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Static Var Compensator Models for Power Flow and Dynamic Performance Simulation

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Abstract - The static var compensator is now mature technology that is widely used for transmission applications. Electric utility industry standardization of basic models is needed, and is recommended in this paper. Description and model requirements for more detailed representations, including supplementary function modules, are included. In addition to transient stability program modeling, requirements for power flow and longer-term dynamics programs are given.

Introduction

Static var systems are applied by utilities in transmission applications for several purposes. The primary purpose is usually rapid control of voltage at weak points in a network. Installations may be the midpoint of transmission interconnections or in load areas. Worldwide, there is a steady increase in the number of installations.

CIGRE defines a static var *system* (SVS) as a combination of a static var *compensator* (SVC) and mechanically switched capacitors and reactors, all under coordinated control [1]. Most of this paper pertains to the modeling of static var compensators.

Components of a static var system may include:

- Transformer between high voltage (HV) network bus and the medium voltage (MV) bus where power electronic equipment is connected. Usually a dedicated transformer is used, but sometimes the tertiary of an autotransformer is used.
- Thyristor-controlled reactors (TCRs) connected to medium voltage bus.
- Thyristor-switched reactors (TSRs) connected to medium voltage bus.
- Thyristor-switched capacitors (TSCs) connected to the medium voltage bus.
- Saturated reactor (SR) connected to the medium voltage bus (not covered in this report).
- Fixed capacitors (FC).
- Harmonic filters connected to the medium voltage bus. At fundamental frequency, the filters are capacitive.
- Mechanically-switched capacitors (MSCs) or reactors (MSRs), usually connected at a high voltage bus.
- Control system, usually with a primary function of regulating the transmission voltage.

This paper describes fundamental frequency, positive phase sequence models for power flow programs and dynamic programs (eigenvalue, transient stability, and longer term dynamics). Generator stator and network elements are modeled in the sinusoidal steady state. These programs are used to study rotor angle stability and voltage stability. Specifically excluded are electromagnetic transient (EMTP or TNA) type models requiring bandwidths exceeding 5 Hertz. Also excluded are open-loop control methods sometimes used in industrial and distribution network applications.

We recommend basic models, and recommend a framework and modules for more detailed models. Because of different application requirements, and because of the different control techniques of equipment suppliers, very detailed models are not appropriate. Once defined, specific detailed controls can be easily programmed—possibly by a higher level language user-defined modeling c⌐¬ability.

CIGRE has described models for static var compensators [1,2]. Since these models were published,

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additional experience with the design and application of static compensators has accumulated. In particular, the standard use of microprocessor controllers results in additional flexibility and new functions.

The recent challenge of longer-term dynamics related to voltage stability requires coordinated control of SVCs, MSCs, LTC transformers, and generator voltage regulators. Fast-acting SVCs can provide a "pilot" for control of slower devices.

Industry Needs

Models need to be standardized to the extent possible. Basic standard models need to be defined, along with data exchange parameters. The goals of this paper are:

1. To promote better modeling of static var systems by programmers and users, and
2. To facilitate data exchange among different computer programs for large-scale simulation.

Basic Description of Static Var Systems

Figure 1 is a one-line diagram of a typical static var system for transmission application. One TCR and two TSCs are assumed, along with a MSC. The TCR reactive power rating is typically slightly larger than the discrete TSC and MSC blocks—this allows continuous (smooth) control over the entire SVS rating. The harmonic filters are capacitive at fundamental frequency, supplying reactive power of 10–30 percent of the TCR rating [3].

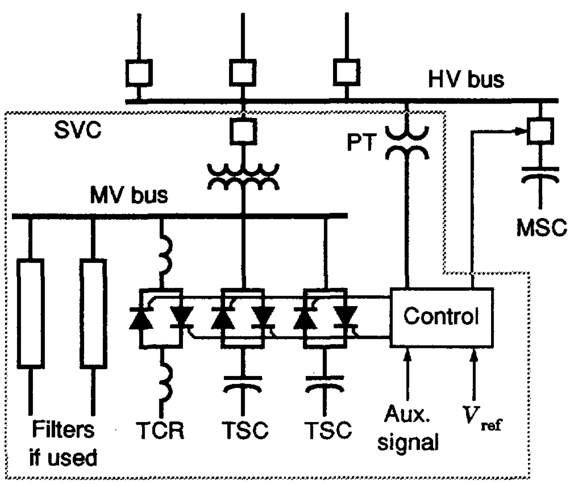


Fig. 1. Typical static var system. The MSCs could be located at the MV bus, or remotely located.

Figure 2 show the steady-state and dynamic voltage–current characteristics of the SVC portion of the system. In the active control range, current/susceptance and reactive power is varied to regulate voltage according to a slope (droop) characteristic. The slope value depends on the desired voltage regulation, the desired sharing of reactive power production between various sources, and other needs of the system. The slope is typically 1–5%. At the capacitive limit, the SVC becomes a shunt capacitor. At the inductive limit, the SVC becomes a shunt reactor (the current or reactive power may also be limited).

The response shown by the dynamic characteristic is very fast (few cycles) and is the response normally represented in transient stability simulation.

Some SVCs have a susceptance/current/reactive power regulator to slowly return the SVC to a desired steady-state operating point. This prevents the SVC from drifting towards its limits during normal operating conditions, preserving control margin for fast reaction during disturbances. During normal operation, voltage is not regulated unless the voltage exceeds a deadband determined by the limits on the output of the susceptance regulator (Figure 2). The susceptance regulator is discussed later in the paper (see Figure 10).

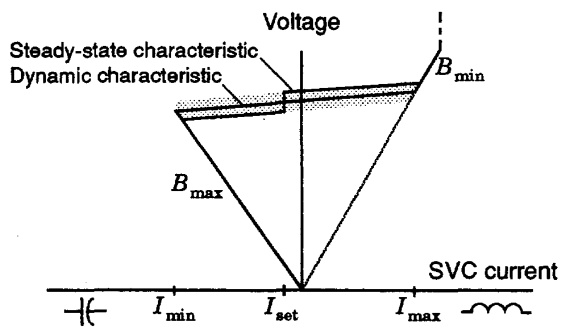


Fig. 2. SVC static characteristics at high voltage bus.

Power Flow Models

Most power flow programs do not include a specific static var compensator model. SVCs are often modeled as a conventional PV (generator) bus with reactive power limits. This results in large errors if the SVC is on limit, operating as a capacitor or reactor. If low voltage is the main concern, the SVC can be modeled as a TCR-FC type of SVC (PV bus with shunt capacitor). For example, for low voltage problems, a ±200 MVAr SVC can be represented as a 200 MVAr capacitor bank, and a PV bus with 400 MVAr inductive limit and zero capacitive limit; the capacitive limit is correctly represented but not the inductive limit.

With a conventional power flow program, a SVC with susceptance regulator can be represented by a PQ (load) bus with voltage constraints.

Often the SVC slope setting must be represented to properly simulate system performance. Coordination and interaction with other SVCs and slower-acting voltage control equipment are studied. Power flow simulation is the primary tool for determining appropriate slope settings. Representation of the slope is essential in the case of weak systems. Because SVCs are sited at critical locations in the network, and because of the regulation of transmission (high side) voltage, representation of SVC slope is usually more important than representation of generator AVR slope.

Should the SVC transformer be represented in power flow and dynamic simulation programs? With ever increasing computer hardware capabilities, and considering the small number of SVCs in a power system, more detailed representation is clearly feasible. Particularly after an SVC has been commissioned or defined, modeling the transformer has benefits such as better representation of losses (real and reactive). The planning or operating engineer will be closer to the real world. Representing transformers is consistent with generator modeling. Fixed or switched capacitor banks are represented at the correct bus.

For tertiary-connected SVCs, the transformer representation is required. The real power flow through the transformer as well as the SVC voltage regulation must be modelled correctly.

If the SVC coupling transformer is explicitly represented, the SVC model (steady state or dynamic) must be adjusted so the correct range of reactive power is delivered to the high voltage bus. Most models and data sets presently used are based on susceptance/current/reactive power limits at the high voltage bus. Appendix A describes the required calculations.

Models using conventional power flow programs. With a conventional power flow program, the slope is represented by connecting the SVC to an auxiliary or phantom bus separated from the SVC high voltage bus by a reactance equal (on the SVC base) to the per unit slope [1]. The auxiliary bus is then the PV bus. If the SVC transformer is represented, the reactance from the high voltage bus to the auxiliary bus is a portion of the transformer leakage reactance; the medium voltage bus is a PV bus with regulation of the auxiliary bus.

Figure 3 shows the concepts of modeling SVC slope using an auxiliary bus.

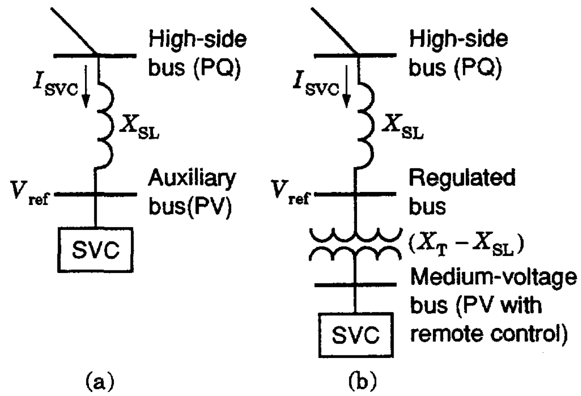


Fig. 3. SVC models with slope representation using conventional power flow PV busses. Figure 3b includes the SVC transformer. (Models are not recommended for advanced power flow programs.)

Requirements for recommended power flow models. An accurate model can be implemented in a power flow program in several ways [1]. The method used will depend on the structure of a power flow program, particularly whether control devices are included in the Jacobian matrix. For continuously controlled SVCs (TCR–FC, TCR–TSC, TCR–MSC), explicit representation of the individual components is not necessary.

Within the control range, the slope should be modeled. Outside the control range, the appropriate susceptance should be represented. The model should interface cleanly with companion dynamics programs. The user should specify the desired slope (per unit on SVC base), control range, and setpoints without being required to add an auxiliary bus and fictitious reactance.

Several SVCs comprising discretely switched TSC and TSR units have been commissioned. For example, reference 4 describes the large SVC at Kemps Creek, Australia. The SVC consists of two 100 MVAr TSRs, two 50 MVAr TSCs, and two 100 MVAr TSCs. The +300/-200 MVAr SVC is controlled in ten steps of 50 MVAr each according to droop and hysteresis characteristics. Comprehensive power flow programs require discontinuous models for TSC/TSR compensators similar to models for continuous compensators.

In voltage regulation mode, the steady state reactive power output of static compensators depends on the voltage setpoint and the droop setting [5]. In power flow base cases, a specified SVC reactive power output may be desired. This provides dynamic reserve and minimizes SVC losses. Power flow models should have provision for reactive power regulation mode, with switchover to voltage regulation mode if voltage is outside a specified bandwidth. See Figure 2.

For outage (post-disturbance) power flow cases, static var systems will respond differently at different snapshots in time. Within a few cycles following a disturbance, SVCs in voltage control will respond according to slope settings with possible large increase in reactive power output. Over tens of seconds or minutes, however, the strategy may be to return to a setpoint (subject to voltage constraints) to allow coordination with slower generator voltage regulators, MSCs, and LTC transformers. Reference 6 describes one implementation. Also, SVCs may initiate switching of MSCs or MSRs.

The power flow program SVS model should have sufficient flexibility to allow the engineer to accurately represent the equipment at various snapshots in time. Utilities use power flow simulation for extensive studies of coordination of SVC setpoint and slope settings, and MSC voltage control settings [7–10].

Data exchange for power flow studies. Data exchange parameters for basic models are capacitive and inductive reactive power range at one per unit high side bus voltage, voltage setpoint, slope, high side reactive power setpoint, and voltage deadband for reactive power control mode. Slope should be in per unit on the specified SVC base.

Data exchange parameters for SVSs represented in more detail at the medium voltage bus, include standard transformer data and the high voltage MSCs or MSRs to be controlled. Reactive power range at one per unit medium voltage bus is required.

Basic Nonlinear Models for Dynamic Performance

The references provide descriptions of dynamic characteristics of static var systems. Two basic models for transient stability programs are recommended as industry standard models. The models are based on the CIGRE models [1] and the other references, especially reference 6. Models used in several production-grade programs have also been reviewed. Individual modules of the basic models are building blocks for detailed models. Model modules for other functions are described in the following section.

Basic models. The structures of Basic Model 1 and Basic Model 2 are similar except for the method of representing slope. The first model is the simplest and is similar to models in most existing transient stability programs. Both are suitable for continuously controlled SVCs. As described later, the models can be modified to represent TSC/TSR types of compensators.

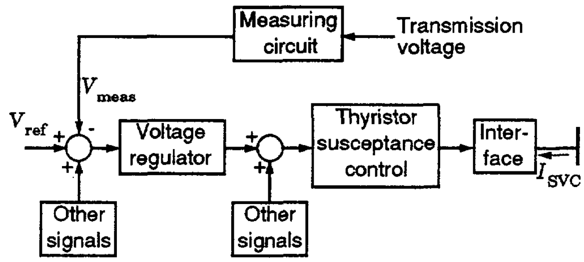


Fig. 4. Basic Model 1. The transfer functions for the measuring circuit and the thyristor susceptance control are normally unity.

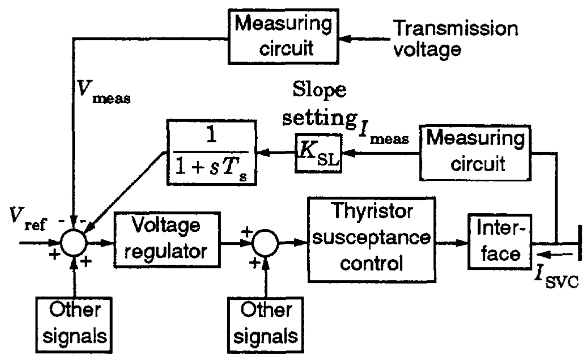


Fig. 5. Basic Model 2. The transfer functions for the measuring circuits and the thyristor susceptance control are normally unity.

Figure 4 shows Basic Model 1. The voltage regulator (Figure 7) is of the proportional type and the gain, K_R, is the inverse of the slope—a gain of 100 pu B_{SVC}/pu ΔV on the SVC base means a 1% slope. This model is often used for preliminary studies.

Figure 5 shows Basic Model 2. The voltage regulator (Figure 8) is of the integral, or proportional plus integral type and the slope, K_{SL}, is realized through current feedback. The gain and slope settings are independent. In some equipment, current is obtained by multiplication of voltage and susceptance [6,11]. In other equipment, reactive power rather than current is measured. Pure integral control is most common. The time constant, T_S (0.01–0.05 seconds), is used by at least one manufacturer to improve SVC control stability. Basic Model 2 represents the physical structure of most, but not all, installed SVCs.

The basic difference between the two models is in the method of realizing the slope. Model 1 gives a voltage to susceptance linear relation. Model 2 gives a voltage to current linear relation. For voltage near one per unit, and for the usual small values of slope, there is not much difference. Since both types of control are used, both models are included.

Measurement modules. The measurement modules convert three phase voltages and currents to a quasi-dc control signal that is proportional to the amplitude of the positive sequence and fundamental frequency content of the measured variable. This is done by instrument transformers, A/D conversion and computation, and filtering. For fundamental frequency simulation, the model is a single low pass filter with a time constant of 1–8 milliseconds (Figure 6). The time constant depends on the actual filter used. If the network exhibits strong resonances near fundamental frequency, more elaborate filters can be required to maintain SVC control stability; the low-frequency response of such filters should be modeled if significant [35,36].

The measurement modules are included in Figure 4 and 5 for completeness. Because of the small time constants, they are not considered part of basic models. In most cases, the modules need not be represented and would not be compatible with the integration step sizes normally used in large-scale simulations.

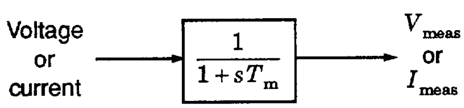


Fig. 6. Measurement module. Voltage is transmission side voltage.

Voltage regulator module—Basic Model 1. Figure 7 shows the model. The gain, K_R, is the reciprocal of the slope setting. K_R is usually between 20 per unit (5% slope) and 100 per unit (1% slope) on the SVC base. The time constant, T_R, is usually between 20 and 150 milliseconds. The lead-lag terms are often zero. For preliminary simulations, phase lead can be used to improve damping of oscillations (at the expense of synchronizing support). The lead-lag terms can also be used to provide adequate phase and gain margins when high steady state gain is used. Integrators should be non-windup.

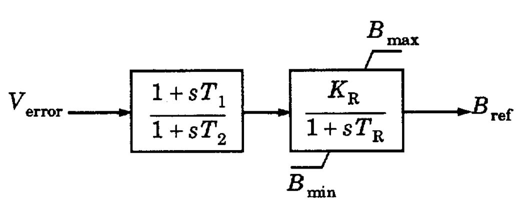


Fig. 7. Voltage regulator model for Basic Model 1.

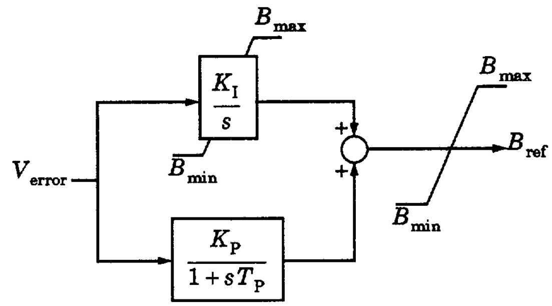


Fig. 8. Voltage regulator model for Basic Model 2.

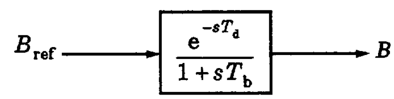


Fig. 9. Thyristor susceptance control.

Voltage regulator module—Basic Model 2. Figure 8 shows the model. The proportional gain, if used, results in a faster response. The time constant, T_P, may be zero. The integrator is non-windup.

Thyristor susceptance control module. Figure 9 shows the CIGRE model for the delays associated with thyristor firing (references 12 and 13 provide alternative models). T_d is the gating transport delay with a value of about one millisecond and T_b represents the effect of thyristor firing sequence control with a value between three and six milliseconds.

This transfer function is included for completeness. It is an approximate representation of the control system and physical constraints at the moment where valve firing is feasible. It illustrates that SVC control has characteristics which, when combined with variation in power system short circuit capacity, can lead to control instability.

Since the bandwidth of a stability program is limited, the thyristor susceptance control is normally not represented.

The nonlinear relationship between B_{ref} and the TCR firing angle is compensated by a linearizing function in the thyristor susceptance control [1,11,24,27]. Since firing angle is not represented explicitly in fundamental frequency models, the linearizing function is not represented explicitly.

TSC and TSR types of SVCs. The thyristor susceptance control module can be modified to represent discontinuous switching of TSC and TSR types of SVCs; models are given in references 2 and 29.

Referring to Figures 4 and 5, an alternative model for discontinuous switching is a deadzone in front of the voltage regulator. The Working Group recommends this method.

Network interface module. The SVC interface with the network can be by either of two methods. The variable susceptance, B, can be used to update the admittance matrix. Alternatively, B is multiplied by voltage to obtain the SVC current. The SVC current is an injection into the network. The choice depends on the network solution method.

Future GTO-based voltage source converter compensators [40] are modeled as a variable voltage without inertia.

Relation between parameters in the two models. If we make some simplifications, correspondences can be derived between the two models. Let $T_m = T_1 = T_2 = T_P = T_d = T_b = T_s = K_p = 0$, then $K_R = 1/K_{SL}$ and $T_R = 1/(K_{SL}K_I)$.

Data exchange for basic models. The minimum data set includes:

1. Q_{max} (inductive) in MVAr at one per unit high-side voltage. This defines B_{min}. This could be available from power flow data.
2. Q_{min} (capacitive) in MVAr at one per unit high-side voltage. This defines B_{max}. This could be available from power flow data.
3. Base SVC MVAr: In some cases this is given by the manufacturer as the TCR or TSC rating rather than the total SVC rating. In the example in the Appendix, the total TSC rating is used.
4. Voltage regulator parameters: For Basic Model 1: K_R, T_R, T_1, and T_2. For Basic Model 2: K_{SL}, K_I, K_P, and T_P. Other parameters are only required if the stability of the SVC control loop is to be studied. These studies are normally made with more complete models using EMTP, TNA, or frequency domain/eigenanalysis programs [19,22,32,36,37,41].

Dynamic Models for other Functions

Modular models for other functions can interface with the basic models. Although some models may not be included in simulation programs, the engineer should be aware of the functions. Some models may be more important for EMTP-type simulations than fundamental frequency simulations. Some models are only required for longer-term dynamic simulations. Functions for sub-synchronous resonance damping are outside the scope of this paper. Some protective type functions are not described, as they seldom need to be represented for fundamental frequency dynamic simulation.

Damping of electromechanical oscillations. In some installations, damping of oscillations is a major purpose of the SVC. The concepts are similar to power system stabilizer (PSS) at generating plants. Early implementations followed the PSS method of adding a continuous supplementary signal to the voltage regulator *input*. This structure has also been used on some recent installations [6]. Damping may be enabled only after identification of oscillations [16].

Another approach is to add a discontinuous damping signal to the voltage regulator *output* [1,14–18]. Special logic is used to select the control mode. For damping support following a large disturbance, the voltage regulator output is frozen. The damping action may be of the bang-bang type.

It's also possible to add a continuous signal for small signal damping to the voltage regulator output [15].

Various local or remote input signals (with appropriate phase compensation) can be used for damping (c.f. references 17, 19, and 38). Possibilities include line power or current, bus frequency or voltage, apparent resistance, and speed or frequency differences from remote locations.

Referring to Figures 4 and 5, the two locations for damping signals are indicated by the blocks labeled *other signals*.

The basic model for continuous damping is similar to PSS analog blocks. Compensation blocks are usually of the non-windup type.

Susceptance (reactive power) regulator. Many SVCs have a provision to regulate reactive power subject to voltage constraints. Usually this is a slow, integrating type of control that operates over tens of seconds or minutes to return reactive power output to a setpoint. This function should be modeled in longer time frame voltage stability and voltage control studies including reactive power coordination studies. The signal is an input to the voltage regulator. References 6 and 16 describe recent implementations.

Figure 10 shows the general structure and the susceptance regulator model. Susceptance is regulated to a value B_{set}. The susceptance regulator limits provide the voltage deadband shown on Figure 2.

The output of the susceptance regulator is sometimes frozen for occurrence of a large disturbance in order to allow full voltage control during system restoration.

Control of MSCs, MSRs, and LTC transformers. As part of a static var *system*, mechanically-switched equipment are controlled.

An approach [20] for transient stability application is to immediately switch available MSCs following short circuit detection and use a TCR with overload capability to regulate voltage. The MSCs are switched off, as required, some ten seconds after energization. This type of SVS can be modeled using basic SVC models. Reference 21 describes another implementation of MSC control to improve transient stability.

Another application is switching of the proper number of MSCs or MSRs to return the SVC to near the reactive power (susceptance) setpoint. Control is based on SVC susceptance order or reactive power output (Figures 10a and 10c). Following a disturbance, mechanical switching may be delayed seconds or tens of seconds to allow for transmission line reclosing and other control action. Switching would typically occur before load restoration by LTC bulk power delivery transformers or distribution voltage regulators. Control for fast deenergization of MSCs may be provided to prevent temporary overvoltage. A SVC could also control tap changing on LTC transformers.

Undervoltage strategies. The control prevents temporary overvoltage following clearing of short circuits, particularly three phase short circuits. The control is important in weak systems where the fault results in load rejection. For voltage below a setpoint (50–70% of normal), TSCs may be blocked. The voltage regulator input may be frozen to prevent integrator windup that would lead to high capacitive output at fault clearing. There may be a delay in TSC deblocking following voltage recovery above a second setpoint. For one recent implementation [6], TSC blocking is at 0.60 per unit voltage with deblocking after the voltage is above 0.68 per unit for 30 milliseconds. Blocking TSCs may also be for preventing of capacitor discharge leading to larger reenergization transients [16].

Examples of implemented undervoltage strategies are provided in the references [6,11,16,22,23].

If a specific detailed model is not used, we recommend a simple default model. The approximate model should freeze the input and output of the voltage regulator whenever voltage drops below a user-specified value or a default value. The SVC should be released when voltage recovers above a user-specified or default value for a user-specified or default length of time. We suggest default values similar to those described above [6].

Response for single-phase faults may not be correctly represented in typical stability programs.

TCR overcurrent limiter and overload. For high voltage, as in load rejection situations, the TCR current is limited as indicated on Figure 2. The current is limited after a short time delay.

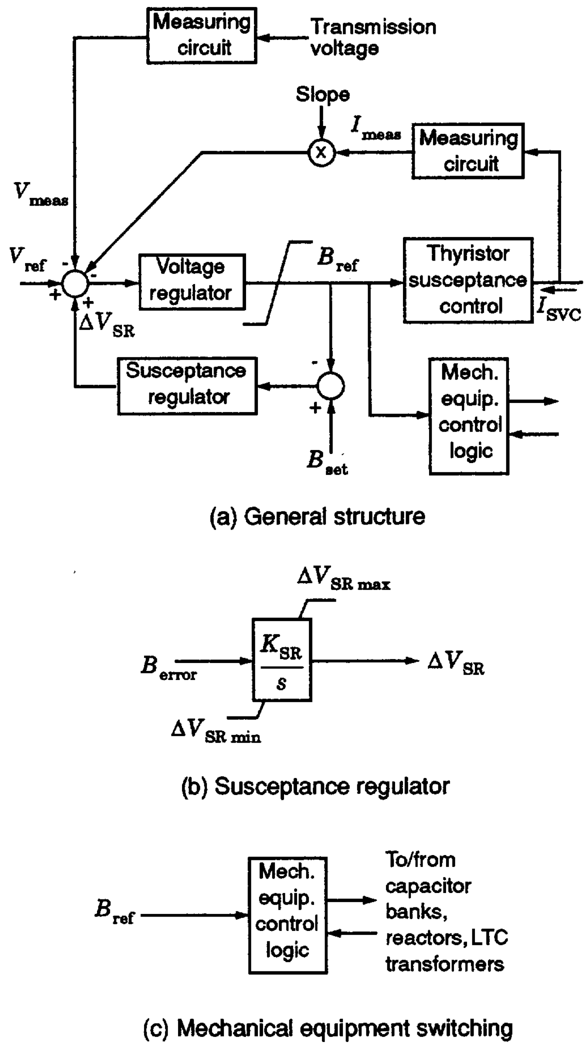


Fig. 10. Susceptance regulator and mechanical equipment switching.

In some designs (particularly in conjunction with mechanically switched capacitor banks), the TCR short-term overload capability is very important. Reference 20 describes an installation where the thyristors are in partial conduction in normal operation, but go into full conduction to provide a much higher ten second dynamic rating. Referring to Figures 7 and 8, this can be represented by a time varying value for B_{min}.

Gain supervisor and gain optimizer. The allowable SVC gain is related to the system voltage strength (short circuit capacity) at the SVC location. SVC instability can occur if the system is weakened by outages. The instability frequency is generally above the bandwidth of transient stability simulations.

Many SVCs have controls to detect oscillations and adjust voltage regulator gains or time constants for stable performance. The need may be due to requirements for fast response during various system conditions. Following automatic gain reduction, gain can be automatically slowly increased to an optimal safe value. The SVC itself can probe the power system and monitor response to reactive power steps or pulses.

References 4 and 13 describe these controls.

It's generally not practical nor necessary to model these controls in stability programs. The proper value of gain is, however, important. The engineer must insure the SVC parameters and response are appropriate for the conditions studied.

In some studies it is necessary to vary the gain as a function of time. The values of gain is determined by complementary EMTP or TNA simulations in which the gain supervisor control is properly modeled.

Small-Disturbance Program Models

For small-disturbance or eigenvalue studies, the above models can be linearized. References 24, 38, and 39 provide examples of small signal stability analysis using linearized SVC models.

Special consideration is needed for discontinuous type SVCs (TSCs and TSRs). One approach is to run simulation with the SVC at fixed output (TSC or TSR within deadband), and run a second simulation assuming continuous control.

Stand-alone MSC and MSR Models

Although not part of SVSs, simulation programs should have the capability to represent stand-alone voltage controlled breaker switched shunt capacitor banks and shunt reactors. The model should consist of undervoltage and overvoltage relays, timers, logic, and circuit breaker delay. The voltage relay models should include both instantaneous and integrating (induction disc or digital accumulator) types.

Sequential insertion of multiple shunt banks at a bus should be possible, with different delays for the sequential switching. This is necessary to prevent fault-induced insertion of excessive capacitance, yet allow rapid sequential insertion of capacitors following an appropriate initial delay. Means should also be provided to permit simultaneous switching of two or more shunt banks if a certain voltage threshold is crossed. This permits the response to be proportional to the magnitude of the disturbance.

Like SVCs, provision should exist to inhibit switching of devices during fault conditions (extreme undervoltage).

User-defined modeling capabilities for TSC/TSR-type compensators may be suitable for MSC/MSR modeling.

Guidelines for Preliminary Studies

Static var compensators have minimal time lags. Compared to generator voltage regulators and power system stabilizers (especially with rotating exciters), the tuning of SVCs is simple, and phase compensation blocks are seldom needed for fundamental frequency voltage regulation.

In exploratory power flow and stability simulations, SVCs may be modeled with wide limits to determine approximate reactive power ratings.

For preliminary simulation studies, Basic Model 1 may be used. The gain (slope) and time constant settings depend on the system short circuit capacity or effective short circuit ratio. A longer time constant, T_R, is required for weak systems. The effect of the simulated disturbances in weakening the system is important.

In the absence of calculations, a gain of $K_R = 33.3$ per unit on the SVC base and a time constant of $T_R = 100$ milliseconds may be used for a moderately strong system. All other time constants may be neglected. The gain corresponds to a 3% slope. Line outage disturbances may be simulated, and the time constant adjusted to provide a fast, well-damped SVC response. Slope values in the range 1–5% could be used.

A rough evaluation of the SVC control loop stability margin and of the SVC response time can be made by using all the parameters presented earlier in the paper (K_R, T_R, T_M, T_d, and T_b) and by simulating the network reaction by its equivalent system impedance Z_{th} (inverse of short-circuit power in per unit on SVC base). For small variation around one per unit, $\Delta V_{system} = Z_{th} \times \Delta B$ [1,25]. Appendix B shows results for sixteen combinations of K_R, T_R, and Z_{th}.

Another approach is to set the desired gain/slope and adjust the time constants by frequency domain calculations [34].

Using Basic Model 2, set the desired slope, K_{SL}. Then adjust the integral gain, K_I, for a fast, well-damped response. See the section "Relation between parameters in the two models."

The worst situation for SVC control stability is a weak system (i.e., Z_{th} high). The stability margin and SVC response should be checked for the weakest network condition. If a very fast response is desired, the settings should be checked by an EMTP, TNA, or frequency domain study using more detailed models. References 19 and 41 illustrate how SVC dynamic behavior changes with control setting, SVC operating point, and network conditions.

Conclusions

Static var system modeling is important for power flow, transient stability, and longer-term dynamics simulation. With the goal of promoting improved modeling we recommend standard models and recommend parameters for data exchange.

For power flow simulation, we recommend improved models with proper representation of limits and with representation of the SVC slope. We also provide guidelines for correct use of models in power flow programs that do not have specific models for static var compensators.

We propose a modular structure for dynamic models and recommend two basic models having different methods of realizing the slope function. We provide guidelines for initial tuning of parameters.

Other SVS functions, including functions, for longer-term dynamics, are described. When needed, these functions would often be implemented by user-defined modeling.

The models are generally valid for strong systems. For weak systems, complementary EMTP-type studies including network dynamics are required.

As a follow-up project, the Working Group intends to use the recommended models to produce benchmark simulation results. Several small systems will be used, and both continuous (TCR) and discrete (TSC/TSR) types of compensators will be studied.

References/Selected Bibliography

1. CIGRE Task Force 38-01-02, *Static Var Compensators*, 1986.
2. CIGRE Working Group 31-01, "Modeling of Static Var Systems (SVS) for System Analysis," *Electra*, No. 51, March 1977
3. D. L. Osborn, "Factors for Planning a Static VAR System," *Electric Power Systems Research*, 17 (1989), pages 5–12.
4. G. Wild and V. E. Henner, "Digital Control of SVC Plants," Canadian Electric Association, Engineering & Operating Division, March 1989, Toronto.
5. F. Aboytes, G. Arroyo, and G. Villa, "Application of Static Var Compensators in Longitudinal Power Systems," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-102, No. 10, pp. 3460–3466, October 1983.
6. D. Dickmander, B. Thorvaldsson, G. Strömberg, D. Osborn, A. Poitras, and D. Fisher, "Control System Design and Performance Verification for the Chester, Maine Static Var Compensator," *IEEE Transactions on Power Delivery*, Vol. 7, No. 3, pp. 1492–1503, July 1992.
7. S. Koishikawa, S. Ohsaka, M. Suzuki, T. Michigami, and M. Akimoto, "Adaptive Control of Reactive Power Supply Enhancing Voltage Stability of a Bulk Power Transmission System and a New Scheme of Monitor on Voltage Security," CIGRE paper 38/39-01, 1990.
8. W. B. Jervis, J. G. P. Scott, and H. Griffiths, "Future Application of Reactive Compensation Plant of the CEGB System to Improve Transmission Network Capability," *CIGRE, Proceedings of 33rd Session*, Vol. II, paper 38-06, 1988.
9. W. B. Jervis, Study Group 38 discussion, *CIGRE, Proceedings of 33rd Session*, Vol. II, 1988.
10. I. M. Welch, P. H. Buxton, and D. S. Crisford, Integration of Reactive Power Compensation Equipment within Substations," CIGRE paper 23-202, 1990.
11. S. Y. Lee, S. Bhattacharya, T. Lejonberg, A. Hammad, and S. Lefebvre, "Detailed Modeling of Static Var Compensators using the Electromagnetic Transients Program (EMTP)," *1991 IEEE Transmission and Distribution Conference*, IEEE publication 91 CH 3070-0, pp. 941–951.
12. L. Gyugyi, "Fundamentals of Thyristor-Controlled Static Var Compensators in Electric Power System Applications," *Application of Static Var Systems for System Dynamic Performance*, IEEE 87TH0187-5-PWR, 1987.
13. J. Belanger, G. Scott, T. Andersson, and S. Torseng, "Gain Supervisor for Thyristor Controlled Shunt Compensators, *CIGRE, Proceedings of 31st Session*, Vol. II, paper 38-01, 1984.
14. A. E. Hammad, "Analysis of Power System Stability Enhancement by Static Var Compensators," *IEEE Transactions on Power Systems*, Vol. PWRS-1, No. 4, pp. 222–227, November 1986.
15. A. E. Hammad, "Applications of Static Var Compensators in Utility Power Systems," *Application of Static Var Systems for System Dynamic Performance*, IEEE 87TH0187-5-PWR, pp. 28–35, 1987.
16. H. Tyll, K. Leowald, F. Labrenz, and D. Mader, "Special Features of the Control System of the Brushy Hill SVC," Canadian Electric Association HVDC and SVC Control Committee, March 1989.
17. J. F. Hauer, "Reactive Power Control as a Means for Enhanced Interarea Damping in the Western U.S. Power System—a Frequency-Domain Perspective Considering Robustness Needs," *Application of Static Var Systems for System Dynamic Performance*, IEEE 87TH0187-5-PWR, pp. 79–923, 1987.
18. E. Lerch, D. Povh, and L. Xu, "Advanced SVC Control for Damping Power System Oscillations," *IEEE Transactions on Power Systems*, Vol. 6, No. 2, pp. 524–535, May 1991.
19. E. V. Larsen and J. H. Chow, "SVC Control Design Concepts for System Dynamic Performance," *Application of Static Var Systems for System Dynamic Performance*, IEEE 87TH0187-5-PWR, pp. 36–53, 1987.
20. J. E. Hadder and S. A. Miske, Jr., "The Odessa SVS—Dynamic Voltage Support for Sudden Loss of Local

Generation," *Application of Static Var Systems for System Dynamic Performance*, IEEE 87TH0187-5-PWR, pp. 60–67, 1987.

21. T. R. Boyko, K. A. Ewy, M. P. Häusler, A. Kara, C. S. Miller, D. R. Torgenson, and E. P. Weber, "Integration of a Static Var System into Fargo Substation," *Fifth International Conference on AC and DC Power Transmission*, IEE, 17-20 September 1991, London, pp. 241–247.
22. A. N. Vasconcelos, A. J. P. Ramos, J. S. Monteiro, M. V. B. C. Lima, H. D. Silva, and L. R. Lins, "Detailed Modeling of an Actual Static Var Compensator for Electromagnetic Transient Studies," IEEE/PES 91 WM 211-3 PWRS.
23. B. Zymler, A. S. V. A. Bittencourt, W. M. da Silva, C. A. M. Fiuza, and E. H. Ellery Filho, Analysis of the Importance of Non-Linear Models of Static Var Compensators (SVC's) in Dynamical Studies using Digital Stability Programs," paper SP-45, *II Symposium of Specialists in Operational and Expansion Planning* (II SEPOPE), 21–25 August 1989, São Paulo, Brazil.
24. S. Arabi, G. J. Rodgers, D. Y. Wong, P. Kundur, and M. G. Lauby, "Small Signal Stability Program Analysis of SVC and HVDC in AC Power Systems," *IEEE Transactions on Power Systems*, Vol. 6, No. 3, pp. 1147–1153, August 1991.
25. R. M. Mathur, editor, *Static Compensators for Reactive Power Control*, Canadian Electrical Association, Cantext Publications, Winnipeg, 1984.
26. K. Hanson, *Application Guide for Static Var Compensators*, Electricity Supply Board Ireland, 1985.
27. T. J. E. Miller, editor, *Reactive Power Control in Electric Systems*, John Wiley & Sons, New York, 1982.
28. A. Edris, "Controllable VAR Compensator: a Potential Solution to Loadability Problem of Low Capacity Power Systems, *IEEE Transactions on Power Systems*, Vol. PWRS-2, No. 3, pp. 561–567, August 1987.
29. H. Frank and T. Petersson, "Thyristor-Switched Shunt Capacitors and their Modeling for Transmission Applications," IEEE/PES paper A 78 105-9, presented at 1978 IEEE/PES Winter Meeting.
30. F. P. Pereira, "Static Var Compensator Model to be used in Conventional Load Flow Programs," paper SP-05, *II Symposium of Specialists in Operational and Expansion Planning* (II SEPOPE), 21–25 August 1989, São Paulo, Brazil.
31. J. L. Jardim and E. M. Brandi, "Effect of Static Var Compensators on the Dynamic Stability of Power Systems," paper SP-06, *II Symposium of Specialists in Operational and Expansion Planning* (II SEPOPE), 21–25 August 1989, São Paulo, Brazil.
32. C. S. Fonseca, J. T. Honda, H. P. O. Junior, and E. H. Ellery, Filho, "Development of a Model to Represent the Coxipó Transient Response in the EMTP Program," paper SP-07, *II Symposium of Specialists in Operational and Expansion Planning* (II SEPOPE), 21–25 August 1989, São Paulo, Brazil.
33. G. Romegialli, and H. Beeler, "Problems and Concepts of Static Compensator Control," *Proceedings of IEE*, Part C, Vol. 128, No. 6, pp. 382–388, November 1981.
34. R. J. Koessler, "Dynamic Simulation of Static Var Compensators in Distribution Systems," *IEEE Transactions on Power Systems*, Vol. 7, No. 3, pp. 1285–12916, May 1992.
35. L. Gérin-Lajoie, G. Scott, S. Breault, E. V. Larsen, D. H. Baker, and A. F. Imece, "Hydro-Québec Multiple SVC Application Control Stability Study," *IEEE Transactions on Power Delivery*, Vol. 5, No. 3, pp. 1543–1551, July 1990.
36. P. Czech, S. Y. M. Hung, N. H. Huynh, and G. Scott, "TNA Study of Static Compensator Performance o the 1982–1983 James Bay System—Results and Analysis," *International Symposium on Controlled Reactive Compensation*, Hydro Québec/EPRI, pp. 323–347, September 1979.
37. S. Lefebvre and L. Gérin-Lajoie, "A Static Compensator Model for the EMTP," *IEEE Transactions on Power Systems*, Vol. 7, No. 2, pp. 477–486, May 1992.
38. N. Martins and L.T. G. Lima, "Eigenvalue and Frequency Domain Analysis of Small-Signal Electromechanical Stability Problems," *Eigenanalysis and Frequency Domain Methods for System Dynamic Performance*," IEEE 90TH0292-33PWR, 1990.
39. A. E. Hammad and M. Z. El-Sadek, "Prevention of Transient Voltage Instabilities due to Induction Motor Loads by Static VAR Compensators," *IEEE Transactions on Power Systems*, Vol. 4, No. 3, pp. 1182–1190, August 1989.
40. E. Larsen, N. Miller, S. Nilsson, and S. Lindgren, "Benefits of GTO-Based Compensation Systems for Electric Utility Applications," IEEE/PES paper 91 SM 397-0 PWRD.
41. A. J. P. Ramos and H. Tyll, "Digital Performance of a Radial Weak Power System with Multiple Static VAR Compensators," *IEEE Transactions on Power Systems*, Vol. 4, No. 4, pp. 1316–1323, November 1989.

Appendix A: Conversion of SVC rating between primary and secondary sides of SVC transformer

A SVC is typically connected to the power system with a coupling transformer.

The reactive power range (capacitive and inductive) for the SVC is usually specified at the high voltage bus of the SVC transformer. For most SVC controls, the controlled output is the susceptance, B, measured on the high voltage bus.

SVC models in most stability programs do not have the SVC transformer imbedded as part of the SVC model. The operating range of reactive power or susceptance of the model is specified (and controlled) at the bus to which the SVC is connected.

If the SVC transformer is represented externally to the SVC model, it is necessary to convert the SVC operating range given on the high voltage side of the SVC transformer to the medium voltage side where the SVC is modeled. The effect of the reactance of the SVC transformer must be accounted for so the correct range of reactive power is delivered to the high voltage bus.

To be strictly correct, if the SVC transformer is modeled external to the SVC model, the parameters for the voltage regulator gain, which are given for the high voltage side, will also need to be adjusted for the medium voltage side where the SVC is modeled. If the same gain parameters given on the high voltage side are used on the medium voltage side, the rate of response for capacitive output will be faster than it should be, but that for the inductive output will be slower. For most stability studies, however, such errors in the response rate will not be critical.

The following equations give the susceptance range, in per unit, on the medium voltage bus, based on parameters given on the high voltage bus.

$$B_{max} = \frac{1}{\left|\frac{S_n}{Q_{cap}}\right| + |X_{tpu}|} \quad \text{(capacitive)}$$

$$B_{min} = \frac{1}{\left|\frac{S_n}{Q_{ind}}\right| - |X_{tpu}|} \quad \text{(inductive)}$$

where:

S_n MVA base

X_{tpu} Reactance of SVC transformer in per unit on S_n base

Q_{cap} Maximum capacitive reactive power on high voltage side bus

Q_{ind} Maximum inductive reactive power on high voltage side bus

Example. The reactive power range specified for a SVC connected to a 230-kV bus is 350 MVAr capacitive and 300 MVAr inductive at one per unit voltage. The SVC transformer (230/20-kV) has a reactance of 12% on a 300 MVA base. The susceptance ranges for the SVC model connected to the 20-kV bus are calculated as follows.

Select 350 MVA as the power base. Hence, $S_n = 350$ MVA, $X_{tpu} = 0.14$ pu, $Q_{cap} = -350$ MVAr, and $Q_{ind} = 300$ MVAr. Then:

$$B_{max} = \frac{1}{\left|\frac{350}{350}\right| + |0.14|} = 0.8772 \text{ pu (capacitive)}$$

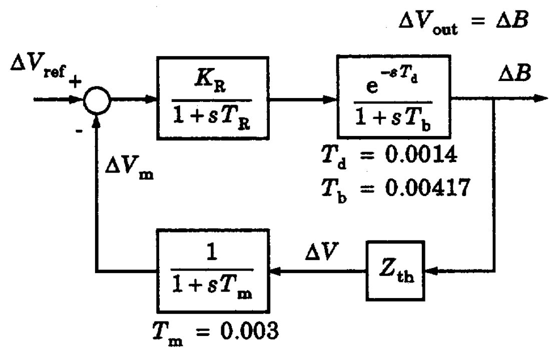
$$B_{min} = \frac{1}{\left|\frac{350}{300}\right| - |0.14|} = -0.9740 \text{ pu (inductive).}$$

The susceptance values correspond to 20-kV power ratings of 307 MVAr capacitive and 341 MVAr inductive.

Appendix B: Simplified evaluation of SVC control loop stability and SVC response time

This appendix provides preliminary guidance on SVC tuning related to system fundamental frequency thévenin impedance, Z_{th} (inverse of short circuit power on the SVC base). If a very fast response is desired, it is very important that the settings be checked by EMTP or TNA simulation using more detailed models that represent network resonances [19].

Based on Figures 1, 6, 7, and 9, Figure B1 shows the block diagram for simplified simulation of SVC control loop stability and SVC response time. The small time constants and time delay are for response simulation above the electromechanical stability bandwidth.



$$\Delta V_{ref} = \frac{1+K_R}{K_R} \quad \text{(step input)}$$

Fig. B1. Simulation block diagram.

Figures B2–B5 show step response for sixteen combinations of thévenin impedance, SVC gain, and SVC time constant. Based on the final value theorem, the step input for each case is such that unity steady state susceptance output change is obtained with stable settings.

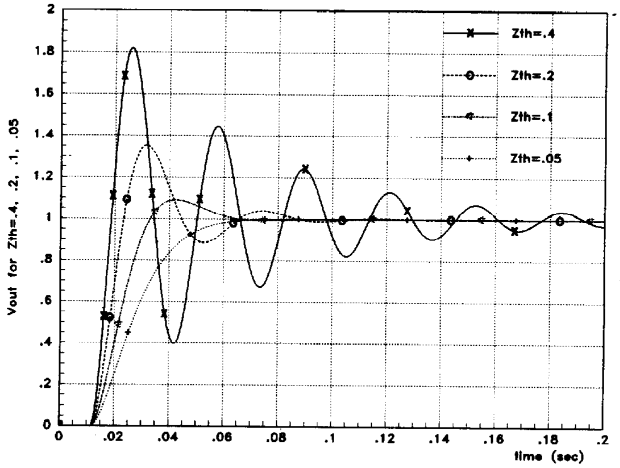


Fig. B2. Response for K_R = 33.33 and T_R = 0.05.

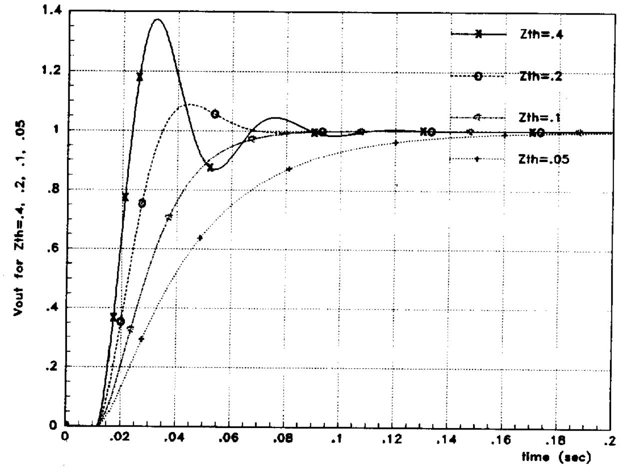


Fig. B4. Response for K_R = 33.33 and T_R = 0.1.

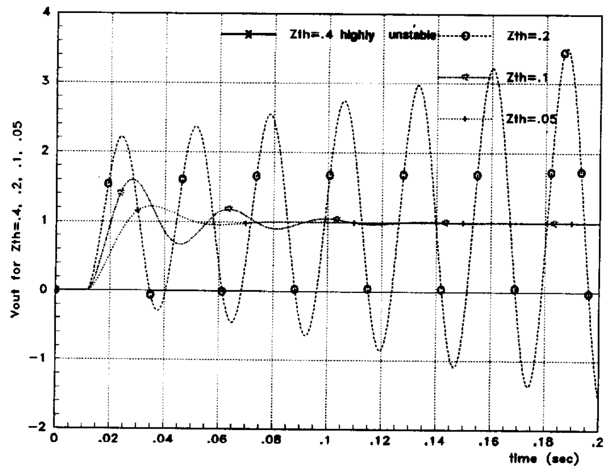


Fig. B3. Response for K_R = 100 and T_R = 0.05.

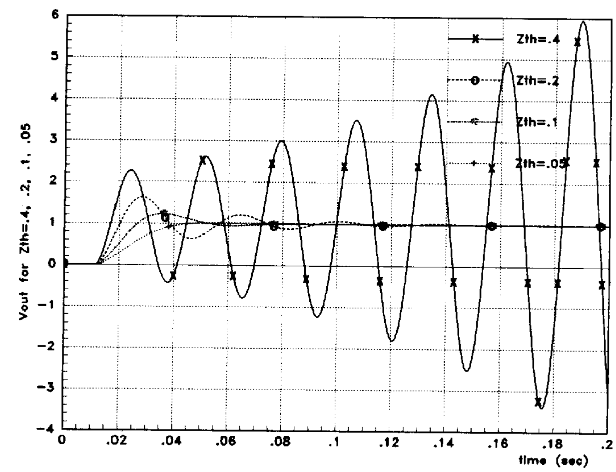


Fig. B5. Response for K_R = 100 and T_R = 0.1.