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STATIC REACTIVE POWER COMENSATORS FOR HIGH VOLTAGE POWER SYSTEMS

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EXECUTIVE SUMMARY

This report documents a study conducted for the U.S. Department of Energy to summarize the role of Static Reactive Power Compensators for High Voltage Power System applications. General Electric completed this study under a subcontract with Los Alamos National Laboratory. The broad objective of this report is to compile, in one easy-to-use document, information useful to the utility system planning engineer in applying Static Var Systems (SVS) to high voltage ac (HVAC) systems.

Section 1 of the report defines the Static Var System as a form of reactive power compensator and discusses the general need for reactive power compensation in HVAC systems. The utility industry has adopted the term Static Var System to refer to a broad class of controllable compensating devices. Other names used for static var systems are: Static Var Control, Static Var Generator, Static Compensator, and Static Var Source. The term static in this context refers to the use of passive compensation devices (capacitors and inductors) and solid state power switches. Section 1 also characterizes the basic system needs for controllable reactive compensation and places the static var system in perspective relative to those needs and with respect to other devices utilized to provide reactive power compensation.

The specific role and benefits of static var systems in HVAC system applications are discussed in Section 2. The various roles of an SVS in HVAC applications are discussed in terms of its eminent ability to perform voltage control as an end in itself and as a means toward stabilizing the bulk power HVAC network.

Included in Section 2 are examples of applying SVS for specific functions, illustrated with the aid of simulation studies to quantify the benefits wherever possible. One example shows how an SVS can be used to prevent an incipient voltage collapse in a load area following the loss of generating plant in that area. This example is a timely demonstration of the use of SVS to maintain import capacity of tie lines when traditional sources of voltage support (generators in vicinity of the load) fail to maintain the load supply voltage.

Another example demonstrates how one or two static var systems can increase the transient stability power limit of a two line system, eliminating the need for a third line to provide the same capacity. The effectiveness of SVS in rapidly reducing the temporary overvoltages which can arise following load rejections on extra high voltage, high capacity lines is also demonstrated. General Electric's Transient Network Analyzer was utilized with an SVS model to show this function.

The use of static var systems for correcting phase voltage imbalance is discussed only briefly because that application is rare in HVAC bulk power systems. The literature can provide adequate background for those unique applications such as for voltage flicker caused by arc furnace loads. The use of an SVS for control of subsynchronous resonance (SSR) shaft oscillations is mentioned. This application has been attempted at only one power plant to the authors' knowledge. Because this is not an HVAC voltage control application (the shaft speed is the control variable in an SSR control case) the report makes only passing reference to this SVS function.

The overall objective of Section 3 is to compare various forms of static var systems on the basis of how they serve the system's needs identified in Section 1. Section 3 includes a detailed discussion of the operating principles of commercially available static var systems. Section 3.3 concentrates on the SVS performance as a device for controlling the positive sequence, fundamental frequency component of HVAC system voltage. Liberal use is made of graphical means for illustrating the transient, dynamic and steady state performance of static var systems.

Section 3.4 contains a comparison of the most common static var systems with respect to their ability to provide rapid and precise voltage control. The SVS types are evaluated on their active power loss characteristics. These comparisons are summarized in Table 3-3. Section 3.4.2 contains a more indepth comparison of the time response and loss characteristics of the three most commonly used types of SVS that utilize solid state power switches (thyristors) to rapidly adapt their reactive power output to the HVAC systems needs.

Section 4 of the report discusses the engineering studies that should be performed by a utility planner contemplating the possible use of SVS in his system. The studies are divided into basic studies that are recommended for every new HVAC application of an SVS, and optional studies that are suggested for unique or occasional applications. The basic studies can be performed by the planner himself utilizing conventional digital computer load flow and stability study programs.

To complement the discussion of basic studies, Appendix D contains SVS modeling concepts to assist the utility engineer in modifying his digital computer programs to incorporate SVS models, should that be necessary. Appendix E includes excerpts from the program user documentation for the Philadelphia Electric Company Load Flow and Stability Programs describing SVS models incorporated in those programs under this contract. To the authors' knowledge, this work constitutes the first time a comprehensive SVS model has been developed and demonstrated in a Load Flow Program.

Appendix C provides a reliability study for a sample SVS application. The sources for the equipment availability data are cited and a quantitative calculation of overall availability is given. An availability in excess of 99% is shown possible, which has been borne out by many years of successful operation of General Electric var systems.

The information compiled in this report forms a good basis for an "SVS Application Guide." Since the study focused on the general role of SVS in HVAC applications and a comparison of the various types, the information is too broad for an application guide specific to any one SVS design. A good SVS application guide, ideally, would contain hard facts based on actual utility experience. It would also include economic comparison of SVS versus other approaches to stability improvement, for instance. Such data would be best accumulated with the cooperation of one or more utilities with SVS experience.

This report, while not a thorough SVS application guide, contains invaluable information for the U.S. utility system planner who is seeking ways to "stretch" his limited transmission system to transport power between generation and load centers. The SVS can be a guardian of system stability or simply a means to mitigate a bothersome voltage regulation problem. The SVS can be frugal with respect to its loss consumption and, conceivably, it may be utilized at strategic locations in a network to reduce active power losses in that network.

Section 1

GENERAL NEED FOR REACTIVE POWER COMPENSATORS IN HVAC SYSTEMS

1.1 STATIC VAR SYSTEMS — A DEFINITION

The Static Var System (SVS) has been defined by CIGRE* Working Group 31-01 as a system or aggregation of shunt connected passive reactive devices and some control means to provide an adjustable reactive power supply on the power system to which it is connected. The basic devices comprising a SVS are: shunt capacitors, linear or nonlinear shunt reactors, and solid state power electronic switches to vary the reactive power drawn from or delivered to the power system. The various possible configurations of SVS are described in the literature [1,2] and in a later Section 3 of this report.

The SVS is a form of reactive power compensation; therefore, to understand the need for Static Var Systems, we first recall the general need for reactive compensation in ac transmission systems.

* CIGRE stands for Conference Internationale de Grands Reseaux Electriques or International Conference on Large High Voltage Electric Systems.

1.2 THE GENERAL NEED FOR COMPENSATION

Reactive compensation is generally required for the following reasons or functions:

- voltage control - maintaining load supply voltage and/or voltage along a transmission system within maximum and minimum limits.
- power system stabilization - maximizing the utilization of ac transmission for active power transfer while maintaining stability between synchronous machines in the system.
- reactive power flow control - usually the minimization of var flows to maintain system losses at a practical minimum and to avoid excessive voltage drops along transmission lines.

1.3 APPROACHES TO COMPENSATION

Three basic classes of reactive compensation are:

- passive compensation with fixed shunt susceptances inductors and capacitors.
- passive compensation with fixed series capacitance.
- active or dynamic shunt compensation with synchronous condensers or Static Var Systems.

A summary of the available forms of compensation and the system needs or functions they fulfill is shown in Table 1-1.

Table 1-1

DIFFERENT FORMS OF COMPENSATION AND THEIR FUNCTIONS

- Shunt Capacitors
  - Steady State Voltage Control
  - Reactive Power Flow Control
- Shunt Reactors
  - Steady State Voltage Control
  - Reactive Power Flow Control
  - Reduction of Switching Surge Overvoltages
- Series Capacitors
  - Power Transfer & Stabilization
  - Reactive Power Flow Control
- Synchronous Condensers
  - Steady State & Dynamic Voltage Control
  - Reactive Power Flow Control
  - Power Transfer & Stabilization
- Static Var Systems
  - Steady State & Dynamic Voltage Control
  - Reactive Power Flow Control
  - Power Transfer & Stabilization

1.4 PROBLEMS OF THE UNCOMPENSATED SYSTEM

The general needs for compensation were grouped earlier in three functional areas: voltage control, power system stabilization, and reactive power flow control. These three needs all stem from the fundamental behavior of voltage and reactive power on an uncompensated transmission system.

This behavior is influenced by system impedance, active and reactive load characteristics as a function of supply voltage, and the behavior of synchronous machines. Therefore, a discussion of the problems associated with uncompensated transmission systems will serve to introduce a further discussion of the needs for compensation.

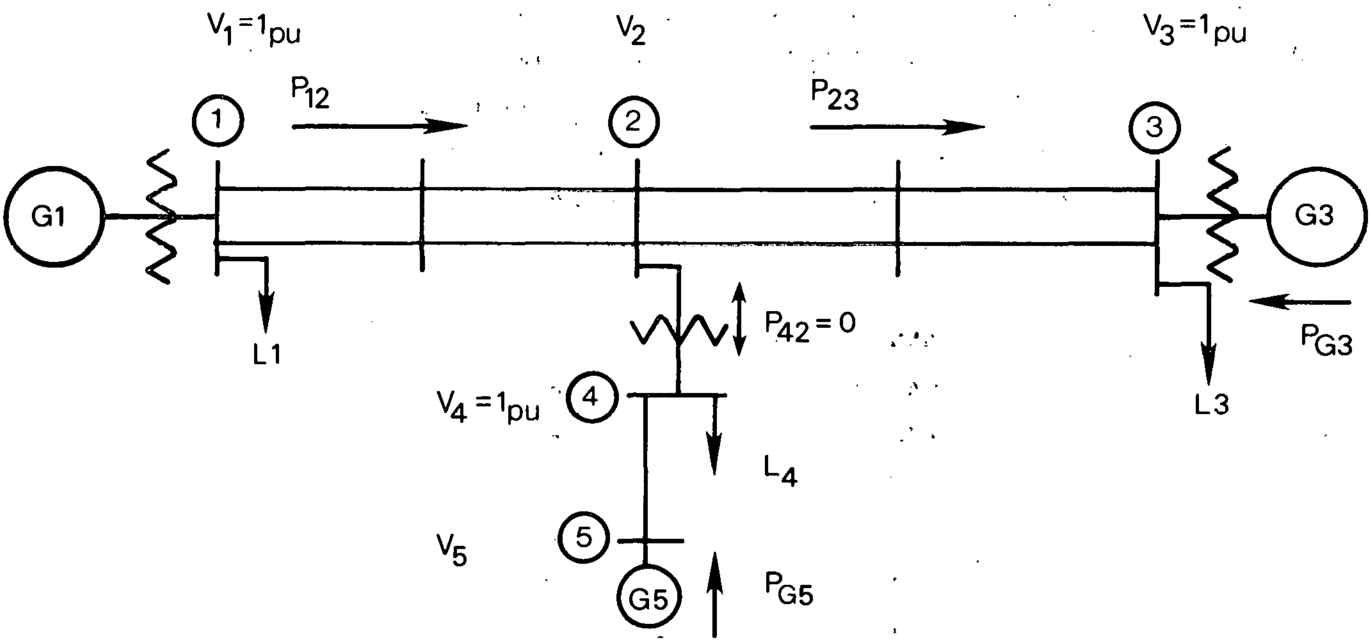
1.4.1 The Uncompensated Transmission Line

To review the undesirable voltage and reactive power flow conditions associated with an uncompensated system, the circuit in Figure 1a will be used.

Figure 1a illustrates a two-circuit tie line between two areas of a system represented by buses 1 and 3 and their associated generation and loads. A third generation/load area is shown tapped off the tie line at bus 2. That third area is assumed to be independent of the other two areas, possessing the tap for emergency or economy transfers only.

For the sake of illustration, first assume the following idealized initial conditions exist in the system of Figure 1a.

- Active power flows P_{12} and P_{23} are the same and numerically equal to the surge impedance loading (SIL) or "natural load" of the respective transmission lines. See Appendix A for a definition of SIL.
- Generation P_{G5} equals exactly the load L_4 and losses in line 5-4 such that no power flows in the transformer (P_{42} = 0) at the mid point of system.
- Voltages of buses 1, 3 and 4 are 1.0 per unit in the initial steady state.
- Load L_3 equals P_{G3} plus P_{23}.



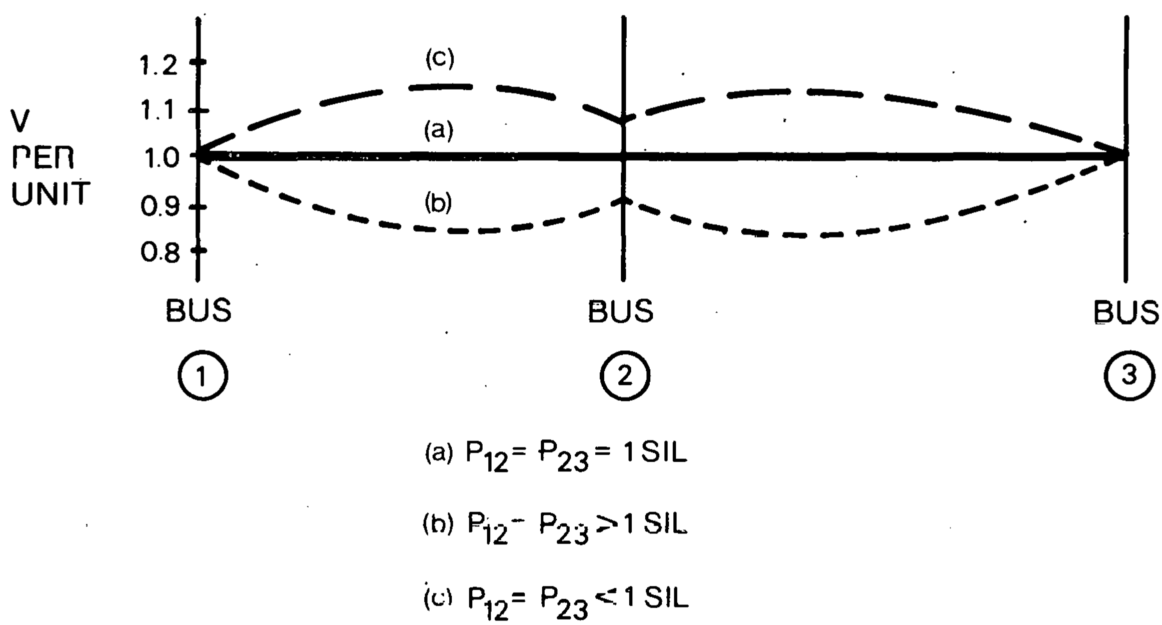


Figure 1 Uncompensated System
a) Voltage Profiles for Three Line Loadings
b) Uncompensated Transmission Line Between Buses 1, 2, 3

These idealized conditions will result in a voltage profile (neglecting losses) along the transmission path bus 1, bus 2, bus 3, as shown by curve (a) of Figure 1b. That voltage profile is "flat" because the active power equals SIL for the lines in question. Since $V_4 = V_2$, no reactive power flows in the mid system step-down transformer, thus the total current and load losses in that transformer are zero.

1.4.2 Low Voltage in the Steady State

Assume now that all loads remain constant while P_{G3} is reduced and P_{G1} is increased (P_{G5} constant) to accommodate a plant shutdown in system 3. The result is that line flows $P_{12} = P_{23}$ increase beyond the lines' surge impedance loading level and voltage profile (b) of Figure 1b results. Two undesirable conditions which result are:

- The reduction in mid system voltage V_2
- Reactive power flows result in the system, thus incurring I^2R losses that did not exist initially.

Such conditions may be unacceptable to a utility system operator striving to supply voltage within ± 5% to all loads while at the same time incurring lowest possible losses in the system. Furthermore, the sagging voltage along the tie line reduces the power transfer capacity of that tie such that a fault and subsequent line outage may cause a loss of stability between systems.

1.4.3 High Voltage in the Steady State

Another scenario could cause the through power $P_{12} = P_{23}$ to be significantly below SIL resulting in a voltage profile as illustrated by curve (c) in Figure 1b. Here again, undesirable reactive power flows result with associated losses. Another bothersome result is that the mid system steady-state voltage V_2 is above the desired $\pm5\%$ control band, and possibly encroaching into the designed overvoltage margin of the transformer and other equipment in the mid-system area.

One way that system planners can guard against such variable voltage and reactive flow condition is to supply shunt reactive power compensation in the area susceptable to voltage swings. One such location in this example is at bus 2. Switchable reactive devices could be switched on and off the system by the dispatch operators to avoid long periods of operation outside the desired $\pm5\%$ voltage range.

A relatively large number of switchable devices, supplied in small incremental MVAR steps, might be requied to keep the voltage V_2 within the $\pm5\%$ range most of the time. Alternatively, a continuously controlled device such as a static var system or synchronous condenser could provide continuous voltage control at bus 2.

1.4.4 Large Variable Industrial Loads

Large power consumers are urged to compensate low power factor loads, thereby reducing the var demand on the power system. The result is less current flow and voltage drop in the supply lines and better utilization o the transmission and distribution lines. This load compensation is particularly important for highly variable industrial loads.

Referring again to the system in Figure 1a, consider what voltage conditions would previal if load L_4 was dominated by a highly variable and rapidly changing industrial load such as strip mining excavators or arc furnace smelting loads. In such cases, the voltage variations may be relatively small ($\pm5\%$ or less) but occur repeatedly and at such a rate as to constitute an objectionable "voltage flicker" condition. The voltage flicker can be reduced by increasing the system's short circuit duty with additional lines or synchronous condensers. Alternatively, a static var system of appropriate rating could be employed to compensate the var swings imposed on the host power system.

The variable var component of the arc furnace load is the principle cause of the voltage flicker. By compensating for most of the variable var demand, the SVS reduces the voltage variations to below the theshold objectionable flicker.

Sometimes, highly variable unbalanced laods cause intolerable phase imbalance in the voltage supplying that load and other residential, commercial and industrial loads. Arc furnaces and single phase traction railway loads are examples of such unbalanced variable loads. In such cases the compensation scheme must be controllable, and capable of individual phase control. A static var system is often used for such applications.

1.4.5 Reactive Requirements of HVDC Converters

High voltage direct current (HVDC) converter terminals consume reactive power during normal operation, and their var demand can vary over a large range whenever the converter power level varies or when the ac system voltage varies. Following major disturbances (faults) in the HVAC system near the converter station, the HVDC system may ramp off and restart when close-to-normal ac voltage returns. The HVDC can present a severe impact reactive load to the HVAC system during the restart phase. The HVDC converter requires reactive power equal to about 60% of the active power during normal operation. During disturbances that reactive demand can rise to 100% of the active power rating of the HVDC link.

Dynamic reactive power compensation is sometimes employed at the HVDC-HVAC interface when the ac system impedance is so high that large ac voltage swings accompany small HVDC power swings. Compensation in the form of switched or fixed capacitor compensation, synchronous condensers, static var systems, or mixtures of all forms are useful to solve this problem.

1.4.6 Load Rejection Overvoltages

When a heavily loaded transmission line suffers a sudden loss of receiving end load, because of some unplanned switching or breaker action, a load rejection overvoltage condition may result. Breaking the circuit of Figure 1a at bus 3 would be such a case. Voltages along that system will rise, in some cases, to values exceeding the capability of surge arresters. If the load rejection isolates a power plant, a momentary overspeed of the generators will cause an increase in frequency on the line. The natural charging current then increases, thus causing a further Ferranti-effect voltage rise. Destructive load-rejection overvoltages are prevented generally by the application of shunt reactors on the EHV transmission lines to absorb some of the charging current.

Those shunt reactors that are vital for overvoltage limitation are often left on the system at all times. As such, they reduce the net SIL capacity of the lines, which limits full utilization of the line conductors for active power transfer. If the reactors could remain off during heavy load conditions, thus allowing more stable transfer of power, and be switched on instantly upon the occurrence of a load rejection, better utilization of the transmission system would be realized. Conventional reactor switching schemes are not fast enough to provide a reliable reduction of load rejection overvoltages, so the reactors are often left on the line at the expense of lost power transfer capability.

Static var systems are capable of rapid reactive switching, thus they could be used for such applications of overvoltage control.

1.4.7 Loss of Stability

Where voltage reductions can occur abruptly, risking system instability, dynamic shunt reactive compensation may be mandatory. Bus voltages along a transmission system undergo a momentary depression, lasting a half second or more, following the loss of a critical line because of a permanent fault. During that first second after the faulted line is cleared, HVAC bus voltages can dip to 60-80% of normal if some dynamic reactive compensation adjustment is not utilized. Such excessive voltage dips usually are caused by extreme synchronizing power swings across the system. Since there is a bilateral cause-effect relationship between voltage dips and synchronizing power swings, dynamic voltage support can also be helpful in preserving stability of the system.

1.4.8 Load Voltage Collapse

The magnitude of the voltage on an HVAC bus at a point where active and reactive load (customer demand) is served, is a function of the load as well as the generator source voltages and impedance drops along the HVAC lines. If suitable voltage support or reactive power compensation is not employed near the load, the load voltage can vary widely with active load changes. Under heavy load conditions the voltage can become very sensitive to even small increases in the active component of load. Futhermore, the reactive flows vary greatly and the combined effort of active and reactive power variations can cause a voltage collapse or a "voltage instability." This problem is of practical importance in today's power systems where increased imports over limited transmission lines are becoming necessary.

To illustrate this phenomenon, refer again to the system in Figure 1a. Assume the generation P_{G5} is out of service so that load L_4 in the middle of the system now be served from remote generating sources P_{G1} and P_{G3}. The active power demanded by load L_4 must now be transported over the HVAC transmission lines. The voltage at load L_4 would be quite sensitive to both the active component of load L_4 and the power factor (or reactive component) of load L_4.

For instance, assume the real power demand of L_4 is large enough to load both lines (from P_{G1} and P_{G3} to their respective surge impedance load levels. Also assume the load L_4 is located about 200 miles from either end (P_{G1} or P_{G3}). If, under those conditions, the voltage V_4 (at load L_4) were 1 per unit for unity power factor load, the voltage V_4 could drop to about 80% for a 97% lagging power factor load at L_4.

Furthermore, if a sizeable fraction of the load is induction motors, a reduction in supply voltage, V_4, will cause a larger reactive demand (lower power factor) which will in itself cause further reduction in V_4. Such a chain reaction can cause a voltage collapse at the load.

The HVDC converter interface discussed in Section 1.4.5 is another example of a reactive power load that can be highly variable with ac voltage magnitude. In both induction motor load and HVDC converter cases, dynamic reaction power compensation can be vital to prevent voltage collapse.

1.5 CHARACTERIZATION OF BASIC SYSTEM NEEDS FOR COMPENSATION

The previous section referred to the power system's basic needs for reactive power compensation within three broad areas of (a) voltage control, (b) stability enhancement and (c) reactive power flow control. In this section the system's needs for reactive compensation will be divided into additional subcategories.

1.5.1 Parameters for Characterizing the System's Needs

There are several ways of defining the system's needs for controllable reactive compensation. Usually the system's needs can be expressed in terms of one or more of the following parameters:

- Magnitude of Compensation
  - MVAR of capacitive (production) capacity.
  - MVAR of inductive (absorption) capacity.
- Speed of Response for Adjustable Compensation
  - Changes required in a number of cycles, or seconds or minutes, etc. (see Section 1.5.2)
- Duration of Need
  - Continuous need.
  - Short time need for specific duration.
- Frequency of Adjustment Required
  - Twice daily to follow typical load cycle.
  - Once every half-second to follow typical synchronizing power swings.
  - Once every half-cycle of power frequency to control voltage flicker.
- Location of Compensation (shunt)
  - Point of greatest voltage variation in system, even if no load is there.
  - Near variable industrial load.
  - Near mixed (residential, etc.) load.
  - Near HVDC converter stations.
  - Near generators.
- Phase Relationship of Voltage Control
  - Balanced control - same on all three phases.
  - Individual phase voltage control.
- Short Circuit Contribution by Compensator
  - Desirable.
  - Undesirable.
  - No preference.

1.5.2 Required Response Time for Adjustable Compensation

Figure 2 illustrates the full range of power system phenomena in terms of characteristic time periods. The abscissa is a logarithmic time scale. The bar at far left represents very high speed phenomena such as lightning and surge overvoltages, which occur in microseconds and milliseconds, respectively.

The bar at the upper right implies that active power flows change in a few minutes to several hours, depending on daily load cycles and planned changes in tie flows. In the center, the bar labeled Transient and Dynamic Stability denotes that stability can be lost in a time span ranging from 0.1 seconds to 30 seconds following a disturbance.

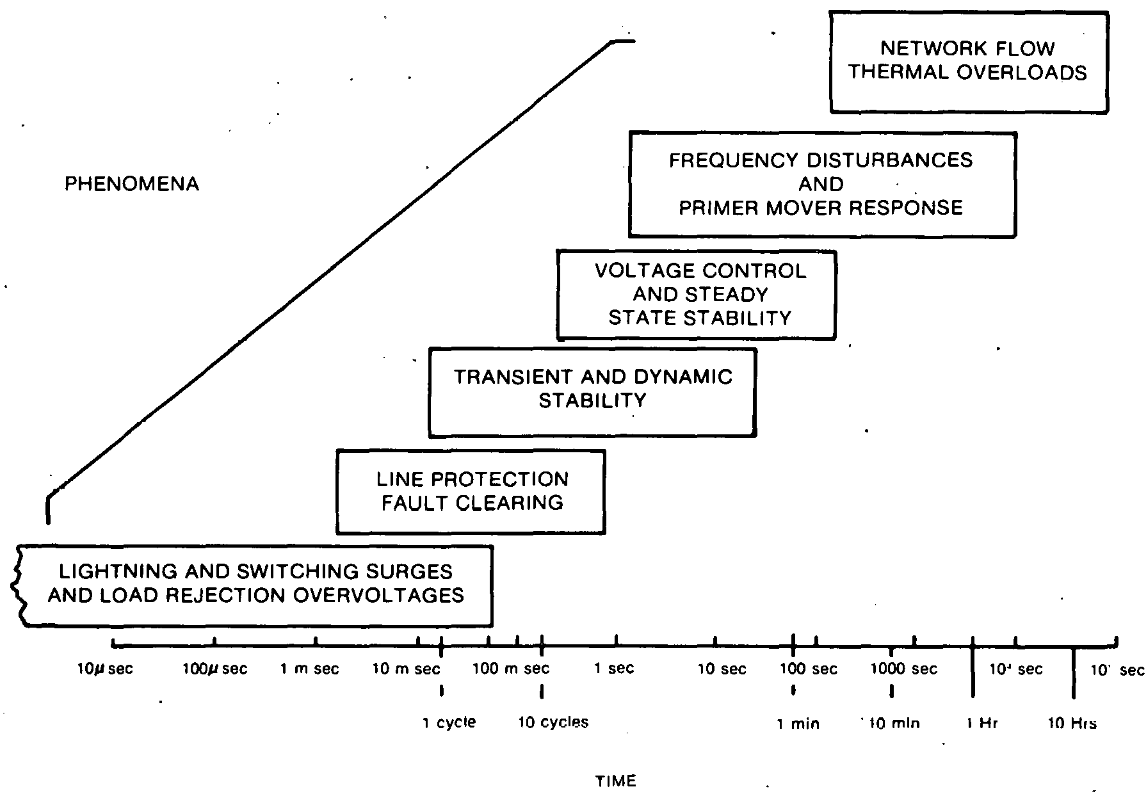


Figure 2 Summary of System Dynamic Performance

Using this same time scale characterization, Figure 3 depicts the need for adjustments in reactive compensation on the HVAC system to serve the various needs listed in Figure 2. For instance, at the upper right, the variable thickness bar indicates that adjustments in reactive compensation are generally desired (or required) in a few seconds to several hours in order to control the slowly varying voltages and reactive flows in the power system caused by daily load cycles and network switching events. The vertical thickness of the bar at any given response time is a relative measure of the benefit to system performance of an adjustment made within that response time. For instance, adjustments in compensation every few seconds would insure a nearly constant voltage profile and the lowest system losses, assuming the initial voltage profile or var flow pattern constituted minimum losses. In contrast, less frequent adjustments would result in longer periods of suboptimal voltage profile and higher losses.

For the other extreme, the bar at the bottom left indicates that if switched reactors were to be used to reduce load-rejection overvoltages, they would have to be switched in a few milliseconds. Such switching speeds are not readily available using mechanical switches for switching off capacitors and switching on reactors. A combination of fixed (always connected) reactors and surge arresters are utilized to satisfy this need today. Static var systems can be a partial solution to these problems in that they can accomplish a required change in compensation in about 0.5-to-2 cycles of the fundamental frequency.

Notice that for adjustable reactive compensators to be effective in controlling voltage flicker or subsynchronous resonance instabilities, the control must occur within fractions of a cycle. The effectiveness is reduced toward zero as the response times become large fractions of a second.

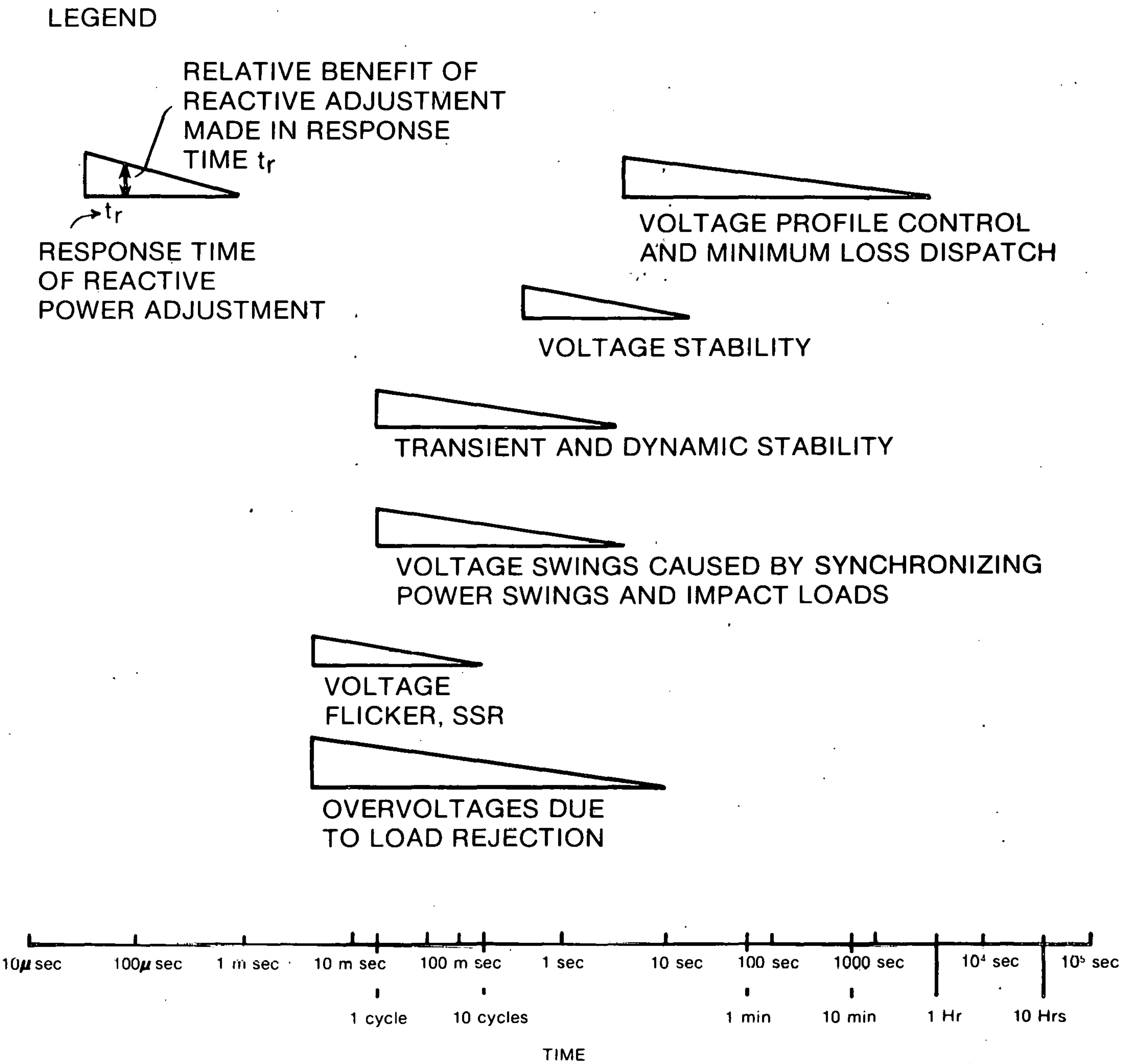


Figure 3 Characterization of System's Need - Response Time for Adjusting Reactive Power Compensation

Similarly, for switched capacitors or other adjustable reactive compensators to be effective in preserving rotor angle stability of synchronous machines, the desired adjustment (switching) should occur in a few cycles. As switching or compensation adjustments are delayed by one second or more, they become totally ineffective in enhancing the first swing transient stability of most systems.

For instance, if switching in a large shunt capacitive bank could be effective in preserving first-swing transient stability for a specific system, it must be switched in before the rotor angle or synchronizing power swing reaches its maximum value. That usually occurs within 0.5 to 1 sec. after a fault occurs. Deploying the capacitive supply only after the peak swing in angle occurs might render the compensation completely useless in preserving stability of the synchronous machines in the system.

1.5.3 Need for Studies

The planner should perform studies to determine quantitatively, the extent of his system's needs in terms of the parameters given in Section 1.5.1. Some possible exceptions to this rule might be in determining the required frequency of change, the speed of response, and whether or not a contribution of short-circuit capacity is desirable. In certain situations, prior experience may be sufficient to dictate these characteristics, making detailed studies unnecessary for every new application.

Having listed the needs for compensation, the next section discusses the role that static var systems can play in the context of the forementioned parameters.

Section 2

THE ROLE AND BENEFITS OF STATIC VAR SYSTEMS IN HVAC APPLICATIONS

In this section the general role of reactive compensation methods is first reviewed in terms of the impact on dynamic performance of the HVAC transmission system. Certain unique characteristics of static var systems are then cited and their utilization in a wide variety of HVAC system voltage and var control applications are discussed. Specific examples are included in order to quantitatively define the benefits of the SVS to ac system performance.

The three broad areas of need mentioned in previous sections can be further divided into twelve subfunctions as shown in Table 2-1. These specific functions have been identified also in Figure 3. In that figure each of those functions was correlated with a range or spectrum of natural dynamic phenomena. As indicated in Figure 3, the reactive power compensation scheme selected to perform any given function must be adjustable at a rate compatible with the system phenomenon it is expected to influence or control.

Table 2-1

FUNCTIONS PERFORMED WITH REACTIVE POWER COMPENSATION

- Reactive Power Flow Control during the Steady State to:
  - Minimize Excessive System Losses
  - Maintain Desired Voltage Profile on Transmission Network

- Control Voltage Variations Due to:
  - Daily Load Cycle
  - Repetitive Impact Loads such as Arc Furnaces (Voltage Flicker)
  - Synchronizing Power Flow Swings
  - Dynamic Variations in HVDC Converter P, Q
  - Load Rejection

- Power System Stability Improvement to:
  - Maintain Steady State Power Transfer Capacity
  - Prevent Transient Instability
  - Prevent Voltage Instability or Voltage Collapse
  - Prevent Oscillatory Dynamic Instability (0-5 Hz oscillations)
  - Prevent Subsynchronous Resonance Instability (5 to 60 Hz oscillations)

Figure 4 shows the response needs repeated from Figure 3 with the response characteristics of various compensation schemes overplotted for comparison. Here, again, the horizontal extension of the bar for each compensation scheme signifies the adjustment response range available with the specific compensation scheme. Of primary interest is the minimum response time or the fastest response possible with the scheme. The thickness (vertical dimension) of the bar signifies the relative ability of the scheme to make the required adjustment at the corresponding response time. These bar thicknesses are not absolute measures of device capabilities, but are merely used to illustrate relative effectiveness of the various compensation schemes.

All devices shown are capable of making slow adjustments to meet the slowly changing reactive requirements associated with controlling steady-state voltage profile and reactive dispatching for minimizing system losses. In contrast, no existing compensation scheme can be adjusted (switched) fast enough to avoid destructive overvoltages occurring in fractions of a millisecond. The bar shown for that range represents the surge arrester, not a reactive compensating device.

In the context of maintaining stability and correcting large voltage dips, generators and synchronous condensers are relatively slow in adjusting their reactive conditions because they possess sizable magnetic field time constants. Switching capacitors or reactors in a few cycles can provide effective protection against some, but not all, stability problems. Repeated on-off-on-off switching of capacitors and reactors to follow post-fault synchronizing power swings is not practical from a maintenance viewpoint with today's mechanical switches.

From a response time viewpoint, the static var system is the best suited for minimizing flicker voltage problems and preventing transient, dynamic and steady-state instabilities.

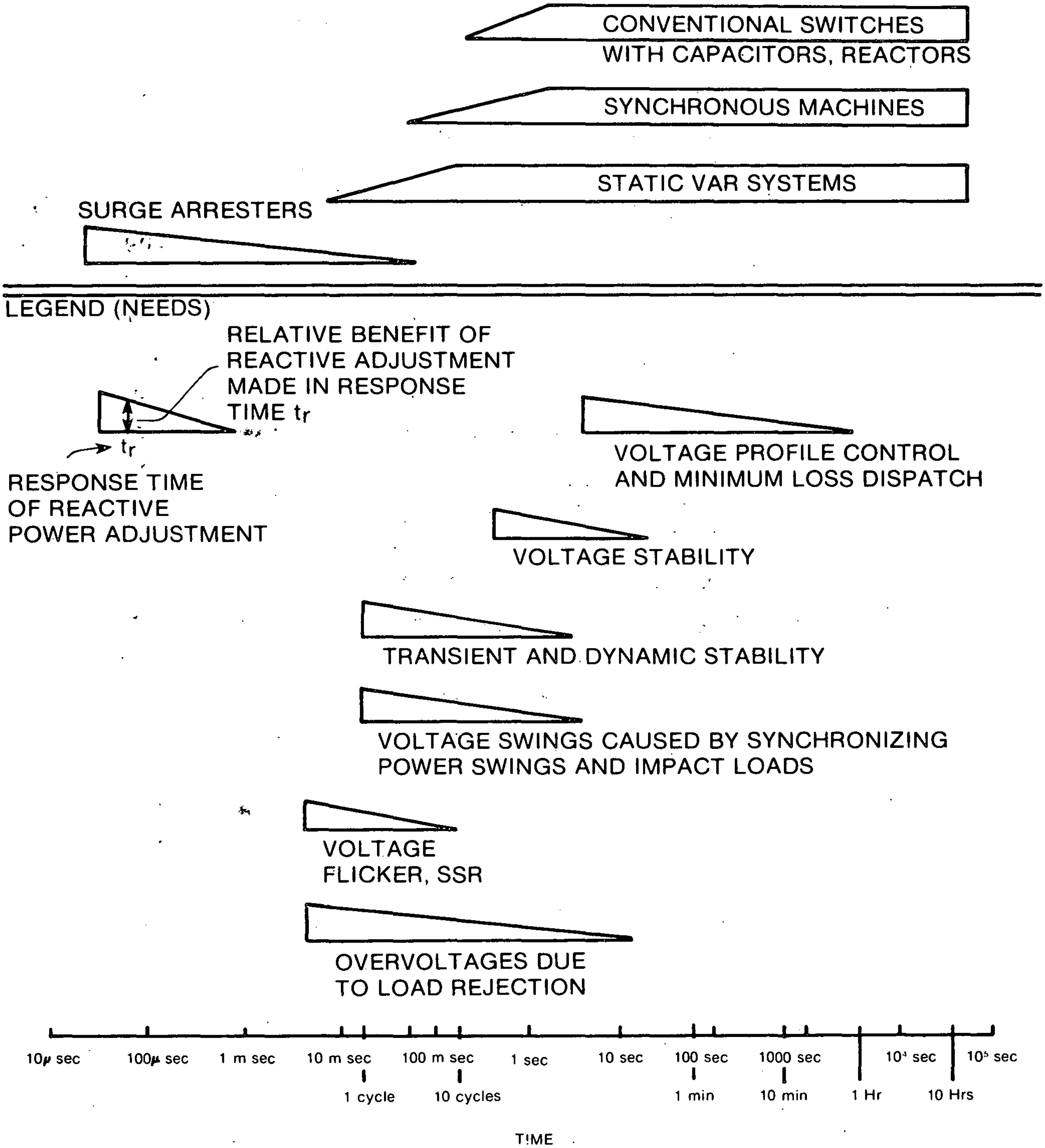


Figure 4 Response Time Capabilities of Reactive Compensation Devices

2.1 THE SPECIFIC ROLES OF STATIC VAR SYSTEMS

The characteristics of static var systems which set them apart from other reactive power compensation methods should be listed before making a case for their role and benefits in HVAC systems. As reactive power compensators they possess the following characteristics:

- Very high speed of response. Depending on the type of SVS, the reactive compensation can be changed in 0.5 to 2 cycles of the power frequency.
- Balanced Three Phase or Individual Phase Control. Again depending on the type of SVS and how it is connected into the system, an SVS can provide reactive compensation or control voltage differently in each phase. The high speed and the ability to control each phase independently, makes the SVS a nearly ideal compensator for solving flicker problems caused by arc furnace loads.
- Continuous Reactive Adjustment. All but one form of SVS is capable of adjusting its reactive compensation every half cycle of the power frequency. The SVS does this automatically in response to some measured parameter which, at the moment of measurement, represents the system's needs. Very small adjustments may be made every half cycle, making it appear as a continuous adjustment. The single exception is the Thyristor-switched Capacitor (TSC) type of SVS which connects or disconnects discrete capacitor banks to the HVAC system, thereby making discontinuous adjustments in compensation.

2.2 THE SVS FOR REACTIVE POWER FLOW CONTROL AND STEADY STATE VOLTAGE PROFILE CONTROL

The control of reactive power flows in HVAC networks for the purpose of reducing system losses or maintaining optimal voltage profiles is important to system operation. The required speed of response is generally so low that the use of one or more static var systems for that purpose alone might be less cost-effective than using switched shunt capacitors and/or reactors.

If static var systems are employed at strategic locations on the HVDC network for dynamic voltage control, they may be programmed to also provide some of the steady-state voltage and/or var flow control. In such cases, care must be taken to insure that a large fraction of the total SVS rating is held in reserve for the dynamic voltage duties it is installed to provide in accordance with functions discussed in Sections 2.3.2 and 2.3.3 to follow.

2.3 THE SVS FOR VOLTAGE CONTROL

2.3.1 Voltage Variations Due to Daily Load Cycles

Figure 5 illustrates a typical daily load cycle - total system load as a function of time in hours. At the bottom of that figure, a time trace of voltage at some key HVAC bus is sketched, as it might appear for the given load cycle.

As noted in Figure 4, these relatively slow changes in voltage can be tracked and corrected without the extreme speed possible with an SVS. The continuous automatic (local) control inherent to an SVS may make it convenient as an alternative to manually directed capacitor and reactor switching. Automatic switching of capacitors and reactors, using local voltage-sensing controls, would be a more cost-effective means for controlling slow daily voltage swings, if that is all that is required.

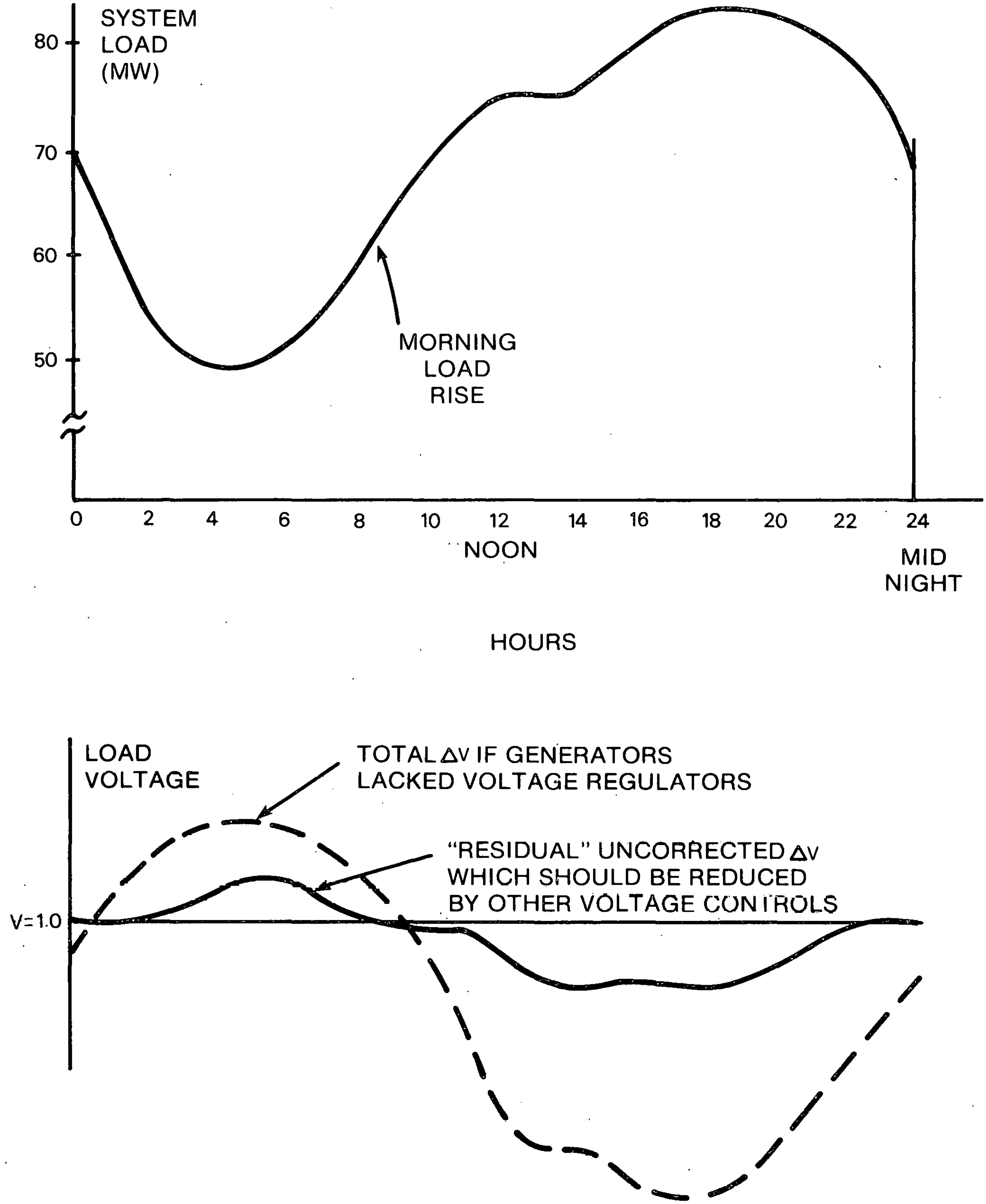


Figure 5 Voltage Control for Load/Voltage Cycles

2.3.2 Repetitive Impact Loads

The voltage swings due to repetitive impact loads such as mining excavators and frequent large motor starts, may require continuously acting voltage control. Switching capacitors on and off with mechanical switches to compensate for highly repetitive impact loads is not practical with today's mechanical switches. A static var system, a synchronous condenser or, occasionally, series capacitors are utilized to minimize the voltage swings on the host HVAC system.

Static var systems are cost-effective in solving this problem, and if the impact loads are single-phase or highly unbalanced three-phase loads, the SVS is probably the best approach. However, economics of the alternatives will ultimately dictate the final choice.

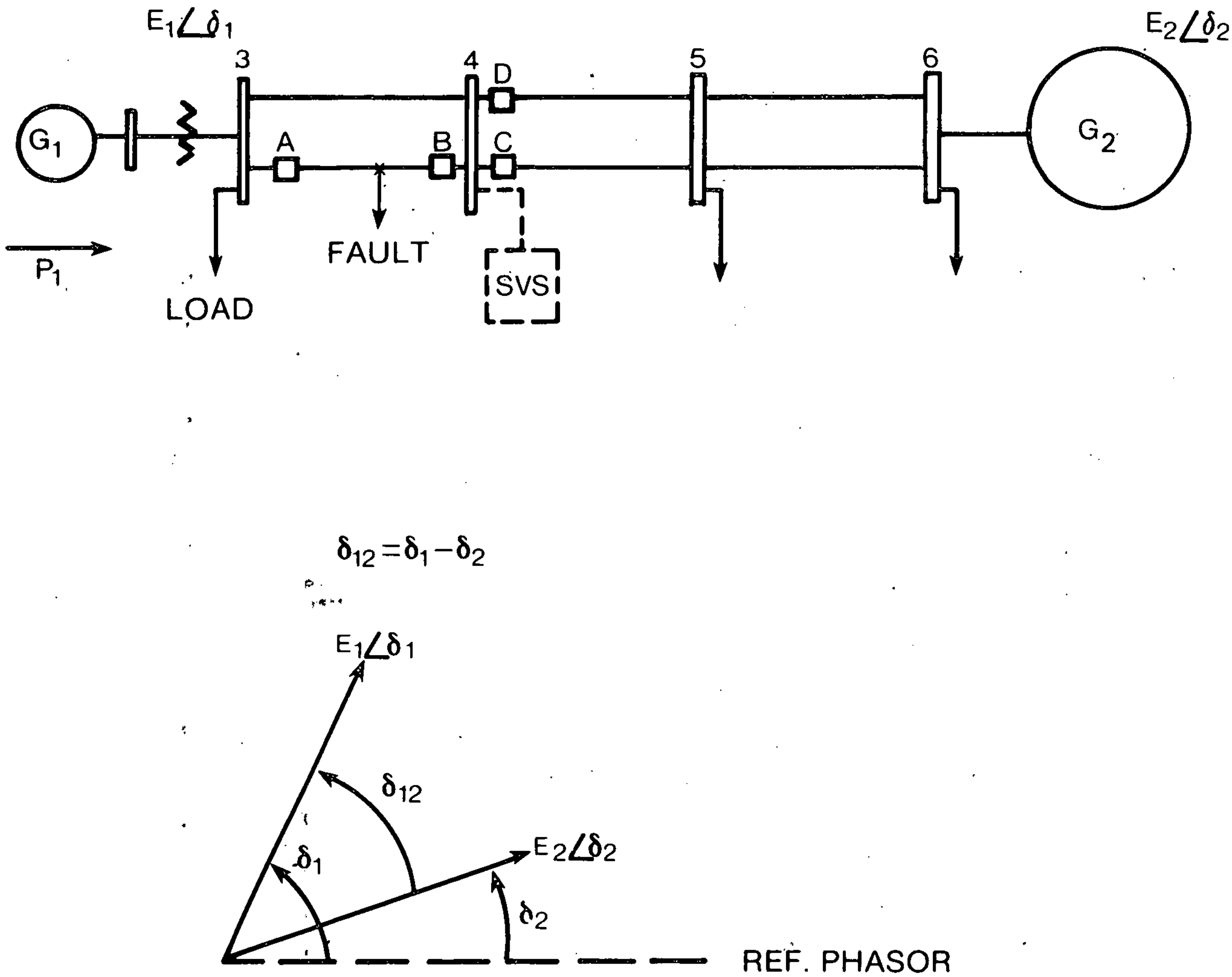
Arc furnaces are a special case of the impact load problem. In this case there is a high frequency component (5-10 voltage dips per second) which causes objectionable flicker in the voltage. It is visible in lighting and therefore objectionable to the human eye as well as to certain electronic equipment. Static var systems have all but replaced other schemes for solving the flicker problem. These applications are generally at lower voltage distribution voltages and only occasionally at a HVAC bus. The control strategy in an SVS designed to solve the flicker problem is unique and not generally applicable to HVAC bus voltage control. The description of that strategy is beyond the scope of this document, but is available in the literature [4].

The popularity of the SVS for this specific problem has resulted in many years of in-field experience of static var systems. The reliability record is excellent, thereby assuring that applications of SVS on HVAC systems will enjoy the same reliable, low maintenance performance characteristics of static compensation and power electronic equipment.

2.3.3 Large Voltage Swings Caused by Severe Synchronizing Power Swings

The high-speed response of an SVS can make it superior to other forms of shunt compensation for preventing intolerable voltage swings caused by synchronizing power swings. A few static var systems have been installed for this reason. A post-fault scenario will give rise to the extreme voltage swings, so an example of typical system performance following a fault will be used for illustration.

Without controlled shunt compensation. During a fault, a greatly reduced voltage is experienced in the vicinity of the fault and the active power drawn from generators on the system is thereby reduced. Figure 6 illustrates a representative system with a fault on an EHV system near a generating source. Because of the reduction in active (MW) load on the generators during the fault, they tend to speed up at a rate proportional to their proximity to the fault and the severity of the fault. A growing separation of rotor angles between generators near and distant from the fault can continue, even after the fault is removed, until one or more generators lose synchronism with respect to the remainder of the generators.



FOR FAULT LOCATION SHOWN, δ_1 WILL INCREASE FASTER THAN δ_2 SO THAT $\delta_{12} = \delta_1 - \delta_2$ WILL INCREASE DURING THE FAULT

Figure 6 Representative System for Illustrating Voltage Swings During and Following Faults

The possibility of synchronism loss is illustrated by curve (a) in Figure 7 for the system in Figure 6. If, however, the fault is removed soon enough, the machines will remain in synchronism but oscillations in angle difference δ_{12} will persist as shown by curve (b) in Figure 7.

Since the power delivered by the generator equals the power transmitted along the line, and the line flow is algebraically proportional to the angular (δ_{12}) separation of the internal generator voltages, the angular swing (curve 7b) and power swing (curve 7c) are in phase.

Assume for the sake of illustration that the initial normal load P along the line was 1 p.u. (SIL) resulting in a relatively flat voltage profile along the line. Following the disturbance the power varies around that 1 p.u. SIL, in an oscillatory manner for several seconds (5-20 seconds usually) following the fault.

As the power swings above 1 p.u. SIL, the steady-state var balance of the transmission line is disturbed and the voltages everywhere between the generators drop. Conversely, when the power swings below 1 p.u. SIL, the voltages along the line rise above their initial values. The result is a swing in EHV system voltages in counter-phase with the power and angle. This phase relationship is seen by comparing curve (d) in Figure 7 (V at bus 4) with angle (curve b) and power (curve c).

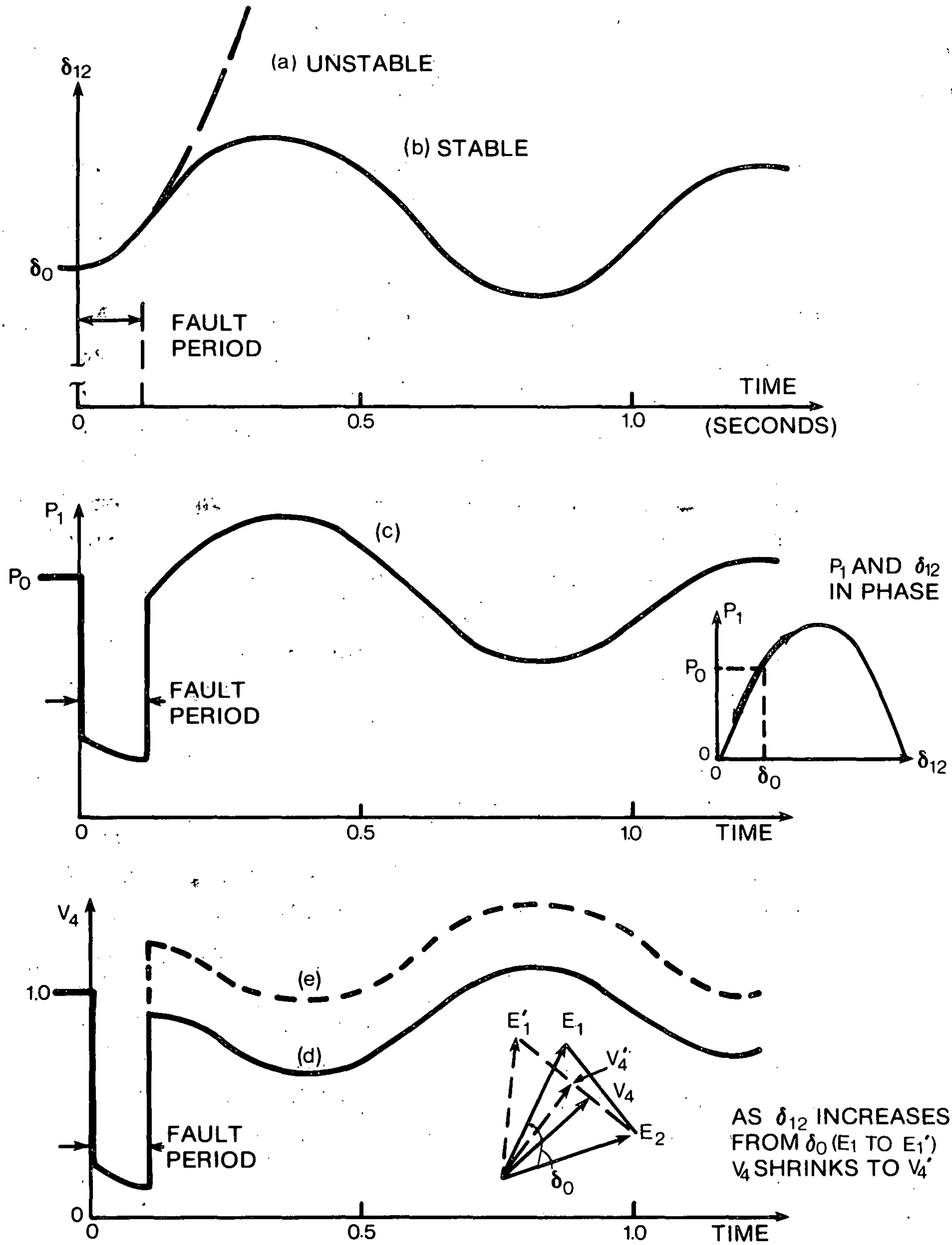


Figure 7 Synchronizing Swings in Power Angle and Voltage V_4 Following Fault Incidence (System in Figure 6)

Concentrating on the voltage excursion shown in curve 7d, which is typical of one possible post-fault behavior, the following observations can be made.

- The voltage during the fault is greatly reduced, with the limiting case being $V_4 = 0$ if the fault was a zero impedance 3-phase fault directly on bus 4.
- Upon removal of the fault by opening breakers A and B, the voltage will recover instantly to a value less than the initial value (curve 7d) but will begin to decrease again in counter-phase with δ_{12} and P.
- The voltage immediately after the fault removal might exceed the value before the fault as depicted in curve (e). However the voltage will again dip due to the P and δ_{12} swings.
- Because power and angle swings persist for many seconds (5-20) after a large disturbance, the swings after one second will be similar to the first swing shown in Figure 7 (curves d and e). The swings shown result in approximately one complete oscillation per second. The frequency of these oscillations vary commonly from 0.5 oscillation per second (two seconds for one cycle) to about five oscillations per second. Higher frequency oscillations usually tend to damp out more quickly than low frequency ones because amortisseur damping effects within the synchronous machines are more effective at high frequencies.
- The voltage at bus 4 will oscillate around a new equilibrium value.

While it oscillates, the voltage repeatedly dips below then rises above its final value. The momentary overvoltage shown in curves 7d and 7e coincides, in time, with the decrease in angle δ and power P in curves 7b and 7c, respectively. The momentary overvoltage during the first oscillation is referred to as the "backswing," since it is during this time that the angle is swinging back after the forward swing which occurred immediately following the fault.

<u>With a Static Var System</u>. The voltage swings illustrated in Figure 8 compare the expected results with and without static var system control action. Curve 8a is the same as curve 7d, reproduced here for ease of comparison. Voltage traces similar to these, but derived through computer simulation with a numerical example, are given later in Section 2.4.2.

Curves 8b through 8d show the potential improvement in voltage swings with successively larger static var systems. Both capacitive and inductive ratings of the SVS were increased simultaneously. In the limit, there is a rating, less than infinite but large, that could cause the voltage swings to be eliminated at the point of SVS application. That is, after an initial post-fault transient adjustment, the voltage would be held constant thereafter by the SVS.

The static var system is extremely qualified for this voltage control duty, as well as for power swing stabilization purposes to be discussed later. To obtain equivalent performance with switched capacitors and reactors only would require many precise switching operations in a short time; a duty not compatible with conventional mechanical switches.

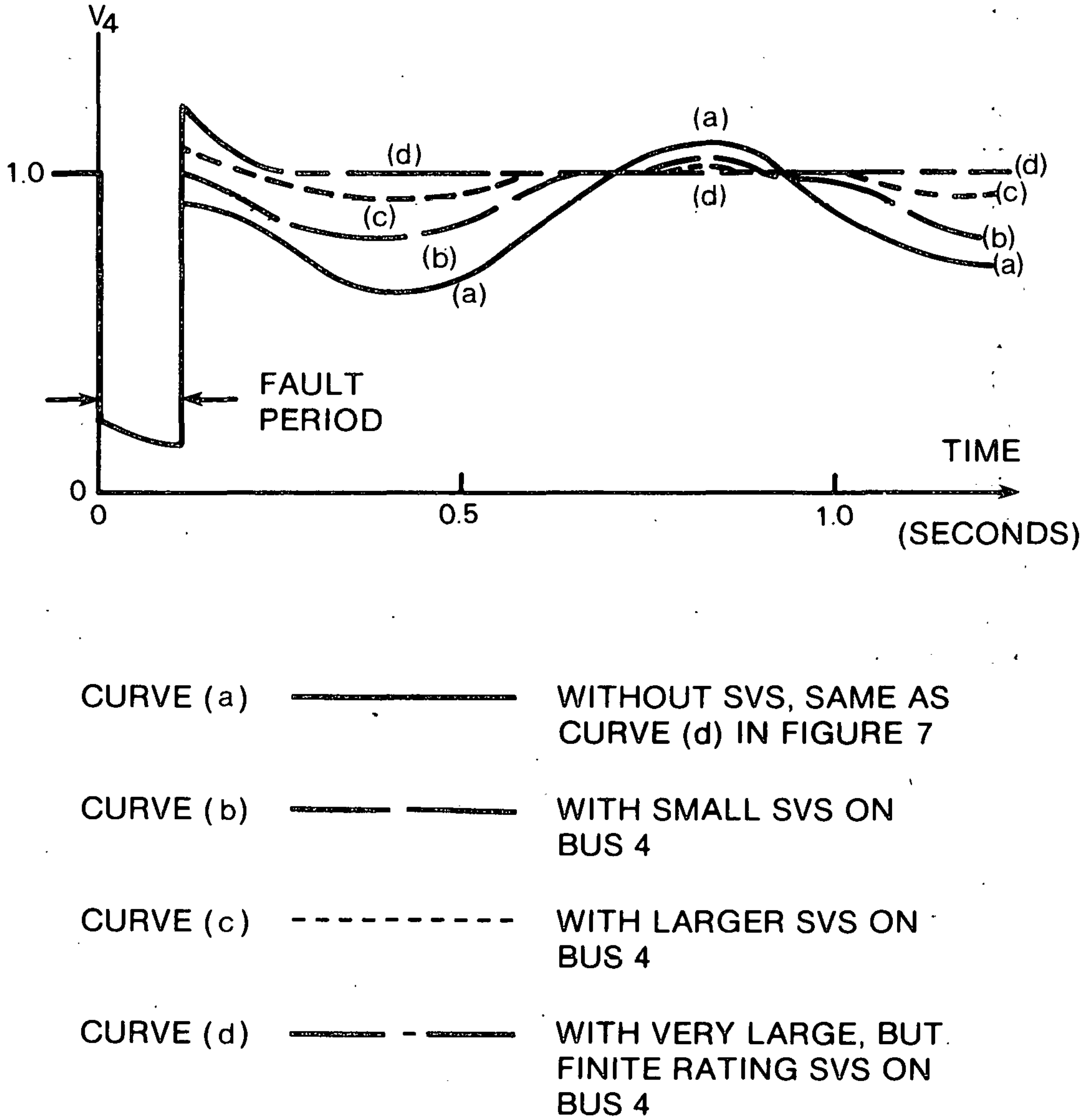


Figure 8 Voltage on Bus 4, System in Figure 6 Without SVS and With Various Rating Static Var Systems on Bus 4

2.3.4 Voltage Swings Near an HVDC Terminal Following Disturbances

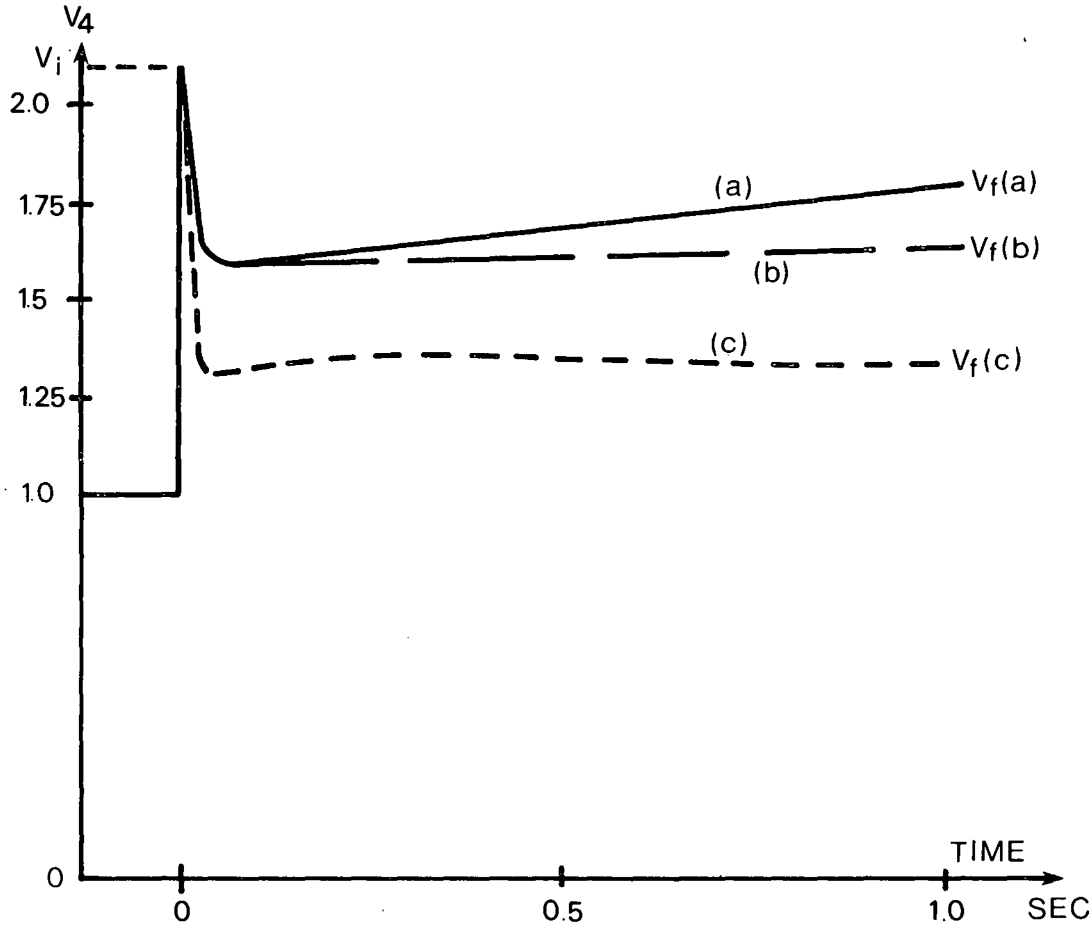
The ac voltage variation at the converter terminal of an HVDC system will vary following a major (fault-initiated) disturbance similar to the curves in the previous section. The HVDC controls attempt to maintain dc voltage and dc current at normal values, or restore them to normal values after an ac fault-initiated shutdown-restart sequence of the HVDC converter. The dc voltage depends on the ac-side voltage and the reactive demand from the ac system increases when the ac voltage drops, thereby causing a further reduction in the ac-side voltage. HVDC controls can be designed to prevent such behavior but if they do not the ac system requires a variable reserve supply of reactive power to insure an optimum overall ac/dc system performance.

Static var systems can be very effective in maintaining ac voltage at the converter terminals and their future use for this application is inevitable. The static var system can also serve to help prevent sustained overvoltages on the ac system caused by an occasional blocking of the HVDC system -- a load rejection overvoltage.

2.3.5 Control of Temporary Power Frequency Overvoltages Caused by Load Rejections

Sustained power frequency overvoltages severe enough to be categorized separately from the momentary overvoltages in Figure 7 can result from a load rejection.

Load Rejection. Should an inadvertent operation of breakers C and D occur in system of Figure 6, then the load on the plant G_1 would be reduced significantly. The voltages at bus 4 may behave as shown in Figure 9 (curves a or b) if no corrective action is taken. The initial value V_i may be in excess of 2 p.u. and result in arrester operation. A maximum value of 1.6-to-1.8 p.u. (V_{fa} or V_{fb}) may



BREAKERS C AND D IN FIGURE 6 OPEN THEREBY CAUSING PARTIAL LOAD REJECTION ON PLANT G_1

(a) NO SVS ON BUS 4, PLANT OVERSPEED

(b) NO SVS ON BUS 4, NO PLANT OVERSPEED

(c) WITH SVS ON BUS 4, WITH OR WITHOUT PLANT OVERSPEED

Figure 9 Load Rejection Overvoltages

persist for a second or more if allowed to go uncorrected by additional reactive compensation means.

In some cases, all the units in plant G_1 would trip on overspeed in about one second and the voltage would collapse. Alternatively, the lines from bus 3 to bus 4 may be tripped. For very large hydro plants that can tolerate overspeed, or when alternative measures are used to prevent tripping <u>all</u> the units in the plant, 1.6 - 1.8 per unit voltages at bus 4 could persist for periods longer than a second. If for no other reason than to save the arresters and breakers from failure, an SVS or a switched reactor bank might be utilized at bus 4 to reduce these overvoltages. Such voltage suppression could be accomplished by using an SVS of appropriate inductive rating to bring the voltage down to 1.3 p.u., as illustrated by curve c in Figure 9, or lower if possible. The equipment would be required to hold that 1.3 p.u. for several seconds or even minutes until some other means can be employed to regulate the voltage.

<u>Example</u>: <u>Control of Severe Overvoltage with an SVS</u>

Partial or total load rejections can cause severe overvoltages as discussed in the previous paragraph. The example that follows deals with the HVAC bus voltage at the input to a high-voltage direct-current (HVDC) line. If the short-circuit capacity of the ac system at an HVDC converter site is low, the ac voltage can be quite sensitive to variations in the real power absorbed or delivered by the HVDC converter.

HVDC converter terminals absorb reactive power equal to approximately 60% of their real power conversion. If the host ac system is relatively high impedance it cannot supply this reactive power without the ac bus voltage falling to an unacceptably low level. To avoid this, capacitor banks are oftentimes applied at the ac bus of the dc terminal. Some of these banks also serve as harmonic filters. One possible disturbance associated with a HVDC rectifier terminal is the load rejection that can occur when the terminal is operating under load and the valves suddenly block. This blocking might be the result of a major fault on the ac system near the terminal at the other end of the dc line which requires a momentary or permanent "shutdown" of the HVDC power flow.

To illustrate the effect of an SVS on such a load rejection, the system of Figure 10a was studied on General Electric's Transient Network Analyzer (TNA). The rectifier terminal was assumed to be operating at its 200 MW rating. The attendant filter and var supply capacitor banks had a total rating of 114 MVAR. The SVS modeled had a net rating as viewed from the 230 kV bus of 0 to 130 MVAR inductive. Three total HVDC shutdown cases were studied.

- Without the SVS in service.
- With the SVS controlling the 230 kV bus voltage with its automatic voltage regulator.
- With the SVS reactor phased on fully by a transfer command from the HVDC converter. In this case, the dc valve blocking control action and the order to the SVS to phase on fully occurred simultaneously.

The results of these three TNA studies are illustrated in Figures 10b, 10c, and 10d respectively. The phase a-to-neutral voltage on 230 kV bus is shown in all three pictures. The valve blocking action (load rejection) occurred at a time very closely coincident with the fifth voltage zero from the left (counting the initial one) in the three oscillographs.

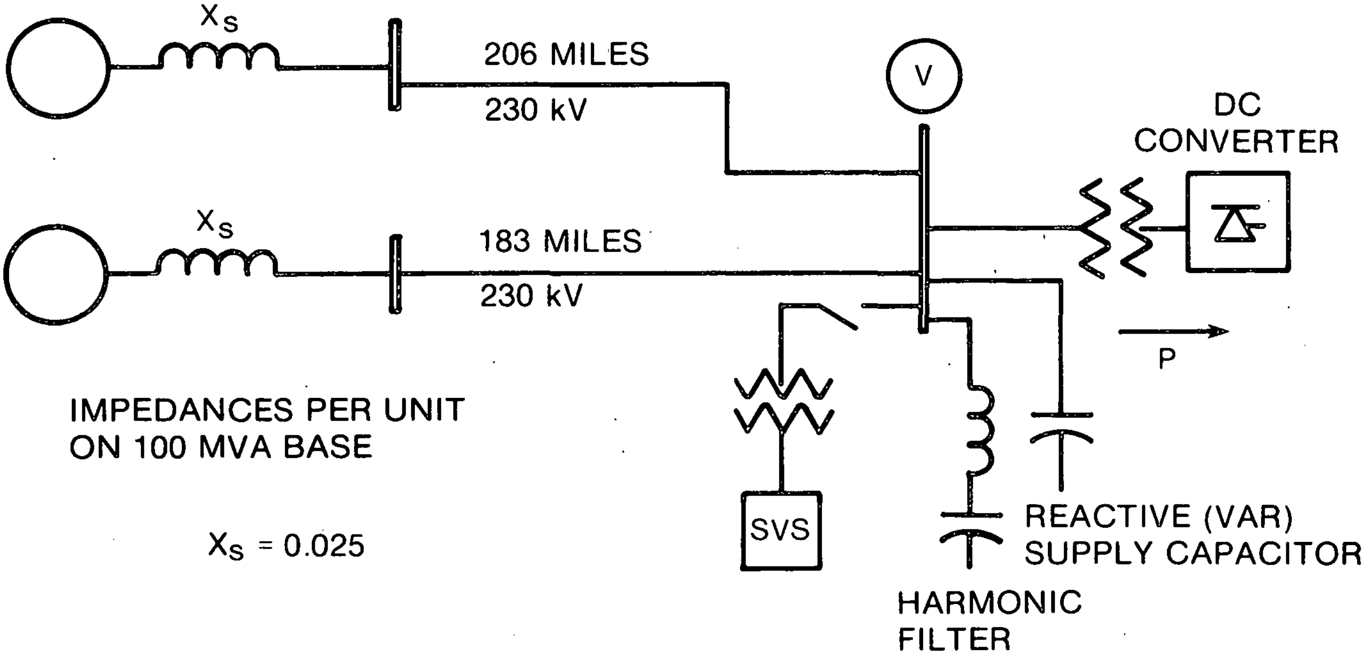


Figure 10 Load Rejection Study Results
a) System Used in Analysis of Load Rejection Overvoltages

Figure 10b HVAC Bus Voltage (V) With No SVS

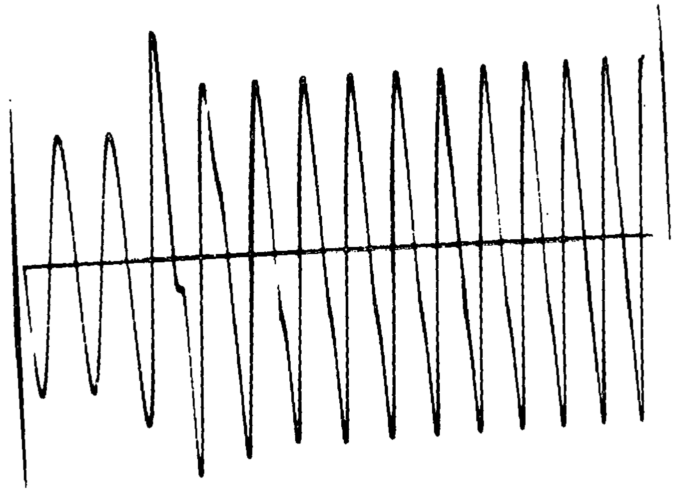


Figure 10C HVAC Bus Voltage (V) With SVS Regulating Voltage Normally

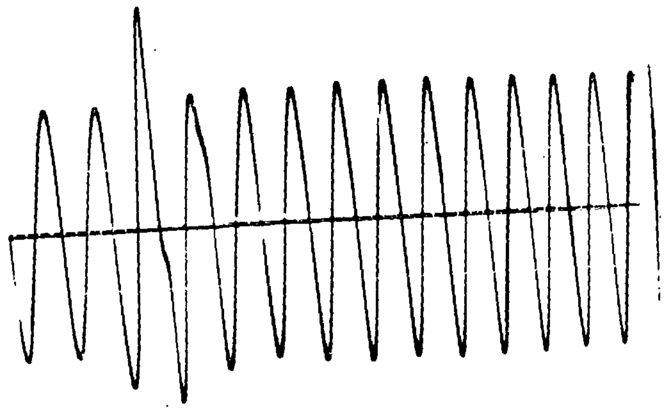
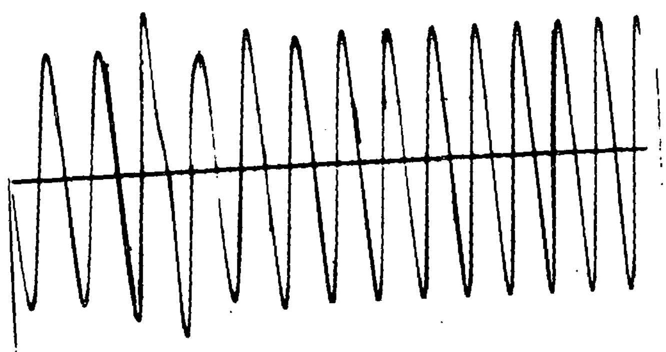


Figure 10D HVAC Bus Voltage (V) With SVS Receiving a Command to Go Full Inductive From DC Converter as it Blocks DC Conduction.



The subsequent peak (+ and -) voltages are tabulated in Table 2-2. When the SVS reacted via its automatic voltage regulators, it was unable to reduce the first (-) and second (+) peak. When given an early warning from the DC controls, the SVS was able to reduce those peaks. In both cases when the SVS was in service, the post disturbance voltage was reduced significantly. An SVS with a greater inductive rating would have controlled the voltage even better. The one utilized in the example was fully utilized and operated above its voltage control range.

Table 2-2
LOAD REJECTION OVERVOLTAGE
EXAMPLE ON TNA

Time	No SVS V Peak	Normal SVS V Peak	Coordinated DC-SVS Control V Peak
0 (1)	± 0.95	± 0.95	± 0.95
0.25 cycle	- 1.27	- 1.2	- 1.11
0.75 cycle	+ 1.65	+ 1.65	+ 1.2
1.25 cycles	- 1.65	- 1.32	- 1.27
1.75 cycles	+ 1.27	+ 1.01	+ 0.90
2.25 cycles	- 1.52	- 1.08	- 1.01
2.75 cycles	+ 1.33	+ 1.01	+ 1.08
Sustained	± 1.33	± 1.02	± 1.02

Notes: (1) Time = 0 when dc blocking occurred or about fifth voltage zero of phase a in oscillographs.

2.4 STABILITY PRESERVATION OR IMPROVEMENT

Dynamic voltage control has long been regarded as invaluable for preserving or maintaining system stability. Electric power generators are equipped with continuously acting voltage regulators to maintain their terminal voltages at a prescribed value despite changes in the generator's output and/or changes in the transmission system which they serve. That voltage control is accomplished indirectly by controlling the field flux in the air gap of the rotating machine.

Any modern, continuously acting voltage regulator can maintain or improve the classical steady-state stability or steady state power transfer capability of the system which it serves. To enhance transient stability following a nearby fault, high-initial-response (HIR) excitation systems with terminal voltage regulators have been developed and improved over the years. The fast-acting HIR exciters reinforce the machine's field flux with great vigor, forcing a maximum flux condition within about 300 to 500 milliseconds. The earlier exciters took 1-5 seconds to effect the same reinforcement of field flux and were unable to match the newer HIR exciters in transient stability improvement.

In spite of improved excitation and voltage regulator response, HVAC voltages in the transmission system distant from the generators can be depressed, threatening the stability of machines on the system. The use of dynamic reactive power compensation at strategic locations in the HVAC system distant from generators can improve stability beyond that achievable with accurate and rapid voltage control at generator terminals only. When such "mid system" dynamic reactive support is required, static var systems can serve the need very effectively. Examples of how one or more static var systems can improve transient stability of representative systems are discussed later in this section.

Another steady-state instability phenomenon that can arise when the reactive component of loads increase as the supply voltage decreases is called voltage instability. Since increased reactive demand can further reduce the supply voltage, a voltage collapse scenario can follow. Static var systems can be effective guardians against incipient voltage instabilities which are likely following equipment outages that cause increased power transfers on transmission lines. An example of this phenomenon is given later in this section.

The high-speed and continuous-control capability of certain static var systems can be exploited to increase the damping of post-disturbance synchronizing power swings or subsynchronous rotor shaft torsional oscillations. In such cases, straightforward control of voltage is not suitable. Additional measured variables are required in those cases, as is discussed later in this section.

2.4.1 STEADY STATE STABILITY AND POWER TRANSFER

By providing precise and continuously acting voltage control at strategic locations in the system, static var systems can help maintain or improve the power transfer capacity of the transmission system. In so doing, the SVS is also helping to maintain the steady-state stability of the synchronous machines in the system. Steady-state instability, in the classic form, occurs when the power level across a given system approaches the maximum of the power-versus-load angle curve.

To illustrate that power level, observe the radial transmission system (equivalent) shown in Figure 11a. Assuming that the voltage regulator on generator G holds its terminal voltage E_t constant for slow changes in load on the line, the generated electrical power P_e and the load angle (δ_t) across the system are related by Figure 11b.

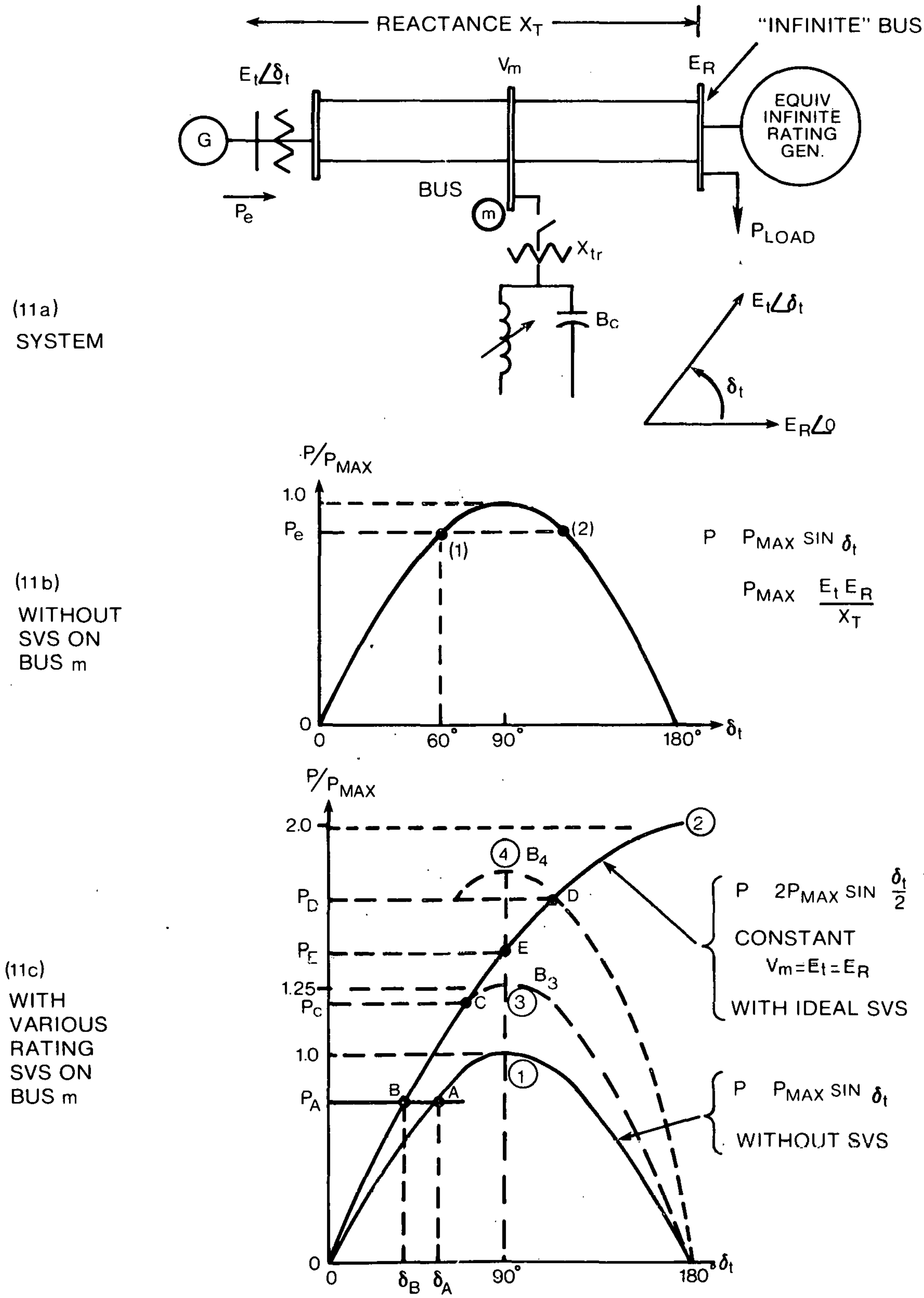


Figure 11 Steady-State Power Transfer Capability, With and Without SVS

That figure prevails if the static var system at bus (m) is not on line.

If plant output, P_e, were increased to the maximum power capability of the radial system P_{max}=1.0, any infinitesimal increase in system reactance or drop in voltages E_t or E_R would result in instability. For the plant power level shown in Figure 11b, point (1) is a stable operating point because the slope of the power angle curve is positive at that point. That same power level coincides with point (2) in Figure 11b also, but point (2) is an unstable point because the slope of the power-angle curves is negative. That is, any increase in angle δ_t would result in a reduction in power capability, and a further increase in angle. This scenario would continue until the generator G loses synchronism with the receiving end system's generators.

The addition of a static var system of infinite capacitive rating would give rise to power angle curve 2 in Figure 11c. In effect, bus (m) becomes a constant voltage bus with $V_m=E_t=E_R$ and the power transfer capability is now double what it was in Figure 11b or curve 1 in Figure 11c.

An SVS with finite capacitive rating can still increase the peak power capacity of the system, as is also shown in Figure 11c. For instance, assume the SVS has a maximum capacitive admittance of B_3. The value B_3 is as seen by the HVAC system "looking into the SVS" from bus (m). B_3 is, therefore, the actual connected capacitive admittance B_C reduced slightly to account for the reactance of the SVS transformer. Assume the peak power capacity of the system in that case coincides with the top of curve 3, which is 1.25 times the peak power of curve 1 without the SVS.

To place the advantage gained with the SVS with net HVAC-side capacitive rating B_3, let's examine practical plant output conditions with and without the SVS. Without the SVS the steady-state stability power limit is 1 per unit, or the top of curve 1. To allow a stability margin for equipment outages and possible faults, the plant G output might be limited to power P_A shown in Figure 11c.

Operating at power level P_A without the SVS yields an angle δ_A across the system and the midpoint bus (m) voltage V_m will be less than $E_t=E_R$. By energizing the SVS and forcing it to control voltage V_m at $V_m=E_t=E_R$, the angle across the system is reduced to δ_B. That is so because now we are operating on the constant V_m line, curve 2 in Figure 11c.

The plant output could now be ramped slowly up to 1.25 per unit before the plant would lose synchronism in the classical steady state sense. The SVS would hold constant $V_m=E_t$ up to point C (for power level P_C) at which time the SVS would appear as a fixed capacitor of admittance B_3.

From a practical operating point of view, the plant output would be kept below power P_C to provide some stability margin for outages. If such were the case, the SVS would be able to hold constant $V_m=E_t$ for all practical power transfers in normal steady-state operation.

If a modest SVC rating can permit increased stable power transfer, then the temptation is to use a very large SVS rating and operate at much higher power levels. Curve (4) would be the power angle diagram achievable with an SVS capacitance rating B_4 (new B_C adjusted for the new SVS transformer) which may be 2 to 3 times larger than B_3.

In this latter case, the SVS would hold V_m constant at $V_m=E_t$ for power outputs up to P_D. The stability of the system at power transfer levels P_E through P_D is due entirely to the SVS holding V_m constant at $V_m=E_t=E_R$. For transmission system designs that rely on reliable SVS operation for steady-state stability [5], duplication of SVS equipment must be provided to insure stability for a single SVS equipment failure.

2.4.2 Transient Stability Preservation or Improvement

The post-fault phenomenon. A system is transiently stable if, following a major disturbance - usually a fault causing the loss of the faulted line or transformer - all of the synchronous machines remain in synchronism. The high-speed response of the static var system makes it a valuable means for preserving synchronism between machines on a system, through rapid HVAC voltage control.

A typical post-fault behavior in voltage and angle was described in detail in Section 2.3.2, with the help of Figures 6, 7, and 8. The SVS action, which showed improved voltage traces in Figure 8, is also valuable in preserving or improving synchronous stability between machines.

Relationship of voltage to stability. There is an algebraic cause-and-effect relationship between angle δ_{12} and voltage V_i on any bus (i) between the generators shown in Figure 6. That relationship is depicted in Figure 7. The greater the angular swings are, the more pronounced will be the voltage swings. The angle δ_{12} here is between internal machine equivalent voltages (or flux phasors), and is not the same as δ_t across the transmission system discussed in relationship to steady state stability.

If the voltages along the system were controlled very tightly, then the angular swings would be smaller and the synchronous machines would be made more stable. The voltage control provided by one or more static var systems can make an improvement in stability; but ideal control (V_4=constant) does not result in zero angular swings but rather a reduction in the swings, as depicted in Figure 12. However, any reduction in angular swings constitutes a more stable system.

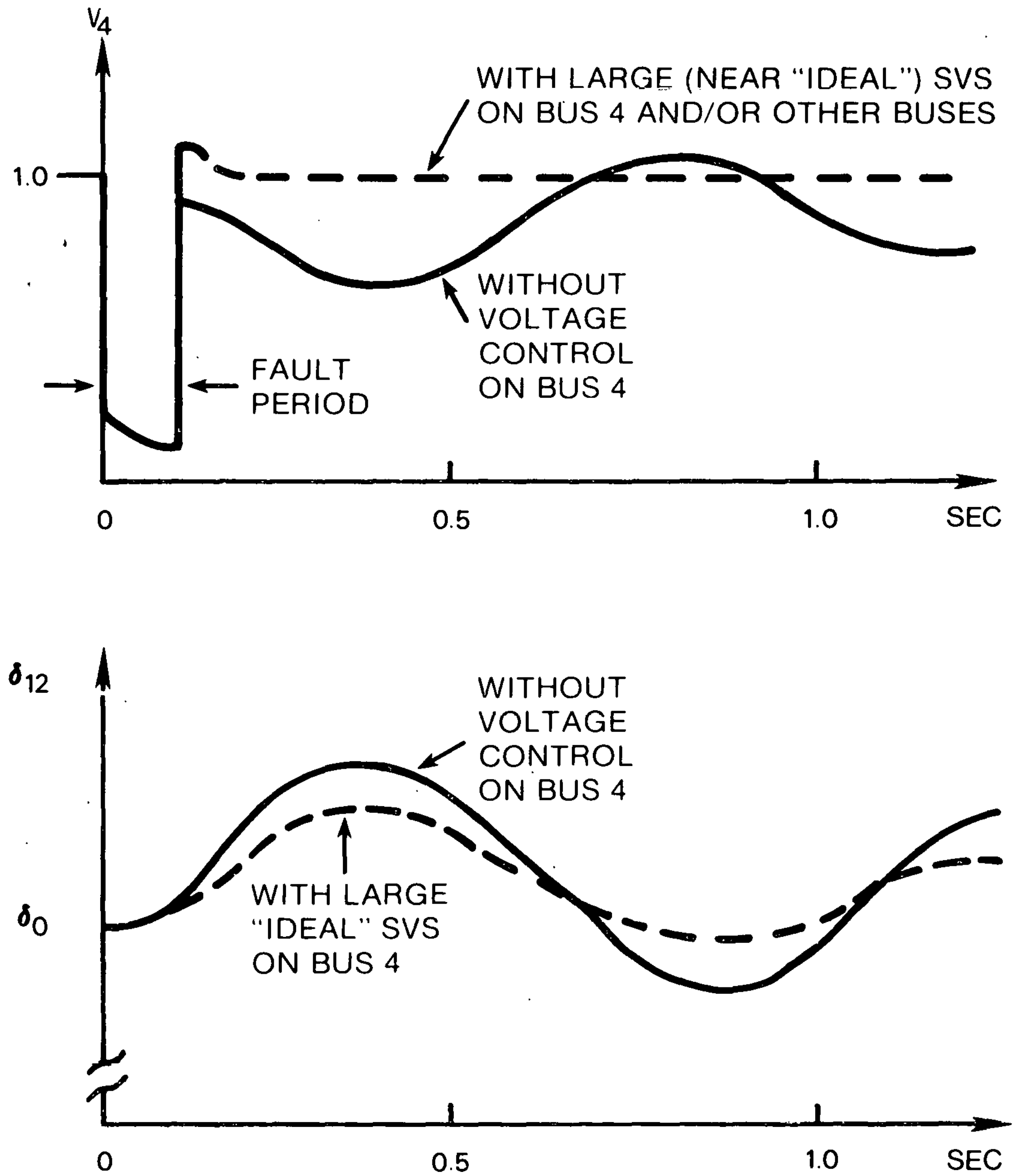


Figure 12 System Performance (Angle) Still Oscillatory Even With Large ("Ideal") SVS -- Bus Swings Reduced, Stability Enhanced

As noted before, dynamic voltage support on the system enhances the transmission system's ability to accommodate or transmit generated power. When the voltage dips, the line loses some of that ability to transport the generated power. During the fault, the electrical active power produced by the generator is reduced, but the mechanical torque applied to the generator shaft by the turbine is changed very little. The tendency for the machine to overspeed appears as a momentary increase in angle separation δ_{12}.

If the generator could be overloaded slightly immediately following the fault, the rotor angle separation δ_{12} could be brought more rapidly toward its final equilibrium value. However, just at the time the generator should be momentarily overloaded, the voltage dip may cause the local customer loads to decrease slightly and also cause a reduction in the transmission system's synchronizing capability. Even if the local customer loads are insensitive to voltage changes, holding system voltage during that forward swing in angle would at least preserve the system's synchronizing power transfer capability.

Examples of how an SVS can improve stability and therefore, permit increased power transfer without risking instability, are given later in this section. The principle and important performance issues will be discussed qualitatively first.

Stabilizing Voltage Support with SVS. The SVS on the network must produce vars when the voltage would otherwise drop, and consume vars when the voltage would otherwise rise above the desired voltage band. Reduction of the voltage dip during first swing is most important in stabilizing the network of generators. The voltage rise portion of the oscillation does not threaten system stability, but must be controlled or damaging overvoltages might result. For example, the high voltage excursions must be controlled to within a safe margin so that line breakers can be operated manually or via relay action at anytime without damage to the breaker.

Likewise, the voltage dips occurring on subsequent swings require capacitive compensation since they can be nearly as severe as the first dip on some weak systems. The consequence of deploying adequate vars to reduce the first voltage dip, only to withdraw those capacitor vars for some time thereafter, could cause the angular swing to appear stable as in curve 7b for the first full oscillation, only to go out of synchronism (like curve 7a) during a subsequent voltage dip.

The magnitude of the voltage swings for a given system configuration and fault-precipitated scenario will vary widely in practice. Also, the magnitude of voltage dip and associated angular swing beyond which instability results, varies widely from system to system. One criterion which a specific utility planner found to apply for his system is as follows:

> Voltage dips on the EHV system of 25% (min first swing V = 0.75) coincided with the transient instability limit. Reducing the voltage dips to 15% (min voltage = 0.85) on first swing would insure the desirable stability margin.

The benefits resulting from the application of static var systems can be further illustrated in the context of some specific examples. Two examples are given, both dealing with representative radial transmission systems.

<u>Increase in transiently stable power transfer - Example 1.</u> The system studied in this example was the 500 kV transmission system shown in Figure 13. This system typifies a transmission tie between remote generation and a

major load-generation area. The transmission circuit consisted of two lines, 300 miles long, with an intermediate switching station. There was assumed to be 500 MW of load at the generation site. For the transient stability investigations, the system disturbance was a zero impedance, 3-phase fault followed by tripping of the faulted line in 5 cycles.

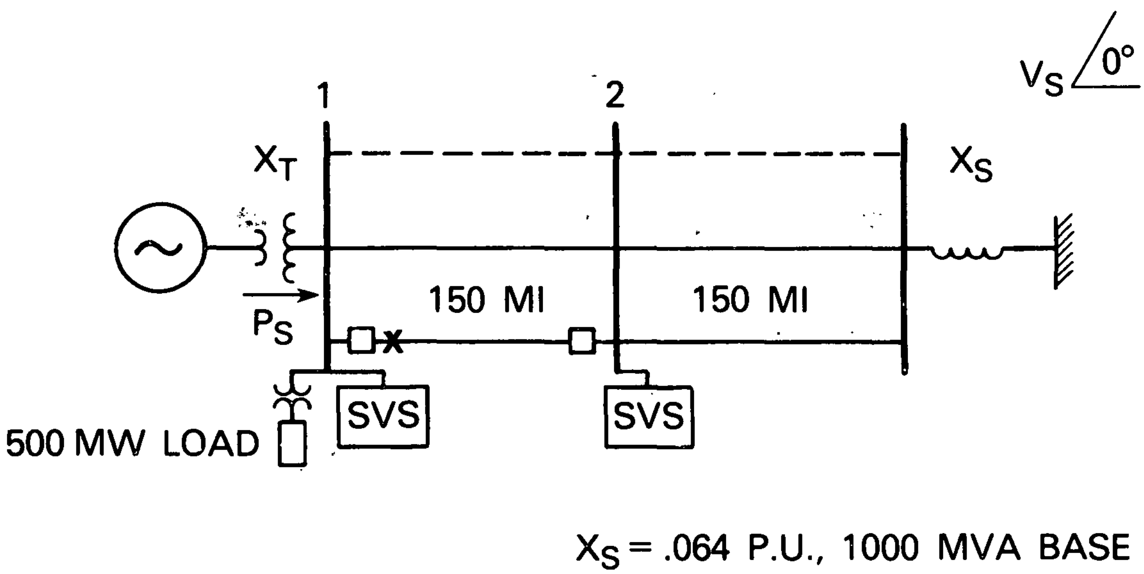


Figure 13 500 kV System Studied in Example 1

The objective of the study was to demonstrate the utilization of static var systems to increase the power that could be transferred over a given set of transmission lines without risking transient instability for a specific fault scenario. This would be analogous to an actual condition in which approval for additional transmission lines is difficult to obtain or in which more economical alternatives are desired. In contrast to the fixed transmission it was presumed that the generation capability (and associated transformers) would be increased, consistent with the increased power transfer capability made possible by the application of the SVS.

The investigations were made using a digital power system stability program.[3] The compensators were considered to be located at Bus 1 and Bus 2. For a number of specific sending end transmitted power levels, P_s, and specific capacitance MVAR rating for the SVS at Bus 1, multiple program runs were made to determine the minimum capacitive MVAR rating required of the Bus 2 SVS to keep the system stable. The resulting curves are displayed in Figure 14 and indicate for each P_s the combination of capacitive MVARs for the Bus 1 and Bus 2 SVS that will maintain system stability. For example, for a P_s of 1100 MW, SVS ratings of 600 MVAR and 230 MVAR at Bus 1 and Bus 2, respectively, are required. The power levels investigated ranged from 720 MW, which is the maximum stable power transfer with no SVS, to 1250 MW, which is the maximum stable power transfer with a third line (shown dashed in Figure 13) in service and no SVS. In all cases, the MVA rating of the generation and associated transformers were made equal to the prefault power flow. The control settings for the compensators were modeled such that compensator output was zero under normal load flow conditions.

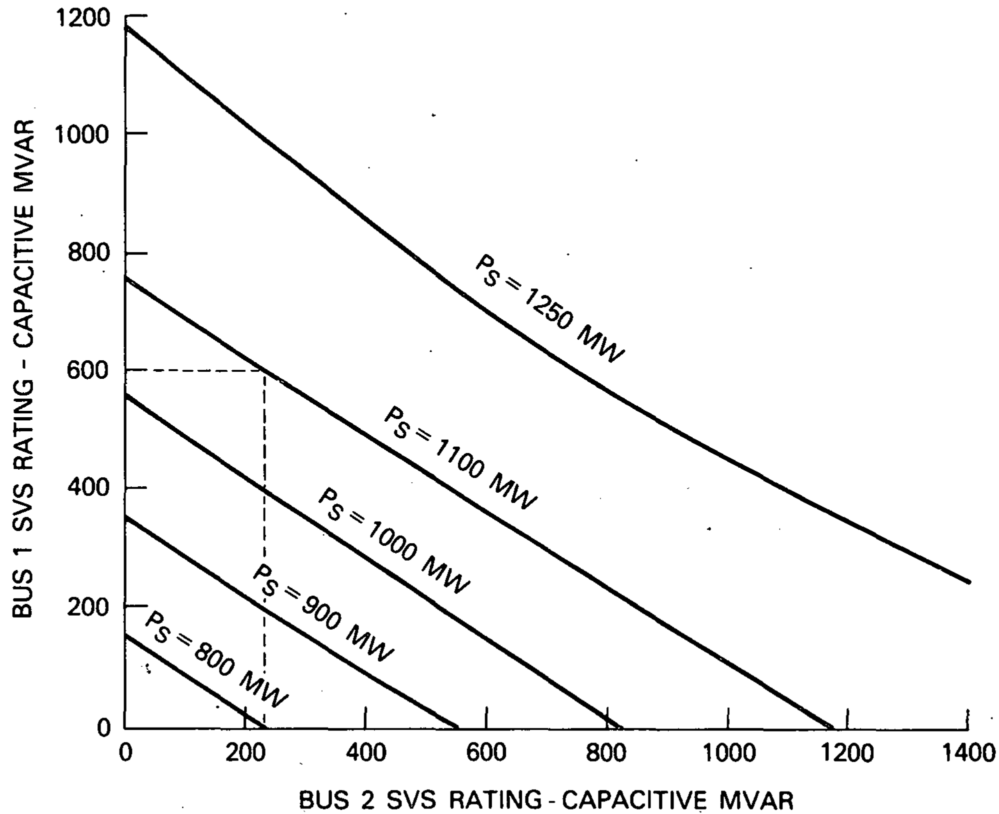


Figure 14 Minimum Combination of SVS Ratings Required for Transient Stability for Various Prefault Power Levels, P_S

For the circuit investigated, the results show that compensators dramatically increase the transiently stable power transfer capability. This increase is approximately equal to 100 MW for each 200 MVAR of added compensation and can be used to achieve from two transmission lines the power level associated with three parallel lines.

The results also indicate the preferred location for the SVS. The preferred location is the location of the compensation that provides the greatest increase in power transfer capability per added MVAR of compensator rating. In the application of compensators to an actual system, a number of fault scenarios and contingencies must be considered and the final choice of location(s) may be a compromise. However, for the fault scenario studied in

Example 1, the preferred location for a single compensator was at Bus 1. This is due to the fact that in the post-fault circuit, Bus 1 is closest to electrical midpoint of the series impedances of the total system. Without compensators, this location experiences the greatest voltage dip during the generator angle swings that follow the fault clearing. This occurs in spite of the fact that the generator was equipped with a high-initial-response excitation system.

Figure 15 illustrates the time domain behavior of the system with and without compensators. In this case, the prefault sending end transmitted power was set at 1000 MW with the local load remaining at 500 MW. Compensators with ratings of 0 to 500 MVAR capacitive were modeled at Buses 1 and 2. Note the reactive power output of the compensators during the voltage dips associated with angular swings of the generator. Note also that the compensators reach the capacitive limit of their control range during the voltage depressions.

For perspective, an approximate transient power angle curve for the above-mentioned circuit condition is illustrated in Figure 16. This curve is contrasted to the corresponding curves for the two- and three-line circuits without compensators. Since the effects on transmitted power (P_S) are of most interest, the calculations for the curves were based upon the assumptions of no local load and a 1000 MVA fixed generation capacity. These curves were calculated for the post-fault circuit condition, with the generation modeled as a constant voltage behind transient reactance. The discontinuity on the curve for the condition with SVS is the point at which the compensators reach the end of their control range and become essentially fixed capacitors for the lower voltages associated with larger angles.

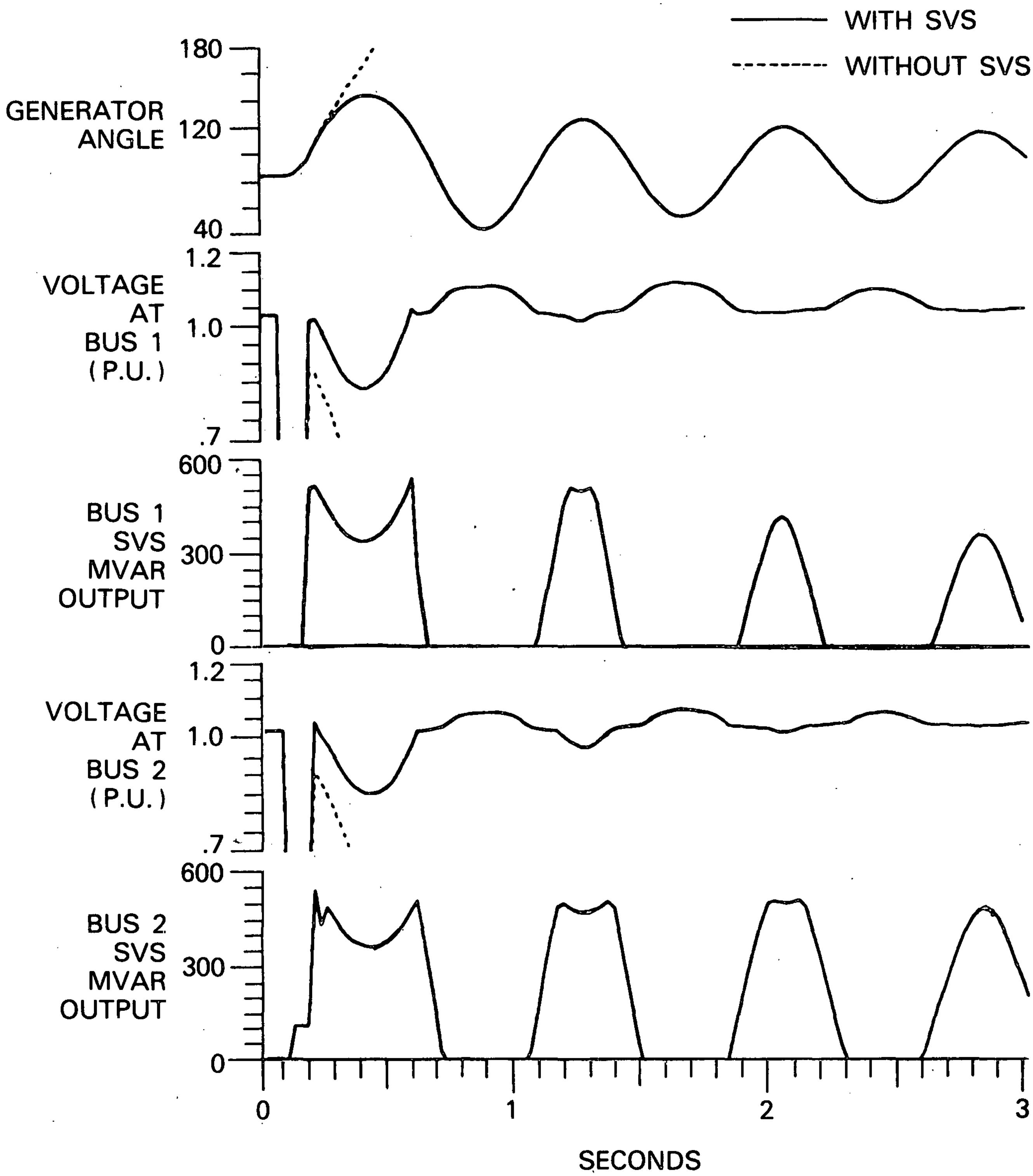


Figure 15 Time Domain Behavior of the System With and Without SVS

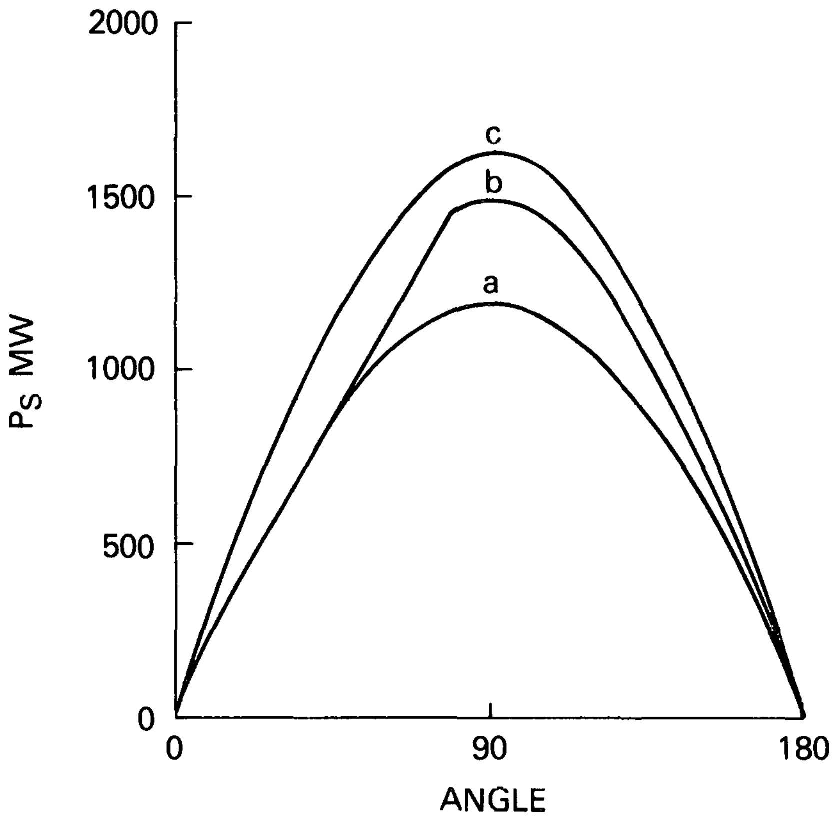


Figure 16 Post-Fault Power Angle Curves for the System of Example 1 With:
a) 2 lines with no SVS
b) 2 lines with SVS
c) 3 lines with no SVS

Additional dynamic simulations were also performed to investigate the effect that other SVS parameters may have on the SVS rating required to achieve transient stability for specific power levels. In all previously discussed simulations, the compensators were modeled with a control gain of 100 (total control range voltage droop of 1%) and a single lag time constant of 33 ms. Two variations from this were investigated and the results are shown in Figure 17. One variation was a reduction in control gain to 20 (total control range voltage droop of 5%). This reduction caused a slight increase in the capacitive rating of the compensator(s) required to achieve transient system stability at a specific power level.

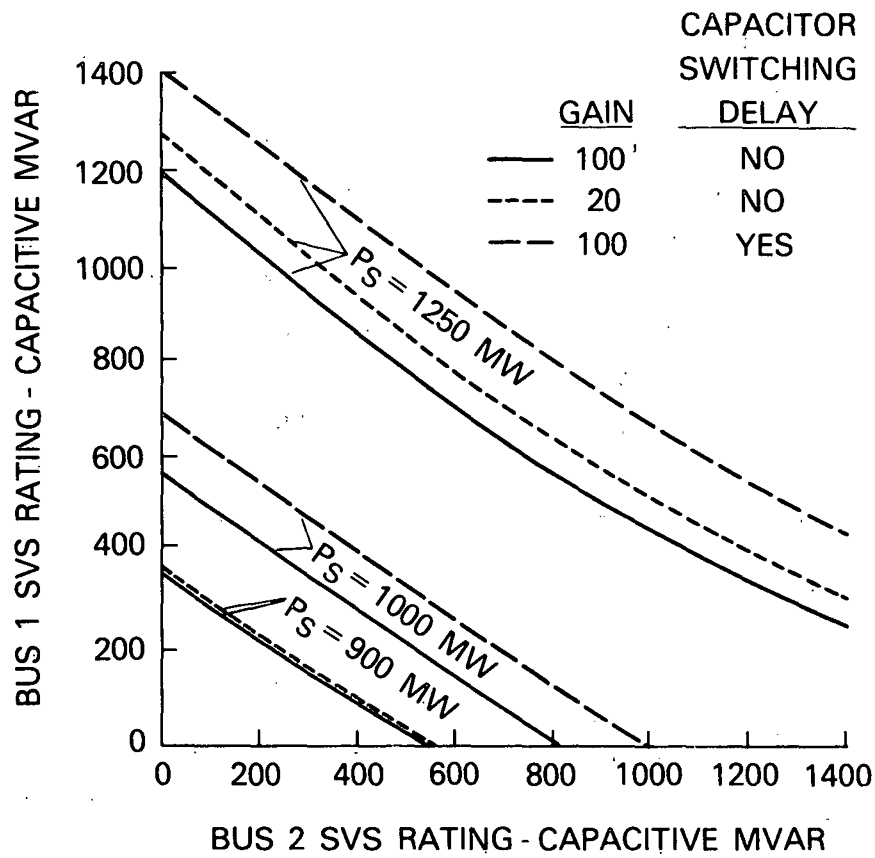


Figure 17 Effect of SVS Gain and Delay on SVS Ratings Required for Various Prefault Power Levels, P_S

The second variation considered was a delay in the availability of reactive power output from the SVS after the fault was cleared. It is during the subsequent angular swing and associated voltage depression that SVS output is most important in achieving first-swing system stability. The compensator capacitors were connected in three cycles (50 ms) after fault clearing. Such a delay might be associated with the SVS approach discussed earlier, in which the capacitors are switched using mechanical switches. As is shown in Figure 17, this 50 ms capacitor switching time required a 20% increase in the capacitive rating of the compensators to maintain transient stability for the specific power levels examined in the simulation.

An additional consideration in the required ratings for SVS is the line-connected shunt reactors. The circuit of Figure 13, as modeled, included 81 MVAR shunt reactors permanently connected to each end of each line section, to achieve 60% compensation of the line capacitance as might traditionally be done for such a circuit. These reactors were modeled in all cases, whether compensators were present or not, to avoid the introduction of an additional variable. In practice, the location, rating, and philosophy of switching shunt reactors should be coordinated with the application of compensators. For the circuit studied, such coordination might result in a reduction of the required capacitive MVAR rating for the SVS.

Increase critical fault clearing time - Example 2. Another investigation of transient stability was performed on the 345 kV system shown in Figure 18. In this example the first swing stability enhancement of the system achieved by a SVS at Bus 2 was quantified in terms of increased critical clearing time. Zero impedance, three-phase faults at either locations A or B were the system disturbances. In all cases, the rating of the generation, the rating of the generator step-up transformers, and prefault load flow (1200 MW) were held constant.

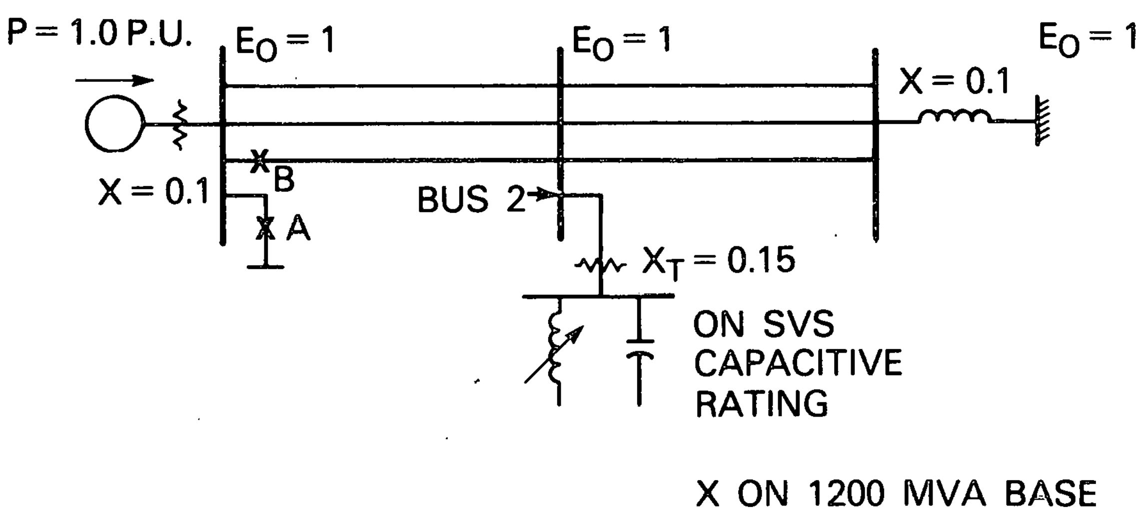


Figure 18 345 kV System Studied in Example 2

The effect of compensator capacitive rating on the critical clearing time for a fault at A is shown in Figure 19 for various lengths for the total transmission circuit. For convenience, the faulted line was assumed to be unloaded. The curves show a definite increase in allowable fault clearing time with increased compensator capacitive rating. Fixed high-voltage shunt reactors, normally used to compensate for line charging, were neglected in these studies.

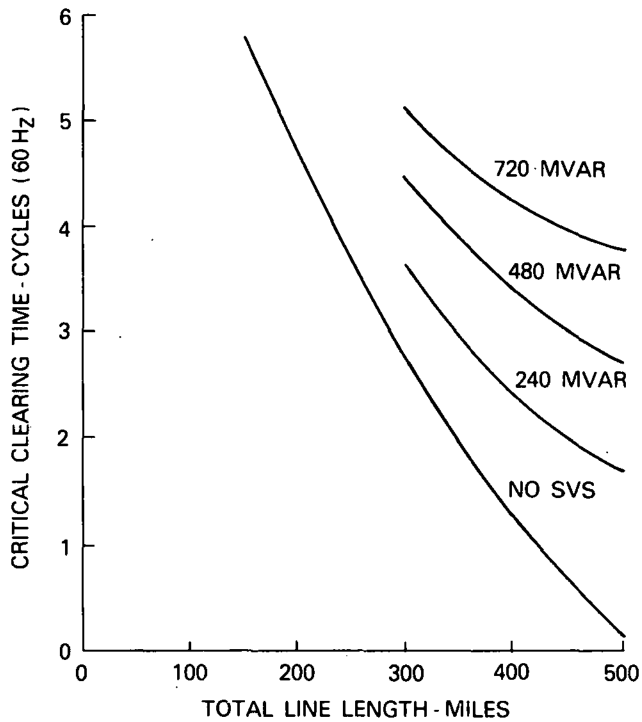


Figure 19 Effect of SVS Capacitive MVAR Rating on Critical Clearing Time for Various Total Line Lengths - Fault at A

The results for a fault at B are shown in Figure 20. Here again, the results show a significant increase in critical clearing time through the use of an SVS. Appendix B of this report contains a discussion of how an SVS can improve transient stability using the familiar equal-area criterion commonly found in text books on power system stability.

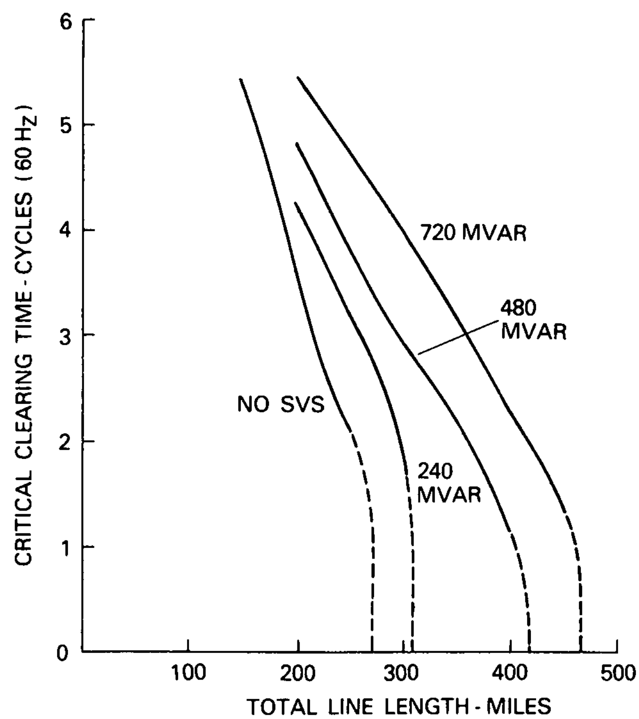


Figure 20 Effect of SVS Capacitive MVAR Rating on Critical Clearing Time for Various Total Line Lengths - Fault at B

2.4.3 Prevention of Voltage Instability or Voltage Collapse

The benefit of a static var system for preventing this form of instability is best covered by example.

The objective of this example was to illustrate that static var systems can be applied to avoid the system problem of sudden voltage collapse. A necessary prerequisite to accomplishing this was to define a representative system that would exhibit the voltage collapse phenomenon in the absence of dynamic voltage support. The system selected for this purpose is shown in Figure 21. The system represents a load area with local generation available to serve only a portion of the load. The load area is thereby dependent on the importation of power over a transmission system. For the investigation, the disturbance chosen was to trip one of the 60 MW generators (opening of breaker A). At the time of this disturbance, the only transmission interconnection in service to the rest of the power system was assumed to be a single 138 kV line.

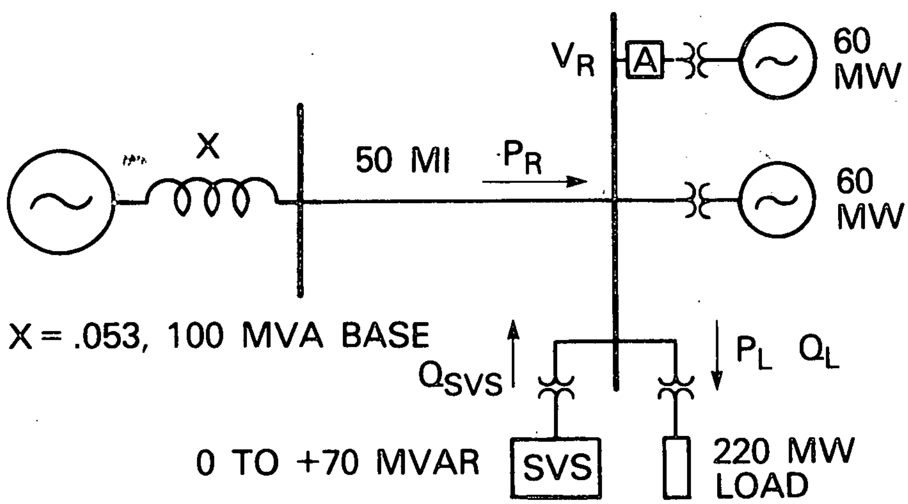


Figure 21 138 kV System Studied in Example 3

Proper modeling of the load proved to be important in the simulation of the voltage collapse phenomenon. The 220 MW load selected consisted of 160 MW of induction motors, with the balance evenly split between constant current and fixed impedance load types. The induction motor load was modeled in detail, including its inertia. Initially, in steady state the reactive power requirement of the motor load was 77 MVAR, which was compensated to unity power factor with a fixed shunt capacitor (not part of the SVS). The other load types were assumed to have no reactive power requirements.

Prior to the disturbance, the local generators were operating at rated MVA and were supplying reactive power to the transmission line in order to maintain 1 p.u. voltage at the receiving-end bus. The local generators were modeled with high-initial-response exciters. The SVS was assumed to be operating initially at zero net MVAR. It was modeled with a gain of 100 (1% voltage slope) and a single time constant of .033 seconds.

The investigations were made using a digital power system stability program.[3] The time domain responses illustrating the effect of the tripping of one of the local generators with and without the SVS is shown in Figure 22. These show that without the SVS, the loss of one local generator precipitates a sudden voltage collapse and stalling of the induction motors. However, with the SVS this collapse is avoided.

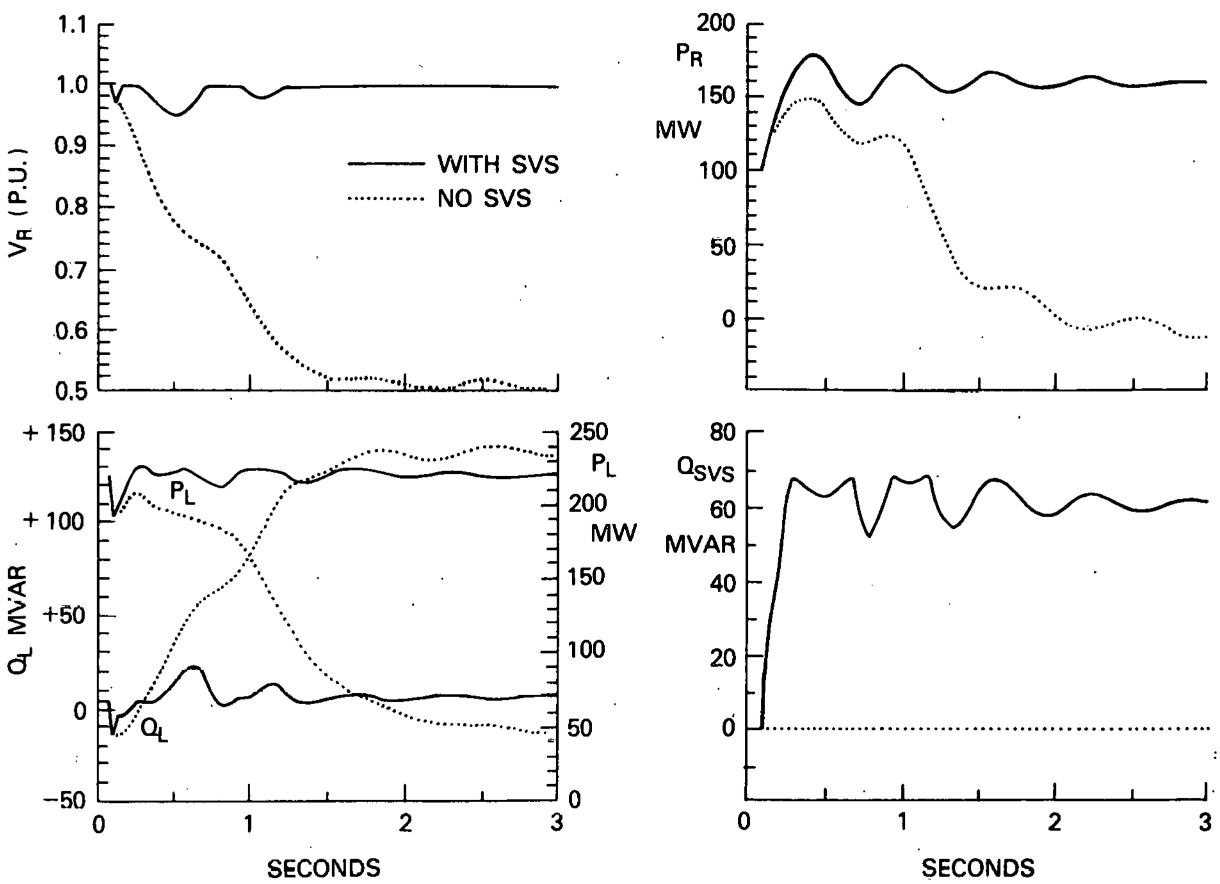


Figure 22 Response of System of Example 3 to Local Generator Trip, With and Without SVS

The reasons for the voltage collapse can be understood in the context of the quasi-steady-state receiving end voltage - versus - power characteristics [6] for the infeeding transmission circuit shown in Figure 23. Each individual curve in the figure is for a specific reactive power condition at the receiving end. The curves are plotted for fixed shunt capacitors or shunt reactors in increments of 25 MVAR (nominal voltage base). As can be seen, such production or absorption can greatly increase or decrease the maximum power limit. As a result, in the time simulation, the reactive power behavior of the load and presence of the SVS are crucial to the final outcome. An important aspect of the load behavior is its voltage versus active power characteristic. The importance of this behavior led to the decision to represent the induction motor load in detail rather than as simply a P, Q load model.

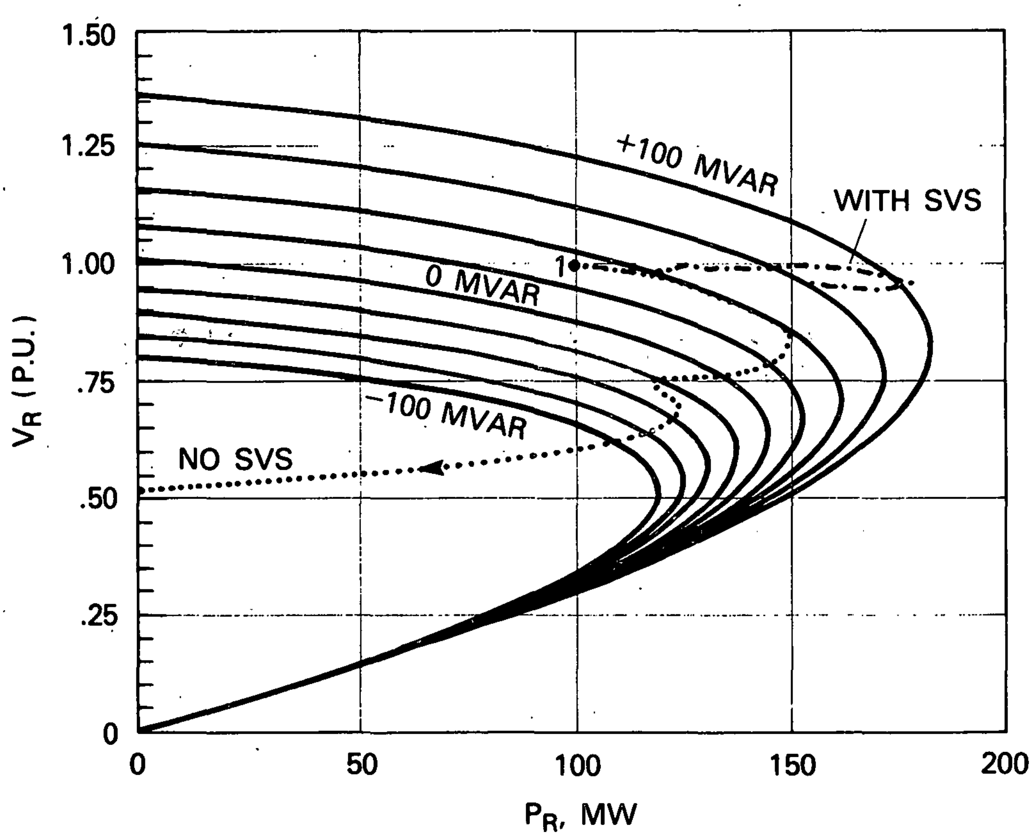


Figure 23 Receiving End Voltage - Power Characteristics

Superimposed on the family of curves of Figure 23 are the trajectories of the system response starting at point 1 for the first 3.0 seconds following generator trip, with and without SVS. It is obvious that the SVS provides the reactive power necessary (some is also provided by the remaining generator) to allow the required increase in imported power required and avoid voltage collapse.

2.4.4 Preventing Dynamic (Oscillatory) Instability

Steady-state instability can result in one of two ways. First, the voltages on the transmission network could decrease slowly due to increased load or wheeling of power, to a point where the transmission network's capability to accommodate the transfer simply drops below a certain critical level. At that time, the steady-state angular separation between machines increases beyond a stable equilibrium and the machines pull out of step (lose synchronism). This problem was addressed earlier under 2.4.1 of this section.

The second way a system can become unstable while in a quasi-steady-state condition is through growing power and angular swings. To assist in preventing first-swing or transient instability, generators are often equipped with high-response excitation systems. The "high gain" exciter is acting through a relatively large generator field time constant in its attempt to control the generator terminal voltage.

As with any control loop with high gain and sizeable time constants, the possibility of loop instability exists. Worst yet, with power systems, the generator's voltage regulator control loop can be stable while the combined effect with the power system can actually lead to growing oscillations. This is referred to as "contributing negative damping."

Any power system that has a characteristically low frequency oscillatory mode, 0.5 to 1 oscillations (cycle) per second, may be vulnerable to the high-gain exciter-induced negative damping effects, particularly for heavy transmission system loading.

To counteract the negative damping influences from the aforementioned characteristics, supplementary stabilizing controls are sometimes added to machine excitation systems. These controls deliberately modulate the input to the generator's voltage regulator, based on the rate of change of the angle δ_1 (defined in Figure 6), and thereby add a measure of anticipatory control action to damp out the power and angular swings.

A similar supplementary power system stabilizer can be utilized with an SVS to consciously add damping to the power swings. In principle, the SVS controls voltage in response to voltage error only, and is thought to enhance only the synchronizing capability. However, by providing a large portion of the system's voltage control needs, the SVS action can reduce the contribution of the destabilizing influence (negative damping) from the high-gain generator exciter action. In effect, the SVS appears to contribute positive damping even though that is not the intended purpose. The addition of auxiliary input signals to the SVS voltage regulator can, through deliberate design, increase the damping of synchronizing power swings.

The comparison in Figure 24 shows that damping of the angular swings can be improved by feeding a properly conditioned signal derived from power flow on the line to the SVS voltage regulator. Notice that the voltage control was compromised slightly in order to add positive damping to the power-angle swings. This compromise is necessary if stability enhancement is of primary importance.

Switched capacitors, SVS or any other form of switchable voltage support can help prevent the first kind

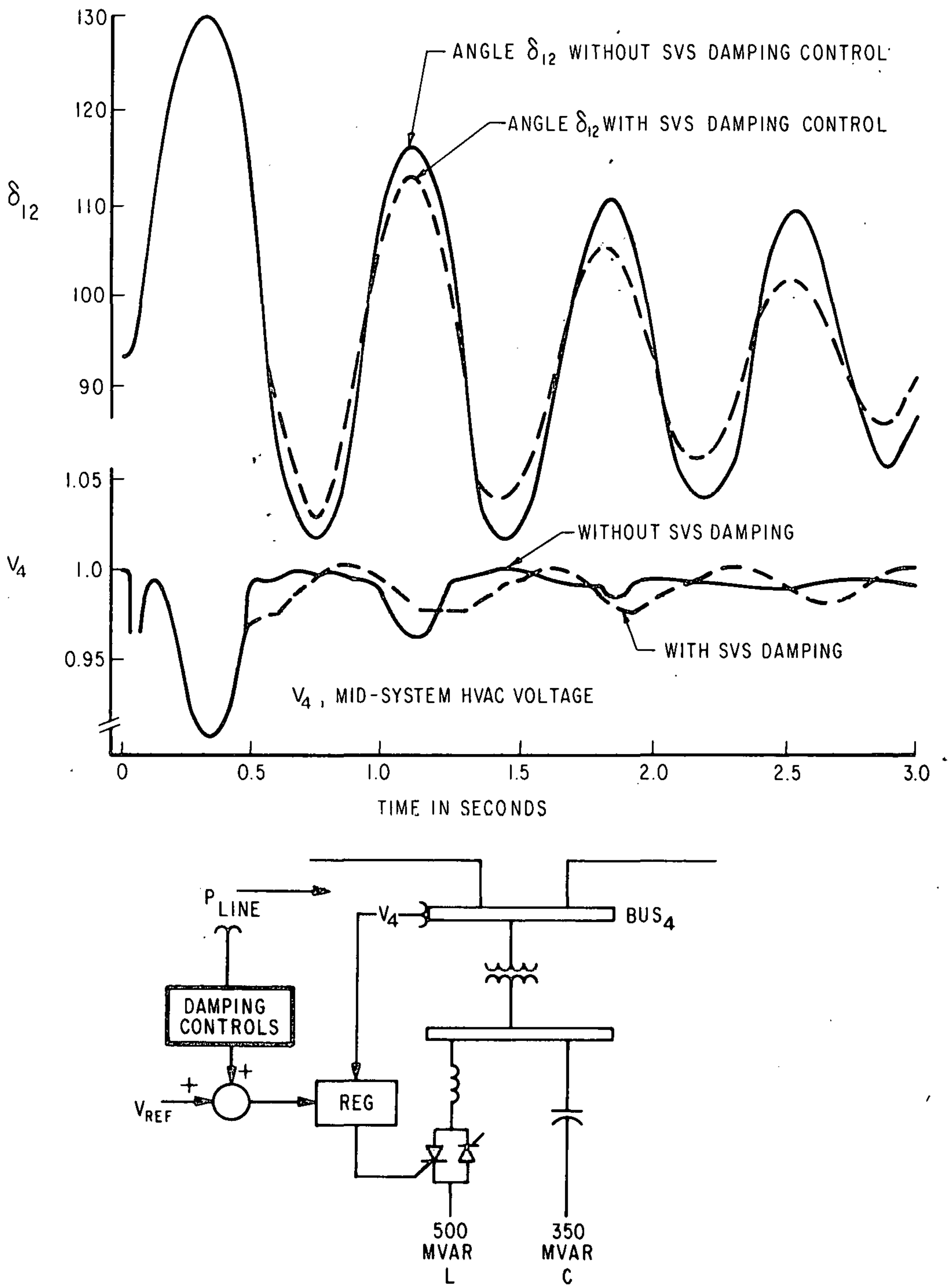


Figure 24 Damping Power (Angle) Swings With Special SVS Damping Controls

of steady state stability discussed in section 2.4.1. However, this latter protection against control-induced instability is more effectively accomplished with continuous control action over a voltage/var range dictated by the specific system's needs. This need would be most common in systems involving long lines, such as in the Western U.S.

2.4.5 Preventing Instability of Subsynchronous Oscillations

This problem is associated with the possible interaction between series compensated transmission systems and steam-turbine shaft (torsional) motions at or near torsional shaft resonant frequencies. These oscillations commonly occur in the 8 to 45 Hz range and can grow to such levels that fatigue life is removed from shaft sections, resulting in ultimate failure of the shaft.

It has been shown by other researchers [7] that an SVS located on the low-voltage terminals of a generator step-up transformer, which responds to changes in shaft speed (on a specific shaft section) rather than voltage can provide a measure of damping of the subsynchronous oscillations.

Since this is not an HVAC application, per se, it is beyond the scope of this report.

2.5 SUMMARY

This section has addressed the basic needs for compensation in HVAC systems and where the role of the static var system in satisfying those needs. The next section compares the various static var systems or static reactive power controllers available today.

Section 3

A COMPARISON OF STATIC VAR SYSTEMS

Several approaches or types of static reactive power compensation (static var) systems have emerged in recent years. In this section, the basic types or configurations are first defined, after which their respective operating principles are discussed. The functional performance of each type is described in terms of the fundamental-frequency voltages and currents. Finally, the salient performance characteristics of the types are summarized and compared with respect to certain key criteria.

3.1 THE BASIC TYPES OF SVS

Commercially available static var systems contain shunt connected reactors and/or capacitors and some control means to regulate voltage. There are three basic types of reactive power control devices which make up all or part of any given static var system.

Those basic "controlled elements" are:

- Thyristor-controlled reactor (TCR)
- Thyristor-switched capacitors (TSC)
- AC saturable reactor (SR)

A fourth type of SVS is based on frequency converter principles [8,9]. That type is only in the conceptual phase at this time.

Where an automatically controlled inductor is required for limiting overvoltages, the saturable reactor (SR) or thyristor-controlled reactor (TCR) may be applied without a parallel capacitor bank. Usually, however, a parallel shunt capacitor bank is used with an SR or TCR to provide reactive power production, as well as var absorption.

The thyristor-switched capacitor (TSC) has been applied as a complete static var system, but where more discriminating voltage regulation is required, a hybrid combination of the TCR and switched capacitors has been formed to produce a "complete" static var system. Further novel derivatives of the basic forms listed above have resulted in the

- Thyristor-Controlled Transformer (TCT)
- Thyristor-Controlled Saturated Reactor (TCSR)

types of static var system.

Combining one or more of the basic types with fixed capacitor (FC) banks or mechanically switched capacitors (MSC) yields the following partial list of <u>technically feasible</u> static reactive power control shown in Table 3-1.

Table 3-1

TECHNICALLY FEASIBLE SVS TYPES

Type	Legend	
1. TCR/FC	TCR -	Thyristor controlled reactor
2. TCT/FC	TCT -	Thyristor controlled transformer
3. TCR/MSC	TSC -	Thyristor switched capacitor
4. TCT/MSC	MSC -	Mechanically switched capacitor
5. TCR/TSC	FC -	Fixed* capacitor
6. TSC	SR -	Saturable (ac) reactor
7. SR	TCSR -	Thyristor-controlled saturable reactor
8. SR/FC		
9. SR/MSC	DCCSR -	DC controlled saturating reactor
10. DCCSR/FC		
11. TCSR/MSC		
12. TCSR/TSC		

* Fixed means not switched via local automatic voltage control.

Electrically, a complete static var system includes capacitors and inductors, both of which may be adjustable as depicted schematically in Figure 25. All but the last (FCP) type SVS listed in Table 3-1 are practical configurations based on Figure 25. More descriptive schematics are given in Figure 26:

Type	Figure
TCR-FC	(26a)
TCT-FC	(26b)
TCR-MSC	(26c)
TCR-TSC	(26d)
SR-FC	(26e)
DCCSR-FC	(26f)

Schematics of the other types listed earlier can be visualized as parts or combinations of those shown in Figure 26.

The next section discusses the operating principles of the basic elements of static var systems in Table 3-1.

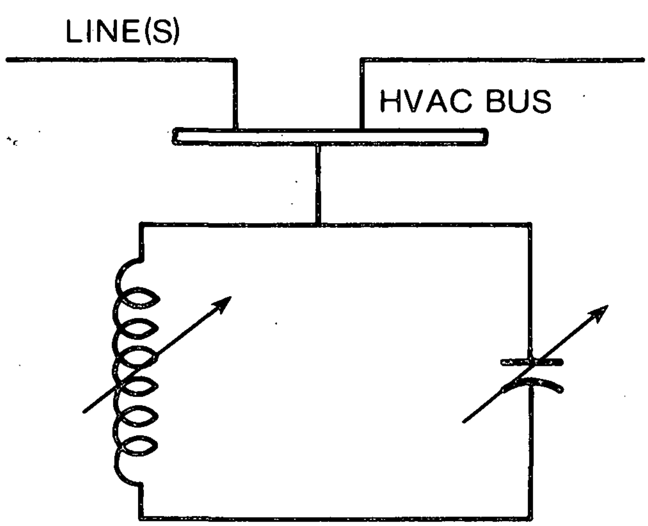


Figure 25. Idealized Static Var System

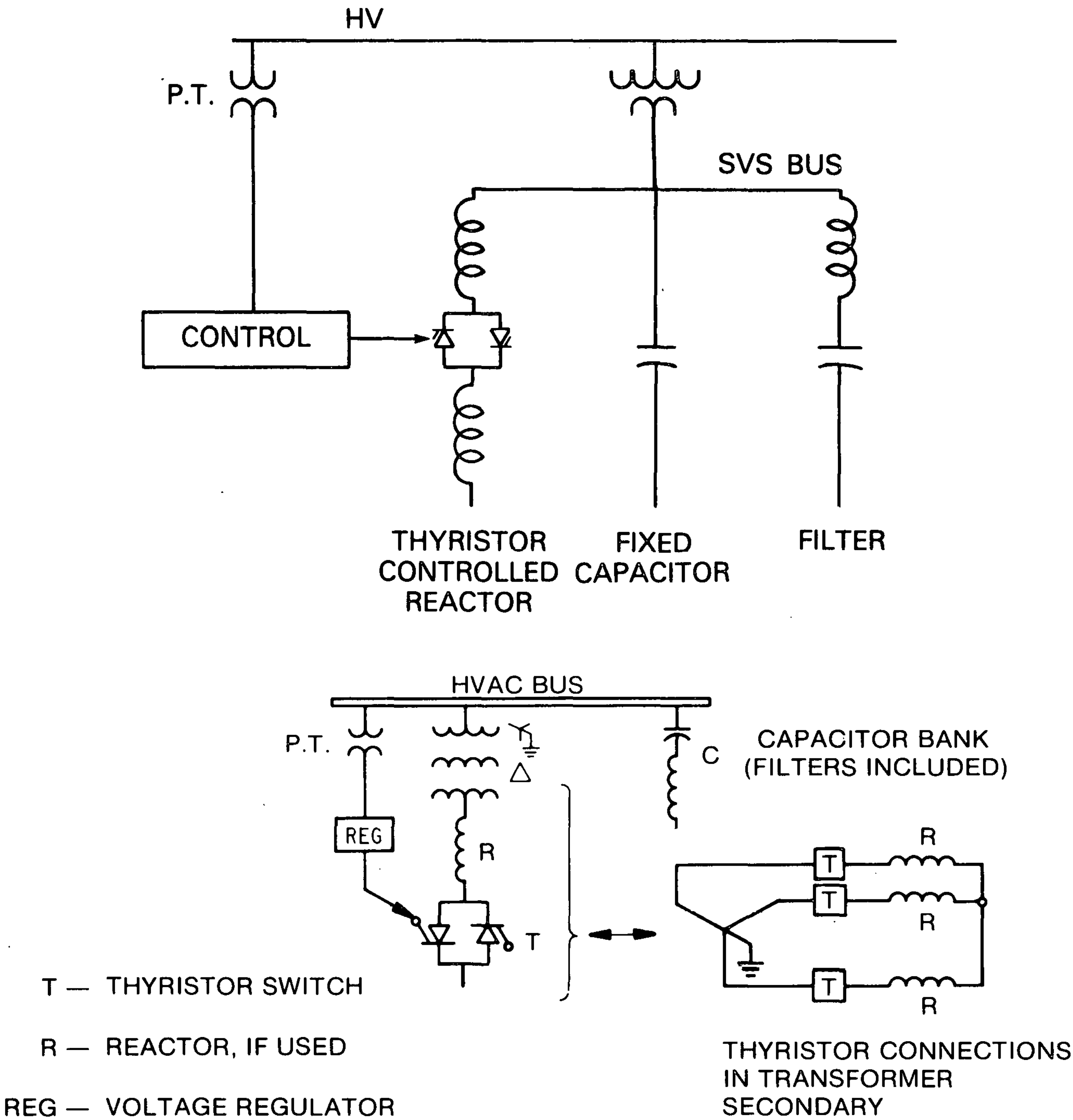


Figure 26. Practical SVS Configurations
a) Basic Circuit for Thyristor Controlled Reactor - Fixed Capacitor Approach (TCR-FC)
b) Thyristor-Controlled-Transformer SVS with Fixed Capacitor (TCT-FC)

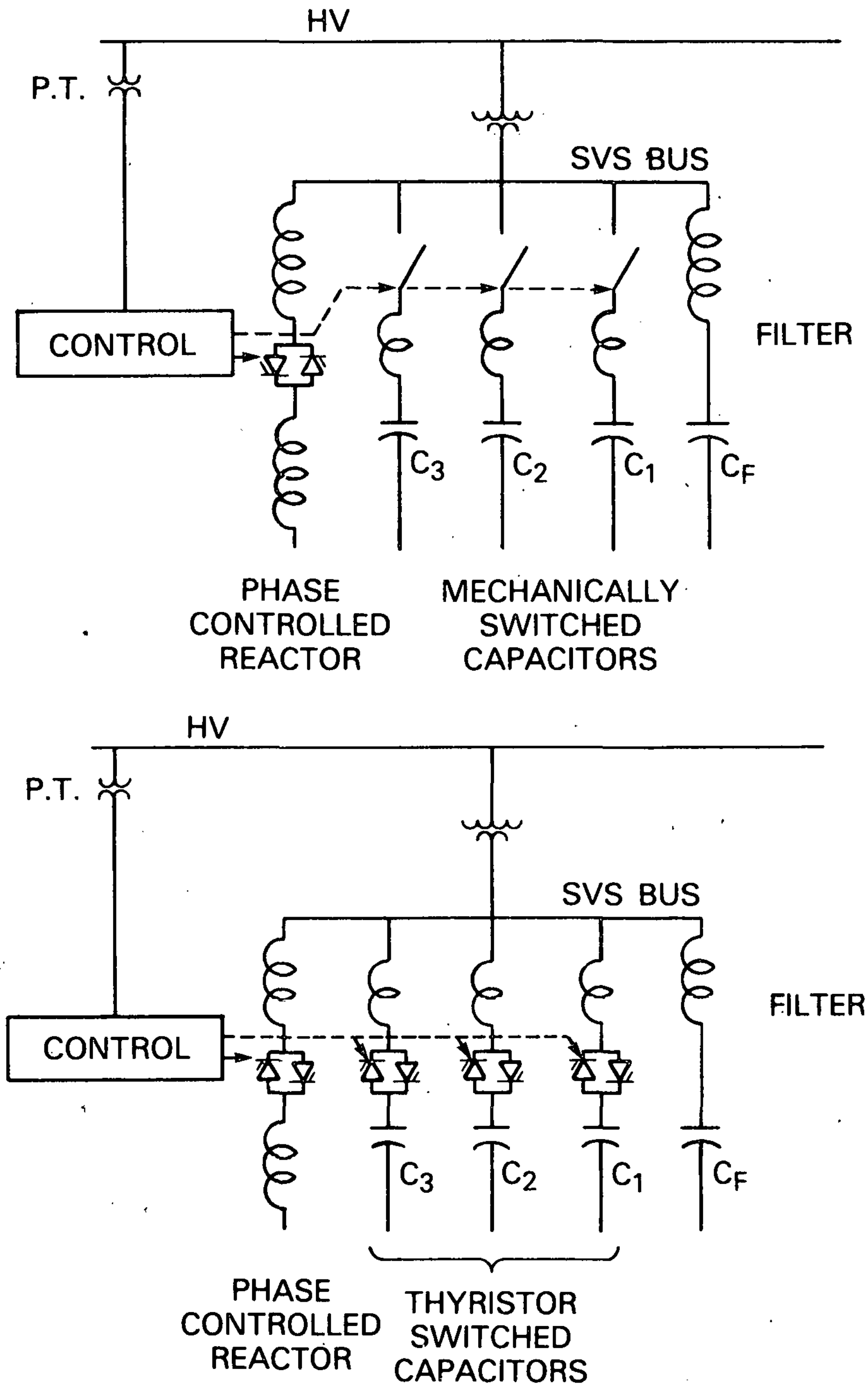
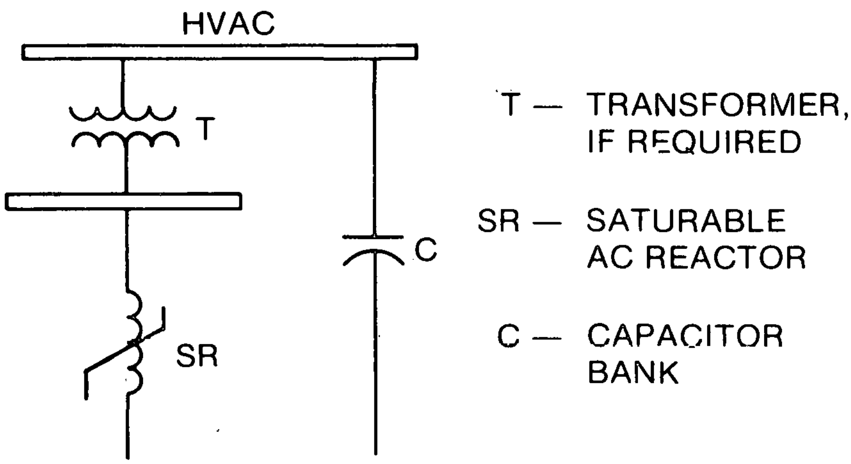


Figure 26. Practical SVS Configurations (Cont'd)
c) Basic Circuit for Thyristor Controlled Reactor - Mechanically Switched Capacitor Approach (TCR-MSC)
d) Basic Circuit for Thyristor Controlled Reactor - Thyristor Switched Capacitor Approach (TCR-TSC)



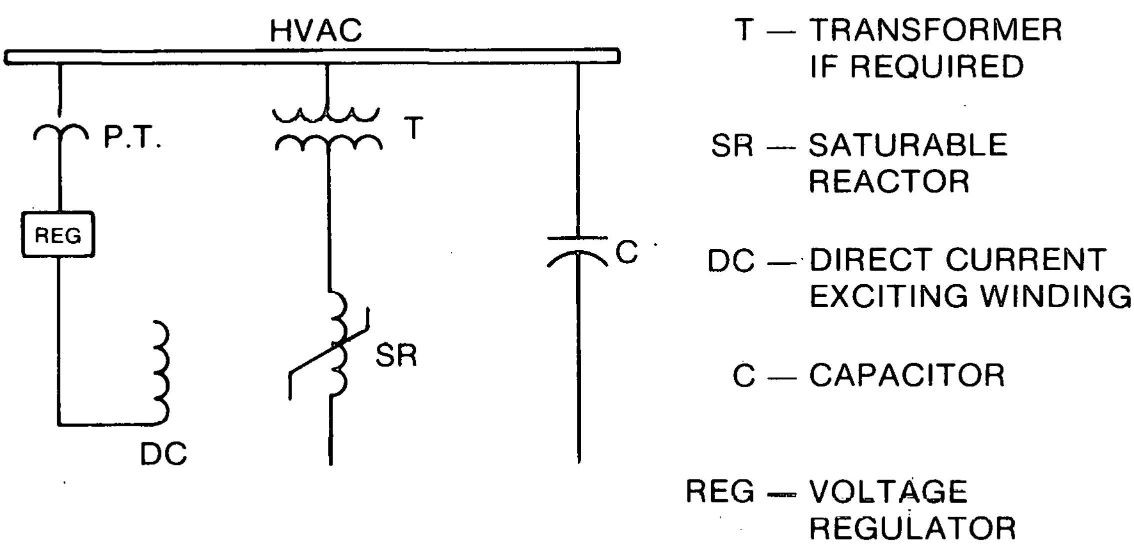


Figure 26. Practical SVS Configurations (Cont'd)
e) Basic Schematic of Self-Saturating Iron Core AC Reactor Type SVS (SR-FC)
f) Basic Schematic of DC-Controlled Saturating Reactor Type SVS

3.2 OPERATING PRINCIPLES OF KEY SVS ELEMENTS

This section describes the basic operating principles of those elements of complete static var systems that provide the local automatic adjustment of reactive power supplied to or absorbed from the HVAC system. In all cases, the controlled portion of the SVS adjusts the fundamental component of reactive current drawn by the device in such a way as to cause the desired adjustment in the voltage supplying that current.

This section is intentionally detailed and the reader can skip to Section 3.3, Fundamental Frequency Performance, if great detail is not desired. That later section (3.3) is more or less independent of the detailed operating information in this section.

The SVS elements to be described are: TCR, TCT, TSC, MSC, SR, and Frequency Converter. The first four operate utilizing the adjustable susceptance principle, so that principle will be described first.

3.2.1 The Adjustable Susceptance Principle

A constant ac voltage can be maintained at the terminals of a controlled susceptance if that susceptance is controlled to absorb or generate precisely the reactive power required to keep the ac voltage constant. A control system is necessary to cause the requisite changes in susceptance, and this may be either open-loop or closed-loop.

The controlled susceptance is always an actual reactor, a transformer, a bank of capacitors, or a mixture of these. Adjustment (or modulation) of the susceptance is affected by either of two principles:

- phase control
- integral-cycle control.

Phase control means that the susceptance is switched into the system for a controllable fraction of every half-cycle. Integral-cycle control means that the susceptance is divided into several parallel units, each of which is always switched in for an integral number of exact half-cycles. The susceptance is varied by controlling the number of units in conduction. A change can be made every cycle, and in some designs, every half-cycle.

The principles of phase control and integral-cycle control are summarized in Figure 27. The control action is achieved by switches; mechanical switches in the case of the MSC, while for the TCR and TSC, thyristors are used because of their timing precision and virtually unlimited switching life.

Phase control is the mode used for a controlled reactor, while integral-cycle control is utilized for a capacitor. Accordingly, the main commercial examples of adjustable-susceptance type SVS that use thyristors are the so-called Thyristor Controlled Reactor (TCR) and the Thyristor Switched Capacitor (TSC). Related to the TCR is the phase-controlled transformer (TCT), in which the reactor is replaced by the leakage reactance of a step-down transformer. Phase control of the capacitor current is not practical because of the charging transients set into motion each time voltage is applied to a capacitor.

3.2.2 The Thyristor-Controlled Reactor Compensator (TCR)

The TCR operates on the phase-controlled, adjustable-susceptance principle. It requires an electronic control system, and it is natural to think of this as having an outer part, which translates the power system's requirements into a desired susceptance signal, and an inner part, which controls the switching of the thyristors to produce the effective desired susceptance. The outer

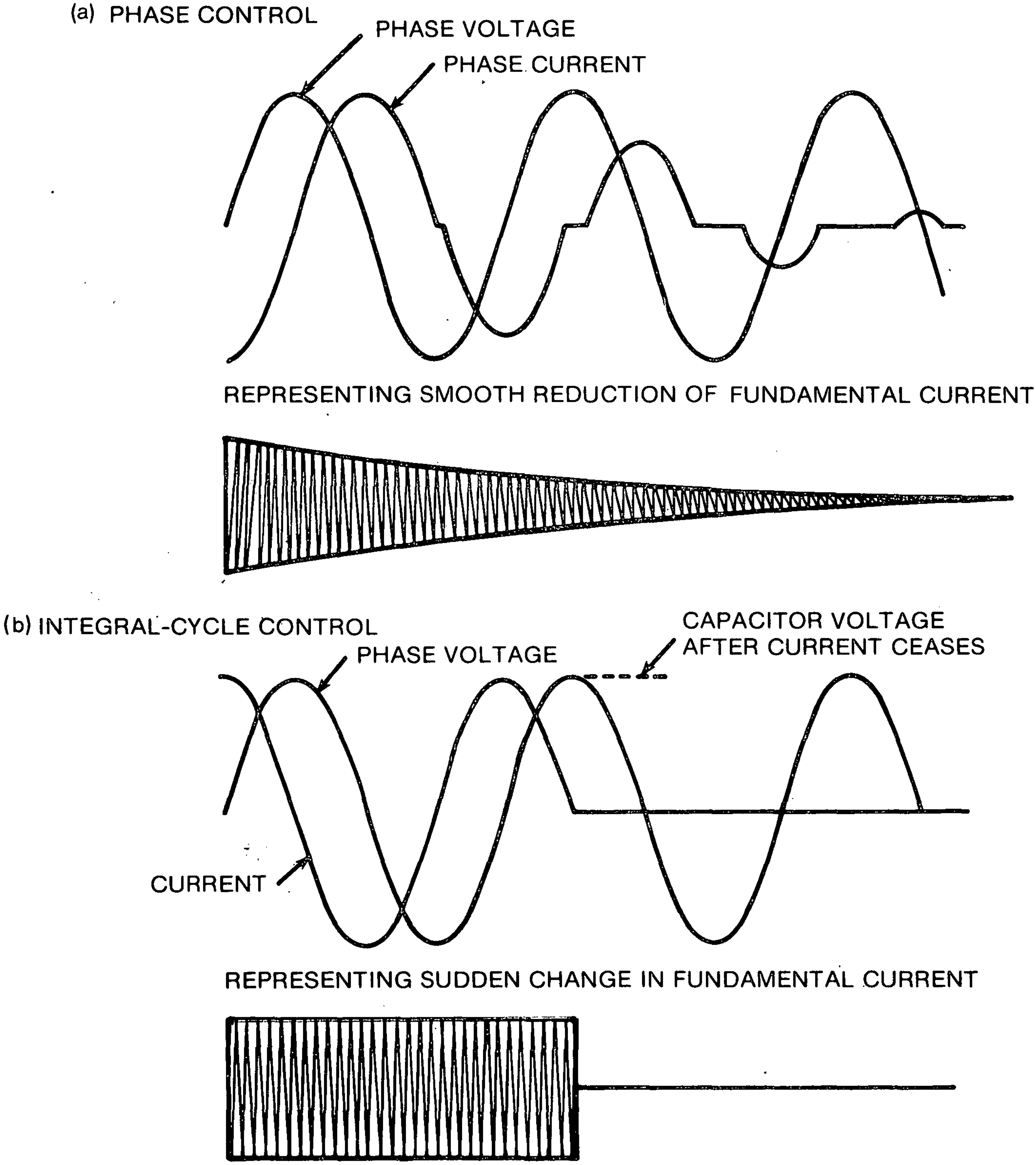


Figure 27. Principles of Phase Control and Integral-Cycle Control Showing the Difference Between Smooth and Stepped Response

control system can include many features in common with ordinary automatic voltage regulators (AVRs) on generators and synchronous condensers, as well as provision for supplementary special-purpose signals.

The simplest form of TCR is the single-phase circuit shown in Figure 28. A practical application of a TCR in a complete SVS (TCR-FC type) is shown in Figure 29, wherein three basic TCRs, as shown in Figure 28, are connected in delta. The delta circuit is used for both technical and economic reasons. Technically, it makes separate control of each TCR very simple so that the SVS can respond correctly to power system or load asymmetry. When balanced three phase control is used, the delta circuit provides a path for the triplen harmonics generated by the phase control action of the thyristor controller.

Economically, the delta circuit reduces the current ratings of the thyristor controller and reactors without proportionally changing the voltage and insulation requirements.

The line-to-line connection of reactor-thyristor controller-reactor is selected to isolate the thyristor controller from system fault capacity. A complete flashover of one reactor would result in only twice rated current. Current transformer and relays are provided in the delta branches to provide time and instantaneous overcurrent protection for the thyristor controller in the event of reactor failure.

Next, we shall determine how the firing angles of the thyristors must be controlled in order to get a prescribed <u>fundamental</u> harmonic component of current. If higher-order harmonic components are assumed to be perfectly filtered, the reactive power of one phase of the compensator can be thought of as the product of the line voltage and the fundamental component of phase current.

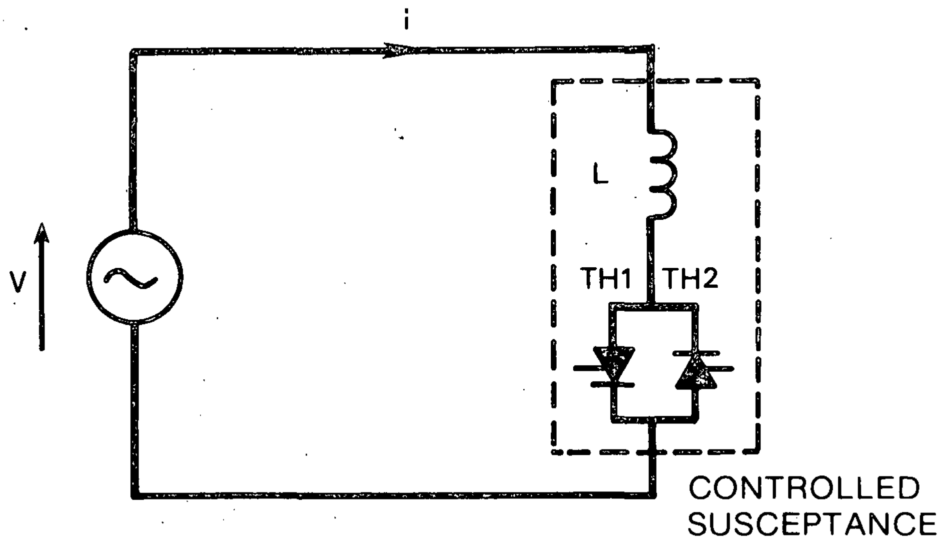


Figure 28. One Phase of Basic Phase-Controlled Reactor

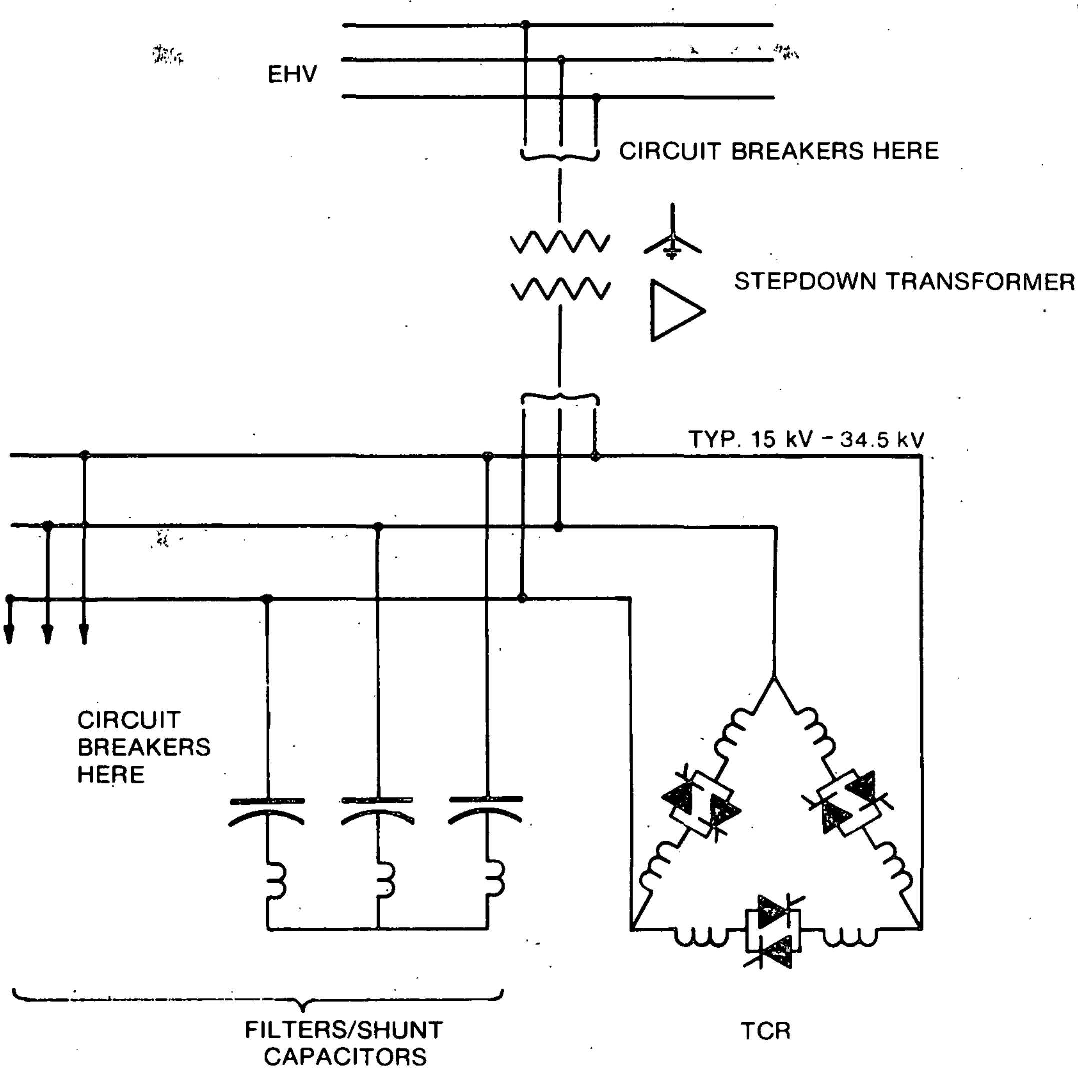


Figure 29. General Layout of Thyristor-Controlled Reactor Compensator With Shunt Capacitors

With balanced sinusoidal line voltages, the currents in each phase of the delta are as shown in Figure 30 for different firing angles, α, measured from a zero-crossing of the line voltage. If the conduction angle is σ, then the current can be expressed as

$$i = \frac{V}{\omega_0 L} \{\cos \alpha - \cos \omega_0 t\} \quad \text{for } \alpha < \omega_0 t < \alpha + \sigma$$

$$i = 0 \quad \text{for } \alpha + \sigma < \omega_0 t < \alpha + \pi$$

where the time origin is chosen to coincide with the positive-going zero crossing of the supply voltage, v, Figure 30. Fourier analysis of this current waveform gives the fundamental component,

$$I_1 = \frac{V}{X_L} \frac{\sigma - \sin \sigma}{\pi}$$

where I_1 and V are expressed as r.m.s. quantities. The relationship between conduction angle σ and fundamental current I_1 is shown in Figure 30. Figure 31 shows the fundamental current again along with the total harmonic current content at each conduction angle, σ.

One of the primary functions of the inner controls of the TCR is to determine the required conduction angle, σ, and from it the firing angle α, and to issue firing pulses to the appropriate thyristors. The input to the control may be I_1 itself, or the desired reactive power $Q=VI_1$, or the desired susceptance I_1/V. A great many analog or algorithmic circuits have been devised to generate the firing pulses. The principle of just one type is illustrated in Figure 32. At each voltage peak the trajectory labeled "prospective fundamental current" is initiated from a function-generator circuit. This

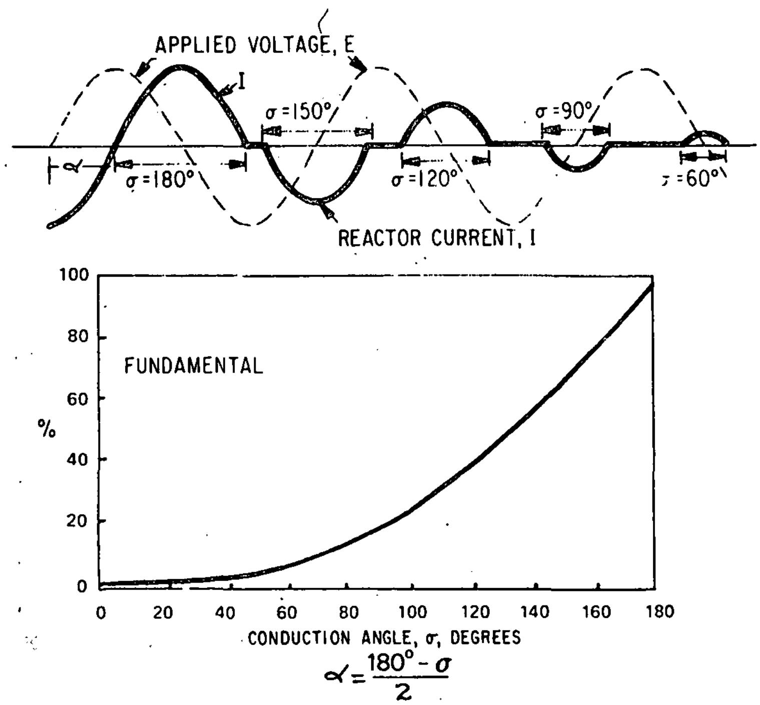


Figure 30. Phase-Controlled Reactor-Voltage and Current Waveforms of One Phase, σ is Conduction Angle

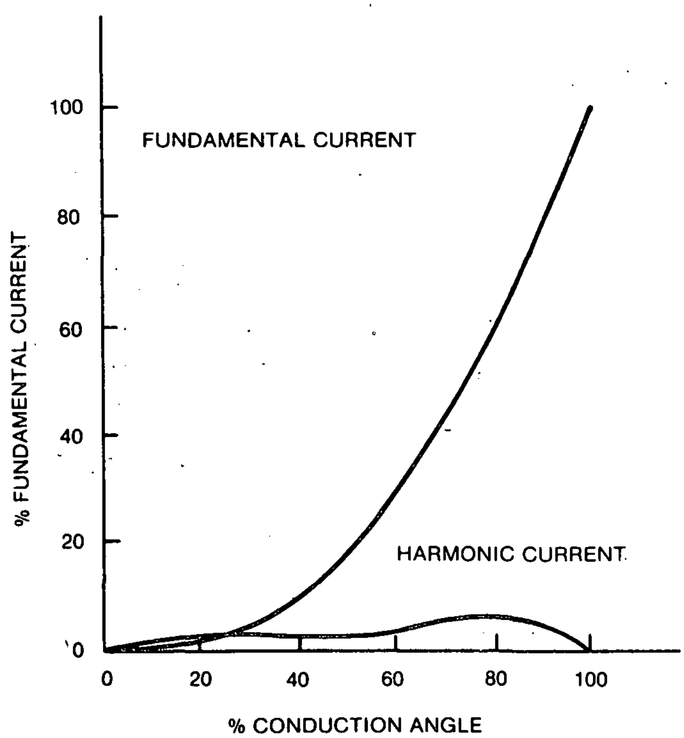


Figure 31. Fundamental and Harmonic Current vs Conduction Angle for Thyristor-Controlled Reactor

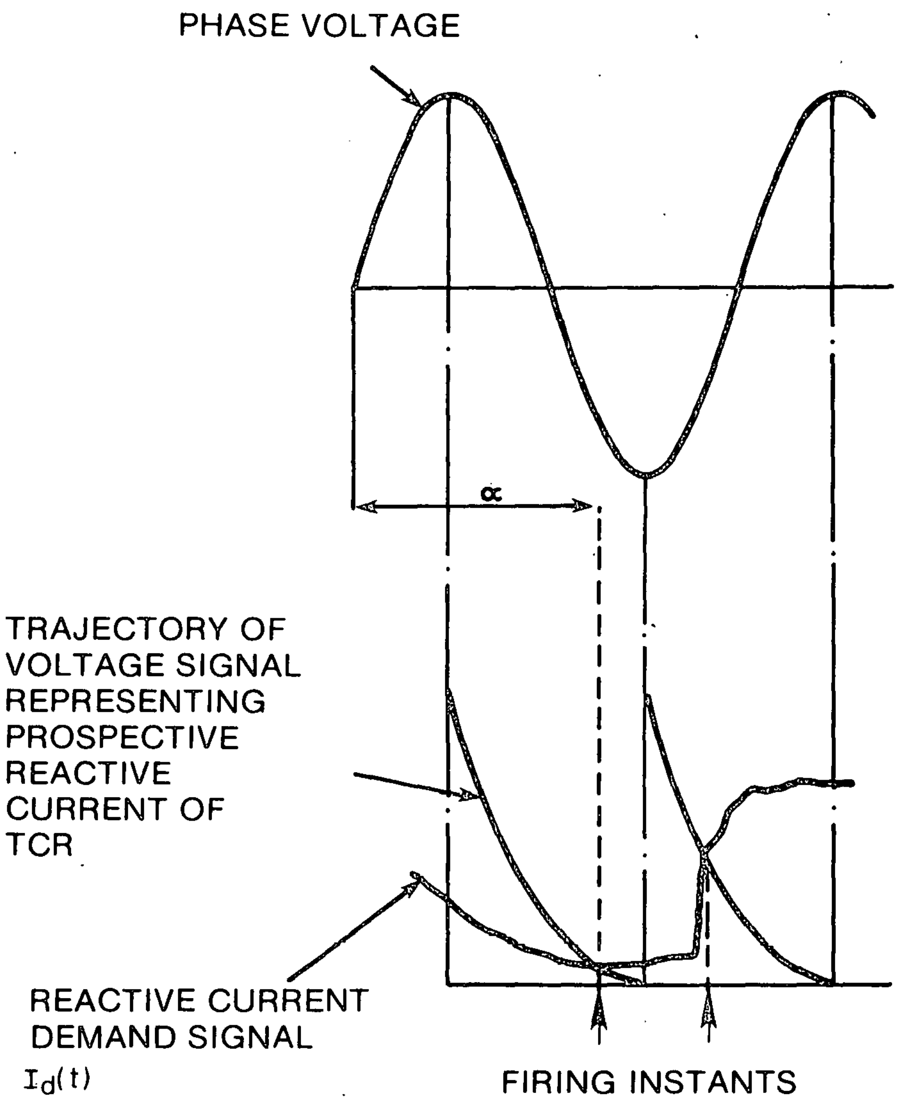


Figure 32. Principle of Determining Firing Instants in TCR

trajectory is defined by the equation for I_1 above, with α increasing linearly with time. The curve labeled $I_d(t)$ is a continuous signal representing the desired compensating current. A comparator detects the instant when the two trajectories cross, and causes a firing pulse to be issued to the appropriate thyristor. Logic circuitry may be used to determine which of the two oppositely poled thyristors in each phase should be fired.

The conduction angle σ in each direction must not exceed π radians (one half-cycle); otherwise, there could not be balance between the positive and negative conduction periods so that dc and even-order harmonic components would arise. Balance is also desirable to equalize the thermal duty of the oppositely poled thyristors, as well as for control stability reasons, and most TCRs have special control circuits designed to achieve this condition.

Harmonics and Power Filters. Figure 33 shows the phase and line current waveforms for a 120-degree conduction angle. Under balanced conditions, triplen harmonics are confined to the delta and do not appear in phase currents. The remaining odd-order harmonics combine and produce harmonics in the phase currents and it is common practice to filter them by means of parallel connected filters as shown in Figure 29. The maximum magnitudes of the characteristic harmonics in the phase current are shown in Figure 34 as percentages of the fundamental current at full conduction, σ = 180 degrees.

The degree of filtering and the tuned frequencies of the filters are very much determined by the frequency-response characteristics of the power system, looking into that system at the point of application. The TCR, together with its filter, must be designed to avoid intolerable current or voltage amplifications (resonances) with the power system.

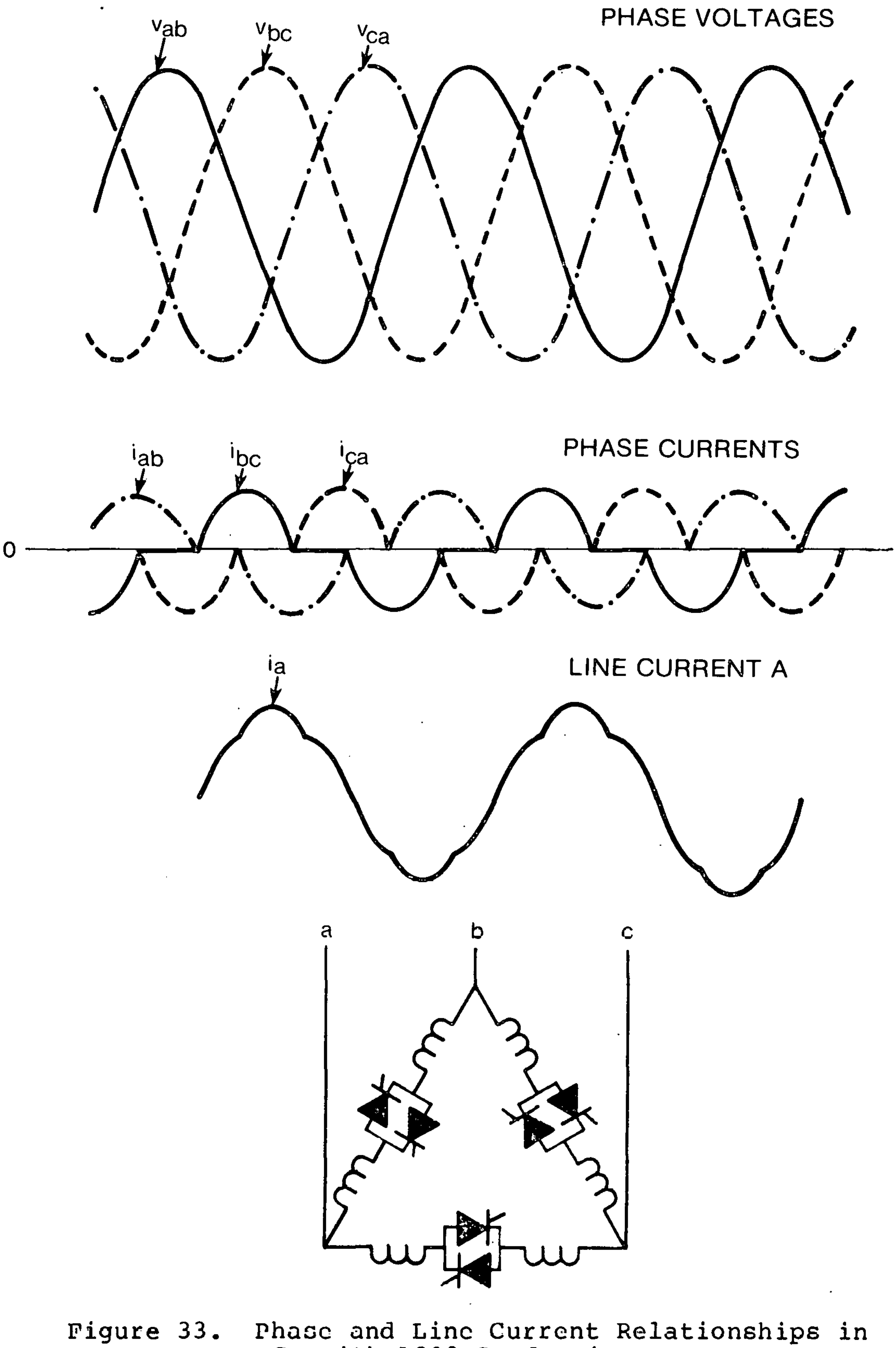


Figure 33. Phase and Line Current Relationships in TCR With 120° Conduction

Sometimes the TCR is split into two parts fed from two secondaries on the stepdown transformer, one being in wye and the other in delta, as shown in Figure 35. This produces a 30-degree phase shift between the voltages and currents of the two TCR's and virtually eliminates the 5th and 7th harmonics from the primary-side line current. This is known as a 12-pulse arrangement (because there are 12 thyristor firings every period). This phase-multiplication technique is the same as is used in rectifier transformers for harmonic cancellation, and has close affinities with the polyphase saturated reactor compensator of the frequency-multiplier type to be described later. With the 12 pulse scheme, the lowest-order characteristic harmonics are the 11th and 13th, and the maximum magnitudes are given in Table 3-2.

The 12-pulse arrangement can be used without filters for the 5th and 7th harmonics, which is an advantage when system resonances occur near these frequencies, especially when the TCR is intended to operate in the lagging (absorbing) regime all the time. The 12-pulse connection has the further advantage that if one half is faulted, the other may be able to continue to operate normally. The generation of positive and negative sequence third harmonic currents under unbalanced conditions is similar to that in the single 6-pulse (Figure 29) arrangement. Additional control circuits are necessary with the 12-pulse TCR to prevent unequal current-sharing between the thyristors, as a result of small differences in the firing angles.

With both 6-pulse and 12-pulse TCR compensators, the need for filters and their frequency responses must be evaluated with due regard to the possibility of unbalanced operation. The influence of other capacitor installations and sources of harmonic currents in the electrical neighborhood of the compensator must also be taken into

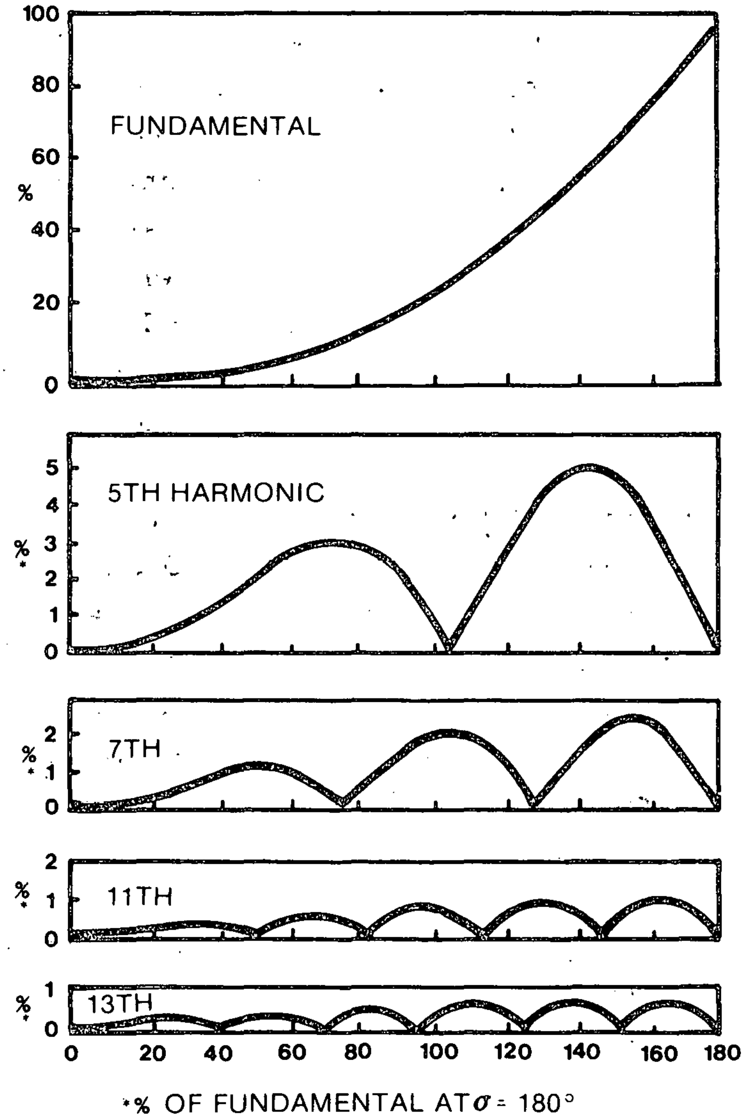


Figure 34. Harmonic Current Generated by a 3-Phase, Delta-Connected, Phase-Controlled Reactor vs Conduction Angle (σ) Degrees

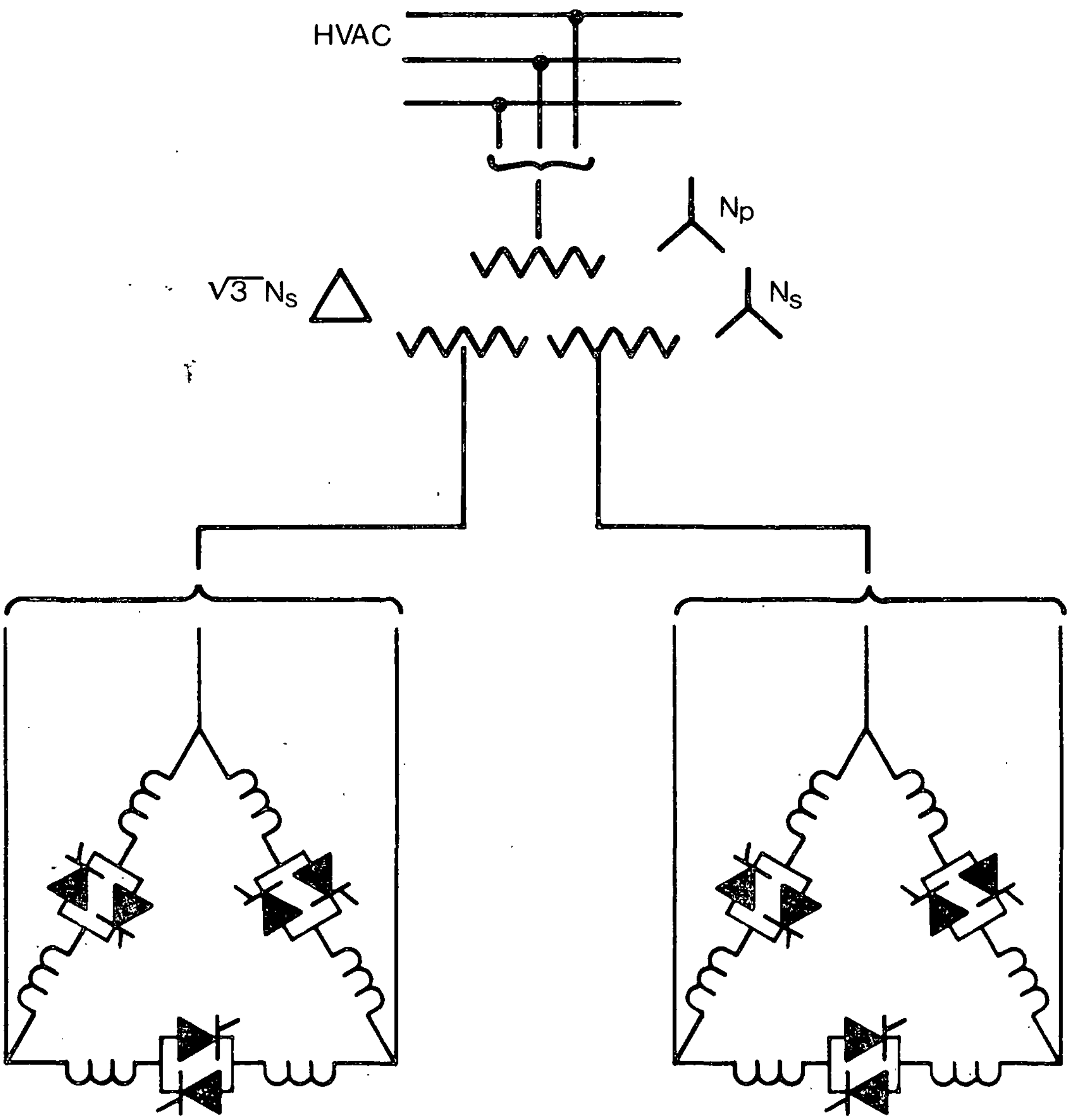


Figure 35. Arrangement of 12-Pulse TCR With Double-Secondary Transformer

Table 3-2

MAXIMUM AMPLITUDES OF HARMONIC CURRENTS IN TCR

	Harmonic Order	Value (%)*
	1	100
	3	(13.78)
	5	5.05
	7	2.59
	9	(1.57)
	11	1.05
	13	0.75
	15	(0.57)
6 pulse	17	0.44
	19	0.35
12 pulse	21	(0.29)
	23	0.24
	25	0.20
	27	(0.17)
	29	0.15
	31	0.13
	33	(0.12)
	35	0.10
	37	0.09

* Values are expressed as a percentage of the amplitude of the fundamental component at full conduction. The values apply to both phase and line currents, except that triplen harmonics shown in parenthesis do not appear in the line currents. Balanced conditions are assumed.

account. Harmonic propagation computer programs [10] are used for this purpose, and sometimes it is necessary to cover quite a large portion of the interconnected power system.

3.2.3 Thyristor Controlled Transformer Compensator (TCT)

A typical layout schematic for a thyristor-controlled transformer is shown in Figure 36. The TCT is shown in combination with a fixed capacitor/filter bank making a complete SVS of the TCT-FC type.

Instead of having separate reactors, the stepdown transformer is designed with a high leakage reactance between primary and secondary; that is, the coils are loosely coupled and the magnetic core is gapped. The leakage reactance is normally about 100% on the transformer rating.

The high-leakage reactance of the TCT helps to limit short-circuit currents for low voltage faults. For optimum voltage and current ratings of the thyristors, and in order to minimize harmonics, the arrangement shown in Figure 36 has been preferred, with wye-connected primary and secondary and a delta tertiary to trap triplen harmonics. In larger ratings, this three-winding arrangement tends to favor three single-phase transformers rather than a single three-phase unit. A two-winding transformer could be used, in principle, but the secondary would have to be delta connected, and in this case, the wye-connected thyristor switches would have to be fired synchronously in pairs to avoid the generation of excessive harmonics.

Harmonic Filtering. The capacitive reactive power supply (FC) and harmonic filters for this configuration must be installed directly on the HVAC bus. The tuning of the filters for this scheme may be critical, as there is no transformer reactance between the filters and the HVAC

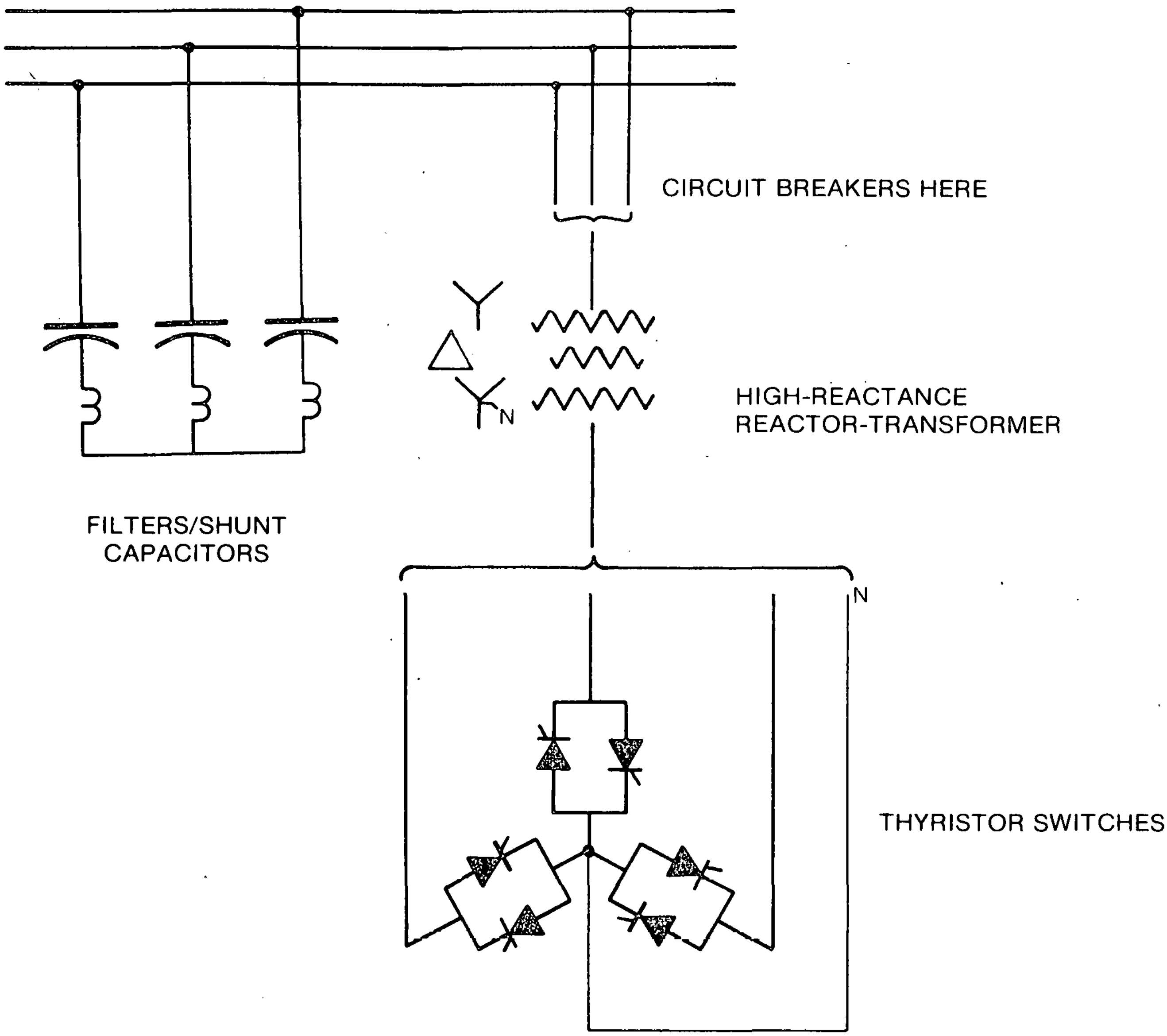


Figure 36. General Layout of Thyristor-Controlled Transformer (TCT)

system bus to bias the total impedance of the filter-transformer as "seen" by the HVAC system. The total transformer bus filter reactance is biased toward the inductive end for higher frequencies. The zeros (and poles) of the filter's impedance, which are necessary to effectively shunt the prescribed harmonics, are forced toward higher frequencies by the transformers inductive reactance, so they are less likely to present resonant "zeros" to the HVAC system. The characteristic harmonics of the TCT are similar to those generated by the TCR.

3.2.4 Switched Capacitor Compensators — TSC and MSC

The thyristor-switched capacitor (TSC) and mechanically switched capacitor (MSC) compensators operate on the adjustable-susceptance principle and generally employ integral-cycle control. With k capacitive susceptances in parallel, each controlled by a switch as shown in Figure 37, the total susceptance can be equal to that of any combination of the k individual susceptances taken 0,1,2, etc., or k at any one time. The total susceptance thus varies in a stepwise manner. In principle, the steps can be made as small and as numerous as desired, by having a sufficient number of individually switched susceptances. For a given number, k, the maximum number of steps will be obtained when no two combinations are equal, which minimally requires that all the individal susceptances be different. This degree of flexibility is not usually sought in power system compensators because of the consequent complexity of the controls, and because it is generally more economic to make most of the susceptances equal. One compromise is the so-called "binary" system in which there are k-1 equal susceptances B and one susceptance B/2. The half-susceptance increases the number of possible combinations to 2k.

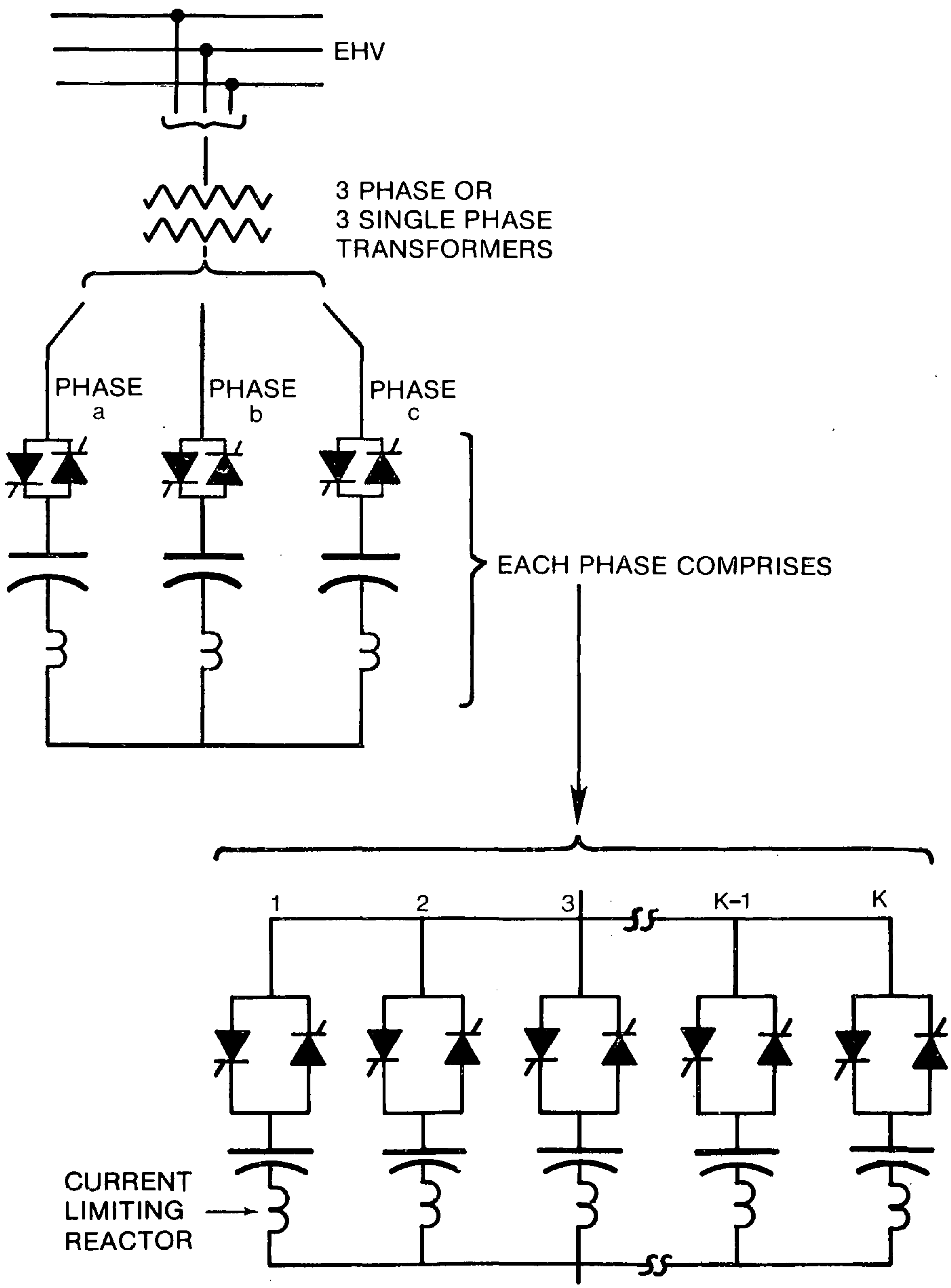


Figure 37. General Layout of Thyristor-Switched Capacitor Compensator

The Concept of Transient-Free Switching. When the current in an individual capacitor reaches a natural zero-crossing, the thyristors can be left untriggered and no further current will flow. The flow of vars supplied to the power system ceases abruptly. The capacitor, however, is left with a trapped charge, as in Figure 38. Because of this charge, the voltage across the thyristors oscillates between zero and twice the peak phase voltage. The only instant when the thyristors can be fired again with transients is when the voltage across them is zero. This coincides with peak phase voltage on the system side assuming no drain-off of trapped charge on deenergized capacitors. The concept of transient-free switching just described applies in the highly idealized case where there is no inductance in series with the capacitors.

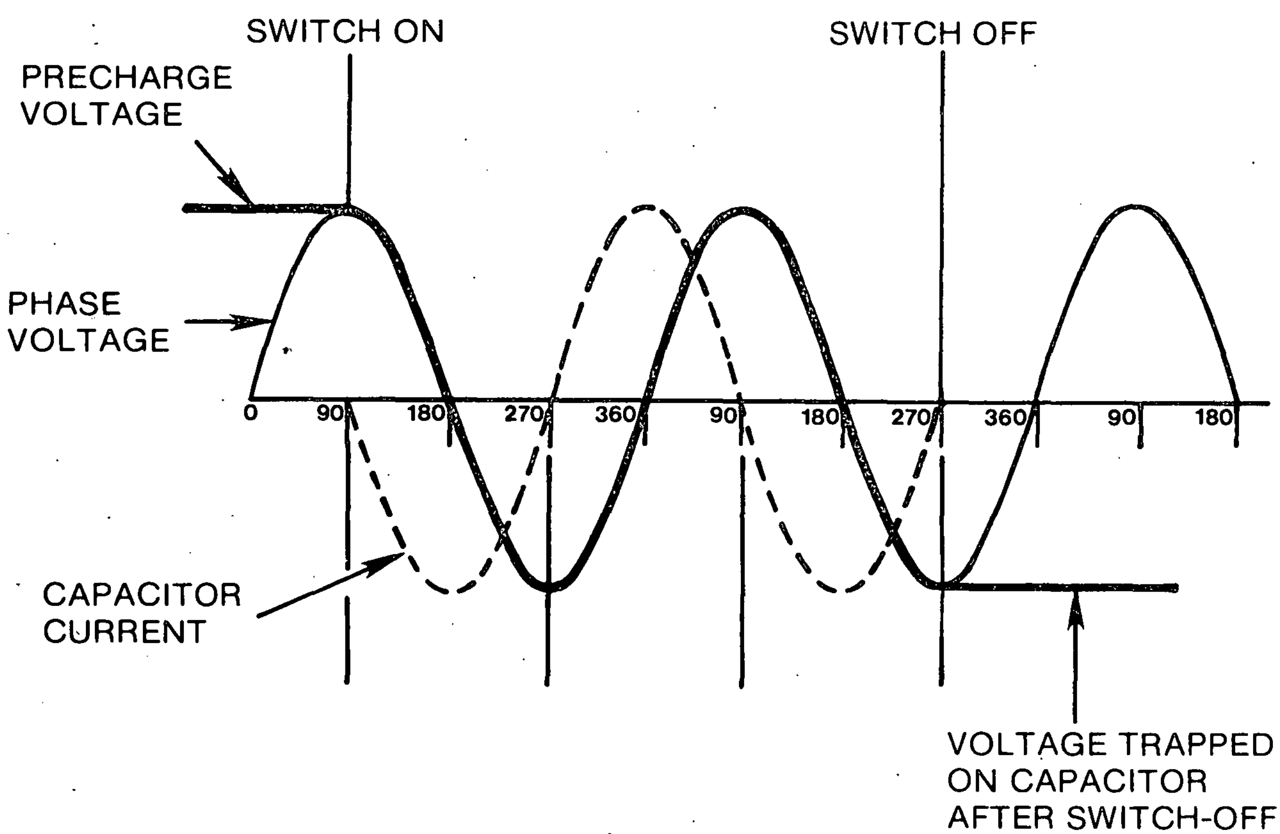


Figure 38. Ideal Transient-Free Switching in the TSC

In practice there is always inductance in series with the capacitors. It exists in the form of the normal inductances of busbars and interconnections. In addition, it is almost always necessary to add a small inductance in series with every switched capacitor in the TSC to limit the rate of change of current (di/dt) in the thyristors, especially when parallel capacitors may discharge through them. The series inductors automatically tune each capacitor leg to some resonant frequency, and this must be very carefully chosen to avoid interference with system resonances.

A more thorough analysis of the switching process in the presence of inductance shows that conditions do exist under which transient-free switching can be obtained, but it will be rare for them to be precisely satisfied. In general, the capacitor switching does excite transients which may be larger or smaller, depending on the resonant frequency of the capacitors with the external system. A switching control system capable of minimizing the switching transients under all conditions can become complicated. The design difficulties are increased by the wide variation which is usually specified for the driving-point impedance of the power system at the point of connection of the TSC.

An example of a severe capacitor-switching transient is shown in Figure 39, where a single capacitor is switched in to a system whose inductance is such that the resonance frequency between it and the capacitor is 3.2 times fundamental frequency. (While this is typical, lower-frequency resonances can occur and these are more onerous than the one shown in Figure 39.) The capacitor is overcharged to 1.5 p.u. voltage, as, for example, following a system disturbance in which the capacitor was switched off. Figure 39 shows the response when the capacitor is switched on again before its trapped charge has had time to

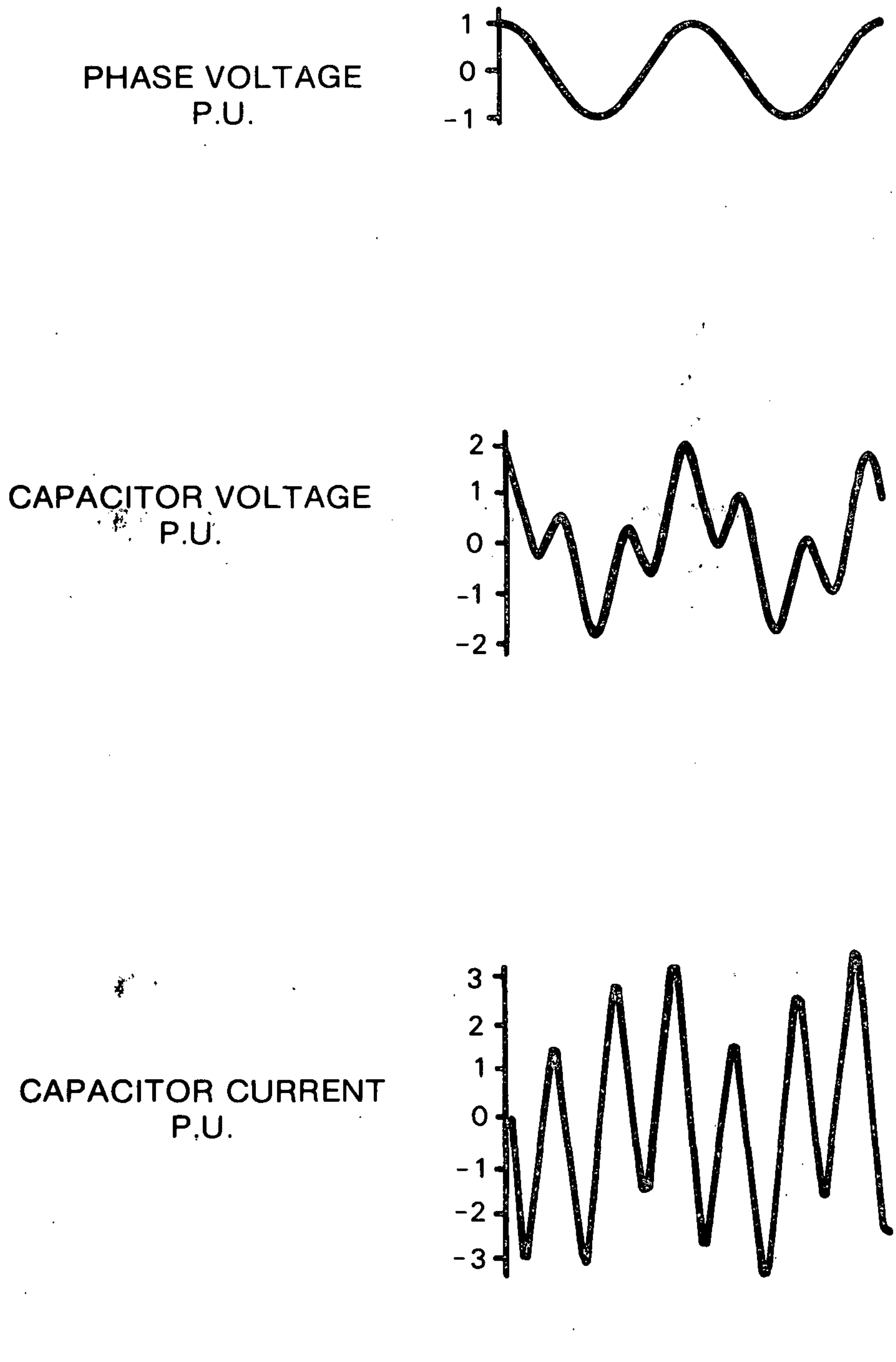


Figure 39. Switching Transients in Thyristor-Switched Capacitor When Capacitor is not Prechanged to Correct Value

decay. The response shown is somewhat unrealistic because such transients will tend to damp out rapidly. Figure 39 therefore serves to illustrate the initial transients which could arise if care is not taken to minimize them.

Static Var Systems Employing Switched Capacitors. Two practical SVS configurations employing mechanically switched capacitors (MSC) and Thyristor Switched Capacitors (TSC) were shown in Figures 26c and 26d, respectively. While true transient-free switching is not feasible and not always necessary, such performance can be approached when the controls employed are sophisticated enough to avoid extreme current oscillations such as shown in Figure 39.

TSC control techniques which have been described in the literature [11] and applied in actual practice [12]. Some employ very sophisticated switching logic. First is the point-on-voltage-wave switching strategy to match trapped charge (if any) on the deenergized capacitors to the supply-side voltage as closely as possible to minimize switching transients. Secondly, a charge maintenance control subsystem periodically reconnects the deenergized capacitors to the line momentarily to restore full charge. Thirdly, the stored charge on the (stand by) deenergized capacitors is sometimes cycled so that the capacitors are not subjected to the same polarity of voltage at all times. This technique permits the use of "conventional" ac capacitors which enjoy a cost advantage over capacitors which can operate on ac or dc over long periods of time.

When teamed up with a parallel TCR, the step change in fundamental frequency voltage resulting from the capacitor switching can be reduced through coordinated TCR, TSC control. While the pure TSC is theoretically free from harmonic generation, practical TSC arrangements with current limiting reactors can result in steady state voltage distortion due to resonance conditions of TSC with the HVAC system. When a TCR is used to make a hybrid TCR-TSC compensator, harmonic filters are required for the TCR making the entire SVS acceptable to the HVAC system from the viewpoints of voltage wave distortion and/or communication-noise generation.

MSC control techniques are also available to minimize switching transients and avoid excessive charging current duty conditions arising out of back-to-back capacitor switching. The term back-to-back capacitor switching refers to energizing a capacitor with some retained trapped charge in the presence of other energized capacitors. If little inductive reactance exists between the energized and deenergized banks, the momentary exchange of energy between capacitor banks with differing voltages can result in large momentary currents and high di/dt.

The point-on-voltage-wave switching logic and charge maintenance control subsystem of the TSC scheme just described minimize the back-to-back capacitor switching problems (high momentary i and di/dt) as well as limiting transients on the HVAC system. Point-on-voltage-wave controls have been demonstrated in the field [13] for a mechanically switched capacitor bank.

A formal charge maintenance control policy, as used in the TSC scheme, is not practical for the MSC. With the MSC, instead, two options are available for reenergizing capacitors with some trapped charge remaining.

First, the point-on-wave logic could keep track of the slowly discharging voltage on all deenergized capacitor banks and switch in each when the ac supply voltage is approximately equal to the trapped charge voltage. This approach relies on the predictable mechanical switch closure times and some "bookkeeping" logic in the point-on-wave switching control.

A second approach would involve switching on only totally discharged capacitors at voltage zeros of the supply voltage. To permit reconnecting a capacitor shortly after disconnecting it, the trapped charge must be removed rapidly. Conventional capacitors discharge in five minutes.

This second approach, therefore, requires a rapid discharge resistor for each capacitor bank, which would be switched across the capacitor the moment it is disconnected from the line, or a potential transformer (PT) permanently connected across each capacitor bank. In the latter case, the PT would be saturated by the dc voltage remaining on the capacitor bank after the ac supply is removed, and the capacitor could be discharged in about 10 cycles.

The MSC would naturally be employed with a parallel TCR to make up a complete TCR-MSC static var system. Both TCR-TSC and TCR-MSC configurations are suitable for HVAC applications. The mechanical switches of the TCR-MSC arrangement will be subject to limitations on the repetition duty and repetition rate. Otherwise, both techniques have relative cost advantages and disadvantages, as will be discussed later in Section 3.4.

3.2.5 Saturated-Reactor Types of Static Var Systems

A great variety of saturating-iron devices have been used for voltage stabilization. At least four basic principles have been applied, but it seems that only one has so far been developed for HVAC transmission system applications. This is the so-called polyphase, harmonic-compensated, self-saturating reactor. A single-line schematic of this type is given in Figure 26e. It is closely related to the phase-multiplying type of frequency multiplier, of which many different versions were developed since about 1912. Only two manufacturers (both European) now offer the polyphase saturated reactor for transmission systems applications.

Other classes of saturated-reactor voltage stabilizer include the ferroresonant constant-voltage transformer, the transductor, and the tapped-reactor/saturated-reactor compensator. The ferroresonant constant-voltage transformer appears to be manufactured in the U.S.A. only in kVA sizes. The transductor has dc control windings and works as an adjustable susceptance. A single-line schematic of this type is given in Figure 26f. Its speed of response compares unfavorably with other types of compensators because of the need to change the dc exciting flux to effect a control on the saturating characteristic. The tapped-reactor/saturated-reactor compensator is, in effect, an attempt to translate the B-H curve of iron into a constant-voltage characteristic. This device is essentially single-phase, and has a series as well as a shunt element. It is, therefore, suitable only for load compensation (e.g., small arc furnaces), and cannot be connected to a power-system busbar for voltage stabilization.

Principles of Operation. The operating principle of the frequency-multiplying type of saturated reactor is quite simple. Consider a plain three-phase, wye-connected reactor (the primary winding in Figure 40), wound on a saturable three-limb core. If the phase voltages are high enough to cause the flux in each limb to exceed the saturation knee of the magnetization curve of the iron, a large current flows for the period when the limb is saturated. This current is in phase quadrature with the voltage and is lagging, tending to absorb reactive power and reduce the terminal voltage. In the absence of the secondary winding, the primary currents are highly nonsinusoidal, and this is one reason why the plain three-phase saturating reactor is not acceptable for fundamental-frequency voltage-stabilization. However, if the series-connected, short-circuited secondary

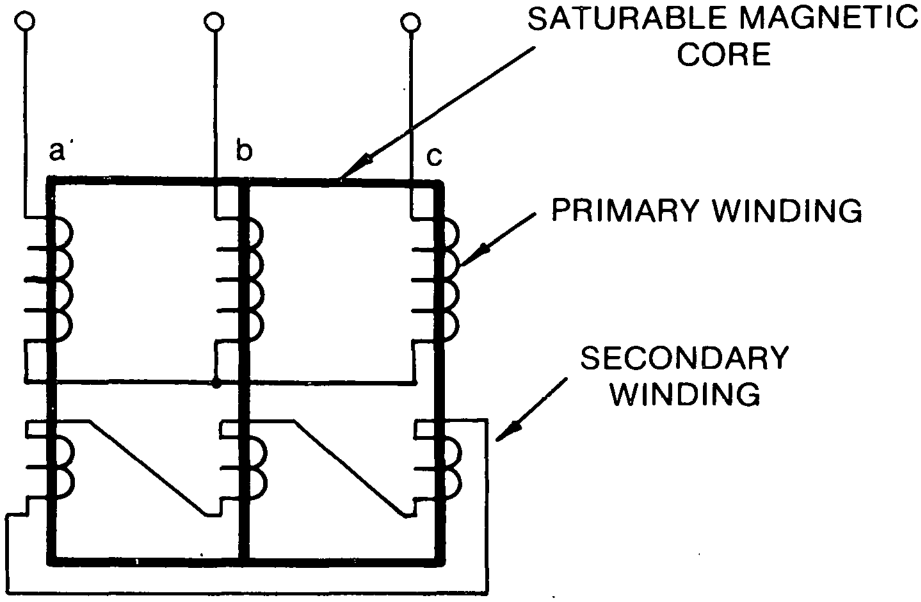


Figure 40. Elementary Frequency Trippler Having Approximately Constant Voltage Characteristics

winding is closed, by three-phase symmetry it will be found that the necessary positive and negative-sequence triplen harmonic components of the magnetomotive forces in each limb can be provided by the secondary current. The primary current is free of these harmonics. The secondary currents are predominantly third-harmonic, and the circuit is thus an elementary frequency-tripler.

The primary currents, under balanced conditions, contain no harmonics lower than 5th and 7th. By inserting a reactor of suitable value in the secondary circuit, even these harmonics could be reduced. This phenomenon of partial harmonic compensation has been exploited, particularly by Friedlander [14] in the development of a practical static var system for HVAC applications.

The harmonic performance and the voltage/current characteristics of the plain frequency tripler are not good enough for application in power systems, and much better characteristics are obtained with frequency multipliers of up to nine times. Such is the case with the treble-tripler reactor. This shares with the plain tripler the open-mesh secondary winding, which carries predominantly 9th harmonic. In order to generate this from a balanced three-phase system, a phase-multiplying arrangement is necessary, as shown in Figure 41. There are nine limbs in the magnetic core, and in common with other magnetic frequency multipliers, only one is unsaturated at a time. Each limb saturates alternately in both directions, giving a total of 18 unsaturations per cycle. In the terminology of the TCR, this corresponds to 18-pulse operation and helps to explain the high-speed response of the reactor by itself. This high response rate is reduced, however, by the series connected capacitor that is commonly used to improve the sensitivity or voltage regulation capability of the SR. This is further discussed in Section 3.3.5.

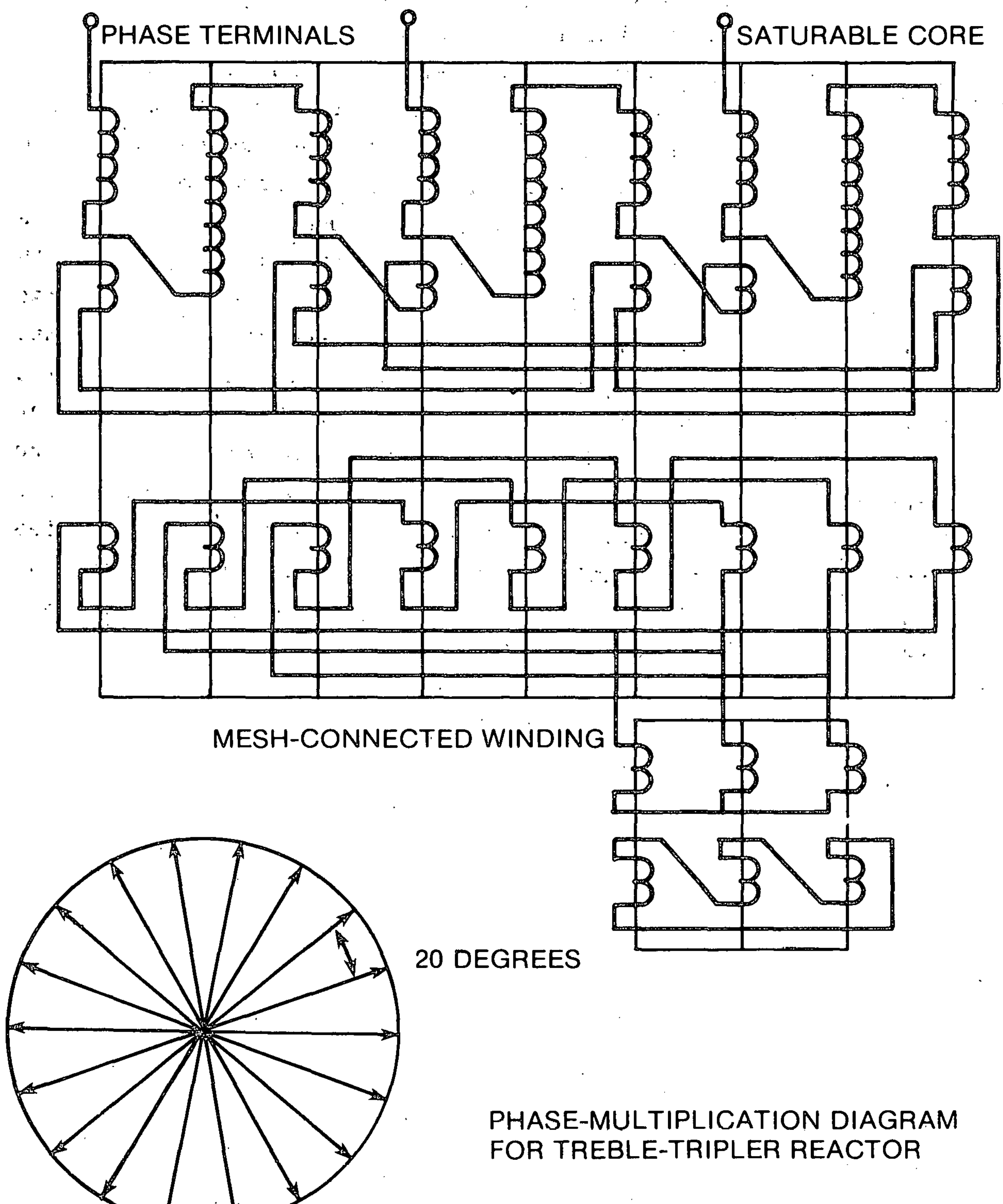


Figure 41. Winding Diagram of Nine-Limb Treble-Tripler Reactor Developed by Friedlander for Voltage Stabilization

The lowest-order characteristic harmonics of the treble-tripler reactor are the 17th and 19th, but by appropriate design of an inductive load in the 9th harmonic mesh circuit, these can be reduced to around 2% by partial harmonic compensation. Plain shunt capacitors can normally be used to absorb these residual harmonics. Under highly unbalanced supply voltages the residual harmonics may become more pronounced. In those cases, tuned harmonic filters designed into the capacitor banks associated with the SVS may be required.

3.3 FUNDAMENTAL FREQUENCY PERFORMANCE

Static var systems employing Thyristor-Controlled Reactor (TCR), Thyristor-Controlled Transformer (TCR), and Saturable Reactor (SR) principles are capable of controlling the individual phase voltages of the bus to which they are connected. These forms of SVS can be very effective where negative sequence as well as positive sequence voltage deviations must be controlled. Zero sequence voltage deviations can also be controlled but somewhat rare transformer connections (such as zig-zag windings) would be required in the SVS transformer.

This section will therefore consider the various static compensation approaches only to the extent they control the balanced three-phase (positive sequence) voltage deviations which can occur in a system. Single-phase equivalent models of the transmission system and static var systems can be assumed for clarity in the discussions that follow. Only the fundamental component of the current in the TCR and TCT is of concern in this performance section. All harmonic currents are assumed to be rendered negligible by the presence of harmonic filters which are supplied on all practical SVS applications where harmonic distortion and communication noise requirements mandate their use.

To characterize the dynamic performance of each SVS we will borrow from synchronous machine theory and system stability theory the notions of subtransient, transient, dynamic and quasi-steady-state periods following a system disturbance. The subtransient period is defined as the first few cycles after a disturbance wherein synchronous machines can be approximated by a constant voltage (flux linkages) behind their subtransient reactances. DC offsets in line currents are assumed to decay in that period leaving only the ac components of current and voltages.

The transient period is defined as that period following the subtransient period wherein synchronous machines behave approximately as a constant voltage behind their transient reactance. The dynamic period will be defined as the next period in time sequence following a disturbance wherein voltages, currents, and all other system variables oscillate around their new equilibrium (final) values, assuming such an equilibrium exists.

The quasi-steady-state period is the final period in time sequence wherein the SVS and system have settled at a post-disturbance equilibrium. <u>The quasi-steady-state characteristic of an SVS described in the literature</u> can be used to <u>characterize the fundamental frequency balanced three-phase performance</u> of the SVS in <u>all four periods defined</u>.

3.3.1 The Ideal Reactive Power Compensator

If an "ideal" reactive compensator were possible it would possess the following two capabilities:

1. Control voltage at its terminals or on a designated nearby HVAC bus in a precisely prescribed way.

The simplest (but not always the best voltage control law) would be: hold constant voltage. To that end the ideal compensator would possess infinite, or at least very large, ratings for production and absorption of reactive power. A graph of controlled voltage V as a function of reactive current is shown in Figure 42.

2. It would appear as if it possessed an internal (generated) voltage equal to the prescribed value of V and no real power or reactive power losses.

Further, it would not possess any delays or time constants, either electrical or mechanical. It would thereby be instantaneously acting, thus holding constant V even in the shortest time interval imaginable. It should also operate asynchronous, or at least be unable to lose synchronism in the rotor-angle stability sense that synchronous machines can lose stability.

Such an "ideal" reactive power compensator is impossible; however, the characteristics of the various SVS types will be compared to the ideal case as a common reference.

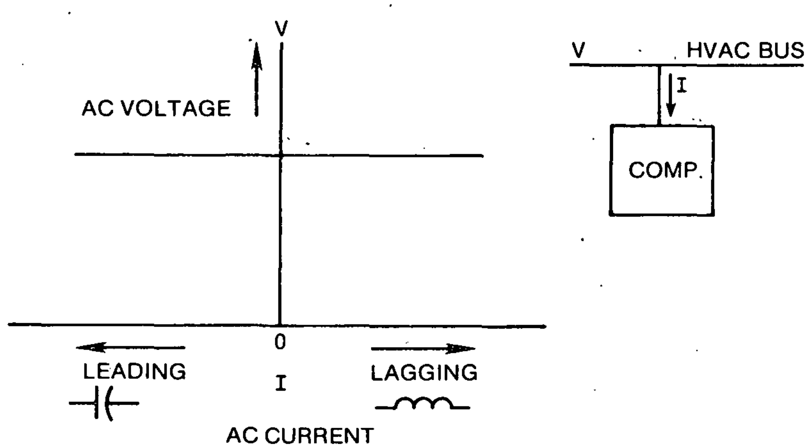


Figure 42. Fundamental V/I Characteristic of Ideal Shunt Compensator

3.3.2 Graphical Illustration of SVS Operation in an HVAC System

The performance of an SVS can be visualized on a graph of controlled HVAC system voltage, V, versus the SVS reactive current, I. This V/I characteristic has been termed in the literature as the steady-state or quasi-steady state SVS characteristic. The positive sequence (balanced 3 phase) fundamental frequency behavior of the SVS during the subtransient, transient and dynamic periods can be visualized, to a first approximation, on these graphs.

The SVS. Consider an SVS composed of a controllable reactor and an unswitched capacitor bank in parallel as shown in Figure 43. The characteristic of steady-state SVS performance can be described by the voltage-vs-net current (I_N) diagram in Figure 43c. That steady-state characteristic is derived by adding the controlled reactor relationship in Figure 43a to the fixed capacitor relationship in Figure 43b.

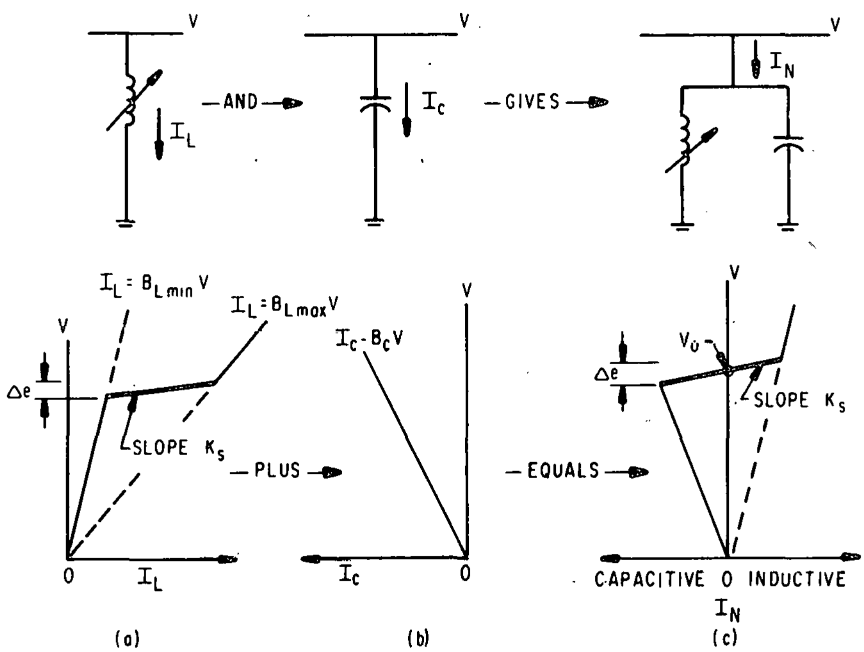


Figure 43. Characteristic of Steady-State Performance Deviation of v-vs-I_n Characteristic From Component Characteristics

For static var systems incorporating thyristors in series with an inductive element, the characteristic in 43a results from continuous feedback control action whereby the inductance, or admittance B_L, is continuously adjusted to maintain the voltage within a prescribed $\Delta\varepsilon$ regulation band. Should the voltage, V, move outside of the $\Delta\varepsilon$ band in spite of SVS control action, the SVS is said to be outside of its control range and thereby behaves as a constant admittance element. As seen in Figure 43c, very low applied voltages cause the SVS to appear as a fixed capacitor since the current in the controlled reactor would be at its minimum. When the system voltage rises outside the $\Delta\varepsilon$ control band, the reactor current is phased on full and the SVS appears as an inductive admittance equivalent to (B_{Lmax} $-B_C$). This latter characteristic is largely linear with current, but eventually saturates. For TCT static var systems using reactor transformers [15] the reason is saturation in the iron core reactor transformer and with the TCR SVS using air core reactors, the step-up transformer ultimately saturates. The self-saturating ac reactor type SVS behaves similarly to Figure 43c with the exception of the reactor characteristic. This type will be discussed more thoroughly in Section 3.3.5.

<u>HVAC System Characteristic with a Reactive Load</u>. The foregoing paragraphs presented the steady state voltage-vs-current characteristic of the SVS equipment without regard for the HVAC power system to which the SVS is connected. The SVS and the power system must be analyzed together to understand completely the SVS performance.

The SVS is not a source of voltage as is a rotating machine, but instead alters the HVAC system voltage at the point of connection by varying the amount and phase of the reactive current - in effect a variable reactive load -

drawn through the effective HVAC system impedance. The SVS "controls" voltage with the same principles by which shunt capacitors and reactors are effective in modifying the HVAC network voltage profile.

Continuing with the graphical illustration of SVS performance in the steady state, Figure 44 depicts the HVAC network as a Thevenin equivalent circuit when viewed from the network bus on which the voltage is to be regulated by an SVS. Theoretically, such an equivalent circuit can be defined for every HVAC network steady-state condition.

Assuming for illustration that the equivalent system impedance is predominantly inductive reactance, the voltage, V, at the controlled bus will increase linearly with capacitive reactive load current and decrease linearly with inductive reactive load current. Figure 44b also illustrates the influence of the equivalent source voltage as it varies $\pm \Delta E_T$ about some nominal value of E_{TO}. Since the system impedance was assumed fixed in Figure 44b, that figure illustrates - as a first order approximation - the effect of SVS reactive current for different system loading conditions with no change in network configuration.

Figure 44c illustrates the effect of SVS reactive current on voltage V for three different system equivalent reactances. The source voltage was assumed unchanging at E_{TO} thereby illustrating, again as a first order approximation, the effectiveness of SVS reactive load current on voltage V for different system short-circuit impedances.

Combined SVS - HVAC System Characteristic. An equation relating the SVS net reactive current and the controlled-bus voltage can be written from the illustrations in Figure 44. That equation is:

$$V = E_{TH} - I_N X_{TH} \qquad (1)$$

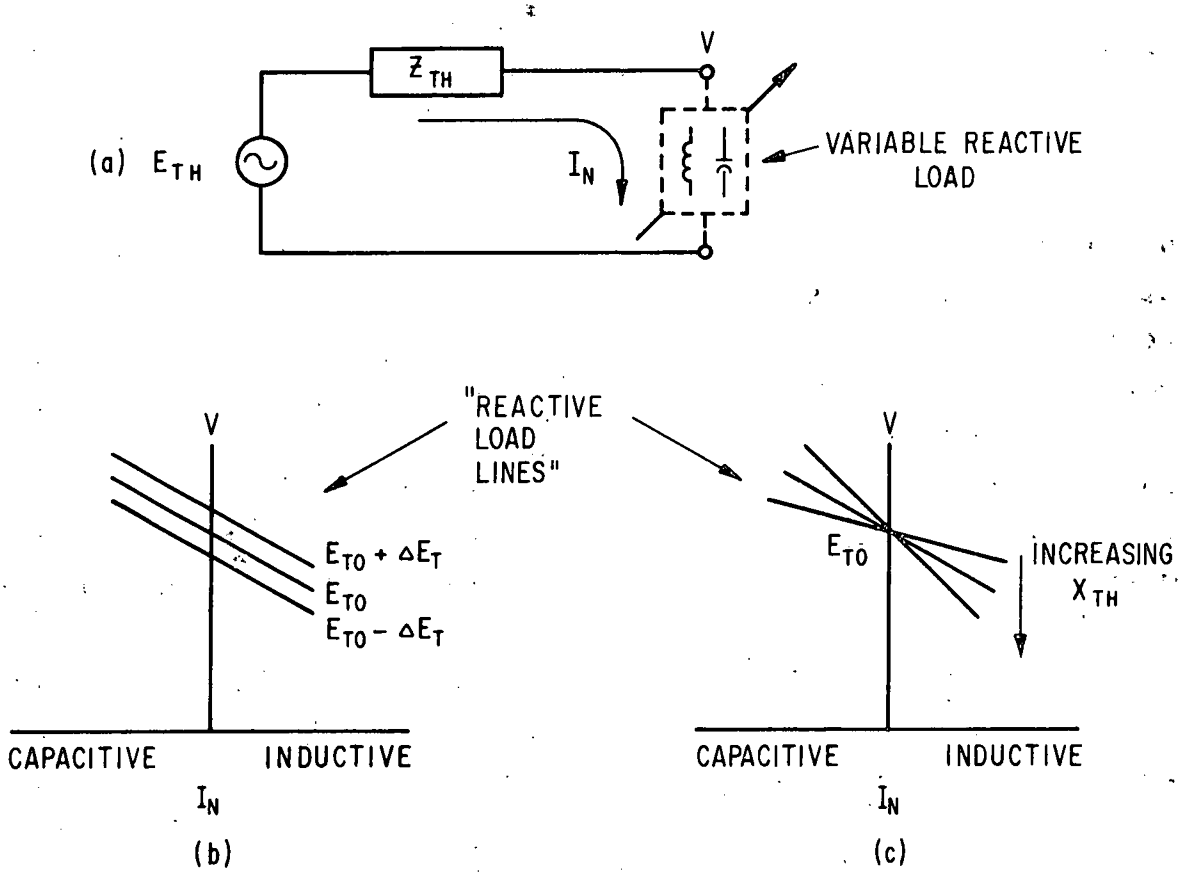


Figure 44. Introduction of "Reactive Load Lines"
a) Thevenin Equivalent circuit of HVAC network as viewed from bus on which SVS is to control v.
b) Variation of v with reactive load for different source voltages E_{TH}, with Z_{TH} unchanged.
c) Variation of v with reactance load for different system impedance $Z_{TH} = jX_{TH}$, with E_{TH} unchanged.

For any given network state, E_{TH} and X_{TH} can be defined, but I_N and V are unknown. A second equation relating those two unknown variables is available from the SVS characteristic in Figure 43c. The equation is:

$$V - V_O = K_S I_N \quad (2)$$

where K_S is the slope of the V, I_N curve when the SVS operates within its control range. For voltages outside the regulating band the ratio of I_N to V is either the net capacitive admittance with the reactor current at minimum or the net inductive admittance when the reactor is full-on. The characteristic in Figure 43c, and thereby the equations relevant for out-of-regulating range operation, will vary with the relative ratings of the inductive and capacitive legs.

Figure 45 graphically illustrates the solution of the SVS characteristic equation (2) and the system load characteristic equation (1). Figure 43c and Figure 44b are combined in Figure 45 by plotting them onto the same V-vs-I_N coordinates with the vertical scale foreshortened for clarity. For illustration purposes, the center curve (E_{TH} = E_{TO} for nominal system conditions) is shown intersecting the SVS characteristic at V_O = E_{TO} and zero SVS current. The value V_O will also be regarded as the setpoint for the SVS voltage regulating equipment in this example.

As the system voltage level drops by ΔE_T, for instance during peak system load conditions, the voltage V would drop to point 2 without an SVS. With the SVS, however, the new operating point would exist at the intersection of the SVS characteristic and the E_{TO} - ΔE_T system "reactive load line." By drawing capacitive current, I_4, the SVS is successful in holding the voltage

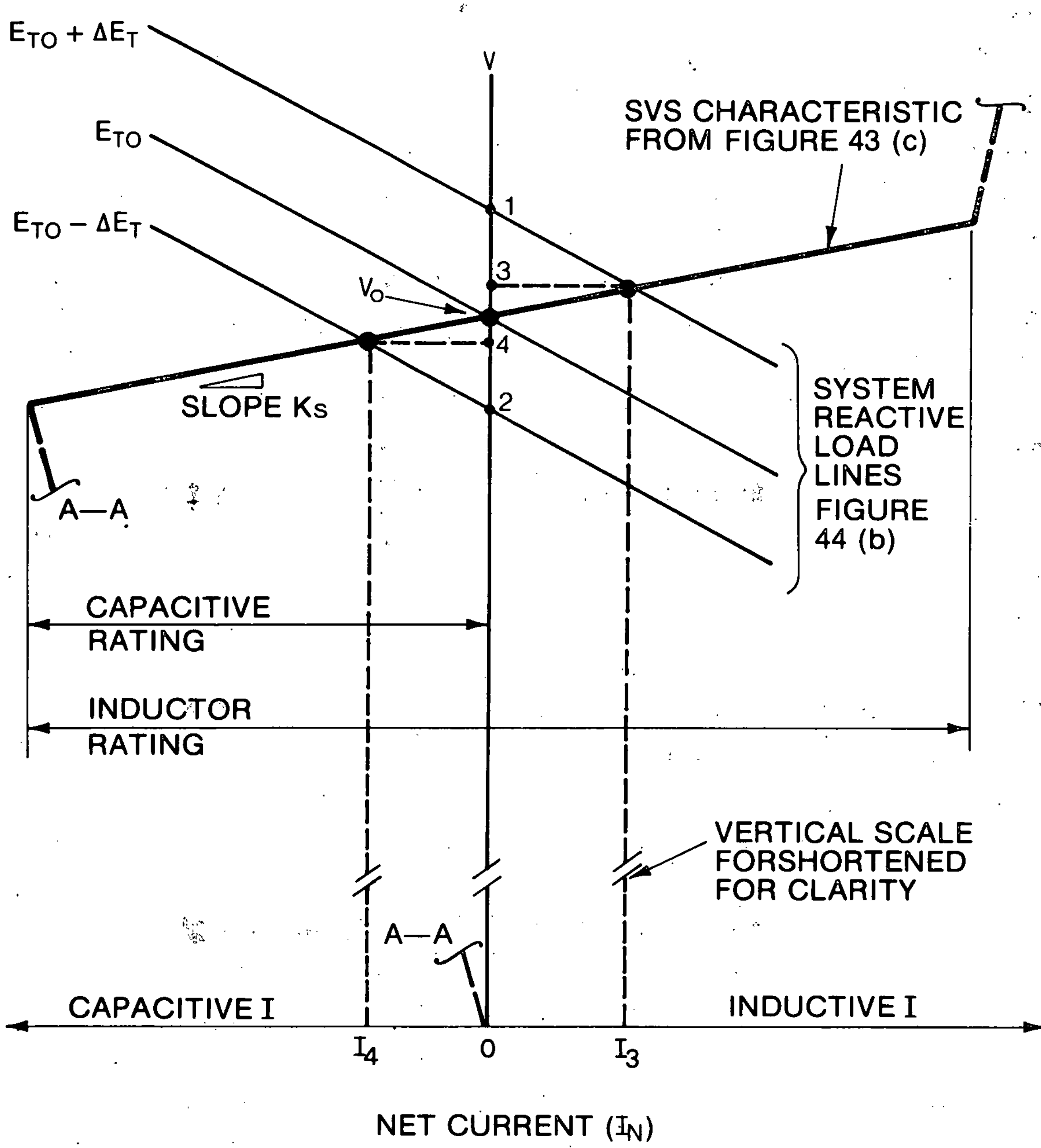


Figure 45. Graphical Solution for SVS Operating Point for Given System Conditions. Also showing capacitor bank and controlled reactor ratings.

up to point 4 on the V axis. If the slope, K_S, of the SVS characteristic were zero, the voltage would have been corrected back to V_O by drawing more capacitive current.

For system conditions such as light load, the E_{TO} + ΔE_T "reactive load line" might prevail and the voltage would only rise to point 3, whereas it would have risen to point 1 without the SVS. The SVS current required to hold voltage to point 3 is inductive current I_3.

The change in the Thevenin equivalent circuit due to a major line outage might include modification of both the source voltage and the impedance, so that the scenario illustrated in Figure 45 is only one very simple example used for illustration of SVS-HVAC system operation.

The variation in the system reactive load line shown in Figure 45 was assumed small relative to the available current rating of the controlled reactor. For a smaller SVS reactor rating or larger variations in system source voltage, the reactor control range could be exceeded. The use of switched capacitor banks can extend the continuous control range to accommodate greater variation in HVAC network conditions. Figure 46b illustrates the use of three capacitor banks, two of which are switched, to obtain the extended control characteristic drawn in Figure 46a. While mechanical switches are implied by the figure, thyristors can be utilized (TSC) as well as mechanical (MSC) switches.

Curve 1 in that figure, would result with only the unswitched capacitor (with filter reactors) bank in service. Curves 2 and 3 correspond to the other possible switched bank combinations. The capacitors could be switched in and out, as needed, entirely under the direction of local voltage sensing controls. Such controls could be an integral part of the voltage regulator for those SVS that use a regulator to adjust the current flow in the inductor leg.

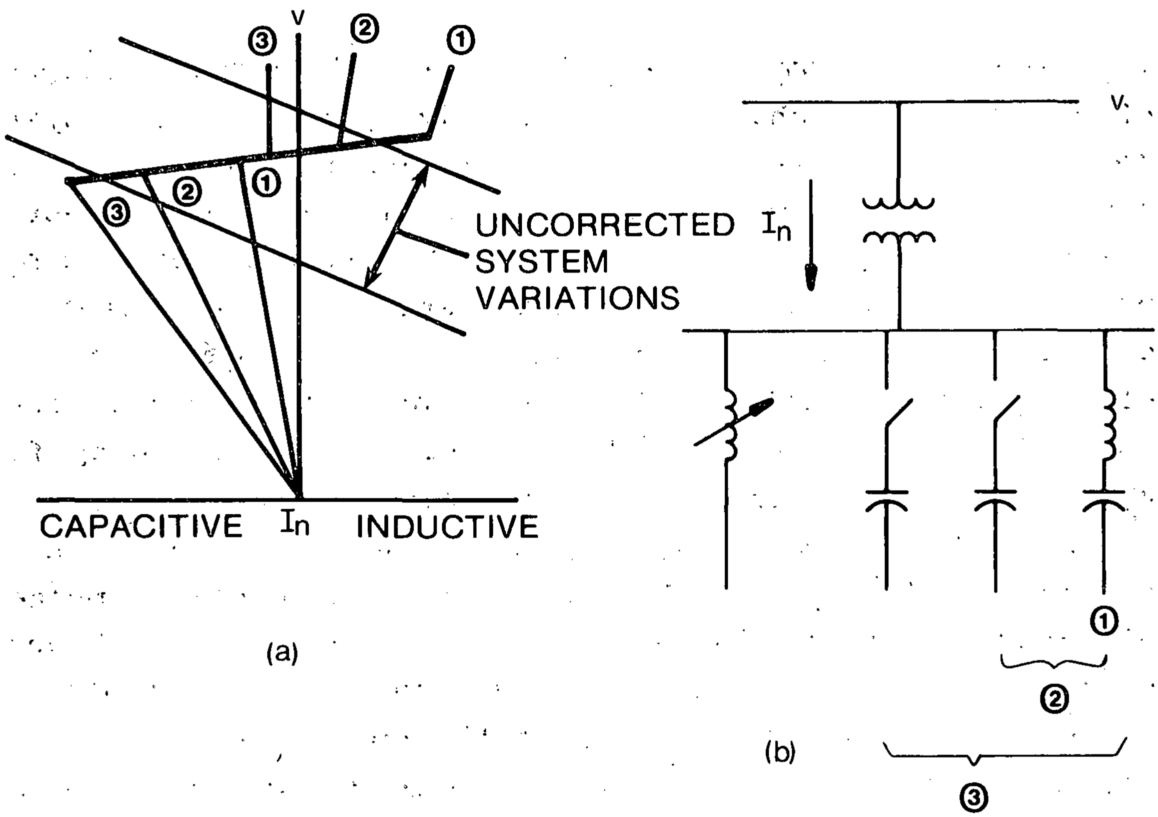


Figure 46. Use of Switched Capacitors to Extend Steady-State Voltage Control Range
a) SVS V-vs-IN characteristic
b) Schematic of SVS with switched capacitors provided to extend continuous control range

The switched capacitors would be useful for the purpose of maintaining the steady-state operating point within a preselected region of the continuous control range. This may be desirable to reserve vital control range for an eventual system disturbance and/or to minimize the steady-state operating losses of the static var system.

Transient and Dynamic SVS Performance. The dynamic response of an SVS can be characterized utilizing the SVS and system reactive load line characteristics previously defined for steady-state behavior. Referring to Figure 45, an abrupt disturbance experienced on the HVAC network, for example, could cause the system characteristic to shift from the center load line labeled E_{TO} to the lower one $E_{TO} - \Delta E_T$ instantaneously. Such a disturbance would cause the voltage V at the bus of interest to abruptly drop from V_O to the voltage corresponding to point 2 on the V axis.

An SVS incorporating thyristors or a self-saturating characteristic to directly change the fundamental component of reactor current in response to the change in V would bring the voltage to a new equilibrium state in approximately 0.5 to 2 cycles of the power frequency. That is, the reactor current would be reduced such that the net SVS current would equal I_4 and the voltage V would correspond to point 4 on the V axis in that time.

The foregoing steady-state and transient performance descriptions are general to all systems. The following sections will discuss specific SVS types relative to their similarities and deviations from the ideal compensator in the fundamental-frequency-balanced characteristics.

3.3.3 Realization with TCR and Fixed Capacitors (FC)

Under balanced conditions at fundamental frequency, each phase of the TCR has a voltage/fundamental current characteristic of the form shown in Figure 47. Values of the conduction angle σ are shown in that Figure. The line with $\sigma = 180°$ (full conduction) corresponds to the normal reactance of the linear reactors, and by appropriate control of the thyristor firing angles any characteristic above this can be obtained. Figure 47 shows a flat-slope characteristic as an example, but a small 1-5% voltage slope is typical. It can be said that the voltage/current characteristic is programmable via electronic controls.

Under fundamental-frequency overvoltage conditions, the best that the TCR can do to limit the voltage is to act as a plain linear reactor (with full conduction). Based on the MVA rating of the reactor, the voltage/current slope is then 1.0 p.u., which may be insufficient to appreciably limit the overvoltage unless the power system is relatively weak. The flat-slope range can be extended out to higher values of overcurrent by adopting the use of smaller conduction angles at normal currents, with a corresponding increase in the average harmonic content of the current.

By adding an unswitched or fixed (FC) capacitor bank in parallel, the TCR voltage control characteristic is biased into the capacitive or reactive power production region, as illustrated in Figure 43. Owing to the rapid fractional cycle control response of the TCR, the TCR-FC configuration yields an extremely high-speed adjustability of reactive power. This, together with its basic simplicity, are the TCR-FC configuration's main advantages.

Two disadvantages to the TCR-FC are:

1. The TCR must be rated to absorb all the FC reactive power plus any additional reactive power required by the system to hold down the controlled voltage V.

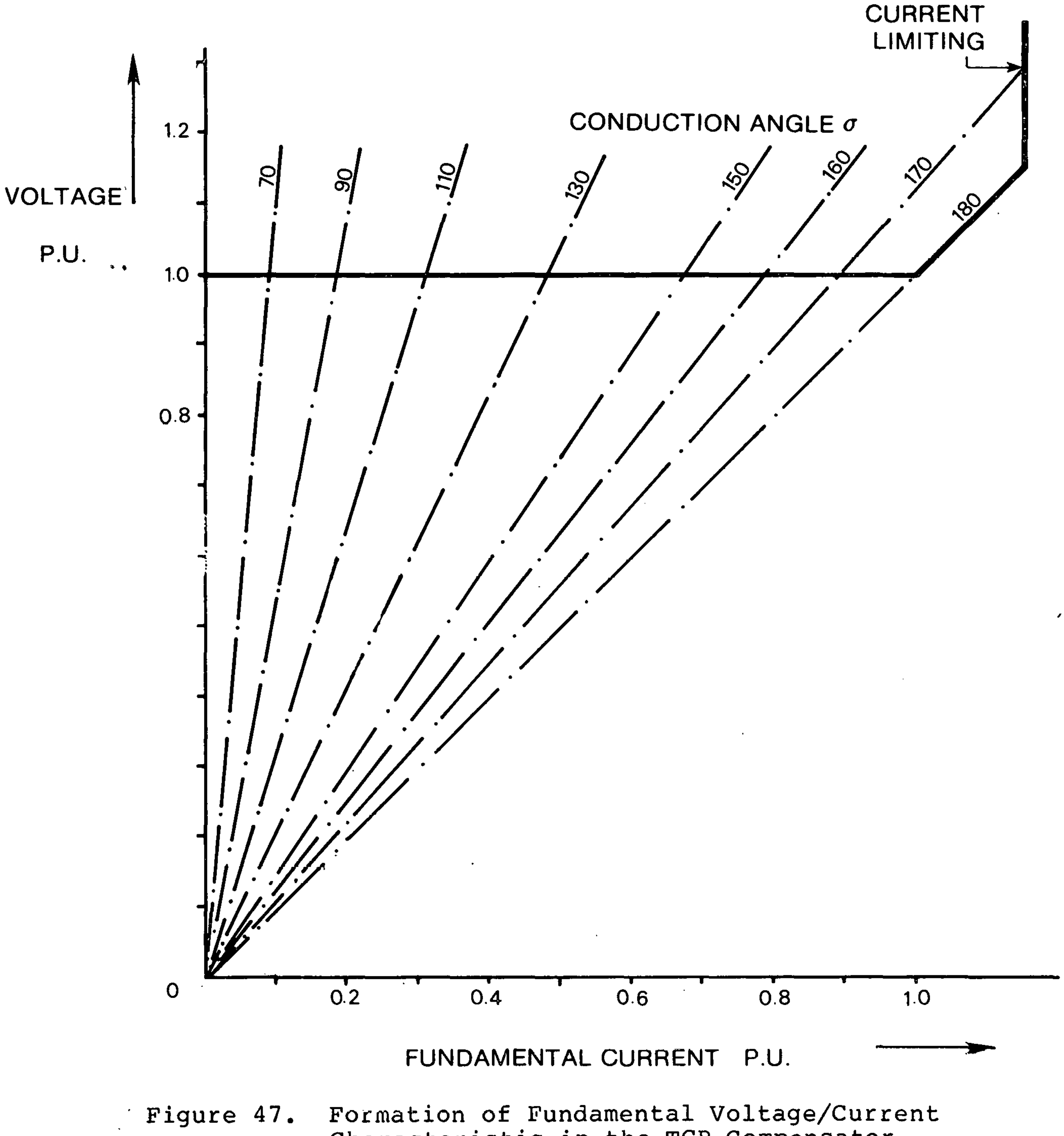


Figure 47. Formation of Fundamental Voltage/Current Characteristic in the TCR Compensator. Numbers show conduction angle 2σ (deg.) Note the current-limiting achieved by phasing back the conduction angle under overvoltage conditions.

2. The active power absorption (losses) of the TCR can be 0.5 to 1% of the total TCR reactive power rating at zero net var output. Most of the losses associated with the TCR are caused by the forward voltage drop across the thyristors during its partly phased-on steady-state operation. These factors are discussed further in Section 3.4 - Comparison of SVS Types.

3.3.4 Realization with TCR and Switched Capacitors

Phase control with the TCR inherently gives a continuous variation of reactive current, whereas integral-cycle control with switched capacitors gives stepped or discontinuous control. The biasing principle of Figure 43 makes it possible to obtain a continuous control over a wide range of lagging and leading currents, by combining an integral-cycle controlled susceptance with a phase-controlled one. This may be done with a small TCR and a relatively small number of thyristor-switched capacitor banks, the so-called TCR-TSC arrangement. A close examination of HVAC system requirements often reveals that the ultrafine timing precision of thyristors is not necessary with the capacitors in this configuration, because the speed of response and continuous control built into the TCR are adequate. In such cases, the switches in the capacitive lag can be mechanical switches, the TCR-MSC arrangement. This approach has been used successfully with the saturated reactor compensator as well as with TCRs.

Because of the extremely fast switching of the thyristors, the TCR, TCT, and TSC when used, are all very rapid in response. In principle, the reactive power of the SVS can be changed between any two points in its entire range within one cycle or less. For special applications like arc-furnace flicker compensation, this rapid response can be fully exploited. In HVAC transmission systems, however, such extreme response speed is usually not necessary except for the largest of disturbances.

The use of switched capacitors, whether thyristor switched or mechanically switched, can permit the use of smaller TCR, TCR or SR controlled reactor legs than are required with unswitched capacitors. Depending on the normal operating point of the SVS, the steady-state SVS losses may also be reduced significantly with switched capacitors. The relative advantages of TCR-TSC versus TCR-MSC (and comparable combinations with TCT and SR reactor legs) depend on the actual steady-state operating point. The actual "float" (operating) point may be with some net var production or absorption, not when $I_N = 0$ as suggested by Figure 43. For most practical operating conditions the TCR-MSC requires fewer losses than the TCR-TSC, as will be discussed in Section 3.4.

3.3.5 Realization with the Saturable Reactor Based Type of SVS (SR-FC)

The voltage/current characteristic of the saturated reactor by itself is shown in Figure 48. There is a slope of between 5-15% (based on the reactor rating), which depends on the reactor design and, in particular, on the after-saturation inductance of the windings. A lower slope reactance would require a more expensive and larger reactor design. The characteristic is very linear above 10% of rated current.

A lower slope reactance can also be obtained by connecting a capacitor in series with the saturated reactor. This slope-correcting capacitor can be sized to make the slope zero or even negative, but typical values of slope are the same as would be specified for a TCR. The effect of the slope-correcting capacitor is shown in Figure 49.

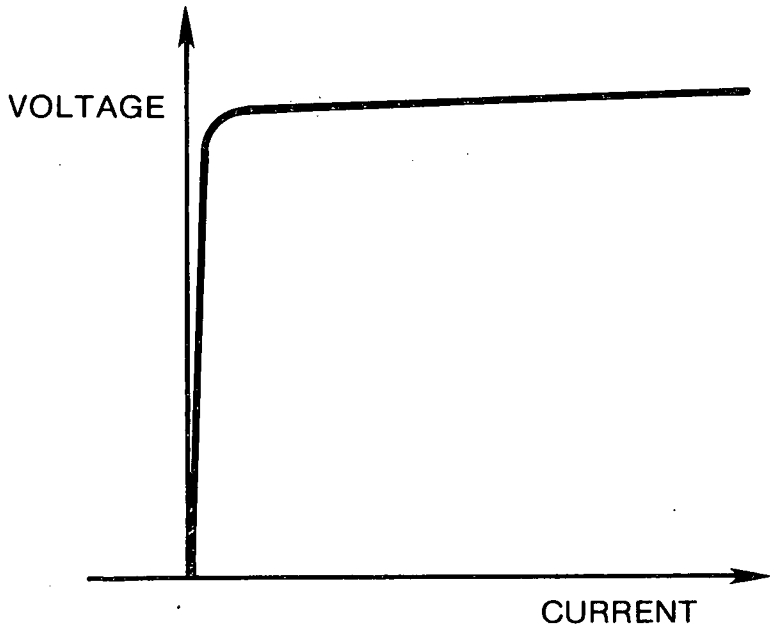


Figure 48. Basic Voltage/Current Characteristic for Polyphase Saturated Reactor

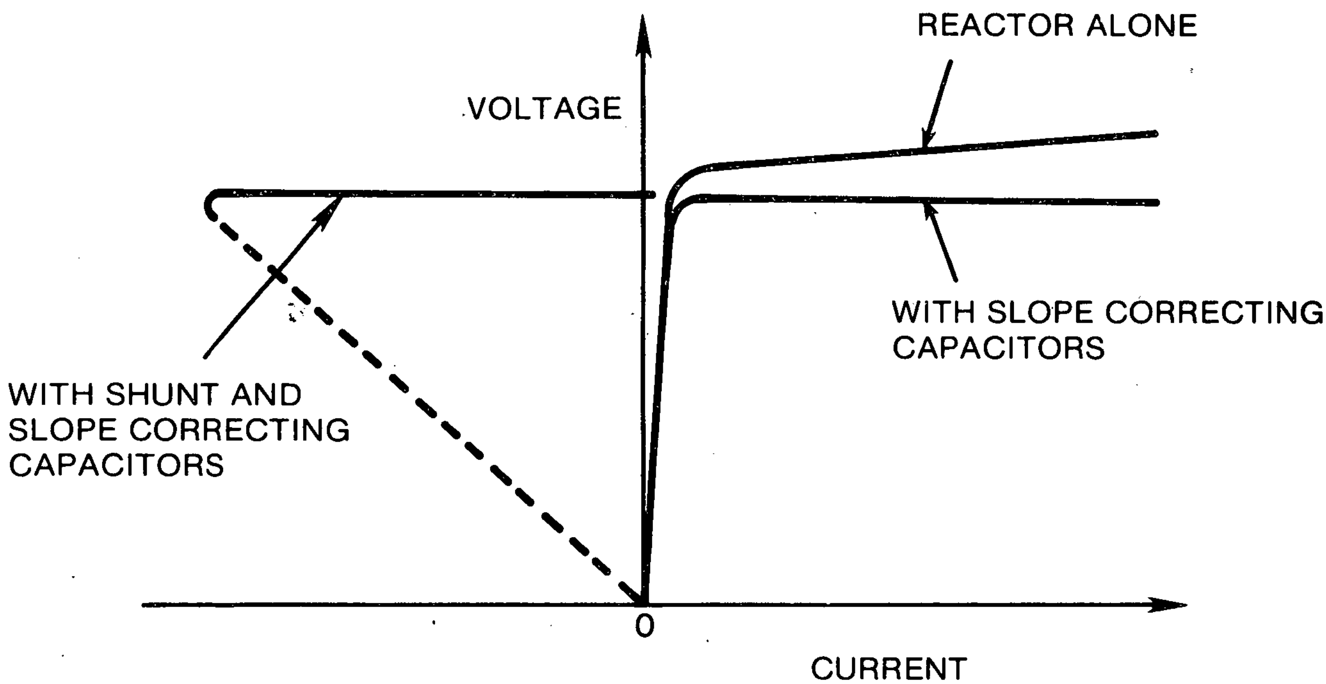


Figure 49. Voltage/Current Characteristics for Saturated Reactor Compensator with Series and Shunt Capacitors

Just as in the TCR compensator, the voltage-stabilized operation can be biased into the leading power-factor region by means of shunt capacitors. These may be designed as filters if the system resonances require it. A stepdown transformer is normally used for EHV connection, because it is said to be uneconomic to design the reactor for direct connection. The transformer may have a load tap changer which can effectively alter the knee-point voltage of the compensator on the high voltage side. It is possible to insert capacitors in series with the transformer as well as the reactor to obtain "flat stabilization" of both the EHV and the compensator busbars. In other respects, the stepdown transformer would be similar to the one used with the TCR compensator. A typical arrangement is shown in Figure 50.

The slope-correcting capacitors can make the saturated reactor compenstor susceptible to subharmonic instability, especially on weak systems, and it is normal practice to have a subharmonic damping filter in parallel with the capacitors. This filter as well as the capacitors must have a voltage rating compatible with any transients that might occur during energization or other system disturbances, and their overload capability limits the otherwise substantial overload capability of the saturated-reactor compensator, unless the capacitor is bypassed by a spark gap or some other device. The slope-correcting capacitors also slow the response of the compensator.

Ferroresonance and subharmonic resonances can be experienced with TCR and TCT type static var systems, particularly under high-voltage conditions or very weak ac lines. These problems can usually be solved by slight modifications in the control action in the TCR or TCT. A passive or active damper, as shown in Figure 50 with the SR, is not generally necessary with TCR or TCT.

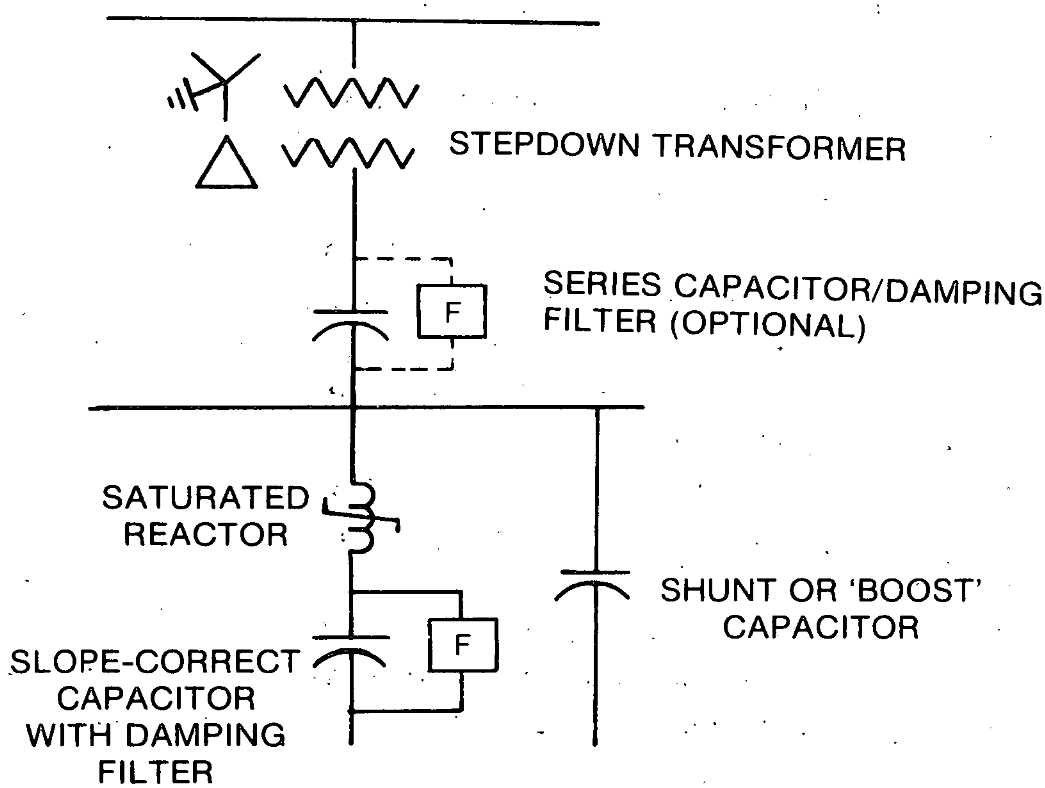


Figure 50. General Layout of Saturated Reactor Compensator with Shunt and Slope-Correcting Capacitors

The SR type static var system losses are comparable to those of similarly rated transformers, and their variation with current is similar to those of the TCR. Noise levels can be quite high near the reactor because of high-frequency magnetostrictive forces, and a brick enclosure is often used. Reliability is comparable with that of similarly rated transformers.

3.3.6 Summary — Fundamental Frequency Performance

All static var systems can be designed to behave similar to the rotating electric (synchronous) compensator for small deviations from the desired voltage setpoint. For small voltage disturbances, the reactive current and the controlled voltage V are related by a linear characteristic until the current limits of the compensator are reached.

When operating outside of their linear V/I control characteristics, the SVS behave different from the synchronous machine and different from the ideal reactive compensator.

The adjustable susceptance types (TCR-FC, TCR-TSC, TCR-MSC, and similar combinations with TCT and SR) behave as constant admittances, thus their reactive supply or absorption capacities drop (rise) as the square of the voltage deviation from nominal voltage. This V vs Q characteristic shown in Figure 51 with the V vs I curves in Figure 51 as have been shown in earlier discussions.

All reactive power compensators, static and synchronous, possess minimum voltages below which they must be taken off line. The minimum voltage trip-off values have not been shown in the V vs I characteristics. For static var systems, the voltage may drop to very low values (0.3 pu and less) for short periods, such as during faults, and the SVS will remain on-line. For long duration drops of that severity, SVS control power and thyristor gating energy can be lost, requiring a shut down. Usually the SVS can restart as soon as voltage recovers.

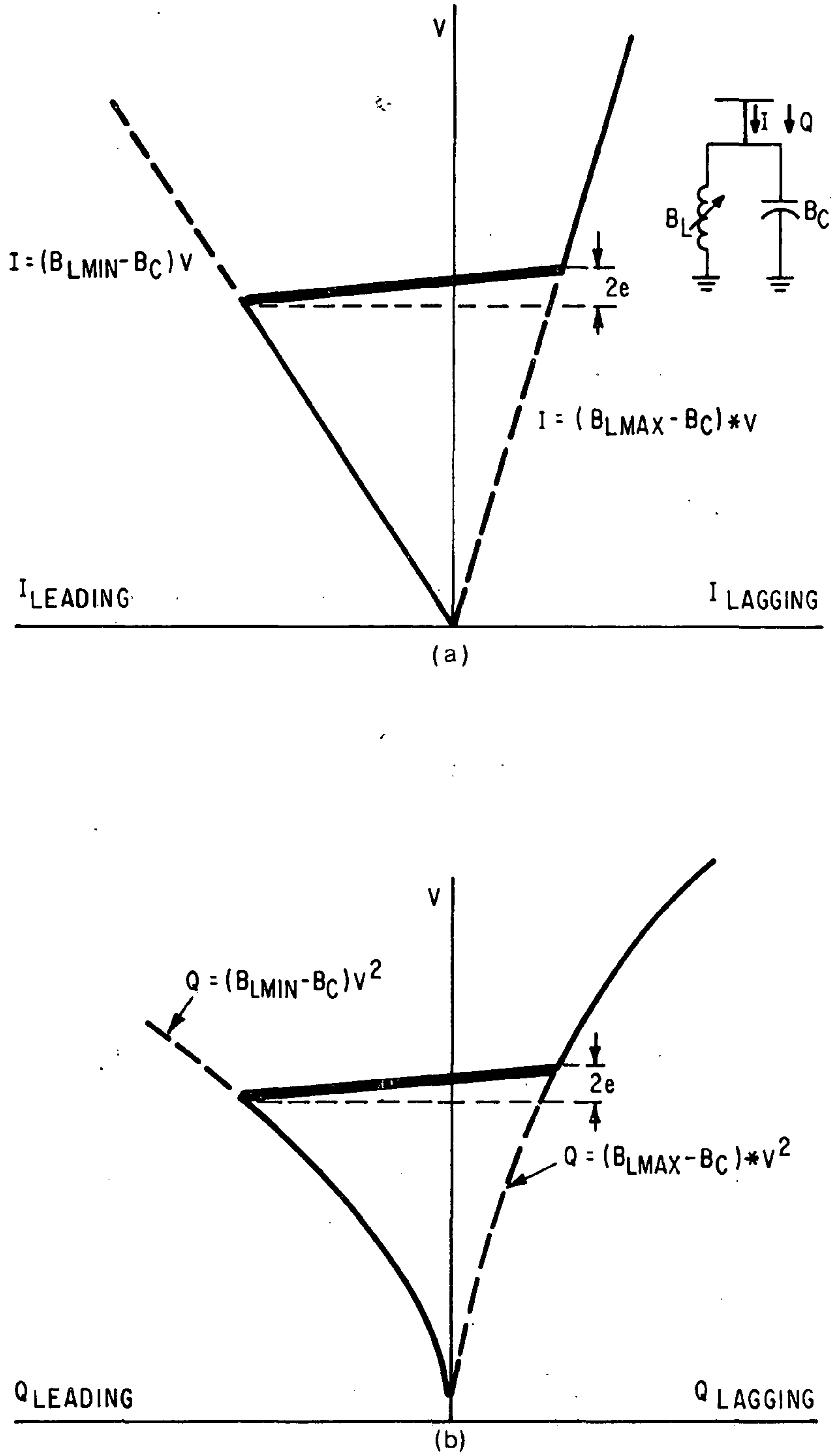


Figure 51. Steady-State SVS Characteristics
a) Voltage-vs-Net SVS Current, I
b) Voltage-vs-Net Vars, Q

3.4 TECHNICAL COMPARISONS OF THE SVS TYPES

An attempt to compare the SVS types discussed in this report, based on selected performance measures, is given in Table 3-3. Where a particular SVS type lacks a feature which others have, no comparison is possible with regard to that feature. Some categories are not applicable to specific types so an N.A. appears in the table.

3.4.1 A Comparison of Performance — All Types

For some performance measures a relative ranking code has been used. A number (1) refers to the best performance (fastest response or lowest losses), and higher numbers are used to signify that there is a measurable difference between types for the given performance measure. These rankings are not hard and fast and may be different in future commercial SVS designs. Not enough information is available on Frequency Converter type static var systems so they are not included in the rankings.

Furthermore, there are many other factors which, in a broad sense, affect performance such as reliability, start-up procedure, and transients and other measures which are more difficult to quantify for all SVS types. The reason is that equipment cost factors should be considered in any ranking. It is beyond the scope of this document to evaluate the relative equipment costs of the SVS types considered.

One extremely important performance measure is the speed of response - item 2 in Table 3-3. Its importance has been discussed in Section 2, particularly with regard to ac system stability enhancement. One utility that has made exhaustive studies of the various SVS types has ranked them all about equal [16] in speed of response as far as stability improvement is concerned. This excluded the TSC because all candidates in their comparison were required to have continuous voltage control capability [5].

Table 3-3
RELATIVE PERFORMANCE COMPARISON

Performance Measure	TSC	TCR-FC TCT-FC	TCR-TSC	TCR-MSC TCT-MSC	SR-FC	SR-MSC
1. Continuous Adjustment	No	Yes	Yes	Yes	Yes	Yes
2. Speed of Response						
2a. Cap. Switching Not Req'd.	N.A.	(1)	(1)	(1)	(1)	(1)
2b. Cap Switching Req'd.	(2)	N.A.	(2)	(3)	N.A.	(3)
3. Losses at Zero I_N						
A. Small (or no) Reactor	(1)	(2)	(1)	(1)	(2)	(1)
B. Reactor rating large compared to capacitive rating.	NA	(1)	(2)	(1)	(1)	(1)
4. Average Losses Over Total Operating Range	(2)	(3)	(2)	(1)	(3)	(1)
5. Lowest Order Characteristic Harmonics Released	N.A.	5 (11)[1]	5 (11)[1]	(5 (11)[1]	17	17
6. Overvoltage Limitation Capability	No	(3) (1)[2]	(2) (1)[2]	(2) (1)[2]	(2)	(1)
7. Control Programability						
7a o v - vs. - I Control Slope	N.A.	Yes	Yes	Yes	No	No
7b o Voltage Set Point	Yes	Yes	Yes	Yes	LTC[3]	LTC[3]
7c o Aux. System Stabilizer	N.A.	Yes	Yes	Yes	No	No
8. Phase Balancing Ability	Limited	Yes	Yes (TCR)	Yes (TCR)	Limited	Limited

Ranking Code: (1) is the best in category, higher numbers mean lower quality of the performance measure. (N.A.) means the performance measure is not applicable.

Notes:

1. If TCR or TCT arranged in 12 pulse groups 11th and 13th are the largest harmonics, harmonic number 5 assumes 6 pulse TCR or converter groups used.

2. With appropriate short term over current rating in the TCR, the over voltage duty can be made same as SR type SVS.

3. The step down transformer may be equipped with an under load tap changer LTC which can be used to make discrete setpoint changes.

Another important performance measure is the steady state losses or total annual energy consumption from losses in the SVS equipment. Two performance measures concerning losses are given in Table 3-3. Item 3 is the losses for zero net output, which is one possible steady-state operating point for static var systems that respond only to emergency system conditions. The SVS would not absorb or produce reactive power until transient instability is imminent or a serious load rejection overvoltage arises.

However, unless an SVS is blocked from regulating the voltage during normal system conditions (nonemergency situations), it will operate at various conditions within its design regulatory range. Therefore, item 4 in Table 3-3 characterizes the losses in terms of the average over the entire SVS control range.

3.4.2 A Comparison of TCR Based SVS Types

Table 3-3 is not thorough because it attempts to cover all types. Therefore, this section contains a more thorough evaluation of the TCR-FC, TCR-TSC, and TCR-MSC approaches that appear to be the most common commercial SVS configurations offered today. Similar comparisons could be made between variations on the basic SVS types employing TCT and SR reactive power control devices.

Thyristor Controlled Reactor and Fixed Capacitor (TCR-FC). The essential ingredients of this approach were shown in Figures 26a and 29. The controllable power branch is the TCR; the main capacitor and filter branches are fixed impedances during normal operation. For practical reasons, the SVS bus voltage is in the range of 12 to 36 kV, which dictates that a power transformer be used for connection to the transmission system. Generally, the transmission system parameter to be controlled is the voltage.

The typical voltage versus reactive power characteristic for this type of SVS is shown in Figure 52a. This characteristic is the locus of the possible steady-state operating points for the SVS when connected to an energized power system. The exact operating point at any time is determined by the SVS control settings and the conditions of the power system, as described in Sections 3.3.2 and 3.3.3.

The TCR-FC approach to SVS has many advantages. Its speed of response to changing system conditions is extremely fast - within 2 to 3 cycles of the power frequency wave for the largest voltage disturbances. Within the control range, the control characteristic is smooth and continuous. The associated control logic and equipment are relatively simple as compared to the other two approaches that will be discussed next. In addition, the technology and equipment involved have the greatest field operating experience.

In the application of any type of equipment to a power system, an area of considerable interest is equipment losses. The characteristic of the steady-state losses versus reactive power operating point for this SVS approach is shown in Figure 52b as a percentage of the capacitive MVAR rating. This characteristic does not include transformer or auxiliary losses. The losses are shown to increase steadily with increased TCR conduction, and are primarily comprised of I_2R losses in the reactor and of thyristor conduction losses.

An evaluation of losses for this equipment is obviously dependent upon the anticipated steady-state operating point or range in a particular application. Utility specifications indicate no unanimous agreement in this regard. However, it can be observed that if a particular application requires the SVS to operate well into the capacitive region most of the time, then the losses associated with this approach will be relatively

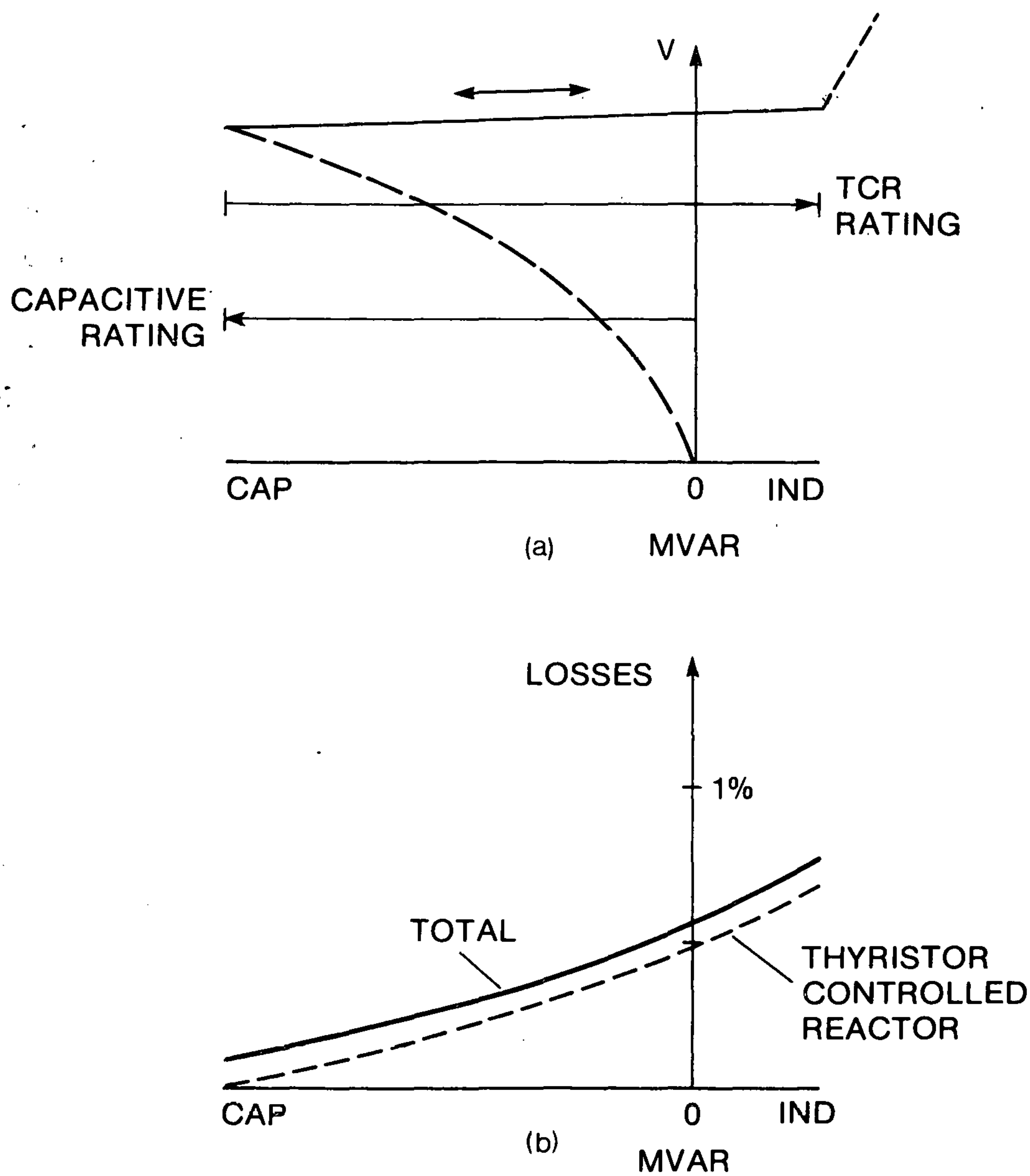


Figure 52. Characteristics of TCR-FC
a) Voltage vs. MVAR
b) Losses vs. MVAR

acceptable. If, on the other hand, the application requires that the SVS operate with the reactor substantially on most of the time, then the equipment losses could become a factor in providing an incentive to examine alternative SVS approaches.

At some operating points, a major portion of these losses are associated with TCR current that serves to compensate for the SVS capacitors. This is most obvious when no reactive power, capacitive or inductive, is required of the SVS. Then the reactor conduction serves no purpose other than to compensate for the current of the SVS capacitor branches. It is obvious that reactor conduction and losses could be reduced if the capacitors could be switched off. Approaches to achieving this are discussed in the next two sections.

Thyristor Controlled Reactor and Thyristor Switched Capacitor (TCR-TSC). Note that the word switched is used rather than phase-controlled. Capacitors do not lend themselves to phase control since any step change in capacitor voltage results in large oscillatory currents. The capacitor bank required for an SVS can be broken up into sections and each section switched with its own set of thyristors, as was shown in Figure 26d. The ability to switch off capacitors, in general, reduces the required MVAR rating for the TCR branch. The equipment still must be connected to the transmission system via a power transformer.

The SVS control must orchestrate the phase control of reactor and the switching of the capacitor to produce the desired overall characteristic. How this is done is illustrated in Figure 53. Figure 53a shows the same typical steady-state voltage-reactive power characteristic that was previously described. Figure 53b shows the points at which

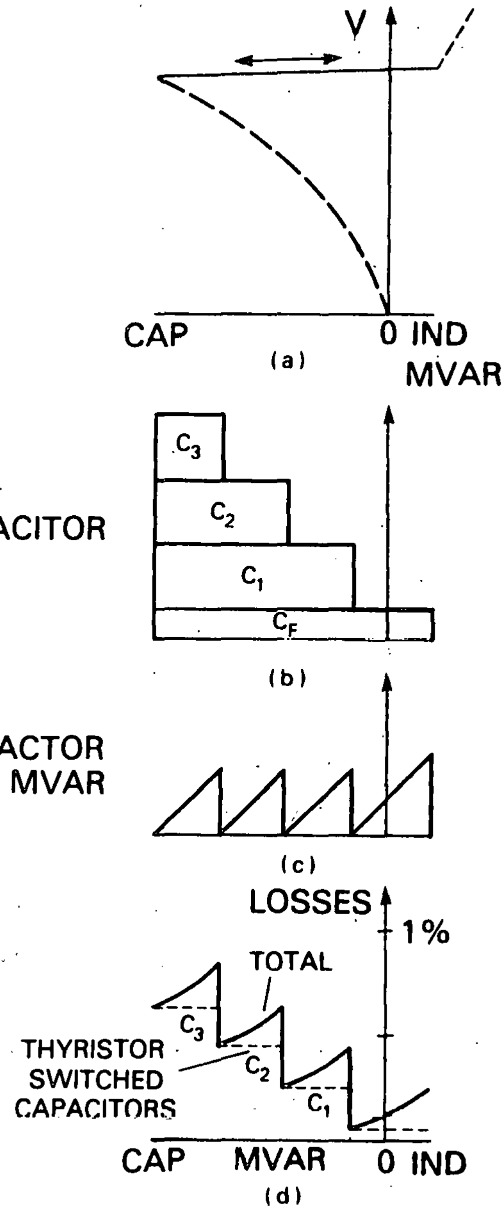


Figure 53. Operational Characteristics of TCR-TSC Approach
a) Voltage vs. SVS MVAR
b) Capacitor Switching vs. SVS MVAR
c) TCR vs. SVS MVAR
d) Losses vs. SVS MVAR

the capacitors would be switched in or out if the steady state operating point slowly traversed the control range. Figure 53c shows the reactive power of the TCR as its conduction is modulated to maintain the smooth control characteristic for the SVS.

An additional task of the control may be to avoid excessive high-frequency transients when the capacitors are switched. This can be accomplished by selected "point-on-the-voltage-wave" gating of the thyristors and a dc charge maintenance system for deenergized capacitor sections. Current-limiting reactors can be utilized in series with each capacitor section to control the magnitude and frequency of the thyristor capacitor switching currents that do occur.

A typical loss characteristic for this approach is shown in Figure 53d (again neglecting transformer and auxiliary losses). Note that in this case the losses are lower near the zero MVAR point, but increase markedly with increased reactive power (capacitive) output of the SVS. These losses are primarily thyristor losses, and increase as more capacitor sections are switched in. This capacitor section switching in discrete steps produces the discontinuous loss characteristic.

Overall for the TCR-TSC approach, the speed for response is only slightly slower than for the TCR-FC approach described first. This speed reduction is the result of the 0.5 to 1 cycle delay in capacitor switching necessary to minimize transients. The control operation is semi-continuous, in that discrete capacitor switching is required. As was described, the losses of the TCR-TSC static var system are relatively low near the zero MVAR operating point, but increase with increasing SVS capacitive MVARs. The task of controlling both the reactor and the capacitor section requires more complex control than for the TCR-FC approach and, in addition, requires more thyristors.

Thyristor Controlled Reactor and Mechanically Switched Capacitors (TCR-MSC). An alternate approach for capacitor switching is to use mechanical switches rather than thyristors. The objective of this is to avoid the expense and losses associated with thyristor capacitor switching, and to achieve lower average steady-state operating losses.

The basic circuit for this approach is shown in Figure 26c. In this case, mechanical switches rather than thyristors are shown in series with each capacitor section. The fact that three capacitor sections are shown here, as was the case with the thyristor-switched capacitors, is only for illustration purposes and does not imply that three sections are uniquely practical or that the number of sections would actually be the same for both approaches for any given application. The reactors in series with each capacitor section serve to limit the transient switching currents.

The capacitor sections in Figure 26c are shown applied to the SVS bus. However, the availability of suitable equipment allows the application of these switched capacitor sections at transmission voltages while the thyristor controlled reactor and filters remain on the lower voltage bus. This is advantageous over the TCR-TSC approach in reducing transformer rating requirements in instances where the SVS capacitive MVAR rating is substantially greater than the net inductive MVAR rating. In some cases, this approach would allow the use of an autotransformer tertiary winding and eliminate the need for a dedicated transformer.

The operation of the TCR-MSC approach during slow system changes is shown in Figure 54. Here, its operation is similar to that of the TCR-TSC approach in that discrete switching in and out of capacitors results as the operating point transverses the control range. Also, as in the TCR-TSC case, the reactor output is coordinated with this

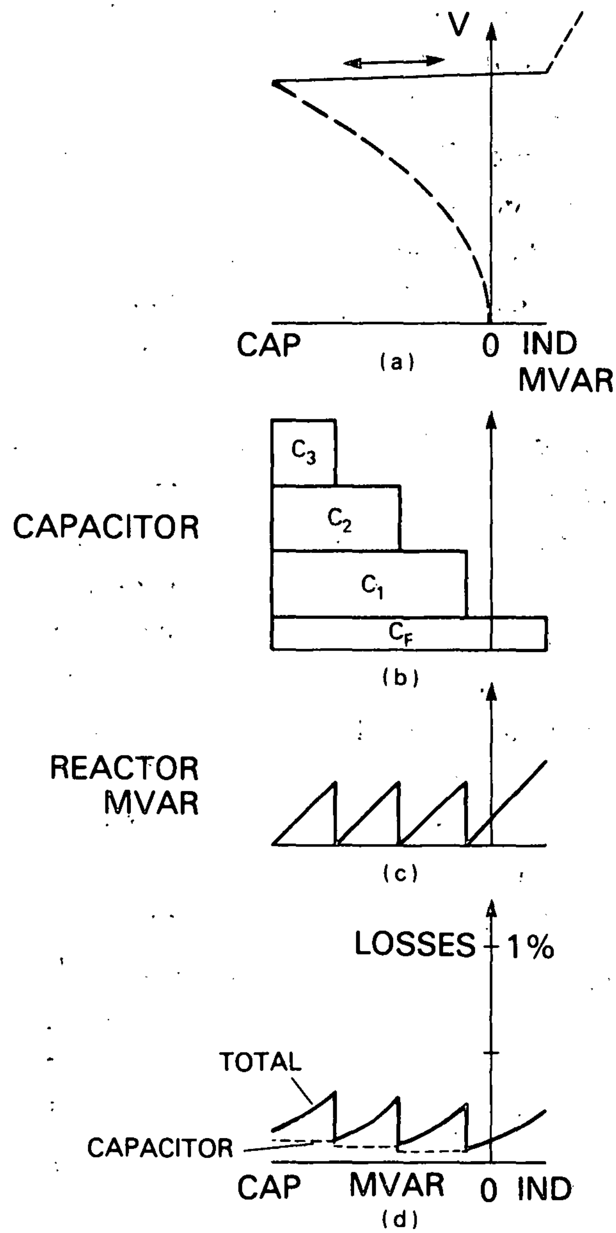


Figure 54. Steady-State Operational Characteristics of TCR-MSC Approach
a) Voltage vs. SVS MVAR
b) Capacitor Switching vs. SVS MVAR
c) TCR vs. SVS MVAR
d) Losses vs. SVS MVAR

switching to maintain a smooth overall voltage - reactive power characteristic. Note that as with the thyristor switched capacitor approach, the reactor steady-state MVAR requirements are reduced by the ability to switch out capacitor sections.

The loss characteristic of this approach is shown in Figure 54d. The curve is still discontinuous as a result of the discrete capacitor switching. However, the substitution of mechanical switches for thyristors in the capacitor sections results in a considerable reduction in losses in the capacitive operating range of the SVS.

The control operation illustrated in Figure 54 has the implicit assumption that it is desirable to have the SVS participate in the control of slow daily system voltage variations. In many transmission applications, however, the SVS is selected for its voltage support only under dynamic system conditions. In such cases, it may be desirable to have the SVS control maintain its steady-state operating point near zero MVAR and keep its capacitive MVARs held in reserve only for emergency system voltage support. Capacitor switching would not then be a daily occurrence.

The "emergency" dynamic system conditions of interest in many SVS applications are the system voltage depressions associated with the temporary angular swings of the system generators that follow a major fault. The control operation of the TCR-MSC approach to such conditions is illustrated in Figure 55. It is different from the steady-state operation shown in Figure 54. When the system voltage falls to a present level, V min, as the result of a fault, the SVS control quickly closes all the capacitor switches.

During the system voltage variations that immediately follow the fault the capacitor switches remain closed. SVS voltage control is provided via the phase control of the thyristors in the reactor branch. The reactor is designed

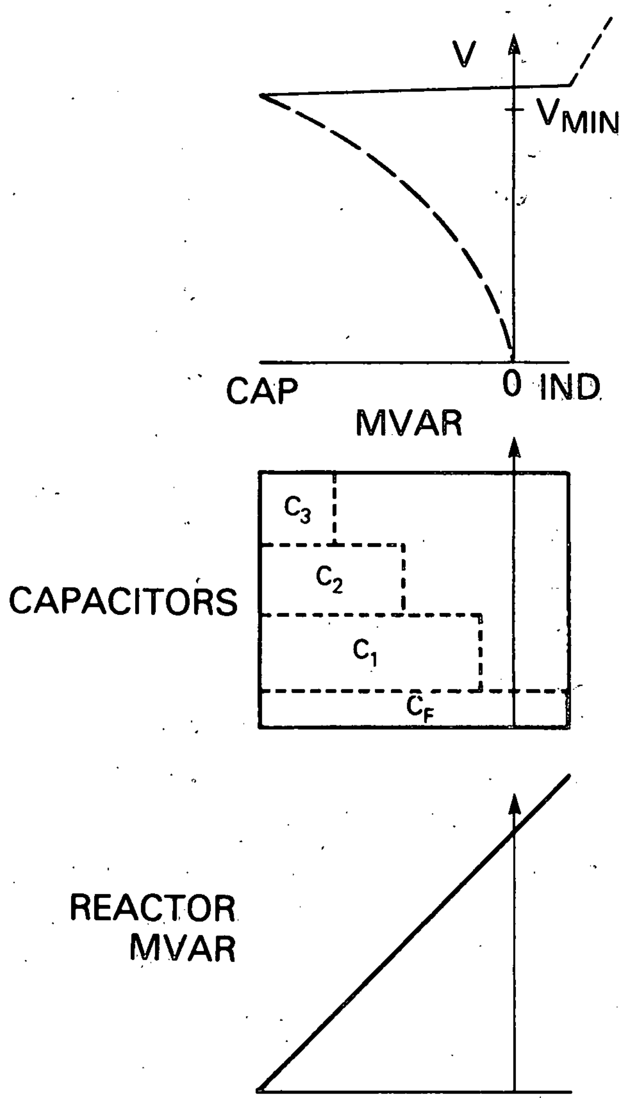


Figure 55. Dynamic System Condition Operation for TCR-MSC Approach

to have the impedance range to temporarily compensate for, if necessary, the combined capcitance of all the capacitor sections. This would utilize the considerable temporary overload capability of the reactors and thyristors of the TCR branch. The temporary extended impedance range for the TCR is made possible by designing it with only partial thyristor conduction under steady-state conditions. Thus only under dynamic conditions would the reactor be phased full-on. After the dynamic system condition is over, the control would direct the switches to deenergize the appropriate number of capacitor sections and return the SVS to the low-loss steady-state operating mode of Figure 54.

The switching of capacitors is obviously an important aspect of this SVS approach. This switching can be carefully done to reduce transients. The technique utilized is point-on-wave-switching, which has been successfully demonstrated in the field [13]. If necessary, high-speed discharge of capacitor-trapped charge can be accomplished as was described in Section 3.3.4.

Summary of Comparison Between TCR Type Static Var Systems. The TCR-MSC approach combines a thyristor-controlled reactor with mechanically switched capacitors to achieve the lowest overall steady-state operating losses of the three approaches discussed. Under dynamic conditions, the capacitors are quickly energized and the temporary extended MVAR capability of the TCR is utilized in the overall voltage control. This approach has a semi-continuous control characteristic and added control complexity when compared to the TCR-FC approach. Because of the mechanical switching, the speed of response is somewhat less than that of the TCR-FC approach. However, the effect of this can be diminished or eliminated by the anticipatory control action of initiating the switching during the system fault. Some TCR-TSC designs are prevented from switching capacitors on during the fault to avoid a loss in TSC controllability.

Section 4

APPLICATION STUDIES FOR STATIC VAR SYSTEMS

Whether an SVS is required for simple voltage control or is vital to ensure system stability, system studies are required to properly prepare for each application.

4.1 BASIC STUDIES FOR SELECTION OF SVS RATINGS

The following features and parameters of an SVS should be determined from planning studies. .

(1) The net capacitive and inductive ratings required for controlling the voltage in the steady state should be determined with power flow studies. The influence of load tap changing transformers, automatically switched and manually operated capacitors and reactors in the vicinity of the planned SVS should be considered since some economies in SVS rating may result. Models of SVS suitable for use in load flow studies are described in Appendices D and E.

(2) The additional capacitive and inductive SVS range required for large, but momentary excursions due to faults, line tripping and load rejection should be identified. The probable steady-state operating points from which the SVS may be called upon to deliver the short-time duty should be considered carefully.

Simulations using a digital stability program will be required for these studies. Suitable SVS models for these studies are described in Appendices D and E.

Possible economies in inductive SVS ratings should be sought through consideration of auxiliary switched capacitor banks to extend the SVS voltage control range. For stabilization or for minimizing voltage dips following faults, capacitors switched on-line quickly after the fault can be quite effective.

Further economies in SVS inductive rating may be realized if those system disturbances that cause overvoltage conditions are infrequent and a short-time overload rating can be specified in terms of inductive MVAR or current and a maximum accumulated time for each event.

(3) Based on the steady-state and dynamic performance studies in (1) and (2), the equipment voltage ratings, steady-state and short-term, should be identified.

(4) Operational features of the SVS should be determined, that is, whether voltage setpoint and droop (slope) should be adjustable and whether those adjustments must be made via supervisory control. An SVS can be totally unmanned [17] if the remote system operator has the capability of starting, stopping, and adjusting its operating point from a centralized dispatch center or some other convenient, manned station.

(5) The startup sequence must be chosen because an SVS may cause a noticeable voltage disturbance when it is brought on-line, particularly since the system is likely

to be in a low voltage state when the SVS is energized. Even under the worst of prestart system conditions, acceptable startup sequences are achievable [17, 18] and the SVS startup sequence can be totally automated to occur in about one second.

The only tools required to perform the studies mentioned above are the conventional digital power flow program and digital stability program. The modeling concepts are described in Appendix D of this report. The SVS models develped for use in the Philadelphia Electric Company (P.E. Co.) load flow and stability programs are documented in Appendix E.

4.2 SPECIAL OPTIONAL STUDIES

Certain additional studies may be desirable, depending on the specific application. For example, if the SVS is needed to exercise individual phase control to correct for steady-state or transient imbalances in system voltage, studies on a TNA or digital transients program may be required.

Similarly, if the SVS under study is of significant rating and is to be applied on an EHV transmission system, its response to surge phenomena may be of importance. If the system already contains significant series compensation, studies on a TNA are advisable.

Some SVS equipment suppliers consultants and utilities have access to the simulation facilities required for such studies of the cycle-by-cycle and phase-by-phase SVS performance. Complete modeling of specific SVS equipment is not required in most cases, but a thorough knowledge of the SVS equipment and its controls are important for such studies. The utility planner should seek the advice of one or more suppliers before attempting studies of extremely detailed SVS behavior.

It is sometimes advisable to request that the SVS supplier perform simulation studies using their simulation facilities as part of a contract to supply a specific SVS for a given application. Some of those studies may duplicate the efforts of the utility for whom the SVS is being supplied, but generally, the suppliers studies would be useful to optimize the control parameters, as well as to get a personal understanding of the environment in which their equipment is destined to operate. Utility planners should encourage such studies and participate with the supplier in the conduct of them.

One routine investigation the utility planner should conduct is a study to determine whether the SVS will require harmonic filters for the specific application. Such analyses have, to date, been conducted by the supplier and have involved simplified HVAC system models and a great deal of state-of-the-art judgement based on the supplier's experience. However, such a study should be conducted by the utility prior to specifying the SVS equipment for its application.

A recently completed research contract sponsored by EPRI [10] has increased the industry's understanding of the HVAC system's response to harmonics generated by devices that utilize power thyristors or rectifiers. That research led to the development of a computational method for use by utilities to predict their HVAC system's response to harmonic currents generated by planned SVS and HVDC systems.

4.3 SUMMARY

Every SVS application should be regarded as a unique application and planning studies should be conducted to predict the SVS and HVAC system's performance. Simulation studies are vital, but an understanding of the basic operation of static var systems in typical HVAC applications is equally important. Exhaustive studies are never possible for any new equipment application, but a good understanding of basic SVS fundamentals can guide the planner in selecting a limited set of studies which are adequate to select and specify the right SVS for his system's specific needs. This report has laid a foundation of fundamental SVS performance in the context of fundamental frequency, balanced three-phase power system operation. The references cited in this paper are a source of more in-depth understanding of the various SVS configurations and their cycle-by-cycle performance. The SVS technology, as applied to HVAC networks, is relatively new and changing rapidly, but most of the basic concepts presented in this paper will be unaffected by the changing SVS technology that can be foreseen.

Appendix A

SURGE IMPEDANCE LOADING

Because ac transmission lines possess both series inductive and distributed shunt capacitive reactance (charging), reactive power may be consumed or "generated" by a transmission line as active power flows through that line. At one unique value of active power, called surge impedance loading (SIL) of the line, the line appears from both ends to neither absorb nor generate reactive power. For a given transmission line operating at voltage V_o and possessing a surge impedance of Z_o, the surge impedance load of "natural power transfer" on that line is

$$P_o = \frac{V_o^2}{Z_o}$$

When the actual power transfer, P, equals the "natural" SIL, P_o, the positive sequence phase voltage and line current are in phase at any point along the line including the end points, indicating no reactive power flowing in the line.

For power transfers, P, less than SIL (P_o) the excess charging vars will flow out of one or both ends of the line. Conversely, for power transfers exceeding the SIL, the excess reactive losses of the line will be absorbed from adjacent systems at one or both ends of the line. This phenomena is illustrated in Figure A-1.

Because loads, and thus line flows into load areas, vary both slowly - due to daily and seasonal load cycles -- and rapidly -- following fault-initiated disturbances, the power in a line never equals SIL for long, if at all. Fixed and variable compensation means are utilized to satisfy the line's needs in order to preserve a reasonable voltage profile and to maintain the lines power carrying capability.

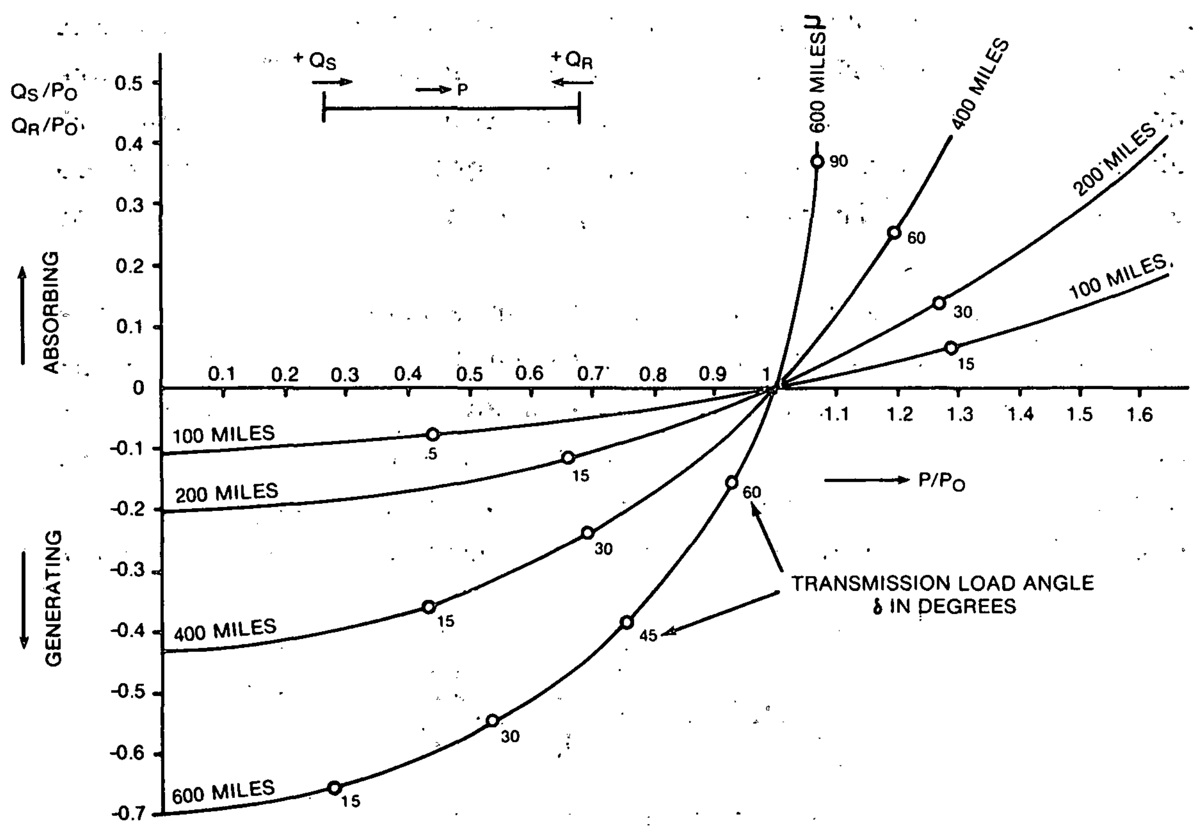


Figure A-1. Terminal Reactive Power Conditions for a Symmetrical Line, as a Function of Power Transmitted and Line Length

Appendix B

TRANSIENT STABILITY USING THE EQUAL AREA STABILITY CRITERION

One way to illustrate the benefit of mid-system voltage control using an SVS for transient stability is to utilize the graphical equal-area criterion familiar to ac system planners. While not a practical tool for studying the stability of realistic systems, the graphical approach can provide helpful insights to guide the planner in his simulation studies.

The familiar equal area criterion applied to the system in Figure B-1 is summarized in Figure B-2. The power angle curves in Figure B-2 are derived assuming internal machine voltages E_1, and E_2 are constant magnitude behind the transient reactances for each machine. This same assumption was made in constructing power-versus-angle curves in Figure 16.

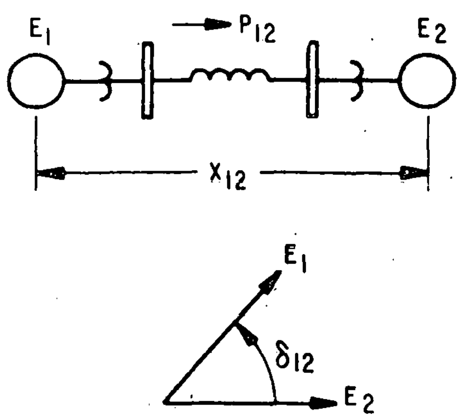


Figure B-1. System Without SVS

SWING EQUATION

$$M \frac{d^2\delta}{dt^2} = P_m - P_e$$

$P_m > P_e$ ACCELERATION

$P_e > P_m$ DECELERATION

KINETIC ENERGY ADDED $= A_1 = \int_{\delta_0}^{\delta_1} (P_m - P_{e2})\, d\delta$

KINETIC ENERGY REMOVED $= A_2 = \int_{\delta_1}^{\delta_2} (P_{e3} - P_m)\, d\delta$

$A_2 > A_1$ - STABLE

$A_2 < A_1$ - UNSTABLE

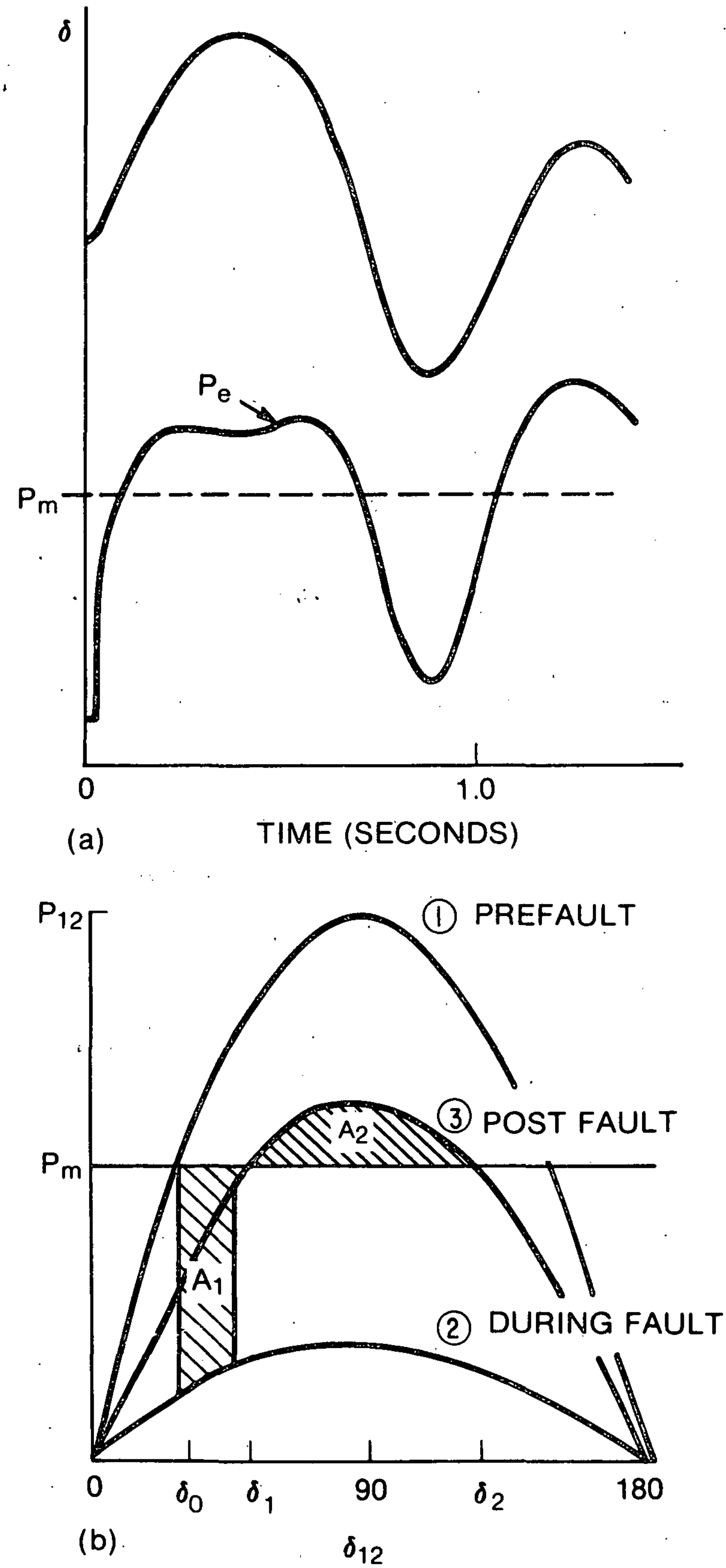


Figure B-2. Equal Area Criterion

Figure B-4a shows the equal area criterion applied to the system model in Figure B-3 with the SVS out of service. A specific fault duration was assumed and generator 1 was assumed to operate at constant mechanical (prime mover) power P_m. Governor dynamics and saliency effects are ignored for simplicity.

The case shown in Figure B-4a corresponds to the critical clearing time for the given fault. Therefore area A_1 equals area A_2 and slightly longer duration fault would cause first swing transient instability.

Assuming the same fault duration and initial power transfer, P_m, for the system with the SVS energized, Figure B-4b would result. Again, A_1 equals A_2, but the unshaded area between the P_m line and curve 3 can be viewed as additional stability margin gained by employing the SVS for mid-system voltage control. The power-versus-angle curves in Figure B-4b apply only for an SVS of high capacitive MVAR rating. The continuous control range of the SVS was not exceeded during the post fault synchronizing power-angle swings.

A smaller (more practical) sized SVS would very likely be over-ranged during the large post fault voltage swings. Therefore, the curves shown in Figure B-4c are more realistic for illustrating the benefit attributable to the SVS.

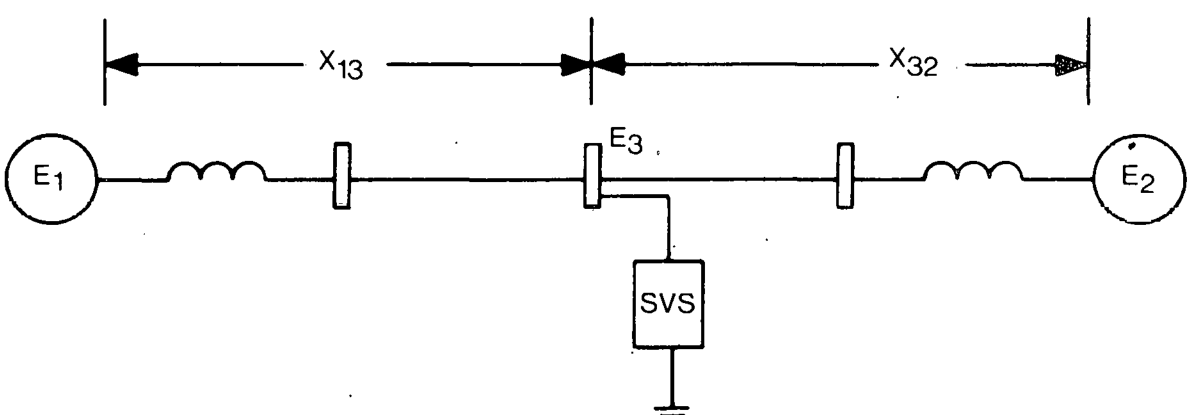


Figure B-3. System with SVS

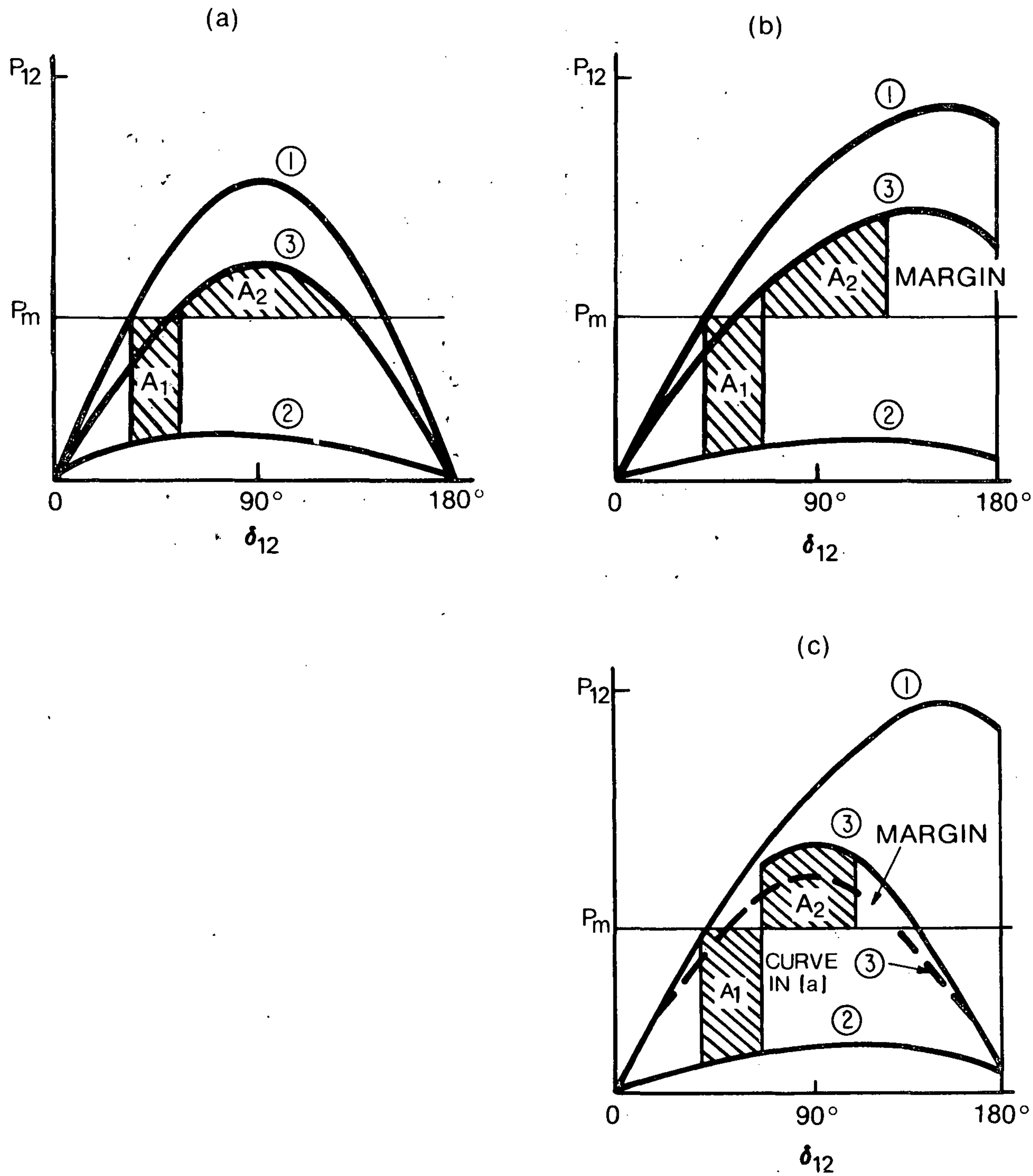


Figure B-4. Stability Margin with SVS
a) No SVS
b) With Large SVS
c) With Modest SVS

Curves 1 and 2 in Figure B-4c correspond to curves 1 and 2 in Figure B-4b, but the post fault curve 3 in Figure B-4c is simply curve 3 of the no SVS case in Figure B-4a with its peak increased to account for the large capacitor bank effectively "switched onto" the mid-system bus by the SVS control action. The dashed curve in Figure B-4c is equivalent to curve 3 in Figure B-4a and is shown only to show the impact of the capacitor bank.

Notice there is still a gain in stability margin (unshaded area above P_m line) in Figure B-4c, but generally that margin will be less than achievable with an extremely large rating SVS. The capacitive rating of the SVS is extremely important to the transient stability of the system to which it is connected.

Appendix C

A RELIABILITY ANALYSIS OF A TCR-FC SVS

A reliability analysis for a typical TCR-FC type SVS is provided in Table C-1. The sample SVS is shown schematically in Figure C-1. That figure shows one of two duplicate static var systems (compensators) contemplated for a 500 kV bus voltage application.

C.1 AVAILABILITY CALCULATION

The calculations for availability show that each 250 MVA SVS of the sample system will have an availability of better than 99%. Detailed calculations are included as well as the recommendations for spares.

The method of calculation is based on published sources of failure rate data, industry surveys, and General Electric Company field experience. The sources of data are listed in Section C-2.

The tabulated detailed calculations are based on the published per unit failure rate λ. The failures per year equals the quantity, n, of each equipment, multiplied by λ, or $n\lambda$.

The hours (r), to repair a failure, or to replace it with a spare part, are based on data and field experience. The hours down per year are then calculated from $n\lambda r$. These hours are totaled for all of the equipment, and added to the scheduled outage to give the total hours of unavailability.

Table C-1

RELIABILITY ANALYSIS

Equipment	Quantity	λ Per Unit Failures	nλ Failures Per Year	r Hours Per Failure	nλr Hours Down Per Year	Spares
500 kV:						
Disconnect	1	.0010	.0010	4	.004	Note 1
Ground Switch	1	.0010	.0010	4	.004	Note 1
Circuit Breaker	1	.0230	.0230	72	1.660	Note 1
Arresters	3	.0008	.0024	4	.010	Yes
CTs	12	.0012	.0144	8	.115	Yes
PTs	3	.0012	.0036	8	.029	Yes
Transformer	1	.0030	.0030	24/6570	.072/19.71	Note 1, 3
34.5 kV:						
CTs	33	.0012	.0396	8	.317	Yes
PTs	8	.0031	.0248	8	.198	Yes
Arresters	3	.0008	.0024	4	.010	Yes
Bus Work	1	.0104	.0104	36	.374	Note 1
Disconnects	8	.0029	.0232	6	.139	Note 1
Vacuum Switches	1	.0029	.0203	6	.122	Note 1
Thyristor Controller	1	.0600	.0600	4	.240	Note 1
Shunt Reactors	6	.0040	.0240	24/1842	.576/44.208	Note 1, 4
Filter/CLR Reactors	21	.0040	.0840	24/1842	2.016/154.728	Note 1, 4
Capacitors	-	No shutdown for single failures				Yes
Ground Level:						
Thyristor Cooling	1	.3600	.3600	3	1.080	Note 1
Control Equipment	1	.5100	.5100	4	2.040	Note 1
Master Control and Regulator	1	.1030	.1030	4	.412	Note 1
Transformer Relaying	1	.0300	.0300	4	.120	Note 1
Feeder Relaying	9	.0200	.1800	4	.72	Note 1
Capacitor Protection	7	.0236	.1652	4	.66	Note 1
A-C Auxiliary Power	1	.2000	.2000	0.5	.10	Note 2
D-C Auxiliary Power	1	.2500	.2500	0.5	.13	
Total Forced Outage			2.1353		11.148/227.112	
Scheduled Outage			2	24	48.00	
Total Downtime					59.148/275/112	
Per Cent Downtime					0.68/3.14	
Per Cent Availability					99.32/96.86	

Note 1 - Spare parts or modules available

Note 2 - Alternate source available.

Note 3 - Failure requiring return to factory, 6570 hours.

Note 4 - Failure requiring return to factory, 1842 hours.

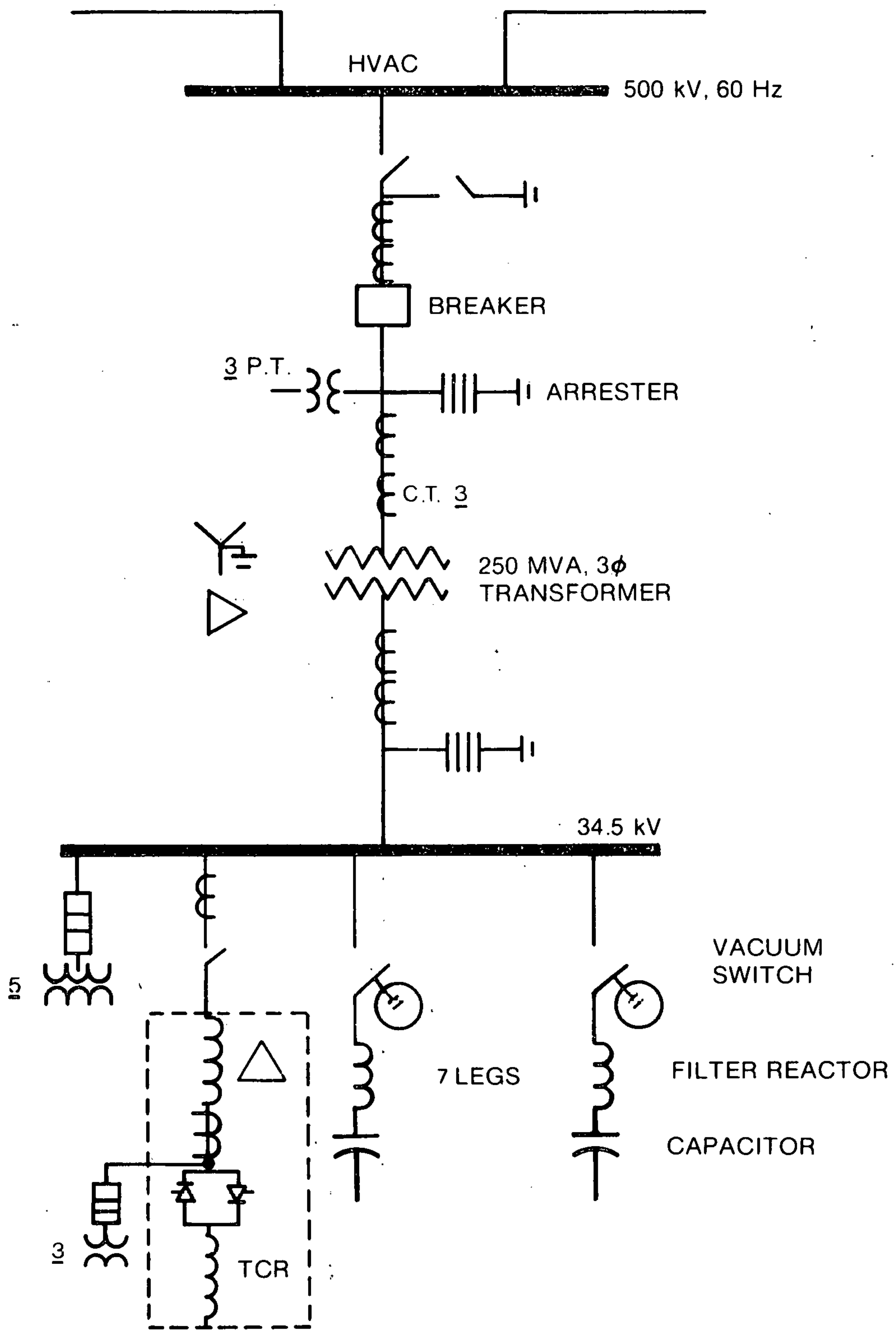


Figure C-1. One of Two Static Var Systems in Sample System Used in Reliability Analysis

If the switching station and compensator are down for any external system reasons, maintenance may be done at that time without being chargeable to the switching or compensating system.

C.2 SOURCES OF FAILURE RATE DATA

1. D.J. Cummings, F.E. Montmeat, A.D. Patton, J. Zemkoski. Power System Reliability: II - Applications and a Computer Program. IEEE Transactions, Vol. PAS-94, pp. 636-43, July 1965.

2. W.H. Dickinson. Report on Reliability of Electric Equipment in Industrial Plants. AIEE Transactions, Part II, pp. 132-51, July 1962.

3. A.D. Patton. Determination and Analysis of Data for Reliability Studies. IEEE Transactions, Vol. PAS-87, pp. 84-100.

4. R.A.W. Conner and R.A. Parkins. Operational Statistics in the Management of Large Distribution Systems. Proceedings of the IEE, Vol. 113, pp. 1823-34, November 1966.

5. S.A. Mallard and V.C. Thomas. A Method for Calculating Transmission System Reliability. IEEE Transactions, Vol. PAS-87, pp. 824-34.

6. Unpublished industry standards.

7. Estimates for HVDC applications.

8. Survey of the Reliability of Electrical Equipment in Industrial Plants. IEEE-IAS Transactions, March/April, June/July, September/October 1974.

9. CIGRE 13-06 World Wide Reliability Survey of Power Circuit Breakers Above 63 kV (not yet published).

10. General Electric Field Experience on HVDC and Static Var Systems.

Appendix D

PERFORMANCE MODELING CONCEPTS FOR STATIC VAR SYSTEMS

General modeling concepts for static var systems are discussed in this section. The models developed are primarily suitable for load flow and transient stability studies and are applicable accurately to all static var systems with a thyristor-controlled reactive element as well as those equipped with a saturated reactor. The models also apply to thyristor switched capacitor type SVS if discrete steps characteristic inherent to the device is assumed many in numbers and thereby small in magnitude.

D.1 MODELING THE SVS FOR LOAD FLOW STUDIES

For the purpose of load flow modeling, an SVS is rightfully assumed to be a shunt element which, either through some feedback control or due to the saturating nature of the device, has a voltage/current characteristic as shown in Figure 43c.

Three alternative methods can be employed to model an SVS in a load flow computer program not equipped with a specific SVS model. The first and simplest is to treat the SVS as one would a synchronous condenser that controls the HVAC bus voltage at some desired value V_0. One would declare the HVAC bus a (P,V) bus in the jargon of power flow solution methods. The data specification would be:

$P = 0$ (no real power generated by SVS)

$V = V_0$, the desired setpoint

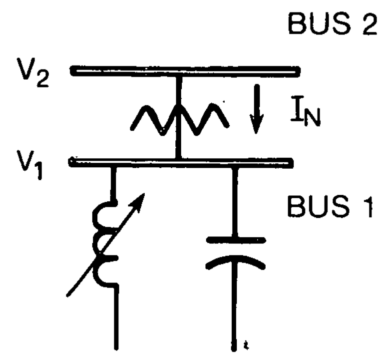
Q_{max} and Q_{min}

This modeling method is illustrated in Figure D-1a, with the resulting SVS characteristic shown by the solid line in Figure D-1b. The correct V-vs-I characteristic is shown dashed for reference. Three problems exist with this method. First, there is no way to represent a drooping control characteristic with the desired slope K_S defined in Figure 43c. Secondly, there is no way for the voltage on the SVS equipment bus, V_1, to be computed. Lastly, the Q_{max}, Q_{min} limit specifications are not appropriate for an SVS.

A second method that will yield the drooping voltage control slope K_S in voltage V_2 is given in Figure D-1c. The actual SVS transformer reactance is replaced by a transformer with reactance X_S equal to the desired slope K_S. There is still no way to compute V_1, and the Q_{max}, Q_{min} limits are still incorrect.

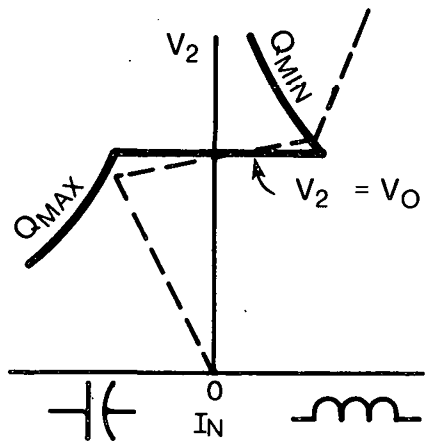
A third method, which eliminates all but the Q limit problem, is given in Figure D-2a. This method involves splitting the actual transformer reactance, X_t, into the equivalent slope reactance X_S and $(X_t - X_S)$ and creating a phantom bus with voltage V_3. By specifying bus 1 the P,V bus, and using a remote-bus-voltage control feature available in some power flow programs, one can compute both V_2 and V_1 correctly over the static var system control range of I_N.

<u>The fourth and preferred method</u> would be to employ the phantom bus concept in the previous method, and force the computational program to change the P,V bus to a constant impedance bus with value X_C or X_L whenever the limits are encountered. This method requires a program code change



(a)

BUS 2 = P, V BUS
(WITH Q_{MAX}, Q_{MIN})



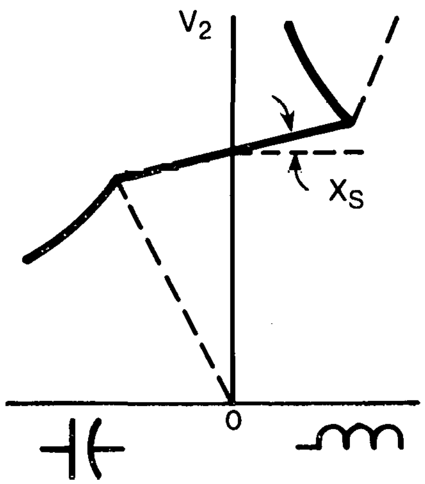
— V_2 HELD AT V_0
IGNORES V-vs-I SLOPE K_S

— NO WAY TO CALCULATE V_1

— LIMITS INCORRECT

(b)

BUS 1 = P, V BUS AND ARTIFICIAL TRANSFORMER IMPEDANCE TO GIVE SLOPE X_S



— V_1 IS STILL NOT CORRECT

— LIMITS INCORRECT

(c)

Figure D-1. SVS Models in Load Flow

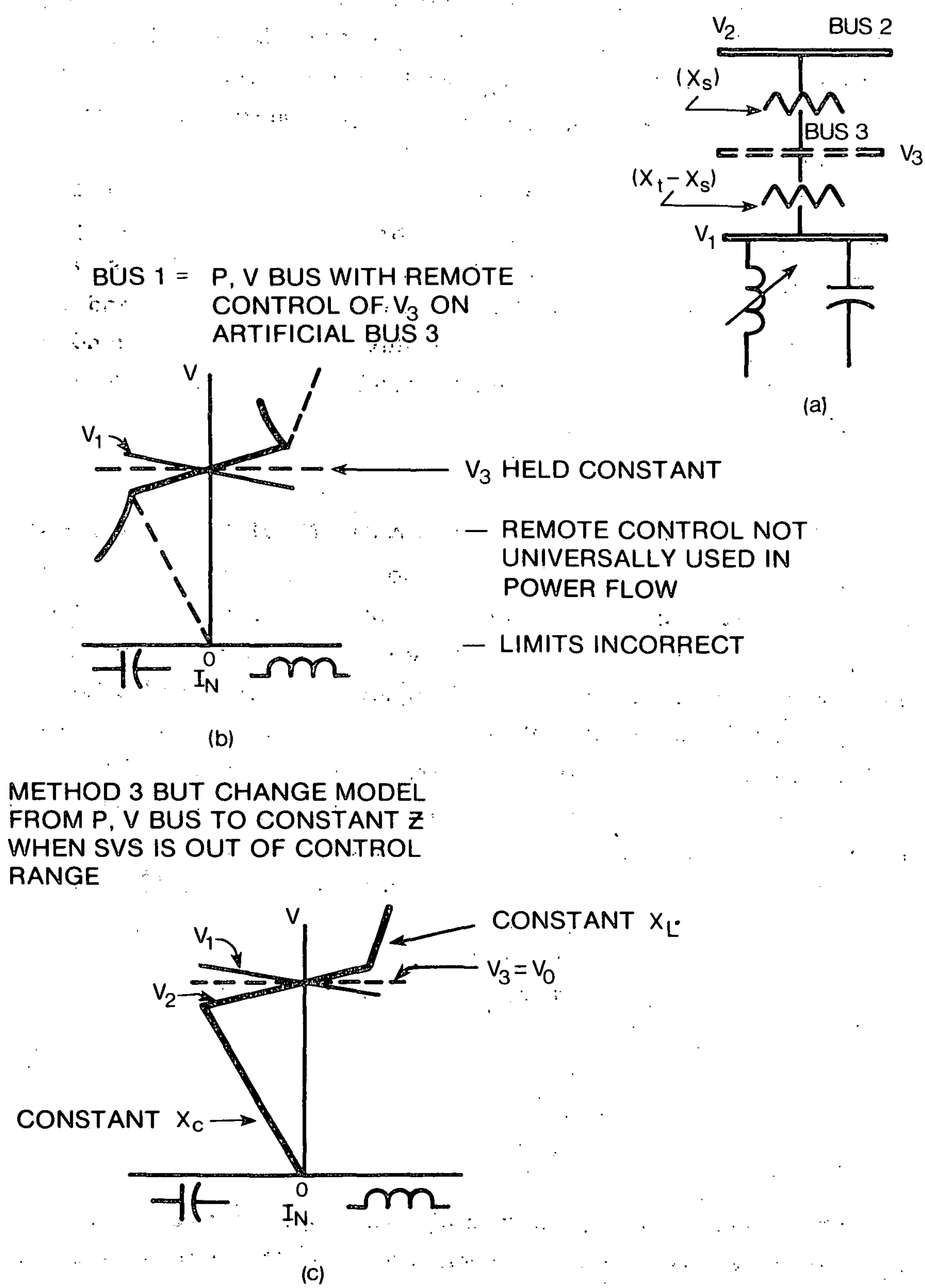


Figure D-2. SVS Models in Load Flow

in most conventional power flow programs. It also requires that the program in use have a remote-bus-voltage control feature to hold $V_3 = V_0$ and still apply the X_C, X_L limits on the SVS equipment bus on which voltage V_1 is computed.

A fifth method, which was adopted by Philadelphia Electric Company (P.E. Co.) in their power flow program, is to specify the HVAC bus (V_2 in Figure D-1a) as a (P,V) bus, except when control limits are encountered, and specify it a constant X_L or X_C bus during limiting conditions. That program change is documented in Appendix E of this report.

D.2 MODELING OF SVS FOR TRANSIENT AND DYNAMIC STABILITY STUDIES

The static var system can be modeled as a time-varying shunt admittance for conventional transient stability studies. These studies are concerned with positive sequence system behavior where the frequency does not appreciably change from its fundamental value. To that end, the general model, shown in block diagram of Figure D-3a, is a sufficient SVS model for the majority of power system transient or dynamic stability studies. In this model the recommended choice of H(s) is either

$$H(s) = \frac{k}{1+sT} \cdot \frac{1+sT_1}{1+sT_2} \qquad (1)$$

or

$$H(s) = \frac{k}{s} \cdot \frac{1+sT_1}{1+sT_2} \qquad (2)$$

The values for gain k and the time constants T, T_1 and T_2 are equal to those recommended for the AVR block in the more detailed representation of SVS discussed later on in this section. It should be noted, however, that the gain k in Eq. 1 is related to the slope of the SVS characteristic in the control region by the following equation

$$K\, K_s\, V_{ref} = 1 \qquad (3)$$

On the other hand, in the cases where H(s) is of integral characteristic (Eq. 2), the incorporation of the slope X_s into the SVS characteristic should be accomplished by a current feedback. This current feedback can be included in the general model by feeding back I_N times the desired droop into the input designated as "other signals" in Figure D-3a.

The more detailed model of SVS, shown by the block diagram in Figure D-3b, may also be utilized in stability studies. The model is oriented, primarily, towards those SVS types which are equipped with thyristor-controlled reactor elements (such as TCR and TCT). The model shown includes a voltage transducer which measures the high-side voltage of the SVS transformer, automatic voltage regulator (AVR), the thyristor-controlled reactive element (TCRE), logic block for capacitor switching and a provision to account for the SVS transformer reactance X_t.

For the TCRE block, a small gating transport delay T_d and a very small time constant T_B is a sufficient representation. The output is the instantaneous value of inductor admittance, B_L.

$$TCRE = \frac{e^{-sT_d}}{(1+sT_B)} \; (B_{L\ RATING}) \qquad (4)$$

Approximate values of 1 ms for T_d and 4 ms for T_B are reasonable for 60 Hz systems. Often this TCRE block can

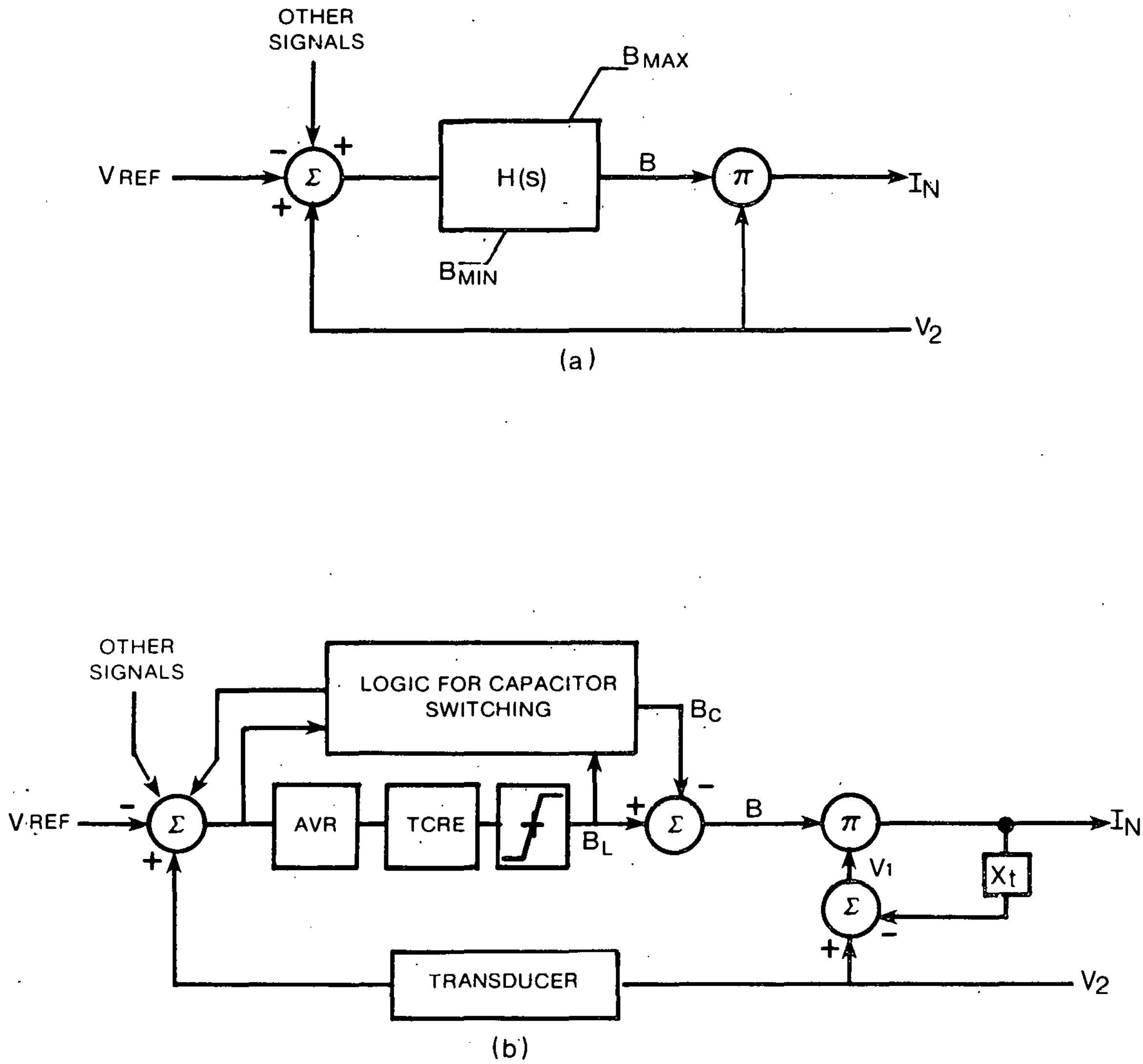


Figure D-3. SVS Models for Stability Studies
a) General Model for All SVS Types
b) More Detailed Model for SVS Equipped with Thyristor Controlled Reactive Elements

be ignored because these time constants are so small. For instance, the TCRE block was ignored in the transfer functions given in equations (1) and (2). Those equations, thereby, include only the automatic voltage regulator (AVR), discussed next.

The choice of automatic voltage regulator depends greatly on the particular application, since it is here that the SVS designer can exercise innovative license to optimize the SVS dynamic performance. A general representation recommended for the AVR is

$$AVR = \frac{k}{1+sT} \circ \frac{1+sT_1}{1+sT_2} \qquad (5)$$

or

$$AVR = \frac{k}{s} \circ \frac{1+sT_1}{1+sT_2} \qquad (6)$$

where

k = gain of the AVR amplifier.

T = a basic time constant chosen to limit bandwidth.

T_1, T_2 = time constants used to tailor the SVC performance for optimized dynamic performance.

The value of gain k, as was discussed earlier, must be chosen consistent with the slope of the SVS characteristic in the control range. Values of 50 to 400 are typical for k, but it is recommended that the user experiment with values until good performance is achieved.

The time constant T is typically quite small, on the order of 50 to 150 milliseconds, but the selection of T_1 and T_2 should be made with the assistance of the supplier, if possible. Numerical stability considerations must be observed for digital stability studies. To insure numerical stability with the SVS model shown, the following relationship should be observed

$$\frac{T_2 \, T}{T_1 \, K \, Z_{12}} \geq 2(\Delta t) \tag{7}$$

where T, T_1, T_2 and K are as defined in Eq. 2.

Z_{12} = transfer impedance relating current I_1 to voltage V_2 or if not known, the short circuit impedance at bus 2 (without SVS) will suffice. The impedance must be in PU on the MVAR rating of the controlled SVS element (reactor in this case).

(Δt) = time step used in computer simulation.

The transducer generally contains a transport delay and one or more time constants. They are generally so small that the transducer can be ignored, giving a unity feedback path.

All control circuit models within the TCRE and AVR block must not suffer from control error windup during periods of simulation when B_L is at either maximum or minimum value limits. When operating in B_L limits, the controller blocks should cease changing their outputs in response to any continuing input error.

The box designated as "Logic for Capacitor Switching" in Figure D-3b is optional. If employed, it should contain one transport delay for switching the capacitor banks. The value for this time delay depends on the form of capacitor switching used (thyristors or mechanical switches). The choice of signals to automatically switch capacitors in and out of service may be dependent on the particular application being considered, and should be made with the assistance of the supplier. Coordination between capacitor switching and the firing angle control in the reactive element is desirable and should be incorporated into the detailed model if the capacitor switching logic is included.

D.3 MODELING FOR FIRST SWING TRANSIENT STABILITY STUDIES

For first-swing, post-fault stability studies, where the ac system performance is sought only out to the first maximum in rotor-angle swings, the SVS may be modeled as a switched shunt reactance, generally a capacitor. The applied fault must be severe enough so that the SVS controlled bus experiences large voltage deviations following the fault. The variations without an SVS must exceed the anticipated SVS control range.

The "first-swing" approximate model can be selected in the following way. First, perform the desired fault simulation without the SVS and observe the voltage swing on the bus destined to be the voltage-control bus for the SVS. If the voltage on that bus tends to drop below the contemplated SVS voltage control range during first rotor-angle swing, the subsequent "with SVS" simulations can be obtained by switching a capacitor onto the bus at the instant of fault clearing. The size of the capacitor should equal the proposed SVS capacitive rating. If, on the other hand, the bus voltage in the "no SVS" simulation has risen outside of the planned SVS control range, the "with SVS" simulation could be obtained with a reactor equal to the proposed net reactive rating of the SVS switched onto the bus at the instant the fault is cleared.

The switched reactance (admittance) model just described is not valid for studies where the time period of simulation includes the backswing of power-angle. Studies of dynamic stability involving several seconds of real time require the more realistic model of the static var system described earlier in the section.

D.4 MODELING SR AND TSC TYPE STATIC VAR SYSTEMS

Models for these types of static var systems were derived by the manufacturers of those types and documented in the literature. The reader is directed to thorough descriptions of those types in References [19] and [20] for the SR type and References [19] and [12] for the TSC type.

Appendix E

STATIC VAR SYSTEM MODELS IN THE PHILADELPHIA ELECTRIC COMPANY LOAD FLOW AND STABILITY STUDY PROGRAMS

Basic models of a generic Static Var System were developed for use in the Philadelphia Electric Company's (P.E. Co.) Load Flow Program (POWERFLO Version 33) and Transient Stability Program (TRANSTAB Version 6) under this contract. Many utility companies besides P.E. Co. utilize these programs for performing power flow and stability studies. This document thereby acts as a means for distributing the results of this effort to all those users of the P.E. Co. programs.

This report includes decriptions of the modeling methods used to incorporate the SVS models into the two programs. Data card specifications are given and results from sample cases are provided. Detailed questions about the programs and their use should be directed to Mr. Stephen Matraszek, Philadelphia Electric Company, P.O. Box 8699, 2301 Market Street, Philadelphia, Pennsylvania 19101.

E.1 REPRESENTATION OF STATIC VAR SYSTEMS IN THE PHILADELPHIA ELECTRIC COMPANY LOAD FLOW PROGRAM

Static Var Systems are represented in the Philadelphia Electric Company Load Flow Program by specifying the maximum value of shunt capacitive reactance and the minimum and maximum values of shunt inductive reactance which can be realized by the static var system and the number of the bus to which the apparatus is attached. In addition, the bus to which the static var system is attached must also be specified as a regulated bus with a large range of reactive generation (-9999 to 9999 MVAR for example). The desired voltage to be held by the static var system and the number of the bus on which this voltage is to be held is specified as part of the regulated bus data for the bus to which the static var system is attached.

Since the static var system is essentially a voltage control device, it is modeled initially by treating the bus to which the static var system is attached as a type P,V node, controlling either its own voltage or the voltage on a remote bus to the value specified to be held by the static var system.

The initial value of shunt reactance of the static var system is set to the average of the minimum and maximum value of shunt reactance of which the device is capable.

For each iteration, the value of shunt reactance currently associated with the static var system is added to the self-admittance term for the bus to which the SVS is attached, so that the presence of the SVS is properly represented in the system Jacobian.

While the SVS bus is represented as a type P,V node, the voltage on the SVS node will be held exactly. Reactive power in excess of that which can be supplied by the shunt reactance of the SVS at the designated voltage may be required to satisfy the power balance around the SVS node.

Fictitious MVAR generation on the SVS node is used, as necessary, to satisfy the power balance around the SVS node during this stage of the solution. During inter-iteration adjustment, the total reactive generation on the SVS bus is computed using the latest iterate of bus voltage for that bus. The total MVAR on the bus is computed by taking the net reactive generation on the bus after the latest iteration, adding the MVAR load originally on the bus (usually zero), and then adding the MVAR being supplied by the shunt reactance of the SVS.

Once the total MVAR on the SVS bus has been computed, the equivalent shunt reactance that would be needed to supply this value of reactive power on the bus is calculated by dividing the total MVAR on the SVS bus by its voltage magnitude squared. If the equivalent shunt reactance falls within the range of values attainable by the SVS, the SVS reactance is set to the value calculated. If this equivalent shunt reactance is less than the minimum attainable reactance of the SVS, the reactance of the SVS is set to its minimum value. Likewise, if the equivalent shunt reactance is greater than the maximum attainable reactance of the SVS, the reactance of the SVS is set to its maximum value. Once the SVS reactance has been set, the value of fictitious reactive generation on the node is reset to zero in preparation for the next iteration.

This process is repeated until the load flow converges to within 10 times the total absolute bus mismatch tolerances specified by the user. At that point, all SVS buses are changed to type P,Q nodes and the reactance of each SVS is fixed at its last calculated value. Since the generation on each SVS bus is reset after each iteration, the fictitious generation on the SVS bus is identically zero once the SVS nodes have been changed to type P,Q nodes. The load flow is then allowed to iterate to convergence. Since no fictitious generation is being used to support the desired voltage when the reactance of an SVS is at one of its limits, the voltage being controlled by that SVS will rise or fall as required to satisfy the network equations.

In summary, while the SVS is operating within the range of attainable reactance, the SVS is modeled as a variable var source. Once the SVS is restricted to either limit of shunt reactance, it is acting as a constant impedance load. Since the SVS bus is treated as a type P,V node until tentative convergence of the case has been achieved, the value calculated for the shunt reactance of the SVS will be the value of shunt reactance necessary to support the specified controlled voltage, provided that the reactance is within the attainable range of the SVS.

E.1.1 Data Specification for SVS Model in Philadelphia Electric Company Load Flow Program

READ STATIC VAR SYSTEM DATA   OPERATION CONTROL CODE 21

Operation control code 21 causes the program to read static var system data. When the program encounters operation control card 21, it reads and processes the static var system data until a card with the digits 9999 in columns 1 through 4 signals the end of the static var system data.

STATIC VAR SYSTEM DATA

The static var system data consists of a single data card for each static var system to be represented. The last static var system data card should be followed immediately by a card containing the digits 9999 in columns 1 through 4.

BUS NUMBER (Columns 1-4)

Enter the number of the bus to which the SVS apparatus is attached in this field.

STATIC VAR SYSTEM REACTANCES (Columns 18-28)

These fields are used to specify the maximum net inductance and maximum net capacitance of the static var system.

Sub-field: MINIMUM NET SHUNT REACTANCE Columns: 18-22

Enter the minimum value of net shunt reactance attainable by the SVS in MVAR at 1.0 per-unit voltage. If the SVS has a net inductive capability, enter the maximum value of net shunt inductance as a negative value in this field. Otherwise, enter the minimum value of net shunt capacitance in MVAR at 1.0 per-unit voltage as a positive value in this field.

Sub-field: MAXIMUM NET SHUNT REACTANCE Columns: 23-28

Enter the maximum net shunt reactance attainable by the SVS in MVAR at 1.0 per-unit voltage. If the SVS has a net capacitive capability, enter the maximum value of net shunt capacitance in this field. Otherwise, enter the minimum value of net shunt inductance in MVAR at 1.0 per-unit voltage as a negative value in this field.

ADDITIONAL DATA REQUIREMENTS

In addition to defining the minimum and maximum values of shunt reactance for the SVS, it is also necessary to define the bus to which the SVS apparatus is attached as a regulated bus with a large range of fictitious reactive generation. It is also necesary to specify the number of the bus on which voltage is to be controlled and the per-unit value of voltage to be held on the controlled bus. The bus to which the SVS apparatus is attached is specified as a regulated bus by placing a "2" in column 8 of the bus data card used to define the bus to which the SVS apparatus is attached. The suggested fictitious MVAR range is -9999 to 9999 MVAR. These values should be entered in columns 41 through 45 and in columns 46 through 50 of the bus data card, respectively. If the SVS is controlling the voltage on the SVS bus, enter the value of per-unit voltage to be held on the bus in columns 23 through 26 of the bus data card.

If the SVS is to control voltage on a bus other than that to which it is attached, enter the number of the controlled bus in columns 52 through 55 of the bus data card for the bus to which the SVS apparatus is attached. Enter the per-unit voltage for the controlled bus in columns 23 through 26 of the bus data card for the controlled bus.

The bus data cards described above are entered after a type 5 control card if the SVS bus and controlled bus are defined as part of the base data for the case. If data from a previously existing case is to be modified, these cards may follow a type 8 control card. If the bus data cards follow a type 8 control card, the change code in column 6 of the bus data cards must be either a 0 (addition) or a 4 (conversion).

E.1.2 Sample Load Flow Run Using SVS Model

The basic radial system model shown in Figure E-1 was modeled in a sample run to demonstrate the use of the modified program. The SVS is shown on bus 3 controlling the voltage to a value of 1.032 per unit. This model is used later in a demonstration of the modified stability program.

The remainder of this section contains key pages of output from the study showing the solution parameters for the example in Figure E-1.

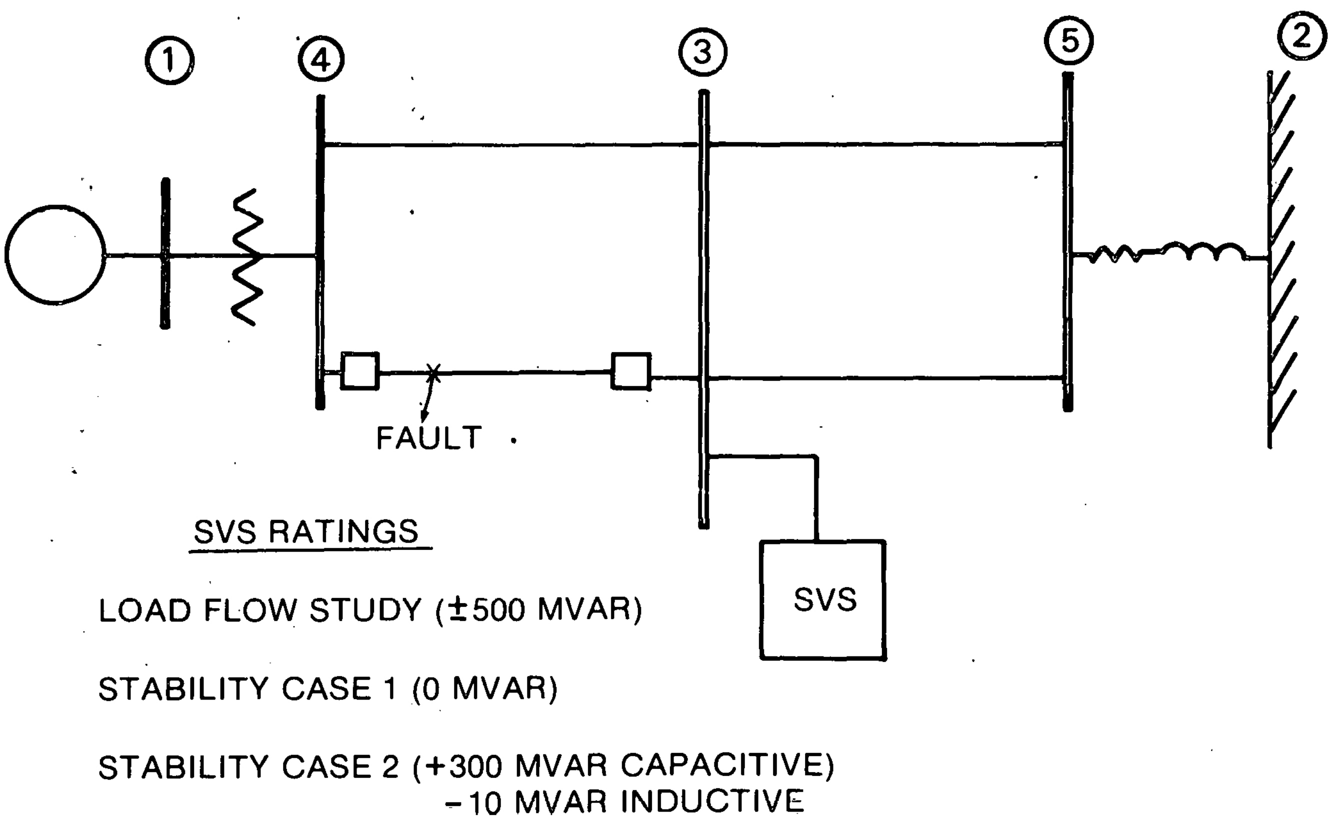


Figure E-1. System Studied for SVS Model Demonstration in P.E. Co. Programs

5 BUS GE TEST SYSTEM FOR SVS MODEL DATE 11/13/80 TIME 10:53:21 PAGE 5

REGULATED BUS SUMMARY

BUS NO.	BUS NAME	X--GENERATION--X MW	MVAR	X-----LIMITS-----X MIN	MAX	ACTUAL VOLTS	DESIRED VOLTS	CONTROLLED BUS
1	BUS 1	900.00	38.61	-500.00	500.00	1.045	1.045	1
3	BUS 3	0.0	-0.00	-500.00	500.00	1.032	1.032	3

* --- INDICATES DESIRED VOLTAGE NOT HELD. F --- INDICATES IDENTICAL MVAR LIMITS.

5 BUS GE TEST SYSTEM FOR SVS MODEL DATE 11/13/80 TIME 10:53:21 PAGE 6

REPORT OF POWER FLOW CALCULATIONS FOR AREA 1, 4 ITERATIONS, SWING BUS IS 2.

X--- B U S - D A T A ---									X--- L I N E - F L O W ---X					
				X--GENERATION--X		X----LOAD----X		CAP/REAC	TO					
BUS	NAME	VOLTS	ANGLE	MW	MVAR	MW	MVAR	MVAR	BUS	NAME	MW	MVAR	TAP	SHIFT
1	BUS 1	1.045	24.9	900.0	38.6R	- 0.0	0.0		4	BUS 4	900.00	38.61		
2	BUS 2	1.000	0.0	-881.4	-99.0	0.0	0.0		5	BUS 5	-881.39	-99.00		
3	BUS 3	1.032	11.2	0.0	-0.0R	0.0	0.0	-4.8	4	BUS 4	-444.75	-27.61		
									4	BUS 4	-444.75	-27.61		
									5	BUS 5	444.75	25.23		
									5	BUS 5	444.75	25.23		
4	BUS 4	1.040	19.7	0.0	0.0	0.0	0.0		1	BUS 1	-895.84	43.88		
									3	BUS 3	447.92	-21.94		
									3	BUS 3	447.92	-21.94		
5	BUS 5	1.008	2.5	0.0	0.0	0.0	0.0		2	BUS 2	882.96	138.33		
									3	BUS 3	-441.48	-69.16		
									3	BUS 3	-441.48	-69.16		
	AREA TOTALS			18.6	-60.4	0.0	0.0	-4.8						

SOLUTION TIME 0.03 CPU SECONDS.
TOTAL TIME 0.11 CPU SECONDS.

PF69 DATA FROM THIS CASE HAS BEEN SAVED AS RECORD 20 IN USER FILE LFHIST0 ON FT16F001.

PF87 THE ABOVE USER FILE ON VOLUME OSVS11 HAS DSNAME=SP.DATA.LFHIST3
OF 99 POSSIBLE USER RECORDS, 34 ARE USED.
THE FILE IS 84.8% UTILIZED.

5 BUS GE TEST SYSTEM FOR SVS MODEL — DATE 11/13/80 TIME 10:53:22 — PAGE 7

	LINES	LTC TRANSFORMERS	PHASE SHIFTERS	BUSTIE BREAKERS
MAXIMUM	2500	500	25	
ACTUAL	6	0	0	0

LINE AND TRANSFORMER DATA

X----FROM BUS----X NO.	NAME	X-----TO BUS-----X NO.	NAME	IMPEDANCE (%) R	X	MVA LINE CHARGING	X--------LTC TRANSFORMER--------X TAP	TMIN	TMAX	CONT	VOLTS	X--PHASE SHIFTING XFMR--X SHIFT	SMIN	SMAX	MW	RATINGS NORM	EMRG
1	BUS 1	4*	BUS 4	0.056	1.110	0.0										0	0
2*	BUS 2	5	BUS 5	0.020	0.500	0.0										0	0
3*	BUS 3	4	BUS 4	0.170	3.560	108.000										0	0
3*	BUS 3	4	BUS 4	0.170	3.560	108.000										0	0
3	BUS 3	5*	BUS 5	0.170	3.560	108.000										0	0
3	BUS 3	5*	BUS 5	0.170	3.560	108.000										0	0
4*	BUS 4	1	BUS 1	0.056	1.110	0.0										0	0
4	BUS 4	3*	BUS 3	0.170	3.560	108.000										0	0
4	BUS 4	3*	BUS 3	0.170	3.560	108.000										0	0
5	BUS 5	2*	BUS 2	0.020	0.500	0.0										0	0
5*	BUS 5	3	BUS 3	0.170	3.560	108.000										0	0
5*	BUS 5	3	BUS 3	0.170	3.560	108.000										0	0

T --- INDICATES TIE LINE OWNER. * --- INDICATES METERING POINT.

5 BUS GE TEST SYSTEM FOR SVS MODEL — DATE 11/13/80 TIME 10:53:22 — PAGE 8

	BUSSES	REGULATED BUSSES	SWING BUS
MAXIMUM	1500	500	
ACTUAL	5	2	2

BUS DATA

X-----BUS ID-----X NO.	NAME	BUS VOLTS	BUS ANGLE	X---BUS LOAD---X MW	MVAR	X----------------BUS GENERATION----------------X MW	MVAR	MIN--LIMITS	--MAX	CONT	VOLTS	LTC VOLTS	STATIC MVAR	AREA
1	BUS 1	1.045	24.94	0.0	0.0	900.00	38.61	-500.00	500.00	1	1.045			1
2	BUS 2	1.000	0.0	0.0	0.0	-881.39	-99.00							1
3	BUS 3	1.032	11.17	0.0	0.0	0.0	-0.00	-500.00	500.00	3	1.032		-4.48	1
4	BUS 4	1.040	19.68	0.0	0.0	0.0	0.0							1
5	BUS 5	1.003	2.50	0.0	0.0	0.0	0.0							1
	SYSTEM TOTALS			0.0	0.0	18.61	-60.40						-4.48	

E.2 REPRESENTATION OF STATIC VAR SYSTEMS IN THE PHILADELPHIA ELECTRIC COMPANY TRANSIENT STABILITY PROGRAM

Static Var Systems are represented in the Philadelphia Electric Company Transient Stability Program by specifying the desired voltage to be maintained by the SVS and the bus number of the bus on which this voltage is to be held. The gain of the automatic voltage regulator of the static var system and the various time constants of the SVS, as well as the value of capacitive reactance in MVAR at 1.0 per-unit voltage and the minimum and maximum values of inductive reactance of the SVS in MVAR at 1.0 per-unit voltage must also be entered. The values describing the SVS are used to drive a digitally simulated analog model of the static var system which yields the shunt reactance on the SVS bus at each time step in the simulation. The output from the analog model for each static var system is used to update the self-admittance of the bus to which each SVS is connected.

Two alternative SVS models are incorporated based on the block diagrams in Figure D-3. The two models contain:

"FULL MODEL" $$H(s) = \frac{K}{1 + sT} \cdot \frac{(1 + sT_1)}{(1 + sT_2)}$$

and "SIMPLIFIED" $$H(s) = \frac{K}{1 + sT}$$

However, the output B was broken into the capacitive B_C (assumes fixed capacitor) and the controllable reactor part B_L.

The data specifications are defined in Section E.2.1 and the actual model analog plugging diagrams are given in Figures E-2 and E-3.

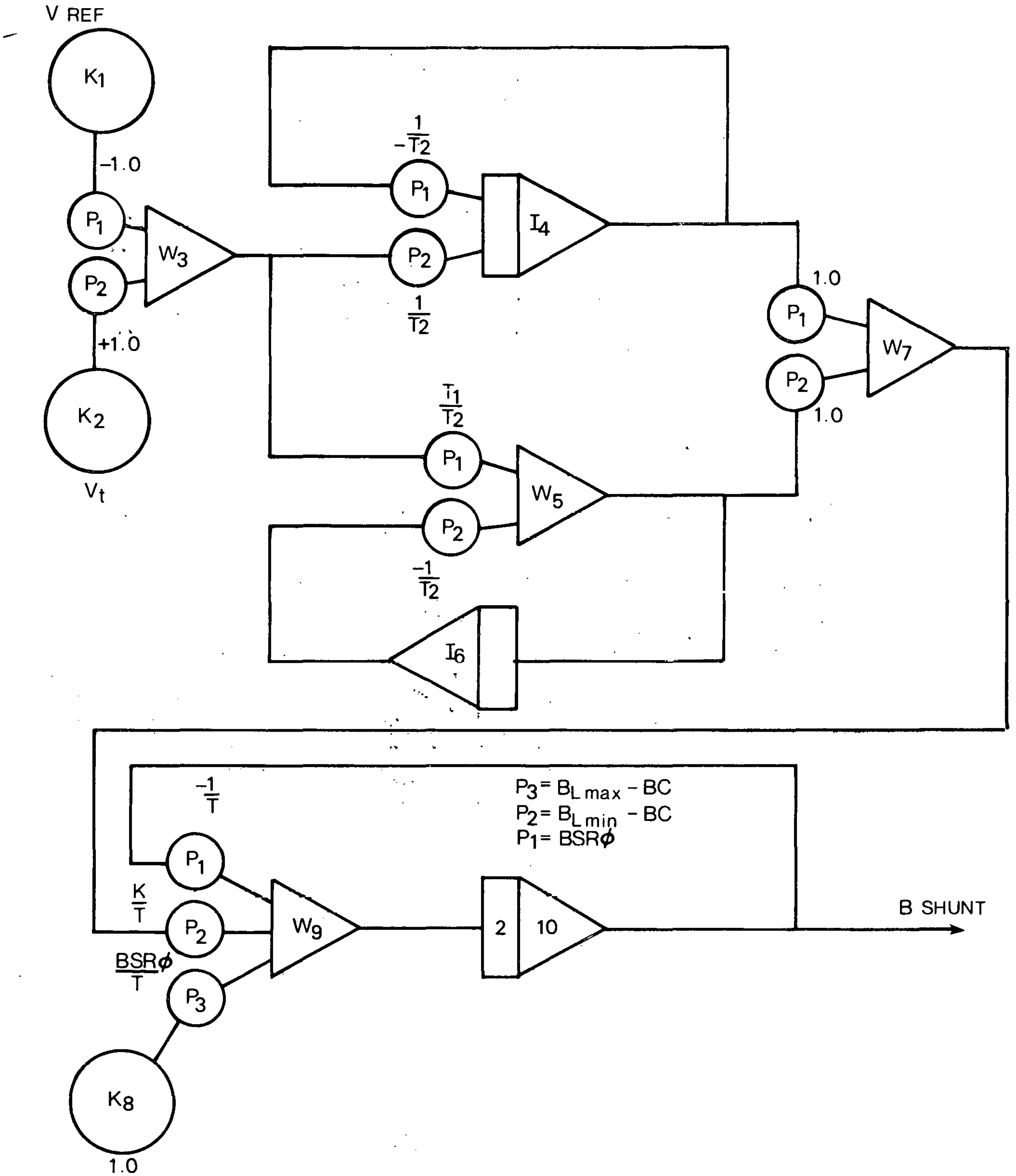


Figure E-2. Computer Logic ("Plugging") Diagram for "Full Model" in P.E. Co. Stability Program

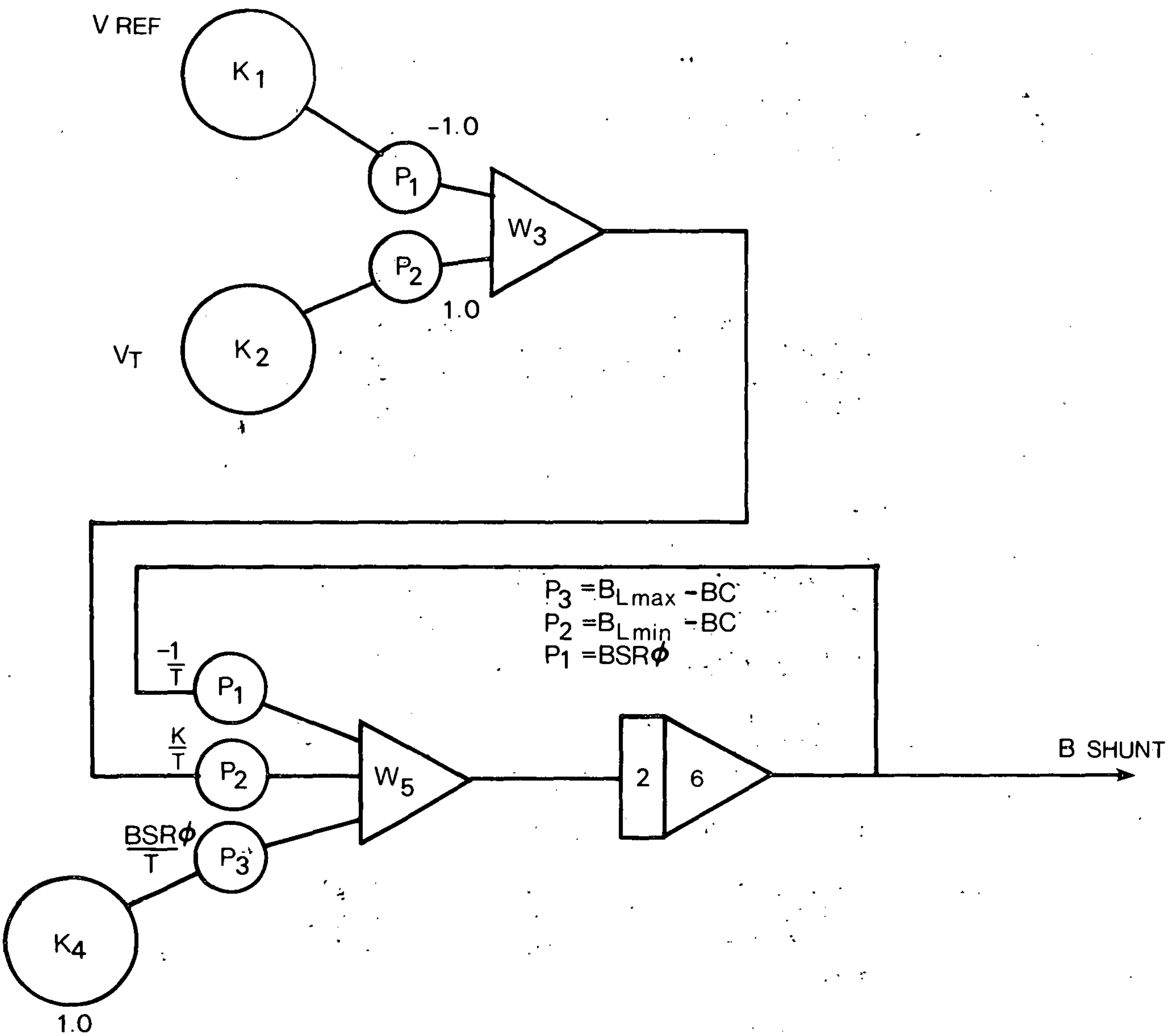


Figure E-3. Computer Logic ("Plugging") Diagram for "Simplified" SVS Model in P.E. Co. Stability Program

E.2.1 Data Specifications for SVS Models Incorporated in Philadelphia Electric Company Power System Stability Program

READ STATIC VAR SYSTEM DATA   OPERATION CONTROL CODE 21

Operation control code 21 causes the program to read static var system data. When the program encounters operation control card 21, it reads and processes the static var system data until a card with the digits 9999 in columns 1 through 4 signals the end of the static var system data.

STATIC VAR SYSTEM DATA

The static var system data consists of a single data card for each static var system to be represented. The last static var system data card should be followed immediately by a card containing the digits 9999 in columns 2 through 5.

BUS NUMBER (Columns 1-4)

Enter the number of the bus on which the SVS is controlling voltage in this field.

STATIC VAR SYSTEM CONSTANTS (Columns 9-80)

The constants described here refer to those used with the standard preplugged static var system. For user devised systems, these descriptions may not apply.

Sub-field: TYPE OF STATIC VAR SYSTEM Columns: 7-8

Enter the code number of the type of static var system to be represented. The value for the pre-plugged static var system is 20. If this field is left blank, a value of 20 will be assumed.

Sub-field: Vref Columns: 9-16

Enter the per-unit voltage which is to be held on the bus controlled by the static var system.

Sub-field: K Columns: 17-24

Enter the gain of the automatic voltage regulator of the SVS in this field.

Sub-field: T Columns: 33-40

Enter the value of the time constant T1 in seconds in this field.

Sub-field: T2 Columns: 41-48

Enter the value of the time constant T2 in seconds in this field.

Sub-field: BC Columns: 49-56

Enter the value of capacitance of the SVS in MVAR at 1.000 per-unit voltage.

Sub-field: BL min Columns: 57-64

Enter the minimum value of inductance of the SVS in MVAR at 1.000 per-unit voltage.

Sub-field: BL max Columns: 65-67

Enter the maximum value of inductance of the SVS in MVAR at 1.000 per-unit voltage.

E.2.2 Sample Stability Run With SVS Model

To demonstrate the functional validity of the SVS model in the Stability Program, two cases were run, Case 1 was without the SVS and Case 2 was with the SVS specified in Figure E-1 controlling the voltage on bus 3.

The voltage traces for these cases are given in Figure E-4 (without SVS) and Figure E-5 (with SVS). The simplified SVS model was utilized in the latter demonstration case. The machine angles are plotted without SVS and with SVS in Figures E-6 and E-7, respectively.

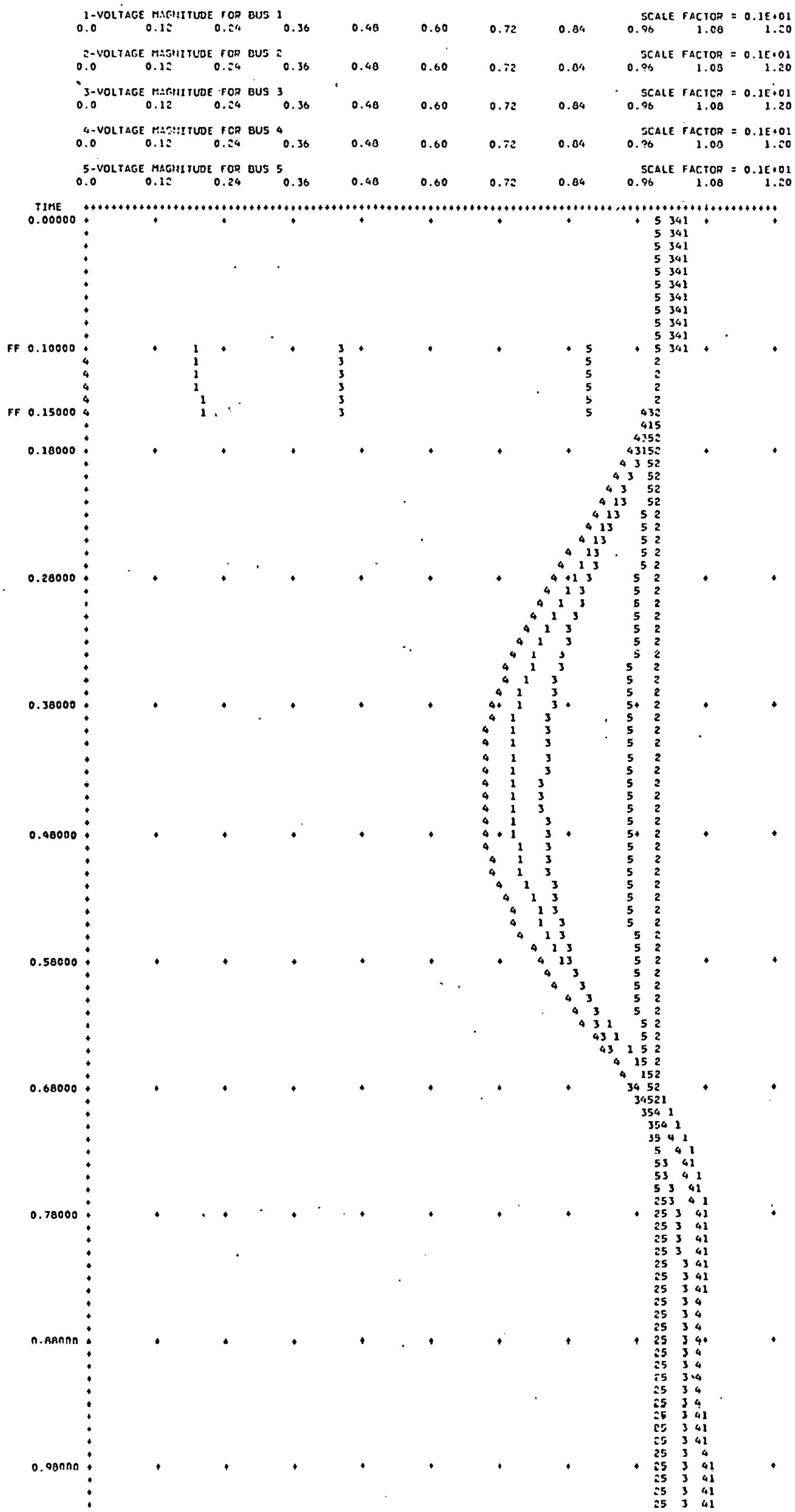


Figure E-4. Bus Voltages - Case 1 (No SVS)

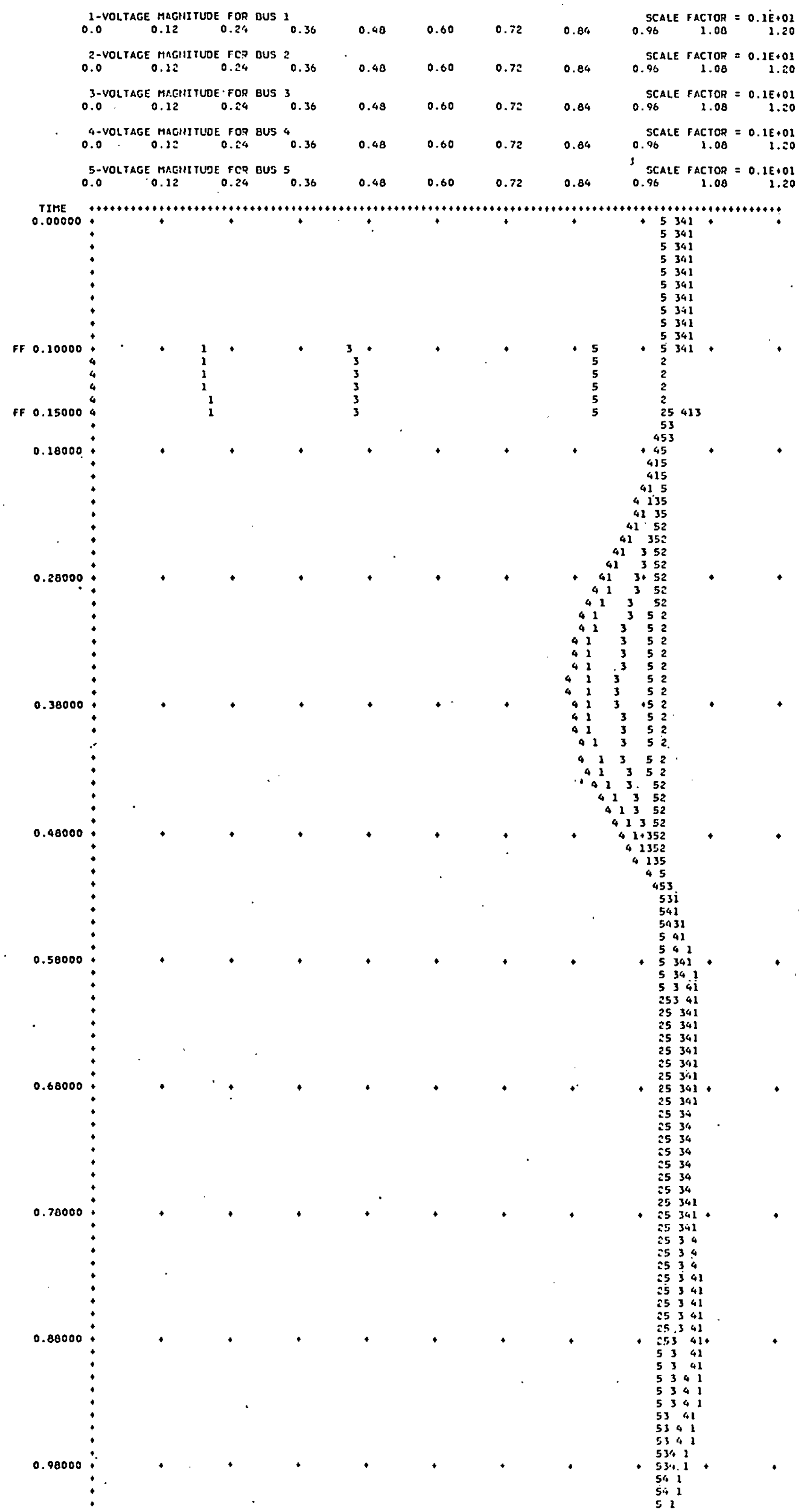


Figure E-5. Bus Voltages - Case 2 with SVS

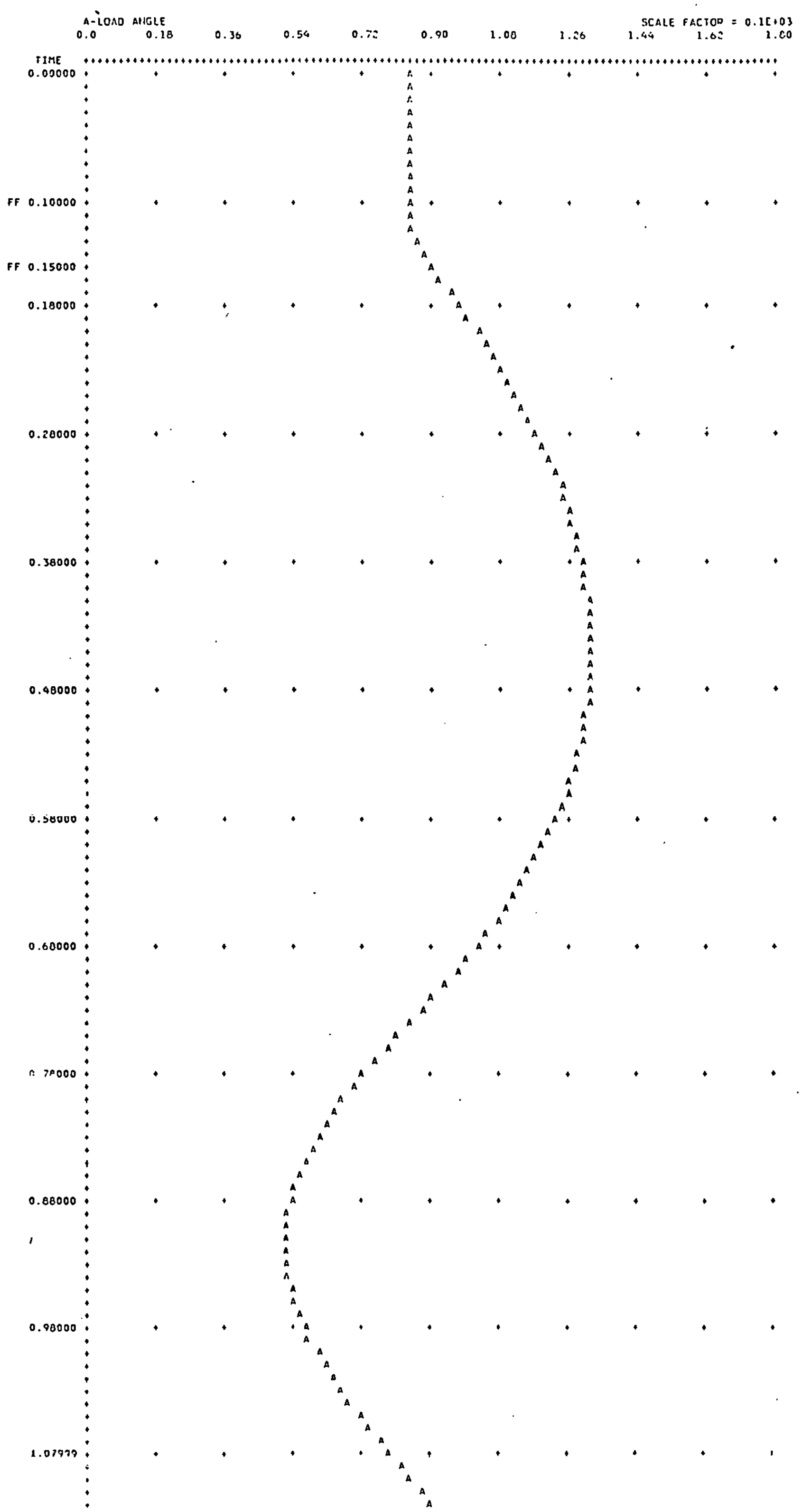


Figure E-6 Machine Angle - Case 1 (No SVS)

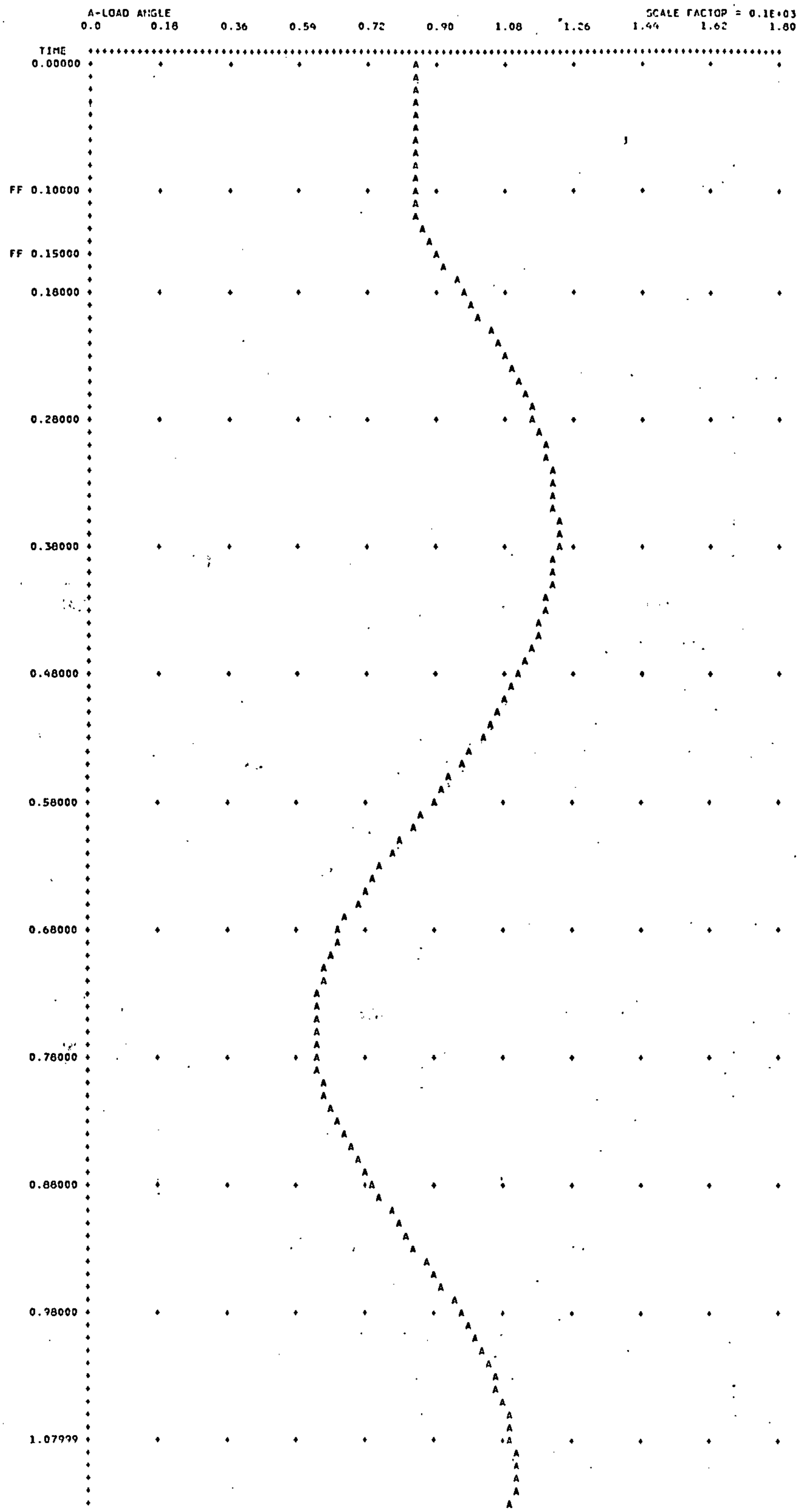


Figure E-7. Machine Angle - Case 2 (With SVS)

Appendix F

REFERENCES

1. Hauth, R., Moran, R., "Introduction to Static Var Systems for Voltage and Var Control," IEEE Tutorial Text 78EH0135-4-Pwr, pp. 48-55, IEEE Summer PAS Meeting, Los Angeles, CA, July 1978.

2. CIGRE, W.G., 31-01, Barthold, L., et al, "Static Shunt Devices For Reactive Power Control," paper 31-08, CIGRE Conference, Paris, France, Aug. 21-29, 1974.

3. Larsen, E.V., Price, W.W., "MANSTAB/POSSIM Power System Dynamic Analysis Programs - A New Approach Combining Nonlinear Simulation and Linearized State - Space/Frequency Domain Capabilities," PICA Conference proceedings, May 1977.

4. Johnson, E., Hasler, P., Moran, R., Titus, C., "Static High Speed Var Control for Arc Furnace Flicker Reduction," proceedings of the American Power Conference, 1972.

5. Elsliger, R., Hotle, Y., Ray, J.C., "Optimization of Hydro-Quebec's 735kV Dynamic-Shunt-Compensated System Using Static Compensators on a Large Scale," IEEE Conference paper A-78-107-5 presented at Winter Power Meeting, Jan. 29-Feb. 3, 1978.

6. Weedy, B.M., "Electric Power Systems," book, second edition, John Wiley & Sons, New York, pp. 161-164.

7. T.H. Putnam, D.G. Ramey, "A Modulated Inductance Stabilizer for Power Systems Subject to Subsynchronous Resonance," Proceedings of International Symposium on Controlled Reactive Compensation held at IREQ, Varennes, Quebec, Canada, September 19-21, 1979.

8. Gyugyi, L. "Reactive Power Generation and Control by Thyristor Circuits," IEEE Transactions on Industry Applications, Vol. IA-15, No. 5, September/October, 1979.

9. Sumi, Y., et al, "New Static Var Control Using Force-Commutated Inverters," IEEE Winter Power Meeting paper, 81 WM228-6, presented in Atlanta, Georgia, February 1-6, 1981.

10. Breuer, G., Chow, J. Gentile, T., et al; "HVDC-AC Harmonic Interaction, Part II-AC System Harmonics Model with Comparison of Calculated and Measured Data," Paper based on EPRI Research Project RP-1138, Submitted for presentation at the IEEE Summer Power Meeting in Portland, OR, July 1981.

11. Frank, J. and Petersson, T., "Thyristor - Switched Shunt Capacitors and Their Modeling For Transmission Applications," IEEE paper A78-105-9, Winter Power Meeting, N.Y., February 1978.

12. Engberg, K, Irner, S., "Static VAR Systems for Voltage Control During Steady State and Transient Conditions," Proceedings of EPRI/Hydro-Quebec Symposium, Varennes, September 1979.

13. "Control of Capacitor Closing Nips Surges," Electrical World, January 1979.

14. Friedlander, E., "Transient Reactance Effects in Static Shunt Reactive Compensators for Long AC Lines," IEEE PAS Transactions, Vol. PAS-95, Sept./Oct. 1976, pp. 1669-1680.

15. Reichert, K., et al, "Controllable Reactor Compensator for More Extensive Utilization of High Voltage Transmission Systems," paper 31-04, CIGRE Conference, Paris, France, Aug., 1974.

16. Czech, P., McGillis, D., "Static Compensators and Their Relation to System Stability," Proceedings of American Power Conference, April 1980.

17. Hauth, R., Newell, R., Humann, T., "Application of a Static VAR System to Regulate System Voltage in Western Nebraska," IEEE Transactions, Vol. PAS-97, No. 5, September/October 1978.

18. Newell, R., Hauth, R., et al, "Staged Field Testing of the Victory Hill Static Var Control," Transactions IEEE, Vol. PAS-99, No. 2, March/April, 1980.

19. CIGRE, W.G., 31-01, "Modeling of Static Shunt VAR Systems (SVS) for Systems Analysis," Electra, Vol. 51, March 1977.

20. O'Kelley, D., and Abu Elnour, M., "Computation of Saturated Reactor Performance," IEEE Winter Power Meeting paper A78 270-1, New York, February 1978.

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