EMERGING PRACTICES IN TECHNOLOGY

Solid-State Synchronous Voltage Sources for Dynamic Compensation and Real-Time Control of AC Transmission Lines

by Laszlo Gyugyi

Background

This paper describes a novel approach in which solid-state synchronous voltage sources are employed for the dynamic compensation and real-time control of power flow in transmission systems. The synchronous voltage source is implemented by a multi-pulse inverter using gate turn-off (GTO) thyristors. It is capable of generating internally the reactive power necessary for network compensation, and is also able to interface with an appropriate energy storage device to negotiate real power exchange with the ac system. The paper develops a comprehensive treatment of power flow control using solid-state synchronous voltage sources for shunt compensation, series compensation, and phase angle control. It also describes the unique *unified power flow controller* that is able to control concurrently or selectively all three network parameters (voltage, impedance, transmission angle) determining power transmission. Comparison of the synchronous voltage source approach with the more conventional compensation method of employing thyristor-switched capacitors and reactors shows its superior performance (including the unmatched capability of using both reactive and real power compensation to counteract dynamic disturbances), uniform applicability, smaller physical size, and potentially lower overall cost.

Keywords

AC transmission, FACTS, line compensation, static var compensator, synchronous condenser, series compensator, phase-angle regulator, energy storage, thyristor, GTO.

Introduction

Alternating current transmission lines are characterized by their per-mile distributed circuit parameters: the series *resistance* and *inductance*, and the shunt *conductance* and *capacitance*. The characteristic behavior of the line is primarily determined by the series inductance *l* and shunt capacitance *c*. A lumped-element representation of a transmission line, together with the sending-end and receiving-end generators, is shown in Figure 1.

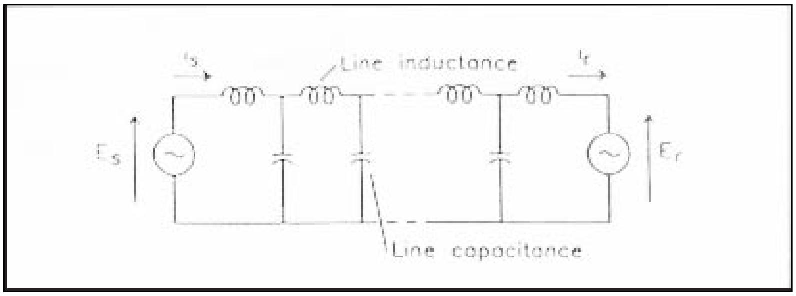


Figure 1— *Lumped element representation of a transmission line*

TRANSMISSION LINES

The transmittable electric power of the system shown in Figure 1 is defined by the following equation [B1]:

$$P = \frac{E_s E_r}{Z_0 \sin\theta} \sin\delta \qquad \text{(Eq. 1)}$$

in which

E_s is the magnitude of the sending-end (generator) voltage,
E_r is the magnitude of the receiving-end (generator) voltage,
δ is the phase angle between E_s and E_r (*transmission* or *load* angle),
Z_o is the *surge* or *characteristic* impedance given by

$$Z_o = \sqrt{\frac{l}{c}} \qquad \text{(Eq. 2)}$$

θ is the *electrical length* of the line expressed in radians by

$$\theta = \beta a \qquad \text{(Eq. 3)}$$

where β is the number of complete waves per unit line length, i.e.,

$$\beta = \omega\sqrt{lc} = 2\pi f \sqrt{lc} \qquad \text{(Eq. 4)}$$

and a is the length of the line.

It is well known that the voltage along the transmission line remains constant only at *surge impedance* or *natural* loading, when the transmitted power is

$$P_o = \frac{V_o^2}{Z_o} \qquad \text{(Eq. 5)}$$

where V_0 is the nominal or rated voltage of the line.

However, transmission lines rarely have surge impedance loading. At lighter loads the transmission line voltage increases and for heavier loads it decreases. The greatest line voltage variation occurs at the line mid-point, as illustrated in Figure 2. (For radial lines, the largest voltage variation occurs at the receiving end.)

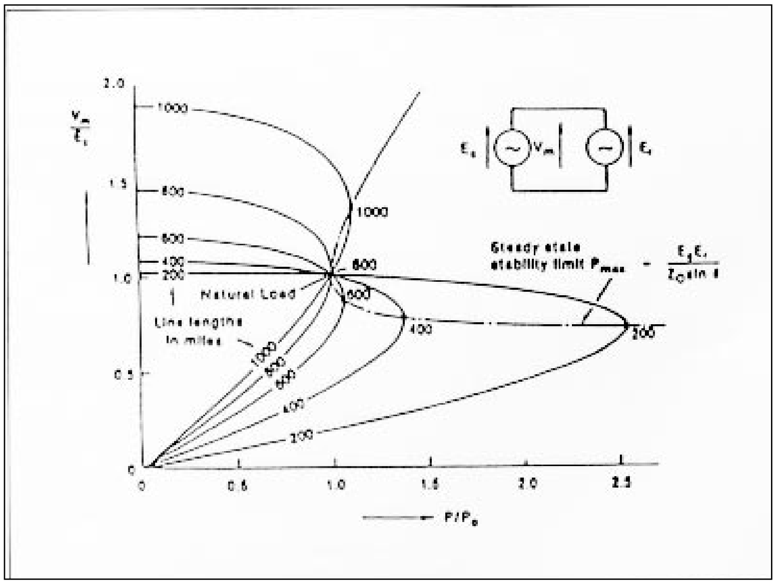


Figure 2—*Variation of midpoint voltage with power along a symmetrical line of different length.*

It has long been recognized that the steady-state transmittable power can be increased and the voltage profile along the line can be controlled by appropriate reactive compensation. The purpose of the reactive compensation is to change the natural electrical characteristics of the transmission line to make it more compatible with the prevailing load demand. Thus, shunt connected, fixed or mechanically switched reactors are applied to minimize line overvoltage under light load conditions, and shunt connected, fixed or mechanically switched capacitors are applied to maintain voltage levels under heavy load conditions. In the case of long transmission lines, *series capacitive* compensation is often employed to establish a *virtual short* line by reducing the inductive line impedance and thereby the electrical length, θ, of the line

Traditional steady-state reactive compensation is not effective in controlling the power transmission when the ac system is subjected to dynamic disturbances. For example, a transmission line fault disrupts the equilibrium between the essentially constant mechanical input power and the electrical power of the generator that is transmittable by the faulted system. As a result, the generator starts to accelerate, increasing the transmission angle δ. By the time the fault clears, angle δ may reach a significantly greater value than that required for the steady-state power transmission of the post-fault system. The transmission system with the fixed reactive compensation cannot accommodate the increased power flow, and an increasing voltage sag along the line towards the mid-point develops. Thus, unless sufficient transient (first swing) stability margin is established for this contingency, the generator may not be able to lose all the kinetic energy it obtained during the fault and may not decelerate enough to establish the transmission angle required for the steady-state equilibrium between the mechanical input power and electrical output power transmitted.

Even with sufficient transient stability margin, the power system may not become stable if its *dynamic stability* is insufficient; that is, if the power system has negative damping.

It has been shown [B2] that both the transient and dynamic stabilities of the power system can be improved if the reactive compensation of the transmission system is made rapidly variable. For example, during the first swing period after fault, increased capacitive shunt compensation helps to maintain the desired voltage profile and minimize the angular swing of the generators. Similarly, power oscillation damping is improved if the line compensation is varied, so as to increase the transmitted electric power when the generators accelerate $(d\delta/dt>0)$ and decrease it when they decelerate $(d\delta/dt<0)$.

In recent years, the need for fast reactive compensation in power transmission systems has become increasingly evident. The utility industry is facing unprecedented problems related to energy cost, environmental, social, and regulatory issues, as well as to the profound changes in the U.S. industrial structure and the geographic shifts of highly populated areas. The present situation may be briefly summarized as follows.

The power demand has shown a steady but geographically uneven growth. The available power generation is often not close to the growing load centers. The locations of new power generation are largely determined by regulatory policies, environmental acceptability, and the cost of available energy. In order to meet the power demand under these often contradictory requirements, the utilities increasingly rely on the utilization of existing generation facilities via power import/export arrangements. Power exportation and importation requires the interconnection of (previously independent) power systems into an ever growing grid, in which individual transmission systems may play no other part but to “wheel” the power from the exporting system to the importing one. However, the existing traditional transmission facilities were not designed to handle the control requirements of an interconnected power system. The power flow in the individual lines of the transmission grid is determined by their impedance and it often cannot be restricted to the desired power corridors. As a consequence, power flow loops develop and certain lines become overloaded, with the overall effect of deteriorating voltage profiles and decreased system stability. Furthermore, while the power transmission requirements have been rapidly growing, the difficulties and escalating cost of right-of-ways have stymied the construction of new lines.

This overall situation demands the review of traditional power transmission theory and practice, and the creation of new concepts that allow the full utilization of existing power generation and transmission facilities without decreasing system availability and security.

The Electric Power Research Institute (EPRI) has initiated the development of *Flexible AC Transmission Systems (FACTS)* in which power flow is dynamically controlled by various power electronic devices. The two main objectives of FACTS are to increase the transmission capacity of lines and control power flow over designated transmission routes.

This paper describes a novel approach in which controllable solid-state *synchronous voltage sources* are employed for the dynamic compensation and *real-time* control of power flow in transmission systems. This approach, when compared to conventional compensation methods employing thyristor-switched capacitors and thyristor-controlled reactors, provides vastly superior performance characteristics and uniform applicability for transmission voltage, impedance, and angle control. It also offers the unique potential to directly exchange *real power* with the ac system, in addition to the independently controllable reactive power compensation, thereby giving a powerful new option for the counteraction of dynamic disturbances.

Basic Relationships for Power Transmission

As Equation 1 indicates, the transmitted power is a function of the transmission line impedance, the magnitude of the sending- and receiving-end voltages, and the phase angle between these voltages. The objective of dynamic transmission system compensation is to control (regulate) these parameters. In order to provide a background for solid-state dynamic compensation and power flow control concepts, the basic power relationships of ac power transmission are reviewed below.

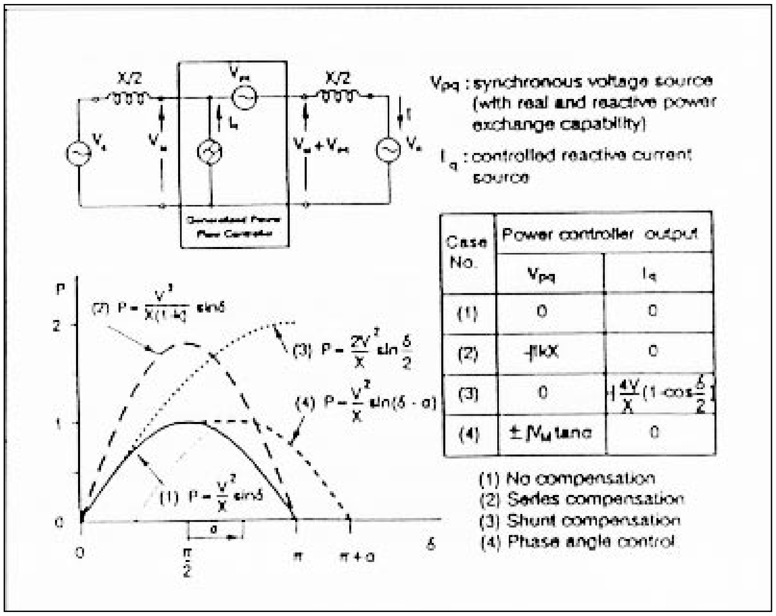
The review of basic relationships for power transmission is, for simplicity, limited to the two-machine model [B3] shown in Figure 3. This model includes the sending-end generator with voltage phasor V_S (bold-faced symbols represent complex quantities), the receiving-end generator with voltage phasor V_R, the transmission line impedance X (assumed inductive) in two sections ($X/2$), and a *generalized power flow controller* operated (for convenience) at the middle of the line. The generalized power flow controller is an ideal device capable of varying the three transmission parameters (voltage, impedance, phase angle) by appropriate series reactive compensation, shunt reactive compensation, and phase-shifting. It can be considered to consist of two controllable elements, an alternating *voltage source* (V_{pq}), inserted in series with the line, and an alternating *current source* (I_q), connected in shunt with the line at the midpoint. Both the magnitude and the angle of voltage V_{pq} are freely variable, whereas only the magnitude of current I_q is variable; its phase angle is fixed at 90 degrees with respect to mid-point voltage V_M. Note that the above definitions for V_{pq} and I_q mean that the former can exchange reactive *and* real power whereas the latter, *only* reactive power.

The four classical cases of power transmission, (1) without line compensation, (2) with series capacitive compensation, (3) with shunt compensation, and (4) with phase angle control, can be obtained by appropriately specifying V_{pq} and I_q in the generalized power flow controller shown in Figure 3.

For case (1) assume that both V_{pq} and I_q are zero (power flow controller is off). The power transmitted between the sending- and receiving-end generators can then be obtained from Equation 1 by replacing $\sin\ \theta$ with $\theta = \beta a = \omega a \sqrt{lc}$ electrically short line). Thus, $Z_o \theta = \omega a l = X$ (series line reactance) and, with $V_R = V_S = V$,

$$P_{(1)} = \frac{V^2}{X} \sin\delta \qquad \text{(Eq. 6)}$$

where δ is the angle between the sending- and receiving-end voltage phasors (the impedances of



Case No.	Power controller output	
	V_{pq}	I_q
(1)	0	0
(2)	$-jIkX$	0
(3)	0	$-j\frac{4V}{X}(1-\cos\frac{\delta}{2})$
(4)	$\pm jV_M \tan\alpha$	0

***Figure 3**—Basic power transmission relationships with different compensations*

the machines are neglected). Power $P_{(1)}$ is shown plotted against angle δ in Figure 3, curve (1). For case (2) assume that $I_q = 0$ and $V_{pq} = -jkXI$; that is, the voltage inserted in series with the line lags the line current by 90 degrees with an amplitude that is proportional to the magnitude of the line current and line impedance. In other words, the voltage source acts at the fundamental frequency precisely as a series compensating *capacitor*. The *degree* of series compensation is defined by coefficient k ($0 \le k \le 1$). With this, the P versus δ relationship becomes:

$$P_{(2)} = \frac{V^2}{X(1-k)} \sin\delta \tag{Eq. 7}$$

Power $P_{(2)}$ is shown plotted against angle δ by curve (2).

For case (3) assume that $V_{pq} = 0$ and $I_q = -j\,(4V/X)[1-\cos(\delta/2)]$; that is, the current source I_q draws just enough capacitive current to make the magnitude of the mid-point voltage, V_M, equal to V. In other words, the reactive current source acts like an ideal shunt *compensator* which segments the transmission line into two independent parts, each with an impedance of $X/2$, by generating the reactive power necessary to keep the mid-point voltage constant, and independent from angle δ. For this case of ideal mid-point compensation, the P versus δ relationship can be written as:

$$P_{(3)} = 2\frac{V^2}{X} \sin\frac{\delta}{2} \tag{Eq. 8}$$

Power $P_{(3)}$ is shown plotted against angle δ by curve (3).

For case (4) assume that $I_q = 0$ and $V_{pq} = \pm jV_M \tan\alpha = \pm jV_M \tan\alpha$; that is, a voltage ($V_{pq}$) with amplitude $\pm V_M \tan\alpha$ is added *in quadrature* to the mid-point voltage (V_M) in order to produce the desired α phase-shift (leading or lagging), just as it is done by tap-changing transformer type phase-shifters. The basic idea behind the phase-shifter is to keep the transmitted power at a desired level, independently of angle δ, in a predetermined operating range. Thus, for example, the power can be kept at its peak value after angle δ exceeds $\pi/2$ (the peak power angle) by controlling the amplitude of quadrature voltage V_{pq} so that the effective phase angle ($\delta - \alpha$) between the sending-and receiving-end voltages stays at $\pi/2$. In this way, the actual transmitted power may be increased significantly, even though the phase-shifter *per se* does not increase the steady-state power transmission limit. (Of course, it does increase the transient and dynamic stabilities of the system.)

Considering $\delta - \alpha$ as the effective phase angle between the sending- and receiving-end voltages, the transmitted power P can be expressed as follows:

$$P_{(4)} = \frac{V^2}{X} \sin(\delta - \alpha) \qquad \text{(Eq. 9)}$$

Power $P_{(4)}$ is shown plotted against angle δ by curve (4).

The expressions given by equations (2) through (4) define the relationship between the transmitted power and the transmission angle with series and shunt compensations and phase shifting. It should be noted that these expressions are for steady-state conditions; that is, they define the transmitted power for given end voltages, line impedance, and angle. For effective *dynamic* compensation, these parameters have to be controlled *in real time*, in order to vary (increase or decrease) almost instantaneously the transmitted power according to prevailing system conditions. The ability to control power rapidly, within appropriately defined boundaries, can increase the transient (first swing) stability, as well as the damping of the system. Increased transient stability and damping allow a corresponding increase in the transmittable steady-state power and thus a higher utilization of the system.

Conventional Thyristor-Controlled Power Flow Controllers

Most of the presently used, or proposed, *power flow controllers* [this term is used in this paper to make a common reference to *static var compensators (SVCs), controllable series compensators, phase-shifters*, and equivalent devices applied in the transmission system for dynamic reactive compensation and power flow control] employ *conventional thyristors* (i.e., those having no intrinsic turn-off ability) in circuit arrangements that are similar to breaker-switched capacitors and reactors, and mechanically operated tap-changing transformers, but have much faster response and are operated by sophisticated controls. Except for the thyristor-controlled phase-shifter, all of these have a common characteristic in that the necessary reactive power required for the compensation is generated or absorbed by traditional capacitor or reactor banks, and the thyristor switches are used only for the control of the combined reactive impedance these banks present to the system during successive periods of the applied voltage. Consequently, conventional thyristor-controlled compensators present a variable reactive *admittance* to the transmission network and therefore generally change the system impedance. Typically, capacitive shunt compensation with the inductive system impedance results in a network resonance somewhere above 60 Hz (fundamental frequency) that may be at, or close to, the dominant harmonic frequencies (3rd, 5th, 7th) of the SVC (and of the ac system). The series capacitive compensation results in an electrical resonance below 60 Hz that can interact with the mechanical resonances of the turbine-generators supplying the line and, in this way, may cause an overall system *sub-synchronous* resonance (SSR).

The network resonances above and below the fundamental (60 Hz) can cause significant problems if they occur at frequencies at which sustained excitation is possible. For this reason, tuned LC filters are usually employed in the SVC to produce impedance zeros and thus prevent parallel resonances at the dominant harmonic frequencies. The mitigation of subharmonic resonance produced by series compensation may require “active” damping via the controls of the thyristor valves.

The conventional thyristor-controlled power flow controllers are discussed briefly to provide a technological background and performance benchmarks for the proposed solid-state synchronous compensators.

Static Var Compensator

Thyristor-controlled static var compensators are extensively treated in the literature [B2]. A typical shunt-connected static var compensator, composed of thyristor-switched capacitors (TSCs) and thyristor-controlled reactors (TCRs), is shown in Figure 4. With proper coordination of the capacitor switching and reactor control, the var output can be varied continuously between the capacitive and inductive ratings of the equipment.

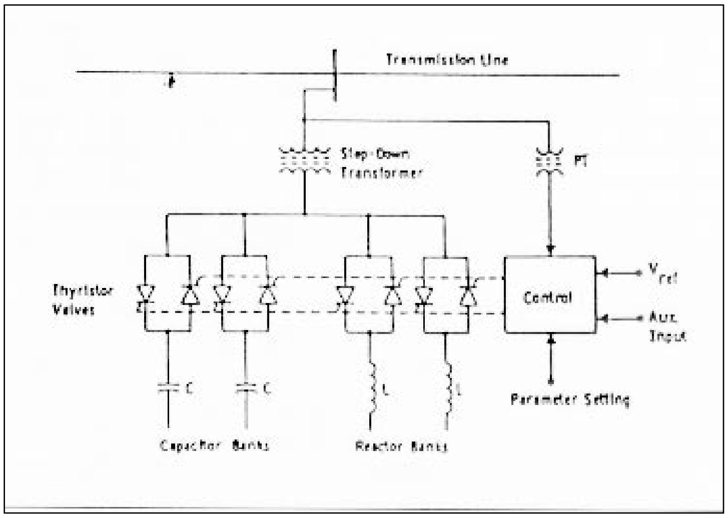


***Figure 4**—Conventional thyristor-controlled static var compensator (SVC)*

The compensator is normally operated to *regulate the voltage* of the transmission system at a selected terminal. The V-I characteristic of the SVC, shown in Figure 5, indicates that regulation with a given *slope* around the nominal voltage can be achieved in the normal operating range defined by the maximum capacitive and inductive currents of the SVC. However, the maximum obtainable capacitive current *decreases* linearly (and the generated reactive power in quadrature) with the system voltage since the SVC becomes a fixed capacitor when the maximum capacitive output is reached. Therefore, the voltage support capability of the conventional thyristor-controlled static var compensator rapidly deteriorates with decreasing system voltage.

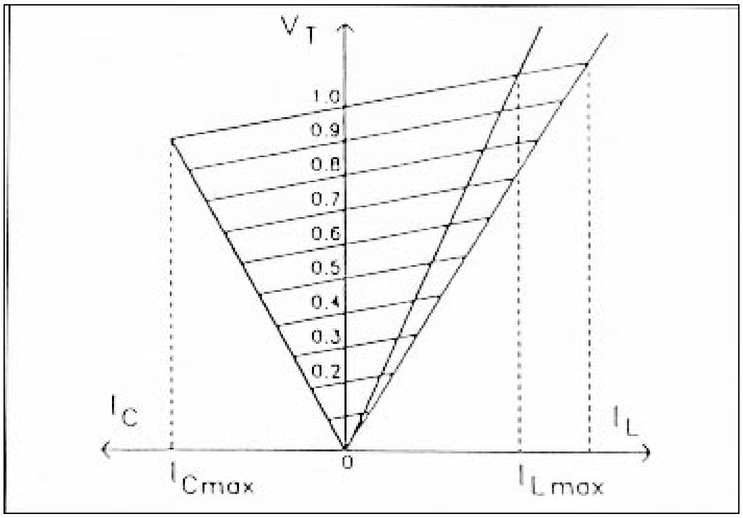


***Figure 5**—V-I characteristic of thyristor-controlled static var compensator*

In addition to voltage support, SVCs are also employed for *transient* (first swing) and *dynamic* stability (damping) improvements. The effectiveness of the SVC for the increase of transmittable power is illustrated in Figure 6, where the transmitted power P is shown against the transmission angle δ for a simple two-machine model at various capacitive ratings defined by the maximum capacitive admittance B_{Cmax}.. It can be observed that the SVC behaves like an ideal mid-point compensator with a P versus δ relationship, as given by Equation 8, until the maximum capacitive admittance B_{Cmax} is reached. From this point on, the power transmission curve becomes identical to that obtained with a fixed, mid-point shunt capacitor whose admittance is B_{Cmax}. The first swing stability improvement is proportional to the $\int P d\delta$ area between the compensated and uncompensated P versus δ curves obtained after fault clearing. As can be seen, this area for relatively large δ swings ($\delta > \pi/2$) sharply decreases unless the rating of the SVC is very large.

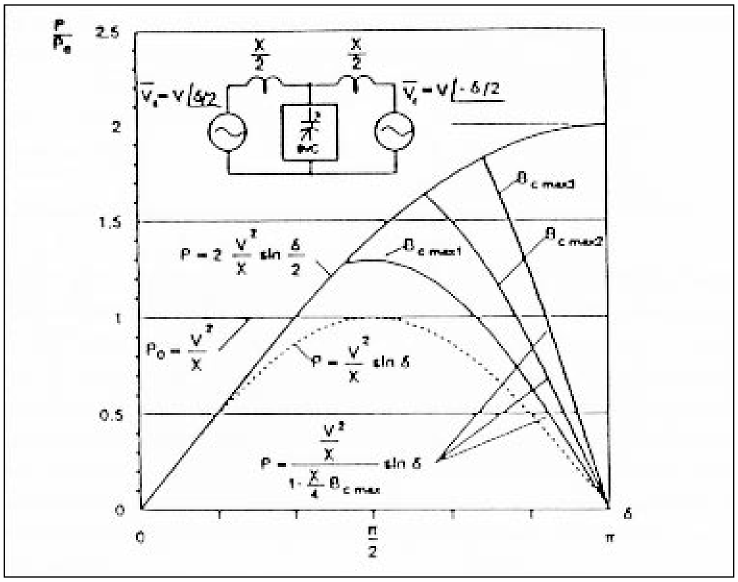


Figure 6*—Transmitted power (P) versus transmission angle (δ) with a mid-point static var compensator of different rating*

The *dynamic stability* improvement (power oscillation damping) can be obtained by alternating the output of the SVC between appropriate capacitive and inductive values so as to oppose the angular acceleration and deceleration of the machines involved. The idea is to increase the transmitted electrical power by increasing the transmission line voltage (via capacitive vars) when the machines accelerate and to decrease it by decreasing the voltage (via inductive vars) when the machines decelerate. The effectiveness of the SVC in power oscillation damping is, of course, a function of the voltage variation it is able, or allowed, to produce.

Controllable Series Compensator

Thyristor-controlled series compensators have not yet been used in practical applications. Such compensators, using thyristor-switched capacitors, or a fixed capacitor in parallel with a thyristor-controlled reactor, or some combinations of these, are presently under development [B4, B5, B6]. The basic schemes are shown schematically in Figures 7(a) and 7(b).

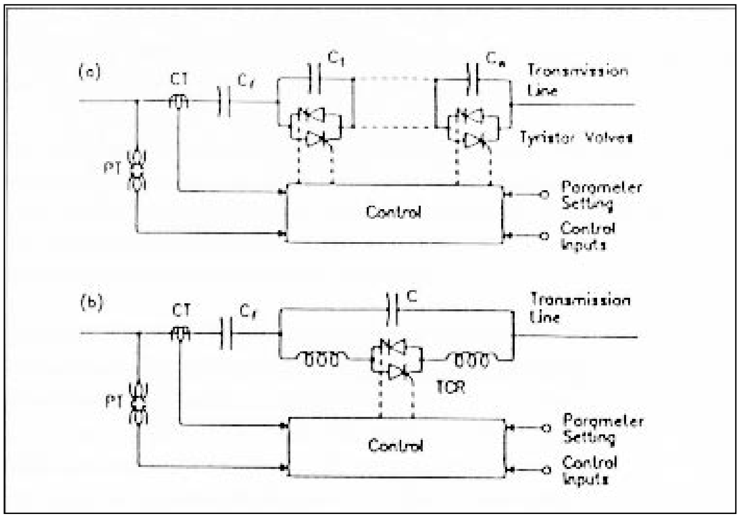


Figure 7*—Controllable series compensator using (a) thyristor-switched capacitors and (b) a thyristor-controlled reactor with a fixed capacitor*

In the thyristor-switched capacitor scheme of Figure 7(a), the degree of series compensation is controlled by increasing or decreasing the number of capacitor banks in series. To accomplish this, each capacitor bank is inserted or bypassed by a thyristor valve (switch). To minimize switching transients and utilize "natural" commutation, the operation of the thyristor valves is coordinated with voltage and current zero crossings. Since the voltage across the series capacitor is a direct function of the line current, the prevention of damaging overvoltage during faults and other surge current conditions usually necessitates the use of a ZnO voltage clamping device or other by-pass arrangement in parallel with the thyristor-switched capacitor banks.

In the fixed-capacitor, thyristor-controlled reactor scheme of Figure 7(b), the degree of series compensation in the capacitive operating region (the admittance of the TCR is kept below that of the parallel connected capacitor) is increased (or decreased) by *increasing* (or *decreasing*) the thyristor conduction period, and thereby the current in the TCR. *Minimum* series compensation is reached when the TCR is *off*. The TCR may be designed to have the capability to limit the voltage across the capacitor during faults and other system contingencies of similar effect.

Thyristor-controlled series compensation is expected to be effective in damping power oscillations and preventing loop flows of power.

Phase-Shifter

Although there is no high-power, non-mechanical phase-shifter in service, the principles for using a phase-shifting transformer with a thyristor tap-changer are well established. Just as the conventional phase-shifter with a mechanical tap-changer, the thyristor-controlled counterpart also provides *quadrature voltage* injection.

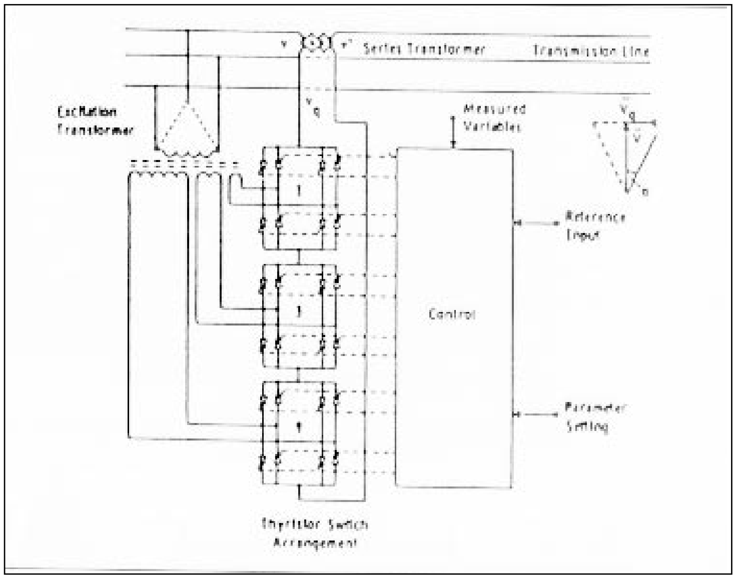


***Figure 8**—Thyristor-controlled tap-changer for phase-angle regulation*

A thyristor-controlled phase-shifting transformer arrangement [B7] is shown in Figure 8. It uses three non-identical transformer windings, in proportions of 1:3:9. It can produce a total of 27 steps using only 12 thyristor switches (of three different voltage ratings) per phase with a switching arrangement that can bypass a winding or reverse its polarity.

The phase angle requirements for power flow control can be determined from angle measurements, if possible, or from power measurements. With these, the thyristor-controlled phase-shifting transformer could be applied to *regulate the transmission angle* to maintain *balanced* power flow in multiple transmission paths, or to *control* it so as to increase the transient and dynamic stabilities of the system. Note that the phase angle between the voltage injected by the phase-shifter (which is, by design, in quadrature with the line to neutral terminal voltage) and the line *current* is arbitrary, determined by the pertinent parameters of the overall power system. This means that, in general, the phase-shifter via the series insertion transformer must exchange with the ac system *both* real and reactive power.

Since the tap-changing transformer type phase-shifter *cannot* generate, or absorb, either real *or* reactive power, it follows that *both* the real and reactive power this type of phase-shifter supplies to, or absorbs from, the line when it injects quadrature voltage *must* be absorbed from it, or supplied to it, by the ac system.

The fact that the tap-changing transformer type phase-shifter cannot generate or absorb reactive power can be a significant disadvantage in practical applications. If the reactive power, exchanged as a result of the quadrature voltage injection, has to be transmitted through the line, the corresponding voltage drop may be substantial. In order to avoid large voltage drops across the line (and their adverse effects on power transmission), the tap-changing type phase-shifter must be either complemented with a controllable reactive shunt compensator to supply the necessary reactive power locally, or must be located close to the power generator.

Power Flow Control by Solid-State Synchronous Voltage Sources

General Concept of Synchronous Voltage Source

The predecessor of modern solid-state synchronous compensators, the *rotating synchronous condenser* has been used extensively in the past for reactive shunt compensation both in transmission and distribution systems. Although the rotating condenser exhibits a number of desirable functional characteristics (high capacitive output current at low system voltage levels and an essentially inductive source impedance that cannot cause harmonic resonance with the transmission network), it suffers from a number of operating shortcomings (slow response, potential for rotational instability, low short circuit impedance, and high maintenance) and lacks the application flexibility needed to meet the power control requirements of modern transmission systems.

The solid-state synchronous voltage source (hereafter referred to just as *synchronous voltage source* or *SVS*) considered in this paper is analogous to an ideal synchronous machine which generates a balanced set of (three) sinusoidal voltages, at the fundamental frequency, with controllable amplitude and phase angle. This ideal machine has no inertia, its response is practically instantaneous, it does not significantly alter the existing system impedance, and it can internally generate *reactive* (both capacitive and inductive) power. Furthermore, it can dynamically exchange *real power* with the ac system if it is coupled to an appropriate energy source that can supply or absorb the power it supplies to, or absorbs from, the ac system.

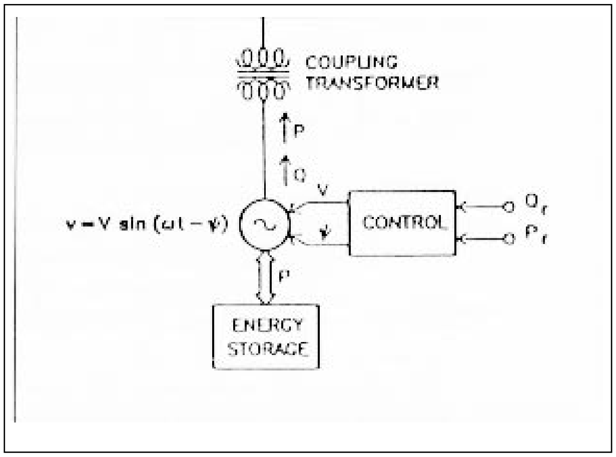


***Figure 9**—Generalized synchronous voltage source*

A functional model of the solid-state synchronous voltage source is shown in Figure 9. Reference signals Q_{ref} and P_{ref} define the amplitude V and phase angle ψ of the generated output voltage and thereby the reactive and real power exchange between the solid-state voltage source and the ac system. If the function of dynamic real power exchange is not required ($P_{ref} = 0$), the SVS becomes a self-sufficient reactive power source, like an ideal synchronous condenser, and the external energy storage device can be disposed of.

Implementation of Synchronous Voltage Source

The solid-state synchronous voltage source can be implemented by various *switching power converters*. However, the switching converter considered here is the *voltage-sourced inverter*. This particular *dc to ac* switching power converter, using *gate turn-off (GTO)* thyristors in appropriate *multi-pulse* circuit configurations, is presently considered the most practical for *high power* utility applications. The detailed description of multi-pulse, voltage-sourced inverters is out of the scope of this paper, and the interested reader is referred to [B8], which explains the basic operating principles, and to [B9], which reports the development of such an inverter with a rating of ±100 MVA for the dynamic compensation of a power system. However, the functional and operating characteristics of this type of inverter, which provides the basic *functional building block* for the comprehensive compensation and power flow control approach described in this paper, are summarized below.

An elementary, *six-pulse*, voltage-sourced inverter is shown in Figure 10a. It consists of six self-commutated semiconductor (GTO) switches, each of which is shunted by a reverse-parallel connected diode. (It should be noted that in a high power inverter, each solid-state switch consists of a number of series-connected GTO thyristor/diode pairs.) With a dc voltage source (which may be a charged capacitor), the inverter can produce a balanced set of three quasi-square voltage waveforms of a given frequency, as illustrated in Figure 10b, by connecting the dc source sequentially to the three output terminals via the appropriate inverter switches.

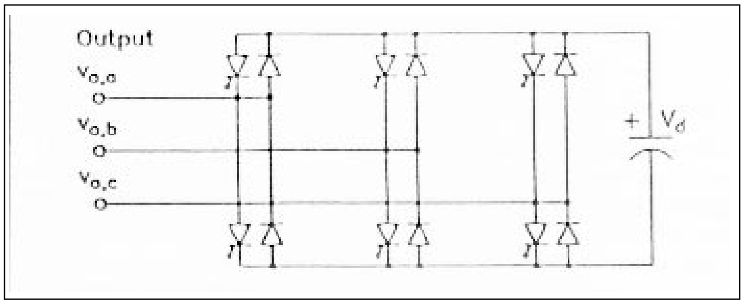


Figure 10a—*Basic six-pulse voltage-sourced inverter*

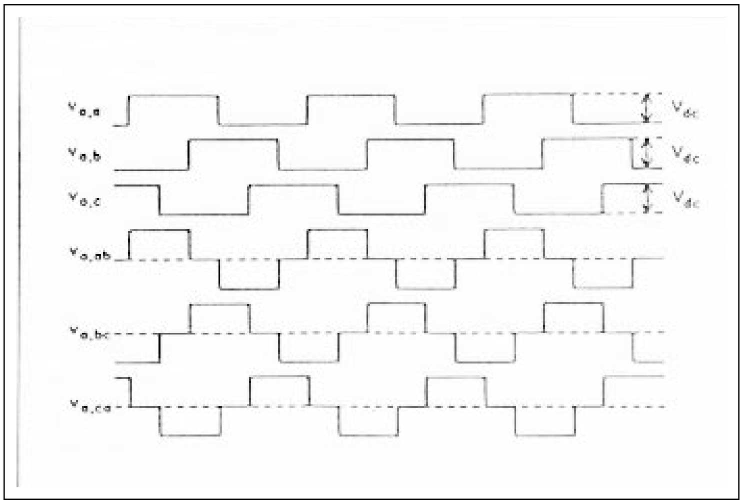


Figure 10b—*Six-pulse inverter output voltage waveforms*

The output voltage waveform of the elementary six-pulse inverter contains harmonic components with frequencies of [6k±1]f (and its input current has related harmonic components with frequencies of 6kf), where f is the fundamental output frequency and k = 1,2,3,... As is evident, the high harmonic content of the output voltage makes this simple inverter impractical for high power applications.

Using the principle of *harmonic neutralization*, the input and output of *n* basic six-pulse inverters (which are operated with appropriate relative phase-displacements) can be combined so as to obtain an overall *P=6n* multi-pulse structure. The frequencies of the harmonics present in the output voltage and input current of this *P-pulse* inverter are *[Pk±1]f* and *Pkf*, respectively. As can be seen, the harmonic spectrum improves rapidly with increasing pulse number, since the order number of the lowest harmonic present in the output voltage is equal to the pulse number minus one, and the lowest harmonic in the input current is equal to the pulse number itself. In addition, the amplitude of these harmonics is inversely related to the pulse number; that is, the amplitude of the *k*th harmonic of the output voltage wave is proportional to *1/[Pk±1]* and that of the dc supply current to *1/Pk*.

Multi-pulse (harmonic neutralized) inverters can be implemented by a variety of circuit arrangements using different magnetic devices. Although specific implementations may be significantly different, the output voltage (and dc supply current) waveforms obtained are essentially the same. A *P=6n* inverter structure is shown schematically in Figure 11b, and the output voltage and current waveforms for *P=48* (*n=8*) are shown in Figure 11a. (The current waveform is shown for 12% coupling transformer reactance when the inverter generates capacitive vars.) As can be observed, at this pulse number (which is a practical choice for high power applications) the output current is essentially a sine-wave and thus the inverter can be considered for all practical purposes as a sinusoidal voltage source.

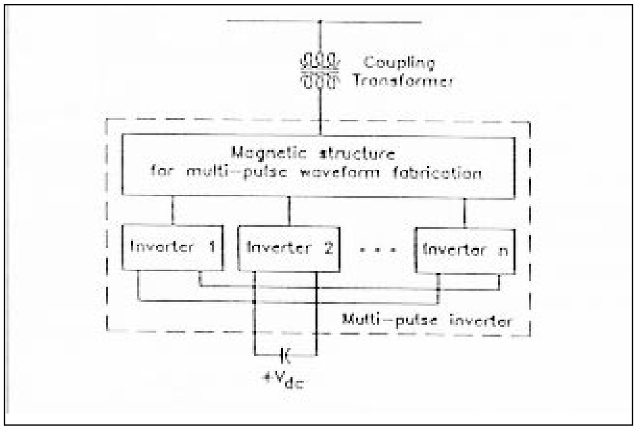


Figure 11a*—Output voltage and current waveforms of a 48-pulse inverter generating reactive (capacitive) power*

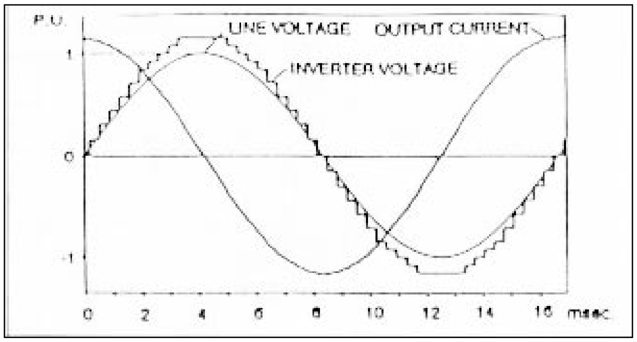


Figure 11b*—A P=6n-pulse inverter using six-pulse inverter modules*

The reactive power exchange between the inverter and the ac system (see Figure 11b) can be controlled by varying the amplitude of the (three-phase) output voltage produced. That is, if the amplitude of the output voltage is increased above that of the ac system voltage, then the current flows through the reactance from the inverter to the ac system, and the inverter generates reactive (capacitive) power for the ac system. If the amplitude of the output voltage is decreased below that of the ac system, then the reactive current flows from the ac system to the inverter and the inverter absorbs reactive (inductive) power. If the output voltage is equal to the ac system voltage, the reactive power exchange is zero.

Similarly, the real power exchange between the inverter and the ac system can be controlled by phase-shifting the inverter output voltage with respect to the ac system voltage. That is, the inverter from its dc energy storage supplies real power to the ac system if the inverter output voltage is made to lead the corresponding ac system voltage. (This is because this phase advancement results in a real component of current through the tie reactance that is in phase opposition with the ac system voltage.) By the same token, the inverter absorbs real power from the ac system for dc energy storage, if the inverter output voltage is made to lag the ac system voltage. (The real component of current flowing trough the tie reactor is now in-phase with the ac system voltage.)

The mechanism by which the inverter internally generates reactive power can be explained, without considering the detailed operation of the solid-state switch array(s) the inverter is composed of, simply by considering the relationship between the output and input powers of the inverter. The key to this explanation resides in the physical fact that the process of energy transfer through the inverter (consisting of nothing but arrays of solid-state switches) is absolutely direct, and thus it is inherent that the net instantaneous power at the ac output terminals must always be equal to the net instantaneous power at the dc input terminals (neglecting losses).

Assume that the inverter is operated to supply only reactive output power. In this case, the real input power provided by the dc source has to be zero. Furthermore, since reactive power at zero frequency by definition is zero, the dc source supplies no input power and therefore it clearly plays no part in the generation of the reactive output power. In other words, the inverter simply interconnects the three output terminals in such a way that the reactive output currents can flow freely between them. Viewing this from the terminals of the ac system, one could say that the inverter establishes a circulating power exchange among the phases.

Although reactive power is internally generated by the action of the solid-state switches, it is still necessary to have a relatively small dc capacitor connected across the input terminals of the inverter. The need for the dc capacitor is primarily required to satisfy the above-stipulated equality of the instantaneous output and input powers. The output voltage waveform of the inverter is not a perfect sine-wave. (As shown in Figure 11a, it is a staircase approximation of a sine-wave.) However, the multi-pulse inverter draws a smooth, almost sinusoidal current from the ac system through the tie reactance. As a result, the net three-phase *instantaneous* power (VA) at the output terminals of the inverter slightly fluctuates. Thus, in order not to violate the equality of the instantaneous output and input powers, the inverter must draw a fluctuating (“ripple”) current from the dc storage capacitor that provides a constant terminal voltage at the input.

The presence of the input ripple current components is thus entirely due to the ripple components of the output voltage, which are a function of the output waveform fabrication technique used. In a high power inverter, using a sufficiently high pulse number, the output voltage distortion and, thereby, capacitor ripple current can be theoretically reduced to any desired degree. Thus, a perfect inverter would generate sinusoidal output voltage and draw pure dc input current without harmonics. (Evidently, for purely reactive output, the input current of the perfect inverter is zero.) In practice, due to system unbalance and other imperfections, as well as to economic considerations, these ideal conditions are not achieved, but approximated satisfactorily by inverters of sufficiently high pulse numbers (24 or higher).

Shunt Compensation by Synchronous Voltage Source

General Compensation Scheme

A shunt-connected solid-state synchronous voltage source, composed of a multi-pulse, voltage-sourced inverter and a dc energy storage device, is shown schematically in Figure 12a. As explained in the previous section, it can be considered as a perfect sinusoidal synchronous voltage source behind a coupling reactance provided by the leakage inductance of the coupling transformer. If the energy storage is of suitable rating, the SVS can exchange *both* reactive and real power with the ac system. The reactive and real power, generated or absorbed by the SVS, can be controlled independently of each other, and any combination of real power generation/absorption with var generation/absorption is possible, as illustrated in Figure 12b. The real power that the SVS exchanges at its ac terminals with the ac system must, of course, be supplied to, or absorbed from, its dc terminals by the energy storage device. By contrast, the reactive power exchanged is internally generated by the SVS, without the dc energy storage device playing any significant part in it.

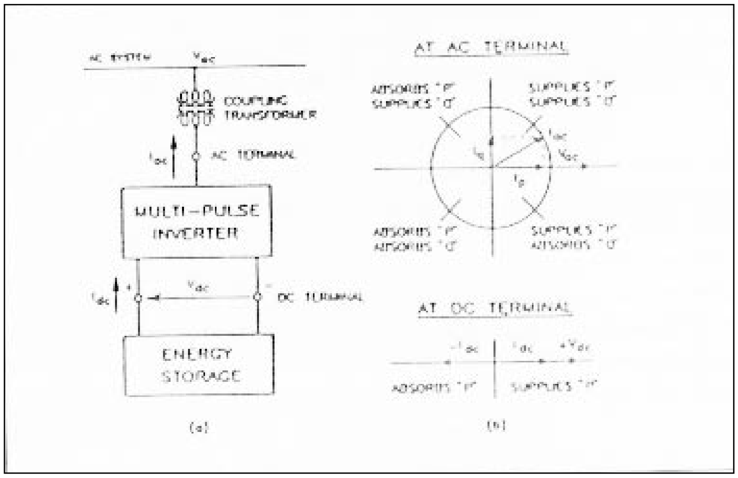


Figure 12*—Shunt-connected synchronous voltage source (a) and its possible operating modes (b) for real and reactive power generation*

The bi-directional real power exchange capability of the SVS; that is, the ability to absorb energy from the ac system and deliver it to the dc energy storage device (large storage capacitor, battery, superconducting magnet) and to reverse this process and deliver power for the ac system from the energy storage device, makes complete, temporary system support possible. Specifically, this capability may be used to improve system efficiency and prevent power outages. Also, in combination with fast reactive power control, dynamic real power exchange provides an extremely effective tool for transient and dynamic stability improvement.

Reactive Power Compensation Scheme

If the SVS is used strictly for *reactive* shunt compensation, like a conventional static var compensator, then the dc energy storage device can be replaced by a relatively small dc capacitor, as shown in Figure 13a. (The size of the capacitor is primarily determined by the "ripple" input current encountered with the particular inverter design.) In this case, the steady-state power exchange between the SVS and the ac system can only be *reactive*, as illustrated in Figure 13b.

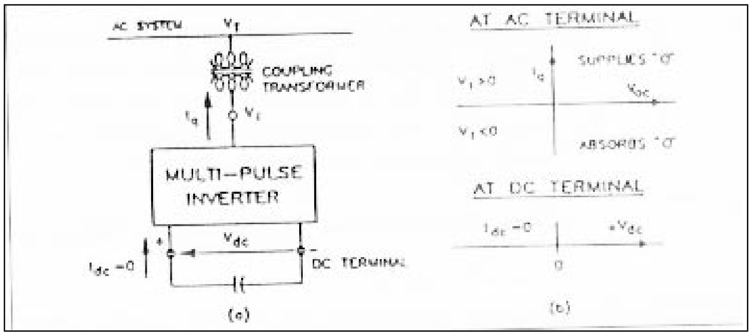


Figure 13*—Synchronous voltage source operated as a static condenser*

When the SVS is used for reactive power generation, the inverter itself can keep the capacitor charged to the required voltage level. This is accomplished by making the output voltages of the inverter lag the system voltages by a small angle. In this way the inverter absorbs a small amount of real power from the ac system to replenish its internal losses and keep the capacitor voltage at the desired level. The same control mechanism can be used to increase or decrease the capacitor voltage, and thereby the amplitude of the output voltage of the inverter, for the purpose of controlling the var generation or absorption. The dc capacitor also has a function of establishing an energy balance between the input and output during the dynamic changes of the var output.

The SVS, operated as a reactive shunt compensator, exhibits operating and performance characteristics similar to those of an *ideal* rotating synchronous condenser and for this reason this specific SVS arrangement is called *static condenser* or *STATCON* [B10]. (The term *advanced static var compensator* or *ASVC* is also frequently used in the literature [B8–B11]. The characteristics of the STATCON are superior to those attainable with the conventional thyristor-controlled static var compensator (SVC).

The V-I characteristic of the STATCON is shown in Figure 14. As can be seen, the STATCON can provide both capacitive and inductive compensation and it is able to control its output current *over the rated maximum capacitive or inductive range* independently of the ac system voltage. That is, the STATCON can provide full capacitive output current at any system voltage, practically down to zero. By contrast, the SVC, being composed of (thyristor-switched) capacitors and reactors, can supply only diminishing output current with decreasing system voltage as determined by its maximum equivalent capacitive admittance. The STATCON is, therefore, superior to the SVC in providing voltage support. Indeed, studies [B10] indicate that a STATCON in a variety of applications can perform the same dynamic compensation as an SVC of considerably higher rating.

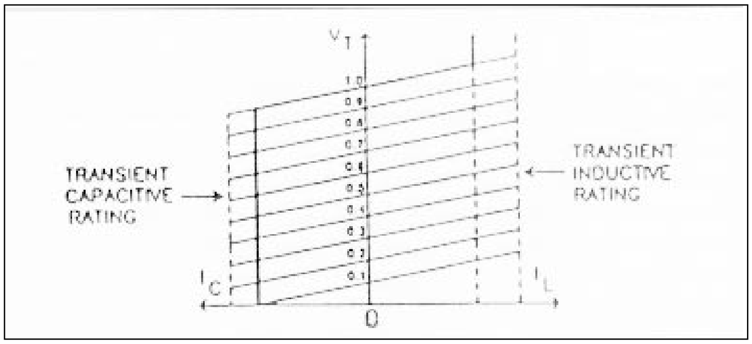


Figure 14*—V-I characteristic of the satic condenser (STATCON)*

As Figure 14 illustrates, the STATCON has an increased transient rating in both the inductive and capacitive operating regions. (The conventional SVC has no means to increase transiently the var generation since the maximum capacitive current it can draw is strictly determined by the size of the capacitor and the magnitude of the system voltage.) The inherently available transient rating of the STATCON is dependent on the characteristics of the power semiconductors used and the junction temperature at which the devices are operated. (Transient rating of the STATCON can, of course, be increased by design at the expense of lower steady-state device utilization.)

It should also be noted that the reactive output, due to the small coupling reactance, naturally and instantaneously adjusts to compensate for system voltage variations. This instantaneous regulation is automatically extended to the transient operating regions, providing a very effective and practically instantaneous voltage support, as well as overvoltage limitation.

The ability of the STATCON to produce full capacitive output current at low system voltage also makes it highly effective in improving the *transient* (first swing) stability. The effectiveness of the STATCON for the increase of transmittable power is illustrated in Figure 15, where the transmitted power P is shown against the transmission angle δ for the usual two-machine model at various capacitive ratings defined by the maximum capacitive output *current* I_{Cmax}.. (This figure is comparable to Figure 6, where the P versus δ plots are shown for an SVC of different capacitive ratings.) It can be observed that, as expected, the STATCON, just like the SVC, behaves like an ideal mid-point shunt compensator with P versus δ relationship as defined by Equation 8 until the maximum capacitive output current I_{Cmax} is reached. From this point on, the STATCON keeps providing this maximum capacitive output *current* (instead of a fixed capacitive admittance like the SVC), independent of the further increasing δ and the consequent variation of the mid-point voltage. As a result, the sharp decrease of transmitted power P in the $\pi/2<\delta<\pi$ region, characterizing the power transmission of an SVC supported system, is avoided and the obtainable $\int Pd\delta$ area representing the improvement in stability margin is significantly increased.

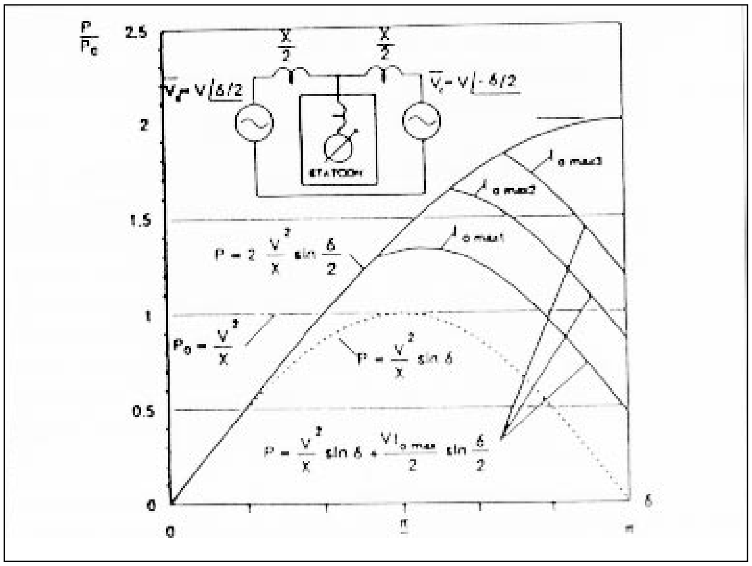


Figure 15*—Transmitted power (P) versus transmission angle (δ) with a mid-point static condenser of different rating*

The increase in stability margin obtainable with a STATCON over a conventional thyristor-controlled static var compensator of identical rating is clearly illustrated with the use of the *equal-area* criterium in Figure 16. The same simple two-machine model considered previously (refer to Figures 6 and 15) is compensated at the mid-point by a static condenser and a static var compensator of the same var rating. For the sake of succinctness, it is assumed that the system transmitting steady-state electric power P_0, at angle δ_0, is subjected to a fault for a period of time

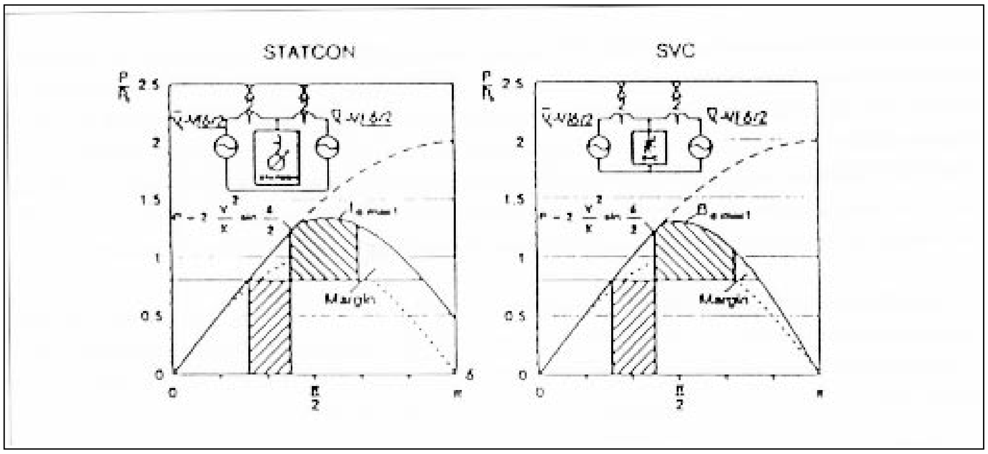


Figure 16*—Transient stability improvement provided by a mid-point static condenser and static var compensator of the same rating*

during which P_0 becomes zero. During the fault the sending-end machine accelerates (due to the constant mechanical input power P_M), absorbing the kinetic energy corresponding to the shaded area *below* the constant P_0 line, and increasing δ_0 to $\delta_1(\delta_1 > \delta_0)$. Thus, when the original system is restored after fault clearing, the transmitted power becomes much higher than P_0 due to the increased transmission angle δ_1. As a result, the sending-end machine starts to decelerate, but δ increases further until the machine loses all the kinetic energy it gained during the fault. The recovered kinetic energy is represented by the shaded area between the P versus δ curve and the constant power line P_0. The remaining dotted area below the P versus δ curve and *above* the constant power line P_0 provides the transient stability *margin*. As can be observed, the transient stability margin obtained with the STATCON is significantly greater than that attainable with the SVC of identical var rating. This of course means that the transmittable power can be increased if the shunt compensation is provided by a STATCON rather than by an SVC, or, for the same stability margin, the rating of the STATCON can be decreased below that of the SVC.

The STATCON also compares favorably with the rotating synchronous condensers. Although the V-I characteristic of the STATCON is similar to that of the rotating condenser, it has much faster response, no mechanical inertia (and thus is free of rotational stability problems), does not increase fault current (its maximum output current is actually electronically limited), and can provide a greater degree of unbalanced reactive power. Furthermore, its construction is modular and thus it can maintain operation at reduced output power when internal power component failures occur (partial availability), and it requires much less maintenance than its rotating counterpart.

Control of Synchronous Shunt Compensator

A functional scheme to control a synchronous voltage source used as a *shunt* compensator is shown in Figure 17, together with the Thevenin equivalent of the ac power system. The terminal voltage v_T of the ac system is assumed to be subjected to dynamic amplitude and frequency variations due to load and system changes, as well as disturbances causing angular machine excursions.

If the SVS is equipped with an energy storage device, then it can exchange reactive *as well as* real power with the ac system. In this case, the *internal* inverter control that derives the gating signals for the GTO thyristors accepts a reference signal (I^*_{qR}) for the desired reactive output current (representing the var demand of the ac system), *and* an independent reference signal (I^*_{dR}) for the desired real output current (representing the required real power exchange with the ac system). From these reference signals the internal control [B11] computes and sets the amplitude and phase angle of the (three-phase) voltage source with respect to the ac system voltage so that the output current of the SVS is composed of the desired reactive and real components. If the SVS is not equipped with an energy storage device, then the reference signal (I^*_{dR}) is kept at zero and the SVS is operated as a static condenser.

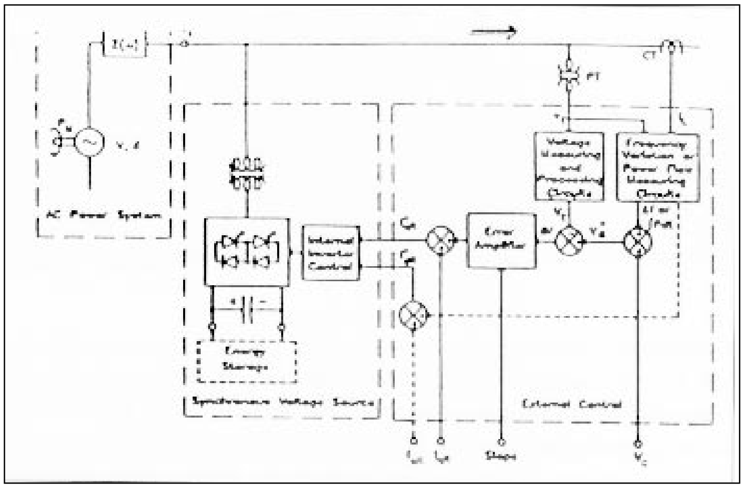


***Figure 17**—Functional control scheme for a synchronous voltage source operated as a (reactive and real power) shunt compensator*

The function of the shunt-connected SVS is to minimize the magnitude and duration of system disturbances by regulating (supporting) the terminal voltage and damping power oscillations. To accomplish this, an *external* control is employed that derives the necessary reference signals for the internal control of the SVS to produce the desired reactive and, if the SVS has energy storage capability, real power output for the ac system to counteract the disturbances.

The basic control loop of the external control is set up to regulate the terminal voltage by means of controlling the *reactive* component of the output current. To this end, as shown in Figure 17, the amplitude V_T of the terminal voltage is measured by the *Voltage Measuring & Processing Circuits*. This measured voltage amplitude is compared with the reference voltage V_R. Note that for the single function of *voltage regulation*, $V_R=V^*_{qR}$. The difference between these two, the *error* signal ΔV_T, is amplified and processed by the *Error Processor and Amplifier* to provide the reference signal I^*_{qR} for the reactive output current.

Power oscillation damping (and the minimization of the first rotational swing) can be accomplished by the modulation of the *reactive* component of output current, or by the modulation of the *real* component of output current, or by the modulation of *both*. (The last two are, of course, possible only if the SVS has energy storage capability.)

Consider first power oscillation damping by the modulation of the reactive output current. With reference to Figure 17, it is seen that it is accomplished by the modification of the voltage reference signal V_R. That is, a signal representing the power oscillation is derived by either direct frequency measurement (yielding Δf) or by the measurement of the real power transmitted (yielding $\int Pdt$) and summed to V_R. (Both Δf and $\int Pdt$ are proportional to the rate of change of the machine angle, $d\delta/dt$, involved.) The added signal causes the output current of the SVS to vary (oscillate) around the operating point defined by the fixed voltage reference V_R. This in turn forces the terminal voltage to increase when, for example, the frequency deviation $\Delta f \sim d\delta/dt$ is positive (in order to *increase* the transmitted power and thereby oppose the acceleration of the generators), and to *decrease* when Δf is negative (to reduce the transmitted power and thereby oppose the deceleration of the generators).

The signal representing the rate of change of generator angle, derived by the *Frequency Variation or Power Flow Measuring Circuits*, can also be used to control the real power exchange between the SVS and the ac system. This can be done by modulating the *real* component of the output current around zero (or around a fixed real power reference if the STATCON is set to absorb from, or supply to, the ac system real power at the time when the disturbance occurred) so as to force the SVS to absorb real power when the generators are accelerating and supply real power when the generators are decelerating.

If fast power oscillations, such as, for example, those associated with sub-synchronous resonance, are encountered or the most effective damping is required, the output of the STATCON can be controlled directly at the I_{qR} and I_{dR} inputs of the internal control. In this case the time constant of the error amplifier is taken out of the control action and the output of the SVS can be varied directly, and very rapidly, in a "bang-bang" manner between the positive and negative current limits.

Series Compensation by Synchronous Voltage Source

General Compensation Scheme

A solid-state synchronous voltage source, consisting of a multi-pulse, voltage-sourced inverter and a dc energy storage device, is shown in *series* with the transmission line in Figure 18a and its possible operating modes are illustrated in Figure 18b. In general, the real and reactive power exchange is controlled by the phase displacement of the injected voltage with respect to the line *current*. For example, if the injected voltage is *in phase* with the line current, then only *real* power is exchanged, and if it is *in quadrature* with the line current then only *reactive* power is exchanged.

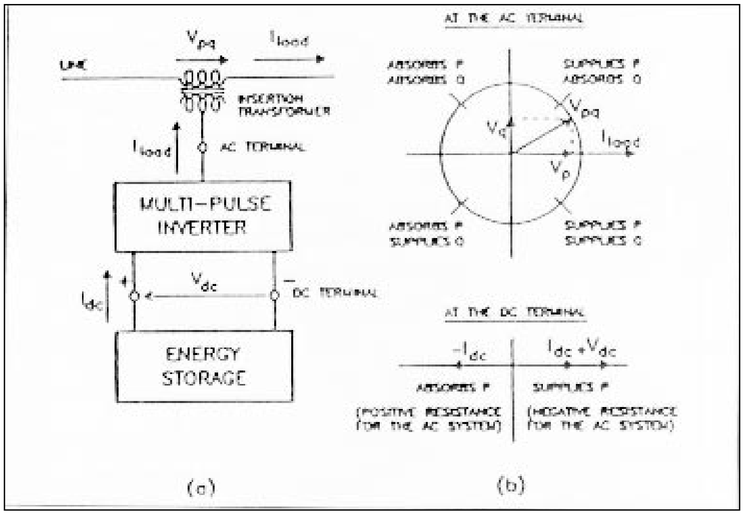


***Figure 18**—Series-connected synchronous voltage source (a) and its possible operating modes (b) for reactive and real power exchange*

The series-connected synchronous voltage source is an extremely powerful tool for power flow control and, as is shown in subsequent sections, it is able to control *both* the transmission line impedance and angle. Its capability to exchange real power with the ac system makes it very effective in improving dynamic stability by means of alternately inserting a *virtual* positive and negative damping resistor in series with the line in sympathy with the angular acceleration and deceleration of the disturbed generators.

Reactive Series Compensation

The concept of using the solid-state synchronous voltage source for series *reactive* compensation is based on the fact that the impedance versus frequency characteristic of the conventionally employed series capacitor, in contrast to filter applications, plays no part in accomplishing the desired line compensation. The function of the series capacitor is simply to produce an appropriate voltage at the *fundamental* (60 Hz) ac system frequency in series with the line to partially *cancel* the voltage drop developed across the inductive line impedance by the *fundamental* component of the line current so that the resulting total voltage drop of the compensated line becomes electrically equivalent to that of a shorter line. Therefore, if an ac voltage source of fundamental frequency, which is locked with a quadrature (lagging) relationship to the line current and whose amplitude is made proportional to that of the line current is injected in series with the line, a series compensation equivalent to that provided by a series capacitor at the fundamental frequency is obtained [B12]. Mathematically, this voltage source can be defined as follows:

$$V_C = -jkXI \tag{Eq. 10}$$

where V_C is the injected compensating voltage phasor, I is the line current phasor, X is the series reactive line impedance, k is the *degree of series compensation* (for conventional series compensation k is defined as X_C/X, where X_C is the impedance of the series capacitor), and $j = \sqrt{-1}$. A series reactive compensation scheme based on this principle is shown in Figure 19. The effect of this compensation on the transmittable power is as defined by Equation (7), with a k that is *continuously* variable.

For normal capacitive compensation, the output voltage must lag the line current by 90 degrees, as illustrated in Figure 19, in order to directly oppose the inductive voltage drop of the line impedance. However, the output voltage of the inverter can be reversed by simple control action to make it lead the line current by 90 degrees. In this case, the injected voltage is in phase with the voltage developed across the inductive line impedance and thus the series compensation has the same effect as if the reactive line impedance was increased. This capability can be exploited to increase the effectiveness of power oscillation damping and, with sufficient inverter rating, it can also be used for fault current limitation.

Series compensation by a synchronous voltage source that can be restricted to the fundamental frequency is superior to that obtained with series capacitive compensation in that it is unable to produce undesired electrical resonances with the transmission network, and for this reason it *cannot* cause sub-synchronous resonance. However, by proper control it can *damp* sub-synchronous oscillations (which may occur because of existing series capacitive compensations) by injecting non-fundamental voltage components with appropriate amplitudes, frequencies, and phase angles, in addition to the fundamental component, in series with the line.

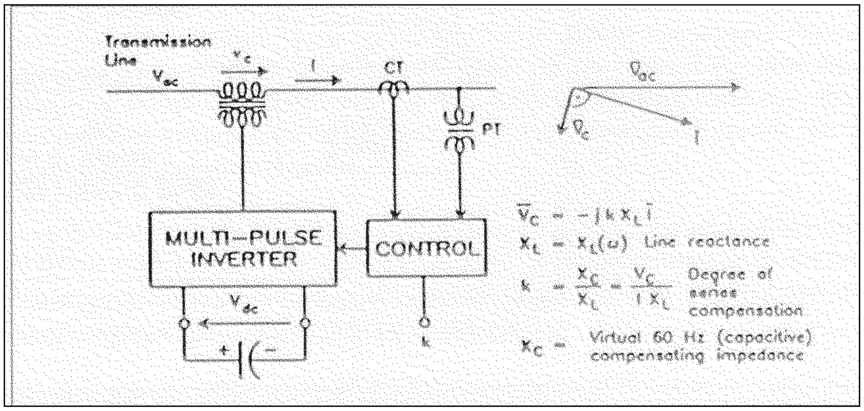


***Figure 19**—Synchronous voltage source operated as a series capacitive compensator*

Due to the stipulated 90-degree phase relationship between the inverter output voltage and the line current (which, via the series insertion transformer, flows through the inverter as the load current), the inverter in the solid-state voltage source theoretically exchanges *only* reactive power with the ac system. As explained previously, the inverter can internally generate all the reactive power exchanged and thus can be operated from a relatively small dc storage capacitor charged to an appropriate voltage. In practice, however, the semiconductor switches of the inverter are not lossless, and therefore the energy stored in the dc capacitor would be used up by the internal losses of the inverter. These losses can be supplied from the ac system itself by making the inverter voltage lag the line current by somewhat less than 90 degrees. (Typical deviation from 90 degrees is a fraction of a degree.) In this way, the inverter absorbs a small amount of real power from the ac system to replenish its internal losses and keep the dc capacitor voltage at the desired level. This control mechanism can also be used to increase or decrease the dc capacitor voltage (by making the inverter voltage lag the line current by an angle somewhat smaller or somewhat greater than 90 degrees) and thereby control the amplitude of the ac output voltage of the inverter and the degree of series compensation.

Control of Series Synchronous Compensator

A simple control scheme for the synchronous voltage source operated as a generalized series compensator is shown in Figure 20. The control scheme has two major functions. One function is to establish the desired series *reactive* (capacitive or inductive) compensation as defined by an externally provided reference, Z_R. The second function is to modulate the series reactive compensation so as to improve transient system stability and provide power oscillation damping.

If the SVS does have a dc energy storage device (as indicated in the figure) then its capability for transient stability improvement and oscillation damping can be significantly enhanced.

The SVS with its *internal* controls can be considered a perfect ac voltage source; it is synchronized to the ac system and its output voltage can be controlled with respect to the line *current* by two *voltage* reference inputs, V^*_{qR} and V^*_{dR}.

Signal V^*_{qR} controls the output voltage component that is *in quadrature* with the line current and therefore it determines the *reactive* (capacitive or inductive) series compensation. It is derived as the product of the reference impedance input (Z_R) and the r.m.s. amplitude of the line current (I) obtained via the *Current Measuring and Processing Circuits*. Transient stability improvement and

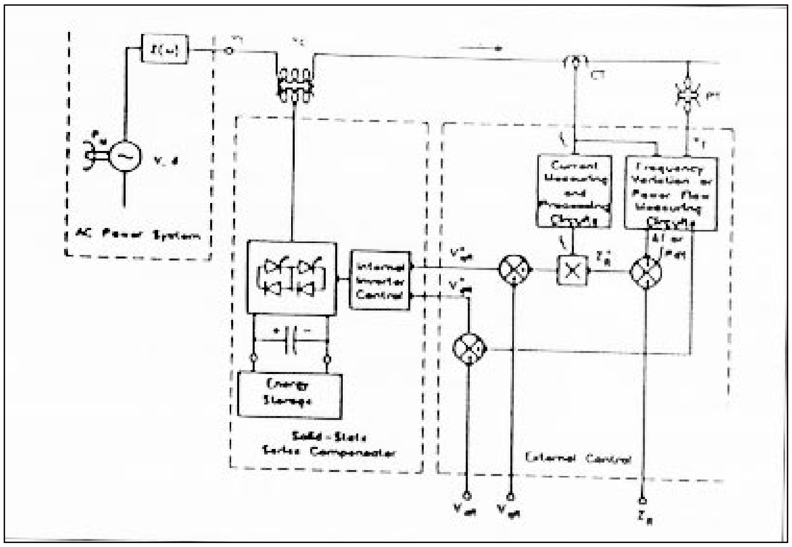


Figure 20—*Basic control scheme for the solid-state series compensator to control (reactive and real) line impedance and improve system stability*

oscillation damping can be achieved by modulating the reference Z_R (which may be set to zero in steady-state) with Δf or $\int Pdt$ (obtained at the output of the *Frequency Variation or Power Flow Measuring Circuits*), which represent the variation of the generator angle, $d\delta/dt$. The objective is, of course, to increase the series *capacitive* compensation when $d\delta/dt > 0$ (i.e., to reduce the line impedance and thereby increase the transmitted power when the generators are accelerating) and conversely to reduce it or, for greater effect, to provide a series *inductive* compensation when $d\delta/dt < 0$ (i.e., to increase the line impedance and thereby reduce the transmitted power when the generators are decelerating).

The modulating signal representing $d\delta/dt$ can also be used as the modulation component of the voltage reference input, V^*_{dR}, to the internal control when the SVS is equipped with an energy storage device. Signal V^*_{dR} controls the output voltage component of the inverter that is *in-phase* (or *in anti-phase*) with the line current and therefore it determines the *real* power exchange with the ac system. Thus the modulation signal representing $d\delta/dt$ commands the solid-state series compensator to *absorb real power* when the generators are accelerating ($d\delta/dt > 0$), and *supply real power* when the generators are decelerating ($d\delta/dt < 0$). The timely injection and absorption of real power is equivalent to the insertion of a negative and, respectively, positive resistive impedance in series with the line, which can be extremely effective for achieving system stabilization.

The SVS can also be used to equalize the currents in parallel lines. A simple control loop can be added to provide an error signal for changing the reference Z_R so as to achieve the desired current in each of the lines compensated.

Phase-Shifting and Multiple Compensating Functions by Synchronous Voltage Sources

Conventional thyristor-controlled tap-changing transformer provides the phase-shifting by injecting a voltage *in quadrature* with the line to neutral system voltage. The magnitude of the injected voltage can be varied in a step-like manner by the tap changing switch arrangement. Since the phase relationship between the injected voltage and the line current is arbitrary, the phase-shifter must, in general, be able to exchange (supply or absorb) *both* real power and vars. Since the tap-changing transformer type phase-shifter has no internal capability to generate or absorb either, it follows that both the real power and vars it supplies to, or absorbs from, the line when it injects quadrature voltage *must* be absorbed from it, or supplied to it, by the ac system. To avoid the voltage variation associated with the reactive power flow, this type of phase-shifters often require the voltage support of a controllable var source, such as a static var compensator.

The solid-state synchronous voltage source represents a fundamentally different approach to transmission angle control. The basic principles of angle control by this method are discussed within the broader concept of the *unified power flow controller (UPFC)* [B3], [B13] which, within its comprehensive functional capabilities, can be operated as an ideal phase shifter.

Basic Principles

Refer back to the generalized series compensator shown in Figure 18. Assume that the injected voltage (V_{pq}) in series with the line can be controlled *without* restrictions (i.e., the dc energy storage has an infinite capacity). That is, the phase angle of phasor V_{pq} can be chosen *independently* of the line current between *0* and 2π, and its magnitude is variable between zero and a defined maximum value, V_{pqmax}.. This implies that voltage source V_{pq} must be able to generate and absorb *both* real and reactive power.

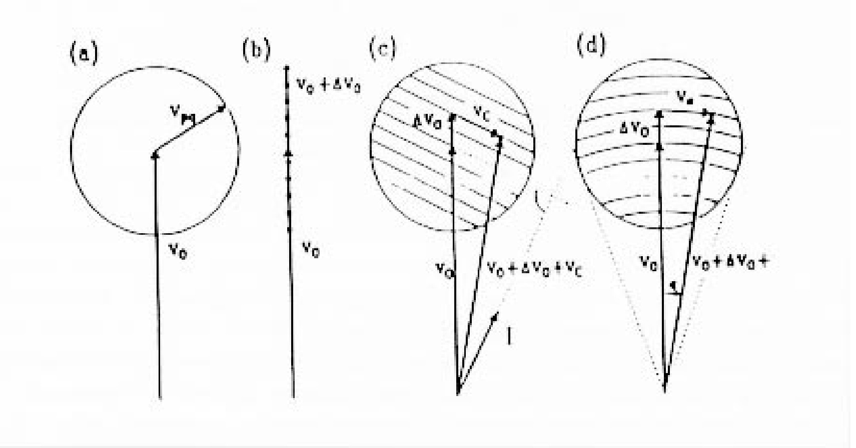


Figure 21*—Phasor diagram illustrating the general concept of series voltage injection (a), and attainable power flow control functions: terminal voltage regulation (b), terminal voltage and line impedance regulation (c), and terminal voltage and phase angle regulation (d)*

Multiple power flow control functions can be achieved by adding an appropriate voltage phasor V_{pq} to the terminal voltage phasor V_o , as shown in Figure 21a. Specifically, by the appropriate definition (control) of phasor V_{pq} , the following power flow control functions can be accomplished:

(1) Dedicated terminal *voltage* regulation or control, which is obtained simply by keeping the angle of V_{pq} zero (i.e., $V_{pq} = \pm \Delta V_o = \pm \Delta V_o$), and thus changing only the magnitude of V_o with respect to that of V_o (or vice versa), as illustrated in Figure 21b.

(2) Combined *series* line compensation *and* terminal voltage control, which is obtained by defining V_{pq} as a sum of voltage phasors V_C and ΔV_o, that is, $V_{pq} = V_C + \Delta V_o$, where phasor V_C is perpendicular to *line current I* (i.e., $V_C = kI\ exp\ (\pm j\pi/2)$) and ΔV_o is in phase with the terminal voltage phasor V_0. Voltage V_C decreases or increases the effective voltage drop across the line segment impedance X_L according to whether V_C lags or leads I, as illustrated in Figure 21c.

(3) Combined *phase angle* regulation *and* terminal voltage control, which is obtained by defining V_{pq} as a sum of V_α and $\Delta V_{o;}$ that is, $V_{pq}=V_\alpha + \Delta V_o$ where $V_\alpha=2V_o sin\ \alpha/2\ exp[\pm j(\pi/2-\alpha/2)]$, and ΔV_o is again in phase with the terminal voltage V_o The selected definition for phasor V_α ensures that the resultant terminal voltage phasor at the end of the line segment, $V'_o=V_o+\Delta V_o+V_\alpha$, has the same magnitude as $V_o + \Delta V_o$ (i.e, $/V_o + \Delta V_o + V_\alpha/ = /V_o + \Delta V_o/ = V_o \pm \Delta V_o$), but its phase angle is different from that of V_o by α, as illustrated in Figure 21d. In practical terms, this means that phase-shifting is achieved without any unintentional magnitude change in the controlled terminal voltage.

(4) Combined terminal voltage regulation *and* series line compensation *and* phase angle regulation, which can be achieved by synthesizing the injected voltage phasor V_{pq} from the three individually controlled phasors, ΔV_o, V_C, and V_α; that is, $V_{pq} = \Delta V_o + V_C + V_\alpha$, as illustrated in Figure 22.

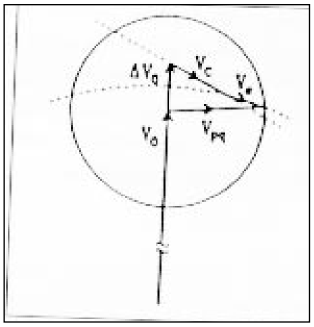


***Figure 22**—Phasor diagram ilustrustrating the simulaneous regulation of terminal voltage, line impedance, and phase angle*

The concept of unrestricted series voltage injection (via the use of a solid-state synchronous voltage source) opens up new possibilities for power flow control. This approach allows not only the combined application of phase angle control with controllable series reactive compensations and voltage regulation, but also the *real-time transition* from one selected compensation mode into another one to handle particular system contingencies more effectively. (For example, series reactive compensation could be replaced by phase-angle control or vice versa.) This may become especially important when relatively large numbers of *FACTS* devices will be used in interconnected power systems, and control compatibility and coordination may have to be maintained in the face of equipment failures and system changes. The approach would also provide considerable operating flexibility by its inherent adaptability to power system expansions and changes *without* any hardware alterations.

Implementation of Multi-Function Compensator

The implementation problem of the unrestricted series compensation is simply that of supplying or absorbing the *real* power that it exchanges with the ac system at its ac terminals, to or from the dc input terminals of the inverter employed in the solid-state synchronous voltage source. The implementation in the proposed configuration called *unified power flow controller (UPFC)* [B3] employs two voltage-sourced inverters operated from a common dc link capacitor; it is shown schematically in Figure 23. This arrangement is actually a practical realization of an *ac to ac* power converter with independently controllable input and output parameters.

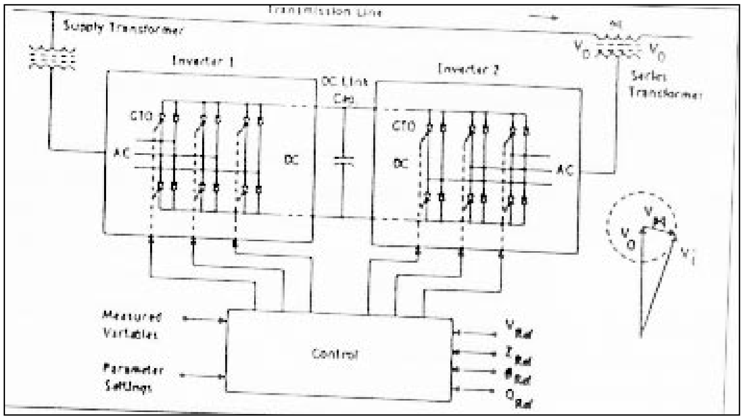


***Figure 23**—Implementation of the unified power flow controller using two "back to back" voltage-sourced inverters with a common dc terminal capacitor*

Inverter 2 in the arrangement shown is used to generate voltage $V_{pq}(t) = V_{pq}\sin(\omega t - \alpha_{pq})$ at the fundamental frequency (ω) with variable amplitude $(0 \leq V_{pq} \leq V_{pqmax})$ and phase angle $(0 \leq \alpha_{pq} \leq 2\pi)$, which is added to the ac system terminal voltage $v_o(t)$ by the series connected coupling (or *insertion*) transformer. With these stipulations, the inverter output voltage injected in series with the line can be used for direct voltage control, series compensation, and phase-shift, as discussed in the previous section.

The inverter output voltage injected in series with the line acts essentially as an ac voltage source. The current flowing through the injected voltage source is the *transmission line current*; it is a function of the transmitted electric power and the impedance of the transmission line. The VA rating of the injected voltage source (i.e., that of *Inverter 2*) is determined by the product of the maximum injected voltage and the maximum line current at which power flow control is still provided. This total VA is made up of two components: one is the maximum *real power* determined by the maximum line current and the component of the maximum injected voltage that is *in phase* with this current, and the other is the maximum *reactive power* determined by the maximum line current and the component of the maximum injected voltage that is *in quadrature* with this current. As explained before, the voltage-sourced inverter used in the implementation *can* internally generate or absorb at its ac terminal all the reactive power demanded by the voltage/impedance/phase-angle control applied, and *only* the real power demand has to be supplied at its dc input terminal.

Inverter 1 (connected in shunt with the ac power system via a coupling transformer) is used primarily to provide the real power demand of *Inverter 2* at the *common dc link* terminal from the ac power system. Since *Inverter 1* can also generate or absorb reactive power at its ac terminal, *independently* of the real power it transfers to (or from) the dc terminal, it follows that, with proper controls, it can also fulfill the function of an independent *static condenser* providing reactive power compensation for the transmission line and thus executing an *indirect* voltage regulation at the input terminal of the unified power flow controller.

It is indicated at the outset that *Inverter 1* could be omitted if a sufficient dc energy storage device was coupled to *Inverter 2*, and the phase-shifting function of the unified power flow controller was used only to handle *transient* disturbances. That is, *Inverter 2* would normally provide series reactive compensation and absorb real power at some pre-determined rate to keep the energy storage device charged. During and following system disturbances, the UPFC would be controlled to provide phase angle control and/or direct real power to stabilize the ac system. With this arrangement, the UPFC would become a generalized solid-state series compensator discussed in the previous section.

The internal control of the solid-state power flow controller, as indicated in Figure 23, is structured so as to accept externally derived reference signals, in an order of selected priority, for the desired reactive shunt compensation, series compensation, transmission angle, and output voltage. These reference signals are used in closed control-loops to force the inverters to produce the ac voltages at the input (shunt-connected) terminals and output (series-connected) terminals of the power flow controller, and thereby establish the transmission parameters desired (Q_{Ref} at the input and V_{Ref}, Z_{Ref}, and α_{Ref} at the output). The control also maintains the necessary dc link voltage and ensures smooth real power transfer between the two inverters.

It is evident that if the unified power flow controller is operated only with the phase angle reference input, it automatically becomes a perfect *phase-shifter*. It internally generates the reactive power involved in the phase-shifting process and negotiates the necessary real power from the ac system. Since the real power component is generally smaller than the total VA demand resulting from phase-shifting, the rating of *Inverter 1* would be normally less than that of *Inverter 2*, unless the “surplus” rating of Inverter 1 is, again, intentionally utilized for controllable reactive shunt compensation.

Summary

There are clear indications that solid-state synchronous voltage sources represent the next technology for ac transmission system compensation and power flow control. This technology offers operating features, functional performance, and application flexibility unattainable by the presently used thyristor-controlled shunt and series compensators.

Thyristor-controlled compensators employ capacitor and reactor banks with fast solid-state switches in traditional shunt or series circuit arrangements. The thyristor switches control the *on* and *off* periods of the fixed capacitor and reactor banks and thereby vary the capacitive and inductive var output. Because these compensators in effect present a variable reactive (shunt or series) *impedance*, they inevitably create “super-harmonic” or “sub-harmonic” resonances with the electric network and, except for losses, they *cannot* exchange real power with the ac system.

Solid-state synchronous voltage sources employ self-commutated dc to ac inverters, using gate turn-off thyristors (or other power semiconductors with intrinsic current turn-off capability), which can internally generate capacitive and inductive reactive power for transmission line compensation, without the use of ac capacitor or reactor banks. The inverter can interface with a dc energy storage device, such as a dc storage capacitor, battery, or superconductive reactor, and in this way can exchange *real power* with the ac system, in addition to the independently controllable reactive power exchange.

The synchronous voltage source can be considered an ideal 60 Hz generator that has no inertia and produces an almost sinusoidal output voltage with independently variable amplitude and phase angle, thus facilitating rapid, decoupled controls for reactive and real power exchange. It can be used uniformly to control transmission line voltage, impedance, and angle by providing reactive shunt compensation, series compensation, and phase-shifting.

When used for reactive shunt compensation, the synchronous voltage source acts like an ideal *static condenser*, being able to maintain the maximum capacitive output current at any system voltage down to zero. This V-I characteristic is superior to that obtainable with the thyristor-controlled static var compensator whose maximum capacitive output current decreases linearly with the system voltage. Because of this V-I characteristic, the VA rating of the static condenser, used for voltage support and transient stability improvement, can be reduced significantly below that required for a static var compensator. If the static condenser is equipped with a suitable energy storage device, it can also be used for load levelling and the minimization of power outages.

As a reactive series compensator, the synchronous voltage source can provide controllable series capacitive compensation without the danger of sub-synchronous resonance. Furthermore, because of its fast response, it can be effective in the mitigation of sub-synchronous resonance caused by conventional series capacitive compensation. Its capability to provide capacitive as well as inductive compensation makes it highly effective in power oscillation damping and, with sufficient rating, it may also be used for fault current limitation. When equipped with an energy storage device, it can insert a virtual positive and negative resistive impedance in series with the line, and thereby dramatically improve the dynamic stability (damping) of the power system.

The special arrangement of two synchronous voltage sources, one in shunt-connection and the other in series-connection, results in the novel unified power flow controller. This arrangement can provide concurrent or selectable voltage, impedance, and angle regulation. The parameters selected for regulation can be changed without hardware alteration, e.g., series reactive compensation can be changed for phase angle regulation or vice versa, to adapt to particular short term contingencies or future system modifications.

The all solid-state implementation of power flow controllers results in a significant reduction in equipment size and installation labor. Furthermore, the uniform all solid-state approach can greatly reduce manufacturing cost and lead time by allowing the use of standard, pre-fabricated power inverter modules for different applications.

Recent advances in high power semiconductor technology resulted in gate turn-off thyristors of sufficient rating to realize high power inverters. Other, more advanced devices, such as the MOS-Controlled Thyristor (MCT) are under development. These devices, combined with recent developments in power circuit topology and control techniques, make the solid-state power flow controller approach practical. The recently reported efforts in the U.S.A., aiming at the installation of a ±100 Mvar static condenser in 1994 [B9] and the development of the unified power flow controller [B13], as well as the on-going work on superconductive energy storage, high energy density batteries, and other energy storage devices, indicate that the utility applications of the new power flow controller technology is becoming a practical reality.

Acknowledgements

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The subject matter of this paper, with different emphasis, has been presented in a shorter form at the 1993 IEEE PES Summer Power Meeting in Vancouver, BC., Canada.

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Biography

Laszlo Gyugyi received his basic technical education at the University of Technology, Budapest, further studied mathematics at the University of London, and electrical engineering both at the University of Pittsburgh, where he received an M.S.E.E. in 1967, and at the University of Salford, England, where he received a Ph.D. in 1970.

Dr. Gyugyi joined the Westinghouse Research and Development Center (now Science & Technology Center) in 1963, where he became Manager of the Power Electronics Department in

1979. During his career he has carried out research and development in different fields of power electronics, ranging from sophisticated aerospace power converters to multi-MVA utility compensators and power flow controllers. In his current position, Dr. Gyugyi is directing the technology and product development efforts in the area of power electronics at the Westinghouse Science and Technology Center.

Dr. Gyugyi holds 64 patents and is co-author of the book “Static Power Frequency Changers” (Wiley, 1976 and Energoatomizdat, 1983). He has numerous societal publications and won the Prize Paper Award, IEEE Power Engineering Society, 1982, for the paper “Characteristics of Static, Thyristor-Controlled Shunt Compensators for Power System Applications.” He also wrote several invited papers, including “Power Electronics in Electric Utilities: Static Var Compensators” (Proceeding of IEEE, Special Issue on Power Electronics, April 1988). He received a Recognition Award from the U.S. National Committee of CIGRE in 1990 for the paper “Advanced Static Var Compensator Using Gate Turn-Off Thyristors for Utility Applications.”

In 1992, Dr. Gyugyi received the Westinghouse Order of Merit (the Corporation’s highest honor) for his creativity and achievements in power electronics, and for his efforts in developing advanced power electronic compensation and control techniques for utility power systems.

Dr. Gyugyi is a Fellow of the Institution of Electrical Engineers, and member of the IEEE Working Groups on Static Var Compensators and Flexible AC Transmission Systems (FACTS).

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