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Final Report

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MASTER

May 12, 1981

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A STUDY OF STATIC REACTIVE POWER COMPENSATORS
FOR HIGH-VOLTAGE POWER SYSTEMS

Contract 4-L60-6964P
Final Report, May 12, 1981

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ABSTRACT

A general study of the application of static VAR compensators (SVC's) to high-voltage transmission systems has been performed. Considerable emphasis has been placed on improvements to synchronous stability, and it is shown that SVC's can provide significant benefits in terms of damping for unstable modes of oscillation and increases in transient stability limits. This report includes descriptions of static VAR compensators, technical and economic comparisons of different compensators, compensator models for system studies, comprehensive study procedures, study results for two small-scale systems, and guidelines for SVC application.

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Section 1

INTRODUCTION AND SUMMARY

This report contains the results of a general study of the application of static VAR compensators (SVC's) to high-voltage transmission systems. Considerable emphasis is placed on improvements in synchronous stability attributable to static VAR compensators. The report includes descriptions of static VAR compensators, technical and economic comparisons of different compensators, compensator models for system studies, comprehensive study procedures, study results for two small-scale systems, and guidelines for SVC application. A summary of the contents of this report and the principal results of the study follow.

THE NEED FOR AND BENEFITS OF SVC'S ON POWER TRANSMISSION SYSTEMS

In Section 2, the concept of static VAR compensation as a means of rapid, continuously controllable shunt reactive compensation is introduced. The basic building blocks (i.e., components) of a typical SVC system are described with emphasis on the solid state switches and associated feedback control systems. Fundamentals of reactor current conduction angle control and capacitor switching using thyristor switches are reviewed. Typical SVC ratings, control strategies, and control system response characteristics are discussed in the context of transmission applications. The interrelationships between SVC rating, speed of response, stability of response, and transmission system impedance are described.

The application of static VAR compensation to power transmission systems has been shown to improve numerous aspects of system performance including:

- 1) reduced voltage flicker due to irregular load fluctuations,
- 2) increased steady state transmission capacity and enhanced transient stability with intermediate bus voltage support,
- 3) improved system dynamic stability by virtue of increased system swing damping,
- 4) control of steady state and temporary overvoltages,

- 5) improved transmission system efficiency and load power factor by virtue of local VAR supply,
- 6) improved HVDC conversion terminal performance during abnormal and recovery situations,
- 7) damping of subsynchronous oscillation,
- 8) correction of phase imbalances or compensation of irregular single-phase loads, and
- 9) provision of lagging compensation required in conjunction with single-pole switching.

A large portion of Section 2 deals with considerations necessary in applying SVC's for compensating long transmission lines and improving system transient stability. For long-line applications, the use of power circle diagrams is illustrated as a reasonably quick means of approximating SVC rating requirements. Power circle diagrams also provide a method for sizing VAR compensators used to enhance transient stability. Increased transient stability margin and a doubling of transmission capacity are described for "ideal" SVC applications, but practical limitations are likewise cited.

A discussion contrasting SVC requirements and response to small versus large system disturbances is also included in Section 2. Alternative techniques for providing short time overload capability and the nature of problems that can develop if shunt capacitors are not disconnected during large system disturbances are cited. Finally, the findings of four U.S. utility interviews on existing and prospective SVC applications are summarized. The four utilities were selected on the basis of a diversity in system characteristics. The major findings of the interviews were:

- 1) A deficiency exists in industry study tools to optimize the size, location, and type of shunt reactive compensation needed on interconnected transmission systems.
- 2) There is a need for fast, on-line, automatic, coordinated dispatching of reactive power across interconnected systems.
- 3) Few, if any, novel applications of SVC's are envisioned. Two potential uses are related to unbalanced loads associated with railroad electrification and stability improvement of isolated small sources of generation.

COMPARISON OF ALTERNATIVE SVC CONFIGURATIONS

In Section 3, ten different SVC configurations and the synchronous condenser are compared and contrasted on technical and economic grounds. Relative to solid-state VAR compensators, the synchronous condenser is cited for deficiencies related to high cost, high losses, high maintenance, and slow response. Little difference could be found between the ten SVC schemes in terms of capital cost, reliability, and, with only one exception, speed of response. Significant differences were evident between the ten configurations in terms of operating costs (i.e., the capitalized cost of losses), harmonic performance, overload capability, flexibility in control and uprating, equipment and control complexity, and performance during large system disturbances. The following is a condensed comparison of the ten schemes considered. The thyristor-controlled reactor, fixed capacitor (TCR-FC) configuration was used as a base for all comparisons.

Thyristor-Controlled Reactor, Fixed Capacitor (TCR-FC)

- Relatively inexpensive
- Flexible in control and uprating
- Significant six-pulse harmonics
- Significant steady-state losses
- Limited overload capability

Segmented TCR-FC

- Reduced six-pulse harmonics
- Increased losses
- Higher cost

Twelve-Pulse TCR-FC

- Small twelve-pulse harmonics
- Special transformer construction
- Higher cost
- Added control complexity

Thyristor-Controlled Transformer, Fixed Capacitor (TCT-FC)

- Inherent overload capability
- Significant six-pulse harmonics
- Special transformer construction
- Harmonic filtering on HV bus

Thyristor-Switched Capacitor, Thyristor-Controlled Reactor (TSC-TCR)

- Reduced harmonics
- Reduced losses
- Improved performance during large disturbances
- Higher cost

Mechanically Switched Capacitor, Thyristor-Controlled Reactor (MSC-TCR)

- Similar performance features as TSC-TCR at reduced cost and losses
- Slower response than other SVC's
- Capacitors may be unavailable for steady-state compensation

Saturable Reactor

- Inherent overload capability
- Excellent harmonic characteristics
- Self-regulation--no active control
- Potential subharmonic resonance
- Limited modularity
- Limited flexibility in control strategy
- Special, complex reactor construction

University of Manitoba Concept

- Enhanced controller stability
- Improved harmonic performance
- Increased total reactance
- Increased losses

Forced Commutated Inverter

- Excellent harmonic characteristics
- Complex, expensive system
- Increased losses
- Inoperable under unbalanced conditions

Superconducting Coil SVC

- Comparable cost to TCR-FC
- Insignificant reactor losses
- Increased thyristor losses

Each of these SVC configurations, except the final three, has been developed and applied at commercial ratings to HV transmission systems. Each of the schemes has specific attributes, advantages, and disadvantages relative to the others. Where a small cost premium is not prohibitive, the TSC/TCR compensator is recognized as the fastest, most flexible, low-loss SVC available today. However, where cost is an overriding concern, the "best" SVC for a certain application can be determined only after a thorough assessment of the requirements and acceptable compromises for that specific application. Section 3 includes a discussion of some of these "other considerations" necessary in selecting the most suitable SVC configuration.

SVC MODELS FOR SYSTEM STUDIES

Two representations for static VAR compensators in system studies are described in Section 4. One is based on nonlinear reactive load formulas that have been used in prior studies to represent SVC's with constant reference voltages. The other has been developed in connection with this project and provides for control of SVC reference voltages. This more versatile model permits as many as three dynamic control channels for each SVC, with control variables from the following list:

- The frequency deviation of any bus voltage
- The speed deviation of any synchronous machine
- The accelerating power of any synchronous machine
- The power flow deviation from initial value over any ac line
- The angle deviation from initial value of any bus voltage

This model with controlled reference voltage has been incorporated in a large-scale stability program, and the data requirements, flowcharts, and mathematical diagrams used in program modification are presented.

SVC APPLICATION STUDIES

Studies of SVC applications to two small-scale systems are presented in detail. These studies serve two purposes:

- To demonstrate the potential for stability improvement by means of static VAR compensators
- To develop and illustrate study procedures which relate stability improvements to the general specifications for SVC's, including their locations, regulating slopes, reactive power requirements, and reference voltage controls

Both small-scale systems studied have unstable modes of synchronizing power flow oscillation for some operating conditions in the absence of static VAR compensators. It is shown in one instance that positive damping can be achieved by SVC's with constant reference voltages; in the other, positive damping is achieved with reference voltage controls sensitive to frequency.

Substantial increases in transient stability limits are attributable to SVC's in both systems, and it is shown that SVC reference voltage control can be an important factor in obtaining high transient stability limits.

Four types of calculations, in addition to load flow, have been used in performing these system studies. They are:

- Self- and mutual-drop coefficient calculations
- Voltage sensitivity calculations
- Eigenvalue calculations
- Transient stability calculations

The self- and mutual-drop coefficient calculations are not intended to be a routine part of SVC application. However, in the context of this project, they establish the viewpoint that voltage regulation reduces incremental self- and mutual-drop coefficients and help to justify a simple formula for the regulating slope of a static VAR compensator in terms of the short-circuit reactance at its terminal bus.

The voltage sensitivity calculations are made to obtain incremental voltage changes at transmission buses associated with incremental power changes at generator buses. Their purpose is to identify buses and operating circumstances where poor incremental voltage regulation may contribute to instability. These calculations are made with a computer program developed specifically to meet the needs of this project. That program is not intended for use as a production program, but the development of a production program should be considered.

Eigenvalues associated with synchronizing power flow oscillations are calculated by means of the computer program AESOPS developed by Westinghouse AST for EPRI. Several aspects of eigenvalue analysis are well suited to the needs of dynamic stability studies:

- The various modes of generator rotor oscillation, which may be mixed with each other and with transients in time-domain simulation, are separated and identifiable in eigenvalue analysis.
- The generator speed deviations for each mode, which are part of the eigenvector, provide a description of the oscillation in physical terms.
- The eigenvalues associated with each mode give a clear indication of the effects of SVC's on individual modes and precise data regarding their effects on oscillation frequencies and damping.

Thorough eigenvalue analyses of both small-scale study systems are included in this report. The representation of SVC's in the AESOPS program is based on the nonlinear reactive load model and therefore excludes studies of reference voltage control. It is desirable to be able to calculate eigenvalues with the effects of SVC auxiliary controls represented, and modification of the AESOPS program to permit this should be considered.

The transient stability study results contained in this report utilize a large-scale computer program modified to accommodate the SVC model with controlled reference voltage. They are made to compare transient stability limits in the absence of SVC's to limits when SVC's are represented. These studies show substantial increases in stability limits using SVC's whose reactive capacity is reserved for system disturbances.

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Section 2

STATIC VAR COMPENSATORS AND THEIR NEED IN HIGH-VOLTAGE TRANSMISSION SYSTEMS

CONCEPT OF AN SVC

With only one or two exceptions, the typical static VAR compensator (SVC) is a solid state device or system, composed of static capacitors and reactors, and controlled conventional and solid state switches (i.e., thyristors), designed to provide rapid, continuously controllable shunt reactive compensation. SVCs have been applied at voltages ranging from 8.3 kV to 735 kV, but for those applications exceeding 34.5 kV, most SVC systems also include some means of voltage transformation to accommodate and more effectively use existing thyristor switch ratings (e.g., 25 kV to 34.5 kV, 1.5 kA). This transformation may take the form of a separate coupling transformer or the tertiary winding of a transformer used for other purposes. Thus, a simplified schematic of an SVC controlled by bus voltage is shown in Figure 2-1.

Figure 2-1. Simplified schematic of an SVC (AVR-Automatic Voltage Regulator control)

For most SVCs, the continuously controllable variable admittance or impedance characteristic is accomplished by using thyristors or conventional switches to "switch" static capacitors, while using thyristors to "control" reactors. This, of course, necessitates a control subsystem and strategy which compares an actual system condition(s) with a reference parameter(s); and then processes the error signal to determine the appropriate thyristor operations. Before further discussing the specifics of SVC control subsystems, a review of the principles, limitations and consequences of utilizing thyristors to "control" reactors and "switch" capacitors is in order.

CONDUCTION ANGLE CONTROL OF REACTOR CURRENT

When applied in series with a reactor, thyristors provide a means of controlling both the waveshape and magnitude of the current which flows through the reactor. Figure 2-2 illustrates the effect of controlling thyristor switch conduction to successively smaller intervals, relative to the 60 Hz voltage waveform, by increasing the firing or delay angle α from 0° to 90° .

Figure 2-2. Waveshapes illustrating conduction angle control of reactor current at firing angles between 0° and 90° .

Note that Figure 2-2 shows that the conduction of current in a thyristor stops at the end of each pulse of current (i.e., at current zeros). To minimize generation of even harmonics and DC in the current wave, some SVC controls for arc furnace application have been designed to fire each current pulse so as to average over a relatively long period the positive and negative pulse areas to zero. This feature is desirable for transmission system applications, but is not as important as in arc furnace applications since in the transmission system, conditions resulting in the generation of second harmonic currents occur only transiently.

Figure 2-2 also indicates that controlling the conduction intervals of the thyristor switch generates harmonic current components of magnitudes dependent on the conduction angle. With identical conduction intervals for the positive and negative current half-cycles, only odd harmonics are generated. Figure 2-3 illustrates the results of a Fourier analysis of conduction angle controlled current waveforms versus firing angle. Note that increased thyristor firing angles result in reduced 60-Hz reactor current magnitudes (i.e., I_{FUND}), and thus reduced levels of lagging reactive compensation. Since the magnitude of the fundamental component does not vary linearly with conduction angle, the SVC control must compute the required conduction angle with the given reactor size to provide the proper magnitude of the fundamental component demanded by the system operating conditions.

Figure 2-3. Harmonic current amplitudes expressed as percent of the maximum fundamental current, versus firing angle for the thyristor-controlled reactor.

As can be seen on Figure 2-3, the most significant odd harmonics are the 3rd, 5th, 7th, 9th, 11th and 13th with maximum magnitudes (occurring at different conduction angles) of 13.8%, 5.0%, 2.5%, 1.6%, 1.0% and 0.7%, respectively, of the rated reactor 60 Hz current. The amplitudes are based on steady state conduction angle values, and during a change in conduction angle the relative magnitudes of the various harmonics change; that is, the SVC acts, in a sense, like a harmonic generator of variable magnitudes.

One problem with the SVC acting as a harmonic generator is the resulting harmonic voltages and currents into the external power system. These harmonics can result in interference on nearby communication networks, a loss of useful life on rotating machines, and severe system resonant overvoltages. Two approaches are commonly used to reduce harmonic current flow back into the external power system: First, to connect the three controlled reactors of a three-phase SVC into delta which removes the flow of triplen harmonics (e.g., 3rd, 9th, etc.) into the external power system; and, second, if necessary, to utilize nearby (parallel connected) shunt capacitor banks as filters for the other significant harmonics, shunting out at least part of the flow of these harmonics into the external power system. Such filters perform properly for steady-state conditions, but their response to transient conditions may be part of an SVC application study.

"SWITCHING" CAPACITORS

Capacitor switching can be accomplished using conventional devices or thyristors. Unlike reactors, capacitor current cannot be phase-controlled. Capacitors are switched either completely "in", or completely "out". Therefore, the main functions of the capacitor switch are 1) speed, and 2) minimization or elimination of system transients during switching. In both respects thyristors are generally superior to conventional switches, but are also more expensive.

Because of the uni-directional current carrying capability of solid state devices, the solid-state switch in series with a capacitor bank may be composed either of a reverse-parallel connected thyristor pair (as in Figure 2-1) or it could be composed of a thyristor in reverse-parallel with a diode. Depending on the applica-

tion, the latter arrangement is less complex and less expensive, but the former arrangement provides greater operating flexibility in allowing the complete disconnection of the capacitor banks.

For full utilization of the fast response and transient-free operation of the capacitor switching function, some of the capacitors should be charged positively and some negatively with the thyristor switch ideally beginning conduction at instants of time when the capacitor voltage and the bus voltage are equal. Such operation requires the overall capacitor bank to be divided into a number of separate subbanks. This reduces switching transients, and provides a semi-continuous range of capacitive VARs with minimum time delay between system demand and SVC response.

Figure 2-4(A) - Simplified schematic of "switched" capacitor and "controlled" reactor for continuously controllable leading VARs.
 (B) - Individual VI relationships for the switched capacitor and controlled reactor where reactor current control occurs at a reference voltage, V_0 .
 (C) - Combined VI characteristic illustrating controllable leading VARs at V_0 .

The control of the capacitor banks inherently does not produce harmonics since switching occurs at current zeros. However, since the capacitors may be completely switched out at times, other means of filtering must be provided to reduce the harmonics generated by the current-controlled reactors, if present. A direct approach is to divide the required reactor into several smaller reactor banks so that all banks except one are either fully on or fully off, as demand requires. The remaining single reactor, being conduction-angle controlled, generates a much lower level of harmonics compared to that which would be generated if the total reactance were being current controlled.

Because capacitors can be switched only in discrete amounts, continuous control of leading reactive compensation can only be accomplished by providing a parallel controlled reactor with a rating at least equivalent to that of the capacitor steps (e.g., as in Figure 2-1). With the capacitor switches "in", control of the lagging reactor current can then compensate for any or all of the leading capacitive current resulting in continuous control of leading compensation as shown in Figure 2-4. In this figure, thyristor control of reactor current is based on bus voltage with the reactor "off" (i.e., $\alpha = 90^\circ$) when $V < V_0$, "on" (i.e., $\alpha = 0^\circ$) when $V > V_0$, and "controlled" (i.e., $0^\circ < \alpha < 90^\circ$) when $V = V_0$.

If the reactor rating exceeds the capacitor rating, then continuously controllable reactive compensation from leading to lagging is possible when the capacitor is switched "in". This arrangement is illustrated in Figure 2-5 which shows the con-

Figure 2-5. Current waveform and components as α increases from 0° to 90° for a thyristor controlled reactor in parallel with a capacitor with $\omega L > \frac{1}{\omega C}$.

trolled-reactor current $i_L(\alpha)$, the constant capacitor current i_C (applied voltage assumed constant), the total compensating current $i(\alpha) = i_L + i_C$ and its fundamental component $i_{fund}(\alpha)$ as the firing angle is increased from 0 to 90 degrees. That is, the current conduction interval of the thyristor switch is reduced from 180 degrees (reactor bank "fully on," absorbing VARs equal to the difference between the reactor bank rating and the capacitor bank rating), to zero degrees (reactor bank "fully off," with the compensator providing VARs equal to the capacitor bank rating).

A VI characteristic that might correspond to the system illustrated in Figure 2-5 is shown below. Note that at the arbitrarily selected reference voltage, V_0 , the linear control range extends from net leading to net lagging VARs.

Figure 2-6 (A) Individual VI relationships for a switched capacitor and controlled reactor.
 (B) Combined VI characteristic illustrating controllable leading to lagging VARs at V_0 .

SVC CONTROL

A description of typical SVC control is best begun with a discussion of SVC response to small system voltage disturbances at frequencies lower than the nominal system frequency. Under such "quasi" steady state conditions, it is useful to consider the Thevenin equivalent of the power system from the bus of application

of the SVC. Figure 2-7A shows this Thevenin equivalent as a voltage, V_s , behind a single series impedance, Z_s . Considering for the moment, the SVC to be a source of either capacitive or inductive current, the bus voltage at the location of the SVC is given by the equation of Figure 2-7A. Graphically this equation is depicted by the solid line on Figure 2-7B which as expected has a slope equal to $-Z_s$. Adding an SVC control or VI characteristic of the type shown in Figure 2-6(B), it is evident that in steady state $V_{SVC} = V_0$ and the SVC will be operating in the inductive range at a current of I_0 .

Figure 2-7. Thevenin equivalent for transmission system from SVC terminals.

The voltage associated with zero SVC current, $V_0 = V_{REF}$ of Figure 2-7B, could be raised to coincide with V_s so that the SVC would then attempt to hold voltages closer to V_s with little changes in SVC current.

In Figures 2-6(B) and 2-7(B) the portion of the SVC VI-characteristic that corresponds to continuous control (i.e., line 1-2 in Figure 2-7B) is shown with zero voltage regulation (i.e., zero slope) at a bus voltage of V_{REF} . However, typical in SVC control system parameters result in the slope of the SVC control characteristic being a non-zero value. The voltage regulation of the SVC may be determined by establishing the allowed variation in terminal voltage as a function of the reactive current output required of the SVC at a given bus. For example, suppose SVC bus voltage is to be held constant, and furthermore that operation of the SVC

at maximum capacitive or inductive ratings produce SVC bus voltage changes of $+\Delta V_{C_{MAX}}$ and $-\Delta V_{L_{MAX}}$, respectively, as determined by the system impedance Z_S . If the source voltage V_S was decreased by an amount ΔV_S equal to $\Delta V_{C_{MAX}}$, full terminal voltage compensation could be obtained, as shown in Figure 2-8, by operating the SVC at the maximum capacitive output current, $I_{C_{MAX}}$. Similarly, if the source voltage was increased by an amount ΔV_S equal to $\Delta V_{L_{MAX}}$, full voltage compensation could again be operated by operating the SVC at the maximum inductive current output, $I_{L_{MAX}}$. Thus, if no SVC bus voltage deviation is permissible over the linear range of SVC control, a flat SVC control characteristic is required (as in Figure 2-8).

Figure 2-8. Terminal voltage versus reactive current for full voltage compensation.

Instead of full compensation of the bus voltage in the event of source voltage changes of $\pm \Delta V_S$, an alternative would permit SVC bus voltage deviations of $-\delta V_C$ and $+\delta V_L$ from V_{REF} . With this strategy, source voltage excursions in excess of the maximum voltage compensation capability of the SVC would still fall within the linear control range of the SVC. Under this condition, the voltage versus reactive current output of the SVC exhibits a sloping characteristic, as shown in Figure 2-9, with the slope, S_{LP} , being defined as follows:

$$S_{LP} = \frac{\delta V_C}{I_{C_{MAX}}} = \frac{\delta V_L}{I_{L_{MAX}}}$$

where,

δV_C is the drop in terminal voltage at maximum capacitive current output, $I_{C_{MAX}}$, of SVC

and,

δV_L is the rise in terminal voltage at maximum inductive current output, $I_{L_{MAX}}$, of SVC.

Figure 2-9. Terminal voltage versus reactive current when full voltage compensation is not required.

Thus, from Figure 2-8 and 2-9, for a capacitor bank of rating Q_C ,

$$I_{C_{MAX}} = \frac{Q_C}{\sqrt{3} V_{L-L}}$$

$$I_{L_{MAX}} = \frac{Q_L}{\sqrt{3} V_{L-L}}$$

where Q_C is the three-phase value of capacitive VAR output of the SVC and Q_L , that value of the inductive VAR input.

Then, the magnitude of the maximum variation in line-to-neutral terminal voltage, $\Delta V_{C_{MAX}}$ and $\Delta V_{L_{MAX}}$, occurring at the maximum SVC capacitive and inductive output current, $I_{C_{MAX}}$ and $I_{L_{MAX}}$, respectively, can be determined as follows:

$$\Delta V_{C_{MAX}} = \frac{Q_C}{\sqrt{3}(V_{L-L}/Z_S)}$$

$$\Delta V_{L_{MAX}} = \frac{Q_L}{\sqrt{3}(V_{L-L}/Z_S)}$$

where

V_{L-L} is the nominal line-to-line voltage,

Z_S is the source impedance,

Q_C is the 3-phase capacitive rating of SVC,

and,

Q_L is the 3-phase maximum inductive rating of the SVC.

The conclusion to be gained from Figures 2-8, 2-9 and the analysis is relatively simple. When the linear control characteristic of an SVC is sloped, a given range of VAR control for the SVC will compensate for larger bus voltage changes than if the control characteristic has zero slope (e.g. compare the $V_S + \Delta V_S$ ranges of Figures 2-8 and 2-9). Conversely, with a sloped control characteristic, a smaller

- AVR - Automatic Voltage Regulator
- FAR - Firing Angle Regulator
- TCR - Thyristor Controlled Reactor
- B - Effective admittance of TCR
- V_{SVC} - Voltage at SVC bus
- Z_S - System impedance at SVC bus
- V_S - System equivalent source voltage
- $H(s)$ - Transfer function of voltage measurement devices
- V_{REF} - Reference (setpoint) voltage
- E - Voltage error

Figure 2-10 (A) - Thevenin equivalent circuit of SVC application.
 (B) - Functional block diagram of SVC controller used for bus voltage regulation.
 (C) - Simplified block diagram.

SVC could compensate a given ΔV_S . The key is the permissibility of the magnitude of the small voltage deviations δV_L and δV_C which result with a sloped control characteristic. In Figure 2-9, the control characteristic slope is exaggerated; for most applications this slope is in the range of 3-5%.

* * *

The foregoing discussion, although providing insight on the effects of a sloped control characteristic, fails to describe how the SVC control characteristic is shaped by SVC control system parameters and settings (and how the SVC responds to other than "quasi-" steady-state conditions.)

In the static VAR compensator, continuously variable leading and lagging reactive compensation is made possible through controlled firing of the SVC thyristor switches. Such control is one of the primary functions of the SVC control system. Figure 2-10b illustrates a typical functional block diagram of a thyristor-controlled reactor SVC controller used for bus voltage regulation. Figure 2-10c is a simplified diagram obtained by considering only small system voltage changes. The SVC control characteristic that results from the scheme illustrated in Figure 2-10 is shown below. (Note the similarity to the characteristic shown in Figure 2-9).

Figure 2-11. - SVC control characteristic corresponding to Figure 2-10.

Several important aspects of the control system and characteristic deserve attention. First the slope of the control characteristic (e.g., the steady state error) can be shown to be inversely proportional to the open loop gain of the control system. Higher gains result in less steady state error (e.g., a smaller control characteristic slope). However, higher gains also result in increased degrees of response instability (i.e., reduced damping). Thus, a flat control characteristic implies an infinite open loop gain and unstable operation. A finite positive slope is therefore almost always specified, with this slope and the associated controller gains established after careful study of SVC interaction with the power system.

From Figure 2-10C note that the system short circuit impedance at the SVC bus $Z_S(s)$, is included in the control loop. The significance of this presence stems from the relationship between this impedance and frequency, since resonances at frequencies within the controller bandwidth can result in excessive gains and instability.

The presence of a system impedance in the control loop gain of the SVC controller also influences control response parameters. Response time, for example, is a function of this impedance plus AVR, FAR and transducer (i.e., $H(s)$) characteristics. Typically, the settling time of the SVC for changes in V_{ref} is 1.5 to 2 cycles. Much of this time can result from relatively slow AVR response. Thus, some controllers bypass the AVR for large voltage disturbances so that settling can be achieved in about 1 cycle.

The SVC controller is typically designed to have a flat frequency response to about 15 Hz such that synchronizing torque is provided by the SVC during system swings that are initiated after faults, generator outages, or line trips. In this regard, when SVCs are applied primarily for the purpose of damping system swings, studies performed for this project and other studies (References 2-1,2) have shown frequency, line power flow, or a phase-shifted voltage signal to be more advantageous control signal than unaltered bus voltage. Control on the basis of these system parameters supplements synchronizing torque with additional damping for stabilizing system swings. Of course, under this type of control, voltage regulation maybe somewhat compromised.

In the preceding discussion of the SVC control characteristic and its slope in the linear range, consideration was restricted to system contingencies which only altered the system voltage (i.e., ΔV_S). However, in general the voltage and slope of the given equivalent load line (i.e., Z_S) can change for different system operating conditions. To determine Thevenin equivalents, load flow studies have been used to show the range of the bus voltages to be expected under peak load and light load conditions. VAR absorption and supply can be varied to determine the "voltage versus VAR sensitivity" at the particular bus for the particular operating conditions. These, again, only show the response to small, relatively slow, changes.

Figure 2-12 illustrates results of a set of load flow studies where, at the critical bus, the voltage was varied $\pm 2\%$, and the amount of VARs to be generated and absorbed was calculated (2-3). From this figure, one can see that a 1% voltage change requires about 30 MVARs under peak load condition, but during a contingency condition (defined as the loss of a major generating unit), a voltage change of 1% requires only about 20 MVARs. This is due to the reduced short circuit capacity of the system; that is, the same capacitive VARs flowing through a larger reactance causes a larger voltage change. A series of load flows in which each bus voltage is varied can be used to obtain the total amount and range of VARs required to maintain system voltage within specified limits under various operating conditions anticipated.

Figure 2-12. Voltage-VAR sensitivity at a 230 kV substation.

REACTIVE REQUIREMENTS IN POWER SYSTEMS

Any AC electrical system requires two types of electrical energy to function properly: real power, causing rotation of loaded motors, arc heating, lighting, etc; and reactive power provided to produce magnetic and electric fields for the transfer of real power. Any system component (e.g., utilization device, transformer, or transmission line) that has inductive reactance characteristics represents a volt-ampere-reactive (VAR) load and real power cannot be transmitted without supplying this reactive load. The VAR load is a function of the square of the current being carried by the component.

In the case of arc furnace systems, the circuit is essentially fixed with the major portion of the system reactance being in the furnace transformer and the secondary leads to the furnace electrodes. Since these reactances are large, mechanically-switched shunt capacitors are generally used in the circuit to provide the VAR required by the load. However, since in the various stages of a melt the real power load fluctuates rapidly in the furnace, there can be large VAR (current) changes back into the source, causing voltage flicker. SVCs with thyristor-current-controlled reactors (TCR) (as contrasted with a compensator with thyristor-switched capacitor, thyristor-controlled reactor (TSC-TCR)) have been applied to absorb the circuit capacitive VAR changes as the load fluctuates, thereby reducing voltage flicker. For arc furnace applications, SVC ratings typically are 25-75 MVAR, 15 to 34.5 kV, but sizes as large as 200 MVAR are now being applied.

In contrast, the characteristics of a transmission system are changed as lines or generation are switched in and out. Also, long transmission lines and underground cables have both significant capacitance as well as inductance, and exhibit a different characteristic depending upon the load being carried. In many situations, system VAR requirements can be adequately supplied by either mechanically switched shunt capacitors or shunt reactors, series capacitors, or combinations of these. However, where there is a need from the standpoint of system stability for large controlled changes in VARs, the synchronous condenser and, now the SVC are beneficial.

Most power utility systems (as contrasted with industrial) applications of SVCs are expected to be on high-voltage, relatively long transmission lines, where the cost of these devices can be justified in terms of improved system capability and performance. Because of the large values of reactive volt-ampere (VARs) associated with long lines (large capacitance) and higher voltages of these transmission installations (VARs proportional to voltage squared), the sizes of transmission applications are generally in excess of 100 MVAR with the range of controlled VARs being proposed as large as 450 MVAR.

For the most effective use of presently existing thyristor ratings and other SVC components, step-up transformers are being used to couple the SVC, operating at a maximum voltage of 25 to 34.5 kV, to the transmission line voltage of as high as 800 kV. This transformation may take the form of a separate transformer or the third winding of a transformer used for other purposes.

A modification of the SVC is also being supplied as a solution to the subsynchronous resonance problem with series capacitors (2-7). The device is basically an SVC but with control sensing of changes in turbine generator torsional oscillations, rather than the sensing of changes in voltage and current used in SVCs for arc furnace and transmission system applications. These different applications point up an additional and very important observation: the flexibility in control sensing and potential for other uses that can be made of the SVC technology.

APPLICATION OF SVCs TO TRANSMISSION SYSTEMS

The ability of the SVC to rapidly and continuously vary reactive compensation in response to changing system conditions can result in numerous improvements in transmission system performance depending on the control objectives and strategy adopted. A list of these improvements includes:

- 1) reduced voltage flicker due to irregular load fluctuations,
- 2) increased steady state transmission capacity and enhanced transient stability with intermediate bus voltage support,

- 3) improved system dynamic stability by virtue of increased system swing damping,
- 4) control of steady state and temporary overvoltages,
- 5) improved transmission system efficiency and load power factor by virtue of local VAR supply,
- 6) improved HVDC conversion terminal performance during abnormal and recovery situations, and
- 7) damping of subsynchronous oscillation,
- 8) to correct phase imbalances or compensate irregular single phase loads.

For further details on these system performance benefits, References 2-1, 11, 12, 13, 14, and 7 are cited. Each of these eight benefits has been demonstrated on existing SVC installations. Analytical studies have also defined another possible application for the SVC; providing the lagging compensation required in conjunction with single pole switching (2-15).

The major applications of SVCs to transmission systems have had the purpose of bolstering transmission capability by voltage support, either because of an already restrictive shortage in system transmission lines, or to reduce the number of required transmission lines because of the large economies in doing so (2-4). The nature of each application creates somewhat different considerations. Two examples illustrating these situations are:

- 1) Delayed or restricted EHV transmission (one line or more) overlaying a lower (HV) voltage system, in which the sudden loss of the EHV transmission imposes at least part of its high power transfer requirements on the underlying HV systems which, without some fast-acting voltage support would pull apart. The practicability of such applications is limited by the loading of the EHV system and the capability of the underlying lower voltage system to absorb the imposed additional power transfer, regardless of the size of the SVC that can be practically applied.

This power transfer requirement, combined with the requirements imposed by the character of the load being served by the underlying LV system (such as mining areas with large drag lines, etc., resulting in large fluctuations on voltage, to which the SVC is added to smooth these voltage "bumps") may make this SVC application additionally attractive.

- 2) Very long EHV transmission required to transmit many gigawatts of power from remote large generating sites into large load areas in line lengths far in excess of what is normally in use (2-4). The cost of additional lines of such lengths has made very attractive the application of SVCs, which essentially supplant the need for additional lines which would normally make the transmission system strong enough for transient and dynamic stability for major disturbances, such as faults and loss of generation. In addition to shunt compensation, transmission capability may be augmented by nominal amounts of series compensation.

Figure 2-13 schematically portrays these two examples.

Both of the above could have been, to some extent, achieved by the use of synchronous condensers with fast excitation response. However, the maintenance cost and other penalties of synchronous condenser application have made SVCs more attractive. Also, it has been claimed that the exceedingly fast dynamic response possible with SVCs over synchronous condenser response has allowed even further reduction in the number of transmission lines that would be otherwise required (2-4).

There are a few SVC installations in operation on transmission systems in the U.S. One installation has been in operation since early 1978 at the 230 kV Shannon Substation on the Minnesota Power & Light System. This installation is the result of a cooperative research and development program sponsored by EPRI, to demonstrate the concept of Static VAR Compensation on a large utility system in conjunction with other voltage control equipment.

Figure 2-13. Schematic Examples of SVC Applications to Transmission Systems

Although this SVC is limited in size compared to the maximum requirements that might be imposed, the installation has offered an opportunity to monitor the SVC operation, within its capability, under such conditions as:

1. normal load cycles,
2. bus voltage oscillations while starting large motors for mining, and
3. loss of generation or major transmission outages.

System studies were made to model the performance of this 40 MVAR SVC (2-5) and to define the location on the system where the full range of the SVC could be utilized and operated under various system load swings and disturbances.

This SVC consists of a thyristor-controlled reactor connected to the 13.8 kV tertiary winding of a 230 to 115 kV autotransformer and a fixed 45 MVAC capacitor bank connected to the 115 kV bus. Two 36 MVAC, 230 kV, capacitor banks can also be switched automatically on control from the SVC, or manually.

The dynamic range of the SVC is 40 MVARs, which can be extended to about 120 MVAR (e.g., -40 MVAR to +80 MVAC) by controlling the two mechanically-switched, 230 kV capacitor banks.

Another SVC installation is operated by Basin Electric Power Cooperative, and is located in western Nebraska at the Victory Hill Substation, in an area where studies indicated a need for steady-state and dynamic control of reactive power. The thyristor-controlled reactor was rated continuously at 40 MVAR at 13.8 kV, and includes a filter bank rated 30 MVAR capacitive at 13.8 kV. The SVC is connected to the 13.8 kV tertiary of a 230 to 115 kV autotransformer. The purpose of this SVC is to regulate the 115 kV bus voltage at the Victory Hill Substation within $\pm 0.5\%$ of the voltage set point. The SVC was to be compatible with other voltage regulating equipment electrically nearby. Numerous application studies of steady state and dynamic requirements were also required for this application (2-6).

Another large scale SVC has been installed in the Central Appalachian Area of the American Electric Power System. It consists basically of two 8.3 kV thyristor-controlled reactors and two 8.3 kV thyristor-switched capacitors. This SVC is connected to the 138 kV transmission system through a 125 MVA transformer and has an overall range of 125 MVAR to 125 MVAC. The range has been extended to +325 MVAC by installing four, 50 MVAR, 138-kV capacitor banks that can be switched under the control of the SVC. A purpose of this application is to help moderate, by extensive reactive correction, the effect on transmission capability of delays in expanding the overlaying EHV transmission. Additionally, the load supplied in this area is characterized by large mining operations with subsequent excessive voltage regulation.

EFFECT OF LONG LINES ON SVC REQUIREMENTS

For long transmission lines or cables, shunt reactive power required at ends of the lines for light load conditions and reasonable terminal voltages can reach high values. Thus, the inclusion of an EHV transmission line or a number of high voltage lines or cables between two systems or parts of a system produces certain VAR requirements upon the two end systems. Where the systems are unable to absorb the VARs with inductive loads or lagging p.f. machines, terminal voltages may rise dangerously under light load conditions. VAR requirements for

transmission lines increase as the square of the operating voltages and directly with the capacitance of the lines. The increased capacitance of bundle conductors commonly used for EHV transmission lines causes a significant increase in VARs. An approximation of line charging for overhead EHV transmission lines can be found in Figure 2-14 (2-8).

Figure 2-14. Curves show line-charging VARs for both single and bundle conductors at various transmission voltages.

A simple way of considering long-line characteristics utilizes "circle" diagrams (2-9) of Q (VAR) vs. P (Power), demonstrating directly what absorption or generation is necessary to hold down or support voltage for particular real power loading of the line. Such circle diagrams can be developed for directly paralleled and series transmission systems but are difficult to derive for network systems, i.e., lateral ties between buses. As mentioned previously, load flow studies with transmission line charging VAR represented can be used to make this analysis.

Using the "ABCD" constants of the transmission line (2-9), the circles are constructed with the following parameters (Fig. 2-15).

Radius of transmission line sending and receiving end circles equals

$$|\bar{E}_S| |\bar{E}_R| / |\bar{B}|$$

Location of center of sending end circle is at $(\bar{A}/\bar{B}) \bar{E}_S^2$

Location of center of receiving end circle is at $-(\bar{A}/\bar{B}) \bar{E}_R^2$

where E_S and E_R are the sending-end and receiving-end voltages, respectively.

The angle θ between $\bar{E}_S$ and $\bar{E}_R$ establishes the corresponding operating points on each circle, i.e., points X and Y on Figure 2-15.

Figure 2-15. Power circle diagram in terms of ABCD constants.

A convenient method for analyzing the effect of and quantitatively anticipating the need for shunt reactive compensation is provided through an examination of these circle diagrams representing the steady-state performance of the transmission line.

Figure 2-16 is a portion of the circle diagram for typical EHV transmission lines of 483 km (300-mile) length using typical line constants. These diagrams may be used as a aid for estimating the reactive requirements of EHV line sections for given conditions of power and VAR flow as determined by the systems that are linked by the EHV line section. For example, Figure 2-16(a) represents

Figure 2-16. Circle diagram for a 300-mile, 500-kV line indicates sending-end (lower) and receiving-end (upper) conditions for transferring power.

their performance of the receiving end of a 500-kV line 300 miles long. Point A on the figure indicates that a power flow of 750 megawatts will require the system at the receiving end to absorb over 100 megavars, either in the inductive load characteristics of the system, by under-excited machines, or by shunt reactive compensation. If the power factor of the receiving end load does not change from that of point A, then about 870 megawatts can be transferred over the line by increasing the sending end voltage to 500 kV with a small increase in absorbed VARs, as shown by point B.

Figure 2-16(b) shows the sending end conditions for the same transmission line. Points A and B correspond to the same points of figure 2-16(a).

(Note that these diagrams do not include series compensation, which could be used for the longer lengths and adds some complication to the discussion that follows.)

For operation at point A, the system at the sending end of the line must absorb approximately 70 megavars in shunt compensation or by other means. If the sending end voltage is raised to 550 kV and operated at point B, the lagging VARs that must be absorbed at the sending end are reduced, and about 70 megavars must actually be supplied to the line to support the voltage at the sending end.

Thus, for these conditions and the voltage changes indicated, an SVC would be required at the receiving end to operate over a range of approximately 100 MVAR to 200 MVAR (inductive absorption) less whatever VARs can be absorbed by other inductive load. In comparison, unless other sources of VARs are present at the sending end, an SVC at this location might be required for these conditions to have an operating range of 100 MVAR (inductive absorption) to 100 MVAC (capacitive generation), if used to boost voltage 5 percent.

Consideration is now being given by some utilities to operation of transmission lines beyond surge impedance loading (SIL); that is, the loading on a line, for given terminal voltage conditions, at which VAR absorption and VAR supply are equal, e.g., the point where the circle diagram (Fig. 2-16) crosses the real power (abscissa) axis. For operation beyond SIL, VARs must be supplied to the line, so an SVC applied at one terminal or the other may be required to have an operating range extending from inductive absorption to capacitive generation. Depending on the system voltage and line length, the magnitude of these VARs can be very large.

System and line constants can also be used to develop curves of voltage variation with receiving end power flow with constant VARs as a parameter. From such curves as Figure 2-17, estimates can be made of SVC capacitive VAR requirements for power swings over a transmission line.

Figure 2-17. Variation of receiving end voltage versus real power for a 200 mile 500-kV transmission line with fixed levels of reactive compensation.

THE EFFECT OF SVCs ON SYSTEM TRANSIENT STABILITY

The power transfer between any two points 1 and 2 in a system, such as the terminals of a transmission line, can be described in terms of voltage, reactance and power angle, by the equation

$$P_{12} = \frac{V_1 V_2}{X} \sin \theta_{12}$$

Where P_{12} is the power, X is the reactance between the terminals, V_1 and V_2 are the voltages at the sending end and receiving end, and θ is the angle between them. (Here, transmission line charging VARs and line resistance have been neglected.) This is the so-called power-angle equation, assuming constant terminal voltages, and may be plotted as shown in Figure 2-18 for the several reactances, X , before a fault (1), during a fault (2), and following clearing of the fault (3). The stability limit P_m can be estimated, as conventionally done, by use of the equal-areas, A_1 equal to A_2 .

Figure 2-18. Power transmission capability as a function of sending to receiving bus voltage angle differential, before (1), during (2), and after (3) a line fault.

In many studies the response of SVCs can be assumed to be instantaneous compared to the slower response of turbine generator excitation systems. Thus, the effect of the SVCs is to hold voltage constant, or within its droop (i.e., linear control) characteristic. If it is assumed that the voltage at the SVC high-voltage bus is held constant, the effect of the SVC is to segment the line (or the total system impedances, if terminal impedances are also considered with line impedances) so that each line section can be considered individually from a power-angle standpoint (Figure 2-19). The impedance of each section being one-half that of the total line, the total stability of the complete transmission system with voltage held constant is very much greater than that without. If HV bus voltage can be held constant, then theoretically the maximum permissible (statically stable) power over the circuit can be doubled over what it could transmit without this SVC action (Figure 2-19).

Figure 2-19. Comparison on power vs. angle with and without ideal SVC.

The transient stability limits of the system without and with the SVC can be estimated through the use of the equal-area approach (2-10) from such plots of the power-angle diagrams as Figure 2-19. Figure 2-20(a) illustrates the improvement in stability of utilizing an "ideal" SVC in an HV system when an overlaid EHV transmission line is lost. Note that even with the SVC action, the stability limitations of the capability of the low voltage system dictate the power limits to impose on the total system.

Figure 2-20. Stability limit based on Equal-area criterion for EHV plus HV system with SVC.

Figure 2-29. MVAR vs. MW for 200 mile 240-kV transmission line with SVC at center.

Obviously, the stability limits are dramatically increased with the SVC acting in concert with another parallel EHV line, the SVC then adding significantly to the stabilizing area under the power-angle diagram.

VAR requirements at the constant voltage SVC bus during transient stability swings can be estimated from the circle diagrams of Q versus P for one of the line sections by relating power at any angle on the power-angle diagram to the same power and angle on the circle diagrams of Q versus P on the succeeding line section. Circle diagrams of Q versus P can be constructed for each line section separately for the given system terminal voltages and SVC bus voltage, to determine what the VAR requirements for each section will be for the given power transfer (Figure 2-21). At the SVC bus, power through the line section from the sending end equals whatever losses are assumed into the SVC plus the power into the line section to the receiving end. The total VAR requirements for the SVC are the sum of the requirements for both sections, as shown by the vertical line on Figure 2-21. The circle diagrams of Figure 2-21 indicate that depending on the magnitude of power swing which occur, the SVC capacitive size can become quite large and the VAR demand very non-linear, if constant voltage is to be maintained at the SVC bus during this swing.

Regulation through the coupling transformer, as well as actual response of the SVC of course, can affect the SVC high-voltage bus voltage and thereby change the resulting power angle curve and the VARs supplied to the line. Figure 2-22(2-11) shows this effect as a function of the ratio of the coupling trans-

Figure 2-22. Family of power-angle curves including coupling transformer regulation. "K" equals the ratio of transformer to line reactance. All curves drop to zero at $\theta=180^\circ$.

former reactance to the total transmission line reactance for an SVC at the center of the line. "Practical" power-angle curves, therefore, depend on the size of the coupling transformer and its reactance and which bus is being regulated.

RESPONSE OF SVCs TO LARGE SYSTEM DISTURBANCES

Disturbances in the power system may be termed "large" when the resultant terminal voltage excursions extend outside of the range of linear control (regulation interval 1-2 of Figure 2-7) of the SVC. Such disturbances are often characterized by rapid voltage change with high frequency content.

System changes that can result in large disturbances, in addition to system faults, are:

- Loss of generation.
- Switching transmission lines, either following faults or without faults.
- Switching other reactors or capacitors.
- Start-up of other SVCs.
- Rejection of load in a transmission system.
- Bypassing or reinsertion of series capacitor banks.

Requirements on SVCs have therefore sometimes been defined on the basis of SVC impact on transmission system performance, rather than simply in terms of capacitor bank and reactor bank sizes under rated voltage conditions.

Examples:

- Temporary overvoltages in certain parts of the transmission system to be limited to some magnitude after first half cycle of temporary overvoltage.

- Typical cyclic operation voltage levels and MVAR requirements that will be imposed on the SVC during disturbances and system emergency operating conditions.
- The minimum speed of response possible by the SVC without instability, and limitations arising from very low natural frequency characteristics of the system.
- Limitations on harmonic generation as a function of transmission characteristics.

Several approaches have been suggested to meet the requirement of absorbing large amounts of VARs during the high overvoltages:

- Use of the short-time overload capability of the step-down (coupling) transformers of the SVC in the saturated state together with switching-on by additional thyristors of larger short-time rated shunt reactors. However, in order to avoid ferroresonance during over-voltage between the transformer and the system, minimum values of transformer saturated reactance have been specified; e.g., no less than 25% of rated reactance, and the knee of the saturation characteristic no less than 115% of rated voltage.
- Use of the inherent short-time overload capability of the saturating reactor together with its coupling transformer.
- Use of short-time overload capabilities of conventional reactors and thyristors.

Part of the problem of SVC application for large disturbances is being able to distinguish when the presence of shunt capacitors will be beneficial, and when detrimental for the operation of the transmission system; i.e., when the capacitors should be left on and when not. During fault conditions, system voltages are us-

ually depressed. This would normally cause the SVC to increase shunt capacitive compensation to try to boost voltages. If the faulted line is cleared without load rejection, this capacitive compensation is needed to replace the capacitance of the line that has been cleared as well as to supply the increased VARs absorbed by the remaining lines with each carrying the additional load component that had been carried by the removed line.

In contrast, should loss-of-load follow faulting then the capacitance of the remaining unfaulted, now unloaded, lines causes overvoltages that are further aggravated by any additional SVC capacitive compensation. In this latter case, what is needed are the equivalent of large shunt reactive compensation to absorb the transmission system's large capacitive VARs in order to control overvoltages. This is especially true if other fixed shunt reactor banks have been switched off prior to the disturbance to increase the power transfer capability of the transmission system. During very large overvoltages of short duration, the SVC may be required to absorb VARs far in excess of the nominal continuous rating of the device.

Although shunt capacitors might be switched out during the fault period as fast as practical with modern breakers (e.g., 2 cycles), fast reclosing is usually not desirable because of reclosing transients due to "trapped" charge voltages on the capacitors. This can complicate the use of fixed-capacitors since it cannot be anticipated ahead of time that, following a disturbance, capacitive compensation will be needed or not to support voltage and improve system stability. Hence, the switching of capacitors with thyristors provides advantages related to speed and freedom from switching transients for such applications.

INDUSTRY COMMENTS: TRANSMISSION APPLICATION OF SVCs

To establish the need and potential applications for static VAR devices on transmission systems, and to obtain a broader "user-oriented" perspective of VAR compensators, four U.S. utilities with diverse system characteristics were selected for interview. Diversity in operation philosophy and VAR requirements were among the prime criteria used to select the utilities. Philadelphia Electric, for example, was chosen on the basis (later shown to be incorrect) that their major VAR requirements would be dictated by their large underground cable system. General Public Utilities and Pennsylvania-Jersey-Maryland Interconnection were selected because of their proximity to P.E. and because of their involvement in a closely-tied, relatively short or compact, overhead EHV system. Basin Electric was chosen because of the broad considerations they have given to the use of SVCs, including combining series compensation with SVC operation, and because they presently have an SVC operating in their transmission system. The Western Area Power Administration was chosen as the fourth utility to be interviewed because of the long-line character of their transmission system and the previous indication of interest in SVCs shown by WAPA management.

Other systems specifically considered but not selected for interview were:

- a) Baltimore G&E - because of the relative compactness of its system and the use of synchronous condensers,
- b) Utah P&L and Georgia Power or Southern Services, Nebraska Public Power District, Texas Utilities because of recent active interest in SVCs for solving transmission contingencies,
- c) AEP & Quebec Hydro as owners of SVCs,
- d) Duquesne Light because of their extensive underground cable system and of large arc-furnace loads, and

- e) Tennessee Valley Authority because of their interest in voltage support during plant startup.

The final choice of utilities for interview was a combined decision by the Westinghouse project team, Dr. H. Boenig of Los Alamos, and Mr. R. Flugum, technical advisor on the project. Appendix D of this report contains a copy of the questionnaire or "basis of discussion" which guided these interviews, and also detailed summaries of the interview discussions. Briefly, the important findings of the four utility interviews can be summarized as follows:

- 1) Overhead transmission system VAR requirements are dominant over underground requirements.
- 2) It is difficult presently to evaluate the need for and economics of fast-response VAR devices, such as SVCs.
- 3) It is difficult with present study "tools" to evaluate the fractional portion of total shunt VAR requirements that should be SVCs.
- 4) With large, heavily-loaded, closely interconnected systems such as PJM, a need exists for fast, on-line, automatic, coordinated, dispatching of VARs across the total interconnected systems, and to quickly identify and take action for potential VAR problem areas.
- 5) It is not evident, with the availability of the fast-acting functions of SVCs, how overloaded transmission systems can operate; i.e., to what level local generation can be reduced, such as in eastern PJM, before transient and dynamic stability problems can not be mitigated with large or multiple installations of SVCs. Nor are the advantages of combined series and shunt compensation, under these circumstances, recognized.
- 6) With large heavily-loaded interconnected systems, large blocks of VAR sources, located in close proximity to load areas could be required. These sizes could possibly exceed those to which synchronous condensers could be built, and exceed the switching capability of available devices to switch shunt capacitors.

- 7) In the planning of VAR sources for multi-utility interconnected systems, mutual agreements are required for locating and operating large VAR blocks.
- 8) New study methods are needed by the Industry to optimize size and location of shunt compensation in large closely interconnected systems.
- 9) System planners have no reservations in the SVC as a new, unproven technology. The basic question remaining unanswered is how best to utilize the SVC.
- 10) Other potential uses of SVCs are:
 - a) In conjunction with railroad electrification, and
 - b) To relieve VAR demands and improve stability of isolated generation, such as small water wheels.

REFERENCES

- 2-1 Olwegard, A., Ahlgren, L., Frank, H., "Thyristor Controlled Shunt Capacitors for Improving System Stability," CIGRE paper 32-20, September 1976.
- 2-2 Schweickardt, H., Romegialli, G., Reichert, K., "Closed Loop Control of Static VAR Sources of EHV Transmission Lines," IEEE paper A78 135-6 presented at IEEE 1978 Winter Power Meeting.
- 2-3 Cronin, J., Ostroski, G., Lordeon, W., Gyugyi, L., "Transmission Voltage Support with Static VAR Generators," IEEE paper A78 108-3 presented at IEEE 1978 Winter Power Meeting.
- 2-4 Elsliger, R., Hotte, Y., Roy, J., "Optimization of Hydro-Quebec's 735-kV Dynamic-Shunt-Compensated System using Static Compensator's on a Large Scale," IEEE paper A78 107-5 presented at IEEE 1978 Winter Power Meeting.
- 2-5 Cronin, J., Lordeon, W., Ostroski, G., "Static VAR Generators for Transmission Systems," Proceedings of the American Power Conference, vol. 39, pp 1133-1143, 1977.
- 2-6 Hauth, R., Humann, T., Newell, R., "Application of a Static VAR System to Regulate System Voltage in Western Nebraska," IEEE Transactions on Power Apparatus & Systems, vol. PAS-97, No. 5, pp. 1955-1964, Sept./Oct. 1978.
- 2-7 Putman, T., Ramey, D., "A Modulated Inductance Stabilizer for Power Systems Subject to Subsynchronous Resonance," Proceedings of the International Symposium on Controlled Reactive Compensation, Varennes, Quebec, pp. 269-289, Sept. 1979.
- 2-8 Taylor, E., "Method Determines Shunt Reactor Requirements for EHV Lines," Transmission and Distribution, pp 28-31, January 1967.
- 2-9 Westinghouse Electrical Transmission and Distribution Reference Book Chapter 9, Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania, 1964.
- 2-10 Byerly, R., Kimbark, E., editors, Stability of Large Electric Power Systems, IEEE Press, New York, 1974.
- 2-11 Gyugyi, L., Otto, R., "Static Shunt Compensation for Voltage Flicker Reduction and Power Factor Correction," Proceedings of the American Power Conference, 1976, pp. 1271-1286.
- 2-12 Hauth, R., Humann, T., Newell, R., "Application of a Static VAR System to Regulate System Voltage in Western Nebraska," IEEE Trans. on Power Apparatus and Systems, vol. PAS-97, No. 5 pp. 1955-1964, Sept./Oct. 1978.

- 2-13 Bahrman, M., Crane, L., Cooper, R., Lordeon, W., "Operating Experience with a Static VAR Generator on the Minnesota Power and Light System," Proceedings of the International Symposium on Controlled Reactive Compensation, Varennes, Quebec, pp. 18-36, Sept. 1979.
- 2-14 Gyugyi, L., Otto, R., Putman, T., "Principles and Application of Static, Thyristor-Controlled Shunt Compensators," IEEE Trans. on Power Apparatus and Systems, vol. PAS-97, No. 5, pp. 1935-1945, Sept./Oct. 1978.

Section 3

COMPARISON OF ALTERNATIVE SVC CONFIGURATIONS

A number of different SVC configurations have been used for transmission system compensation, and several schemes are presently under development or testing. Figures 3-1 (A-J) are simplified one-line diagrams of some of these configurations. Variations of systems A through G have been applied at commercial ratings on existing transmission systems; configurations H-I-J are as yet in development or prototype testing.

Prior to specific comparison of each of these configurations on technical performance and economic criteria, several general comments on SVC reliability, speed of response and capital cost are appropriate. First, in terms of reliability, experience to date indicates there is, or would be, little difference between any of the 10 schemes. The fundamental building blocks (i.e., components) for each configuration are basically the same, and relatively equal degrees of complexity apply to each scheme. Steady-state, or small-disturbance, response characteristics for each of the illustrated schemes are likewise basically identical. Each of the systems, except G, utilize feedback control for the thyristor switches, and as described in Section 2 the typical settling time for such control is 1.5 to 2 cycles.

In the comparisons that follow, qualitative comments regarding the cost of the various SVC configurations depicted in Figure 3-1 are given. To place these comments in the proper perspective, several facts regarding SVC "economics" should be cited.

Relatively speaking, the most expensive components in a typical static VAR compensator are the solid state devices used for reactive power control. On the basis of kVA rating, thyristor switches range 5 to 10 times more expensive than conventional interrupting devices. Special non-conventional reactor and transformer designs are likewise typically "high cost" items, as are HV and EHV harmonic filter banks. Given this information, one inherently assumes that those

* See footnote

Figure 3-1. One line diagrams of alternative SVC configurations

Figure 3-1 (continued). One line diagrams of alternative SVC configurations.

* Footnote - The splitting of thyristor controlled reactors across the thyristor switch is typical practice for the protection of the thyristors.

configurations with multiple thyristor switches and/or special reactive devices are far more expensive than the relatively simple scheme of Figure 3-1(a). However, competitive marketplace pressure have resulted in somewhat of a decoupling of "cost" and "price." For example, recent quotes on transmission SVC projects reveal only a 15-20% differential between the installed prices of commercial VAR compensator systems (i.e., Figs. 3-1a to 3-1g). On the average, these systems are quoted in the range of \$20-24 per kVA of controlled range of reactance, in 1981 dollars. Thus, in the comparisons which follow, the terminology "high cost" refers to quoted prices near \$24 per kVA, whereas "low cost" implies quotes of about \$20 per kVA.

In simple terms the cost of an SVC system includes not only the installed price (i.e., capital cost), but also operating costs which include, maintenance and losses. For solid state SVC systems, the predominant operational costs are those associated with SVC losses. In fact, at today's generation and energy prices, the capitalized costs of losses frequently outweigh capital costs by a significant margin. Hence, perhaps the most important measure of economic comparison between alternative SVC systems is the capitalized costs of losses of the SVC system at its normal operating point, which in most cases is near 0 MVAR (i.e., the SVC is "idling" with all compensation in "reserve" for a system contingency). In terms of losses there are significant differences between SVC configurations, and the ensuing comparisons will cite these differences.

In the following sections, each of the ten SVC types depicted in Figure 3-1 will be discussed from the perspective of technical and economic capabilities and limitations. However, as a prelude to these comparisons it is interesting to briefly consider the former mainstay of dynamic VAR supply: the synchronous condenser.

SYNCHRONOUS CONDENSER

The advantages of fast acting voltage support equipment for improving the operation of a power system have been recognized for years. The synchronous condenser has been the "work horse" of dynamic VAR supply, and it is not unusual to find system planners comparing the characteristics and features of modern SVC systems with those of the synchronous condenser.

Some advantages of the SVC compared to a rotating synchronous condenser are:

- a) The synchronous condenser is limited in sizes. In theory, due to its modularity, the size of the SVC is unlimited.
- b) The response time to a change of output or input of the synchronous condenser following a demand signal is limited by the time constant of the rotor field circuit, which may be several seconds. The SVC can respond, in theory, in one cycle or less, but in practice it may be desirable to slow the response somewhat compatible with other system requirements.
- c) The rotor of a synchronous condenser may fall "out-of-step" with the rest of the system following a system disturbance that reduces condenser terminal voltage. Although there are no inherent "mechanical instabilities" possible in an SVC, the control gains, time responses, and transfer of operation outside the linear region (of Figure 2-9) must be coordinated if electrical instabilities are not to result.
- d) The synchronous condenser has comparatively high losses. Some SVC types are characterized by very low losses.
- e) Experience with the synchronous condenser has shown it to have generally high maintenance requirements. Experience to date with SVCs indicates maintenance requirements can be minimal.
- f) Design and construction of the synchronous condenser usually imposes a limitation on the ratio of VARs that can be supplied to those that can be absorbed. In theory, no such limitation exists on the SVC.

Additionally, the SVC can have the capability of having individual phase voltage control in order to handle unbalanced three phase circuits, while the synchronous condenser is inherently a three-phase device.

A rotating synchronous condenser, however may, in some applications by virtue of higher transient and extended time overload capability, have advantage over some forms of SVCs. Nonetheless, with proper consideration of ambient conditions in sizing, some overload capability is realizable in most types of SVCs.

THYRISTOR-CONTROLLED REACTOR (TCR), "FIXED" CAPACITOR (FC)

For the TCR-FC system shown in Figure 3-1(a), continuously controllable lagging to leading VARs are provided by thyristor control of reactor current only. Leading VARs are supplied by two or more fixed capacitor banks. The TCR is generally rated larger than the total of fixed capacitance to compensate (or cancel) this capacitance and provide net lagging VARs as shown in Figure 3-2. Given the proportional relationship between harmonic magnitudes and TCR size, the large reactor required in the TCR-FC can be a source of significant odd harmonics. Arranging the TCR and coupling transformer secondary in delta serves to cancel triplen harmonics, but the remaining six-pulse harmonics (e.g., $6k \pm 1$

Figure 3-2. VAR output versus VAR demand characteristic for the TCR-FC compensator.

where $K = 1, 2, 3, \dots$) must be filtered. Thus small reactors are usually included in the fixed capacitor branches to tune these branches as filters to dominant harmonics (e.g., 5th, 7th and high pass).

For a normal steady state operating point of 0 MVAR, 60-Hz current in the TCR is controlled by the thyristor switches to a level sufficient to cancel the leading current drawn by the fixed capacitor. Generally this current is below the reactor rating, and so the thyristors are in partial conduction (i.e., $0^\circ < \alpha < 90^\circ$). Harmonics are thus continually generated and must be filtered, and the continuously circulating current between the TCR and FC gives rise to significant losses in the thyristors and controlled reactor. Figure 3-3 illustrates qualitatively the relationship between losses and VAR output of a TCR-FC static VAR device. Typical no-load losses for the TCR-FC are about 0.9% of the reactor rating.

Figure 3-3. Relationship between per unit VAR output and losses for the TCR-FC compensator.

Flexibility in control and uprating are definite advantages of the TCR-FC over some alternative SVC schemes. Control strategies, parameters and reference set-points can be easily changed, and due to the modular nature of the reactive elements, the rating of the TCR-FC system can be increased by adding capacitor or

TCR banks (limited only by the coupling transformer rating). Excessive short time overload capability is not an inherent feature of the TCR-FC system since the controlled reactors are typically of the standard air core design. Thus, for applications where transient excessive system overvoltages are expected, the TCR must be designed for short term overloading, or separate thyristor switched overload reactors must be employed. From the perspective of overload capability, the coupling transformer is important in the performance of all types of SVCs. The saturation characteristics of this transformer must be carefully specified to avoid problems during extreme system transient overvoltages.

SEGMENTED TCR-FC

In the segmented TCR-FC compensator (Figure 3-1 b), the single large TCR is replaced by two or more smaller TCR "segments." The components, operation and performance of the segmented TCR-TC system are identical to the straight TCR-FC in all regards except harmonic characteristics. By dividing the total controlled reactor into two or more smaller TCRs, a significant reduction in harmonics can be achieved. Harmonic filter requirements are likewise reduced. This improved harmonic performance is a result of an operating procedure which permits conduction angle control of only one reactor step, with all other reactors either totally "on" or totally "off." Since harmonics magnitudes are proportional to the size of the controlled reactor, but are negligible for thyristor firing angles of 0° ("on") and 90° ("off"), controlling only one small reactor step minimizes harmonic generation. For a four segment TCR-FC, Table 3-1 and Figure 3-4 illustrate sequential TCR control for harmonic reduction as a function of increasing demand for lagging VARs from 0 to 1.0 pu.

TABLE 3-1

Thyristor Firing Angles for Sequential TCR Control

Demand For Lagging VARs	TCR Segment #			
	1	2	3	4
0.0-0.25 pu	$\alpha = 90^0$	$\alpha = 90^0$	$\alpha = 90^0$	$0^0 < \alpha < 90^0$
0.25-0.50 pu	$\alpha = 90^0$	$\alpha = 90^0$	$\alpha = 0^0$	$0^0 < \alpha < 90^0$
0.50-0.75 pu	$\alpha = 90^0$	$\alpha = 0^0$	$\alpha = 0^0$	$0^0 < \alpha < 90^0$
0.75-1.00 pu	$\alpha = 90^0$	$\alpha = 0^0$	$\alpha = 0^0$	$0^0 < \alpha < 90^0$

$\alpha = 90^0$ (TCR totally "off")

$\alpha = 0^0$ (TCR totally "on")

Improved harmonic performance for the segmented TCR-FC system is not achieved without trade-offs, however. Segmenting necessitates more than one thyristor switch, and if these switches are used at less rated capacity, the reduced efficiency can result in higher steady state losses. Therefore, both in terms of capital cost and the capitalized cost of losses, the segmented TCR-FC is generally more expensive than the unmodified TCR-FC.

12-PULSE TCR-FC

The harmonic characteristics of the segmented TCR-FC are further improved through the use of the twelve pulse configurations shown in Figure 3-1(c). By using two coupling transformers or one transformer with two secondary windings (one wye connected, the other delta), and splitting the controlled and fixed reactive elements between these secondaries, the 30^0 phase shift between secondary voltages results in an effective cancellation of all but characteristic 12 pulse harmonics (e.g., 11th, 13th, 23rd, 25th, etc.). Filtering requirements are thus reduced. Tuned filters are typically replaced with low Q, high pass filters which are provided by small reactors in series with the SVC capacitor banks. The tradeoffs

Figure 3-4. Waveforms illustrating the method of controlling the reactor banks sequentially to achieve harmonic reduction.

necessary for improved harmonic characteristics are once again related to capital and operating costs. A more complex transformer design is required, more thyristor switches are required, and complexity is added to the thyristor firing angle control as a result of the 30° secondary voltage phase differential.

HIGH IMPEDANCE THYRISTOR CONTROLLED TRANSFORMER (TCT)

As with the TCR-FC, the thyristor controlled transformer SVC (Figure 3-1 d) relies on fixed capacitors for leading VARs, and a thyristor controlled reactance for lagging VARs and continuous and controllability from leading to lagging compensation. However, for the TCT, this controlled reactance is provided by the impedance of a

specially designed transformer instead of air core reactors. The transformer is designed with a series impedance of approximately 100%, and delta connected thyristor switches on the secondary control of the flow of short circuit current through this impedance.

The design of the high impedance transformer is complicated due to the 100% impedance requirement, but on the other hand short circuit forces are not a major concern. The secondary voltage of the transformer is typically selected to efficiently utilize the ratings of the thyristor switches. The switches and transformer secondary windings are configured in a delta arrangement to "absorb" triplen harmonics. An advantage of the TCT scheme over other TCR schemes relates to the inherent overload capability of an iron core transformer compared to air core reactors, and to a TCT design with a high, linear saturation characteristic. Thus, during severe transient overvoltages the TCT has the capacity for excessive short term VAR absorption. Overload reactors are generally not required.

A comparative disadvantage of the TCR-FC system is its capital cost. Not only is a specialty transformer required, but also the capacitor banks and filters required for leading VARs and harmonic filtering must be located on the high voltage bus. As shown in Figure 3-1(d) some savings can be realized by using a double tuned filter design for these HV capacitors.

THYRISTOR SWITCHED CAPACITORS (TSC), THYRISTOR CONTROLLED REACTOR (TCR)

The TSC-TCR compensator (Figure 3-1 e) generally consists of one thyristor-controlled reactor, and n capacitor banks each in series with a solid state switch. The number of capacitor banks, n , is determined from practical considerations that include operating voltage level, maximum compensation requirement, and current rating of the solid-state switches. The total capacitive output range is divided into n operating intervals. In the first operating interval of leading VARs, the output of the compensator is controllable in the zero to $\text{VAR}_{\text{max}}/n$ range, VAR_{max} being the total rating provided by all capacitor banks. In this interval, one capacitor bank is switched in, and, at the same time, the current in the thyristor-controlled reactor bank is adjusted so that the sum between the

VAR output of the capacitor bank (leading) and that of the reactor bank (lagging) equals the compensation requirement. In the second, third, fourth,..., and nth operating intervals, the output of the compensator is controllable by switching in the second, third, fourth,..., and nth capacitor banks, and using the thyristor-controlled reactor bank to absorb the surplus capacitive VARs. This operation is depicted in Figure 3-5. The fundamentals and requirements of using thyristor to switch capacitors were discussed in Section 2.

Figure 3-5. VAR output versus VAR demand characteristic of the TSC-TCR type compensator.

The scheme is very similar to a conventional controlled-reactor scheme (with fixed capacitor) except that the rating of the reactor bank is kept relatively small (nearly $1/n$ times the maximum output), and the value of the capacitor bank is changed in discrete steps so as to keep the operation of the reactor bank within its normal control range.

To ensure that the switching conditions at the end points of the intervals are not indeterminate, the rating of the reactor bank has to be somewhat larger in practice than that of one capacitor bank in order to provide enough overlap between the "switching in" and "switching out" VAR values. Also, in practical systems, it is necessary to connect a relatively small reactor in series with each capacitor bank to reduce inrush current in the solid-state switch and ensure that resonances with the power system impedance do not take place at major harmonic frequencies.

Continuously controllable lagging compensation from the TSC-TCR arrangement can be provided up to the rating of the controlled reactor bank. All capacitor banks are switched out, and the reactor bank is controlled in the usual manner. However, when operating in this mode, no harmonic filters are available for attenuating the harmonics generated by conduction angle control of the reactor. This may or may not lead to significant problems. For example, since the rating of the TCR is small (compared to TCR rating in a TCR-FC compensator), harmonics will be reduced and can possibly be neglected, depending on system characteristics and SVC control system harmonic sensitivity. On the other hand, a small amount of "fixed" capacitors, serving as tuned filters, may be required as shown in Figure 3-1(e).

The TSC-TCR compensator was developed specifically for utility applications with the intention of overcoming two major shortcomings of compensators employing "fixed" capacitors; performance during large system disturbances and operating losses. Disturbances in the power system are termed large when the SVC control error signal is such to result in compensation demands outside the linear control range of the SVC. Such disturbances are often characterized by rapid voltage change (i.e., high frequency content).

For large disturbances the response of the "fixed" capacitor type compensators is inseparably tied to the fact that the SVC circuit includes the permanently connected (uncontrolled) capacitor. Under these conditions where the reactor switches are non-conducting, the SVC degenerates into a fixed capacitor. But under

those conditions where the reactor switches are conducting, the compensator is actually a parallel LC circuit exhibiting an inductive admittance only below its natural resonant frequency. By design this resonant frequency is usually close to the power system frequency. Thus, as shown in Figure 3-6, at frequencies somewhat above the system frequency, the SVC is capacitive irrespective of the thyristor switch firing angle.

Figure 3-6. The admittance versus frequency characteristic of the FC-TCR type compensator.

B_C = admittance of capacitor C. $B_L(\alpha)$ = admittance of reactor L at firing angle α .

The implication of this phenomenon is that during a major system disturbance oscillations will be established between the system (i.e., its impedance) and the fixed capacitor or parallel LC circuit. These oscillations can result in system voltage transients of significant magnitude, especially if the disturbance is followed by load rejection, and can also interfere in SVC control and measurement (Ref. 3-1).

Unlike "fixed" capacitor compensators, the TSC-TCR scheme possesses the capability to provide leading and lagging VAR compensation both independently and rapidly. This capability can be used to maximum advantage in devising strategies to provide optimum performance during large disturbances in the power system. Since the capacitor bank can be switched in and out rapidly, without appreciable disturbance to the power system, oscillations can be avoided, and thus the transients caused by the compensator can be minimized.

In comparison to "fixed" capacitor type compensators, the TSC-TCR also has a distinct advantage in terms of steady state losses. In SVCs, the major contributors to losses are thyristor switches and reactors. Thus for "fixed" capacitor SVCs, losses are a function of TCR current as depicted in Figure 3-3; increasing as compensation needs change from leading to lagging. Under no load conditions (e.g., 0 MVAR), losses are a significant percentage of the SVC rating due to circulating current between the FC and TCR. For the TSC-TCR, however, when neither leading or lagging compensation is required (i.e., 0 MVAR), all capacitance and reactance is disconnected. No-load losses are thus negligible. As a demand for lagging VARs increase, losses increase proportionally. But even under full conduction TCR losses are not as high as in FC compensators since the rating of the TSC-TCR reactor is much smaller. As a demand for leading VARs increases, losses also increase proportionally, but in a sawtooth fashion due to losses in the capacitor step thyristor switches and in the TCR. This loss characteristic is illustrated in Figure 3-7, superimposed on the TCR-FC loss characteristic. The TSC-TCR loss characteristic is generally advantageous in those utility applications where the compensator is used for dynamic compensation and is not required to maintain a high average VAR output for the normally functioning power system.

Figure 3-7. Loss characteristic of TSC/TCR compensator compared to TCR-FC compensator.

An obvious disadvantage of the TSC-TCR compared to FC type compensators is its capital cost. A smaller TCR rating results in some savings, but these savings are more than consumed by the capacitor switches and increased control complexity. Just as with conventional mechanical devices, capacitor switching duty effectively doubles the voltage rating requirements of the solid state capacitor switches. Therefore, the cost of solid state devices for capacitor switching are typically 50-75% higher than identically rated (i.e., MVAR) devices for reactor control. This cost differential translates to a typical premium of 15-20% for TSC-TCR compared to TCR-FC compensators.

MECHANICALLY SWITCHED CAPACITORS (MSC), THYRISTOR CONTROLLED REACTOR (TCR)

The MSC-TCR compensator can provide many of the same performance features as the TSC-TCR, but at a lower total SVC system cost. Conventional mechanical switches, typically vacuum or SF₆ devices, are used in lieu of the thyristors to switch a number of capacitor steps. These capacitors can be placed on either the high voltage bus or the coupling transformer secondary. However, when the capacitors are switched on the HV bus, a "fixed" harmonic filter is recommended in parallel with the TCR on the transformer secondary to reduce harmonic loading on the transformer (see Figure 2-1(f)). Existing MSC-TCR compensator systems are located on the Minnesota Power and Light, and AEP systems. These applications are discussed in references 3-2 and 3-3.

Compared to TSC, the MSC compensator has a two-fold cost advantage; lower first cost and lower operating cost (i.e., losses), both a result of replacing solid state switches with mechanical devices. The cost advantage, however, is not achieved without some sacrifice in performance. At best, the mechanical switching (i.e., closing) of capacitors can be accomplished in 4 cycles compared to $\frac{1}{2}$ -1 cycle for thyristor switches. The open-reclose operation using mechanical switches is dependent on a rapid discharging of the capacitors, but can be accomplished in 15 cycles or so. Again this compares to $\frac{1}{2}$ -1 cycle for thyristor switches. For some applications the slower response may have little or no impact on system stability enhancement or swing damping. Alternatively, the slower response may prove the difference between system stability or collapse. In either case, some studies (3-4) indicate that the slower MSC response may result in the requirement of up to 25% higher SVC rating to maintain transient stability.

Another disadvantage of the MSC compared to TSC configuration results from the slower response and "life" of the mechanical switches. Both of these factors somewhat preclude the use of the MSC-TCR as a means of steady state voltage regulation during minor system fluctuations since the recommended operating philosophy is to hold all capacitance in "reserve" for major disturbances (e.g., most or all capacitors are disconnected during normal system operation). Thus, a significant investment in shunt capacitance is unusable except during rare system disturbances.

SATURABLE REACTOR (SR)

The typical saturable reactor VAR compensator (Figure 3-1 g) is unique in that the device does not generally employ any solid state switches or active control. The SR is a self-regulating device that responds only to changes in its terminal voltage. The terminal voltage regulation characteristic of the SR compensator is dependent on the natural saturation characteristics of the iron-core reactor, the existence and rating of a series capacitor for saturation slope compensation, and the existence and rating of shunt capacitors. A typical SR voltage regulation characteristic, with and without series and shunt capacitors, is shown in Figure 3-8.

Figure 3-8. Voltage regulation characteristic of saturable reactor compensators with and without shunt and slope-correction capacitors.

The SR-type compensator has the best harmonic characteristics of any commercially available SVC. The usual harmonics associated with saturation in iron-core devices are internally compensated by specially designed multi-coupled-core twin and treble-tripler reactors (3-5). For example, under balanced system conditions, the treble-tripler reactor design internally attenuates all but relatively small characteristic 18-pulse harmonics (e.g., $18n \pm 1$ where $n = 1, 2, 3, \dots$). Imbalance in the system phase voltages or SVC phase and mutual impedances do, however, give rise to non-characteristic low order odd harmonics. Thus, the shunt capacitor banks associated with the SVC system are relied on for filtering as well as leading VARs.

Twin and treble-triple reactor design ratings extend to about 270 MVAR and 132 kV. The need for a couple transformer and the problems associated with its saturation are therefore eliminated except at EHV levels. Without series slope-correction capacitors, the SR-type compensator has the fastest response of any commercial SVC. Slope-correction capacitors slow this response slightly such that SR response time is roughly identical to the $1\frac{1}{2}$ -2 cycle settling time of "solid state" SVCs. A considerable amount of overload capacity can be easily and inexpensively provided in SR designs compared to TCR schemes. A practical limitation on overload ability is frequently the rating of series slope-compensating capacitors, but techniques are available to bypass these capacitors and so increase the saturation slope during overload conditions.

Without a coupling transformer, solid state switches, and active control elements the simplicity of an SR compensator is ideally suited for HV (i.e., up to 132 kV) applications in remote areas where trouble-free, reliable operation is of tantamount importance. But the SR compensator is not without its share of technical and economic deficiencies.

Slope-correction capacitors in series with the SR provide a means of modifying the voltage regulation characteristic of the compensator system. However, the potential of subsynchronous resonance resulting from these capacitors must be thoroughly studied, and sub-harmonic filtering across these capacitors (as in Figure 3-1(g)) may be required. SR-type compensators are also far less flexible,

in terms of control and uprating, than "solid-state" SVCs. Modularity applies only to shunt capacitors which provide filtering and leading VARs, and the absence of a means of active control severely curtails control strategy flexibility. Varying the amount of series capacitors will influence the slope of the voltage regulation characteristic, but changing the reference setpoint (e.g., saturation point) necessitates load-tap changing on the coupling transformer. Furthermore, SR-type compensators, because they respond only to terminal voltage changes, cannot provide the high degree of system stability enhancement and power swing damping that can be accomplished with control parameters other than bus voltage. For smaller installations, SR-type compensator control flexibility has been enhanced through the use of a DC-controlled reactor with an active feedback control system. The DC-controlled SR compensator is considerably more complex and expensive, and much slower than the un-controlled SR.

Generally speaking, SR compensators, even given their simplicity, are cost-comparable to "solid-state" SVCs. This is partially due to the uniqueness of the twin or treble-tripler reactor designs. If losses are included in the comparison, SR compensators tend to be more "lossy" than "switched" capacitor SVCs, since at no-load the SR scheme has excitation losses in both the coupling transformer and reactor itself.

UM CONCEPT

The University of Manitoba (UM) SVC concept (Figure 3-1 h) is a modification of the standard TCR-FC configuration with two parallel reactors, one in each leg of the anti-parallel thyristor switch, used to provide continuously controllable lagging VARs (Ref.3-6). Unlike standard TCR configurations, in which thyristor firing angles are limited to $0^\circ < \alpha < 90^\circ$ to prevent a DC component of reactor current, the UM reactor-thyristor arrangement results in permissible firing angles of $0^\circ < \alpha < 180^\circ$. The benefit of this wider spread of firing angle is a reduced sensitivity of reactive power to firing angle adjustment (Figure 3-9), and hence enhanced SVC controller stability.

Another significant advantage of the UM configuration is improved harmonic performance. Compared to the harmonic characteristics of typical TCR configura-

Figure 3-9. Relationships between lagging compensation and thyristor firing angle for the UM and TCR compensator configurations.

tions (Figure 2-3), the UM design has regions of firing angle where no, or insignificant amounts of harmonics are generated (Figure 3-10).

The improved technical performance characteristics of the UM configuration are not, however, realized without some economic compromise. In order to provide 1.0 of inductive reactance using parallel reactors (as in the UM concept), each reactor must necessarily be rated at 2.0 pu. Furthermore, when firing angles greater than 90° are used, a DC component of current of up to 1.0 pu circulates between the parallel thyristor-reactor assemblies. The result is that each of the UM reactors must carry a 3.0 pu (1.0 + 2.0) rating for a total of 6.0 pu of reactance, compared to a single 1.0 pu reactor for standard TCR configurations. The larger reactor sizes and circulating DC current also result in much higher losses in the UM scheme. To a certain extent these losses can be reduced by using more expensive, high Q reactors in the thyristor switch assembly. However, practical considerations concerning the additional costs of these reactors and the higher losses of the UM system have, as yet, prevented its commercialization.

Figure 3-10. Harmonic performance of the UM compensator as a function of firing angle.

FORCED-COMMUTATED INVERTER SVC

The forced-commutated inverter (FCI) SVC depicted in Figure 3-1(i) uses a 36-pulse voltage fed inverter for VAR control. Basically, the DC voltage is provided to the inverter by a charged DC capacitor. The capacitor is initially charged through the rectification of a low voltage source. The rectifier and low voltage source comprise the SVC start-up circuit. In operation, the inverter AC output voltage is adjusted in magnitude and phase relative to the system voltage, such that the voltage differential when applied across the reactance of the coupling transformer results in either lagging or leading VAR compensation.

Compared to conventional SVC types, the forced-commutated inverter SVC has substantially improved harmonic performance. The 36-pulse inverter generates insignificant $36k \pm 1$ harmonics, and filtering is not required. Static capacitors and controlled reactors are eliminated as sources of leading and lagging VARs, but a DC storage capacitor and commutating reactors and capacitors are required for the FCI. The response time of the FCI is comparable to conventional

compensator schemes, and like conventional SVCs, system voltage imbalances give rise to significant non-characteristic harmonic generation. However, with the FCI these conditions necessitate disconnection.

A prototype 20 MVAR forced-commutated inverter SVC is presently under test on a 77-kV system in Japan, and a 120 MVAR device is planned. At this stage of development, it is too early to assess the cost of a commercially practical FCI compensator, although it is expected that such a system would be relatively expensive. Furthermore, in terms of operating costs, the full-load losses of the FCI will average 2-3% of rating, in comparison to losses of 0.9-1.2% of rating for TCR and TSC schemes.

SUPERCONDUCTING COIL SVC (SAVAR)

Concern over the losses associated with standard SVC schemes using conventional reactors has led to an SVC concept utilizing a superconducting coil and a current-fed AC/DC converter as shown in Figure 3-1(j). In this scheme a nominally steady direct current is maintained in the superconducting coil with the controlled line-commutated converter "injecting" lagging or zero current into the AC system via the coupling transformer. "Fixed" capacitors serve to provide leading VARs and filtering for the characteristic harmonics of the 6 pulse AC/DC converter.

Compared to conventional SVC configurations, reactor losses are almost completely eliminated by the superconducting coil. However, thyristor losses are much higher. The increased thyristor losses arise because in the 6-pulse AC/DC converter bridge, two thyristors are always conducting, and each of these thyristors conducts a higher average current than do thyristors in the TCR arrangement. Thus, as Figure 3-11 indicates, the losses of both SAVAR and conventional SVCs increase roughly in proportion to lagging VAR output. Because of combined reactor and thyristor losses at the higher levels of VAR output, conventional TCR schemes are more lossy than the SAVAR. But at lower levels of VAR output, high SAVAR thyristor losses result in higher overall losses than the conventional TCR configuration.

Figure 3-11. Comparison of loss characteristic for SAVAR and TCR-type compensators.

SAVAR systems, are as yet, still in the concept and laboratory phases, but feasibility studies (Ref. 3-7) indicate the capital costs of such systems to be comparable to conventional SVC types, at least at ratings of 40 MVAR. Hence, given the loss characteristic of Figure 3-11, SAVAR systems will be most suitable where steady state conditions dictate a need for the SAVAR to operate near rated lagging VAR output.

GENERAL CONSIDERATIONS IN THE SELECTION OF SVCs FOR APPLICATION TO HIGH-VOLTAGE SYSTEMS

The application of static VAR compensators for shunt compensation of transmission systems is a relatively new concept to many utility planners and operators. However, recent environmental, technological and economic pressures have created a demand for the type of rapid response and improved system performance afforded by SVCs. Several SVC configurations have been developed and successfully applied to meet this demand. Each of the schemes has specific attributes, advantages and disadvantages relative to other SVC types. Tradeoffs related to speed of response, flexibility, losses and cost are common between the various configurations. The TSC/TCR compensator is generally recognized as the fastest, most flexible, low loss SVC available today. These characteristics are ideal for most utility applications where a 15-20% cost premium is not prohibitive. However, where cost

is an overriding concern, the "best" SVC for a certain application can only be determined after a thorough assessment of the requirements and acceptable compromises for that specific application. Among the considerations in selecting the need for and end type of SVC to be used are the following:

- The requirements of the system to which the SVC is applied from the standpoint of a need for very rapid changes in VARs, either generating or absorbing within the SVC linear control range. This may be predicted by the effects of sudden significant changes in the transmission system (e.g., loss of a line) or by peculiar loads on the system (e.g., large operations such as drag lines). Needs of systems with resulting slow or small changes may be adequately met with conventionally switched reactor and/or capacitor banks of nominal sizes. It should be kept in mind, however, that moderately rapid switching off and on by conventional means of capacitor banks may be limited by inrush problems and others associated with the charge left on a capacitor for minutes when it is switched off.
- Whether or not the SVC is to respond to large system disturbances outside of its normal linear control range.
- The need for control parameters other than voltage to provide system damping for system transient and dynamic stability. This implies properly timed switching of the capacitors to appropriately damp power swings between the line terminals. Such an application was made on 400-kV transmission systems in Iran and Norway-Sweden (3-8). Candidate control quantities are rate of change of power, frequency deviations, etc.

The capability of the SVC to switch capacitors on a cycle-by-cycle basis lends itself, with additional control, to damping oscillations, which would otherwise be poorly damped, between machines in one part of a transmission system and those in another, following a disturbance such as loss of generation or of load in one or the other parts of the system.

Also to be mentioned in this context is the use of a form of SVC for damping of turbine-generator rotor oscillations due to subsynchronous resonance with series capacitors (3-9).

- The economic importance of losses of the SVC under no-load conditions, or during the mode of operation (VAR generation or absorption) in which the SVC will be during the majority of its operating time.

Loss evaluations of equipment have recently become of greater importance in the application of apparatus to utility systems with the higher cost of energy sources. (In some cases, for example, the cost of losses may overcome the added cost of the more sophisticated switched capacitor types of compensators over the fixed capacitor types).

- Requirements on restriction of harmonic generation during balanced and unbalanced system conditions.
- Selection of bus voltage to be regulated.

Voltage control of a bus is usually from other than the low voltage SVC bus and may be for a HV bus, or one of the high voltages of the autotransformer.

In the case of autotransformers, care should be exercised in the selection of the proper HV or EHV bus in order to achieve desired overall voltage support and VAR flow control. This selection is predicated on which system voltage level is more sensitive to VAR changes as determined from load flow studies, the autotransformer winding-winding impedances and to the types of loads on this bus and their sensitivity to voltage change (3-10).

- Rating requirements for coupling transformer.

Requirements placed on the coupling transformer are similar to those with the more conventional forms of shunt reactor or capacitor banks

connected to tertiaries or low voltage windings; e.g., considerations of the effect of impedance between the windings upon the voltage of the LV bus and on other windings of the transformer, when the HV bus voltage is regulated, and hence on the ratings of the capacitors and reactors. However, with current controlled reactors, effects related to harmonic currents must be considered. With significantly larger capacitor banks than are conventionally used, LV bus operating voltages may be higher. (Similar to conventional LV banks, the capacitors on the transformer secondary or tertiary winding have been usually ungrounded, so considerations of circuit breaker and surge arrester applications have been similar to those with conventional forms of LV compensation.)

- Use of transformer tertiaries to apply the SVC.

In some applications, instead of the two-winding transformer, the SVC has been coupled to the HV system through the tertiary of existing autotransformers.

Whether existing shunt reactor banks can be used and modified to form an SVC by adding thyristors with proper control depends on both economical and technical considerations. A large portion of the cost of a solid state SVC lies in the thyristors and their controls, and therefore for highest economies, the thyristors should be used near their optimum current ratings. In general, using effective cooling with typical thyristor technology (e.g., approximately 1500 amperes for a single-stack, reverse-parallel connected thyristor pair), a delta-connected shunt reactor bank size of about 60 MVAR at 13.8 kV, 100 MVAR at 23 kV, or 150 MVAR at 34.5 kV can be obtained. Thus, a consideration in answer to this question is how well existing shunt reactors can be fitted into one of these sizes and what is the cost penalty in not operating at the thyristor optimum. In some cases, it may be more economical to replace the reactors of the existing bank with reactors of sizes optimized to the thyristor ratings.

Other factors with regard to the ratings of the transformer tertiary winding must be considered; for example, how does the MVA rating of the tertiary compare to the desired SVC size and to the optimum bank size as dictated by thyristor economics; what will be the operating voltages of the tertiary winding between the extremes of MVAR desired of the SVC how do these voltages affect the required SVC ratings?

- Operational requirements arising from utilizing an SVC in conjunction with series compensation. Series and SVC shunt compensation can complement each other. But the nature of the system reactance (inductive or capacitive) can affect the control strategy. (Many control strategies assume the circuit to be inductive when deciding whether to increase inductive or to increase capacitive current.)
- Ability in control during, and power supply for, "cold start" of an SVC at the end of an unenergized transmission line to provide full inductive VARs required to limit overvoltages while energizing the line. The thyristor switches, for example, associated with the reactors must be fully conducting when voltage is first applied to the line.

The application of SVCs for special purposes significantly influences the functional requirements and suitability of alternative configurations. For example, several recent studies have investigated the application of controlled reactive compensation in single-pole switching situations. Such studies imply that the principles developed for single-pole switching with conventional fixed shunt reactors can be extended to controlled compensation. The basic SVC scheme studied, however, has utilized the high-reactance transformer configuration. It is presently not seen how the TCR or TSC-TCR SVC could be used for the same purpose.

REFERENCES

- 3-1 Gyugyi, L., Taylor, E., "Characteristics of Static, Thyristor Controlled Shunt Compensators for Power Transmission System Applications," IEEE Trans. on Power Apparatus and Systems. Vol. PAS-99, No. 5, pp. 1795-1804, Sept./Oct. 1980.
- 3-2 Bahrman, M., Crane, L., Cooper, R., Lordeon, W., "Operating Experience with a Static VAR Generator on the M.P. & L. System," Proceedings of the International Symposium on Controlled Reactive Compensation, Varennes, Quebec, pp. 18-36, Sept. 1979.
- 3-3 Keane, J., Chu, D., Gutman, R., Rahman, M., Veraas, O., "Application of Static VAR Compensators for Steady State and Dynamic Voltage Control," Proceedings of the International Symposium on Controlled Reactive Compensation, Varennes, Quebec, pp. 228-251, Sept. 1979.
- 3-4 Miske, S., Hauth, R., Nozari, F., Moran, R., "Static VAR Systems: Dynamic Shunt Compensation for Transmission Systems," paper presented to the Pacific Coast Electric Association Engineering and Operating Conference, Los Angeles, March 1981.
- 3-5 Thanawala, H., Williams, W., Young, D., "Static VAR Compensation-Ten Years of Experience of Design and Operation Using Saturated Reactors," Proceedings: Transmission Static VAR Systems Seminar, EPRI Report EL-1047-SR, Section 2, April 1979.
- 3-6 Mathur, R. M., "Thyristor Controlled Compensators: Evaluation of a New Concept," Proceedings of the International Symposium on Controlled Reactive Compensation, Varennes, Quebec, pp. 376-389, Sept. 1979.
- 3-7 As yet unpublished studies by Westinghouse sponsored by the U.S. Department of Energy and the Los Alamos National Laboratory under contract 4-L20-6966P.
- 3-8 Olwegard, A., Ahlgren, L., Frank, H., "Thyristor Controlled Shunt Capacitors for Improving System Stability," CIGRE paper 32-20, September 1976.
- 3-9 Putman, T., Ramey, D., "A Modulated Inductance Stabilizer for Power Systems Subject to Subsynchronous Resonance," Proceedings of the International Symposium on Controlled Reactive Compensation, Varennes, Quebec, pp. 169-289, Sept. 1979.
- 3-10 Bahrman, M., Crane, L., Nylander, F., Parenteau, R., Wood, C., "Application of a Static VAR System to the M.P. & L. Transmission Network," Proceedings: Transmission Static VAR Systems Seminar, EPRI Report EL-1047-SR, Section 8, April 1979.

Section 4

COMPUTER MODELS

Two representations for static VAR compensators are discussed in the following paragraphs. One is based on nonlinear load formulas which permit the attenuation of transient bus voltage variations. The other provides for dynamic alteration of a bus reference voltage so that the reactive power at the bus can be controlled by auxiliary variables, such as frequencies or line flows, as well as bus voltage variations. The model with dynamic auxiliary control has been incorporated into a large-scale stability program, and the data requirements, flowcharts, and integrator diagrams used in program modification are presented.

Symbols used in this section are defined in Table 4-1.

STATIC VAR COMPENSATORS REPRESENTED AS NONLINEAR LOADS

It is common practice in stability analysis to provide nonlinear functions of voltage and frequency for the representation of apparent loads at high-voltage transmission buses. A general mathematical form is presented in reference 4-1.

$$P = \left(a_1 V_T^{m_1} f^{n_1} + a_2 V_T^{m_2} f^{n_2} + a_3 V_T^{m_3} f^{n_3} \right) P_Z ; V_T \geq V_L \quad (4-1)$$

$$Q = \left(a_4 V_T^{m_4} f^{n_4} + a_5 V_T^{m_5} f^{n_5} + a_6 V_T^{m_6} f^{n_6} \right) Q_Z ; V_T \geq V_L \quad (4-2)$$

The real and reactive components of load are in pu on the system MVA base, voltage is in pu on the bus voltage base, and the frequency is normalized using the nominal system frequency. The coefficients and exponents are selected to characterize particular bulk loads. The factors P_Z and Q_Z are determined using a solved load flow which provides values of P , Q , and V_T at the nominal frequency.

Table 4-1
DEFINITIONS OF SYMBOLS

Representation Based on Nonlinear Load Formulas

P	-	Real power in pu on the system MVA base
Q	-	Reactive power in pu on the system MVA base
I	-	Reactive current in pu on the system MVA base and the bus voltage base
V_T	-	Voltage in pu on the bus voltage base
f	-	Frequency in pu on the nominal system frequency

Representation with Auxiliary Control

B	-	SVC susceptance in pu using the system MVA base and the terminal bus voltage base
B_0	-	
B_1	-	
B_2	-	
B_L	-	Inductor susceptance in pu using the system MVA base and the terminal bus voltage base
V	-	SVC control voltage in pu on the terminal bus voltage base
V_0	-	
V_1	-	
V_2	-	
h	-	Regulating slope, $(B_2 - B_1) \div (V_2 - V_1)$, see Figure 4-2
I	-	Net SVC current
I_L	-	Inductor current
I_{MAX}	-	Maximum inductor current

Table 4-1 (Continued)

DEFINITIONS OF SYMBOLS

U_1	-	} Auxiliary control channel input signals
U_2	-	
U_3	-	
V_{A1}	-	} Auxiliary control channel output voltage, in pu on terminal voltage base
V_{A2}	-	
V_{A3}	-	
K	-	} Auxiliary control channel input signal transducer and time constant
T_R	-	
T_E	-	Auxiliary control channel reset time constant
T_D	-	Auxiliary control channel communications delay
A_0	-	} Auxiliary control channel filter parameters
A_1	-	
A_2	-	
A_3	-	
A_4	-	
V_R	-	Reference voltage in pu on the terminal bus voltage base
Q	-	Net SVC reactive power in pu on the system MVA base, positive if inductive
Q_0	-	Initial net SVC reactive power in pu on the system MVA base, positive if inductive
V_T	-	Terminal bus voltage in pu
V_{T0}	-	Initial terminal bus voltage in pu

An equivalent admittance can be substituted for the nonlinear function at a particular bus when the voltage at that bus falls below V_L . This acknowledges the fact that information regarding bulk loads, in the best of circumstances, is valid for small excursions of voltage and frequency. Substitution of equivalent admittances also avoids network solution failures which might otherwise occur during low voltage transients. Continuity is achieved by evaluating an equivalent admittance at the voltage V_L and the existing transient frequency.

A regulating effect on bus voltage can be simulated through an appropriate choice of coefficients and exponents in Eq. 4-2. Let

$$a_4 = n_5 = n_6 = 0 \quad (4-3)$$

$$m_5 = 1 \quad (4-4)$$

$$m_6 = 2 \quad (4-5)$$

Then

$$Q = \left(a_5 V_T + a_6 V_T^2 \right) Q_Z \quad ; \quad V_T \geq V_L \quad (4-6)$$

The reactive component of current is

$$I = \left(a_5 + a_6 V_T \right) Q_Z \quad ; \quad V_T \geq V_L \quad (4-7)$$

Positive values of Q and I are inductive in keeping with convention.

The graph of current as a function of voltage in Figure 4-1 is based on Eq. 4-7 for voltage above V_L and on constant capacitive reactance for voltage below V_L . Above V_L , any tendency for voltage to rise is associated with a tendency toward inductive current which attenuates the voltage rise.

Figure 4-1. Reactive current as a function of voltage for a static VAR compensator represented as a nonlinear load.

Nonlinear load formulas have been used to simulate SVC's in various prior investigations and are used to obtain some of the results presented in this report. The principal limitation associated with their use is the inability to control reactive current by means of variables other than terminal bus voltage. This limitation can be alleviated to some extent by making use of the frequency-dependent factors in Eq. 4-2. However, it is desirable to be able to study the effects of other control variables, such as generator speed deviations and transmission line power flows. The use of the nonlinear load feature to represent SVC's may also interfere with nonlinear load representation, especially in situations which involve a large number of SVC's.

STATIC VAR COMPENSATOR REPRESENTATION INCLUDING AUXILIARY CONTROL

A static VAR compensator model which includes dynamic auxiliary control is presented in Figure 4-2. The upper diagram shows the SVC susceptance as a function of the control voltage. The latter is determined as indicated by the block diagram and may involve as many as three control variables.

Figure 4-2. Static VAR compensator representation with auxiliary control.

The voltage-susceptance diagram presumes a fixed capacitor in parallel with a variable inductor but is applicable to any equipment combination which provides a similar variation of susceptance with voltage. The susceptance is inductive to the left of the vertical axis and capacitive to the right. Both limits may lie on the same side of the vertical axis.

The slope in the regulating range is

$$h = \frac{B_2 - B_1}{V_2 - V_1} < 0 \quad (4-8)$$

Three equations correspond to the voltage-susceptance diagram.

$$B = hV \quad V_2 \leq V \leq V_1 \quad (4-9)$$

$$B = B_2 \quad V < V_2 \quad (4-10)$$

$$B = B_1 \quad V > V_1 \quad (4-11)$$

Voltage is in pu on the terminal voltage base, and susceptance is in pu using the terminal voltage base and the system MVA base. Let inductive current be positive. Then the SVC pu current in the regulating range is

$$I = -BV_T = -hVV_T = -h[V_T^2 - (V_R + V_A)V_T] \quad (4-12)$$

The reactive power on the system MVA base in the regulating range is

$$Q = V_T I = -h[V_T^3 - (V_R + V_A)V_T^2] \quad (4-13)$$

The susceptance of the variable inductor is

$$B_L = B - B_2 \quad (4-14)$$

and the inductor current is

$$I_L = -B_L V_T \quad (4-15)$$

This current is compared in simulation to a prescribed inductor current limit, and the inductive susceptance and net SVC susceptance adjusted if necessary to avoid exceeding the inductor current limit.

The control voltage V_A acts to augment the fixed reference voltage V_R and is derived from as many as three system variables chosen from the following list:

- the frequency at any bus
- the speed of any synchronous machine
- the accelerating power of any synchronous machine
- the power flow over any line
- the voltage angle deviation at any bus

In the absence of all three control channels, the control voltage is simply the difference in the terminal voltage and a fixed reference.

A detailed block diagram for a control channel is shown in Figure 4-3. Provision is made to limit the excursion of the output variable of each channel and to limit the sum of the output variables as indicated in Figure 4-2.

Figure 4-3. Control channel mathematical block diagram.

STABILITY PROGRAM MODIFICATION FOR THE SVC MODEL WITH AUXILIARY CONTROL

Stability program modification to accommodate the SVC model with auxiliary control involves changes to the network solution routines and additions to numerical integration routines.

The general nature of the changes to the network solution calculations are shown by the flowchart of Figure 4-4, which is executed for each iteration of the

Figure 4-4. Flow diagram for the calculation of B, I, and Q for iterative network solution procedure.

solution process. The terminal voltage, V_T , changes from one iteration to the next, but the components of auxiliary control voltage are momentarily constant, being determined by numerical integration. These calculations yield the SVC susceptance, current, and reactive power, taking into account the limits on susceptance and the inductor current limit. Any of these three variables may be used to represent the SVC, depending on the network solution procedures employed beyond this flowchart.

The representation for an auxiliary control channel in terms of integrals is shown in Figure 4-5. There are various paths between the input and output signals, depending on the specification of parameters. The reset transfer function is replaced by unity if T_E is zero. If all the parameters for a particular channel except K and A_0 are zero, then integrals are not involved in simulating that channel. In this event, the input signal cannot be a transmission line power flow or a terminal voltage angle without violating the assumption that the components of auxiliary control voltage are constant for the network solution calculations. This restriction on channel parameters and input signals is reasonable and preferable to alternatives.

The Westinghouse Stability Program has been modified to incorporate the SVC model with auxiliary control. Data requirements are set forth in Forms 4-1 through 4-4. The parameters on Forms 4-1 and 4-2 are essential for each SVC. Data for a control channel is specified on Forms 4-3 and 4-4 and is required for each control channel.

A flowchart which includes data diagnostics and initial condition calculations is shown in Figure 4-6.

REFERENCE

- 4-1. IEEE Committee Report "Procedures for the Exchange of Power Plant and Load Data for Synchronous Stability Studies," Paper No. 81 WM 065-2, presented at the IEEE PES Winter Meeting, Atlanta, Georgia, February 1-6, 1981.

Figure 4-5. Control channel block diagram in terms of integrals.

Figure 4-6. Flowchart for data diagnostics and initial condition calculations.

- SVC Terminal Bus No. } These fields provide for visual
- SVC ID } recognition only and may be omitted.
- B_1, B_2 . Extremes of susceptance, in pu on the system MVA base.
Both values may be either positive or negative.
- $V_1 - V_2$. Regulating range, in pu on the terminal voltage base.
- I_{MAX} . Inductive current limit, in pu on the system MVA base.
If no value is entered, the inductive current is not limited.
- Q_0 . Initial reactive power:
Inductive is positive.
Capacitive is negative.
- ΔV_A . Limit on V_A , in pu on the terminal voltage base.

- SVC Terminal Bus No. } These fields provide for visual
- SVC ID } recognition only and may be omitted.
- K. This coefficient must be compatible with the dimensions of the control channel input signal and the channel output signal which is voltage in per unit on the SVC terminal voltage base.
- A_0, A_1, A_2 . At least one of these coefficients must be nonzero.
- T_R, T_E, T_D . In seconds. If T_E is entered as zero, the function

$$\frac{ST_E}{1 + ST_E}$$

is treated as unity. The lag T_D cannot exceed ten network solution intervals.

Form 4-4. SVC Auxiliary Control Channel Card

Section 5

STUDIES OF A SMALL HYPOTHETICAL SYSTEM

The system of Figure 5-1 is used to provide illustrations of analytical methods related to the application of static VAR compensators. Detailed data for this system is contained in Appendix A.

The studies to be described are intended primarily to indicate improvements in stability behavior that can be achieved by means of static VAR compensators. They necessarily include techniques for establishing the regulating characteristics, locations, and ratings of SVC's as well as their influence on system performance.

Four types of studies have been performed and are reported here. They involve:

- Self- and mutual-drop coefficient calculations
- Voltage sensitivity calculations
- Eigenvalue calculations
- Synchronous stability calculations

Figure 5-1. Diagram for hypothetical system A.

The first three study categories utilize various linear system models and consequently are not concerned with SVC equipment ratings, but only with their regulating characteristics. Stability calculations are of course nonlinear, and SVC equipment ratings strongly influence system performance.

One of the effects of voltage regulation is to reduce the incremental self- and mutual-drop coefficients associated with a transmission network. The studies described in this report develop a procedure for calculating these effects and utilize the results of those calculations as a basis for choosing the regulating characteristics for SVC's in the system of Figure 5-1.

The voltage sensitivity calculations are made primarily to identify the buses most in need of regulation and the circumstances under which this need arises. In addition, these calculations yield information regarding the reactive power requirements at synchronous machine buses with and without SVC's at transmission buses and provide data regarding relationships within generators pertinent to their dynamic behavior.

The eigenvalue calculations pertain to the five modes of synchronizing power flow oscillation of the study system and show the effects of voltage regulation on the frequencies and damping of those oscillations.

Time domain stability calculations are used to demonstrate the effects of SVC's on both small-disturbance stability limits and transient stability limits. The simulation of synchronizing power flow oscillations and transmission line faults both yield information regarding the ratings of SVC's required to achieve performance objectives.

The synchronous machines in Figure 5-1 are equipped with automatically controlled excitation systems which regulate voltages at buses 3, 4, 6, 11, and 12. The voltage at bus 1 is assumed to be constant. Voltages at buses 2, 5, 7, and 10 are not regulated, and these buses are regarded as potential sites for static VAR compensators.

SELF- AND MUTUAL-DROP COEFFICIENTS

The equivalent circuit of Figure 5-2 can be used to represent a static VAR compensator within its regulating range. The reactive current and reactive power associated with the equivalent circuit are:

$$I_r = (V_T - V_{T0})/X \quad (5-1)$$

$$Q = (V_T^2 - V_{T0}V_T)/X \quad (5-2)$$

These are similar in form to Eqs. 4-6 and 4-7 for the nonlinear load representation of a static VAR compensator.

Figure 5-2. Equivalent circuit for a static VAR compensator represented as a nonlinear reactive load.

In essence, the reactance in Figure 5-2 parallels the short-circuit reactance, reducing the sensitivity of the bus voltage to various kinds of disturbances. Clearly, the equivalent circuit reactance must bear some relationship to the short-circuit reactance at the bus if the SVC is to influence bus voltage variations significantly.

To pursue this concept, consider the two-bus network of Figure 5-3. For simplicity, the network consists entirely of reactances. All of the voltages are assumed to be in phase, and the currents are assumed to be in quadrature with the voltages. The currents ΔI_{S1} and ΔI_{S2} are disturbances which tend to alter

the bus voltages. The currents ΔI_1 and ΔI_2 drawn by the SVC's compensate for the disturbances and diminish the voltage changes that would otherwise occur.

Figure 5-3. Diagram of a two-bus network with SVC equivalent circuits connected to both buses.

The incremental bus voltages in this network are:

$$\begin{bmatrix} \Delta V_1 \\ \Delta V_2 \end{bmatrix} = \begin{bmatrix} X_{11} & X_{12} \\ X_{21} & X_{22} \end{bmatrix} \begin{bmatrix} \Delta I_{S1} - \Delta I_1 \\ \Delta I_{S2} - \Delta I_2 \end{bmatrix} \quad (5-3)$$

The SVC currents depend on the bus voltages and can be written as follows:

$$\begin{bmatrix} \Delta I_1 \\ \Delta I_2 \end{bmatrix} = \begin{bmatrix} X_1^{-1} & 0 \\ 0 & X_2^{-1} \end{bmatrix} \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \end{bmatrix} \quad (5-4)$$

Substituting Eq. 5-4 into Eq. 5-3 and collecting coefficients,

$$\begin{bmatrix} 1 + X_{11}/X_1 & X_{12}/X_2 \\ X_{21}/X_1 & 1 + X_{22}/X_2 \end{bmatrix} \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \end{bmatrix} = \begin{bmatrix} X_{11} & X_{12} \\ X_{21} & X_{22} \end{bmatrix} \begin{bmatrix} \Delta I_{S1} \\ \Delta I_{S2} \end{bmatrix} \quad (5-5)$$

Solving for the voltage increments,

$$\begin{bmatrix} \Delta V_1 \\ \Delta V_2 \end{bmatrix} = \begin{bmatrix} 1+X_{11}/X_1 & X_{12}/X_2 \\ X_{21}/X_1 & 1+X_{22}/X_2 \end{bmatrix}^{-1} \begin{bmatrix} X_{11} & X_{12} \\ X_{21} & X_{22} \end{bmatrix} \begin{bmatrix} \Delta I_{S1} \\ \Delta I_{S2} \end{bmatrix} \quad (5-6)$$

An effect of voltage regulation is to modify the self- and mutual-drop coefficient matrix, and it is worthwhile to examine regulation from that viewpoint.

Assume that the ratio of the self-drop coefficient to the SVC equivalent circuit reactance is the same at both buses. That is

$$K = X_{11}/X_1 = X_{22}/X_2 \quad (5-7)$$

The modified self- and mutual-drop coefficient matrix can then be written:

$$\begin{bmatrix} X'_{11} & X'_{12} \\ X'_{21} & X'_{22} \end{bmatrix} = \begin{bmatrix} 1+K & KX_{12}/X_{22} \\ KX_{21}/X_{11} & 1+K \end{bmatrix}^{-1} \begin{bmatrix} X_{11} & X_{12} \\ X_{21} & X_{22} \end{bmatrix} \quad (5-8)$$

This relationship can be expanded to accommodate any reasonable number of buses and used to calculate the modified self- and mutual-drop coefficient matrix as a function of K. Buses which do not have SVC's are represented in the matrix to be inverted by columns in which K is zero.

Modified self- and mutual-drop coefficient matrices have been calculated for the system of Figure 5-1, with SVC's at buses 2, 5, 7, and 10, for K's of 0.33, 0.66, 1.00, 1.33, 1.67, and 2.00. The curves of Figure 5-4 are obtained from those calculations and show the ratios of the modified self-drop coefficients to the original coefficients for the buses with SVC's.

One SVC, acting alone, would reduce the self-drop coefficient at its terminal bus by one half with K set to one. All four curves in Figure 5-4 pass below 0.5 at K=1, indicating some improvement in regulation at each bus due to the response of

Figure 5-4.: Ratios of modified self-drop coefficients to original self-drop coefficients.

a static VAR compensator at another bus. However, even at buses 5 and 7 which are adjacent, this effect is slight.

The arrays of Figure 5-5, from which the curves of Figure 5-4 are plotted, display the effects of regulation on the entire self- and mutual-drop coefficient matrix. Entries in these arrays express the elements of the modified matrix as percentages of the corresponding elements in the original matrix. Note that the four SVC's acting together drastically reduce certain of the mutual-drop coefficients, implying that a regulated bus is significantly shielded from disturbances at another regulated bus.

The preceding discussion provides a basis for choosing the regulating characteristics of SVC's which have been used in this project. The factor $1/X$ in Eq. 5-2 is replaced by K/X_{SC} , where X_{SC} is the short-circuit reactance of the bus. Moreover, on the assumption that the regulation should be no more precise than

	1	2	3	4	5	6	7	10	11	12
1	99	73	73	64	39	39	48	53	53	53
2	73	73	73	64	39	39	48	53	53	53
3	73	73	89	64	39	39	48	53	53	53
4	64	64	64	82	51	51	62	68	68	68
5	40	40	39	51	70	70	56	42	41	42
6	47	40	39	51	70	79	56	42	42	42
7	49	48	48	62	56	56	69	51	51	51
10	52	53	53	68	42	41	51	73	73	73
11	48	53	53	68	41	41	51	73	90	73
12	50	53	53	68	41	41	51	73	73	89

k = 0.33

	1	2	3	4	5	6	7	10	11	12
1	99	42	42	31	7	7	14	16	16	16
2	42	42	42	31	7	7	14	16	16	16
3	40	42	76	31	7	7	14	16	16	16
4	29	31	31	66	15	15	29	35	35	35
5	8	7	7	15	38	38	20	8	8	8
6	17	7	7	15	38	58	20	8	8	8
7	14	14	14	29	20	20	38	16	15	15
10	15	16	16	35	8	8	16	41	41	41
11	8	16	16	35	8	8	16	41	79	41
12	11	16	16	35	7	7	16	41	41	77

k = 1.33

	1	2	3	4	5	6	7	10	11	12
1	99	58	58	47	19	19	29	33	33	33
2	58	58	58	47	19	19	29	33	33	33
3	57	58	83	47	19	19	29	33	33	33
4	46	47	47	74	31	31	45	51	51	51
5	20	20	19	31	54	54	36	21	21	21
6	29	20	19	31	54	69	36	21	21	21
7	29	29	28	45	36	36	53	31	31	31
10	32	33	33	51	21	21	31	57	57	57
11	25	33	33	51	21	21	31	57	85	57
12	28	33	32	51	21	21	32	57	57	84

k = 0.67

	1	2	3	4	5	6	7	10	11	12
1	99	36	36	26	4	4	10	12	12	12
2	39	39	39	26	4	4	10	12	12	12
3	35	36	74	26	4	4	10	12	12	12
4	25	26	26	63	12	12	25	30	30	30
5	5	4	4	12	34	34	15	5	5	5
6	15	5	4	12	34	55	15	5	5	5
7	11	10	10	25	15	15	33	12	12	12
10	11	12	12	30	5	5	12	36	36	36
11	3	12	12	30	5	5	12	36	77	36
12	7	12	12	30	5	5	12	36	36	75

k = 1.67

	1	2	3	4	5	6	7	10	11	12
1	99	48	49	37	11	11	19	22	22	22
2	48	48	48	37	11	11	19	22	22	22
3	47	48	79	37	11	11	19	22	22	22
4	36	37	37	69	21	21	35	42	42	42
5	12	11	11	21	45	45	26	13	12	13
6	21	11	11	21	45	63	26	13	12	12
7	20	19	19	36	26	26	44	21	21	21
10	21	22	22	42	13	12	21	48	48	48
11	14	22	22	42	12	12	21	48	81	48
12	17	22	22	42	12	12	22	48	48	80

k = 1.00

	1	2	3	4	5	6	7	10	11	12
1	99	32	32	23	3	3	8	10	9	10
2	32	32	32	23	3	3	8	10	10	10
3	31	32	72	23	3	3	8	10	9	9
4	21	23	23	62	9	9	22	27	27	27
5	4	3	3	9	30	30	12	4	4	4
6	14	3	3	9	30	52	12	4	4	4
7	8	8	8	22	12	12	29	9	9	9
10	9	10	10	27	4	4	9	32	32	32
11	0	10	9	27	4	3	9	32	75	32
12	4	10	9	26	3	3	10	32	32	74

k = 2.00

Figure 5-5. Modified self- and mutual-drop coefficients for the system of Figure 5-1 with SVC's at buses 2, 5, 7, and 10, expressed as percentages of the original self- and mutual-drop coefficients.

necessary to accomplish objectives, a value of 1.33 has been chosen for K. The shape of the curves in Figure 5-4 suggests that the principal benefits of regulation are attained with this value. Equation 5-2 becomes

$$Q = (1.33/X_{SC}) (V_T^2 - V_{T0}V_T) \quad (5-9)$$

Differentiating Eq. 5-9 with respect to V_T ,

$$(dQ/dV_T) = (1.33/X_{SC})(2V_T - V_{T0}) \quad (5-10)$$

At the reference voltage,

$$(dQ/dV_T) = 1.33/X_{SC} \quad , \quad V_T = V_{T0} \quad (5-11)$$

Parameters of the SVC's at buses 2, 5, 7, and 10 are listed in Table 5-1.

Table 5-1

SHORT-CIRCUIT REACTANCES AND REGULATING SLOPES
FOR SVC'S APPLIED TO THE SYSTEM OF FIGURE 5-1

<u>Bus Number</u>	<u>X_{SC} in Per Unit on a 100 MVA Base</u>	<u>Regulating Slope MVAR/Percent Voltage</u>
2	0.1138	11.69
5	0.1685	7.89
7	0.1811	7.34
10	0.1034	12.86

VOLTAGE SENSITIVITY TO POWER CHANGE

Incremental changes in bus voltage due to incremental changes in generator power have been calculated for the system of Figure 5-1. The ratios

$$r_{IK} = \Delta V_I / \Delta P_K \quad ; \quad I = 2, 5, 7, 10 \quad ; \quad K = 1, 3, 4, 6, 11, 12 \quad (5-12)$$

have been calculated, where I and K are bus numbers. The synchronous condenser and infinite bus are included with the generators. These ratios have been calculated with no SVC's, with SVC's at buses 5 and 7, and with SVC's at buses 2, 5, 7, and 10. In all cases, the voltages at buses 1, 3, 4, 6, 11, and 12 are assumed to be perfectly regulated by field voltage adjustments.

Incremental changes in the reactive power from synchronous machines and from SVC's corresponding to incremental changes in generator real power have also been calculated and expressed as ratios:

$$n_{IK} = \Delta Q_I / \Delta P_K \quad ; \quad I = 1, 2, 3, 4, 5, 6, 7, 10, 11, 12 \quad ; \quad K = 1, 3, 4, 6, 11, 12 \quad (5-13)$$

The ratio is zero when I is 2, 5, 7, or 10 and SVC's are not represented at those buses.

These calculations have been made with a computer program created for this purpose that utilizes a solved load flow as input data. The mathematical relationships underlying the program are presented in Appendix B.

Voltage sensitivities in the absence of SVC's are summarized in Table 5-2. Six operating conditions, corresponding to different levels of generation at bus 6, are included in that summary. The ratios are calibrated in percent per 100 MW of power change. A negative ratio signifies a drop in voltage for an increase in power; a positive ratio signifies a rise in voltage for an increase in power.

The greatest sensitivity is at bus 7 for an increase in power at bus 6. The six operating conditions show the effects of changing stress in the transmission

Table 5-2

VOLTAGE CHANGES AT LOAD AND TIE BUSES DUE TO POWER INCREASES
AT GENERATOR BUSES, IN PERCENT PER 100 MW, WITH GENERATOR BUS
VOLTAGES CONSTANT AND THE VOLTAGES AT BUSES 2, 5, 7, AND 10 UNREGULATED

Power Level at Bus 6	Bus at Which Voltage Increment Occurs	Bus at Which Real Power Increment Occurs					
		1	3	4	6	11	12
90 MW	2	-1.11	-1.11	-.05	-.05	-.05	-.05
	5	-.02	-.02	-.02	-1.69	-.02	-.02
	7	.05	.05	.06	-3.35	.06	.06
	10	-.13	-.13	-.14	-.12	-.44	-.44
120 MW	2	-.41	-.86	-.10	-.08	-.10	-.10
	5	.09	.09	.09	-2.28	.09	.09
	7	.31	.31	.34	-4.52	.32	.32
	10	-.12	-.12	-.13	-.11	-.43	-.43
135 MW	2	-.09	-.74	-.13	-.10	-.12	-.12
	5	.14	.13	.14	-2.61	.14	.14
	7	.45	.45	.47	-5.17	.45	.45
	10	-.13	-.13	-.13	-.10	-.43	-.43
150 MW	2	.24	-.62	-.14	-.10	-.13	-.13
	5	.19	.18	.20	-2.97	.19	.19
	7	.58	.57	.61	-5.89	.58	.58
	10	-.10	-.10	-.10	-.08	-.39	-.39
165 MW	2	.51	-.54	-.18	-.13	-.18	-.18
	5	.25	.24	.26	-3.36	.25	.25
	7	.76	.75	.79	-6.65	.75	.75
	10	-.14	-.14	-.15	-.11	-.44	-.44
180 MW	2	.79	-.45	-.21	-.15	-.20	-.20
	5	.30	.29	.31	-3.81	.29	.29
	7	.91	.89	.93	-7.55	.89	.89
	10	-.13	-.13	-.14	-.10	-.43	-.43

system in the vicinity of bus 7. The steady-state change in generation at bus 6 for the six operating conditions is absorbed at the infinite bus. Load flow data for these six conditions is included in Appendix A.

Incremental ratios of reactive power to real power, in MVAR/MW, are shown in Table 5-3. Positive ratios signify that capacitive reactive power is required to regulate voltage in the presence of a power increase; negative ratios signify that inductive reactive power is required.

The high ratio at bus 4 for a power change at bus 6 indicates that the condenser at bus 4 is supplying reactive power to regulate the voltage at bus 4 in the presence of the voltage drop at bus 7. Similarly, an increase in real power at bus 6 is accompanied by a relatively high increase in reactive power to regulate the voltage at bus 6 in the presence of the voltage drop at bus 5.

Voltage sensitivities with SVC's at buses 5 and 7 are shown in Table 5-4. The SVC at bus 5 has a regulating characteristic of 7.89 MVAR/percent voltage in accordance with Table 5-1, while that at bus 7 has a regulating characteristic of 7.34 MVAR/percent voltage.

Voltage sensitivity at bus 5 is reduced to about 55 percent of that in Table 5-2, and at bus 7, to about 50 percent of Table 5-2. From Figure 5-5, with $K=1.33$, a reduction to 38 percent might have been expected at both buses. The difference is apparently due to the fact that the original self- and mutual-drop coefficients, and of course the short-circuit reactances of Table 5-1, include generator transient reactances, whereas the voltage sensitivity calculations assume constant machine terminal buses. This suggests that machine internal reactances should be ignored in calculating a regulating characteristic to achieve a specific reduction in voltage sensitivity.

The voltage sensitivities at buses 2 and 10 are not affected, within the precision of the calculations, by the SVC's at buses 5 and 7. The constant voltage at bus 4 shields buses 2 and 10 from the effects of the SVC's at buses 5 and 7.

Table 5-3

RATIOS OF REACTIVE POWER CHANGES TO REAL POWER CHANGES
AT GENERATOR BUSES, IN MVAR/MW, WITH GENERATOR BUS VOLTAGES CONSTANT
AND THE VOLTAGES AT BUSES 2, 5, 7, AND 10 UNREGULATED

Power Level at Bus 6	Bus at Which Reactive Power Increment Occurs	Bus at Which Real Power Increment Occurs					
		1	3	4	6	11	12
90 MW	1	.048	.036	.001	.001	.001	.001
	3	.090	.034	.004	.003	.004	.004
	4	.195	.196	-.147	.312	.080	.080
	6	.001	.001	.001	.152	.001	.001
	11	.011	.011	.012	.010	-.020	.036
	12	.011	.011	.012	.010	.036	-.020
120 MW	1	-.048	.030	.005	.004	.005	.005
	3	.034	.015	.009	.007	.008	.008
	4	.090	.112	-.169	.415	.059	.059
	6	-.013	-.013	-.014	.266	-.014	-.014
	11	.011	.011	.012	.010	-.020	.036
	12	.011	.011	.012	.010	.036	-.020
135 MW	1	-.093	.028	.007	.005	.006	.006
	3	.008	.006	.011	.008	.010	.010
	4	.040	.073	-.178	.473	.050	.050
	6	-.021	-.021	-.022	.329	-.021	-.021
	11	.012	.011	.012	.009	-.020	.036
	12	.012	.011	.012	.009	.036	-.020
150 MW	1	-.135	.026	.009	.006	.008	.008
	3	-.017	-.003	.013	.010	.013	.013
	4	-.008	.035	-.188	.536	.041	.041
	6	-.029	-.029	-.030	.397	-.029	-.029
	11	.012	.012	.012	.009	-.019	.037
	12	.012	.012	.012	.009	.037	-.019
165 MW	1	-.177	.023	.010	.007	.009	.009
	3	-.041	-.011	.015	.011	.014	.014
	4	-.055	-.002	-.198	.606	.031	.031
	6	-.038	-.038	-.040	.471	-.038	-.038
	11	.012	.011	.012	.009	-.020	.036
	12	.012	.011	.012	.009	.036	-.020
180 MW	1	-.217	.021	.012	.008	.011	.011
	3	-.065	-.019	.017	.012	.016	.016
	4	-.105	-.041	-.212	.682	.018	.018
	6	-.049	-.048	-.050	.554	-.048	-.048
	11	.012	.012	.013	.009	-.019	.037
	12	.012	.012	.013	.009	.037	-.019

Table 5-4

VOLTAGE CHANGES AT LOAD AND TIE BUSES DUE TO POWER INCREASES AT GENERATOR BUSES, IN PERCENT PER 100 MW, WITH GENERATOR BUS VOLTAGES CONSTANT, THE VOLTAGES AT BUSES 5 AND 7 REGULATED BY SVC'S, AND THE VOLTAGES AT BUSES 2 AND 10 UNREGULATED

Power Level at Bus 6	Bus at Which Voltage Increment Occurs	Bus at Which Real Power Increment Occurs					
		1	3	4	6	11	12
90 MW	2	-1.11	-1.11	-.05	-.05	-.05	-.05
	5	-.02	-.02	-.02	-.97	-.02	-.02
	7	.03	.03	.04	-1.75	.03	.03
	10	-.13	-.13	-.14	-.12	-.44	-.44
120 MW	2	-.41	-.86	-.10	-.08	-.10	-.10
	5	.04	.04	.04	-1.29	.04	.04
	7	.17	.17	.18	-2.32	.17	.17
	10	-.12	-.12	-.13	-.10	-.43	-.43
135 MW	2	-.09	-.74	-.13	-.10	-.12	-.12
	5	.06	.06	.06	-1.46	.06	.06
	7	.24	.23	.25	-2.62	.24	.24
	10	-.13	-.13	-.13	-.10	-.43	-.43
150 MW	2	.24	-.62	-.14	-.10	-.13	-.13
	5	.09	.09	.09	-1.64	.09	.09
	7	.30	.30	.31	-2.95	.30	.30
	10	-.10	-.10	-.10	-.07	-.39	-.39
165 MW	2	.51	-.54	-.18	-.13	-.18	-.18
	5	.11	.11	.12	-1.84	.11	.11
	7	.39	.38	.40	-3.27	.38	.38
	10	-.14	-.14	-.15	-.11	-.44	-.44
180 MW	2	.79	-.45	-.21	-.15	-.20	-.20
	5	.13	.13	.14	-2.05	.13	.13
	7	.45	.44	.46	-3.63	.44	.44
	10	-.13	-.13	-.14	-.10	-.43	-.43

Incremental ratios of reactive power to real power, in MVAR/MW, with SVC's at buses 5 and 7 are shown in Tables 5-5 and 5-6. For power increase at bus 6, there is significant reactive power supplied by each of the SVC's and a corresponding reduction in reactive power from the synchronous machines at buses 4 and 6.

Voltage sensitivities with SVC's at buses 2, 5, 7, and 10 are shown in Table 5-7. In accordance with Table 5-1, the SVC at bus 2 has a regulation characteristic of 11.69 MVAR/percent voltage and at bus 10, 12.86 MVAR/percent voltage. Voltage sensitivities at buses 5 and 7 are not affected, within the precision of calculations, by the SVC's at buses 2 and 10.

Incremental ratios of reactive power to real power with SVC's at buses 2, 5, 7, and 10 are shown in Tables 5-8 and 5-9.

The incremental reactive power requirements to hold constant voltages at all buses are presented in Tables 5-10 and 5-11 in terms of MVAR/MW of increased real power at the various generator buses.

Graphs of voltage sensitivities at buses 5 and 7 are presented in Figures 5-6 and 5-7. Ratios of reactive power change to real power change are shown in Figures 5-8 through 5-11.

The real and reactive power changes at generator terminal buses can be used to calculate corresponding steady-state changes within the generator. In particular, changes in the phasor diagram of Figure 5-12 can be calculated using the machine synchronous reactances. Formulas for incremental values of the internal angle, the direct and quadrature axis components of terminal voltage and stator current, and the excitation voltage are derived in Appendix B.

With the voltages at buses 5 and 7 not regulated, the relatively high ratio of reactive power change to real power change at bus 6 contributes to an oscillatory instability revealed in subsequent eigenvalue studies. An examination of the steady-state incremental internal variables of the generator at bus 6 offers an

Table 5-5

RATIOS OF REACTIVE POWER CHANGES AT LOAD AND TIE BUSES TO REAL POWER CHANGES AT GENERATOR BUSES, IN MVAR/MW, WITH GENERATOR VOLTAGES CONSTANT, THE VOLTAGES AT BUSES 5 AND 7 REGULATED BY SVC'S, AND THE VOLTAGES AT BUSES 2 AND 10 UNREGULATED

Power Level at Bus 6	Bus at Which Reactive Power Increment Occurs	Bus at Which Real Power Increment Occurs					
		1	3	4	6	11	12
90 MW	2	.000	.000	.000	.000	.000	.000
	5	.001	.001	.001	.072	.001	.001
	7	-.002	-.002	-.002	.122	-.002	-.002
	10	.000	.000	.000	.000	.000	.000
120 MW	2	.000	.000	.000	.000	.000	.000
	5	-.003	-.003	-.003	.096	-.003	-.003
	7	-.012	-.012	-.013	.164	-.012	-.012
	10	.000	.000	.000	.000	.000	.000
135 MW	2	.000	.000	.000	.000	.000	.000
	5	-.005	-.005	-.005	.109	-.005	-.005
	7	-.017	-.017	-.018	.187	-.017	-.017
	10	.000	.000	.000	.000	.000	.000
150 MW	2	.000	.000	.000	.000	.000	.000
	5	-.006	-.006	-.007	.123	-.006	-.006
	7	-.022	-.021	-.023	.212	-.022	-.022
	10	.000	.000	.000	.000	.000	.000
165 MW	2	.000	.000	.000	.000	.000	.000
	5	-.009	-.008	-.009	.138	-.008	-.008
	7	-.028	-.028	-.029	.238	-.028	-.028
	10	.000	.000	.000	.000	.000	.000
180 MW	2	.000	.000	.000	.000	.000	.000
	5	-.010	-.010	-.010	.155	-.010	-.010
	7	-.033	-.033	-.034	.268	-.033	-.033
	10	.000	.000	.000	.000	.000	.000

Table 5-6

RATIOS OF REACTIVE POWER CHANGES TO REAL POWER CHANGES AT GENERATOR BUSES,
IN MVAR/MW, WITH GENERATOR BUS VOLTAGES CONSTANT, THE VOLTAGES AT BUSES
5 AND 7 REGULATED BY SVC'S, AND THE VOLTAGES AT BUSES 2 AND 10 UNREGULATED

Power Level at Bus 6	Bus at Which Reactive Power Increment Occurs	Bus at Which Real Power Increment Occurs					
		1	3	4	6	11	12
90 MW	1	.048	.036	.001	.001	.001	.001
	3	.090	.034	.004	.003	.004	.004
	4	.196	.198	-.146	.229	.081	.081
	6	.001	.001	.001	.036	.001	.001
	11	.011	.011	.012	.010	-.020	.036
	12	.011	.011	.012	.010	.036	-.020
120 MW	1	-.048	.030	.005	.004	.005	.005
	3	.034	.015	.009	.007	.008	.008
	4	.097	.120	-.161	.297	.067	.067
	6	-.006	-.006	-.006	.107	-.006	-.006
	11	.011	.011	.012	.010	-.020	.036
	12	.011	.011	.012	.010	.036	-.020
135 MW	1	-.093	.028	.007	.005	.006	.006
	3	.008	.006	.011	.008	.010	.010
	4	.052	.085	-.166	.334	.062	.062
	6	-.009	-.009	-.010	.144	-.009	-.009
	11	.012	.012	.012	.009	-.020	.036
	12	.012	.012	.012	.009	.036	-.020
150 MW	1	-.135	.026	.009	.006	.008	.008
	3	-.017	-.003	.013	.010	.013	.013
	4	.008	.051	-.172	.373	.056	.056
	6	-.013	-.013	-.013	.183	-.013	-.013
	11	.012	.012	.012	.009	-.019	.037
	12	.012	.012	.012	.009	.037	-.019
165 MW	1	-.177	.023	.010	.007	.009	.009
	3	-.041	-.011	.015	.011	.014	.014
	4	-.034	.019	-.176	.414	.052	.052
	6	-.016	-.016	-.017	.224	-.016	-.016
	11	.012	.011	.012	.009	-.020	.036
	12	.012	.01	.012	.009	.036	-.020
180 MW	1	-.217	.021	.012	.008	.011	.011
	3	-.065	-.019	.017	.012	.016	.016
	4	-.078	-.015	-.185	.456	.044	.044
	6	-.022	-.021	-.022	.267	-.021	-.021
	11	.012	.012	.013	.009	-.019	.037
	12	.012	.012	.013	.009	.037	-.019

Table 5-7

VOLTAGE CHANGES AT LOAD AND TIE BUSES DUE TO POWER INCREASES
AT GENERATOR BUSES, IN PERCENT PER 100 MW, WITH GENERATOR BUS VOLTAGES
CONSTANT AND THE VOLTAGES AT BUSES 2, 5, 7, AND 10 REGULATED BY SVC'S

Power Level at Bus 6	Bus at Which Voltage Increment Occurs	Bus at Which Real Power Increment Occurs					
		1	3	4	6	11	12
90 MW	2	-.66	-.66	-.03	-.03	-.03	-.03
	5	-.02	-.02	-.02	-.97	-.02	-.02
	7	.03	.03	.04	-1.75	.03	.03
	10	-.09	-.09	-.10	-.08	-.30	-.30
120 MW	2	-.25	-.51	-.06	-.05	-.06	-.06
	5	.04	.04	.04	-1.29	.04	.04
	7	.17	.17	.18	-2.32	.17	.17
	10	-.09	-.08	-.09	-.07	-.29	-.29
135 MW	2	-.05	-.45	-.08	-.06	-.07	-.07
	5	.06	.06	.06	-1.46	.06	.06
	7	.24	.23	.25	-2.63	.24	.24
	10	-.09	-.09	-.09	-.07	-.29	-.29
150 MW	2	.14	-.37	-.08	-.06	-.08	-.08
	5	.09	.08	.09	-1.64	.09	.09
	7	.30	.29	.31	-2.95	.30	.30
	10	-.07	-.06	-.07	-.05	-.27	-.27
165 MW	2	.30	-.33	-.11	-.08	-.10	-.10
	5	.11	.11	.12	-1.84	.11	.11
	7	.39	.38	.40	-3.27	.38	.38
	10	-.10	-.10	-.10	-.07	-.30	-.30
180 MW	2	.47	-.27	-.13	-.09	-.12	-.12
	5	.14	.13	.14	-2.05	.13	.13
	7	.45	.44	.46	-3.63	.44	.44
	10	-.09	-.09	-.09	-.07	-.30	-.30

Table 5-8

RATIOS OF REACTIVE POWER CHANGES AT LOAD AND TIE BUSES TO
REAL POWER CHANGES AT GENERATOR BUSES, IN MVAR/MW, WITH GENERATOR VOLTAGES
CONSTANT AND THE VOLTAGES AT BUSES 2, 5, 7, AND 10 REGULATED BY SVC'S

Power Level at Bus 6	Bus at Which Reactive Power Increment Occurs	Bus at Which Real Power Increment Occurs					
		1	3	4	6	11	12
90 MW	2	.074	.074	.004	.003	.003	.003
	5	.001	.001	.001	.072	.001	.001
	7	-.002	-.002	-.002	.122	-.002	-.002
	10	.011	.011	.012	.010	.037	.037
120 MW	2	.028	.058	.007	.005	.007	.007
	5	-.003	-.003	-.003	.096	-.003	-.003
	7	-.012	-.012	-.013	.164	-.012	-.012
	10	.011	.011	.011	.009	.036	.036
135 MW	2	.006	.050	.009	.007	.008	.008
	5	-.005	-.005	-.005	.109	-.005	-.005
	7	-.017	-.017	-.018	.187	-.017	-.017
	10	.011	.011	.011	.009	.036	.036
150 MW	2	-.016	.042	.009	.007	.009	.009
	5	-.006	-.006	-.007	.123	-.006	-.006
	7	-.022	-.021	-.023	.212	-.022	-.022
	10	.008	.008	.009	.006	.033	.033
165 MW	2	-.034	.037	.012	.009	.012	.012
	5	-.009	-.008	-.009	.138	-.008	-.008
	7	-.028	-.027	-.029	.238	-.028	-.028
	10	.012	.012	.012	.009	.038	.038
180 MW	2	-.053	.031	.014	.010	.014	.014
	5	-.010	-.010	-.010	.155	-.010	-.010
	7	-.034	-.032	-.034	.268	-.032	-.032
	10	.011	.011	.012	.008	.037	.037

Table 5-9

RATIOS OF REACTIVE POWER CHANGES TO REAL POWER CHANGES
AT GENERATOR BUSES, IN MVAR/MW, WITH GENERATOR BUS VOLTAGES CONSTANT
AND THE VOLTAGES AT BUSES 2, 5, 7, AND 10 REGULATED BY SVC'S

Power Level at Bus 6	Bus at Which Reactive Power Increment Occurs	Bus at Which Real Power Increment Occurs					
		1	3	4	6	11	12
90 MW	1	.033	.021	.000	.000	.000	.000
	3	.054	-.002	.002	.002	.002	.002
	4	.168	.169	-.152	.224	.066	.066
	6	.001	.001	.001	.036	.001	.001
	11	.007	.007	.008	.007	-.032	.024
	12	.007	.007	.008	.007	.024	-.032
120 MW	1	-.054	.019	.003	.003	.003	.003
	3	.021	-.013	.005	.004	.005	.005
	4	.085	.098	-.167	.292	.051	.051
	6	-.006	-.006	-.006	.107	-.006	-.006
	11	.008	.008	.009	.007	-.031	.025
	12	.008	.008	.009	.007	.025	-.031
135 MW	1	-.094	.017	.005	.004	.005	.005
	3	.005	-.019	.007	.005	.006	.006
	4	.046	.065	-.173	.329	.046	.046
	6	-.009	-.009	-.010	.144	-.009	-.009
	11	.008	.008	.009	.007	-.031	.025
	12	.008	.008	.009	.007	.025	-.031
150 MW	1	-.132	.017	.007	.005	.007	.007
	3	-.009	-.023	.009	.006	.008	.008
	4	.010	.035	-.178	.369	.041	.041
	6	-.013	-.013	-.013	.183	-.013	-.013
	11	.009	.009	.010	.007	-.030	.026
	12	.009	.009	.010	.007	.026	-.030
165 MW	1	-.170	.015	.007	.005	.007	.007
	3	-.025	-.029	.009	.007	.009	.009
	4	-.028	.004	-.185	.408	.035	.035
	6	-.016	-.016	-.017	.224	-.016	-.016
	11	.008	.008	.008	.006	-.031	.025
	12	.008	.008	.008	.006	.025	-.031
180 MW	1	-.206	.015	.009	.006	.009	.009
	3	-.039	-.034	.010	.007	.010	.010
	4	-.067	-.028	-.193	.450	.027	.027
	6	-.022	-.021	-.022	.267	-.021	-.021
	11	.009	.009	.009	.006	-.030	.026
	12	.009	.009	.009	.006	.026	-.030

Table 5-10

RATIOS OF REACTIVE POWER CHANGES AT LOAD AND TIE BUSES TO REAL POWER CHANGES
AT GENERATOR BUSES, IN MVAR/MW, WITH ALL BUS VOLTAGES CONSTANT

Power Level at Bus 6	Bus at Which Reactive Power Increment Occurs	Bus at Which Real Power Increment Occurs					
		1	3	4	6	11	12
90 MW	2	.184	.183	.009	.007	.009	.009
	5	.006	.006	.007	.186	.006	.006
	7	-.006	-.006	-.007	.248	-.006	-.006
	10	.034	.035	.039	.032	.118	.118
120 MW	2	.069	.143	.017	.013	.016	.016
	5	-.002	-.002	-.002	.246	-.002	-.002
	7	-.026	-.026	-.028	.326	-.027	-.027
	10	.033	.033	.036	.028	.115	.115
135 MW	2	.015	.125	.021	.016	.020	.020
	5	-.005	-.005	-.006	.278	-.005	-.005
	7	-.036	-.036	-.038	.366	-.036	-.036
	10	.034	.033	.036	.027	.115	.115
150 MW	2	-.040	.104	.023	.017	.022	.022
	5	-.009	-.009	-.009	.311	-.009	-.009
	7	-.046	-.045	-.048	.408	-.045	-.045
	10	.026	.025	.027	.020	.106	.106
165 MW	2	-.086	.091	.031	.022	.029	.029
	5	-.012	-.011	-.012	.346	-.012	-.012
	7	-.059	-.057	-.060	.449	-.057	-.057
	10	.039	.037	.039	.028	.119	.119
180 MW	2	-.133	.076	.036	.025	.034	.034
	5	-.014	-.014	-.014	.384	-.014	-.014
	7	-.069	-.066	-.069	.494	-.065	-.065
	10	.037	.035	.037	.026	.116	.116

Table 5-11

RATIOS OF REACTIVE POWER CHANGES TO REAL POWER CHANGES AT GENERATOR BUSES,
IN MVAR/MW, WITH ALL BUS VOLTAGES CONSTANT

Power Level at Bus 6	Bus at Which Reactive Power Increment Occurs	Bus at Which Real Power Increment Occurs					
		1	3	4	6	11	12
90 MW	1	.011	-.001	-.001	-.001	-.001	-.001
	3	-.000	-.056	-.000	-.000	-.000	-.000
	4	.125	.126	-.162	.124	.035	.035
	6	-.002	-.002	-.002	-.118	-.002	-.002
	11	-.000	-.000	-.000	-.000	-.056	-.000
	12	-.000	-.000	-.000	-.000	-.000	-.056
120 MW	1	-.062	.001	.001	.001	.001	.001
	3	.001	-.055	.000	.000	.000	.000
	4	.072	.071	-.170	.158	.027	.027
	6	.000	.000	.000	-.099	.000	.000
	11	.001	.001	.001	.001	-.055	.001
	12	.001	.001	.001	.001	.001	-.055
135 MW	1	-.096	.003	.002	.002	.002	.002
	3	.001	-.055	.001	.000	.001	.001
	4	.047	.046	-.173	.176	.025	.025
	6	.001	.001	.001	-.091	.001	.001
	11	.001	.001	.001	.001	-.055	.001
	12	.001	.001	.001	.001	.001	-.055
150 MW	1	-.127	.005	.004	.003	.004	.004
	3	.002	-.054	.002	.001	.002	.002
	4	.027	.026	-.172	.197	.026	.026
	6	.001	.001	.001	-.082	.001	.001
	11	.004	.004	.004	.003	-.052	.004
	12	.004	.004	.004	.003	.004	-.052
165 MW	1	-.160	.004	.004	.003	.003	.003
	3	.000	-.056	.000	.000	.000	.000
	4	-.001	-.001	-.178	.212	.020	.020
	6	.002	.002	.002	-.073	.002	.002
	11	-.000	-.000	-.000	-.000	-.056	-.000
	12	-.000	-.000	-.000	-.000	-.000	-.056
180 MW	1	-.190	.005	.005	.003	.004	.004
	3	-.000	-.056	-.000	-.000	-.000	-.000
	4	-.026	-.025	-.182	.229	.016	.016
	6	.000	.000	.000	-.067	.000	.000
	11	.001	.001	.001	.001	-.055	.001
	12	.001	.001	.001	.001	.001	-.055

Figure 5-6. Incremental voltage regulation at bus 7 for an incremental increase in generation at bus 6.

Figure 5-7. Incremental voltage regulation at bus 5 for an incremental increase in generation at bus 6.

Figure 5-8. Ratios of reactive power change at bus 4 to real power change at bus 6.

Figure 5-9. Ratios of reactive power change at bus 6 to real power change at bus 6.

Figure 5-10. Ratios of reactive power change at bus 5 to real power change at bus 6.

Figure 5-11. Ratios of reactive power change at bus 7 to real power change at bus 6.

Figure 5-12. Incremental stator current components and excitation voltage for the generator at bus 6.

explanation of the effects of the SVC's which is consistent with the results of the eigenvalue calculations.

Curves of ΔI_D , ΔI_Q , and ΔE_{EX} for the generator at bus 6 are plotted in Figure 5-12 for three circumstances:

- Constant voltages at all buses
- SVC's at buses 5 and 7 with voltages at buses 2 and 10 unregulated
- Voltages at buses 2, 5, 7, and 10 unregulated

As the voltage sensitivity at bus 5 increases, and the generator incremental MVAR/MW required to maintain constant terminal voltage likewise increases, the incremental direct axis component of stator current increases, while the quadrature axis component decreases. In addition, the incremental excitation voltage increases with increasing voltage sensitivity at bus 5. The implication is that the induced field current and the field voltage variations associated with oscillations will increase as the voltage sensitivity at bus 5 increases. The induced field current and variational field voltage are essentially in phase, so that the exciter is an energy source at the oscillation frequency which is strengthened by increased voltage sensitivity at bus 5.

EIGENVALUE STUDIES

There are five modes of oscillation associated with synchronizing power flow among the five machines and infinite bus of Figure 5-1. Eigenvalues which characterize these oscillations have been calculated using AESOPS, a computer program developed by Westinghouse AST under contract with EPRI. Static VAR compensators are represented in AESOPS by the nonlinear reactive load model of Section 4, or more precisely, by linear approximations derived from that model. A general description of AESOPS is provided by reference 5-1, and complete information in references 5-2 through 5-6.

The results of eigenvalue calculations for this study system without SVC's and with 150 MW generation at bus 6 are presented in Table 5-12. The upper part of

Table 5-12

MODES OF OSCILLATION ASSOCIATED WITH SYNCHRONIZING POWER FLOW IN SYSTEM A,
150 MW GENERATION AT BUS 6, NO STATIC VAR COMPENSATORS

<u>Mode</u>	<u>Eigenvalue</u>	<u>Frequency in Hertz</u>	<u>Successive Positive Peak Ratio</u>
1	0.236 + j 2.984	0.475	1.643
2	-0.123 + j 5.585	0.889	0.871
3	-0.249 + j 9.282	1.477	0.845
4	-0.113 + j11.246	1.790	0.939
5	-0.385 + j14.577	2.320	0.847

Normalized Speed Deviations

Mode	3	4	6	11	12
1	0.31 + j0.01	0.49 + j0.00	1.00 - j0.00	0.50 + j0.01	0.59 - j0.01
2	0.30 + j0.01	0.42 + j0.04	-0.34 + j0.07	0.52 + j0.01	1.00 - j0.00
3	1.00 - j0.01	0.35 + j0.03	-0.03 + j0.01	0.16 - j0.02	-0.22 + j0.01
4	-0.45 - j0.01	1.00 + j0.03	-0.03 + j0.00	0.37 - j0.08	-0.17 + j0.01
5	-0.04 - j0.01	-0.31 + j0.03	-0.01 + j0.00	1.00 + j0.01	-0.08 + j0.00

that table lists eigenvalues, oscillation frequencies, and successive positive peak ratios. The frequencies are in ascending order and numbered for convenience. The mode 1 eigenvalue is in the right half-plane, and the successive positive peak ratio is greater than one, indicating an oscillation which increases with time. The other four modes of oscillation are stable and decay with time. The oscillation frequencies and successive peak ratios are plotted in Figure 5-13.

The lower portion of Table 5-12 contains speed deviations of the five synchronous machines for each mode of oscillation, normalized by dividing each speed deviation by the largest. The speed deviations are part of the eigenvector and provide a description of the oscillation. For mode 1, the speed deviations are interpreted to mean that all machines oscillate coherently relative to the infinite bus; for mode 2, the generator at bus 6 moves in opposition to the machines at buses 3, 4, 11, and 12. The coordinate axes for the complex speed deviations for each mode are oriented to maximize the sum of the squares of the real components.

The normalized speed deviations enable simulations in the time domain which emphasize particular modes of oscillation. Each generator is given an initial speed deviation proportional to the real part of its complex speed deviation, scaled to produce some desired peak angle deviation. The generator rotor angles of Figure 5-14 are from a simulation of mode 1 and indicate an oscillation frequency and successive positive peak ratio consistent with the data of Table 5-12.

Eigenvalues have been calculated for six levels of generation at bus 6, with no SVC's, with SVC's at buses 5 and 7, and with SVC's at buses 2, 5, 7, and 10. Eigenvalues for these conditions are presented in Tables 5-13, 5-14, and 5-15. Oscillation frequencies and successive positive peak ratios are presented in Tables 5-16, 5-17, and 5-18. Speed deviations are not significantly different from those in Table 5-12 and are not shown.

The principal effect of the SVC's is to improve the damping of mode 1. Other modes of oscillation are not significantly changed by the SVC's. The oscillation frequencies and successive positive peak ratios for mode 1 from Tables 5-16,

Figure 5-13. Oscillation frequencies and successive positive peak ratios for the five modes of oscillation listed in Table 5-12.

NOTE: In this figure, and in similar figures which follow in this section and in Section 6, the scales associated with the vertical axes are determined by the plotting program. Differences in scales must be considered in making comparisons.

Figure 5-14. Generator rotor angles from a simulation of mode 1 with an initial angle swing of 20° at bus 6 and the voltages at buses 2, 5, 7, and 10 unregulated.

Table 5-13

EIGENVALUES FOR SYSTEM A FOR VARIOUS LEVELS OF GENERATION AT BUS 6
WITHOUT STATIC VAR COMPENSATORS

Generation at bus 6

Mode	90 MW	120 MW	135 MW	150 MW	165 MW	180 MW
1	$0.011 + j 3.074$	$0.111 + j 3.133$	$0.170 + j 3.023$	$0.236 + j 2.984$	$0.308 + j 2.934$	$0.387 + j 2.870$
2	$-0.137 + j 5.650$	$-0.134 + j 5.641$	$-0.129 + j 5.620$	$-0.123 + j 5.585$	$-0.114 + j 5.534$	$-0.104 + j 5.466$
3	$-0.247 + j 9.267$	$-0.249 + j 9.284$	$-0.249 + j 9.285$	$-0.249 + j 9.282$	$-0.247 + j 9.273$	$-0.246 + j 9.260$
4	$-0.097 + j 10.986$	$-0.103 + j 11.088$	$-0.107 + j 11.162$	$-0.113 + j 11.246$	$-0.120 + j 11.340$	$-0.128 + j 11.439$
5	$-0.397 + j 14.492$	$-0.393 + j 14.521$	$-0.390 + j 14.545$	$-0.385 + j 14.577$	$-0.378 + j 14.617$	$-0.371 + j 14.667$

Table 5-14

EIGENVALUES FOR SYSTEM A FOR VARIOUS LEVELS OF GENERATION AT BUS 6
WITH STATIC VAR COMPENSATORS AT BUSES 2, 5, 7, AND 10

Generation at bus 6

Mode	90 MW	120 MW	135 MW	150 MW	165 MW	180 MW
1	$-0.014 + j 3.110$	$0.006 + j 3.152$	$0.015 + j 3.163$	$0.025 + j 3.169$	$0.034 + j 3.175$	$0.045 + j 3.172$
2	$-0.108 + j 5.623$	$-0.106 + j 5.646$	$-0.103 + j 5.645$	$-0.099 + j 5.634$	$-0.095 + j 5.617$	$-0.090 + j 5.590$
3	$-0.218 + j 9.236$	$-0.219 + j 9.255$	$-0.220 + j 9.259$	$-0.220 + j 9.259$	$-0.220 + j 9.256$	$-0.220 + j 9.250$
4	$-0.106 + j 10.959$	$-0.110 + j 11.050$	$-0.112 + j 11.117$	$-0.116 + j 11.195$	$-0.120 + j 11.286$	$-0.126 + j 11.385$
5	$-0.390 + j 14.494$	$-0.384 + j 14.528$	$-0.380 + j 14.556$	$-0.375 + j 14.593$	$-0.370 + j 14.637$	$-0.363 + j 14.692$

Table 5-15

EIGENVALUES FOR SYSTEM A FOR VARIOUS LEVELS OF GENERATION AT BUS 6
WITH STATIC VAR COMPENSATORS AT BUSES 5 AND 7

Generation at bus 6

Mode	90 MW	120 MW	135 MW	150 MW	165 MW	180 MW
1	$-0.026 + j 3.123$	$0.016 + j 3.142$	$0.040 + j 3.138$	$0.067 + j 3.124$	$0.091 + j 3.112$	$0.116 + j 3.089$
2	$-0.121 + j 5.643$	$-0.119 + j 5.656$	$-0.118 + j 5.655$	$-0.117 + j 5.648$	$-0.114 + j 5.631$	$-0.111 + j 5.607$
3	$-0.240 + j 9.258$	$-0.242 + j 9.275$	$-0.242 + j 9.278$	$-0.242 + j 9.278$	$-0.241 + j 9.273$	$-0.240 + j 9.265$
4	$-0.098 + j 10.970$	$-0.105 + j 11.076$	$-0.109 + j 11.152$	$-0.115 + j 11.241$	$-0.121 + j 11.337$	$-0.130 + j 11.443$
5	$-0.395 + j 14.491$	$-0.390 + j 14.519$	$-0.387 + j 14.544$	$-0.382 + j 14.576$	$-0.375 + j 14.615$	$-0.368 + j 14.665$

Table 5-16

OSCILLATION FREQUENCIES, IN HERTZ, AND SUCCESSIVE POSITIVE PEAK RATIOS FOR SYSTEM A
WITH VARIOUS LEVELS OF GENERATION AT BUS 6 AND WITHOUT STATIC VAR COMPENSATORS

Generation at bus 6

Mode	90 MW		120 MW		135 MW		150 MW		165 MW		180 MW	
	f	SPR	f	SPR	f	SPR	f	SPR	f	SPR	f	SPR
1	0.489	1.022	0.486	1.256	0.481	1.424	0.475	1.643	0.467	1.933	0.457	2.335
2	0.899	0.858	0.898	0.861	0.894	0.865	0.889	0.871	0.881	0.878	0.870	0.888
3	1.475	0.846	1.478	0.845	1.478	0.845	1.477	0.845	1.476	0.846	1.476	0.846
4	1.748	0.946	1.765	0.943	1.776	0.942	1.790	0.939	1.805	0.936	1.821	0.932
5	2.306	0.842	2.311	0.844	2.315	0.845	2.320	0.847	2.326	0.850	2.334	0.853

Table 5-17

OSCILLATION FREQUENCIES, IN HERTZ, AND SUCCESSIVE POSITIVE PEAK RATIOS FOR SYSTEM A
WITH VARIOUS LEVELS OF GENERATION AT BUS 6 AND STATIC VAR COMPENSATORS AT BUSES 2, 5, 7, AND 10

Generation at bus 6

Mode	90 MW		120 MW		135 MW		150 MW		165 MW		180 MW	
	f	SPR	f	SPR	f	SPR	f	SPR	f	SPR	f	SPR
1	0.495	0.972	0.502	1.012	0.503	1.031	0.504	1.050	0.505	1.069	0.505	1.093
2	0.896	0.887	0.899	0.889	0.898	0.891	0.897	0.896	0.894	0.900	0.890	0.904
3	1.470	0.862	1.473	0.862	1.474	0.861	1.474	0.861	1.473	0.861	1.472	0.861
4	1.744	0.941	1.759	0.940	1.769	0.939	1.782	0.937	1.796	0.935	1.812	0.933
5	2.307	0.844	2.312	0.847	2.317	0.849	2.322	0.851	2.330	0.853	2.338	0.856

Table 5-18

OSCILLATION FREQUENCIES, IN HERTZ, AND SUCCESSIVE POSITIVE PEAK RATIOS FOR SYSTEM A
WITH VARIOUS LEVELS OF GENERATION AT BUS 6 AND STATIC VAR COMPENSATORS AT BUSES 5 AND 7

Generation at bus 6												
Mode	90 MW		120 MW		135 MW		150 MW		165 MW		180 MW	
	f	SPR	f	SPR	f	SPR	f	SPR	f	SPR	f	SPR
1	0.497	0.948	0.500	1.032	0.499	1.083	0.497	1.144	0.495	1.201	0.492	1.267
2	0.898	0.874	0.900	0.376	0.900	0.877	0.899	0.878	0.896	0.881	0.892	0.883
3	1.473	0.845	1.476	0.349	1.477	0.849	1.477	0.849	1.476	0.849	1.475	0.850
4	1.746	0.945	1.763	0.942	1.775	0.940	1.789	0.938	1.804	0.935	1.821	0.931
5	2.306	0.843	2.311	0.345	2.315	0.846	2.320	0.848	2.326	0.851	2.334	0.854

5-17, and 5-18 are plotted in Figure 5-15. The improvement in damping is substantial, particularly at the higher levels of generation at bus 6, and most of the improvement is achieved with the SVC's at buses 5 and 7. Further improvements in damping can be achieved with auxiliary SVC controls sensitive to frequency and will be demonstrated using time-domain simulation and the SVC model of Section 4 which includes auxiliary controls. The AESOPS program has not been modified to accommodate that model.

SIMULATED OSCILLATIONS

Oscillations corresponding to mode 1 eigenvalues have been simulated with the Westinghouse Stability program which has been modified to accommodate the SVC model of Figure 4-2. Parameters for that model are listed in Table 5-19 for the SVC's at buses 2, 5, 7, and 10. The rate of change of reactive power with respect to voltage in Table 5-19 is the same as that in Table 5-1, so the results obtained with this model can be expected to be similar to those obtained with AESOPS using data for the nonlinear reactive load model.

The results to be described include some simulations with large angle swings with the objective of determining the associated extremes of the SVC reactive power. The regulating range of each SVC in Table 5-19 is therefore chosen to avoid the limits on susceptance rather than to represent predetermined ratings.

The generator rotor angles and SVC reactive powers in Figures 5-16 through 5-19 are from simulations of mode 1 with SVC's at buses 5 and 7. The magnitude of the initial positive angle swing at bus 6 is 20 degrees in Figure 5-16, 60 degrees in Figure 5-17, 100 degrees in Figure 5-18, and intended to be 140 degrees in Figure 5-19. The latter simulation results in a loss of synchronism between the infinite bus and the machines at buses 3, 4, 6, 11 and 12. This loss of synchronism is associated with a collapse of voltage at bus 2 and does not occur for this magnitude of angle swing with a static VAR compensator at bus 2.

The frequency of the oscillation in Figure 5-16 is quite close to that obtained with AESOPS listed in Table 5-18. The successive positive peak ratio estimated from Figure 5-16 is about one, whereas the eigenvalue analysis yields 1.144 for

Figure 5-15. Oscillation frequencies and successive positive peak ratios for mode 1 with the level of generation at bus 6 varying from 90 MW at the left to 180 MW at the right.

Table 5-19

MODEL PARAMETERS FOR THE STATIC VAR COMPENSATORS USED IN SIMULATIONS
OF MODE 1 WITH 150 MW GENERATION AT BUS 6

Symbol	Symbol Definition	Bus 2	Bus 5	Bus 7	Bus 10
Q	Initial reactive power	0	0	0	0
V_R	Reference voltage	1.0410	1.0540	1.0200	1.0360
$V_1 + V_R$	Maximum voltage in regulating range	1.1694	1.2441	1.2243	1.1526
$V_2 + V_R$	Minimum voltage in regulating range	0.9127	0.8640	0.8158	0.9194
B_1	Minimum susceptance	-1.5000	-1.5000	-1.5000	-1.5000
B_2	Maximum susceptance	1.5000	1.5000	1.5000	1.5000
Q_1	Reactive power at minimum susceptance	-2.0510	-2.3220	-2.2480	-1.9930
Q_2	Reactive power at maximum susceptance	1.2500	1.1200	0.9980	1.2680
dQ/dV_T	MVAR/percent voltage at one pu voltage	11.6900	7.8900	7.3400	12.8600

- Voltages are in pu on the SVC terminal voltage base V_B .
- Reactive powers are in pu on the system MVA base, S_B , which is 100.
- Susceptances are in pu on the admittance base $Y_B = S_B / V_B^2$.

Figure 5-16. Generator rotor angles and SVC reactive powers from a simulation of mode 1 with an initial angle swing of 20° at bus 6 and SVC's at buses 5 and 7.

Figure 5-17. Generator rotor angles and SVC reactive powers from a simulation of mode 1 with an initial angle swing of 60° at bus 6 and SVC's at buses 5 and 7.

Figure 5-18. Generator rotor angles and SVC reactive powers from a simulation of mode 1 with an initial angle swing of 100° at bus 6 and SVC's at buses 5 and 7.

Figure 5-19. Generator rotor angles and SVC reactive powers from a simulation of mode 1 with an intended initial angle swing of 140° at bus 6 and SVC's at buses 5 and 7.

this ratio. The apparent increase in damping is attributable in part to nonlinearities which are beginning to be apparent with 20 degree angle swings, and in part due to differences between the nonlinear reactive load model for SVC's used by AESOPS and the model of Figure 4-2.

As the magnitude of the swing increases, the apparent damping increases, and the oscillation frequency declines. Some of the nonlinear effects are quite evident in the reactive power curves of Figures 5-17 and 5-18. The differences in inductive and capacitive compensation at buses 5 and 7 indicate that the oscillation causes a change in average voltage and, consequently, a change in average load power. In Figure 5-18, the voltages at buses 5 and 7 clearly have variations other than the mode 1 oscillation.

The generator rotor angles and SVC reactive powers in Figures 5-20 through 5-23 are from simulations of mode 1 with SVC's at buses 2, 5, 7, and 10. The oscillation with 140 degrees initial angle swing at bus 6 is now stable, as indicated in Figure 5-23, and at bus 2 there are rather large swings in capacitive reactive power at twice the generator rotor oscillation frequency. Otherwise, these simulations are quite similar to those with SVC's at buses 5 and 7 only.

The peak reactive powers from the SVC's in these various simulations are listed in Tables 5-20 and 5-21. The contents of Table 5-21 are plotted in Figure 5-24 and provide a general indication that ratings to achieve improvements in stability are dependent on the severity of the disturbances to which the system is subjected.

The generator rotor angles and SVC reactive powers in Figure 5-25 are from a simulation of mode 1 with SVC's at buses 5 and 7, each of which has an auxiliary controller sensitive to frequency. With reference to Figure 4-2, each SVC has an auxiliary control channel which will increase the reference voltage by one per unit for a change in frequency of one Hertz. The damping of this oscillation is in sharp contrast to the simulation of Figure 5-14 and demonstrates the potential for dynamic stability improvement by means of voltage regulation. Spontaneous oscillations can no doubt be avoided with relatively low-rated static VAR compensators.

Figure 5-20. Generator rotor angles and SVC reactive powers from a simulation of mode 1 with an initial angle swing of 20° at bus 6 and SVC's at buses 2, 5, 7, and 10.

Figure 5-21. Generator rotor angles and SVC reactive powers from a simulation of mode 1 with an initial angle swing of 60° at bus 6 and SVC's at buses 2, 5, 7, and 10.

Figure 5-22. Generator rotor angles and SVC reactive powers from a simulation of mode 1 with an initial angle swing of 100° at bus 6 and SVC's at buses 2, 5, 7, and 10.

Figure 5-23. Generator rotor angles and SVC reactive powers from a simulation of mode 1 with an initial angle swing of 140° at bus 6 and SVC's at buses 2, 5, 7, and 10.

Table 5-20

PEAK REACTIVE POWERS FROM MODE 1 SIMULATIONS WITH 150 MW
GENERATION AT BUS 6 AND SVC'S AT BUSES 5 AND 7

<u>Peak Angle Swing in Degrees</u>	Peak Reactive Power in MVAR			
	Bus 5		Bus 7	
	<u>Ind</u>	<u>Cap</u>	<u>Ind</u>	<u>Cap</u>
20	7.6	8.4	7.9	9.8
60	19.1	30.5	19.0	35.1
100	28.5	56.4	28.6	65.3

Table 5-21

PEAK REACTIVE POWERS FROM MODE 1 SIMULATIONS WITH 150 MW
GENERATION AT BUS 6 AND SVC'S AT BUSES 2, 5, 7, AND 10

<u>Peak Angle Swing in Degrees</u>	Peak Reactive Power in MVAR							
	Bus 2		Bus 5		Bus 7		Bus 10	
	<u>Ind</u>	<u>Cap</u>	<u>Ind</u>	<u>Cap</u>	<u>Ind</u>	<u>Cap</u>	<u>Ind</u>	<u>Cap</u>
20	1.3	4.9	7.5	8.5	7.5	9.3	3.1	3.8
60	2.3	25.7	18.3	32.4	17.4	34.2	7.6	16.6
100	4.4	59.5	25.1	65.9	20.6	66.1	13.4	37.0
140	6.2	101.7	28.6	111.6	22.1	99.1	18.4	68.8

Figure 5-24. Peak reactive powers from mode 1 simulations with 150 MW generation at bus 6 and SVC's at buses 2, 5, 7, and 10.

Figure 5-25. Generator rotor angles from a simulation of mode 1 with an initial swing of 20° at bus 6 and SVC's at buses 5 and 7 with frequency as an auxiliary control signal.

TRANSIENT STABILITY STUDIES

Stability studies have been performed to determine the effects of SVC's on the transient stability limit of the generator at bus 6. The results to be described involve the simulation of a three-phase fault near bus 5 on one of the lines to bus 7. The fault is cleared in 0.1 seconds by opening both ends of the faulted line simultaneously. Reclosing is not considered.

The generator rotor angles in Figure 5-26 are from a simulation without SVC's and with 135 MW generation at bus-6. The system is stable, although the oscillations following the fault are poorly damped. The generator rotor angles in Figure 5-27 are from a simulation with 144 MW generation at bus 6 and also without SVC's. That simulation is terminated at about 1.5 seconds when the angle separation between the generator at bus 6 and the synchronous condenser at bus 4 reaches 360 degrees, indicating loss of synchronism. The transient stability limit for the generator at bus 6 is about 140 MW.

The generator rotor angles and SVC reactive powers in Figure 5-28 are from a simulation with SVC's at buses 5 and 7 and 150 MW generation at bus 6. The SVC's are represented by the model of Figure 4-2 without auxiliary control. The generation at bus 6 is raised to 165 MW in Figure 5-29 and 180 MW in Figure 5-30. Higher levels of generation at bus 6 are incompatible with the generator rating and have not been studied.

The static VAR compensators in these simulations have the parameters listed in Table 5-19. The regulating range is deliberately large to avoid restricting the reactive power excursions required by voltage regulation. Peak reactive powers which occur within the first cycle of the low frequency oscillation are listed in Table 5-22 and plotted in Figure 5-31. This information can be used to establish equipment ratings associated with specific transient stability objectives. If reactive power capabilities less than those listed in Table 5-22 are selected, the transient stability limit at bus 6 does not necessarily fall below the value shown. The parameters of Table 5-19 can be revised to account for altered SVC capability, and the simulations repeated to verify the transient stability limit.

Figure 5-26. Generator rotor angles from a simulation of a three-phase fault at bus 5, with no SVC's and 135 MW generation at bus 6.

Figure 5-27. Generator rotor angles from a simulation of a three-phase fault at bus 5, with no SVC's and 144 MW generation at bus 6.

Figure 5-28. Generator rotor angles and SVC reactive powers from a simulation of a three-phase fault at bus 5 with SVC's at buses 5 and 7 and 150 MW generation at bus 6.

Figure 5-29. Generator rotor angles and SVC reactive powers from a simulation of a three-phase fault at bus 5 with SVC's at buses 5 and 7 and 165 MW generation at bus 6.

Figure 5-30. Generator rotor angles and SVC reactive powers from a simulation of a three-phase fault at bus 5 with SVC's at buses 5 and 7 and 180 MW generation at bus 6.

Figure 5-31. Reactive power excursions for static VAR compensators at buses 5 and 7 following fault at bus 5.

Table 5-22

REACTIVE POWER EXCURSIONS FOR STATIC VAR
COMPENSATORS FOLLOWING FAULT AT BUS 5

Generation at Bus 6 in MW	Bus 5		Bus 7	
	Capacitive MVAR	Inductive MVAR	Capacitive MVAR	Inductive MVAR
150	42.4	11.6	49.2	2.8
165	56.6	17.3	62.4	6.3
180	79.1	27.6	72.7	13.4

The generator rotor angles and SVC reactive powers in Figure 5-32 are from a simulation in which both SVC's have auxiliary control channels responsive to frequency. Each control channel gain is set to produce one per unit change in the reference voltage for one Hertz change in frequency. Changes in reference voltage are limited to 0.1 per unit, and the effects of limiting are evident in the reactive power curves for both SVC's during the first capacitive swing. The peak capacitive reactive power for the SVC at bus 5 is 91.3 MVAR with frequency sensitive auxiliary control, and 86.9 MVAR for the SVC at bus 7. Satisfactory damping can no doubt be achieved with smaller capacitive swings than those which occur in Figure 5-32.

SUMMARY

Analytical methods have been described which relate system stability characteristics to the general specifications for static VAR compensators, including their locations, regulating slopes, peak reactive power requirements, and auxiliary controls.

The studies performed illustrate the potential for improved synchronous stability performance by means of static VAR compensators. The benefits attributable to SVC's take the form of greatly increased damping for modes of oscillation which are unstable in the absence of SVC's, and substantial increases in transient stability limits.

Figure 5-32. Generator rotor angles and SVC reactive powers from a simulation of a three-phase fault at bus 5 with SVC's at buses 5 and 7 sensitive to frequency deviation and 180 MW generation at bus 6.

REFERENCES

- 5-1. R. T. Byerly, R. J. Bennon, and D. E. Sherman, "Eigenvalue Analysis of Synchronizing Power Flow Oscillations in Large Electric Power Systems," presented at PICA 81, Philadelphia, PA, May 5-8, 1981.
- 5-2. EPRI EL-727, Contract 744-1. Frequency Domain Analysis of Low-Frequency Oscillations in Large Electric Power Systems. Final Report Part 1 - Basic Concepts, Mathematical Models, and Computing Methods.
- 5-3. EPRI EL-727, Contract 744-1. Frequency Domain Analysis of Low-Frequency Oscillations in Large Electric Power Systems. Final Report Part 2 - Computer Program Documentation.
- 5-4. EPRI EL-727, Contract 744-1. Frequency Domain Analysis of Low-Frequency Oscillations in Large Electric Power Systems. Final Report Part 3 - Studies of the MAPP System.
- 5-5. EPRI EL-727, Contract 744-1. Frequency Domain Analysis of Low-Frequency Oscillations in Large Electric Power Systems. Final Report Part 4 - Interim Reports on Linear System Models.
- 5-6. EPRI EL-727, Contract 744-1. Frequency Domain Analysis of Low-Frequency Oscillations in Large Electric Power Systems. Final Report Part 5 - Studies of a Large System.

Section 6

NEW ENGLAND TEST SYSTEM STUDIES

The studies to be described were made with two objectives:

- To further illustrate the potential for improved synchronous stability behavior by means of static VAR compensators
- To demonstrate an orderly approach to SVC application studies related to stability goals, using voltage sensitivity calculations, eigenvalue calculations, and transient stability calculations

These studies pertain to the system of Figure 6-1, designated the New England Test System (NETS). The machine at bus 39 is an equivalent for a major subsystem and is virtually an infinite source, with low internal impedance and an inertia constant of 500 on a 100 MVA base. In contrast, the sum of the inertia constants for the machines at buses 30 through 38 is 283 on the 100 MVA base, with individual machine inertia constants in the range from 26 through 42. Detailed network and power plant data is contained in Appendix C.

Figure 6-1. Single-line diagram for New England Test System.

VOLTAGE SENSITIVITY CALCULATIONS

The voltages at buses 30 through 38 are regulated by generator field controls. The voltage at bus 39 is almost constant by virtue of the low internal impedance of the generator at that bus. Consequently, buses 30 through 39 are excluded in this study as possible locations for static VAR compensators.

To identify buses and circumstances in which poor voltage regulation may contribute to instability, voltage sensitivities have been calculated for a base load flow using the program described in Section 5 and Appendix B. In particular, the ratios

$$r_{IK} = \Delta V_I / \Delta P_K \quad ; \quad I = 1, 2, \dots, 29 \quad ; \quad k = 30, 31, \dots, 39 \quad (6-1)$$

have been calculated, assuming constant generator terminal voltages. These ratios are shown in Table 6-1. The largest sensitivities are at buses 26, 27, 28, and 29 for an increase in generation at bus 38. This region of the system is shown in more detail in Figure 6-2, with line reactances and the real components of load indicated.

Increasing the steady-state generation at bus 38 stresses the transmission network in the vicinity of buses 26, 27, 28, and 29 and provides a study situation which can be used to demonstrate improvements in stability due to static VAR compensators. Four levels of generation at bus 38 have been studied: 830 MW, 1080 MW, 1330 MW, and 1580 MW. Generation at bus 39 is reduced to compensate for the increased generation at bus 38. Load flows corresponding to these four operating conditions are contained in Appendix C.

The voltage sensitivities of Table 6-1 correspond to 830 MW at bus 38. Voltage sensitivities at buses 26, 27, 28, and 29 for all four levels of generation at bus 38 are shown in Table 6-2.

Table 6-1

VOLTAGE CHANGES AT LOAD BUSES DUE TO POWER INCREASES AT GENERATOR BUSES,
IN PERCENT PER 1000 MW, WITH GENERATOR BUS VOLTAGES CONSTANT
AND THE VOLTAGES AT BUSES 1 THROUGH 29 UNREGULATED

Load Buses	Generator Buses									
	30	31	32	33	34	35	36	37	38	39
1	-.27	.05	-.04	-.31	-.29	-.32	-.33	-1.14	-.81	.88
2	.36	.18	.07	-.27	-.22	-.28	-.32	-2.04	-1.37	.53
3	-.11	-.05	-.25	-.59	-.50	-.62	-.70	-1.35	-1.17	.26
4	-.08	-.74	-1.09	-.63	-.56	-.66	-.72	-.64	-.66	.18
5	-.09	-1.13	-1.30	-.53	-.48	-.55	-.60	-.43	-.47	.23
6	-.09	-1.15	-1.32	-.52	-.47	-.54	-.58	-.39	-.44	.22
7	-.10	-1.13	-1.28	-.52	-.48	-.54	-.58	-.40	-.45	.26
8	-.11	-1.11	-1.25	-.53	-.49	-.55	-.59	-.40	-.45	.26
9	-.10	-.58	-.63	-.30	-.28	-.31	-.32	-.22	-.25	.14
10	-.06	-.73	-1.51	-.48	-.43	-.50	-.55	-.33	-.39	.14
11	-.08	-.85	-1.52	-.51	-.46	-.53	-.58	-.36	-.42	.17
12	-.06	-.78	-1.48	-.51	-.45	-.53	-.58	-.35	-.41	.15
13	-.07	-.77	-1.53	-.55	-.48	-.57	-.63	-.38	-.44	.12
14	-.07	-.71	-1.32	-.73	-.64	-.77	-.85	-.47	-.57	.12
15	-.09	-.29	-.59	-1.25	-1.06	-1.31	-1.48	-.41	-.68	.09
16	-.07	-.15	-.33	-1.39	-1.16	-1.47	-1.68	-.36	-.69	.09
17	-.14	-.14	-.31	-1.11	-.94	-1.17	-1.33	-.59	-1.20	.08
18	-.12	-.10	-.29	-.95	-.81	-1.00	-1.12	-.87	-1.20	.16
19	-.03	-.06	-.13	-1.52	-.88	-.55	-.63	-.14	-.26	.03
20	-.01	-.03	-.06	-.76	-.95	-.28	-.31	-.07	-.13	.02
21	-.02	-.08	-.20	-.93	-.77	-2.01	-2.13	-.23	-.46	.08
22	-.00	-.03	-.10	-.50	-.41	-1.57	-1.81	-.12	-.24	.05
23	-.01	-.04	-.11	-.52	-.43	-1.50	-2.32	-.12	-.25	.05
24	-.05	-.12	-.28	-1.26	-1.05	-1.71	-2.08	-.32	-.63	.09
25	-.94	-.40	-.43	-.34	-.30	-.35	-.39	.57	-.25	-.45
26	-.55	-.18	-.24	-.41	-.33	-.44	-.51	-.26	-2.78	-.20
27	-.38	-.11	-.22	-.64	-.52	-.68	-.79	-.47	-2.20	-.06
28	-.28	-.09	-.12	-.21	-.17	-.22	-.25	-.13	-3.71	-.10
29	-.18	-.05	-.08	-.14	-.11	-.14	-.17	-.08	-3.16	-.06

Figure 6-2. Line reactances and bus loads near bus 38.

Table 6-2

VOLTAGE SENSITIVITIES IN THE ABSENCE OF SVC'S, IN PERCENT PER 1000 MW,
AS A FUNCTION OF THE GENERATION AT BUS 38

Bus	Generation at Bus 38			
	830 MW	1080 MW	1330 MW	1580 MW
26	-2.78	-5.12	-8.01	-12.19
27	-2.20	-4.01	-6.23	-9.45
28	-3.71	-6.21	-9.31	-13.72
29	-3.16	-5.18	-7.71	-11.32

Regulating slopes for SVC's at buses 26, 27, 28 and 29 are calculated from short-circuit reactances as in Section 5. Specifically, the regulating slope at the operating voltage is set to $1.33/X_{SC}$. Values of short-circuit reactances and regulating slopes are listed in Table 6-3.

Table 6-3

SHORT-CIRCUIT REACTANCES AND REGULATING SLOPES
FOR SVC'S APPLIED TO THE SYSTEM OF FIGURE 6-2

<u>Bus Number</u>	<u>X_{SC} in Per Unit on a 100 MVA Base</u>	<u>Regulating Slope MVAR/Percent Voltage</u>
26	0.0225	59.11
27	0.0227	58.59
28	0.0375	35.47
29	0.0329	40.43

A static VAR compensator at any one of these four buses will influence voltage regulation at the other three, and various combinations of SVC's can be examined for their effects on voltage sensitivity. Only two such combinations have been considered in this study: SVC's at buses 26, 27 and 29; and SVC's at all four buses.

Voltage sensitivities without SVC's, with SVC's at all four buses, and with SVC's at buses 26, 27, and 29 are presented in Table 6-4. Regulation curves corresponding to Table 6-4 are plotted in Figure 6-3. Incremental reactive power changes for individual SVC's, in MVAR/MW, are listed and summed in Table 6-5 for the purpose of comparing the total SVC reactive power requirement for the two voltage regulation schemes. These totals are plotted in Figure 6-4. The general impression is that omitting the SVC at bus 28 yields a small saving in the incremental reactive power requirement at the expense of substantially poorer regulation at bus 28. The eigenvalue and transient stability studies discussed in the following paragraphs involve SVC's at all four buses.

Table 6-4

VOLTAGE SENSITIVITIES, IN PERCENT PER 1000 MW, TO INCREASED GENERATION AT BUS 38

Bus No.	830 MW at Bus 38			1080 MW at Bus 38			1330 MW at Bus 38			1580 MW at Bus 38		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
26	-2.78	-0.91	-1.06	-5.12	-1.70	-1.95	-8.01	-2.56	-2.95	-12.19	-3.60	-4.19
27	-2.20	-0.60	-0.67	-4.01	-1.07	-1.19	-6.23	-1.57	-1.75	-9.45	-2.16	-2.43
28	-3.71	-1.43	-2.26	-6.21	-2.29	-3.65	-9.31	-3.23	-5.23	-13.72	-4.35	-7.21
29	-3.16	-1.49	-1.81	-5.18	-2.32	-2.84	-7.71	-3.25	-4.03	-11.32	-4.36	-5.51

(1) No SVC's

(2) SVC's at buses 26, 27, 28 and 29

(3) SVC's at buses 26, 27 and 29

Figure 6-3. Voltage regulation as a function of the generation at bus 38: a) no SVC's; b) SVC's at buses 26, 27, and 29; c) SVC's at buses 26, 27, 28, and 29.

Table 6-5

STATIC VAR COMPENSATOR REACTIVE CHANGES IN MVAR/MW INCREASED GENERATION AT BUS 38

Bus No.	830 MW at Bus 38		1080 MW at Bus 38		1330 MW at Bus 38		1580 MW at Bus 38	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
26	0.051	0.060	0.096	0.111	0.148	0.171	0.214	0.249
27	0.034	0.038	0.061	0.067	0.091	0.101	0.128	0.144
28	0.048	--	0.078	--	0.113	--	0.157	--
29	0.057	0.070	0.090	0.110	0.129	0.160	0.177	0.224
Total	0.190	0.168	0.325	0.288	0.481	0.432	0.676	0.617

(1) SVC's at buses 26, 27, 28 and 29

(2) SVC's at buses 26, 27 and 29

Figure 6-4. Ratio of SVC incremental reactive power to incremental generation at bus 38 as a function of the generation level at bus 38.

EIGENVALUE STUDIES

There are nine modes of synchronizing power flow oscillation among the ten machines of Figure 6-1. The eigenvalues, oscillation frequencies, successive positive peak ratios, and normalized generator speed deviations for these nine modes are presented in Table 6-6 for operating conditions corresponding to 830 MW at bus 38. Except for mode 6, which represents a sustained oscillation, all modes are positively damped. Various procedures for improved damping of mode 6 could be examined, including the application of one or more static VAR compensators near bus 30. However, within the limited resources of this study, improved damping for mode 6 is ignored in order to concentrate attention on the more interesting problem of operating the generator at bus 38 at relatively high power levels.

Eigenvalues for all nine modes of oscillation, without SVC's and with SVC's at buses 26, 27, 28, and 29, are shown in Table 6-7 for the four levels of generation at bus 38. Corresponding values of oscillation frequencies and successive positive peak ratios are listed in Table 6-8. Modes 3 through 9 are relatively unaffected by the change in generation at bus 38, either without the SVC's or with them.

Without SVC's, the eigenvalue for mode 2 is somewhat altered by the change in generation. The oscillation frequency drops from 0.953 Hz at 830 MW to 0.663 Hz

Table 6-6

EIGENVALUES, OSCILLATION FREQUENCIES, SUCCESSIVE POSITIVE PEAK RATIOS, AND
 NORMALIZED SPEED DEVIATIONS FOR THE NEW ENGLAND TEST SYSTEM WITH
 830 MW GENERATION AT BUS 38 AND NO SVC'S

Mode Number	Eigenvalues	Frequency in Hertz	Successive Peak Ratio	Normalized Speed Deviations											
				30	31	32	33	34	35	36	37	38	39		
6-10	1	-0.28 + j3.84	0.611	0.632	Real	.44	.50	.55	.80	1.00	.81	.80	.80	.49	.58
				Imag.	.09	.04	.03	.02	0.00	.05	.06	.06	.07	.05	
	2	-0.26 + j5.99	0.953	0.761	Real	.14	-.15	-.15	-.33	-.77	-.24	-.23	.18	1.00	0.00
				Imag.	.04	-.04	-.03	-.01	.03	-.02	-.03	0.00	0.00	0.00	
	3	-0.25 + j6.35	1.010	0.780	Real	.20	1.00	.76	-.22	-.85	0.00	0.00	.09	-.38	-.05
				Imag.	.06	0.00	-.06	-.01	.04	-.04	-.04	0.00	0.00	0.00	
	4	-0.25 + j6.99	1.112	0.805	Real	-.09	-.53	-.22	-.08	-.84	1.00	.95	.05	-.16	0.00
				Imag.	.38	-.18	-.03	-.01	-.11	0.00	.09	.14	-.15	-.01	
	5	-0.28 + j7.45	1.185	0.792	Real	-.05	-.91	1.00	-.01	.01	-.14	-.13	0.00	-.01	0.00
				Imag.	.01	.06	0.00	0.00	.01	-.02	-.04	.01	-.01	0.00	
	6	0 + j6.96	1.108	1.000	Real	1.00	-.24	-.15	-.01	.02	-.13	-.12	.33	-.29	-.02
				Imag.	0.00	.07	.01	-.01	.21	-.16	-.17	-.13	0.00	0.00	
	7	-0.31 + j8.48	1.379	0.794	Real	-.08	-.02	-.05	1.00	-.30	-.16	-.23	.17	-.03	0.00
				Imag.	.03	0.00	0.00	0.00	.01	.07	-.09	-.05	0.00	0.00	
	8	-0.40 + j8.67	1.379	0.746	Real	-.23	-.03	-.04	-.22	.05	-.05	.03	1.00	-.09	-.01
				Imag.	.05	0.00	-.01	.05	-.02	-.01	-.03	0.00	-.02	0.00	
	9	-0.37 + j8.74	1.391	0.770	Real	.01	.01	.01	.05	0.00	-.74	1.00	-.05	.01	0.00
				Imag.	-.02	0.00	.01	.12	-.01	-.09	0.00	.11	0.00	0.00	

Table 6-7

EIGENVALUES FOR THE NEW ENGLAND TEST SYSTEM AS A FUNCTION OF THE GENERATION AT BUS 38

Mode	Regulation at Buses 26, 27, 28 and 29	Generation at Bus 38			
		830 MW	1080 MW	1330 MW	1580 MW
1	Without SVC's	-0.280 + j3.842	-0.212 + j3.352	0.524 + j2.719	1.330 + j1.802
	With SVC's	-0.262 + j4.077	-0.266 + j3.983	-0.260 + j3.864	-0.251 + j3.696
2	Without SVC's	-0.260 + j5.990	-0.284 + j5.422	-0.268 + j4.679	-0.240 + j4.168
	With SVC's	-0.243 + j6.239	-0.238 + j6.188	-0.229 + j6.186	-0.213 + j5.761
3	Without SVC's	-0.251 + j6.348	-0.248 + j6.319	-0.246 + j6.299	-0.242 + j6.287
	With SVC's	-0.225 + j6.479	-0.236 + j6.408	-0.244 + j6.342	-0.242 + j6.306
4	Without SVC's	-0.242 + j6.989	-0.231 + j6.982	-0.210 + j6.967	-0.197 + j6.963
	With SVC's	-0.263 + j7.009	-0.254 + j6.989	-0.239 + j6.972	-0.224 + j6.951
5	Without SVC's	-0.276 + j7.446	-0.275 + j7.449	-0.271 + j7.452	-0.267 + j7.459
	With SVC's	-0.275 + j7.447	-0.274 + j7.449	-0.271 + j7.453	-0.267 + j7.460
6	Without SVC's	-0.000 + j6.965	-0.007 + j6.951	-0.036 + j6.941	-0.045 + j6.960
	With SVC's	-0.016 + j6.056	-0.007 + j7.036	-0.011 + j7.026	-0.024 + j7.025
7	Without SVC's	-0.312 + j8.477	-0.309 + j8.472	-0.305 + j8.449	-0.299 + j8.430
	With SVC's	-0.313 + j8.476	-0.310 + j8.466	-0.306 + j8.449	-0.299 + j8.426
8	Without SVC's	-0.404 + j8.668	-0.401 + j8.666	-0.403 + j8.650	-0.403 + j8.642
	With SVC's	-0.404 + j8.669	-0.403 + j8.666	-0.404 + j8.657	-0.406 + j8.643
9	Without SVC's	-0.364 + j8.740	-0.365 + j8.737	-0.363 + j8.728	-0.360 + j8.718
	With SVC's	-0.366 + j8.740	-0.364 + j8.735	-0.362 + j8.727	-0.361 + j8.716

Table 6-8

OSCILLATION FREQUENCIES AND SUCCESSIVE POSITIVE PEAK RATIOS FOR THE
NEW ENGLAND TEST SYSTEM AS A FUNCTION OF THE GENERATION AT BUS 38

Mode	Regulation at Buses 26, 27, 28 and 29	Generation at Bus 38							
		830 MW		1080 MW		1330 MW		1580 MW	
		f	SPR	f	SPR	f	SPR	f	SPR
1	Without SVC's	0.611	0.632	0.533	0.672	0.433	3.360	0.287	102.9
	With SVC's	0.649	0.668	0.634	0.658	0.615	0.655	0.588	0.653
2	Without SVC's	0.953	0.761	0.863	0.719	0.745	0.698	0.663	0.697
	With SVC's	0.993	0.783	0.985	0.785	0.985	0.792	0.917	0.792
3	Without SVC's	1.010	0.780	1.006	0.781	1.002	0.782	1.001	0.785
	With SVC's	1.031	0.804	1.020	0.793	1.009	0.785	1.004	0.786
4	Without SVC's	1.112	0.805	1.111	0.813	1.109	0.828	1.108	0.837
	With SVC's	1.115	0.790	1.112	0.796	1.110	0.806	1.106	0.817
5	Without SVC's	1.185	0.792	1.186	0.793	1.186	0.796	1.187	0.799
	With SVC's	1.185	0.793	1.186	0.794	1.186	0.796	1.187	0.799
6	Without SVC's	1.108	1.000	1.106	0.993	1.105	0.968	1.108	0.960
	With SVC's	1.123	0.986	1.120	0.994	1.118	0.990	1.118	0.978
7	Without SVC's	1.349	0.794	1.348	0.795	1.345	0.797	1.342	0.800
	With SVC's	1.349	0.793	1.347	0.794	1.345	0.797	1.341	0.800
8	Without SVC's	1.379	0.746	1.379	0.748	1.377	0.746	1.375	0.746
	With SVC's	1.380	0.746	1.379	0.747	1.378	0.746	1.376	0.744
9	Without SVC's	1.391	0.770	1.391	0.769	1.389	0.770	1.388	0.771
	With SVC's	1.391	0.769	1.390	0.769	1.389	0.770	1.387	0.771

at 1580 MW, while the successive positive peak ratio drops slightly. With SVC's, the eigenvalue for mode 2 is relatively insensitive to the generation changes at bus 38.

The eigenvalue for mode 1, in the absence of SVC's, is drastically affected by the change in generation. The frequency drops from 0.611 Hz at 830 MW to 0.287 Hz at 1580 MW. The eigenvalue moves into the right half-plane at some level of generation between 1080 MW and 1330 MW and, at 1580 MW, has a successive positive peak ratio of over one hundred. In contrast, with the SVC's, the eigenvalue for mode 1 is relatively insensitive to the changes in generation.

The Westinghouse stability program was used to validate the extreme instance of instability represented by the mode 1 eigenvalue with 1580 MW at bus 38 and no static VAR compensators. Steady-state conditions corresponding to the appropriate load flow from Appendix C were used to initialize generators for the simulation, following which the oscillation shown in Figure 6-5 occurred spontaneously. Similar angle variations occurred for other machines, with loss of synchronism at about eight seconds.

TRANSIENT STABILITY STUDIES

Studies have been performed to determine, in the absence of SVC's, the transient stability limit of the generator at bus 38. Other studies then show that this limit can be significantly increased with SVC's and indicate the extremes of SVC reactive power during the transient period. The disturbance in all the stability runs is a three-phase fault at bus 26 on the line to bus 28, cleared in 0.05 seconds by opening both ends of the faulted line simultaneously. Reclosing is not considered.

The generator rotor angles in Figure 6-6 are from a simulation without SVC's and with 830 MW generation at bus 38 and indicate a stable system. The generator rotor angles in Figure 6-7 are from a simulation with 955 MW generation at bus 38, also without static VAR compensators. The latter simulation is terminated after 1.9 seconds due to loss of synchronism between bus 38 and the rest of the system. An examination of the transient electrical power at bus 38 from these two simulations suggests that the transient limit is about 900 MW.

Figure 6-5. Simulation of mode 1 without SVC's and with 1580 MW at bus 38.

Figure 6-6. Generator rotor angles from a simulation of a three-phase fault at bus 26 on the line to bus 28 with 830 MW generation at bus 38 and without SVC's.

Figure 6-7. Generator rotor angles from a simulation of a three-phase fault at bus 26 on the line to bus 28 with 955 MW generation at bus 38 and without SVC's.

The generator rotor angles and SVC reactive powers in Figure 6-8 are from a simulation with SVC's at buses 26, 27, 28, and 29 and 1080 MW generation at bus 38. The SVC's are represented by the model of Figure 4-2 without auxiliary control. The SVC model parameters are listed in Table 6-9, with regulating ranges deliberately large to avoid restricting the reactive power excursions required by voltage regulation. Simulations at other levels of generation at bus 38 use adjusted SVC reference voltages to keep the initial reactive powers at zero.

The generation at bus 38 is raised to 1330 MW in Figure 6-9 and to 1580 MW in Figure 6-10. The latter indicates that a rapid loss of synchronism occurs between the generator at bus 38 and the remainder of the system. Stable operation with 1580 MW generation at bus 38 is achieved, as indicated in Figure 6-11, by means of an auxiliary control channel on each SVC sensitive to the speed deviation of the generator at bus 38. These control channels have a gain which raises the SVC reference voltage by 0.1 pu for a speed increase of 0.5 Hz. With reference to Figure 6-2, raising the SVC reference voltages increases load at buses 26, 27, 28, and 29 and decelerates the generator at bus 38. The auxiliary signal also produces significant damping of mode 1 and mode 2 oscillations.

The extremes of reactive compensation are summarized in Table 6-10. No effort has been made to investigate the effects of limiting reactive power excursions.

Figure 6-8. Generator rotor angles and SVC reactive powers from a simulation of a three-phase fault at bus 26 on the line to bus 28 with 1080 MW at bus 38 and with SVC's at buses 26, 27, 28, and 29.

Table 6-9

MODEL PARAMETERS FOR THE STATIC VAR COMPENSATORS USED IN TRANSIENT SIMULATIONS
EVALUATED WITH 1080 MW GENERATION AT BUS 38

Symbol	Symbol Definition	Bus 26	Bus 27	Bus 28	Bus 29
Q	Initial reactive power	0	0	0	0
V_R	Reference voltage	1.0417	1.0291	1.0373	1.0393
$V_1 + V_R$	Maximum voltage in regulating range	1.2955	1.2851	1.3756	1.3361
$V_2 + V_R$	Minimum voltage in regulating range	0.7879	0.7731	0.6990	0.7425
B_1	Minimum susceptance	-15.0000	-15.0000	-15.0000	-15.0000
B_2	Maximum susceptance	15.0000	15.0000	15.0000	15.0000
Q_1	Reactive power at minimum susceptance	-25.1748	-24.7722	-28.3841	-26.7774
Q_2	Reactive power at maximum susceptance	9.1180	8.9653	7.3290	8.2696
dQ/dV_T	MVAR/percent voltage at one pu voltage	59.1100	58.5900	35.4700	40.4300

- Voltages are in pu on the SVC terminal voltage base V_B .
- Reactive powers are in pu on the system MVA base, S_B , which is 100.
- Susceptances are in pu on the admittance base $Y_B = S_B \div V_B$

Figure 6-9. Generator rotor angles and SVC reactive powers from a simulation of a three-phase fault at bus 26 on the line to bus 28 with 1330 MW at bus 38 and with SVC's at buses 26, 27, 28, and 29.

Figure 6-10. Generator rotor angles and SVC reactive powers from a simulation on a three-phase fault at bus 26 on the line to bus 28 with 1580 MW at bus 38 and with SVC's at buses 26, 27, 28, and 29.

Figure 6-11. Generator rotor angles and SVC reactive powers from a simulation of a three-phase fault at bus 26 on the line to bus 28 with 1580 MW at bus 38 and with SVC's at buses 26, 27, 28, and 29 which have auxiliary controls sensitive to the speed of the generator at bus 38.

Table 6-10

EXTREMES OF REACTIVE COMPENSATION

<u>Bus</u>		Generation at Bus 38		
		<u>1080 MW</u>	<u>1330 MW</u>	<u>1580 MW*</u>
26	Capacitive	122	237	361
	Inductive	0	0	0
27	Capacitive	68	129	236
	Inductive	7	13	0
28	Capacitive	95	173	218
	Inductive	10	29	150
29	Capacitive	151	288	403
	Inductive	32	51	0

*Includes speed-sensitive auxiliary controls

Section 7

SVC APPLICATION GUIDELINES

This study has been focused on high-voltage applications of static VAR compensators to obtain improvements in synchronous stability with regard to the damping of oscillations and increased transient stability limits. Improved stability behavior and improved regulation may well be common goals in any particular study, but it is also possible to apply SVC's for voltage support and to reduce flicker without any special interest in stability. For this reason, SVC applications for improved voltage regulation and for improved stability are discussed separately in the following paragraphs.

SVC APPLICATION FOR STEADY-STATE VOLTAGE REGULATION

The methodology for applying the VAR compensator for voltage regulation involves two fundamental decisions: location and rating or size. In general, when an SVC is applied for voltage support and regulation, the bus in need of such support is immediately obvious from load flow data and/or the characteristics of nearby loads. However, where the SVC is intended more for "system" voltage support, in contrast to a specific bus, the greatest contribution can be expected from an SVC located at the bus with the lowest short circuit capacity (e.g., the highest short circuit impedance). Determining this bus can be accomplished through voltage sensitivity calculations as described in Sections 5 and 6.

Once the SVC bus has been selected, a procedure discussed in Section 2 can be used to estimate the required SVC rating (i.e., range of control) and steady-state control characteristic. The procedure involves developing curves of bus voltage versus reactive current as illustrated in Figure 7-1(a). Each of the curves is representative of a different system operating condition (e.g., light load, heavy load, various combinations of transmission lines outages, various combinations of generator outages). The intersection of each of the curves with the voltage axis equals bus voltage with no compensation and is simply the bus voltage which results from a load flow study of the system operating condition of interest.

Figure 7-1. (a) Bus voltage versus reactive current for different system operating conditions: (1) normal, (2) light load, (3) heavy load, (4) light load with line out, (5) heavy load with generator out. (b) Voltage limits combined with "sensitivity" curves establish leading and lagging current (i.e., rating) requirements. (c) An SVC control characteristic with bus voltage linear control range between $V(\text{min})$ and $V(\text{max})$.

The slopes of the curves in Figure 7-1(a) are simply the Thevenin equivalent system impedances from the SVC bus. For systems with only relatively short transmission lines, this impedance equals the short circuit impedance. But for "long" line systems, this impedance should be determined using both the series and shunt elements of line impedance.

To establish the required rating of the SVC, the voltage "sensitivity" curves of Figure 7-1(a) are combined with the desired voltage control limits as in Figure 7-1(b). As shown, only the "highest" and "lowest" sensitivity curves are needed to determine the required leading and lagging compensation. With the system operating according to condition (5) in Figure 7-1(a), the SVC can maintain a bus voltage of $V(\min)$ by delivering maximum leading (capacitive) compensation, I_C . Likewise, if the system is operating according to condition (4), the SVC prevents voltage elevation above $V(\max)$ through lagging (inductive) compensation in the amount of I_L amperes. Between $V(\max)$ and $V(\min)$, the SVC delivers controlled compensation between I_C amps leading and I_L amps lagging. A steady-state control characteristic which fits the foregoing discussion is shown in Figure 7-1(c). (This characteristic is appropriate only for small system disturbances, since the high frequency phenomenon which accompanies large system disturbances results in a different controller response.) Compensation is linearly controlled between $V(\min)$ and $V(\max)$. Below $V(\min)$ and above $V(\max)$, the SVC reverts to a simple capacitance and inductance, respectively. The slope of the control characteristic between $V(\min)$ and $V(\max)$, i.e., within the linear range of control, relates to the open loop DC gain of the SVC controller (see Section 2). Therefore, by combining the information available from a figure such as 7-1 with desired SVC frequency (time) response, most of the important parameters or specifications of the SVC system and controller can be determined.

The preceding discussion describes a procedure that can be used to determine the location, size, and some control parameters of static VAR compensators applied to transmission systems for steady-state voltage regulation. Admittedly, the procedure is oversimplified but nonetheless provides an excellent technique for approximating SVC application parameters. For additional detail on SVC application studies, procedures, and considerations for bus voltage regulation, especially SVC response to large system disturbances, the reader is referred to Sections 2 and 3.

SVC APPLICATION STUDIES RELATED TO STABILITY OBJECTIVES

The small-system studies presented in Sections 5 and 6 illustrate the potential for improved synchronous stability performance by means of static VAR compensators.

The improvements include damping for unstable modes of oscillation and significant increases in transient stability limits.

These studies also demonstrate methods for relating stability performance to the general specifications for static VAR compensators, including locations, regulating slopes, peak reactive power requirements, and auxiliary controls. A summary of the study procedures described in Sections 5 and 6 follows with comments regarding their application to practical large-system studies.

The self- and mutual-drop coefficient matrix calculations described in Section 5 provide a useful viewpoint of the effects of voltage regulation and support an important concept: the regulating slope of a static VAR compensator must necessarily bear some relationship to the short-circuit reactance at its terminal bus if voltage variations at the bus are to be significantly reduced. The changes in the self-drop coefficient due to regulation imply that much of the benefit of regulating a particular bus voltage can be realized if the regulating slope is K/X_{SC} , where X_{SC} is the short-circuit reactance of the bus, and K is in the range from one to two. The dimension of K/X_{SC} is reactive power in pu on the system MVA base divided by voltage in pu on the SVC terminal bus voltage base.

Self- and mutual-drop coefficient calculations help to justify this simple formula for the initial estimate of the regulating slope of a static VAR compensator but provide no indication of buses that may require regulation. There is no motivation to perform self- and mutual-drop calculations in connection with any particular system study.

The voltage sensitivity calculations described in Sections 5 and 6 provide a means of identifying buses and operating conditions where poor voltage regulation may contribute to instability. The voltage sensitivities are relative, and there is no simple correlation between their numerical values and the risk of instability. Nevertheless, they offer clues to possible stability problems which can be investigated by means of load flow and stability calculations.

In those instances where such investigations or prior knowledge indicate the need for improved voltage regulation, preliminary decisions regarding locations of

SVC's can be based on relative voltage sensitivities. The voltage sensitivity calculations show the accumulative effects of multiple SVC's on the incremental regulation at all buses and the incremental reactive power requirements from all sources. The effects of SVC location on incremental regulation can be studied, and regulating slopes, initially calculated from short-circuit reactances, can be adjusted to achieve particular objectives, such as uniform regulation or a desired distribution of incremental reactive power from various sources.

The voltage sensitivity program used in Sections 5 and 6 is designed and dimensioned to meet the needs of this project and is not intended as a production program. The development of a production program for voltage sensitivity calculations should be considered.

The discussion of voltage sensitivities in Section 5 points up the fact that poor incremental regulation of transmission bus voltages causes relatively high incremental ratios of reactive power to real power at nearby generators. This affects incremental relationships within the generator, as illustrated in Figure 5-12, such that the induction damping associated with rotor oscillation is diminished. Thus, inadequate incremental voltage regulation is likely to be accompanied by inadequate damping for some modes of oscillation. Eigenvalue calculations are logically included in any investigation which concerns the damping of oscillations and can be expected to contribute useful information in many SVC application studies.

Eigenvalue analysis separates the modes of synchronizing power flow oscillation which are generally mixed with each other and with transients in time-domain simulation. The eigenvalue associated with each mode gives a clear and precise indication of the oscillation frequency and damping and is sensitive to design and operating changes. Eigenvalue studies will indicate which modes are significantly influenced by SVC's and provide quantitative data regarding the choice of model parameters.

The AESOPS studies in Sections 5 and 6 show the effects of SVC's on the eigenvalues of all modes of oscillation for selected operating conditions. The SVC locations are those indicated by the voltage sensitivity calculations, and the

regulating slopes are those calculated from short-circuit reactances. As indicated in Figure 5-15 and in Table 6-7, unstable oscillations can be favorably influenced simply by reducing transmission bus voltage variations. Frequently, however, it will be necessary to use appropriate auxiliary controls to achieve damping by means of static VAR compensators. It is desirable to be able to calculate eigenvalues with the effects of SVC auxiliary controls represented, but the AESOPS program has not been modified to incorporate such controls.

In lieu of eigenvalue calculations which include the effects of SVC auxiliary control, the corresponding oscillations can be simulated in the time domain. Examples of simulations which emphasize a particular mode of oscillation are shown in Figure 5-14, Figures 5-16 through 5-23, and Figure 5-25. All of these are obtained by assigning to each generator in the time-domain simulation an initial speed deviation proportional to that generator's normalized speed deviation for that mode as calculated by AESOPS.

The simulation of Figure 5-14 can be compared with that of Figure 5-16 to see the effects of SVC's without auxiliary control, and then with Figure 5-25 to see the effects of SVC's with auxiliary control sensitive to frequency. Frequency deviation will in general provide an effective auxiliary control signal for improved damping, although it may be desirable to use generator speed deviation in some cases, or the difference in two frequencies obtained for a transmission line power flow measurement with a phase-lead filter.

The time-domain functions of Figure 5-25 include unrestricted SVC reactive power requirements for the particular level of oscillation simulated. Larger variations in reactive power would accompany larger levels of oscillation. In those instances where the primary purpose of SVC application is to suppress essentially spontaneous oscillations, relatively low-rated SVC's will suffice. Simulations similar to those of Figure 5-25, with limits on the regulating ranges of SVC's, variations in auxiliary control, and different levels of oscillation will supply information for determining the lowest equipment ratings which provide acceptable damping.

Time-domain simulations of faults and other disturbances provide the ability to relate transient stability performance to SVC capabilities. The transient studies

reported in Sections 5 and 6 indicate that significant increases in transient stability limits can be obtained by means of static VAR compensators.

All of the transient simulations reported involve SVC's in locations indicated by voltage sensitivity calculations, with regulating slopes calculated from short-circuit reactances. The regulating range of each SVC is deliberately large enough to avoid restrictions on reactive power. Practical studies might well begin with no restrictions on reactive power capability to establish the corresponding stability limits for later reference. However, a goal in most instances will be to restrict regulating ranges and observe the effects of system performance.

Although auxiliary controls are most often considered for improved damping, their effects on transient stability limits can be significant. The simulations of Figures 6-10 and 6-11 show the benefits of auxiliary controls sensitive to generator speed deviation. The auxiliary controls respond to an increase in generator speed during the fault of 0.5 Hz by boosting the reference voltage on four nearby buses by 0.1 per unit. The additional post-fault load helps to decelerate the generator and prevent loss of synchronism.

It should be noted that this hypothetical study treats the loads as impedances and that other load models can be expected to produce different results. Generally speaking, it would be wise to consider variations in load modeling in connection with any practical system study in which SVC specifications are to be developed.

All of the studies of SVC's in Sections 5 and 6 assume that the initial reactive power for each SVC is zero. Thus, all of the reactive capability is reserved for improved stability performance. The implication is that controlled reactors are fully-conducting or almost fully-conducting all of the time to compensate for the normal capacitive current. Practical system studies may involve similar assumptions in the process of arriving at the general specifications for SVC's which include locations, regulating slopes, reactive power requirements, and auxiliary controls. Detailed SVC design may involve switched reactive elements which approximate the general specifications based on system studies. In that case, additional studies may be needed to verify the system performance using the detailed design equipment features.

Appendix A

DATA FOR HYPOTHETICAL SYSTEM A

Transmission line data for the system of Figure 5-1 is listed in Table A-1 and transformer data in Table A-2. Bus data is listed in Table A-3 for six levels of generation at bus 6. Generator data is contained in Table A-4 and excitation system data in Table A-5.

Table A-1

TRANSMISSION LINE PARAMETERS FOR THE SYSTEM OF FIGURE 5-1

(Impedances are in pu on a 100 MVA base.)

<u>Bus No.</u>	<u>Bus No.</u>	<u>No. of Circuits in Parallel</u>	<u>R in PU</u>	<u>X in PU</u>	<u>Line Charging in MVAR at 1.0 PU Voltage</u>
1	2	2	0.08	0.6	2.5
2	4	2	0.08	0.4	10.0
4	7	2	0.08	0.4	10.0
4	10	4	0.08	0.4	10.0
5	7	2	0.08	0.4	10.0

Table A-2

TRANSFORMER PARAMETERS FOR THE SYSTEM OF FIGURE 5-1

(The tapped side corresponds to the bus listed on the left. Impedances are in pu on a 100 MVA base.)

<u>Bus No.</u>	<u>Bus No.</u>	<u>R in PU</u>	<u>X in PU</u>	<u>Transformer Tap Ratio</u>
2	3	0.02	0.12	1.02
5	6	0.01	0.06	1.02
10	11	0.02	0.12	1.02
10	12	0.02	0.12	1.02

Table A-3

BUS DATA FOR SIX LEVELS OF GENERATION AT BUS 6.

Bus	Voltage	Angle	Load		Generation	
			MW	MVAR	MW	MVAR
1	1.0500	359.99	0.0	0.0	52.332	-2.058
2	1.0388	351.72	100.0	25.0	0.000	0.000
3	1.0500	357.99	0.0	0.0	100.000	16.243
4	1.0500	346.24	100.0	25.0	0.000	26.802
5	1.0682	1.46	0.0	0.0	0.000	0.000
6	1.0500	4.32	0.0	0.0	90.000	-7.085
7	1.0504	352.29	30.0	15.0	0.000	0.000
10	1.0360	346.19	200.0	50.0	0.000	0.000
11	1.0500	352.45	0.0	0.0	100.000	18.654
12	1.0500	352.45	0.0	0.0	100.000	18.654
1	1.0500	359.99	0.0	0.0	25.100	-1.994
2	1.0407	356.05	100.0	25.0	0.000	0.000
3	1.0500	2.32	0.0	0.0	100.000	14.660
4	1.0500	353.45	100.0	25.0	0.000	34.534
5	1.0623	15.02	0.0	0.0	0.000	0.000
6	1.0500	18.80	0.0	0.0	120.000	-1.200
7	1.0375	2.63	30.0	15.0	0.000	0.000
10	1.0360	353.40	200.0	50.0	0.000	0.000
11	1.0500	359.65	0.0	0.0	100.000	18.654
12	1.0500	359.65	0.0	0.0	100.000	18.654
1	1.0500	359.99	0.0	0.0	12.481	-1.018
2	1.0408	358.06	100.0	25.0	0.000	0.000
3	1.0500	4.33	0.0	0.0	100.000	14.529
4	1.0500	356.81	100.0	25.0	0.000	40.904
5	1.0585	21.65	0.0	0.0	0.000	0.000
6	1.0500	25.89	0.0	0.0	135.000	3.825
7	1.0293	7.59	30.0	15.0	0.000	0.000
10	1.0360	356.76	200.0	50.0	0.000	0.000
11	1.0500	3.01	0.0	0.0	100.000	18.654
12	1.0500	3.01	0.0	0.0	100.000	18.654
1	1.0500	0.00	0.0	0.0	.512	.469
2	1.0410	360.00	100.0	25.0	0.000	0.000
3	1.0500	6.26	0.0	0.0	100.000	14.764
4	1.0500	.03	100.0	25.0	0.000	48.925
5	1.0540	28.22	0.0	0.0	0.000	0.000
6	1.0500	32.92	0.0	0.0	150.000	9.994
7	1.0200	12.43	30.0	15.0	0.000	0.000
10	1.0360	360.00	200.0	50.0	0.000	0.000
11	1.0500	6.23	0.0	0.0	100.000	18.654
12	1.0500	6.23	0.0	0.0	100.000	18.654

Table A-3 (Continued)

BUS DATA FOR SIX LEVELS OF GENERATION AT BUS 6

Bus	Voltage	Angle	Load		Generation	
			MW	MVAR	MW	MVAR
1	1.0500	359.99	0.0	0.0	-10.800	2.386
2	1.0399	1.79	100.0	25.0	0.000	0.000
3	1.0500	8.06	0.0	0.0	100.000	15.316
4	1.0500	3.07	100.0	25.0	0.000	58.621
5	1.0490	34.73	0.0	0.0	0.000	0.000
6	1.0500	39.89	0.0	0.0	165.000	17.407
7	1.0086	17.15	30.0	15.0	0.000	0.000
10	1.0360	3.02	200.0	50.0	0.000	0.000
11	1.0500	9.28	0.0	0.0	100.000	18.654
12	1.0500	9.28	0.0	0.0	100.000	18.654
1	1.0500	359.99	0.0	0.0	-21.440	4.654
2	1.0389	3.52	100.0	25.0	0.000	0.000
3	1.0500	9.79	0.0	0.0	100.000	16.135
4	1.0500	5.98	100.0	25.0	0.000	70.046
5	1.0432	41.24	0.0	0.0	0.000	0.000
6	1.0500	46.87	0.0	0.0	180.000	26.195
7	.9958	21.76	30.0	15.0	0.000	0.000
10	1.0360	-5.93	200.0	50.0	0.000	0.000
11	1.0500	12.18	0.0	0.0	100.000	18.654
12	1.0500	12.18	0.0	0.0	100.000	18.654

Table A-4

GENERATOR DATA

Bus	3	4	6	11	12
X_D	1.920	1.000	1.216	1.720	1.670
X_Q	1.900	0.750	0.756	1.640	1.610
X'_D	0.362	0.350	0.336	0.263	0.364
X'_Q	1.130	--	--	0.467	0.536
R_A	0.004	0.002	0.002	0.002	0.002
X_L	0.194	0.170	0.153	0.145	0.170
T'_{D0}	5.690	5.000	11.500	4.120	7.800
T'_{Q0}	1.500	--	--	1.475	1.388
H	2.700	2.000	7.400	1.600	6.100
D	--	--	--	--	--
S_1	0.120	0.120	0.120	0.120	0.120
S_2	0.480	0.480	0.480	0.480	0.480
X_p	0.362	0.350	0.336	0.263	0.364
Data MVA Base	115	150	175	115	115

Table A-5
EXCITATION SYSTEM DATA

Bus	3	4	6	11	12
K_A	400	400	400	400	400
T_A	0.02	0.05	0.05	0.02	0.02
T_B	--	--	--	--	--
T_C	--	--	--	--	--
V_{RMAX}	7.30	3.50	3.50	7.30	8.20
V_{RMIN}	-7.30	-3.50	-3.50	-7.30	-8.20
T_E	0.80	0.95	0.95	0.80	1.30
K_E	1.00	-0.17	-0.17	1.00	1.00
S_1	0.50	0.22	0.22	0.50	0.50
S_2	0.82	0.95	0.95	0.86	1.10
K_F	0.03	0.04	0.04	0.03	0.03
T_F	1.00	1.00	1.00	1.00	1.00

Note: S_2 is exciter saturation at ceiling
 S_3 is exciter saturation at 75% of ceiling

Appendix B

VOLTAGE SENSITIVITY CALCULATIONS

Voltage sensitivity calculations are based on a linear system model formulated in terms of the real and imaginary incremental variations of the bus voltages and the currents injected by either a synchronous machine or by a static VAR compensator. It is assumed that a bus will not have both a synchronous machine and a static VAR compensator and may have neither.

With four incremental variables per bus, four equations per bus are required. Two equations at each bus are obtained by summing incremental currents around the bus. A third equation concerns the incremental real power associated with the injected current. The fourth equation at synchronous machine buses is derived from the assumption that the terminal voltage is perfectly regulated by machine excitation. The fourth equation at all other buses, including those with SVC's, specifies the incremental reactive power associated with the injected current. Mathematical symbols are defined in Table B-1.

The summation of currents at bus L can be written

$$Y_{LL}E_L - \sum Y_{LK}E_K = I_L \quad ; \quad K \neq L \quad (B-1)$$

where Y_{LL} includes the bus load. It is feasible to use nonlinear load functions and replace them by linear approximations in the linear system model as in Section 7 of Reference 5-2. However, for simplicity, loads are treated as admittances in this analysis. The summation of currents can be expressed as two real incremental equations as follows:

$$G_{LL}\Delta E_{LR} - B_{LL}\Delta E_{LI} - \sum (G_{LK}\Delta E_{KR} - B_{LK}\Delta E_{KI}) = \Delta I_{LR} \quad ; \quad K \neq L \quad (B-2)$$

$$B_{LL}\Delta E_{LR} + G_{LL}\Delta E_{LI} - \sum (B_{LK}\Delta E_{KR} + G_{LK}\Delta E_{KI}) = \Delta I_{LI} \quad ; \quad K \neq L \quad (B-3)$$

Table B-1

DEFINITIONS OF MATHEMATICAL SYMBOLS

$E_L = E_{LR} + jE_{LI}$	}	Voltage at bus L
$\Delta E_L = \Delta E_{LR} + j\Delta E_{LI}$		
$E_K = E_{KR} + jE_{KI}$	}	Voltage at bus K
$\Delta E_K = \Delta E_{KR} + j\Delta E_{KI}$		
$I_L = I_{LR} + jI_{LI}$	}	Injected current at bus L
$\Delta I_L = \Delta I_{LR} + j\Delta I_{LI}$		
P_L, Q_L	}	Real and reactive power associated with injected current at bus L
$\Delta P_L, \Delta Q_L$		
$Y_{LL} = G_{LL} + jB_{LL}$		Self admittance at bus L, including load
$Y_{LK} = G_{LK} + jB_{LK}$		Mutual admittance between bus L and bus K
K_L		Slope of regulating characteristic for SVC at bus L
E_D, E_Q	}	Direct and quadrature axis components of synchronous machine terminal bus voltage phasor
$\Delta E_D, \Delta E_Q$		
I_D, I_Q	}	Direct and quadrature axis components of synchronous machine terminal bus voltage phasor
$\Delta I_D, \Delta I_Q$		
$\delta, \Delta\delta$		Angle by which positive quadrature axis leads the terminal voltage phasor
$E_{EX}, \Delta E_{EX}$		Excitation phasor

The power associated with the injected current of bus L is:

$$P_L = E_{LR} I_{LR} + E_{LI} I_{LI} \quad (B-4)$$

Incrementally,

$$\Delta P_L = E_{LR} \Delta I_{LR} + E_{LI} \Delta I_{LI} + I_{LR} \Delta E_{LR} + I_{LI} \Delta E_{LI} \quad (B-5)$$

The effects of increasing the power at a particular generator bus are obtained by setting the corresponding ΔP_L to some positive value and all other power increments to zero.

Voltage is assumed to be constant at generator buses, which implies a relationship between the real and imaginary voltage increments. Specifically,

$$V_L^2 = E_{LR}^2 + E_{LI}^2 \quad (B-6)$$

where $V_L = |E_L|$. Incrementally,

$$V_L \Delta V_L = E_{LR} \Delta E_{LR} + E_{LI} \Delta E_{LI} \quad (B-7)$$

At generator buses,

$$0 = E_{LR} \Delta E_{LR} + E_{LI} \Delta E_{LI} \quad (B-8)$$

The reactive power associated with the injected current at bus L is:

$$Q_L = E_{LI} I_{LR} - E_{LR} I_{LI} \quad (B-9)$$

Incrementally,

$$\Delta Q_L = E_{LI} \Delta I_{LR} - E_{LR} \Delta I_{LI} + I_{LR} \Delta E_{LI} - I_{LI} \Delta E_{LR} \quad (B-10)$$

Another incremental relationship for an SVC at bus L involves the slope of the regulating characteristic:

$$\Delta Q_L = -K_L \Delta V_L = -K_L \left[(E_{LR}/V_L) \Delta E_{LR} + (E_{LI}/V_L) \Delta E_{LI} \right], \quad (B-11)$$

Combining Eqs. B-10 and B-11,

$$\begin{aligned} 0 = E_{LI} \Delta I_{LR} - E_{LR} \Delta I_{LI} + \left[I_{LR} - K_L (E_{LI}/V_L) \right] \Delta E_{LI} \\ - \left[I_{LI} + K_L (E_{LR}/V_L) \right] \Delta E_{LR} \end{aligned} \quad (B-12)$$

A static VAR compensator is represented at bus L by a nonzero value of K_L . If K_L is zero, bus L does not have an SVC.

The linear system model consists of Eqs. B-2, B-3, and B-5 for each bus, Eq. B-8 for generator buses, and Eq. B-12 for all others. After solving for the real and imaginary incremental components of bus voltage and injected current, Eq. B-7 yields the voltage magnitude variations and Eq. B-10, the incremental reactive powers associated with the injected currents.

The voltage sensitivity program utilizes branch and bus data from a solved load flow to construct the linear system model described in the preceding discussion. The real and reactive power changes obtained at the generator buses also permit calculation of changes within the generator. In particular, changes in the phasor diagram of Figure B-1 can be calculated if the load flow data is augmented by the machine synchronous reactances. In the following equations, and in the diagram of Figure B-1, the subscript L, which identifies a particular bus, is omitted.

Figure B-1. Synchronous machine steady-state phasor diagram.

The initial value of the internal angle between the terminal voltage phasor and the quadrature coordinate axis is:

$$\delta = \arctan \frac{P X_Q}{V^2 + Q X_Q} \quad (B-13)$$

where V is $|E|$. The real and reactive powers at the terminal bus are:

$$P = E_D I_D + E_Q I_Q \quad (B-14)$$

$$Q = E_Q I_D - E_D I_Q \quad (B-15)$$

Make the following substitutions in Eqs. B-14 and B-15:

$$E_D = E \sin \delta \quad (B-16)$$

$$E_Q = E \cos \delta \quad (B-17)$$

$$I_D = \frac{E_{EX} - E \cos \delta}{X_D} \quad (B-18)$$

$$I_Q = \frac{E \sin \delta}{X_Q} \quad (B-19)$$

The resulting familiar power angle formulas are:

$$P = \frac{E_{EX} E \sin \delta}{X_D} + \left(\frac{E^2 \sin 2\delta}{2} \right) \left(\frac{1}{X_Q} - \frac{1}{X_D} \right) \quad (B-20)$$

$$Q = \frac{E_{EX} E \cos \delta}{X_D} - E^2 \left(\frac{\sin^2 \delta}{X_Q} + \frac{\cos^2 \delta}{X_D} \right) \quad (B-21)$$

Incrementally,

$$\Delta P = \left(\frac{E \sin \delta}{X_D} \right) \Delta E_{EX} + \left[\frac{E_{EX} E \cos \delta}{X_D} + \left(E^2 \cos 2\delta \right) \left(\frac{1}{X_Q} - \frac{1}{X_D} \right) \right] \Delta \delta \quad (B-22)$$

$$\Delta Q = \left(\frac{E \cos \delta}{X_D} \right) \Delta E_{EX} - \left[\frac{E_{EX} E \sin \delta}{X_D} + \left(E^2 \sin 2\delta \right) \left(\frac{1}{X_Q} - \frac{1}{X_D} \right) \right] \Delta \delta \quad (B-23)$$

Equations B-22 and B-23 can be solved for the incremental excitation voltage and internal angle. From Eqs. B-16 through B-19,

$$\Delta E_D = (E \cos \delta) \Delta \delta \quad (B-24)$$

$$\Delta E_Q = -(E \sin \delta) \Delta \delta \quad (B-25)$$

$$\Delta I_D = \frac{\Delta E_{EX} + (E \sin \delta) \Delta \delta}{X_D} \quad (B-26)$$

$$\Delta I_Q = \frac{(E \cos \delta) \Delta \delta}{X_Q} \quad (B-27)$$

Appendix C

DATA FOR NEW ENGLAND TEST SYSTEM

Transmission Line and Transformer Data	C-2/C-3
Report of Load Flow Calculation, 830 MW at Bus 38	C-4/C-9
Report of Load Flow Calculation, 1080 MW at Bus 38	C-10/C-15
Report of Load Flow Calculation, 1330 MW at Bus 38	C-16/C-21
Report of Load Flow Calculation, 1580 MW at Bus 38	C-22/C-27
Power Plant Data	C-28/C-32
Summaries of Synchronous Machine Initial Conditions	C-33/C-34

TRANSMISSION LINE AND TRANSFORMER DATA

LINE TERMINALS		CHARGING MVAR	IMPEDANCE		----- ADMITTANCE -----		LINE RATING	TAP RATIO	TAP LIMIT		MTR	OWN	CNO
			R (PU)	X (PU)	BC/2(PU)	G (PU)			TMIN	TMAX			
1	2	69.870	.0035	.0411	.3494	2.0571	-24.1557	0.00			0	0	1
1	39	75.000	.0010	.0250	.3750	1.5974	-39.9361	0.00			0	0	1
2	3	25.720	.0013	.0151	.1286	5.6596	-65.7379	0.00			0	0	1
2	25	14.600	.0070	.0086	.0730	56.9291	-69.9414	0.00			0	0	1
2	30	0.000	0.0000	.0161	0.0000	0.0000	-55.2486	0.00	1.025		0	0	1
3	4	22.140	.0013	.0213	.1107	2.8548	-46.7741	0.00			0	0	1
3	16	21.380	.0011	.0133	.1065	6.1763	-74.6771	0.00			0	0	1
4	5	13.420	.0008	.0128	.0671	4.8638	-77.8210	0.00			0	0	1
4	14	13.820	.0008	.0129	.0691	4.7890	-77.2224	0.00			0	0	1
5	6	4.340	.0002	.0026	.0217	29.4118	-382.3525	0.00			0	0	1
5	8	14.760	.0008	.0112	.0738	6.3452	-88.8325	0.00			0	0	1
6	7	11.300	.0006	.0092	.0565	7.0588	-108.2353	0.00			0	0	1
6	11	13.850	.0007	.0082	.0695	10.3352	-121.0690	0.00			0	0	1
6	31	0.000	0.0000	.0250	0.0000	0.0000	-40.0000	0.00	1.070		0	0	1
7	8	7.800	.0004	.0046	.0390	18.7617	-215.7598	0.00			0	0	1
8	9	36.040	.0023	.0363	.1502	1.7385	-27.4381	0.00			0	0	1
9	39	120.000	.0010	.0250	.6000	1.5974	-39.9361	0.00			0	0	1
10	11	7.290	.0004	.0043	.0365	21.4477	-230.5630	0.00			0	0	1
10	13	7.290	.0004	.0043	.0365	21.4477	-230.5630	0.00			0	0	1
10	32	0.000	0.0000	.0200	0.0000	0.0000	-50.0000	0.00	1.070		0	0	1
12	11	0.000	.0016	.0435	0.0000	.8444	-22.9574	0.00	1.006		0	0	1
12	13	0.000	.0016	.0435	0.0000	.8444	-22.9574	0.00	1.006		0	0	1
13	14	17.230	.0009	.0101	.0862	8.7532	-98.2299	0.00			0	0	1
14	15	36.600	.0018	.0217	.1830	3.7964	-45.7680	0.00			0	0	1
15	16	17.100	.0009	.0094	.0855	10.0931	-105.4166	0.00			0	0	1
16	17	13.420	.0007	.0089	.0671	6.7829	-111.6688	0.00			0	0	1
16	19	30.400	.0016	.0195	.1520	4.1796	-50.9351	0.00			0	0	1
16	21	25.480	.0008	.0135	.1274	4.3742	-73.8149	0.00			0	0	1
16	24	6.800	.0003	.0059	.0340	8.5960	-169.0544	0.00			0	0	1
17	18	13.150	.0007	.0082	.0666	10.3352	-121.0690	0.00			0	0	1
17	27	32.160	.0013	.0173	.1608	4.3192	-57.4789	0.00			0	0	1
19	33	0.000	.0007	.0142	0.0000	3.4631	-70.2518	0.00	1.070		0	0	1
19	20	0.000	.0007	.0138	0.0000	3.6663	-72.2778	0.00	1.060		0	0	1
20	34	0.000	.0009	.0180	0.0000	2.7709	-55.4170	0.00	1.005		0	0	1
21	22	25.650	.0008	.0140	.1283	4.0683	-71.1961	0.00			0	0	1
22	23	18.460	.0006	.0096	.0923	6.4851	-103.7613	0.00			0	0	1

TRANSMISSION LINE AND TRANSFORMER DATA

LINE TERMINALS	CHARGING MVAR	IMPEDANCE		----- ADMITTANCE -----		LINE RATING	TAP RATIO	TAP LIMIT		MTR	OWN	CNO
		R (PU)	X (PU)	BC/2 (PU)	G (PU)			TMIN	TMAX			
22 35	0.000	0.0000	.0143	0.0000	0.0000	-69.5301	0.00	1.025		0	0	1
23 24	36.100	.0022	.0350	.1805	1.7889	-28.4590	0.00			0	0	1
23 36	0.000	.0005	.0272	0.0000	.6756	-36.7523	0.00	1.000		0	0	1
25 26	51.300	.0032	.0323	.2565	3.0374	-30.6588	0.00			0	0	1
25 37	0.000	.0006	.0232	0.0000	1.1140	-43.0746	0.00	1.025		0	0	1
26 27	23.960	.0014	.0147	.1198	6.4205	-67.4157	0.00			0	0	1
26 28	78.020	.0043	.0474	.3901	1.8982	-20.9248	0.00			0	0	1
26 29	102.500	.0057	.0625	.5145	1.4472	-15.8680	0.00			0	0	1
28 29	24.900	.0014	.0151	.1245	6.0878	-65.6607	0.00			0	0	1
29 38	0.000	.0008	.0156	0.0000	3.2787	-63.9344	0.00	1.025		0	0	1

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3, SWING BUS = 39.

X-----E L S O A T A-----X

FROM BUS	NAME	AC	VOLTS	ANGLE	-- GEN/LOAD --		TO BUS NAME	MW	MVAR	LDG	FCT O CAP L TAF	CT. NO.	RR. NO.
1		0	1.048	-9.6	0.00	0.00							
		0		LOAD	0.00	0.00	2	-118.57	-29.17	122.		1	1
				SHNT	0.00	0.00	39	118.57	29.17	122.		1	2
				RESO	.00	.00							
2		0	1.049	-7.0	0.00	0.00							
		0		LOAD	0.00	0.00	1	119.02	-42.31	126.		1	1
				SHNT	0.00	0.00	3	364.68	52.05	376.		1	3
				RESO	-.00	.00	25	-233.71	81.40	247.		1	4
							30	-250.00	-131.14	282.	1.025	1	5
3		0	1.030	-9.9	.00	.00							
		0		LOAD	322.00	2.40	2	-362.58	-100.06	377.		1	3
				SHNT	0.00	0.00	4	74.57	112.85	136.		1	6
				RESO	.00	.00	18	-34.00	-15.24	37.		1	7
4		0	1.004	-10.7	.00	.00							
		0		LOAD	500.00	184.00	3	-74.72	-131.56	151.		1	6
				SHNT	0.00	0.00	5	-163.17	-4.36	163.		1	8
				RESO	-.00	.00	14	-262.11	-48.06	266.		1	9
5		0	1.005	-9.5	0.00	0.00							
		0		LOAD	0.00	0.00	4	163.38	-5.80	163.		1	8
				SHNT	0.00	0.00	6	-481.11	-52.93	484.		1	10
				RESO	.00	.00	8	317.73	58.73	323.		1	11
6		0	1.007	-8.8	0.00	0.00							
		0		LOAD	0.00	0.00	5	481.58	54.56	485.		1	10
				SHNT	0.00	0.00	7	425.56	91.36	436.		1	12
				RESO	.00	.00	11	-343.51	-36.52	345.		1	13
							31	-564.03	-109.41	575.	1.070	1	14
7		0	.997	-11.0	.00	.00							
		0		LOAD	233.80	64.00	6	-424.64	-85.40	433.		1	12
				SHNT	0.00	0.00	8	151.04	1.40	151.		1	15
				RESO	.00	-.00							

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3. SWING BUS = 39.

X-----BUS DATA-----X

FROM					-- GEN/LOAD --	TO				FACT C	CT.	PR.		
BUS	NAME	AC	VOLTS	ANGLE	MW	MVAR	BUS NAME	PL	MVAR	LDC	CAF L	TAP	NO.	NO.
8		0	.996	-11.5	.00	.00								
		0		LOAD	522.00	176.00	5	-316.90	-61.82	323.			1	11
				SHMT	0.00	0.00	7	-190.89	-7.45	191.			1	15
				RESO	-.00	.00	9	-14.22	-106.73	108.			1	16
9		0	1.028	-11.3	0.00	0.00								
		0		LOAD	0.00	0.00	8	14.40	70.67	72.			1	16
				SHMT	0.00	0.00	39	-14.40	-70.67	72.			1	17
				RESO	.00	.00								
10		0	1.017	-6.4	0.00	0.00								
		0		LOAD	0.00	0.00	11	347.04	72.66	355.			1	18
				SHMT	0.00	0.00	13	302.96	36.89	305.			1	19
				RESO	.00	.00	32	-650.00	-109.55	659.	1.070		1	20
11		0	1.013	-7.2	0.00	0.00								
		0		LOAD	0.00	0.00	6	344.33	31.95	346.			1	13
				SHMT	0.00	0.00	10	-346.55	-74.92	355.			1	18
				RESO	.00	.00	12	2.22	42.96	43.			1	21
12		0	1.000	-7.2	.00	.00								
		0		LOAD	8.50	88.00	11	-2.19	-42.18	42.	1.006		1	21
				SHMT	0.00	0.00	13	-6.31	-45.82	46.	1.006		1	22
				RESO	-.00	-.00								
13		0	1.014	-7.1	0.00	0.00								
		0		LOAD	0.00	0.00	10	-362.60	-40.53	365.			1	19
				SHMT	0.00	0.00	12	6.35	46.76	47.			1	22
				RESO	.00	.00	14	296.26	-6.23	296.			1	23
14		0	1.012	-8.8	0.00	0.00								
		0		LOAD	0.00	0.00	4	262.67	43.06	266.			1	9
				SHMT	0.00	0.00	13	-255.49	-2.83	296.			1	23
				RESO	-.00	.00	15	32.82	-40.23	52.			1	24

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3, SWING BUS = 39.

X-----BUS DATA-----X

FROM BUS	NAME	AC	VOLTS	ANGLE	-- GEN/LOAD --	
					MW	MVAR
15		0	1.016	-9.2	.00	.00
		0		LOAD	320.00	153.00
				SHNT	0.00	0.00
				RESO	-.00	.00
16		0	1.032	-7.8	.00	.00
		0		LOAD	329.40	32.30
				SHNT	0.00	0.00
				RESO	-.00	.00
17		0	1.034	-8.8	0.00	0.00
		0		LOAD	0.00	0.00
				SHNT	0.00	0.00
				RESO	.00	.00
18		0	1.031	-9.6	.00	.00
		0		LOAD	158.00	30.00
				SHNT	0.00	0.00
				RESO	-.00	.00
19		0	1.050	-3.2	0.00	0.00
		0		LOAD	0.00	0.00
				SHNT	0.00	0.00
				RESO	.00	.00
20		0	.991	-4.6	.00	.00
		0		LOAD	680.00	103.00
				SHNT	0.00	0.00
				RESO	-.00	.00

TO BUS NAME	PL	MVAR	LDG	PCT O CAP L	TAP	CT.. R.O.	BR. R.O.
14	-32.79	2.94	33.			1	24
16	-287.21	-155.94	327.			1	25
15	288.12	147.50	324.			1	25
17	206.05	-41.27	210.			1	26
19	-451.29	-55.07	455.			1	27
21	-329.60	14.10	330.			1	28
24	-42.68	-97.55	106.			1	29
16	-205.77	30.59	208.			1	26
18	192.25	11.46	193.			1	30
27	13.51	-42.05	44.			1	31
3	34.01	-7.34	35.			1	7
17	-192.01	-22.66	193.			1	30
16	454.37	59.66	458.			1	27
20	174.73	-9.45	175.	1.060		1	33
33	-629.10	-50.21	631.	1.070		1	32
19	-174.51	13.76	175.			1	33
34	-505.49	-116.76	519.	1.009		1	34

REPORT OF LOAD-FLCK CALCULATION

TOTAL ITERATIONS = 3, SWING BUS = 39.

X-----BUS DATA-----X
FROM

BUS	NAME	AC	VOLTS	ANGLE	MW	MVAR
21		0	1.032	-5.4	.00	.00
		0		LOAD	274.00	115.00
				SHNT	0.00	0.00
				RESO	-0.00	.00

22		0	1.050	-0.9	0.00	0.00
		0		LOAD	0.00	0.00
				SHNT	0.00	0.00
				RESO	.00	.00

23		0	1.045	-1.1	.00	.00
		0		LOAD	247.50	84.60
				SHNT	0.00	0.00
				RESO	-0.00	.00

24		0	1.038	-7.7	.00	-0.00
		0		LOAD	308.60	-92.20
				SHNT	0.00	0.00
				RESO	-0.00	.00

25		0	1.058	-5.7	.00	.00
		0		LOAD	224.00	47.20
				SHNT	0.00	0.00
				RESO	.00	.00

26		0	1.052	-6.9	.00	.00
		0		LOAD	139.00	17.00
				SHNT	0.00	0.00
				RESO	-0.00	-0.00

27		0	1.038	-8.9	.00	.00
		0		LOAD	281.00	75.50
				SHNT	0.00	0.00
				RESO	-0.00	.00

TO	BUS NAME	MW	MVAR	LDG	PCT O	CT. NO.	ER. NO.
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16		330.42	-27.38	332.		1	28
22		-604.42	-87.62	611.		1	35

21		607.20	108.55	617.		1	35
23		42.80	41.90	60.		1	36
35		-650.00	-150.46	667.	1.025	1	37

22		-42.77	-61.76	75.		1	36
24		353.84	-0.24	354.		1	38
36		-558.57	-22.60	559.	1.000	1	39

16		42.71	90.86	100.		1	29
23		-351.31	1.34	351.		1	38

2		237.69	-92.70	255.		1	4
26		76.65	-17.89	79.		1	40
37		-528.34	83.39	542.	1.025	1	41

25		-76.48	-37.46	85.		1	40
27		268.49	67.44	277.		1	42
28		-140.82	-21.61	142.		1	43
29		-190.18	-25.36	192.		1	44

17		-13.50	7.67	16.		1	31
26		-267.50	-83.17	280.		1	42

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3. SWING BUS = 39.

X-----B L S D A T A-----X

FROM BUS	NAME	AC	VCLTS	ANGLE	-- GEN/LOAD -- MW	MVAR	TO BUS NAME	MW	MVAR	LDG	PCT C CAP L	CT. TAP	BR. %C. NO.
35		0	1.049	4.0	650.00	211.12R							
		0		LOAD	0.00	0.00	22	650.00	211.12	663.			1 37
				SHNT	0.00	0.00							
				RESD	-0.00	-0.00							
36		0	1.064	6.7	560.00	100.44R							
		0		LOAD	0.00	0.00	23	560.00	100.44	569.			1 39
				SHNT	0.00	0.00							
				RESD	-0.00	-0.00							
37		0	1.028	1.1	540.00	.65R							
		0		LOAD	0.00	0.00	25	540.00	.65	540.			1 41
				SHNT	0.00	0.00							
				RESD	-0.00	-0.00							
38		0	1.027	6.4	830.00	22.66R							
		0		LOAD	0.00	0.00	29	830.00	22.66	830.			1 46
				SHNT	0.00	0.00							
				RESD	-0.00	-0.00							
39		0	1.030	-11.1	1000.00	87.88S							
		0		LOAD	1104.00	250.00	1	-118.40	-105.78	155.			1 2
				SHNT	0.00	0.00	5	14.40	-56.34	58.			1 17
				RESD	-0.00	-0.00							

NOTE * UNDER OL COLUMN INDICATES LINE S PCT. CAP. IS GREATER THAN 100 P.C.

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 30 SAVING BUS = 39.

X----- BUS DATA -----X													
FROM	NAME	AC	VOLTS	ANGLE	-- GEN/LOAD --		TO	NAME	MW	MVAR	LOG	PCT D	CT. PR.
BUS					MW	MVAR	BUS					CAP L	TAP NO. NO.
1		0	1.042	-7.8	0.00	0.00	2		-250.07	-6.36	250.		1 1
		0		LOAD	0.00	0.00	39		250.07	6.36	250.		1 2
				SHNT	0.00	0.00							
				RESO	.00	-.00							
2		0	1.043	-2.3	0.00	0.00	1		252.12	-45.56	256.		1 1
		0		LOAD	0.00	0.00	3		350.93	86.34	361.		1 3
				SHNT	0.00	0.00	25		-353.85	123.79	374.		1 4
				RESO	-.00	.00	39		-250.00	-164.63	299.	1.005	1 5
3		0	1.025	-5.1	.00	.00	2		-349.33	-95.33	362.		1 3
		0		LOAD	322.00	2.40	4		129.15	192.15	159.		1 6
				SHNT	0.00	0.00	18		-54.81	-9.22	95.		1 7
				RESO	-.00	-.00							
4		0	1.000	-6.5	.00	.00	3		-121.80	-119.20	170.		1 6
		0		LOAD	500.00	184.00	5		-101.67	-13.92	103.		1 8
				SHNT	0.00	0.00	14		-276.83	-50.88	281.		1 9
				RESO	-.00	-.00							
5		0	1.002	-5.7	0.00	0.00	4		101.75	1.80	102.		1 8
		0		LOAD	0.00	0.00	6		-475.19	-60.07	479.		1 10
				SHNT	0.00	0.00	8		373.44	58.27	376.		1 11
				RESO	.00	-.00							
6		0	1.004	-5.0	0.00	0.00	5		475.65	61.64	486.		1 10
		0		LOAD	0.00	0.00	7		470.12	93.17	474.		1 12
				SHNT	0.00	0.00	11		-361.74	-35.69	363.		1 13
				RESO	.00	-.00	31		-564.63	-119.12	576.	1.075	1 14
7		0	.993	-7.5	.00	.00	6		-468.74	-53.48	476.		1 12
		0		LOAD	233.89	84.00	8		234.94	-.69	235.		1 15
				SHNT	0.00	0.00							
				RESO	-.00	-.00							

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3, SWING BUS = 39.

X-----BUS DATA-----X

FROM BUS	NAME	AC	VOLTS	ANGLE	-- GEN/LOAD --	
					PW	MVAR
8		0	.992	-8.1	.00	.00
		0			522.00	176.00
				LOAD	0.00	0.00
				SHNT	0.00	0.00
				RESO	-0.00	-0.00

9		0	1.026	-10.0	0.00	0.00
		0			0.00	0.00
				LOAD	0.00	0.00
				SHNT	0.00	0.00
				RESO	.00	-0.00

10		0	1.015	-2.4	0.00	0.00
		0			0.00	0.00
				LOAD	0.00	0.00
				SHNT	0.00	0.00
				RESO	.00	-0.00

11		0	1.010	-3.3	0.00	0.00
		0			0.00	0.00
				LOAD	0.00	0.00
				SHNT	0.00	0.00
				RESO	.00	-0.00

12		0	.997	-3.2	.00	.00
		0			88.00	88.00
				LOAD	0.00	0.00
				SHNT	0.00	0.00
				RESO	.00	-0.00

13		0	1.012	-3.0	0.00	0.00
		0			0.00	0.00
				LOAD	0.00	0.00
				SHNT	0.00	0.00
				RESO	-0.00	-0.00

14		0	1.009	-4.5	0.00	0.00
		0			0.00	0.00
				LOAD	0.00	0.00
				SHNT	0.00	0.00
				RESO	.00	.00

TO BUS	NAME	PW	MVAR	LOG	PCT O CAP L	CT. TAP	CT. NO.	BR. NO.
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5		-372.29	-56.91	377.			1	11
7		-234.72	-4.82	235.			1	15
9		65.51	-114.57	143.			1	16

8		-84.83	81.86	118.			1	16
39		84.83	-81.86	118.			1	17

11		382.15	75.45	382.			1	18
13		267.65	44.17	271.			1	19
32		-650.00	-119.62	661.		1.070	1	20

5		382.75	33.51	384.			1	13
10		-381.56	-76.56	380.			1	18
12		-1.19	43.05	43.			1	21

11		1.82	-42.25	42.		1.006	1	21
13		-9.72	-45.74	47.		1.006	1	22

10		-267.56	-48.56	272.			1	19
12		9.76	46.71	46.			1	22
14		267.00	1.85	268.			1	23

4		277.15	47.05	281.			1	9
13		-257.22	-12.88	253.			1	23
15		-15.94	-34.19	40.			1	24

REPORT OF LOAD-FLOW CALCULATION

X----- BUS DATA -----X

FROM

BUS NAME AC VOLTS ANGLE -- GEN/LOAD --

15 0 1.012 -4.2 .00 .00

0 LOAD 320.00 153.00

SHNT 0.00 0.00

PFSD -0.00 -0.00

16 0 1.029 -2.5 .00 .00

0 LOAD 329.40 32.30

SHNT 0.00 0.00

RESO -0.00 -0.00

17 0 1.029 -3.3 0.00 0.00

0 LOAD 0.00 0.00

SHNT 0.00 0.00

RESO -0.00 -0.00

18 0 1.026 -4.4 .00 .00

0 LOAD 158.00 30.00

SHNT 0.00 0.00

RESO -0.00 -0.00

19 0 1.049 2.1 0.00 0.00

0 LOAD 0.00 0.00

SHNT 0.00 0.00

RESO .00 .00

20 0 .990 .7 .00 .00

0 LOAD 680.00 103.00

SHNT 0.00 0.00

RESO -0.00 .00

TOTAL ITERATIONS = 3 SWING BUS = 39.

TO

BUS NAME P MW PVAR LDC PCT O CT. BR.

14 18.45 -3.34 20. 1 24

16 -339.95 -149.96 372. 1 25

15 341.14 144.57 371. 1 25

17 152.03 -15.13 154. 1 26

19 -451.73 -65.51 454. 1 27

21 -329.56 6.59 330. 1 28

24 -42.57 -102.42 111. 1 29

16 -152.78 2.30 153. 1 26

18 253.33 8.96 253. 1 30

27 -100.56 -11.86 101. 1 31

3 94.51 -12.12 96. 1 7

17 -252.51 -17.68 254. 1 30

16 454.35 71.56 460. 1 27

20 174.74 -11.58 175. 1.000 1 33

33 -528.69 -59.68 532. 1.000 1 32

19 -174.52 17.31 175. 1 33

34 -505.45 -120.31 520. 1.000 1 34

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3, SWING BUS = 39.

X-----B U S D A T A-----X

FROM -- GEN/LOAD --

BUS NAME AC VOLTS ANGLE MW MVAR

21 0 1.030 -0.1 0.00 0.00

0 LOAD 274.00 115.00

SHNT 0.00 0.00

RESO 0.00 -0.00

22 0 1.049 4.3 0.00 0.00

0 LOAD 0.00 0.00

SHNT 0.00 0.00

RESO 0.00 0.00

23 0 1.044 -4.1 0.00 0.00

0 LOAD 247.50 84.60

SHNT 0.00 0.00

RESO 0.00 0.00

24 0 1.035 -2.4 0.00 -0.00

0 LOAD 308.60 -92.20

SHNT 0.00 0.00

RESO -0.00 -0.00

25 0 1.056 -0.3 0.00 0.00

0 LOAD 224.00 47.20

SHNT 0.00 0.00

RESO -0.00 -0.00

26 0 1.042 0.5 0.00 0.00

0 LOAD 139.00 17.00

SHNT 0.00 0.00

RESO -0.00 -0.00

27 0 1.029 -2.3 0.00 0.00

0 LOAD 281.00 75.50

SHNT 0.00 0.00

RESO -0.00 -0.00

TO BUS NAME MW MVAR LOG PCT O CT. PR.

-----CAP L TAP NO. VO.-----

16 330.39 -19.68 331. 1 26

22 -004.39 -95.32 012. 1 35

21 607.19 116.73 618. 1 35

23 42.61 42.35 40. 1 36

35 -650.70 -159.38 669. 1.025 1 37

22 -42.78 -62.15 75. 1 36

24 353.14 5.37 354. 1 38

36 -558.56 -27.52 559. 1.000 1 39

16 42.75 95.83 195. 1 29

23 -351.30 -3.63 351. 1 38

2 362.19 -128.64 314. 1 4

26 -47.45 23.70 53. 1 40

37 -534.34 57.74 541. 1.005 1 41

25 47.59 -78.76 52. 1 40

27 753.83 48.74 337. 1 42

28 -260.87 6.51 261. 1 43

29 -301.75 8.45 310. 1 44

17 108.08 -28.53 103. 1 31

26 -561.63 -54.97 326. 1 42

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3, SWING BUS = 39.

X-----BUS DATA-----X

FROM BUS	NAME	AC	VOLTS	ANGLE	-- GEN/LOAD --		TO BUS NAME	MW	MVAR	LDC	PCT 0 CAP L	TAP	CT. NO.	BR. NO.
28		0	1.037	7.3										
		0		LOAD	206.00	27.60	25	263.66	-60.67	270.			1	43
				SHNT	0.00	0.00	29	-469.66	32.47	471.			1	45
				RESO	.00	-.00								
29		0	1.039	11.1	.00	.00								
		0		LOAD	283.50	24.90	26	314.99	-59.45	321.			1	44
				SHNT	0.00	0.00	28	472.56	-28.07	473.			1	45
				RESO	.00	-.00	38	-1071.05	60.61	1073.	1.025		1	46
30		0	1.048	.1	250.00	180.30R								
		0		LOAD	0.00	0.00	2	250.00	180.30	308.			1	5
				SHNT	0.00	0.00								
				RESO	-.00	.00								
31		0	.982	3.8	573.23	218.01R								
		0		LOAD	9.26	4.60	6	564.03	213.41	603.			1	14
				SHNT	0.00	0.00								
				RESO	.00	.00								
32		0	.983	5.6	650.00	216.78R								
		0		LOAD	0.00	0.00	10	650.00	216.78	685.			1	20
				SHNT	0.00	0.00								
				RESO	.00	-.00								
33		0	.997	7.3	632.00	117.08R								
		0		LOAD	0.00	0.00	10	632.00	117.08	643.			1	32
				SHNT	0.00	0.00								
				RESO	.00	.00								
34		0	1.012	5.9	508.00	170.76R								
		0		LOAD	0.00	0.00	20	508.00	170.76	536.			1	34
				SHNT	0.00	0.00								
				RESO	.00	.00								

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3, SWING BUS = 39.

X-----BUS DATA-----X

FROM	BUS	NAME	AC	VOLTS	ANGLE	-- GEN/LOAD --		TO	BUS NAME	MW	MVAR	LOG	PCT OL	CAP L	TAP	CT. NO.	BR. NO.
35	0		1.049	9.3		650.00	220.25R										
	0				LOAD	0.00	0.00	22		650.00	220.25	650.				1	37
					SHNT	0.00	0.00										
					RESO	.00	.00										
36	0		1.064	12.0		560.00	105.62R										
	0				LOAD	0.00	0.00	23		560.00	105.62	570.				1	39
					SHNT	0.00	0.00										
					RESO	.00	.00										
37	0		1.028	6.5		540.00	6.31R										
	0				LOAD	0.00	0.00	25		540.00	6.31	540.				1	41
					SHNT	0.00	0.00										
					RESO	.00	.00										
38	0		1.027	20.4		1080.00	113.99R										
	0				LOAD	0.00	0.00	29		1080.00	113.99	1080.				1	46
					SHNT	0.00	0.00										
					RESO	.00	.00										
39	0		1.030	-11.1		769.96	134.83S										
	0				LOAD	1104.00	250.00	1		-249.48	-71.94	260.				1	2
					SHNT	0.00	0.00	9		-84.56	-43.18	95.				1	17
					RESO	0.00	.00										

NOTE * UNDER OL COLUMN INDICATES LINE S FCT. CAP. IS GREATER THAN 100 P.C.

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3, SWING BUS = 39.

X-----BUS DATA-----X

FROM -- GEN/LOAD --

BUS NAME AC VOLTS ANGLE MW MVAR

1 0 1.034 -6.1 0.00 0.00

0 LOAD 0.00 0.00

SHNT 0.00 0.00

RESO .00 -.00

2 0 1.034 2.3 0.00 0.00

0 LOAD 0.00 0.00

SHNT 0.00 0.00

RESO -.00 .00

3 0 1.016 -.4 .00 .00

0 LOAD 322.00 2.40

SHNT 0.00 0.00

RESO -.00 -.00

4 0 .994 -2.4 .00 .00

0 LOAD 500.00 184.00

SHNT 0.00 0.00

RESO -.00 -.00

5 0 .997 -2.0 0.00 0.00

0 LOAD 0.00 0.00

SHNT 0.00 0.00

RESO .00 .00

6 0 1.000 -1.4 0.00 0.00

0 LOAD 0.00 0.00

SHNT 0.00 0.00

RESO .00 -.00

7 0 .988 -4.1 .00 .00

0 LOAD 233.00 84.00

SHNT 0.00 0.00

RESO -.00 -.00

TO BUS NAME MW MVAR LDC PCT O CT. HR.

2 -374.50 23.02 375. 1 1

39 374.50 -23.02 375. 1 2

1 375.21 -42.33 382. 1 1

3 337.51 62.04 348. 1 3

25 -467.12 173.16 498. 1 4

35 -250.00 -712.86 328. 1.025 1 5

2 -336.41 -91.62 349. 1 3

4 167.48 88.24 189. 1 6

18 -153.08 .98 153. 1 7

3 -167.10 -102.79 196. 1 6

5 -42.51 -25.98 50. 1 8

14 -290.48 -55.23 256. 1 9

4 42.53 12.97 44. 1 8

6 -469.60 -72.46 475. 1 10

8 427.07 59.45 431. 1 11

5 475.06 74.93 476. 1 10

7 512.70 97.35 522. 1 12

11 -418.73 -36.65 420. 1 13

31 -564.13 -134.74 580. 1.070 1 14

6 -511.16 -83.34 518. 1 12

8 277.26 -.66 277. 1 15

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3, SWING BUS = 19.

X-----BUS DATA-----X

FROM	NAME	AC	VOLTS	ANGLE	-- GEN/LOAD --	TO	BUS NAME	PW	MVAR	LDG	PCT D	CT.	BR.
BUS					KW	MVAR					CAP L	TAP	NO.
8		0	.987	-4.8	.00	.00	5	-425.57	-52.95	429.		1	11
		0		LCAD	522.00	176.00	7	-276.55	-3.23	277.		1	15
				SHNT	0.00	0.00	9	186.11	-119.72	217.		1	16
				RESO	-.00	-.00							
9		0	1.022	-8.7	0.00	0.00	8	-179.50	97.27	214.		1	16
		0		LCAD	0.00	0.00	39	179.50	-97.27	204.		1	17
				SHNT	0.00	0.00							
				RESO	.00	-.00							
10		0	1.011	1.6	0.00	0.00	11	418.17	89.56	424.		1	18
		0		LCAD	0.00	0.00	13	233.83	55.61	243.		1	19
				SHNT	0.00	0.00	32	-650.00	-136.17	604.	1.070	1	20
				RESO	.00	-.00							
11		0	1.006	.6	0.00	0.00	6	418.96	37.14	428.		1	13
		0		LCAD	0.00	0.00	10	-418.47	-89.38	428.		1	18
				SHNT	0.00	0.00	12	-4.50	43.24	43.		1	21
				RESO	.00	-.00							
12		0	.993	.7	.00	.00	11	4.83	-42.43	47.	1.016	1	21
		0		LCAD	8.55	88.00	13	-13.73	-48.57	47.	1.005	1	22
				SHNT	0.00	0.00							
				RESO	.00	-.00							
13		0	1.007	1.0	0.00	0.00	10	-233.80	-60.58	241.		1	19
		0		LCAD	0.00	0.00	12	13.06	68.58	45.		1	22
				SHNT	0.00	0.00	14	220.54	14.00	221.		1	23
				RESO	-.00	-.00							
14		0	1.003	-.2	0.00	0.00	4	291.19	52.77	258.		1	9
		0		LCAD	0.00	0.00	13	-220.10	-26.52	222.		1	23
				SHNT	0.00	0.00	15	-71.09	-26.25	76.		1	24
				RESO	.00	-.00							

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3. SWING BUS = 39.

X----- BUS DATA -----X

FROM BUS	NAME	AC	VOLTS	ANGLE	-- GEN/LOAD --	
					MW	MVAR
15		0	1.006	.6	.00	.00
		0		LOAD	320.00	153.00
				SHNT	0.00	0.00
				RESO	-0.00	-0.00
16		0	1.023	2.6	.00	.00
		0		LOAD	329.40	32.30
				SHNT	0.00	0.00
				RESO	-0.00	-0.00
17		0	1.019	2.1	0.00	0.00
		0		LOAD	0.00	0.00
				SHNT	0.00	0.00
				RESO	-0.00	-0.00
18		0	1.017	.7	.00	.00
		0		LOAD	152.00	30.00
				SHNT	0.00	0.00
				RESO	-0.00	-0.00
19		0	1.047	7.3	0.00	0.00
		0		LOAD	0.00	0.00
				SHNT	0.00	0.00
				RESO	.00	-0.00
20		0	.989	5.9	.00	.00
		0		LOAD	680.00	103.00
				SHNT	0.00	0.00
				RESO	-0.00	.00

TO BUS NAME	MW	MVAR	LOG	PCT C CAP L	TAP	CT. NO.	RR. NO.
14	71.18	-9.60	72.			1	24
16	-391.18	-143.40	417.			1	25
15	392.79	141.68	417.			1	25
17	101.17	27.37	155.			1	26
19	-451.12	-84.40	459.			1	27
21	-329.80	-6.22	320.			1	28
24	-42.65	-110.73	119.			1	29
16	-101.10	-40.40	155.			1	26
18	311.98	3.98	312.			1	30
27	-210.69	36.42	214.			1	31
3	153.33	-20.04	155.			1	7
17	-311.23	-9.96	311.			1	30
16	454.39	80.63	463.			1	27
29	174.76	-19.13	176.	1.000		1	33
33	-629.07	-711.60	633.	1.075		1	32
19	-174.54	23.10	176.			1	33
34	-505.46	-126.40	521.	1.039		1	34

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3, SWING BUS = 35.

X-----BUS DATA-----X														
FROM	NAME	AC	VOLTS	ANGLE	-- GEN/LOAD --		TO				PCT D	CT.	BR.	
BUS					MW	MVAR	BUS NAME	PW	MVAR	LOG	CAP L	TAP	NO.	
21		0	1.026	5.1	.00	.00								
		0		LOAD	274.00	115.00	16	330.73	-6.50	330.			1	28
				SHNT	0.00	0.00	22	-604.23	-108.50	514.			1	35
				RESO	.00	-.00								
22		0	1.047	9.5	0.00	0.00								
		0		LOAD	0.00	0.00	21	607.18	139.77	521.			1	35
				SHNT	0.00	0.00	23	42.82	43.11	61.			1	36
				RESO	.00	-.00	35	-650.00	-173.80	673.	1.075		1	37
23		0	1.041	9.3	.00	.00								
		0		LOAD	247.50	84.60	22	-42.80	-62.62	76.			1	36
				SHNT	0.00	0.00	24	353.85	14.19	354.			1	38
				RESO	.00	.00	36	-558.56	-35.57	559.	1.300		1	39
24		0	1.029	2.7	.00	-.00								
		0		LOAD	308.60	-92.20	16	42.09	104.31	113.			1	29
				SHNT	0.00	0.00	23	-351.29	-12.11	351.			1	38
				RESO	-.00	-.00								
25		0	1.051	5.1	.00	.00								
		0		LOAD	224.00	47.20	2	483.56	-168.80	512.			1	4
				SHNT	0.00	0.00	26	-169.22	-44.75	189.			1	40
				RESO	-.00	-.00	37	-538.24	36.63	540.	1.085		1	41
26		0	1.023	8.2	.00	.00								
		0		LOAD	139.00	17.00	25	170.42	-127.89	213.			1	40
				SHNT	0.00	0.00	27	495.78	23.56	495.			1	42
				RESO	-.00	-.00	28	-378.47	42.75	381.			1	43
							29	-426.73	44.59	429.			1	44
27		0	1.014	4.2	.00	.00								
		0		LOAD	281.00	75.50	17	211.48	-61.78	220.			1	31
				SHNT	0.00	0.00	26	-452.48	-13.72	453.			1	42
				RESO	-.00	-.00								

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3, SWING BUS = 39.

----- BUS DATA -----

FROM					-- GEN/LOAD --			
BUS	NAME	AC	VOLTS	ANGLE	MW	MVAR		
28		0	1.016	18.3	.00	.00		
		0		LOAD	206.00	27.60		
				SHNT	0.00	0.00		
				RESD	.00	-.00		
29		0	1.022	23.3	.00	.00		
		0		LOAD	283.50	26.90		
				SHNT	0.00	0.00		
				RESD	.00	-.00		
30		0	1.048	4.8	250.00	232.06		
		0		LOAD	0.00	0.00		
				SHNT	0.00	0.00		
				RESD	-.00	.00		
31		0	.982	7.5	573.23	235.65		
		0		LOAD	9.20	4.60		
				SHNT	0.00	0.00		
				RESD	.00	.00		
32		0	.983	9.6	650.00	235.03		
		0		LOAD	0.00	0.00		
				SHNT	0.00	0.00		
				RESD	.00	.00		
33		0	.997	12.5	632.00	131.09		
		0		LOAD	0.00	0.00		
				SHNT	0.00	0.00		
				RESD	.00	.00		
34		0	1.012	11.0	508.00	177.25		
		0		LOAD	0.00	0.00		
				SHNT	0.00	0.00		
				RESD	.00	.00		

TO													
BUS NAME	MW	MVAR	LDG	PCT 0	CT.	BR.							
				CAF L	TAP	NO.							
28	384.04	-55.68	389.			1 43							
29	-590.64	28.28	591.			1 45							
28	437.17	-37.73	439.			1 44							
28	595.39	-2.69	595.			1 45							
38	-1316.06	13.72	1316.	1.025		1 46							
2	250.00	232.06	341.			1 5							
6	564.83	231.05	610.			1 14							
15	650.00	235.03	641.			1 20							
19	632.00	131.09	645.			1 32							
20	508.00	177.25	538.			1 34							

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3. SAVING BUS = 19.

----- BUS DATA -----													
FROM	NAME	AC	VOLTS	ANGLE	-- GEN/LOAD --		TO				PCT C	CT. NO.	BR. NO.
BUS					MW	MVAR	BUS NAME	MW	MVAR	LOG	CAP L	TAP	
35		0	1.049	14.5	650.00	235.98R							
		0		LOAD	0.00	0.00	22	650.00	235.98	652.			1 37
				SHMT	0.00	0.00							
				RESO	.00	.00							
36		0	1.064	17.2	560.00	114.54R							
		0		LOAD	0.00	0.00	23	560.00	114.54	572.			1 39
				SHMT	0.00	0.00							
				RESO	.00	.00							
37		0	1.028	11.9	540.00	27.32R							
		0		LOAD	0.00	0.00	25	540.00	27.32	541.			1 41
				SHMT	0.00	0.00							
				RESO	.00	.00							
38		0	1.027	34.9	1330.00	252.02R							
		0		LOAD	0.00	0.00	29	1330.00	252.02	1355.			1 46
				SHMT	0.00	0.00							
				RESO	.00	.00							
39		0	1.030	-11.1	551.63	204.51S							
		0		LOAD	1104.00	255.00	1	-373.18	-23.96	374.			1 2
				SHMT	0.00	0.00	9	-179.18	-21.11	180.			1 17
				RESO	0.00	.00							

NOTE * UNDER OL COLUMN INDICATES LINE S PCT. CAP. IS GREATER THAN 100 P.C.

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3, SWING BUS = 39.

X-----BUS DATA-----X														
FROM					-- GEN/LOAD --		TO					PCT O	CT.	BR.
BUS	NAME	AC	VOLTS	ANGLE	MW	MVAR	BUS NAME	PW	MVAR	LOG	CAP L	TAP	NO.	NO.
1		0	1.023	-4.4	0.00	0.00								
		0		LOAD	0.00	0.00	2	-490.46	59.36	454.			1	1
				SHNT	0.00	0.00	39	490.46	-59.36	454.			1	2
				RESO	.00	-0.00								
2		0	1.021	6.9	0.00	0.00								
		0		LOAD	0.00	0.00	1	498.81	-34.21	500.			1	1
				SHNT	0.00	0.00	3	325.93	79.64	336.			1	3
				RESO	-0.00	.00	25	-574.75	232.26	620.			1	4
							39	-250.00	-277.71	374.		1.025	1	5
3		0	1.004	4.2	.00	.00								
		0		LOAD	322.00	2.40	2	-324.50	-89.37	337.			1	3
				SHNT	0.00	0.00	4	216.51	76.11	222.			1	6
				RESO	-0.00	-0.00	18	-208.61	16.66	209.			1	7
4		0	.985	1.7	.00	.00								
		0		LOAD	560.00	164.09	3	-209.85	-81.26	225.			1	6
				SHNT	0.00	0.00	5	13.74	-41.55	44.			1	8
				RESO	-0.00	-0.00	14	-303.88	-61.19	310.			1	9
5		0	.990	1.6	0.00	0.00								
		0		LOAD	0.00	0.00	4	-13.73	26.65	32.			1	8
				SHNT	0.00	0.00	6	-464.45	-96.57	473.			1	10
				RESO	.00	-0.00	8	478.12	61.92	482.			1	11
6		0	.993	2.2	0.00	0.00								
		0		LOAD	0.00	0.00	5	464.41	92.25	474.			1	10
				SHNT	0.00	0.00	7	553.41	153.66	563.			1	12
				RESO	.00	-0.00	11	-454.29	-39.22	456.			1	13
							31	-564.23	-156.68	525.		1.070	1	14
7		0	.981	-0.7	.00	.00								
		0		LOAD	233.80	84.00	6	-551.47	-84.97	558.			1	12
				SHNT	0.00	0.00	8	317.67	.97	316.			1	15
				RESO	-0.00	-0.00								

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3, SLING BUS = 49.

X----- BUS DATA -----X														
FROM	NAME	AC	VOLTS	ANGLE	-- GEN/LOAD --		TO	NAME	MW	MVAR	LDG	PCT 0	CI.	BR.
BUS					MW	MVAR	BUS					CAP L	TAP	NO.
3		0	.979	-1.6	.00	.00	5		-476.27	-45.53	476.			1 11
		0		LOAD	522.00	176.00	7		-317.25	-3.64	317.			1 15
				SHNT	0.00	0.00	9		271.13	-122.63	292.			1 16
				RESO	.00	-.00								
9		0	1.017	-7.4	0.00	0.00	8		-269.50	116.96	264.			1 16
		0		LOAD	0.00	0.00	39		269.50	-116.96	264.			1 17
				SHNT	0.00	0.00								
				RESO	.00	-.00								
10		0	1.005	5.5	0.00	0.00	11		448.92	87.89	457.			1 18
		0		LOAD	0.00	0.00	13		201.08	71.97	214.			1 19
				SHNT	0.00	0.00	32		-650.00	-159.86	665.	1.070		1 20
				RESO	.00	-.00								
11		0	.999	4.4	0.00	0.00	6		455.76	40.69	455.			1 13
		0		LOAD	0.00	0.00	10		-440.09	-80.28	455.			1 18
				SHNT	0.00	0.00	12		-7.67	43.59	44.			1 21
				RESO	.00	-.00								
12		0	.987	4.6	.00	.00	11		7.70	-42.74	43.	1.056		1 21
		0		LOAD	8.50	88.00	13		-16.25	-45.26	40.	1.056		1 22
				SHNT	0.00	0.00								
				RESO	.00	-.00								
13		0	1.001	5.0	0.00	0.00	10		-200.50	-77.34	215.			1 19
		0		LOAD	0.00	0.00	12		16.14	46.31	49.			1 22
				SHNT	0.00	0.00	14		184.55	31.53	187.			1 23
				RESO	.00	-.00								
14		0	.996	3.9	0.00	0.00	4		304.67	10.31	311.			1 9
		0		LOAD	0.00	0.00	13		-184.33	-44.61	190.			1 23
				SHNT	0.00	0.00	15		-120.34	-15.70	121.			1 24
				RESO	.00	-.00								

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3, SING BUS = 39.

X-----BUS DATA-----X

FROM BUS	NAME	AC	VOLTS	ANGLE	-- GEN/LOAD --		TO BUS NAME	VV	MVAR	LOG	PCT D CAP L	TA	ST. VO.	BR. NO.
15		0	.998	5.4	.00	.00								
		0		LOAD	320.00	155.00	14	120.00	-17.47	102.			1	24
				SHNT	0.00	0.00	16	-440.00	-135.53	461.			1	25
				RESO	-0.00	-0.00								
16		0	1.014	7.7	.00	.00								
		0		LOAD	329.40	32.30	15	442.50	138.09	464.			1	25
				SHNT	0.00	0.00	17	51.72	90.16	104.			1	26
				RESO	-0.00	-0.00	19	-450.02	-112.05	485.			1	27
							21	-329.39	-25.37	130.			1	28
							24	-42.02	-123.13	133.			1	29
17		0	1.005	7.5	0.00	0.00								
		0		LOAD	0.00	0.00	14	-50.64	-102.81	115.			1	26
				SHNT	0.00	0.00	18	367.43	-4.74	367.			1	30
				RESO	-0.00	-0.00	27	-316.48	107.74	334.			1	31
18		0	1.003	5.8	.00	.00								
		0		LOAD	158.00	50.00	3	208.49	-32.58	211.			1	7
				SHNT	0.00	0.00	17	-366.49	2.58	366.			1	30
				RESO	-0.00	-0.00								
19		0	1.043	12.4	0.00	0.00								
		0		LOAD	0.00	0.00	16	454.22	120.17	470.			1	27
				SHNT	0.00	0.00	20	174.80	-28.16	177.	1.000		1	33
				RESO	.00	-0.00	33	-629.82	-92.00	636.	1.070		1	32
20		0	.987	11.0	.00	.00								
		0		LOAD	680.00	103.00	15	-174.97	32.63	176.			1	33
				SHNT	0.00	0.00	34	-905.43	-125.63	903.	1.015		1	34
				RESO	-0.00	-0.00								

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3, SWING BUS = 39.

X-----B U S D A T A-----X

FROM BUS	NAME	AC	VOLTS	ANGLE	-- GEN/LOAD --		TO BUS NAME	PW	MVAR	LDG	PCT D CAP L	TAP	CT. NO.	BR. NO.
21		0	1.019	10.2										
22		0	1.043	14.7										
23		0	1.038	14.5										
24		0	1.021	7.8										
25		0	1.042	10.5										
26		0	.994	15.9										
27		0	.990	10.8										

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3 SWING BUS = 59.

X-----BUS DATA-----X													
FROM	NAME	AC	VOLTS	ANGLE	-- GEN/LOAD --		TO	BUS NAME	PW	MVAR	LOC	PCT C	CT. BR.
					MW	MVAR						CAP L	TAP NO. NO.
28		0	.984	30.1	.00	.00	26		504.16	-41.57	506.		1 43
		0		LOAD	206.00	27.60	29		-710.16	13.97	710.		1 45
				SHNT	0.00	0.00							
				RESO	.00	-.00							
29		0	.996	36.4	.00	.00	26		556.40	1.36	556.		1 44
		0		LOAD	283.50	26.90	28		717.46	40.35	719.		1 45
				SHNT	0.00	0.00	38		-1559.36	-68.65	1561.	1.025	1 46
				RESO	.00	-.00							
30		0	1.048	9.4	250.00	303.18R	2		250.00	303.18	303.		1 5
		0		LOAD	0.00	0.00							
				SHNT	0.00	0.00							
				RESO	-.00	.00							
31		0	.982	11.1	573.23	260.77R	6		564.23	256.17	612.		1 14
		0		LOAD	9.20	4.60							
				SHNT	0.00	0.00							
				RESO	.00	.00							
32		0	.983	13.6	650.00	261.44R	10		650.00	261.44	701.		1 20
		0		LOAD	0.00	0.00							
				SHNT	0.00	0.00							
				RESO	.00	-.00							
33		0	.997	17.6	632.00	152.35R	19		632.00	152.35	610.		1 32
		0		LOAD	0.00	0.00							
				SHNT	0.00	0.00							
				RESO	.00	.00							
34		0	1.012	16.2	508.00	187.11R	20		508.00	187.11	541.		1 34
		0		LOAD	0.00	0.00							
				SHNT	0.00	0.00							
				RESO	.00	.00							

REPORT OF LOAD-FLOW CALCULATION

TOTAL ITERATIONS = 3, SAVING BUS = 39.

X-----BUS DATA-----X									
FROM	NAME	AC	VOLTS	ANGLE	-- GEN/LOAD --		TO	PCT C	CT. BR.
BUS	NAME	AC	VOLTS	ANGLE	MW	MVAR	BUS NAME	LOG	NO. NO.
35		0	1.049	14.5	650.00	235.98R			
		0		LOAD	0.00	0.00	22	650.00 235.98	1 37
				SHNT	0.00	0.00			
				RESO	.00	.00			
36		0	1.054	17.2	560.00	114.54R			
		0		LOAD	0.00	0.00	23	560.00 114.54	1 39
				SHNT	0.00	0.00			
				RESO	.00	.00			
37		0	1.028	11.9	540.00	27.38R			
		0		LOAD	0.00	0.00	25	540.00 27.38	1 41
				SHNT	0.00	0.00			
				RESO	.00	.00			
38		0	1.027	34.9	1330.00	258.02R			
		0		LOAD	0.00	0.00	29	1330.00 258.02	1 46
				SHNT	0.00	0.00			
				RESO	.00	.00			
39		0	1.030	-11.1	551.63	204.93S			
		0		LOAD	1104.00	250.00	1	-373.18 -23.96	1 2
				SHNT	0.00	0.00	9	-179.18 -21.11	1 17
				RESO	0.00	.00			

NOTE * UNDER OL COLUMN INDICATES LINE'S PCT. CAP. IS GREATER THAN 100 P.C.

0 XC= .100 XDP= .031 TCCP=10.200 HC= 42.0 PCTP= 100.0 VRTYP= 0 1
 BUS NO. 30 XG= .069 XQP= 0.000 TGCP= 0.000 D= 4.00 PCTG= 100.0 GOVTYP= 1
 UNIT ID RG= .000 XDPF= 0.000 TDOPF= 0.000 S1= .15 EASE= 100.
 XL= .013 XQPP= 0.000 TCOPP= 0.000 S2= .43 XP= 0.000

THE MACHINE TYPE USED TO REPRESENT THIS MACHINE IS 2

VOLTAGE REG TR= 0.00 KA= 5. TA= .06 TB= 0.00 TC= 0.00 VRMAX= 1.00 VRMIN= -1.00 PC= 0.00 XC= 0.00
 EXCITER TE= .25 KE= -.05 S1= .08 S2= .26 EFMAX= 0.00 EFMIN= 0.00
 DAMPING KF= .040 TF= 1.00

GOV SERVO K1= 210.0 T1= 0.00 T2= 0.00 T3= 0.00
 ENERGY SYSTM K2= 1.259 K3=-21.440 K4= 0.000 T4= .20 T5=74.40 T6= .565

0 XC= .295 XDP= .070 TDOP= 6.560 HC= 30.3 PCTP= 100.0 VRTYP= 0 1
 BUS NO. 31 XG= .282 XQP= .170 TGCP= 1.500 D= 9.75 PCTG= 100.0 GCVTYP= 1
 UNIT ID RG= .000 XDPF= 0.000 TDOPF= 0.000 S1= .07 EASE= 100.
 XL= .035 XGPP= 0.000 TGOFP= 0.000 S2= .39 XP= 0.000

THE MACHINE TYPE USED TO REPRESENT THIS MACHINE IS 4

VOLTAGE REG TR= 0.00 KA= 6. TA= .05 TB= 0.00 TC= 0.00 VRMAX= 1.00 VRMIN= -1.00 PC= 0.00 XC= 0.00
 EXCITER TE= .41 KE= -.63 S1= .66 S2= .88 EFMAX= 0.00 EFMIN= 0.00
 DAMPING KF= .057 TF= .50

GOV SERVO K1= 110.1 T1= 0.00 T2= 0.00 T3= 0.00
 ENERGY SYSTM K2= 1.000 K3= .755 K4= 0.000 T4= .45 T5= .19 T6=54.000

0 XQ= .250 XQP= .053 TDOP= 5.700 HC= 35.8 PCTP= 100.0 VPTYP= 0 1
 BUS NO. 32 XQ= .237 XQP= .089 TDOP= 1.500 D=10.00 PCTQ= 100.0 GOVTYP= 1
 UNIT ID RG= .000 XDPP= 0.000 TDOPP= 0.000 S1= .08 BASE= 100.
 XL= .030 XGPP= 0.000 TGOPP= 0.000 S2= .28 XP= 0.000

THE MACHINE TYPE USED TO REPRESENT THIS MACHINE IS 4

VOLTAGE REG TR= 0.00 KA= 5. TA= .06 TB= 0.00 TC= 0.00 VRMAX= 1.00 VRMIN= -1.00 RC= 0.00 XC= 0.00
 EXCITER TE= .50 KE= -.02 S1= .13 S2= .34 EFMAX= 0.00 EFMIN= 0.00
 DAMPING KF= .080 TF= 1.00

GOV SERVO K1= 43.4 T1= 0.00 T2= 0.00 T3= 0.00
 ENERGY SYSTEM K2= 1.000 K3= 1.000 K4= 0.000 T4= 3.00 T5= 5.00 T6= 5.000

0 XC= .262 XCF= .044 TDOP= 5.690 HC= 28.6 PCTP= 100.0 VRTYP= 0 1
 BUS NO. 33 XC= .258 XCF= .166 TDOP= 1.500 D=10.00 PCTC= 100.0 GOVTYP= 1
 UNIT ID RG= .000 XDPP= 0.000 TDOPP= 0.000 S1= .14 BASE= 100.
 XL= .030 XGPP= 0.000 TGOPP= 0.000 S2= .59 XP= 0.000

THE MACHINE TYPE USED TO REPRESENT THIS MACHINE IS 4

VOLTAGE REG TR= 0.00 KA= 5. TA= .06 TB= 0.00 TC= 0.00 VRMAX= 1.00 VRMIN= -1.00 RC= 0.00 XC= 0.00
 EXCITER TE= .50 KE= -.05 S1= .08 S2= .31 EFMAX= 0.00 EFMIN= 0.00
 DAMPING KF= .080 TF= 1.00

GOV SERVO K1= 119.5 T1= 0.00 T2= 0.00 T3= 0.00
 ENERGY SYSTEM K2= 1.000 K3= .750 K4= 0.000 T4= .24 T5= .18 T6= 10.000

0 XD= .670 XDP= .132 TDCP= 5.400 HC= 26.0 PCTP= 100.0 VRTYP= 0 1
 BUS NO. 34 XG= .620 XGP= .166 TQGP= .440 D= 3.00 PCTG= 100.0 GOVTYP= 1
 UNIT IC RG= .000 XDRP= 0.000 TCOFP= 0.000 S1= .15 BASE= 100.
 XL= .054 XQPP= 0.000 TQOPP= 0.000 S2= .60 XP= 0.000

THE MACHINE TYPE USED TO REPRESENT THIS MACHINE IS 4

VOLTAGE REG TR= 0.00 KA= 40. TA= .02 TB= 0.00 TC= 0.00 VRMAX=10.00 VRMIN=-10.00 RC= 0.00 XC= 0.00
 EXCITER TE= .79 KE= 1.00 S1= .67 S2= .91 EFMAX= 0.00 EFMIN= 0.00
 DAMPING KF= .030 TF= 1.00

GOV SERVO K1= 153.8 T1= 0.00 T2= 0.00 T3= 0.00
 ENERGY SYSTM K2= 1.000 K3= .533 K4= 0.000 T4= .12 T5= .15 T6= 9.640

0 XD= .254 XDP= .050 TDCP= 7.300 HC= 34.8 PCTP= 100.0 VRTYP= 0 1
 BUS NO. 35 XG= .241 XGP= .081 TQGP= .400 D=10.00 PCTG= 100.0 GOVTYP= 1
 UNIT IC RG= .006 XDRP= 0.000 TCOFP= 0.000 S1= .09 BASE= 100.
 XL= .022 XQPP= 0.000 TQOPP= 0.000 S2= .25 XP= 0.000

THE MACHINE TYPE USED TO REPRESENT THIS MACHINE IS 4

VOLTAGE REG TR= 0.00 KA= 5. TA= .02 TB= 0.00 TC= 0.00 VRMAX= 1.00 VRMIN= -1.00 RC= 0.00 XC= 0.00
 EXCITER TE= .47 KE= -.04 S1= .06 S2= .25 EFMAX= 0.00 EFMIN= 0.00
 DAMPING KF= .075 TF= 1.25

GOV SERVO K1= 130.8 T1= 0.00 T2= 0.00 T3= 0.00
 ENERGY SYSTM K2= 1.000 K3= 1.000 K4= 0.000 T4= 3.00 T5= 5.00 T6= 5.000

0 XC= .295 XDP= .049 TDCP= 5.660 HC= 26.4 PCTF= 100.0 VRTYP= 0 1
 PLS NO. 36 XG= .292 XQP= .186 TQOP= 1.500 D= 8.00 FCTQ= 100.0 GOVTYP= 1
 UNIT ID RG= .030 XDPP= 0.000 TDOPP= 0.000 S1= .14 BASE= 100.
 XL= .032 XQPF= 0.000 TQCPP= 0.000 S2= .53 XP= 0.000

THE MACHINE TYPE USED TO REPRESENT THIS MACHINE IS 4

VOLTAGE REG TR= 0.00 KA= 40. TA= .02 TB= 0.00 TC= 0.00 VRMAX= 6.50 VRMIN= -6.50 PC= 0.00 XC= 0.00
 EXCITER TE= .73 KE= 1.00 S1= .53 S2= .74 EFMAX= 0.00 EFMIN= 0.00
 DAMPING KF= .030 TF= 1.00

GOV SERVO K1= 117.3 T1= 0.00 T2= 0.00 T3= 0.00
 ENERGY SYSTM K2= 1.000 K3= .500 K4= 0.000 T4= .20 T5= .18 T6= 7.500

0 XC= .290 XDP= .057 TDCP= 6.700 HC= 24.3 PCTF= 100.0 VRTYP= 0 1
 PLS NO. 37 XG= .280 XQP= .091 TQCP= .410 D= 9.00 FCTQ= 100.0 GOVTYP= 1
 UNIT ID RG= .001 XDPP= 0.000 TDOPP= 0.000 S1= .08 BASE= 100.
 XL= .028 XQPF= 0.000 TQOPP= 0.000 S2= .27 XP= 0.000

THE MACHINE TYPE USED TO REPRESENT THIS MACHINE IS 4

VOLTAGE REG TR= 0.00 KA= 5. TA= .02 TB= 0.00 TC= 0.00 VRMAX= 1.00 VRMIN= -1.00 PC= 0.00 XC= 0.00
 EXCITER TE= .53 KE= -.05 S1= .07 S2= .28 EFMAX= 0.00 EFMIN= 0.00
 DAMPING KF= .065 TF= 1.26

GOV SERVO K1= 107.5 T1= 0.00 T2= 0.00 T3= 0.00
 ENERGY SYSTM K2= 1.000 K3= 1.000 K4= 0.000 T4= 3.00 T5= 3.00 T6= 4.000

0 XD= .211 XDP= .057 TDOP= 4.790 HC= 34.5 PCTP= 100.0 VRTYP= 0 1
 BUS NO. 38 XC= .205 XGF= .059 TGCP= 1.960 D=14.00 PCTQ= 100.0 GOVTYP= 1
 UNIT ID RG= .000 XDPP= 0.000 TDOPF= 0.000 S1= .11 EASE= 100.
 XL= .030 XGPP= 0.000 TGOFP= 0.000 S2= .45 XF= 0.000

THE MACHINE TYPE USED TO REPRESENT THIS MACHINE IS 4

VOLTAGE REG TR= 0.00 KA= 40. TA= .02 TB= 0.00 TC= 0.00 VRMAX=10.50 VRMIN=-10.50 FC= 0.00 XC= 0.00
 EXCITER TE= 1.40 KE= 1.00 S1= .62 S2= .85 FFMAX= 0.00 EFFMIN= 0.00
 DAMPING KF= .030 TF= 1.00

GOV SERVO K1= 165.5 T1= 0.00 T2= 0.00 T3= 0.00
 ENERGY SYSTM K2= 1.000 K3= .720 K4= 0.000 T4= .38 T5= .10 T6= 6.000

0 XC= .020 XDF= .006 TDOP= 7.000 HC=500.0 PCTP= 100.0 VRTYP= 0 0
 BUS NO. 39 XC= .019 XGP= .008 TGOP= .700 D=10.00 PCTQ= 100.0 GOVTYP= 0
 UNIT ID RG= .000 XDPP= 0.000 TDOPF= 0.000 S1= 0.00 EASE= 100.
 XL= .003 XGPP= 0.000 TGOFP= 0.000 S2= 0.00 XF= 0.000

THE MACHINE TYPE USED TO REPRESENT THIS MACHINE IS 4

10SYNCHRONOUS MACHINES.

SUMMARY OF SYNCHRONOUS MACHINE INITIAL CONDITIONS

BUS NO.	BUS NAME	UNIT ID.	GENERATOR ANGLE DEG	INTERNAL VOLTAGE	CURRENT	TERMINAL VOLTAGE	TURBINE POWER MW	FIELD VOLTAGE
30		0	2.24	1.09 3.65	2.76 -34.71	1.05 -4.61	250.107	1.441
31		0	43.79	1.12 32.82	6.21 -19.86	.98 0.00	574.270	2.505
32		0	45.87	1.11 24.55	6.94 -15.96	.98 1.60	651.876	2.361
33		0	49.93	.92 39.32	6.43 -7.73	1.00 2.05	632.510	2.273
34		0	52.61	1.37 31.22	5.28 -17.59	1.01 .61	508.391	4.453
35		0	43.42	1.18 22.91	6.51 -13.97	1.05 4.02	676.089	2.457
36		0	49.59	1.00 42.30	5.35 -3.46	1.06 6.71	560.773	2.334
37		0	53.24	1.01 22.34	5.25 1.05	1.03 1.12	541.849	1.931
38		0	59.37	1.14 30.63	8.09 4.85	1.03 6.41	831.963	2.178
39		0	-1.13	1.04 -6.87	9.75 -16.14	1.03 -11.12	1000.950	1.066

SUMMARY OF SYNCHRONOUS MACHINE INITIAL CONDITIONS

BUS NO.	BUS NAME	UNIT ID.	GENERATOR ANGLE DEG	INTERNAL VOLTAGE	CURRENT	TERMINAL VOLTAGE	TURBINE POWER MW	FIELD VOLTAGE
30		0	6.42	1.10 2.22	2.94 -35.69	1.05 .11	250.121	1.482
31		0	46.35	1.13 36.31	6.25 -17.05	.98 3.77	574.283	2.534
32		0	49.40	1.11 28.45	6.97 -12.80	.98 5.64	651.895	2.384
33		0	54.72	.93 44.37	6.45 -3.19	1.00 7.31	632.914	2.290
34		0	57.54	1.38 36.37	5.29 -12.71	1.01 5.67	508.392	4.475
35		0	48.35	1.19 22.08	6.54 -9.42	1.05 9.30	676.309	2.476
36		0	54.57	1.00 47.43	5.36 1.31	1.06 11.99	560.775	2.348
37		0	58.25	1.02 27.68	5.25 5.86	1.03 6.53	541.850	1.942
38		0	75.51	1.24 49.48	10.58 14.35	1.03 20.38	1083.358	2.806
39		0	-3.46	1.04 -7.86	7.59 -21.06	1.03 -11.12	770.536	1.067

SUMMARY OF SYNCHRONOUS MACHINE INITIAL CONDITIONS

BUS NO.	BUS NAME	UNIT ID.	GENERATOR ANGLE DEG	INTERNAL VOLTAGE		CURRENT		TERMINAL VOLTAGE		TURBINE POWER MW	FIELD VOLTAGE
30		0	11.27	1.12	12.66	3.26	-38.11	1.25	4.76	250.148	1.543
31		0	49.73	1.14	39.57	6.31	-14.87	.98	7.48	574.386	2.582
32		0	52.54	1.12	32.20	7.93	-10.26	.98	9.62	651.928	2.422
33		0	59.11	.94	49.29	6.47	.78	1.00	12.59	632.922	2.322
34		0	52.15	1.39	41.37	5.31	-8.19	1.01	11.04	509.395	4.514
35		0	52.90	1.19	33.11	6.59	-5.44	1.05	14.51	576.710	2.510
36		0	59.25	1.01	52.40	5.37	5.65	1.06	17.21	560.780	2.371
37		0	52.18	1.03	52.81	5.26	9.91	1.03	11.91	541.854	1.982
38		0	88.94	1.38	67.39	13.20	23.89	1.03	34.87	1335.226	3.597
39		0	-5.59	1.04	-8.80	5.71	-31.50	1.03	-11.12	551.955	1.076

SUMMARY OF SYNCHRONOUS MACHINE INITIAL CONDITIONS

BUS NO.	BUS NAME	UNIT ID.	GENERATOR ANGLE DEG	INTERNAL VOLTAGE		CURRENT		TERMINAL VOLTAGE		TURBINE POWER MW	FIELD VOLTAGE
30		0	15.53	1.14	17.80	3.75	-41.12	1.05	9.37	250.197	1.627
31		0	52.10	1.16	42.82	6.41	-13.32	.98	11.14	574.340	2.653
32		0	55.29	1.14	35.81	7.13	-8.36	.98	13.55	651.981	2.479
33		0	53.07	.46	53.81	6.52	4.89	1.00	17.64	632.935	2.370
34		0	56.47	1.40	46.24	5.35	-4.05	1.01	16.17	508.400	4.574
35		0	57.15	1.31	38.01	6.67	-2.10	1.05	19.59	677.371	2.562
36		0	53.70	1.02	57.21	5.40	9.51	1.06	22.39	560.788	2.408
37		0	55.00	1.06	37.74	5.29	10.22	1.03	17.32	541.878	2.062
38		0	100.59	1.55	84.97	16.06	33.87	1.03	50.47	1587.739	4.719
39		0	-7.78	1.05	-9.68	4.44	-51.72	1.03	-11.12	347.277	1.090

Appendix D

STATIC VAR COMPENSATION ON TRANSMISSION SYSTEMS

BASIS OF DISCUSSION

1. What sort of VAR control problems has your transmission system experienced, or anticipate?
2. What has been your general philosophy towards the solution of these problems?
 - Have series capacitors been considered?
 - High speed reclosing?
 - Have fixed or switched shunt reactors and capacitors been applied?
 - Is LTC on transformers relied upon heavily?
 - Are synchronous machines used to absorb VARS?
3. What features are most important for your system compensation needs? (e.g. continuous control of reactive power, speed of response, reliability, maintainability, single phase control, etc.)
4. What concerns, if any, do your planning and operating organizations have regarding the use of static VAR compensation?
5. In studying the feasibility of static VAR compensation, of what importance are operational and economic benefits such as improved system efficiency, lowered transmission losses, increased transmission capability, and possibly deferred transmission expansion?
6. In general, what are your plans for transmission expansion?
 - Is single pole switching under consideration?
 - Is HVDC being considered?
 - What contingencies are included in your stability criteria?
7. If utilized, would static VAR compensation be connected to line, bus, or transformer tertiary?
 - What are your typical transformer sizes and associated tertiary ratings?
8. Approximately what range of short circuit capacities do you anticipate at HV buses?
9. For the automatic control of shunt compensation, what control variables and strategies seem to offer the most advantages for your system?

Summary of Meeting with Philadelphia Electric Company

(August 14, 1980 with Messrs. Hunt, Palmer, Louie, Braid, Brecht, and Blake of Philadelphia Electric, and Mr. J. Willson of PJM Interconnection Office)

Character of Utility's System; Impacts on VAR Control; Philosophy of VAR Control

P.E. imports about 30 percent of its energy mainly over an east-west 500 kV system from generation utilizing Western PA coal (and others). Although there is some 66-kV and some 128-kV cable in the system, the reactive characteristics of the overhead transmission greatly outweigh those of the underground. Therefore, PE has experienced few reactive problems associated with cable.

Load diversity is characterized roughly as 30% (in KW-hr) residential, 35% large industrial (including some large arc furnaces), and 35% commercial. System power factor is approximately 95%. Large customers are required by contract to correct power factor. To date, shunt capacitors (up to 34.5 kV) have been applied by PE in some load areas and switched by dispatcher control.

Recently, with the economic pressure to minimize the use of oil-fired generation, large shunt capacitor banks are being considered for application at 230 kV to replace the loss of these larger sources of dynamic VARs and permit an increased importation of power.

Load Tap Changers (LTC) has been supplied on almost all the larger (230/500 kV) tie transformers. However, because of negative impacts of VAR flows in neighboring interconnected utilities, LTCs are fixed by system operators and only adjusted for contingency situations to support the 230 kV system. Such an operating practice also serves to keep reactive power reserves in the generator for added contingencies.

System Voltage Levels

HV buses, (69, 138 and 230 kV) have been essentially unregulated. P.E. has not practiced voltage scheduling by any formal reactive power dispatching, to date. However, since the presently identified indicators of system security is the voltage level of 230 kV buses and the expected voltage drop for the worst critical contingency considerations are being given to regulating this bus. (The 500 kV system operates typically between 525 kV and 500 kV. The system can be operated at 10% below nominal, although such operation could create stability problems. On the other hand, only a 5% reduction in 230 kV system voltage is permissible. PJM 500 kV lines (averaging 50 miles in length) have contingency loadings 2 to 3 times SIL. Certain operating restrictions in the West limit higher voltages on the 500 kV system.

Synchronous Condensers

Few synchronous condensers are now in operation because of high cost, although one newer 167 kV MVAR condenser is still in service. However, the voltage regulator on this unit is at most times disabled. Also, losses are estimated at 1/2 to 1 MW not including the coupling transformer losses. The one-minute overload capability of synchronous condensers is recognized as an advantage. Maintenance requirements continue to be a major detractor from their use.

Considerations of Large VAR Sources Including Static VAR Compensators

A basic question being considered in the installation of the large amounts of shunt capacitive compensation is what proportion of total system capacitive shunt compensation should be continuously controllable (i.e., SVC). It is too early to be considering standardization of SVC size, but P.E. feels confident about their use. Preliminary considerations are being given to switched capacitor installations of 100 to 300 MVAC switched in 50 to 150 MVAC blocks as predicated by available switching devices.

A simplistic study methodology is needed by the industry to size and locate large shunt capacitor banks. Also needed is rapid real time control of VAR flow. In the past, system operators automatically dispatched MWs, and had MW flow primarily in mind. Changes in MWs were generally slow enough to be followed by the system dispatchers. However, during heavy system load conditions, VAR changes and requirements to support voltage can be so rapid that the dispatcher has too little time to make interconnected system-oriented decisions, and some means to automatically dispatch MVARs is needed.

One scenario of future system operation of eastern PJM is that all base (oil-fired) generation would be removed from service, with local generation being available only for peaking demands. Western coal energy resources would then be utilized to as full an extent as the transmission system would permit; i.e., the transmission system would be operated up to the thermal limits of lines and equipment. Problems associated with this mode of operation have not been fully quantified, but IX voltage drop across the 500 kV system would most likely exceed permissible ranges. Series capacitors have been investigated as a potential solution to the VAR restrictions of PJM, but do not appear to be cost effective due to extremely high loading levels (i.e., 3 SIL). Shunt compensation seems a more viable alternative.

By 1983, transmission system growth could relieve VAR demands in eastern Pennsylvania. Nonetheless, PJM could utilize fast-acting VAR devices for VAR support during contingency or emergency conditions. At this time, PE is uncertain of the value of speed of response.

Additional Applications of SVCs

Future expansions and modifications of electrified eastern railroad systems, and their impact on unity demand, could require use of SVCs or other solid state devices. These systems generally represent irregular single, or phase-to-phase loads to the utility.

Summary of Meeting with General Public Utilities

(August 15, 1980 with Messrs. Massey, Scarf, Matijasich, and Barrick)

Character of Utility System

GPU is charged with the bulk-power planning activity for, and is the holding company of, three operating utilities: Jersey Central, Metropolitan Edison, and Penelec. GPU does studies for and with the individual companies and coordinates efforts in the PJM "bulk power system." GPU participates with PJM in conducting broad system studies of load flow, stability, etc. Major GPU generation in this system is usually jointly owned by the GPU operating companies and PJM.

System Voltage Levels

A voltage criterion of 5 percent post-contingency voltage drop has been established from load flow studies to provide safe margins in system operation. Normally voltage levels during system operation are 5 percent above nominal in the western 500-kV area with a 5 percent drop across the system.

Voltage/VAR Control

Reactive problems exist presently in PJM due to heavy west to east power transfer. Jersey Central has recognized these voltage problems at 230 kV loads and has already added shunt compensation.

All 500/230 kV transformers have LTC, but taps are changed only on operator command and in the event of a significant disturbance. Peak-load and light-load voltage scheduling has been done at the generators. Tap settings are established from load flow studies at peak and light load, with further voltage level variability achieved by changing excitation in the generators. In any event, changes in transformer taps are always coordinated through PJM.

Three areas of voltage problems in the BPU system are anticipated:

- 1) In Jersey Central when Oyster Creek generation (i.e., 600 MW) is off.
- 2) In the northeast division of PENELEC, since there is essentially no generation in this area.
- 3) In the eastern division of PENELEC (Lewistown) on the 230 kV system after a loss of 500 kV transmission. There is no generation in this area, and only one 230 kV line interconnects this area of PENELEC to PP&L.

VAR Compensation Needs

The PJM VAR deficiency problem is unique in that existing transmission and generation facilities are adequate to meet stringent reliability criteria (e.g., 1 day in 10 years), but economic dispatch involves removing eastern PJM oil-fired generation in favor of western coal-fired generation. Resulting 500 kV transmission loadings create voltage problems in the eastern PJM system. Shunt capacitive or SVC compensation is seen as a possible solution, but study tools to determine where to locate such compensation and how to partition between fixed and controllable compensation are unavailable.

Other Potential VAR Problems

Railroad electrification will present an unusual sporadic, single-phase load to Jersey Central. In the northwestern corner of the GPU system, an HVDC intertie with Ontario Hydro could create the need for SVC compensation.

Summary of Meeting With Basin Electric Power Cooperative

(August 26, 1980, with Messrs. Robert Newell and Larry W. Allen)

Character of Utility System

Basin Electric Power Cooperative was organized in 1961 to operate power plants in the Dakotas and Wyoming and as a regional wholesale power supplier for REC's in 8 Missouri River Basin states. Most generation is coal fired, cooled with water. Although one-fourth of system generation is hydro, none of this is operated by Basin Electric.

Power is delivered through a coordinated 8600-mile regional Joint Transmission System (JTS) developed by the federal government and consumer-owned power systems used by WAPA generation. Included in JTS are 530 miles of 345 kV transmission lines and facilities constructed and owned by Basin Electric. One 299-mile line, from the Antelope Valley Generating Station near Beulah, North Dakota, to the Broadland Substation near Huron, South Dakota, is being constructed for 500 kV, but will initially be operated at 345 kV. The majority of the load, however, is on 115 kV and 230 kV systems. The federal government's contribution to the JTS is approximately 7,000 miles of 345, 230, and 115 kV lines.

Seasonal diversity across the area covered by Basin Electric is possible due to differences in timing of crop irrigation in the southern part (western Nebraska) and heating load during the winter season. The area includes 9 distributing utilities, all more or less operating individually but drawing power generated in the coal fields in western North Dakota.

The Transmission System, Its VAR Control and Load Characteristics

Some Coops in western Nebraska have significant irrigation loads, but otherwise, except for a DC tie at Stegall near Vistory Hill, no particularly peculiar loads were cited. Basin Electric looks to the coops

to provide their own power factor compensation, and Basin plans on the basis of having 95 percent power factor or better at the load areas.

There are very few synchronous condensers in the system; Western Area Power Administration (WAPA), for example, has one at Fargo, but this will probably be replaced. No VAR problems have been experienced when any of the hydro generation has been out of service. Locally controlled LTCs are on 230 and 115 kV transformers, but none are on the 345 kV system. Basin Electric and WAPA conduct the studies for determining no-load tap positions from the bulk transmission system. Although there is a WAPA-Basin in Electric system dispatch center at Watertown, each of the connected companies has its own dispatch center, and there is no central control of system VAR flow. Voltage loads near generation are kept within approximately ± 3 to $3\frac{1}{2}$ percent, and an attempt is made to keep voltages within a 5 percent band at the load end of the transmission system.

Both line-connected and transformer-tertiary-connected reactors are used, with the tertiary-connected reactors being sometimes switched to control voltage. In the Watertown area, consideration is being given to switching off line-connected shunt reactors to utilize the capacitance of the transmission line for voltage support during loaded conditions. Conventionally-switched HV capacitors have not been considered, nor has there been a requirement to replace the VARs lost when a transmission line is switched off, since there are excess VARs presently in the transmission system as evidenced by the need to use shunt reactors. Also, some 345 kV lines have been taken out of service for voltage control when some of the generation was off.

The 500 kV transmission line between the generation complex near Antelope Valley, North Dakota, and the Huron Substation in South Dakota is being built in preparation for additional generation in 1988 in the North Dakota coal fields and as a start on establishing a 500 kV grid. Large loads of several hundred MWs are developing in South Dakota and Nebraska. The loads are presently being served by 345 kV lines terminating in the

Watertown and Ft. Thompson substations. The choice of a 500 kV voltage level for the third line was influenced, to some extent, by the plans of neighboring power pools. Preliminary studies by Basin and by these neighboring power pools of the development of large generation sites, utilizing North Dakota coal, have considered 500-kV with static VAR compensation. The Mid-Continent Area Power Pool (MAPP) considers the primary advantage of SVC application to be stability enhancement and not steady state voltage support. Only the close-knit Iowa utilities have given little attention to the use of SVCs. The nine utilities included in the Basin area have been agreeable to considering application of SVCs.

Included in the JTS system are a back-to-back DC tie of 110 MW to the Western system and two DC lines into Minnesota. The DC tie at Stegall was built by Tri-State, a member of Basin Electric, as part of a cooperative venture. Basin Electric has a 35-year lease on the capacity of this tie. The existing SVC, supplied by the General Electric Co. near Victory Hill, is close to this DC tie and assists in VAR support in that area.

Because of the tight electrical connections in the generating area made up of Antelope, Garrison, and other neighboring plants, faults on this "bus" have caused shut-downs of the DC system to Minnesota, affecting system stability and loads at some distance from the generation. Faults on the 345 kV lines parallel to the DC out of the same area also cause DC shut-down. Basin Electric representatives do not expect an SVC to totally solve the voltage collapse problem. Considerably more generation is to be added over the next several years (1600 MW by 1984-85), and the resulting faults in this area can be much more significant.

What system conditions would "trigger" recognizing a need for SVC?

Future needs for SVCs will be tied to generation additions and the requirements to increase loading on the existing transmission system. Siting studies have been done independently of transmission studies,

so there may be a need to operate closer to steady state stability limits. First swing stability is the primary concern which necessitates VAR support at the receiving ends of the lines. For example, Basin planning studies for 1985 indicate potential stability problems at Watertown and Huron if one of the three major north-south transmission links (e.g. two 345 kV lines and one 500 kV line) is lost due to a fault.

While studying operation of the 500-kV line from Antelope Valley to Huron, series compensation of 35 and 50 percent was first considered. With two large generators in the coal fields, 50 percent was needed, but this alternative was rejected in favor of an SVC concurrent with the first 500 MW of generation. However, when a second 500 MW come on line, the SVC would be inadequate, and 35 percent compensation on all three EHV lines (345 to 500 kV) will be considered.

Other Uses of SVCs

(The Basin Electric representatives had no other suggestions for other uses of SVCs.)

Where would shunt VAR Compensation be located? Would size of compensation be standardized?

The sites presently being considered include both the Watertown and Huron stations. In the Watertown load area there presently exist voltage problems during swings. But perhaps the most critical contingency will be the loss of the 500-kV line (initially operated at 345 kV).

The rationale for selecting two SVCs rather than one relates to the need to support three line terminals during fault initiated swings. The Big Bend generating facility, being sufficiently close, provides required VAR support at Ft. Thompson. No such support is available at Huron or Watertown. Initial estimates indicate a need for 250 MVAC of controlled,

and 150 MVAC of switched capacitance at Watertown, and 150 MVAC of controlled with 100 MVAC of switched capacitance at Huron.

Some transformer tertiaries would be available for connecting an SVC to the system, but the tertiary capacity is generally 20 percent or less. Thus, Basin does not have the option of using tertiary-connected SVCs of the larger sizes anticipated. There is a 345 to 115 kV step-down load tap at Groton that has been discussed for a possible tertiary connected SVC.

Is there a need for the fast response capability of the SVC? Are there any concerns about the use of SVCs?

In the Watertown area, during system swings, a significant VAR effect is needed within a few cycles. Although the critical response times had not been determined, 4 or 5 cycle response has been deemed too long for this application. Since 345 or 500 kV lines are not reclosed following fault clearing, there could be a need for rapid capacitive VAR compensation. Positive sequence voltage control is being considered, with control ties among SVCs if they are electrically close. The reason that Basin has not given thought toward finalizing controls is the lack of modeling tools for other than voltage control. At this time, they have not gotten to the point of optimization in their planning studies.

Because of severe problems associated with certain loads in the Basin area, utilities have been most appreciative of the ability of SVCs to alleviate these problems, and SVC concerns have been overshadowed. Such concerns may dictate having several smaller units. The generally good performance of the SVC at Victory Hill has alleviated some of the concern.

Summary of Meeting With Western Area Power Administration (Western)

(August 27, 1980, with Western's Engineering Personnel)

Western Area Power Administration Attendees

Robert Krahn, Assistant Administrator for Engineering

Lloyd Greiner, Director, Division of System Engineering

Gordon McCone, Chief, System Studies Branch, Division
of System Engineering

Ivor McCoy, Technical Branch, Division of System Engineering

Jim Tomsic, System Studies Branch, Division of System
Engineering

Don Voelker, Division of Operation and Maintenance

Character of Western's System

Western was established December, 1977, with the responsibility for the federal electric bulk power marketing and transmission operation and maintenance systems in 15 central and western states. Western sells wholesale power to cooperatives, municipalities, public utility districts, as well as private utilities, irrigation districts and government agencies. The 8050 MW for which Western coordinates transmission is generated at hydro plants owned by the Water & Power Resources Service, the Corps of Engineers, and the International Boundary and Water Commission and at the Navajo coal-fired plant near Page, Arizona. In its capacity of transmission marketing, Western sets rates and payment, and is allowed to enter into pooling agreements.

System Operational and VAR Control Philosophy

The system is a bulk transmission system essentially delivering power at 69 kV and higher. Therefore, primary concerns are of bulk power transfer capacity and efficiency, especially for the long lines emanating from hydro plants. High-speed reclosing for single-line-ground faults

has generally been practiced on Western's high-voltage lines. Normally on 230 kV lines, total trip and reclose time is 20 cycle (dead-time). However, because of longer dead times usually required on EHV the longer 345 kV lines have not been high-speed reclosed, nor has any application of single-pole switching been made.

The character of the system varies from extremely long lines to some "tight" transmission configurations (e.g., around Denver). Voltage scheduling practices range from 95 to 105 percent with the system intact. (This, however, is not necessarily an operating criterion.) LTCs are changed by dispatchers as required. Power factors of at least 95 percent are required of customers.

In planning new interconnections, VAR flow is minimized. Loop flow in the southwest over WAPA lines has created some operating problems and led to installing phase-angle regulators in order to control flow.

There are very few synchronous condensers still in operation on the system. Most are 30 or 40 years old and are unreliable.

On the average, Western transmission lines are loaded less than SIL. However, there are some transmission "bottle-necks" which are loaded well above SIL. A principal thrust over the next several years is to remove these "bottlenecks" by upgrading transmission. For example, in Wyoming and Colorado there have been relatively long lines loaded well beyond their desired limit with consequence of low voltage in load areas near the middle of these lines.

Load Peculiarities and Var Control Problems Experienced

Load areas generally do not include heavy industry; however, there are extensive irrigation loads, some of which operate on a 24 hour basis during the irrigation season. Therefore, voltage problems associated with loads have been minimal, and load changes are so moderate that operators can compensate with changes in transformer taps.

The hydro system is cycled with the load, with some hydro generation being taken off during marginal loading conditions. An operating practice in South Dakota has been to switch out some circuits during light load since the preference is to avoid motoring hydrounits merely for VAR absorption.

Many local load areas are growing so rapidly that the existing 115 kV is becoming inadequate. In such cases, shunt capacitors have been applied for voltage support during line outage conditions. But in general, the system has been sufficiently "capacitive" to require shunt reactors.

In North Dakota, system voltage sensitivity has required keeping 2-30 MVAR synchronous condensers in service. Elsewhere there are numerous shunt reactors, many on transformer tertiaries switched for voltage vernier control. In other locations, capacitors are switched by dispatchers in single blocks as large as 10 MVAR. Problems have been experienced in switching capacitors, because of the size of the step being switched, and the relative strength of the local system.

Series Capacitors Applications

Series capacitors are still being considered as a means to increase line transmission capacity. Usually such use is to alter the division of power between lines and improve stability using a fairly low amount of compensation. Since generation is basically hydro, there is little concern about SSR problems. However, where series capacitors are used in connection with thermal generation, the sizing and location of the capacitors have been selected to avoid SSR problems.

A concern in many areas is the need to minimize inadvertent power flow. This has motivated the application of both series compensation and phase-angle regulators.

Planning studies considering optimal utilization of all available generation indicate that too much intermediate voltage control would be

required if all series capacitors were replaced. These studies have identified broad benefits in applying SVCs. Western, therefore, sees a general trend toward the use of SVCs.

System Conditions that Would "Trigger" a Need for SVCs

SVCs provide a means of assuring full utilization of available hydro resources for the purpose of displacing some oil-fired generation. The emergence of voltage restraints on bulk power transfer, and any marked sensitivity of system transfer capability to voltage levels can likewise be addressed by SVCs because of their rapid response in the inductive or capacitive mode.

In heavily loaded areas and for line outage conditions, or where there are presently a large number of shunt reactors, the capacitive mode would be most desirable.

SVC size standardization was not viewed as practical by WAPA at the present time.

Possible SVC Locations

Western and Basin Electric are studying the North Dakota-South Dakota region for possible SVC application sites. Preliminary results indicate Fargo, ND to be a good application point for an SVG. The Watertown and Huron stations in SD are being considered as SVC locations to maximize capability of all transmission between North and South Dakota. The need and size for an SVC at Fargo, as opposed to fixed or switched capacitors, is somewhat dependent on the decision regarding Watertown and Huron, and on the finalization of MANDAN project plans.

As generation is added in North Dakota coal fields, there is a tendency to maximize use of existing and new transmission, such that, overall area reliability is reduced.

Options for upgrading transmission include the use of series capacitors or the construction of new lines. However, SSR potential restricts the use of series compensation, and the addition of strategically located SVCs can result in a sufficient transmission capacity increase to negate the necessity of additional lines. In other areas, such as across Arizona into Southern California or from Montana, as line loadings approach stability limits, additional lines may have to be added.

Another possible application relates to a small hydro plant feeding radially into a 161 kV line. With the loss of this line, load areas near the plant experience overfrequency and overvoltage. Installation of an SVC was considered for the purpose of absorbing capacitive VARs when the line is tripped so as to limit overexcitation. However, the least costly solution was to drop the hydro generation when the line opened and bring the hydro back on quickly. Future plans to upgrade this system to 230 kV may shift the economics back in favor of the SVC since load rejection problems will worsen.

SVCs have been considered for voltage and stability purposes at intermediate points on several long transmission lines. However, plans to add generation at some of these locations reduce the cost effectiveness of the SVC applications. Since there is limited intermediate generation near load areas in the eastern Dakotas, these areas looked like good candidate locations.

Is Fast Response of SVC Needed?

In general, Western plans for applying SVCs do not include line loadings far in excess of SIL because of the average 200+ mile line lengths of the system. However, even at these loadings, transient stability considerations dictate a requirement for fast response. Dynamic instability has been controlled through increased damping provided by d.c. modulation and power system stabilizers.

Concerns about SVC Application

System operators have expressed some concern over prospective SVC applications primarily from the standpoint of maintenance requirements. Performance evaluation of the Victory Hill SVC should be helpful in alleviating some of this concern.

Some concern was expressed over SVC harmonic generation especially at older stations where control circuitry interference could prove a significant problem. Perhaps the greatest concern expressed was over SVC cost, which Western feels may significantly affect their widespread application. It was also acknowledged that wider application would follow reduced cost of SVCs.

Other Applications

Other possible applications of SVCs are near hydro sites. Hydro generators are normally operated near unity power factor to maximize efficiency, and therefore generally not used for VAR supply. Also, in times of minimum water flow, machines usually are taken off line, and are unavailable to absorb VARs. If the units are used for voltage control under these conditions, there is an economic penalty which must be considered. SVCs can serve these VAR source and sink purposes. However, for the smaller 30 or 40 MW hydro plants, SVC applications may not be cost effective. Both the Corps of Engineers and the Water and Power Resources are studying the possibility of uprating units, or adding units, to produce more kilowatts from a given plant. SVCs may be applied near the uprated plants.

Western believes that "mobile" or "relocatable" SVCs of 10 to 50 MVAR or as large as 100 MVAR would be very useful for temporary installations during emergency or contingency conditions.