POWER OSCILLATION DAMPING USING LEAD-LAG CONTROLLED SVC

Karo Naqshi[2], Mohyeddin Rahmani[1], Behrooz Vahidi[1], Seyed Hossein Hosseinian[1]
1-Department of Electrical Engineering, Amirkabir University of Technology
Tehran 1591634311, Iran
2- Deptartment of Electrical Engineering, University of Science and Technology, Tehran, Iran

ABSTRACT: *This paper proposes a new method to small signal stability improvement using controlled static VAR compensator (SVC). The linearized Phillips–Heffron model of a power system installed with a Static Var Compensator (SVC) is presented in order to increase the stability of the system parameters. Configuration of SVC in the power systems is widely adopted and effective to improve the power quality. In order to enhance the dynamic stability of power systems, this paper introduces the combination of static VAR compensator and lead-lag controller to compensate the reactive power. Feeding back the control signals, helps the controller to decrease the frequency oscillations of rotor, which are not negligible in the absence of lead-lag controller. The generator speed fluctuation (Δω) is the signal, which the combination of controller and SVC use to create the desired damping. As the result, creating the better damping for SVC, leads to better dynamic performance of system parameters, as well as reducing the steady-state errors. Also the settling times are reduced. The simulations are carried out for Single-Machine Infinite-Bus power system at two modes of operating.*

Key Words: Static VAR compensator (SVC), Lead-Lag damping controller, Small signal stability, Phillips-Heffron model

1. INTRODUCTION

With great developments of modern power electronic devices, new application possibilities in several fields was made, like electrical power systems (EPS) and motor drives for electrical vehicles. The development of Flexible AC Transmission Systems (FACTS) devices is improving fast with the introduction of modern control techniques and new and improved power semiconductor devices [1,2]. Reactive power compensation is an important issue in electrical power systems and shunt FACTS devices play an important role in controlling the reactive power flow to the power network. Because of the good and fast response of the FACTS devices, and also their good ability to accommodate themselves to the system, many efforts have been made to use these devices instead of traditional power system stabilizers (PSS). This fast response of the FACTS devices, also results in reducing the transients of the system parameters.

To overmatch the small disturbances, the power system must have a good dynamic stability which also maintains the synchronism between the system parameters. These small disturbances are the result of any change in power system, so they are continuously forced to the system. Many factors affect the dynamic response of the system to small disturbances, such as point of operating, system characteristics and the type of generator excitation.

One of the most employed FACTS in the power systems are Static VAR Compensators (SVCs), in recent years SVC has been adopted widely since dynamic reactive-power control gives significant advantages for power system operation. Moreover the voltage control as a main task, SVC may also be employed for additional tasks resulting in improvement of the transmission capability [3-5].

The addition of dynamic voltage support or active power flow modification equipment can postpone the need for new transmission equipment and may also eliminate or postpone the need for new facilities. SVCs and FACTS devices provide rapid response to voltage irregularities and offer the opportunity to significantly improve the system performance in a cost effective manner.

An important prospect when using SVCs is damping of power oscillations. Damping of power system oscillations plays a vital role not only in improvement the transmission capability but also for stabilization of power system parameters after critical faults, especially in inappropriate coupled systems. To achieve this objective, it is necessary to improve the SVC control concept by introducing signals which reflect power system oscillations. The normally used SVC voltage control is not suitable to effectively damp these oscillations [6-8]. To increase the effectiveness of SVCs, the complementary auxiliary control signals are adopted to decrease the rotor electro-mechanical frequency oscillations. In this paper the lead-lag controller is proposed using the generator speed fluctuation (Δω), as a modulated signal to SVC.

The operation of SVC is described briefly in part II. Section III includes the model of power system e.g. single-machine infinite-bus, synchronous generator and exciter, and lead-lag controlled SVC. The simulations are carried out for Single-Machine Infinite-Bus power system and results are in part IV. Conclusions and future works are presented in section V to verify the validity of the proposed method.

2. STATIC VAR COMPENSATOR (SVC)

A Static VAR Compensator (SVC) is an electrical device for providing fast-acting reactive power on high-voltage electricity transmission networks. SVCs are part of the Flexible AC transmission system device family, regulating voltage and stabilizing the system. The term static refers to the fact that the SVCs have no moving parts (other than circuit breakers and disconnectors, which do not move under normal SVC operation). Prior to the invention of the SVC, power factor compensation was the preserve of large rotating machines such as synchronous condensers. A SVC provides benefits at the transmission, distribution and end user level.

The SVC is an automated impedance matching device, designed to bring the system closer to unity power factor. If the power system's reactive load is capacitive (leading), the SVC will use reactors (usually in the form of Thyristor-Controlled Reactors) to consume VARs from the system, lowering the system voltage. Under inductive (lagging) conditions, the capacitor banks are automatically switched in, thus providing a higher system voltage. They also may be placed near high and rapidly varying loads, such as arc furnaces, where they can smooth flicker voltage.

These local compensation systems use shunt connected elements to absorb/inject reactive power. The SVC maintains a set point of one or more elements of the power equation. The SVC modifies the voltage at the supply point and is characterized by fast response time, low power losses, high reliability, and low maintenance.

A main modeling topology of Static VAR Compensator consisting of a series capacitor bank (C) with a thyristor-controlled reactor (L) is shown in Fig 1.

The design of a SVC is conditioned by factors ranging from economical aspects to very detailed electrical specifications. The design criteria definition has a vital role in the way the SVC unit performs in simulations [9].

3. POWER SYSTEM MODEL

3.1 Single machine infinite bus

As mentioned above, in this paper a Single-Machine Infinite-Bus is considered Fig 2. The system is equipped with a lead-lag controlled SVC and the generator is connected to the infinite-bus through the transmission line. The transmission line has impedances of Z = $R_e + jX_e$.

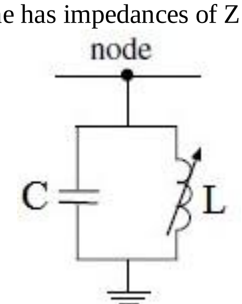


Figure 1 Basic SVC Topology

Unified Philips-Heffron model for the single machine power system is used and state equation from $\dot{X} = AX + BU$ and $Y = CX + DU$ are obtained. State vector X and the input vector U (after linearization) are as follows.

$$X^T = \left[\Delta\delta,\ \ \Delta\omega,\ \ \Delta E'_q,\ \ \Delta E_{fd}\right],$$

$$U = \left[\Delta T_m,\ \ \Delta V_{ref\,1},\ \ \Delta V_{ref\,2}\right]$$

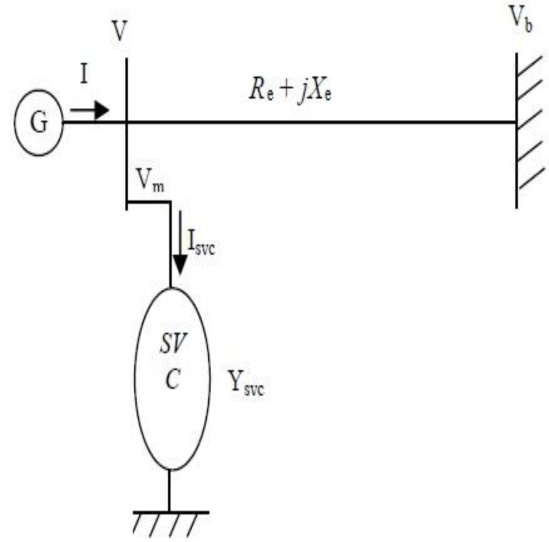


Figure 2: Single machine infinite bus system with a SVC

3.2 Synchronous Generator and Exciter

The generator is represented by the forth-order model comprising of the electromechanical swing equation, generator speed equation and the generator internal voltage equation. The swing equation is shown by equation (1) and (2).

$$\dot{\delta} = \omega.\omega_s \quad (1)$$

$$\dot{\omega} = (T_m - T_{e1} - T_{e2} - D\omega)/2H \quad (2)$$

$$T_{e1} = K_1.\delta \quad (3)$$

$$T_{e2} = K_2.E'_q \quad (4)$$

where, T_m the input torque of the generator; H and D are the inertia constant and damping coefficient respectively; δ and ω are the rotor angle and speed respectively; ω_s is the synchronous speed and $K_{1,2}$ are Philips-Heffron coefficients.

The internal voltage behind transient reactance E'_q is calculated by (5).

$$E''_q = (K_3(E_{fd} - K_4\delta) - E'_q)/K_3T'_{do} \quad (5)$$

Where, E_{fd} is the field voltage; T'_{do} is the open circuit field time constant; and $K_{3,4}$ are Philips-Heffron coefficients.

The excitation system shown in Fig 3. is considered in this work. It is described by equation (6).

$$E'_{fd} = (K_a(V_{ref} - K_5\delta - K_6E'_q) - E_{fd})/T_A \quad (6)$$

Where, K_A and T_A are the gain and time constants of the excitation system respectively; V_{ref} is the reference voltage; and $K_{5,6}$ also are Philips-Heffron coefficients.

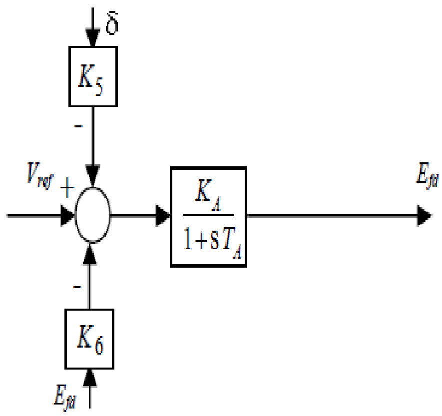
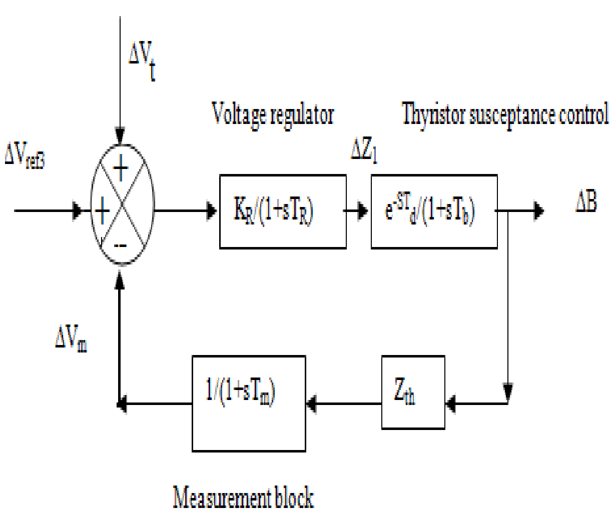


Figure3. Exciter Topology

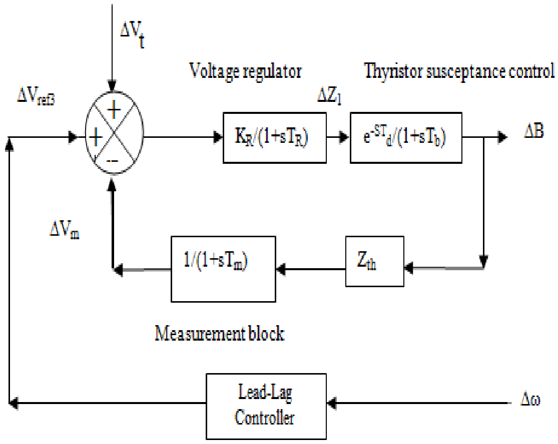
3.3 Lead-lag controlled SVC

This paper used the basic stability model of SVC which is shown in fig 4 (a) [10]. This model is utilized for testing the single-machine infinite-bus systems. This model of SVC consists of different parts. The voltage regulator block this provides the measurement of susceptance in order to measure the current through SVC controller. The thyristor susceptance control block which measures the correct value of susceptance by using the firing angle values at any time and assigns this value to susceptance. And the Zth (thevenins impedance) of the SVC controller which is constant.

To increase the effectiveness of SVC, Lead-Lag controller is used, Fig 4 (b), which will result in more damping in the system and also the low frequency oscillations that have the mechanical base, have been damped more quickly. have b subsidiary signal introduces an additional damping in the system and damps the rotor mechanical low frequency oscillations quickly. This controller uses the generator deviation Δω to obtain ΔV_{ref} signal.



(a). SVC Main Stability Model



(b). SVC Model With Lead-Lag Controller

Figure 4. SVC Model

So, Unified Philips-Heffron model is developed as shown in Fig 5. and [A], [B] are defined as below:

[A] =

$$\begin{pmatrix} 0 & \omega_s & 0 & 0 \\ -K_1*(2H)^{-1} & -D*(2H)^{-1} & -K_2*(2H)^{-1} & 0 \\ -K_4*T_{do}^{'\,-1} & 0 & -K_3^{-1}*T_{do}^{'\,-1} & -T_{do}^{'\,-1} \\ -K_5*K_A*T_A^{-1} & 0 & -K_6*K_A*T_A^{-1} & -T_A^{-1} \end{pmatrix}$$

$$B = \begin{pmatrix} 0 & 0 \\ (2H)^{-1} & 0 \\ 0 & 0 \\ 0 & K_A*T_A^{-1} \end{pmatrix}$$

Where, $X^T = \left[\Delta\delta, \quad \Delta\omega, \quad \Delta E'_q, \quad \Delta E_{fd}\right]$,

$U = \left[\Delta T_m, \quad \Delta V_{ref\,1},\right]$

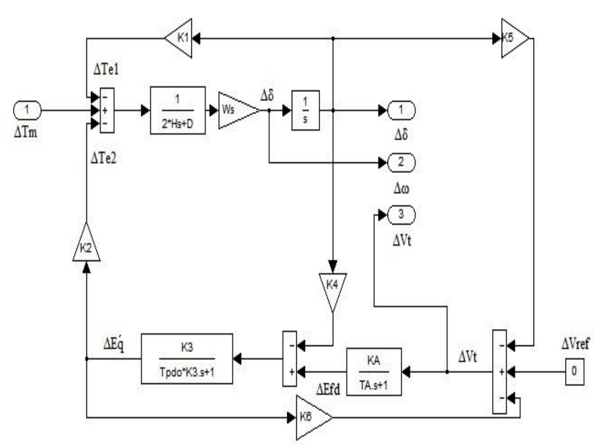


Figure 5 Unified Philips-Heffron Model

And also Unified Philips-Heffron model with SVC and Lead-Lag controller is developed as shown in Fig 6.

When Lead-Lag controlled SVC is added to the Unified Philips-Heffron model, the sixth-order model must be investigated, and ΔB and Δ'B are added to the state variables and ΔV_{ref2} is added to input vector U. [A] and [B] are changed consecutively.

4. SIMULATION AND RESULTS

The proposed approach has been implemented on the system shown in Fig 2. At first, DC load flow should be performed to obtain system operating points. According to these operating points, K_1 to K_6 is defined through (8) to (13).

$$K_1=\frac{-1}{\Delta}[I_q^o V_b(X'_d-X_q)\{(X_e+X_q)\sin(\delta^o) -R_e\cos(\delta^o)\}+V_b\{(X'_d-X_q)I_q^o-E_q'^o\}\times \{(X_e+X'_d)\cos(\delta^o)+R_e\sin(\delta^o)\}] \quad (7)$$

$$K_2=\frac{1}{\Delta}[I_q^o\Delta-I_q^o(X'_d-X_q)(X_e+X_q)-R_e(X'_d-X_q)I_d^o+R_eE_q'^o] \quad (8)$$

$$\frac{1}{K_3}=1+\frac{(X_d-X'_d)(X_e+X_q)}{\Delta} \quad (9)$$

$$K_4=\frac{V_b(X_d-X'_d)}{\Delta}[(X_e+X_q)\sin(\delta^o)-R_e\cos(\delta^o)] \quad (10)$$

$$K_5=\frac{1}{\Delta}[\frac{V_d^o}{V_t}X_q\{R_eV_b\sin(\delta^o)+ V_b\cos(\delta^o)(X_e+X'_d)\}+(\frac{V_q^o}{V_t}X'_d\times (\{R_eV_b\cos(\delta^o)-V_b(X_e+X_q)\sin(\delta^o)\})] \quad (11)$$

$$K_6=\frac{1}{\Delta}[\frac{V_d^o}{V_t}X_qR_e-\frac{V_q^o}{V_t}X'_d(X_e+X_q)]+\frac{V_q^o}{V_t} \quad (12)$$

$$\Delta=R_e^2+(X_e+X_q)\times(X_e+X'_d) \quad (13)$$

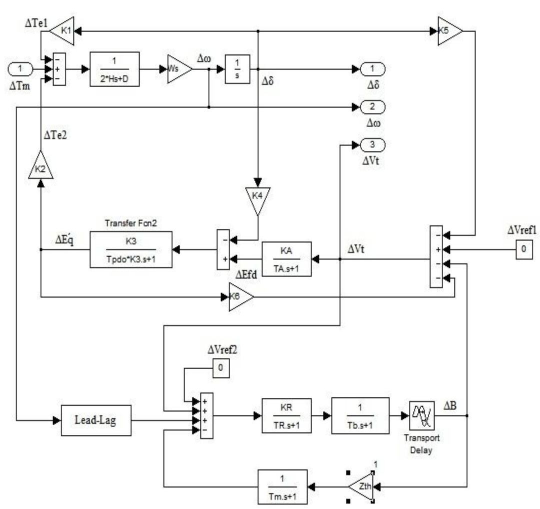


Figure 6. Unified Philips-Heffron Model with SVC & Lead-Lag Controller

The time-domain simulations have been performed on the Single-Machine Infinite-Bus power system. This system is simulated with and without SVC, and also with Lead-Lag damping controlled SVC for two operation conditions and three different modes, no SVC, SVC without controller, and SVC with controller. And results are compared with PID controller which has been used in other papers.

- Operation condition 1: D=0,
- Operation condition 2: D=0.5.
- Case Study 1: No SVC,
- Case Study 2: SVC without Lead-Lag Controller,
- Case Study 3: with Lead-Lag Controller.

The results of Single-Machine Infinite-Bus power system for different case studies are shown in Fig 7-12.

As shown in Fig 7-12, SVC is a very important device to reduce the settling time of rotor oscillations and the fluctuations of terminal voltage.

The system without SVC has major rotor oscillations and large settling times. SVC decreases the settling times significantly, but additional complementary signal that comes from the Lead-Lag controller improves the effectiveness of SVC. This proves the fact that a set of SVC and its complementary controller could be more useful to improve the dynamic performance of power systems.

1. **Operation Condition I**:

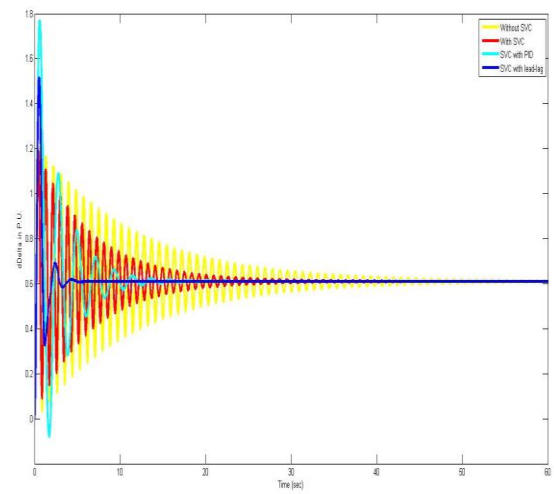


Figure 7. Δδ for D=0

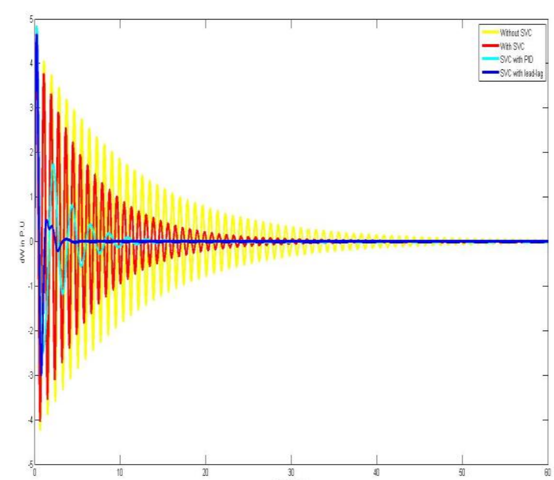


Figure 8. Δω for D=0

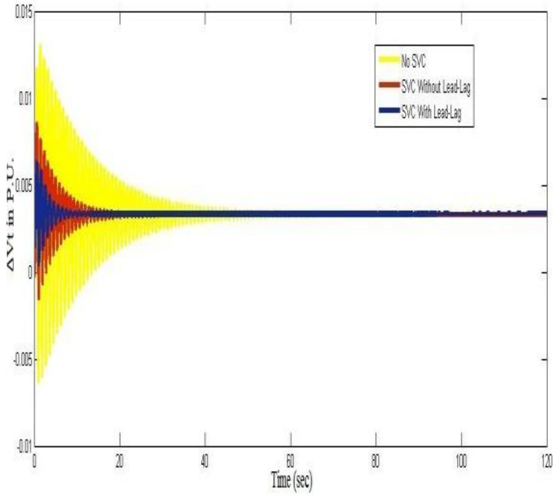


Figure 9. ΔVt for D=0

2. **Operation Condition II**:

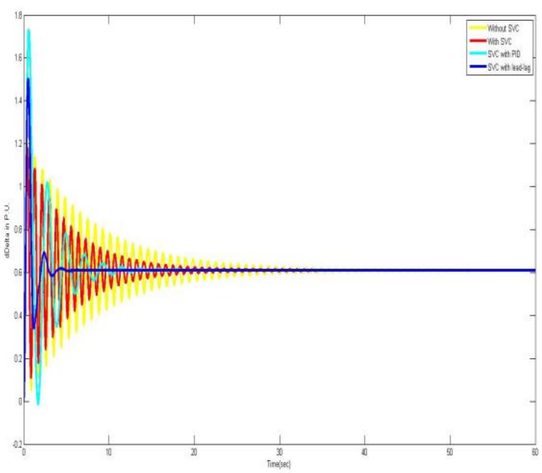


Figure 10. Δδ for D=0.5

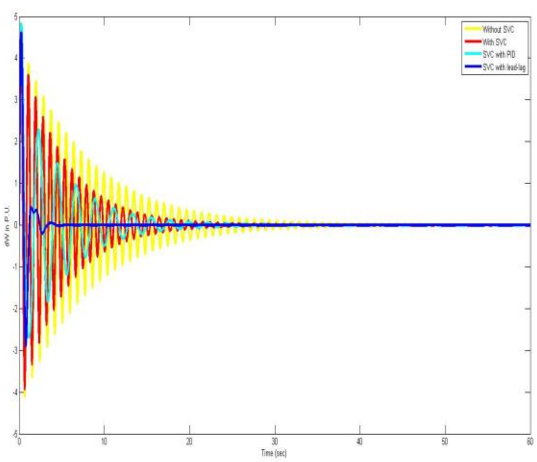


Figure 11. Δω for D=0.5

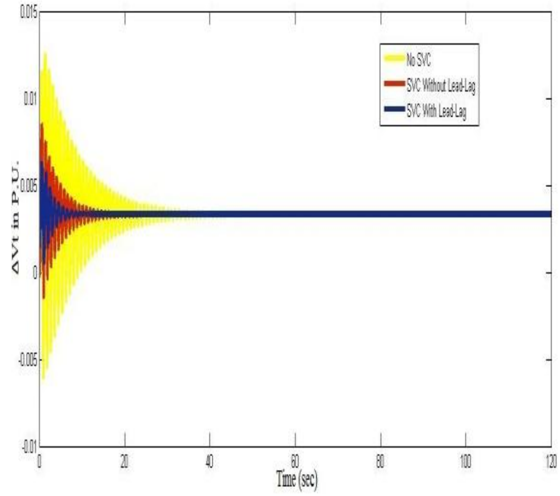


Figure 12. ΔVt for D=0.5

5. CONCLUSION

In this paper a new method has been tested to increase the small signal stability using SVC with Lead-Lag controller. Besides damping of oscillations in the generator, terminal voltages have also been tested on Single-Machine Infinite-Bus power system.

The conclusions are that SVC as one of the FACTS devices, can improve the dynamic performance of power system with appropriate controllers. The simulations which are implemented on Single-Machine Infinite-Bus power system prove the effectiveness of SVC with Lead-Lag controller. And results show that this combination of the SVC and lead-lag controller not only damps out the rotor mechanical frequency oscillations and terminal voltage fluctuations, but also enhances the limits of machine reactive power. Moreover, SVC with controller seems to be more effective in real-time control of the power system compared with traditional power system stabilizers.

APPENDIX

Data for Single-Machine Infinite-Bus power system:

R_e=0, X_e=0.5, $V_t = 1\angle 15$ pu, $V_b = 1.05\angle 0$ pu , T_A=0.2 sec, R_s=0 pu, X_q=2.1 pu, X_d=2.5 pu ,X'_d=0.39 , ω_s=377, H=3.2, T'_{do}=9.6 sec, K_A=400.

Data for basic SVC stability model:

KR: Voltage regulator Gain = 1

TR: Voltage regulator time constant = 0.025seconds

Td: Thyristor susceptance control firing angle delay = 0.025 seconds

Tb: Thyristor susceptance control time constant = 0.0375 seconds

Zth: The thevinin's impedance = 0.02 pu

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