurate and is not a good approximation in view of the strong influence of the load voltage sensitivity on the dynamic performance of the power system. The parameters of typical loads vary seasonally, and in some cases change over day. Consequently, the SVC stabilizers tuned under constant impedance load model may become unacceptable under other load-model parameters.

The subject of this paper is to investigate important aspects related to the effect of loads and their parameters uncertainty on tuning of SVC stabilizers. The author has initially addressed this problem in (Ellithy, *et al*. 1989; Choudhry, *et al.* 1986). Proportional-integral (PI) type stabilizer is considered as the additional stabilizer with the SVC. The gain-settings of SVC PI stabilizer are determined using pole-placement (eigenvalue-placement) technique to improve the damping of electromechanical oscillations mode in power systems. The interaction between typical load parameters and the tuning gains of the SVC stabilizer is investigated. Finally, the time domain simulations of the system under disturbance conditions are performed to demonstrate the effect of the load parameters on tuning of the SVC PI stabilizer.

2. Power System under Study

The power system under study is a synchronous generator connected to a large power system, of which the single-line diagram is shown in Fig. 1. The generator is equipped with IEEE type-1 excitation system. Full order model (7th order model) of the generator is utilized in the analysis and simulations. The load is connected at a generator terminal and the SVC is connected at the mid-point of transmission line. The system parameters and nominal operating point values are given in Appendix.

2.1 Model of SVC with Additional Stabilizer

The thyristor-controlled reactor (TCR) type SVC (Chang, *et al.* 1992; Lee, *et al.* 1988; IEEE Special Stability Control Working Group 1994; El-Metwally, *et al.* 2003), shown in Fig. 1, is used in the present study.

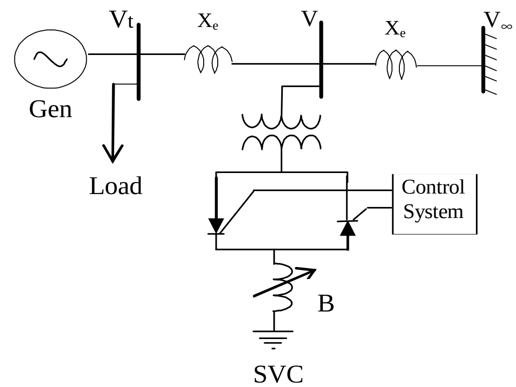


Figure 1. Power system single-line diagram

The model of the SVC with additional proportional-integral (PI) stabilizer is shown in Fig. 2. The stabilizer uses the generator speed deviation ($\Delta\omega$) as a feedback signal to generate the auxiliary stabilizing signal ΔV_s (a stabilizer output signal) to the SVC. The signal ΔV_s is added to the main input of the SVC to damp out the electromechanical oscillations mode. The signal ΔV_s causes fluctuations in the SVC suceptance and, hence, in the bus voltage. If the SVC stabilizer is tuned correctly the voltage fluctuations act to modulate the power transfer to damp out the electromechanical oscillations mode. The equation of the SVC controller (Fig. 2) is given by

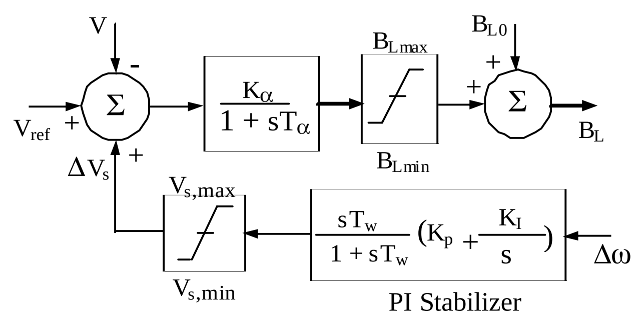


Figure 2. Block diagram of SVC with PI stabilizer

$$\Delta B_L = \frac{K_\alpha}{1+sT_\alpha}(\Delta V_s + V_{ref} - V) \tag{1}$$

where the auxiliary stabilizing signal (SVC stabilizer output signal) ΔV_s is given as

$$\Delta V_s = \left(\frac{sT_w}{1+sT_w}\right)\left(K_P + \frac{K_I}{s}\right)\Delta\omega \tag{2}$$

where K_P and K_I are the SVC stabilizer gain settings. The firing control system of the thyristors is represented by a single time constant T_α and gain K_α. The wash out circuit is introduced in the stabilizer to assure no permanent effect in the terminal voltage due to a prolonged error in the low frequency that might occur in an overload and to assure that the wash out circuit will not have any effect on the phase shift or gain on the low frequency.

The variable inductive susceptance B_L of SVC is a function of the thyristor firing angle α and is given by

$$B_L = -\frac{(2\pi - 2\alpha + \sin 2\alpha)}{\pi x_s} \ ; \ \pi/2 \le \alpha \le \pi \tag{3}$$

where x_s is the reactance of the SVC fixed inductor.

2.2 Load Model

This paper follows the recommendation of the IEEE working group (IEEE Task Force on Load Representation for Dynamic performance 1995) and utilities (Xu, *et al*. 1997; Ohyama, *et al*. 1985) in utilizing the voltage-dependent load model for composite load representation. Utilities normally perform field tests, or in some cases perform regression analysis to establish system load models to be used for power-flow and stability studies. These models are in the form of

$$P_L = P_{L0}\left(\frac{V_t}{V_{t0}}\right)^{n_p} \quad Q_L = Q_{L0}\left(\frac{V_t}{V_{t0}}\right)^{n_q} \tag{4}$$

where

P_L and Q_L are the load active and reactive power;

V_t is the load bus voltage;

n_p and n_q are the load parameters.;

P_{L0}, Q_{L0}, and V_{t0} are the nominal value of load active power, load reactive power, and bus voltage prior to a disturbance.

For small disturbance studies of system damping, the linearized version of Eq. (4) is given by

$$\Delta P_L = n_p \frac{P_{L0}}{V_{t0}} \Delta V_t \quad \Delta Q_L = n_q \frac{Q_{L0}}{V_{t0}} \Delta V_t \tag{5}$$

where

$$\Delta V_t = \frac{1}{V_{t0}}(V_{q0}\Delta V_q + V_{d0}\Delta V_d)$$

The load representation given in Eq. (4) makes it possible the modeling of all typical voltage-dependent load models by selecting appropriate values of the load parameters n_p and n_q. The values of n_p and n_q depend on the nature of the load and can vary between 0 to 3.0 for n_p and 0 to 6.0 for n_q. The load parameters of the composite load (industrial, commercial and residential loads) can be determined by the following equations (Ohyama, *et al*. 1985; Berg 1973):

$$\begin{aligned} n_p &= \sum_{i=1}^{n} n_{pi}\left(\frac{P_{li}}{P}\right); \quad P = \sum_{i=1}^{n} P_{li} \\ n_q &= \sum_{i=1}^{n} n_{qi}\left(\frac{Q_{li}}{Q}\right); \quad Q = \sum_{i=1}^{n} Q_{li} \end{aligned} \tag{6}$$

where P_{li} and Q_{li} are the active and reactive power of i^{th} component and n_p, n_q are their load parameters. The measurement values of the parameters (n_p, n_q) of various kinds of typical power system composite loads are reported in (Xu, *et al*. 1997; Ohyama, *et al*. 1985; Concordia, *et al*. 1982).

3. Design of SVC PI Stabilizer

The gain-settings (K_P and K_I) of the SVC PI stabilizer are determined using the pole placement by moving the eignvalues associated with the electromechanical oscillations mode to a prescribed value on the left-half complex plane. It is well known that improving the damping of these oscillations mode can enhance the damping characteristic of a power system. The design procedures and their associated results are given below.

3.1 System without SVC Stabilizer

In the design of the SVC stabilizer using the pole-placement technique, the nonlinear equations of the power system are first linearized around an operating point to obtain the state-variables model of the system. In the present study, the state-variables model of the system is obtained using the component connection model (CCM) technique (Ellithy, *et al*. 1989; Choudhry, *et al*. 1986). The equations describe the state-variable model given in (El-Metwally, *et al*. 2003).

The state-variables model of the system is expressed as

$$\frac{dX}{dt} = AX + BU \quad Y = CX \tag{7}$$

where

$X = (\Delta i_q\ \Delta i_d\ \Delta i_q\ \Delta i_{kkq}\ \Delta i_{kkd}\ \Delta i_{fd}\ \Delta\delta\ \Delta\omega\ \Delta V_F\ \Delta E_{fd}\ \Delta V_R\ \ \Delta B_L)^T$ is the state-variables vector. The state variables X_1 to X_7 correspond to the generator, X_8 to X_{11} correspond to the excitation system and X_{12} corresponds to the SVC.

$Y = \Delta\omega$, the output signal.

$U = \Delta V_s$, the control signal (stabilizer output signal) to the SVC.

The system eigenvalues without SVC PI stabilizer (open-loop system) for fixed load parameters $n_p = n_q = 2$ (constant impedance load) are listed in the first column of Table 1.

Table 1. System eigenvalues at load model parameters $n_p = n_q = 2$

	Without SVC Stabilizer (K_P=0.0, K_I=0.0)	With SVC Stabilizer (K_P=19.892, K_I=178.895)
$\lambda_{1,2}$	-212.210 ± j842.990	-212.700 ± j842.930
λ_3	-98.782	-89.620
λ_4	-72.361	-79.480
λ_5	-38.992	-38.820
$\lambda_{6,7}$	*-0.679 ± j11.362*	*-2 ± j11**
$\lambda_{8,9}$	-9.893 ± j14.903	-9.070 ± j14.630
$\lambda_{10,11}$	-0.645 ± j0.837	-0.650 ± j 0.900
λ_{12}		-10.220

*: Exact pole placement

The eigenvalues associated with the electromechanical oscillations mode of the synchronous generator are depicted by the complex pair eigenvalues $\lambda_{6,7}$. The damping ratio ζ of this poorly damped oscillations mode without the SVC stabilizer ($\lambda_{6,7} = \sigma \pm j\beta = -0.67896 \pm j11.362$) is given as

$$\zeta = \frac{\sigma}{\sqrt{\sigma^2 + \beta^2}} x100 = 6\%$$

The damping ratio ζ = 6% for the electromechanical mode is not good enough. The poor damping of this mode can be also seen from the system time response in Figs. 3 and 4. The eigenvalues for this mode should be shifted to more desirable locations by the SVC stabilizer (*ie*. the SVC stabilizer is needed to improve the damping of this mode). The tuning gains of the SVC stabilizer are described in the following section.

3.2 Determination of SVC Stabilizer Gains using Pole Placement Technique

The gain-settings (K_P and K_I) of the SVC stabilizer will be determined to improve the damping ratio of the electromechanical mode by shifting the eigenvalues $\lambda_{6,7}$ to desired locations. An expression for the gains has been derived by the author in Ellithy (1997) and is given by

$$K_1 = \frac{b_2}{ga_{22}} - \frac{a_{21}b_1}{ga_{11}a_{22}}; \quad K_P = \frac{b_1}{a_{11}} - \frac{K_I a_{12}}{a_{11}}$$

where: (8)

$$g = 1 - \frac{a_{21}a_{12}}{a_{21}^2}; \; b_1 = \frac{(real \;\; part\,(h))}{s}$$

$$b_2 = \frac{(imaginary \;\; part\,(h))}{s}$$

$$m = 1 - \sigma T_\omega; \quad a_{11} = \beta^2 T_\omega - \sigma m; \; a_{12} = m;$$

$$a_{22} = -\beta m - \alpha\beta T_\omega; \; a_{22} = \beta T_\omega; \; h = \frac{1}{d}$$

$$s = \frac{T_\omega}{\left(m^2 + \beta^2 T_\omega^2\right)}$$

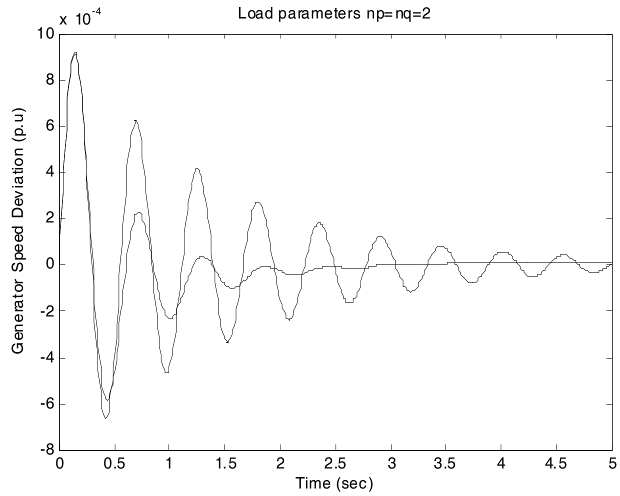
$\lambda_6 = -\sigma - J\beta$ is the desired eigenvalue location associated with the electromechanical oscillations mode.

$$D = c\,[\lambda_6\, \mathrm{I} - A]^{-1}\, B$$

where *A*, *B* and *C* system matrices are given in (7).

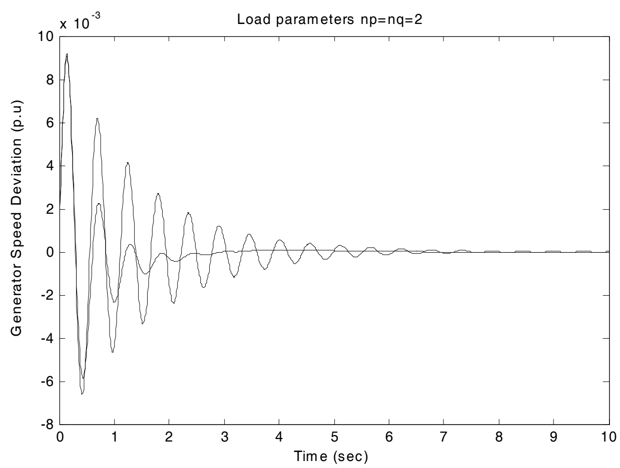
If the eigenvalues $\lambda_{6,7} = -2 \pm j11$ (*ie*. the damping ratio of the electromechanical mode ζ = 18%) are selected at the desired locations, then the gains K_P and K_I for the SVC stabilizer can be computed using (8). The results are given in Table 1.

The eigenvalues of the closed-loop system (system with the SVC stabilizer) are given in the second column of Table 1. Considerable improvement in the system damping can be expected in view of the closed-loop eigenvalues. The improvement in the damping can also be seen from the system dynamic performance shown in Figs. 3 and 4.



-- Without SVC stabilizer
_ With SVC stabilizer tuned at $n_p = n_q = 2$

Figure 3. The system dynamic response at load parameters $n_p = n_q = 2$ for 5% change in T_m

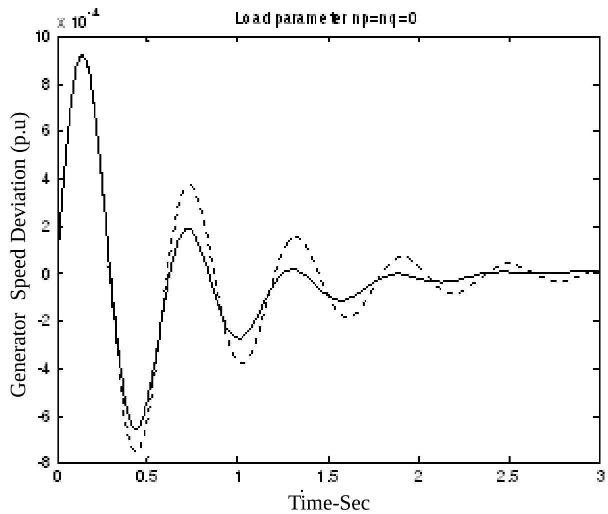


-- Without SVC stabilizer
_ Without SVC stabilizer tuned at $n_p = n_q = 2$

Figure 4. The system dynamic response at load parameters $n_p = n_q = 2$ for 50% change in T_m

4. Effect of Load Parameters on SVC Stabilizer Tuning

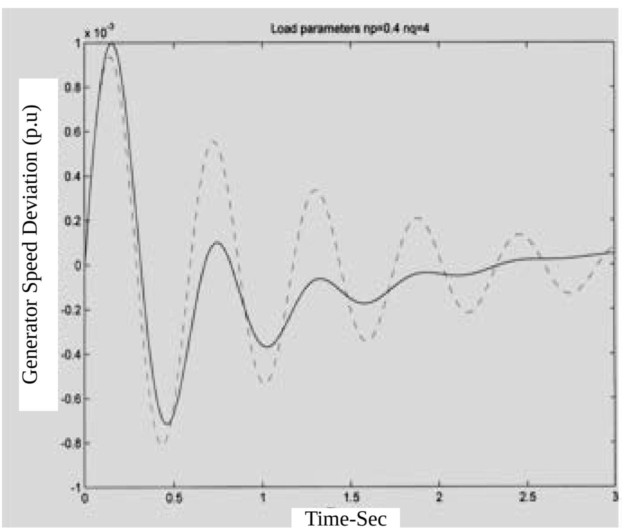
The tuned gains (K_P=19.892and K_I=178.895) of the SVC stabilizer at the parameters $n_p = n_q = 2$ are used to check the damping characteristics and stability of the system under different load model parameters. Based on these fixed gains, tuned at load parameters $n_p = n_q$ =2, the damping of the electromechanical oscillations mode is reduced under other load parameters as shown in Figs. 5, 6, 7 and 9. The tuned gains of the SVC stabilizer at other different load parameters are also used to check the system stability under different load parameters. Based on these fixed gains, the system damping is reduced and the system may become unstable under other load param-



-- With SVC stabilizer tuned at $n_p = n_q = 2$

- With SVC stabilizer tuned at $n_p = n_q = 0$

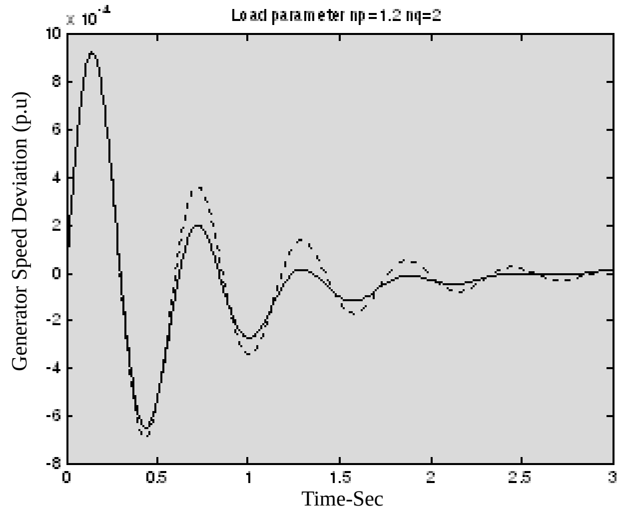
Figure 5. The system dynamic response at load parameters $n_p = n_q = 0$ for 50% change in T_m



-- With SVC stabilizer tuned at $n_p = n_q = 2$

- With SVC stabilizer tuned at $n_p = 0.4$, $n_q = 4$

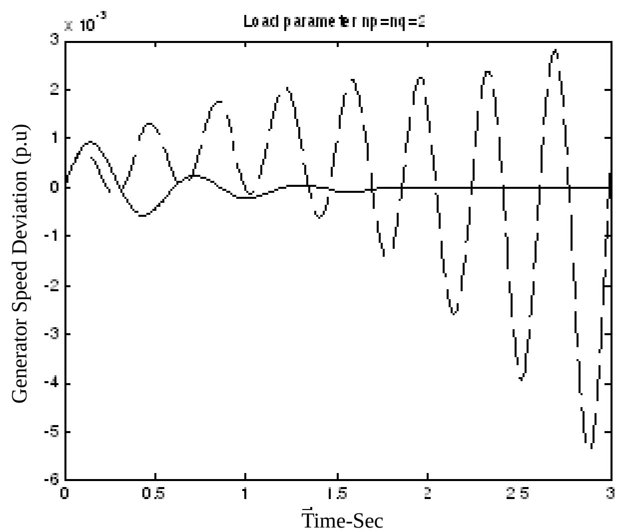
Figure 6. The system dynamic response at load parameters $n_p = 0$, $n_q = 4$ for 5% change in T_m



-- With SVC stabilizer tuned at $n_p = n_q = 2$

- With SVC stabilizer tuned at $n_p = 1.2$, $n_q = 2$

Figure 7. The system dynamic response at load parameters n_p=1.2, n_q=2 for 5% change in T_m



-- With SVC stabilizer tuned at $n_p = 0$, $n_q = 6$

- With SVC stabilizer tuned at $n_p = n_q = 2$

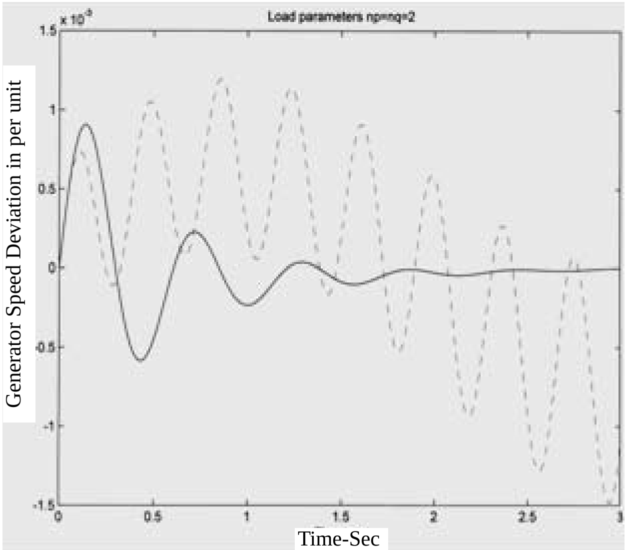
Figure 8. The system dynamic response at load parameters $n_p = n_q = 2$ for 5% change in T_m

eters as shown in Figs. 8 and 9. The decreases in the system damping are caused by the eigenvalues $\lambda_{6,7,}$ which are associated with the systems electromechanical oscillations mode.

In order to improve the damping of the oscillations mode (*ie*. improving the damping ratio of the eigenvalues $\lambda_{6,7}$) over a wide range of load model parameters, the SVC stabilizer gains K_P and K_I must be tuned. The computed SVC stabilizer gains (K_P and K_I) for typical load model parameters are given in Figs. 10 and 11. These gains have been computed by (8) with the eigenvalues $\lambda_{6,7}$ fixed at the desired locations of -2±j11. From these figures, it can be observed that the variations in the load model parameters (n_p, n_q) have a considerable influence on the tuning of the SVC stabilizer. While not reported in the paper, the author has also investigated the influence of load parameters when the load is located at the SVC bus. The results obtained indicated no significant departure from the results presented here in so far as the influence of the load parameters on the tuning of the SVC stabilizers.

5. Conclusions

This paper has examined the influence of voltage-dependent load models on the effectiveness of the SVC proportional-integral stabilizer for damping the electromechanical oscillations mode in power systems.



-- With SVC stabilizer tuned at $n_p = 0, n_q = 4$
- With SVC stabilizer tuned at $n_p = n_q = 2$

Figure 9. The system dynamic response at load parameters $n_p = n_q = 2$ for 5% change in T_m

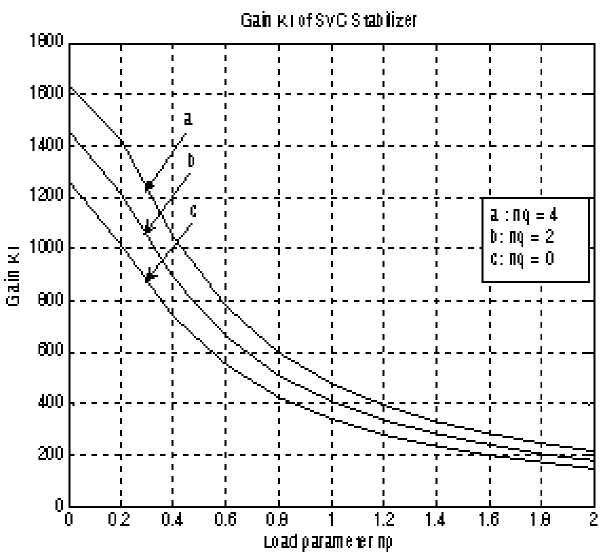


Figure 10. The computed SVC stabilizer gain K_1 at different load model parameters

The impact of load model parameters on the SVC stabilizer tuning gains obtained via pole-placement technique is investigated and it is shown that load models have remarkable influence on the stabilizer tuning gains. The results have also shown that the SVC stabilizer tuned gains under specific load parameters could contribute to the worse damping of electromechanical oscillations and reduce system stability under other load parameters. In particular, simulation with constant active power loads shows system instability when the SVC stabilizer is designed assuming constant impedance load. The results presented in this paper reinforce the need for including the load model parameters in the SVC stabilizers tuning for damping the oscillations mode of power systems.

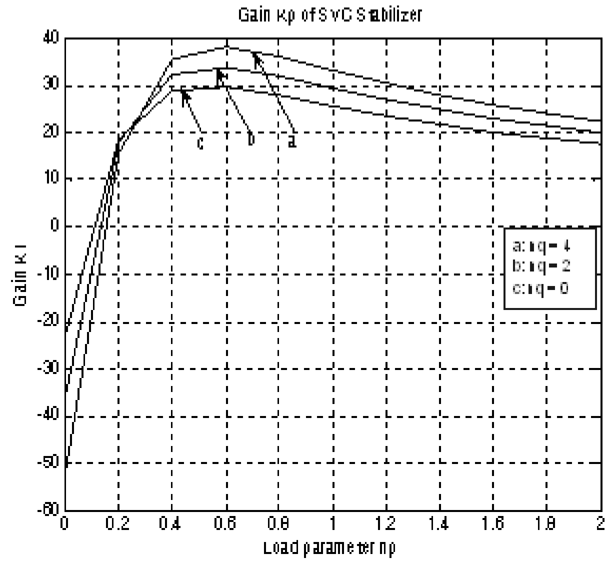


Figure 11. The computed SVC stabilizer gain K_p at different load model parameters

Acknowledgments

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Appendix

System parameters and nominal operating values:

Synchronous Generator

x_d =1.7 x_q=1.64 x_{ls}=0.15
x_{kkd}=1.605 x_{kkq}=1.526 x_{ffd} =1.651
x_{ad} =1.55 x_{aq} =1.49 r_a=0.001096
r_{fd}=0.000742 r_{kq}=0.054 r_{kd}=0.0131
H=2.37sec

IEEE Type-1 Excitation System

K_A=400 T_A=0.05 sec K_F = 1.0
T_F =1.0 sec K_E=-0.17 T_E= 0.95 sec

Transmission Line

x_1= 0.15 x_2=0.15

Static Var Compensator (SVC)

K_α =20 T_α = 0.02 sec X_s = 0.8
α_o=1400 B_{L0}=-0.164 T_w = 0.1 sec
$V_{s\ limit}$ = 0.1

Nominal Operating Values

P_G =1.0 pf_G = 0.85 P_{L0} =1.25 pf_l = 0.5
V_t = 0.976 V = 0.987 V_∞ =1.0 δ_0 = 43.146^0