DYNAMIC COMPENSATION OF AC TRANSMISSION LINES BY SOLID-STATE SYNCHRONOUS VOLTAGE SOURCES

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Abstract - 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

It is a well established practice to use reactive power compensation to increase the transmittable power in ac power systems. Fixed or mechanically-switched capacitors and reactors have long been employed to increase the steady-state power transmission by controlling the voltage profile along the lines.

During the last decade it has been convincingly demonstrated[1,2] that both the *transient* and *dynamic* stabilities (i.e., first swing stability and damping) of the power system can also be improved, and voltage collapse can be prevented, if the reactive compensation of the transmission lines is made rapidly variable by solid-state, *thyristor* switches and electronic control.

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 increasing public concern about the health effect of transmission lines and the difficulties and escalating cost of right-of-ways have stymied the construction of new lines.

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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.

POWER FLOW CONTROL BY SOLID-STATE SYNCHRONOUS VOLTAGE SOURCES

Conventional Thyristor-Controlled Power Flow Controllers

Most of the presently used, or proposed, *power flow controllers*[3] [this term is used in this paper to make a common reference to *static var compensators*[1,2] *(SVCs), controllable series compensators*[4-6], *phase-shifters*[7], 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 which 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. 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. (Phase shifters based on tap-changing transformers have no var generation or absorption capability.) Consequently, conventional thyristor-controlled compensators present a variable reactive *admittance* to the transmission network and therefore generally change the system impedance.

The conventional thyristor-controlled power flow controllers are not described in this paper, but are used as benchmarks to evaluate the operating and performance characteristics of the proposed solid-state synchronous compensators.

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.

A functional model of the solid-state synchronous voltage source is shown in Figure 1. 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.

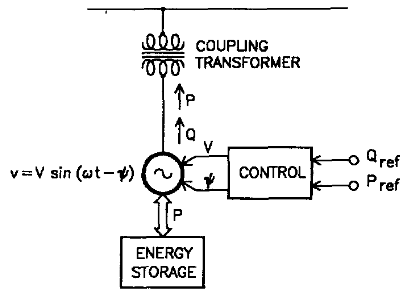

Fig. 1. - Generalized synchronous voltage source.

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 delineation of multi-pulse, voltage-sourced inverters is out of the scope of this paper, and the reader is referred to two publications which describe their basic operating principles[8] for reactive power generation and the development of a ±100 Mvar system[9] for the dynamic compensation of power transmission lines. However, the functional and operating characteristics of this type of inverters, which provide the basic *functional building block* for the comprehensive compensation and power flow control approach proposed in this paper, are summarized below.

An elementary, *six-pulse*, voltage-sourced inverter is shown in Figure 2a. 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 2b, by connecting the dc source sequentially to the three output terminals via the appropriate inverter switches.

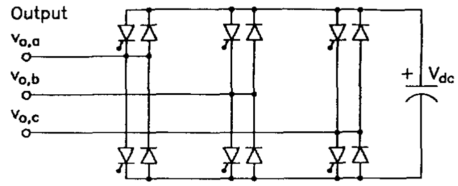

Fig. 2a. - Basic six-pulse voltage-sourced inverter.

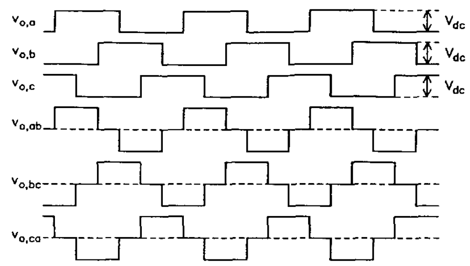

Fig. 2b. - Six- pulse inverter output voltage waveforms.

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 $1/[Pk\pm1]$ 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 3a, and the output voltage and current waveforms for $P=48$ ($n=8$) are shown in Figure 3b.

The reactive power exchange between the inverter and the ac system (see Figure 3a) 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. 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 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

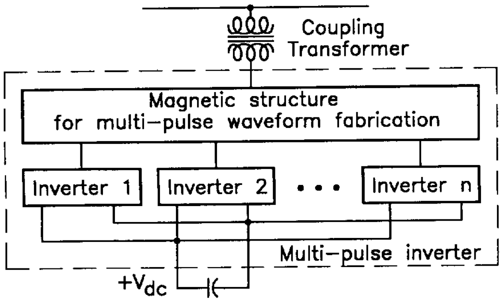

Fig. 3a. - A P=6n-pulse inverter using six-pulse inverter modules.

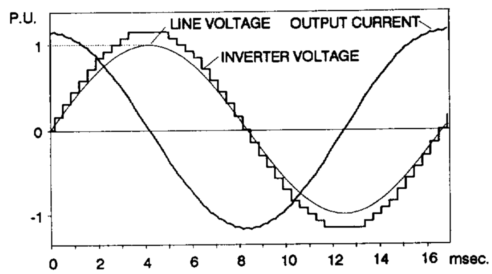

Fig. 3b. - Output voltage and current waveforms of a 48-pulse inverter generating reactive (capacitive) power.

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 3b, 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 4a. As explained in the

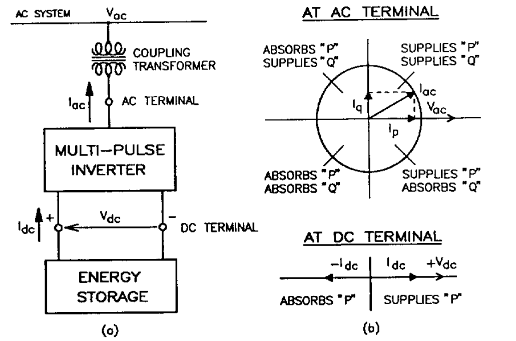

Fig. 4. - Shunt-connected synchronous voltage source (a) and its possible operating modes (b) for real and reactive power generation.

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 4b. 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.

When compared to the conventional thyristor-controlled static var compensator, which can negotiate *only* reactive power exchange with the ac system, the synchronous voltage source clearly has significant operating and application advantages. 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 only 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 5a. In this case, the steady-state power exchange between the SVS and the ac system can only be *reactive*, as illustrated in Figure 5b.

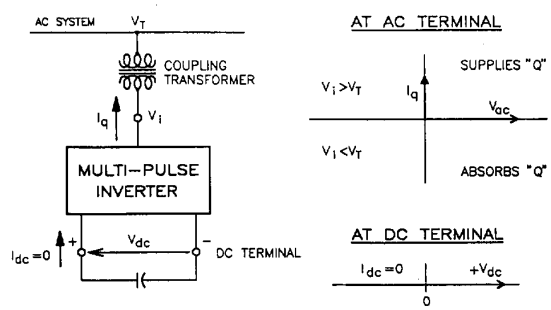

Fig. 5. - Synchronous voltage source operated as a static condenser.

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 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*[10]. (The term *advanced static var compensator* or *ASVC* is also frequently used in the literature[8-11].) 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 6a and that of the static var compensator in Figure 6b. 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[10] indicate that a STATCON in a variety of applications can perform the same dynamic compensation as an SVC of considerably higher rating.

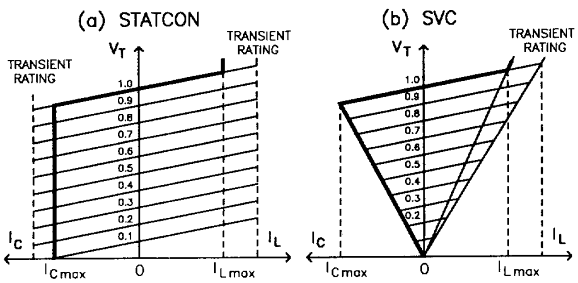

Fig. 6. - V-I characteristic of the static condenser (a) and of the static var compensator (b).

As Figure 6 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.

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. This is illustrated in Figure 7a, where the transmitted power P is shown against the transmission angle δ for the usual two-machine system[1] compensated at the mid-point by a STATCON with different var ratings, defined by its maximum capacitive output *current* I_{Cmax}. For comparison, an equivalent P versus δ relationship is shown for the static var compensator in Figure 7b. It can be observed that the STATCON, just like the SVC, behaves like an ideal mid-point shunt compensator with a power transmission relationship defined by equation[1] $P = (2V^2/X)\sin(\delta/2)$ 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.

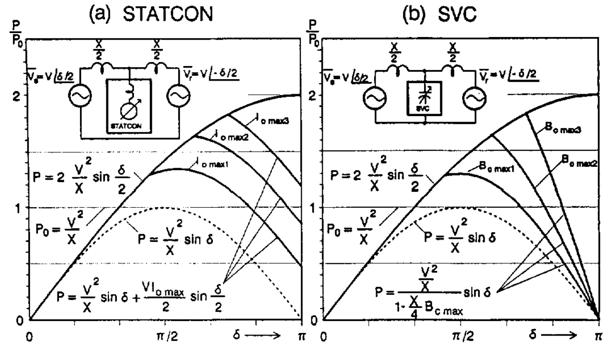

Fig. 7. - Transmitted power (P) versus transmission angle (δ) with a mid-point static condenser (a), and a mid-point static var compensator (b), of different rating.

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 8. The same simple two-machine model considered above 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

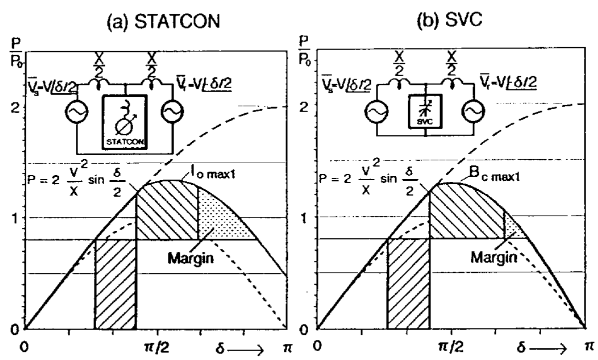

Fig. 8. - Transient stability improvement provided by a mid-point static condenser and a static var compensator of the same rating.

P_0, at angle δ_0, is subjected to a fault for a period of time 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 δ_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.

Control of Synchronous Shunt Compensator

A functional scheme to control a synchronous voltage source used as a *shunt* compensator is shown in Figure 9, 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.

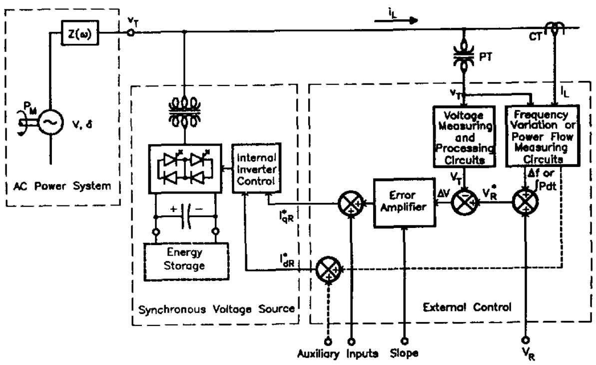

Fig. 9. - Functional control scheme for a synchronous voltage source operated as a (reactive and real power) shunt compensator.

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[11] 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.

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 9, 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*, $V_R = V^*_R$.) 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*.

Consider first power oscillation damping by the modulation of the reactive output current. With reference to Figure 9, 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.

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 10a and its possible operating modes are illustrated in Figure 10b. 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.

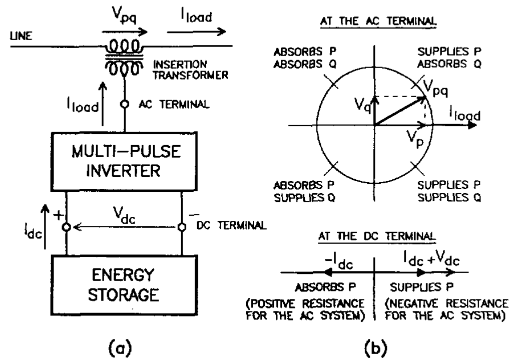

Fig. 10. - Series-connected synchronous voltage source (a) and its possible operating modes (b) for reactive and real power exchange.

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 much more effective than the conventional thyristor-controlled series capacitive compensator in providing power oscillation damping. This is because it is not only able to change the series reactive impedance of the line but also to alternately insert 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[12]. Mathematically, this voltage source can be defined as follows:

$$V_C = -jkXI \tag{1}$$

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 11. The effect of this compensation on the transmittable power can be seen from the expression, $P = \{V^2/X(1-k)\}\ sin\delta$, given[3] for a simple two machine system with a k that is *continuously* variable $(0 < k < 1)$.

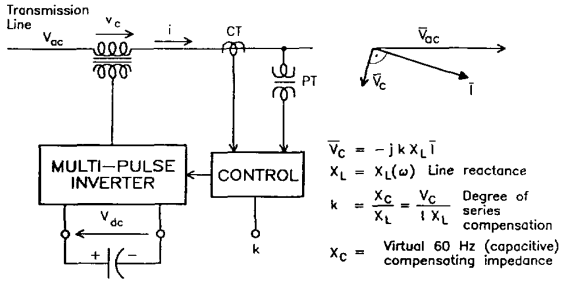

Fig. 11. - Synchronous voltage source operated as a series capacitive compensator.

For normal capacitive compensation, the output voltage must lag the line current by 90 degrees, as illustrated in Figure 11, 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, with proper implementation, unable to produce undesired electrical resonances with the transmission network, and for this reason it *cannot* cause sub-synchronous resonance. However, by suitable controls it can *damp* sub-synchronous oscillations (due to existing series capacitive compensation) by injecting non-fundamental voltage components with appropriate amplitudes, frequencies, and phase angles, in addition to the fundamental component, in series with the line.

Control of Series Synchronous Compensator

A simple control scheme for the synchronous voltage source operated as a generalized series compensator is shown in Figure 12. 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.

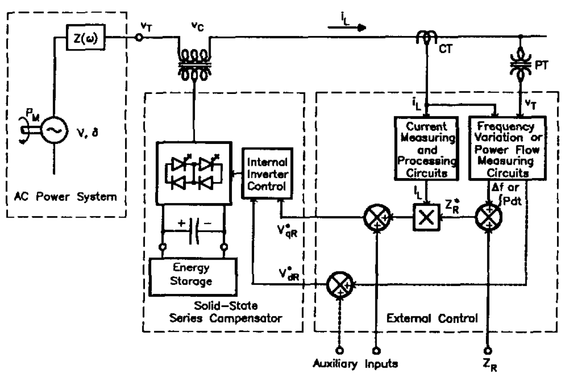

Fig. 12. - Basic control scheme for the solid-state series compensator to control (reactive and real) line impedance and improve system stability.

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 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-based series compensator 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[7]. 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)*[3,13] which, within its comprehensive functional capabilities, can be operated as an ideal phase shifter.

Basic Principles

Refer back the generalized series compensator shown in Figure 10. 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.

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 13a. Specifically, by the appropriate definition

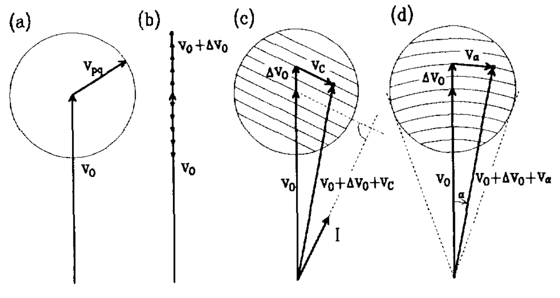

Fig. 13. - Phasor diagram illustrating the general concept of series voltage injection (a), and attainable power flow control functions: terminal voltage regulation (b), terminal voltage and line impedance regulation (c), and terminal voltage and phase angle regulation (d).

(control) of phasor V_{pq}, i.e, by synthesizing V_{pq} from phasors ΔV_0 (representing voltage magnitude), V_C (representing series impedance compensation), and V_α (representing phase shift), the following power flow control functions can be accomplished[3]:

(1) Dedicated terminal *voltage* regulation or control, as illustrated in Figure 13b.

(2) Combined *series* line compensation *and* terminal voltage control, as illustrated in Figure 13c.

(3) Combined *phase angle* regulation *and* terminal voltage control, as illustrated in Figure 13d.

(4) Combined terminal voltage regulation *and* series line compensation *and* phase angle regulation, as illustrated in Figure 14.

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 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.

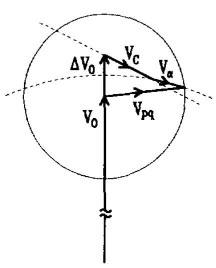

Fig. 14. - Phasor diagram illustrating the simultaneous regulation of terminal voltage, line impedance, and phase angle.

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)*[3] employs two voltage-sourced inverters operated from a common dc link capacitor; it is shown schematically in Figure 15.

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.

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.

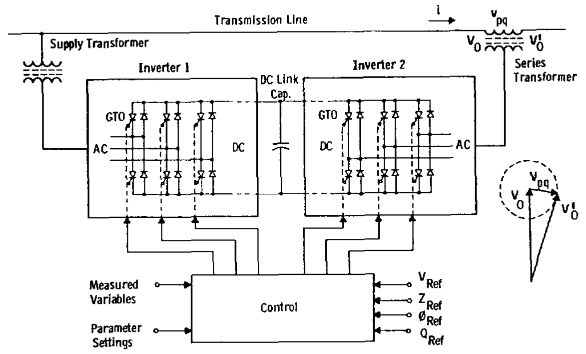

Fig. 15. - Implementation of the unified power flow controller using two "back to back" voltage-sourced inverters with a common dc terminal capacitor.

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. (*Inverter 2* itself generates the reactive power demand corresponding to the *series* line compensation). 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 follows from the previously discussed operating principles that, for generalized series compensation, *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 exchange to stabilize the ac system.

The internal control of the solid-state power flow controller 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*.

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.

Solid-state synchronous voltage sources employ self-commutated dc to ac inverters, using gate turn-off thyristors (or other similar power semiconductors), 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 negotiate *real* *power* with the ac system, in addition to the independently controllable reactive power exchange.

The synchronous voltage source can be considered as 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 inherent 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 (GTO) 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 the installation of a ±100 Mvar static condenser in 1994[9] and the development of the unified power flow controller[13], 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.

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