Reactive Power Generation and Control by Thyristor Circuits

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Abstract—**Generally, static var generators function as variable reactances (capacitive or inductive impedances) or controllable ac current and voltage sources. Possible methods of var generation and control by static thyristor circuits are reviewed, and new approaches are described in which power frequency changers (cycloconverters) are employed. Oscillographic recordings illustrate the operation and performance of practical systems, including a 35-Mvar arc furnace compensator.**

INTRODUCTION

IN RECENT YEARS there has been a greatly increased demand for controllable var sources to regulate and stabilize transmission lines and to compensate large lagging industrial loads, such as electric arc furnaces, electrical machines, and line commutated thyristor drives.

Traditionally, rotating synchronous condensers and fixed or mechanically switched capacitor/inductor banks have been used for var compensation and power factor correction. Recent advances in high-power thyristor technology and electronic circuitry have prompted the development of controllable static var sources—often called var generators—and several large installations are presently in service. These systems are conceptually simple; they usually comprise shunt capacitors and inductors in conjunction with thyristors on/off or phase-controlled switches. Their commercial success is due to their acceptable cost, coupled with desirable technical features, such as extremely fast response time, flexibility of control, and continuous operation with virtually no maintenance.

In addition to using relatively simple thyristor switch arrangements to vary the effective impedance of a passive power factor correction network by switching "in" and "out" capacitor/inductor banks, or by controlling the current flow in them, thyristor circuits can also be used to realize controllable static current and voltage sources for var generation. Some of these schemes are the true static equivalents of the rotating synchronous condenser, providing similar steady-state performance with much faster response time and superior control characteristics.

This paper reviews various methods of static var generation and control using conventional thyristor circuits and describes novel approaches in which static frequency changers are employed.

VARIABLE IMPEDANCE TYPE VAR GENERATORS

Two basic schemes for the variable impedance type var generator are considered: one controls the leading vars by synchronously switching capacitor banks to the lines, the other achieves the same objective with a fixed capacitor bank in parallel with a thyristor-controlled "variable" inductor.

Switched Capacitor Scheme

An obvious method of providing controllable leading vars for an ac system is to switch in and out appropriately dimensioned capacitor banks. In this scheme a static electronic switch, employing in essence a pair of antiparallel connected thyristors, is used with each capacitor bank. The number of capacitor banks required is determined by the maximum allowed step change of reactive current. The power factor compensation follows the reactive power consumption in a steplike manner.

The switching of the capacitor banks can be made essentially transient free by choosing the instants of switching at the natural zero crossings of the capacitor current; consequently, when the capacitor banks are switched out, they remain charged to the positive or negative peak value of the line voltage. Thus, in normal operation, a charged capacitor bank may be switched in when its voltage is equalled by the supply voltage. Therefore, the theoretical response time of this scheme is one cycle for "switching in" (assuming that the capacitor bank is charged to the "wrong" polarity) and one-half cycle for "switching out."

It is mentioned in the literature [1] that ordinary ac power factor correction capacitors cannot be subjected to direct voltage because the askarel, normally used as impregnant, will be dissociated. For this reason it is necessary to charge these types of capacitors alternately to positive and negative voltages at a slow subcycle rate. This can be accomplished quite readily by the thyristor switch. It is worth noting that the new dielectric fluids developed to replace askarel (such as, for example, isopropylbiphenyl) remain stable under direct voltage, making charge reversal on the standby capacitor banks unnecessary.

In a three-phase system the thyristor-controlled capacitor banks are usually connected in delta as shown in Fig. 1. This arrangement is particularly advantageous when unbalanced reactive power consumption is anticipated. In practice, it is necessary to connect appropriately dimensioned inductors in series with the individual capacitor banks in order to limit the current in the thyristors due to possible differences

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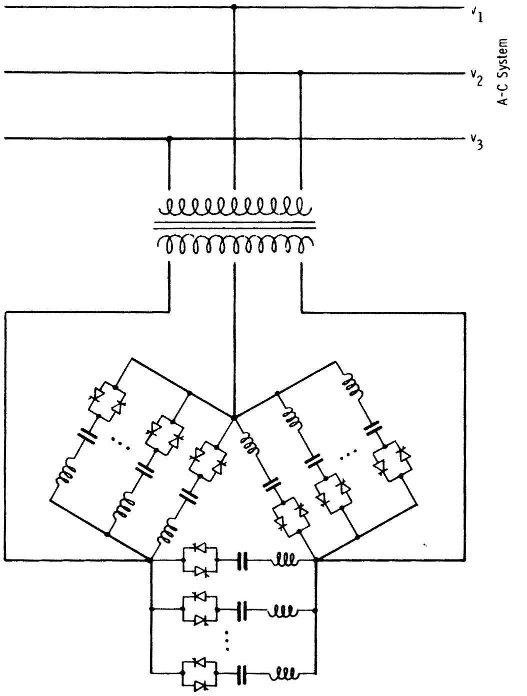

Fig. 1. Static var generator scheme using thyristor switched capacitor banks.

between line and capacitor voltages at the switching instants selected, and to reduce the risk of establishing resonances with the ac system impedance for those frequencies at which excitation by harmonic load currents is anticipated. Thus, current-limiting inductors are usually used with the capacitor banks to form *LC* notch filters at the low-order characteristic harmonics.

Despite the attractive theoretical simplicity of the switched capacitor scheme, its popularity has been hindered by a number of practical disadvantages: the var compensation is not continuous; each capacitor bank requires a separate thyristor switch and therefore it is not economical for high-voltage applications unless a step-down transformer is used; the steady-state voltage across the nonconducting thyristor switches is twice as high as the peak supply voltage; and the thyristor switch must be rated for, or protected by external means, against line voltage transients and fault currents.

Fixed-Capacitor Thyristor-Controlled Inductor Scheme

The basic system consists of a fixed capacitor in parallel with a thyristor-controlled inductor as shown in Fig. 2. With this arrangement a variable *reactance* (i.e., a purely capacitive or inductive impedance) can be realized by controlling the current flow in the inductor and thereby varying its effective impedance. This is achieved by delaying the closure of the thyristor switch by an angle α in each half-cycle with respect to the peak of the applied voltage to control the current conduction intervals. The control process is illustrated in Fig. 2, where the controlled inductor current $i_L(\alpha)$, the fixed-capacitor current i_C, and the total current $i(\alpha)$, with its fundamental component $i_{\text{fund}}(\alpha)$, are shown together with the applied voltage v as the conduction interval of the thyristor switch is reduced from maximum to zero (α increased from 0° to 90°). In this illustration ωL is assumed to be smaller than $1/\omega C$, that is, the rating of the inductor is assumed to be higher than that of the capacitor for the purpose of realizing a reactance with a range of control in both the inductive and capacitive domains.

From these operating principles it follows that the effective impedance of, and thereby the fundamental current in the fixed-capacitor thyristor-controlled inductor compensator is continuously variable, that is, any value between the rated capacitive and inductive maxima can be obtained. On the other hand, adjustment of the effective impedance, and thus of the compensating current, can only take place at *discrete instants of time*, that is, an adjustment cannot be made more often than once in each half-cycle. However, it should also be noted that within one half-cycle the current can be changed from maximum lagging to maximum leading or vice versa.

The technique of controlling the conduction intervals of the thyristor switch generates harmonic current components, as the waveforms in Fig. 2 indicate. For identical positive and negative current half-cycles only odd harmonics are generated; the most significant of these are the third, fifth, seventh, ninth, eleventh, and thirteenth with *maximum* amplitudes of 13.8 percent, 5.0 percent, 2.5 percent, 1.6 percent, 1.0 percent and 0.7 percent, respectively, of the rated fundamental *inductor* current. These harmonics can be kept out of the line currents by replacing the fixed capacitor with a filter network that draws the same fundamental current at the system frequency and provides low-impedance shunt paths at the harmonic frequencies.

In a three-phase system the thyristor-controlled inductors are normally delta connected (to compensate unbalanced loads); the capacitors (filters) may be delta or wye connected. A three-phase arrangement and associated waveforms for a balanced operating condition are shown in Fig. 3. It is worth noting that under balanced operating conditions the compensating currents do not contain triplen (third, ninth, etc.) harmonic components since they circulate inside the closed delta.

The mechanism of compensation is illustrated for three different three-phase loads by the vector diagrams shown in Fig. 4. In Fig. 4 (a) the compensation of a balanced lagging load is illustrated: the reactive components of load currents I_{l1}, I_{l2}, and I_{l3} are cancelled to obtain the real line currents I_1, I_2, and I_3. In Fig. 4 (b) an unbalanced set of load currents, (I_{l1}, I_{l2}, I_{l3}) is transformed by the delta-connected compensator drawing capacitive currents (I_{C12}, I_{C23}, I_{C31}) into a set of *balanced* real line currents (I_1, I_2, I_3). In Fig. 4 (c) another set of unbalanced load currents is transformed into a balanced set of real line currents by the compensator. This latter transformation requires that one element of the compensator, connected between phases 1 and 3, be inductive.

Fast response and the capability to balance loads make the fixed-capacitor thyristor-controlled inductor scheme particularly advantageous for compensating electric arc furnaces [2] - [4], which present a rapidly varying generally unbalanced load with a poor lagging power factor. The operation of a 35-Mvar installation compensating a 50-ton arc furnace is

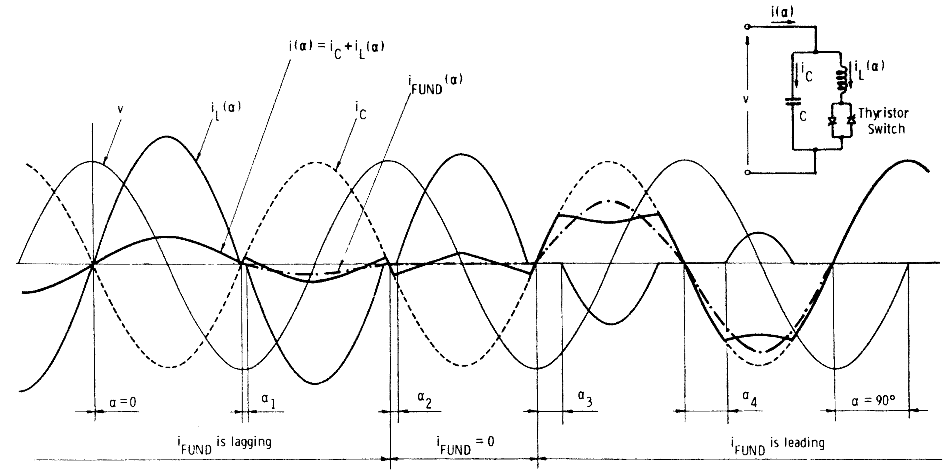

Fig. 2. Fixed-capacitor, thyristor-controlled inductor type var generator and associated waveforms.

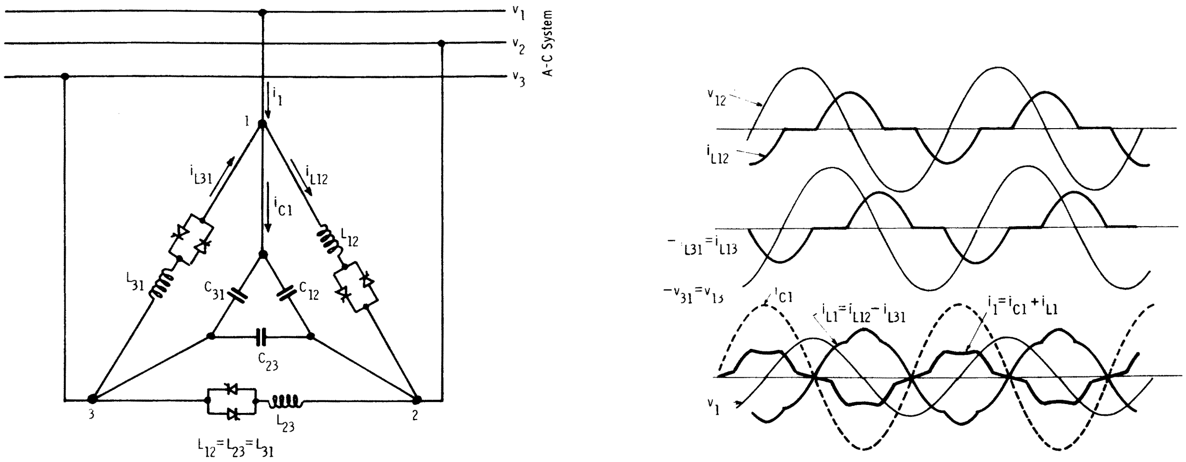

Fig. 3. Three-phase fixed-capacitor thyristor-controlled inductor type var generator and associated waveforms under balanced operating condition.

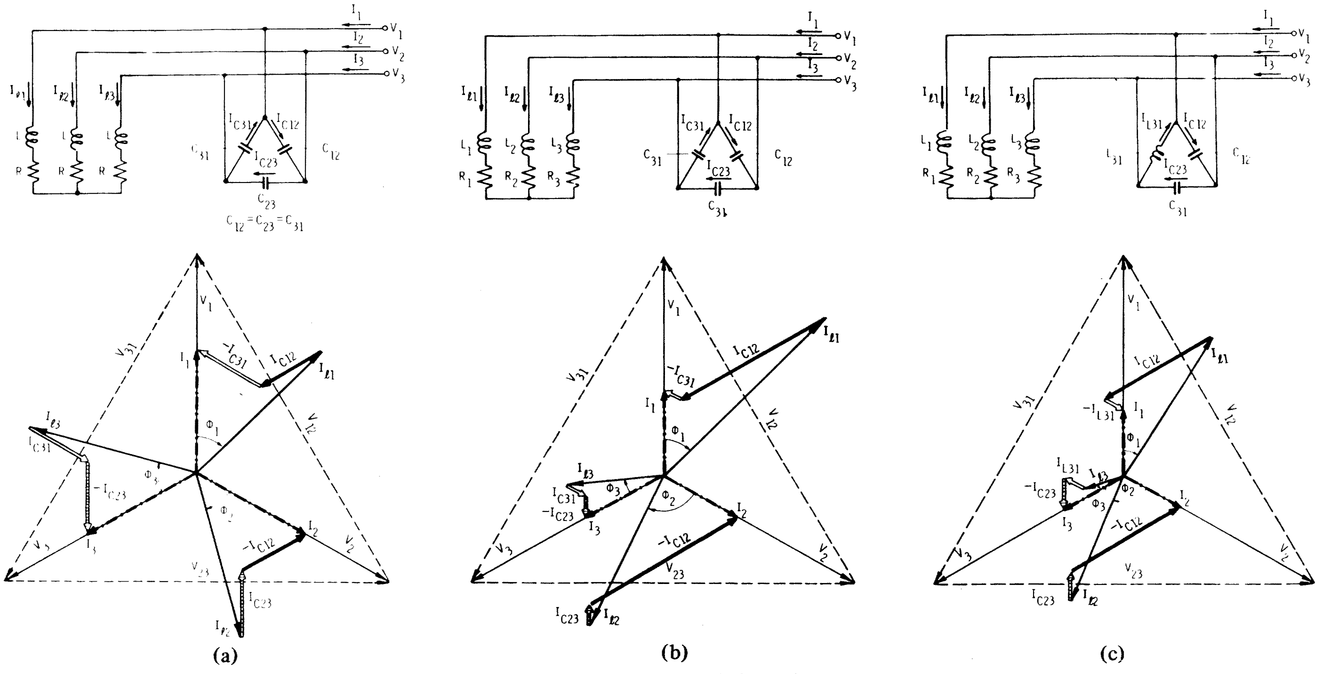

Fig. 4. Vector diagrams illustrating compensation of three-phase balanced and unbalanced loads with three appropriate reactances connected in delta.

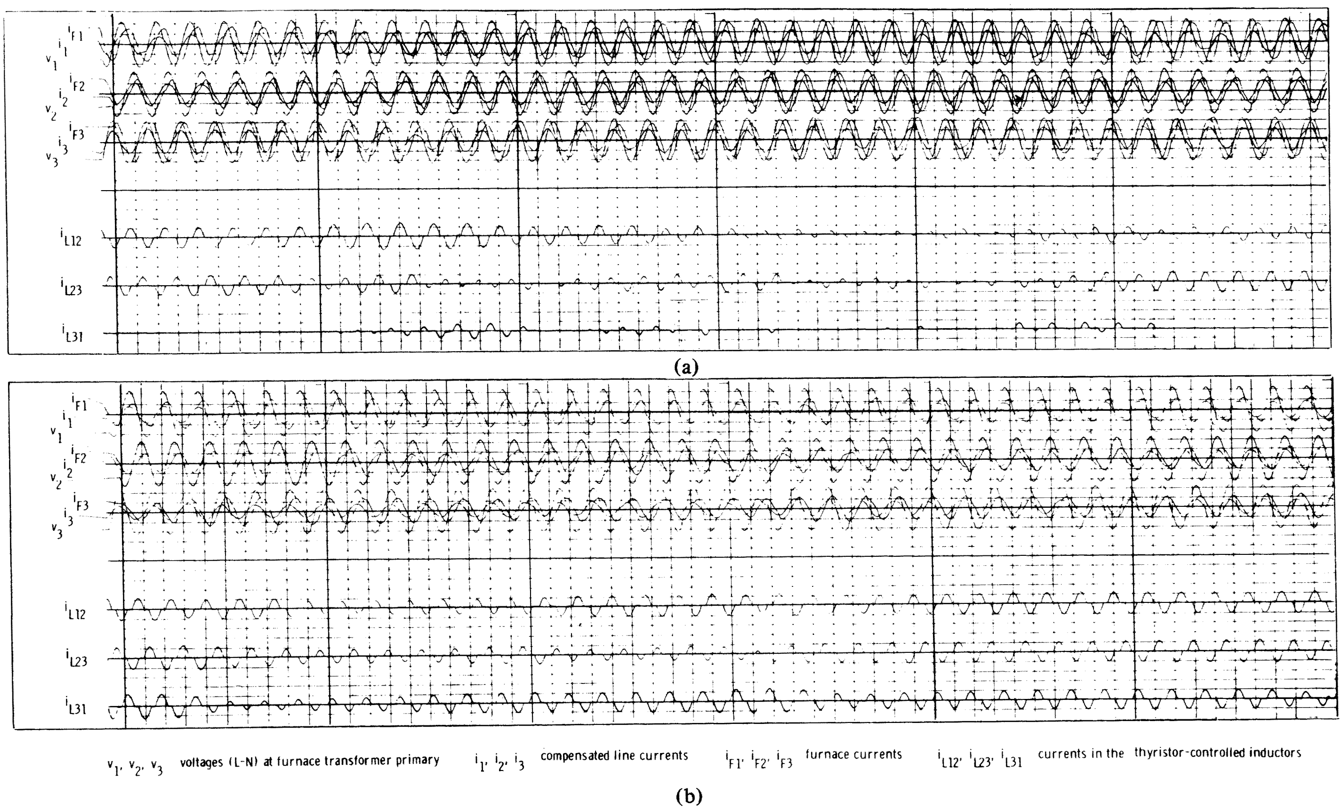

Fig. 5. Oscillographic recordings showing operation of 35-MVA fixed-capacitor thyristor-controlled inductor type static var generator in compensating the currents of electric arc furnace during (a) melt down, and (b) refining.

illustrated in Fig. 5, where each of the three furnace currents is shown with the corresponding line-to-neutral voltage and compensated line current superimposed. The currents in the three delta-connected thyristor-controlled inductors are also shown on separate traces.

The fixed-capacitor thyristor-controlled inductor scheme is presently perhaps the best solution for a controllable static var source. It offers excellent performance and high reliability at an acceptable cost. Its major disadvantage is that the fixed capacitor must be complemented by an inductor of the same rating to provide variable leading vars.

CURRENT SOURCE TYPE VAR GENERATORS

A current source type var generator can be realized by an inductively loaded ac/dc converter[1] as shown in Fig. 6. The converter may be naturally (line) or force commutated. The naturally commutated converter can only provide lagging vars; by contrast, the force-commutated converter can provide both lagging and leading vars. Converters are usually used to provide balanced three-phase output; independent control of the output phases, though possible, is uneconomical.

A naturally commutated converter can only operate if the thyristors are fired at such delay angles where the dc current is "naturally" transferred from one pair of thyristors to the next pair. This generally restricts the delay angle to the range 0-180°, measured from the earliest point of natural commutation. The phase of the ac line current lags the corresponding voltage by an angle equal to the firing delay angle. Thus, when the converter is used as a reactive var source, the firing delay angle is 90°, the mean output dc voltage is theoretically zero, and the ac converter input current lags the corresponding voltage by 90°, as shown in Fig. 6(a). In order to establish and maintain the required dc current in the inductor the firing

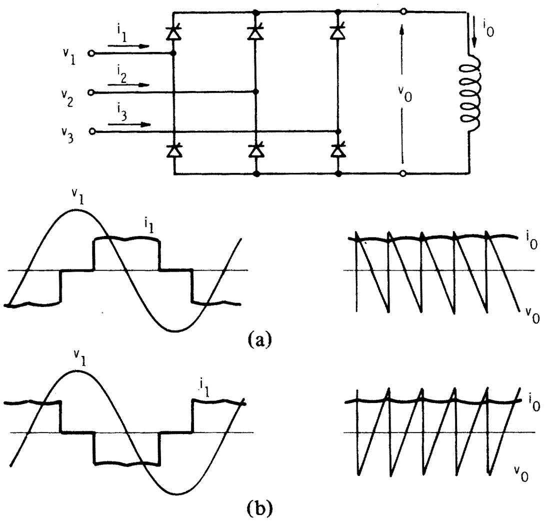

Fig. 6. Current source type var generator employing ac/dc converter. Typical waveforms at (a) for providing lagging vars with naturally commutated thyristors and at (b) for providing leading vars with force-commutating thyristors.

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[1] Other approaches, for example, using reactively loaded cycloconverters, are also possible; however, these are generally uneconomical.

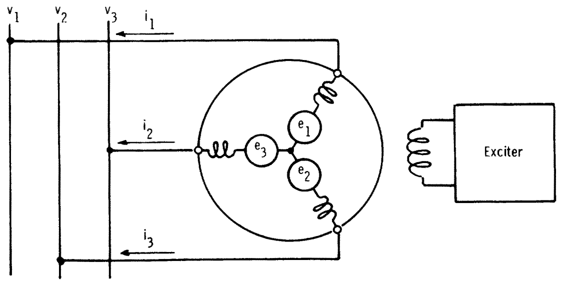

Fig. 7. Basic voltage source type var generator employing a rotating synchronous condenser.

delay angle must, in practice, be slightly less than 90° so that there is just enough dc voltage to overcome the thyristor voltage drops and the resistances of the inductor and the ac system. Evidently, the magnitude of the dc current and, consequently, the amplitude of the resultant ac line currents can be controlled by the adjustment of the firing delay angle. Thus, the naturally commutated converter can be viewed at the ac lines as a continuously variable balanced three-phase inductor. To provide controllable leading vars the converter inputs must be shunted by three-capacitor banks of appropriate rating so that the combined current drawn from the ac system becomes leading as the converter current is decreased.

In order to make the converter input currents leading it is necessary to advance the firing angles by 90° with respect to the earliest point of natural commutation. In this operating mode, however, the converter thyristors must be force commutated. Functionally, the operation is similar to that previously discussed; the mean dc output voltage is zero and the converter input currents lead the corresponding input voltages by 90° as shown in Fig. 6(b). Again, the firing angle is advanced slightly less than 90° in practice to establish and maintain the dc inductor current required. Since the force-commutated converter is capable of operating over the total firing angle range of 0-360°, it can provide both leading and lagging line currents, i.e., it can act both as a variable balanced three-phase capacitor and inductor.

The ac/dc converter is one of the simplest static arrangements to provide controllable power factor correction. However, it is not suitable for compensating unbalanced loads; its response time is relatively long and it can introduce considerable amounts of harmonic currents into the ac system. Both the response time and harmonic distortion can be improved by increasing the pulse number of the converter; the harmonic problem can be solved by filtering.

VOLTAGE SOURCE TYPE VAR GENERATORS

The basic principle of voltage source type var generators can be introduced by considering a conventional rotating synchronous condenser, shown schematically in Fig. 7. For purely reactive power flow the three phase induced electromotive forces (EMF's) e_1, e_2, and e_3 of the synchronous rotating machine are in phase with the system voltages v_1, v_2, and v_3. By controlling the excitation of the machine, and hence the amplitude E of its voltage, the reactive power can be controlled; increasing E above the amplitude V of the system voltages causes leading (capacitive) current to be drawn from the ac system, whereas decreasing E below V produces a lagging (inductive) load on the ac system. Under either operating condition a small amount of real power of course flows from the ac system to the machine to supply its mechanical and electrical losses. In the following two sections static realizations of the rotating synchronous condenser model, using dc/ac inverters and ac/ac frequency changers, are discussed.

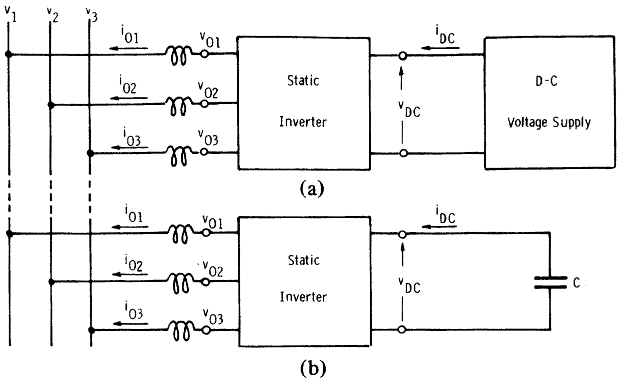

Fig. 8. Static voltage source type var generator employing a dc/ac inverter. (a) Conventional arrangement with separate dc supply. (b) Self-sufficient operation from storage capacitor.

Voltage Source Type var Generators Employing dc/ac Inverters

A ac/ac inverter can be represented at its output terminal as an ac voltage source. For the present discussion it is assumed that the inverter output voltages are sinusoids, although the basic operating principles remain valid for any waveshape produced by a practical inverter.

Suppose that the outputs of a three-phase inverter are connected through three inductors to an ac system as shown in Fig. 8(a). For purely reactive power flow the inverter output voltages v_{O1}, v_{O2}, and v_{O3} are kept in phase with the ac system voltages v_1, v_2, and v_3. By controlling the amplitude V_O of the inverter output voltages, the reactive power can be controlled from full leading to full lagging. That is to say, increasing V_O above the amplitude V of the system voltages, causes leading (capacitive) current to be drawn from the ac system, and vice versa, decreasing V_O below V results in lagging (inductive) current in the ac system.

When the inverter is operated strictly as a reactive power source, as described above, it absorbs no real power from the ac system and thus its losses have to be replenished from a separate dc supply. However, the dc supply can be dispensed with if a suitable dc reservoir capacitor is used (Fig. 8(b)) and each inverter output voltage is made to lag slightly the corresponding ac system voltage. A real component of current will then flow from the ac system to the inverter, and the losses will be accommodated thereby. The dc reservoir capacitor has to carry the input "ripple" current of the inverter. This ripple current is, of course, a function of the type, circuit configuration, and operating mode of the inverter used; however, it can generally be accommodated quite readily when the output currents are balanced.

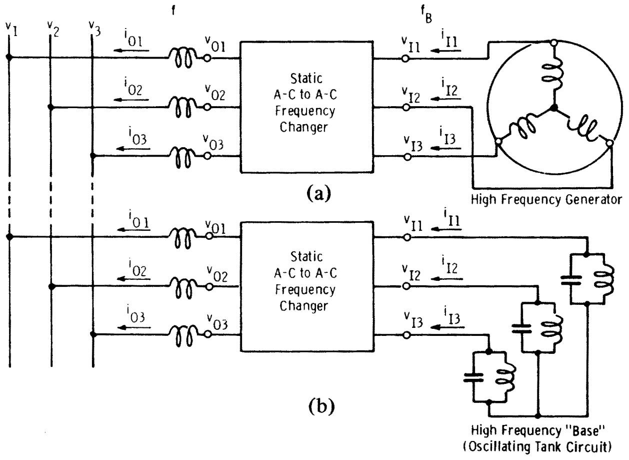

Fig. 9. Static voltage source type var generator employing ac to ac frequency changer. (a) Conventional arrangement with separate high-frequency ac source. (b) Self-sufficient operation from LC tank circuits (HF base).

In conclusion, the inverter in principle provides an excellent solution for static var generation; it can provide continuously variable leading and lagging vars without using large LC storage components at the ac system frequency. Its main disadvantage is that it requires forced commutation in the inverter which hinders its high-power application. In addition, it is not suitable (without considerable cost penalty) for handling unbalanced var demands.

Voltage Source Type var Generators Employing ac/ac Frequency Changers

An alternate method of implementing the operating principle of the rotating synchronous condenser is illustrated in Fig. 9(a). Here, a generator of relatively high frequency feeds a static ac/ac frequency changer, which converts the generator frequency f_B to the ac system frequency f. The output terminals of the frequency changer are connected to the ac system via small inductors. Assuming that the frequency changer is controlled to produce the output voltage waves v_{O1}, v_{O2}, and v_{O3}, whose wanted components are in phase with the corresponding system voltages v_1, v_2, and v_3, respectively, it is evident, as for the synchronous condenser in Fig. 7, that reactive power can be supplied in either direction to the ac system by simple amplitude control of the frequency changer voltages. Thus the frequency changer will draw leading current from—that is, it *supplies* lagging current to—the ac system when the amplitude V_O of its output terminal voltages is greater than that of the system voltages V. Conversely, it will draw lagging current whenever V_O is smaller than V.

As the amplitude of the fundamental output voltage of the frequency changer is varied, in order to control the reactive system current, it might naturally be assumed that this varying reactive power would be reflected through the frequency changer to the machine. As will be seen, this is not necessarily so. There are frequency changers [6], for example, which can be operated with a unity input displacement (power) factor. However, any frequency changer, because of its nonsinusoidal input current, will draw some harmonic (extrabasal) current from the machine.

Since the machine in Fig. 9(a) theoretically handles only reactive and/or harmonic power, it can be replaced by a multiphase static oscillating LC tank circuit—which is termed [6] a "high-frequency base," or "HF base"—as shown in Fig. 9(b). As with the scheme in (a), control of the reactive power at the ac system side can be obtained through control of the voltage generated at the output terminals of the frequency changer. The varying reactive load that may be reflected to the tank circuit by the frequency changer, as the reactive power at the ac system side is varied, has the same effect as a variable reactance (inductance or capacitance, depending upon the type of frequency changer used) connected in parallel with the passive LC circuit; that is, it causes a variation in the natural operating frequency of the HF base. Since frequency changers can operate from a variable frequency source without any difficulty, this frequency variation of the HF base, provided it is kept within reasonable limits by appropriate design of the tank circuit, does not affect the operation of the system.

In an actual system the amplitude of the oscillation in the tank circuit, and thus the amplitude of the input voltage of the frequency changer, cannot be maintained without replenishing the energy used up by the losses. The power required for this purpose can be obtained by establishing just sufficient real power flow from the ac system to the HF base. This can be accomplished quite simply by introducing an appropriate small phase shift between the output voltages of the frequency changer and the ac system voltages. In a practical scheme this phase shift would be "closed-loop" controlled so as either to maintain the voltage of the oscillating tank circuit constant or possibly to vary this voltage in an incremental manner in sympathy with the output var demand.

In order to exemplify this general approach further, two specific types of frequency changers—the classical naturally commutated cycloconverter (NCC) and the newly conceived [6] unity displacement factor frequency changer (UDFFC)—will now be considered in such a scheme. From the standpoint of the ac system the performance of the NCC and the UDFFC are similar; either can provide continuously variable leading and lagging vars with practically negligible distortion of the current wave. From the viewpoint of the HF base, however, the two types of frequency changers differ significantly.

As is known, the NCC always presents a lagging reactive load to the HF base regardless of whether the reactive power supplied to the ac system is lagging or leading. As the reactive current (leading or lagging) supplied to the ac system by the NCC is varied, the reactive lagging load on the HF base also varies. Thus, to a first approximation, the NCC can be regarded as constituting a variable inductive load on the HF base. As a consequence the HF base frequency will increase as a function of the reactive output power supplied to the system. It is therefore essential to have an LC tank circuit with a sufficiently large "reservoir" of internal oscillating energy to keep the frequency variation within practical limits [5].

The UDFFC, having a unity input displacement factor, on the other hand requires no reactive input power under any

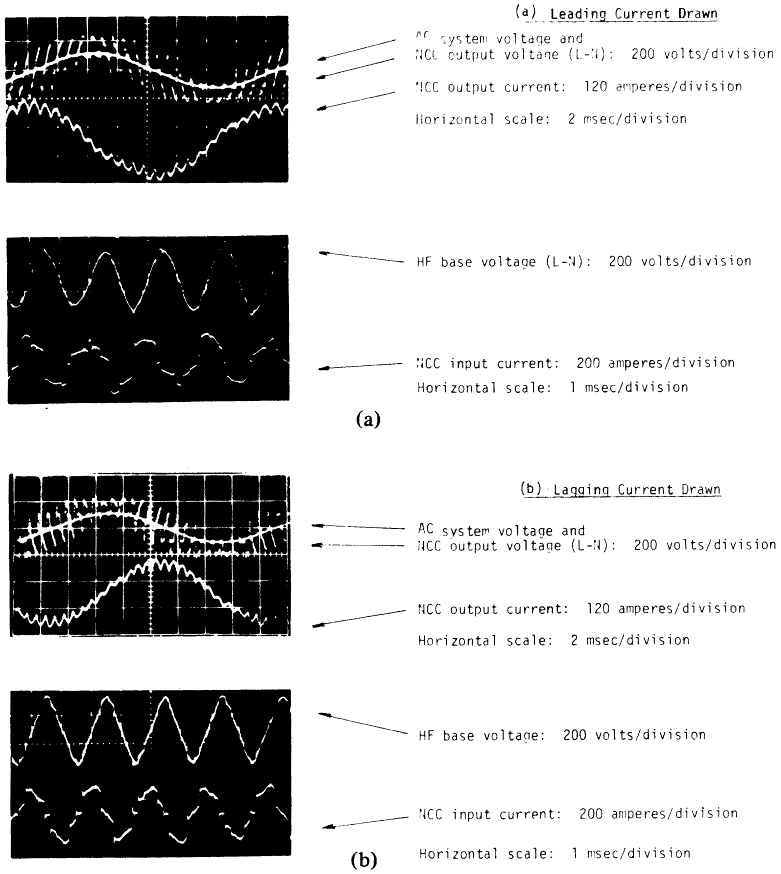

Fig. 10. Oscillograms illustrating operation of var generator using NCC operated from "high-frequency base," as shown in Fig. 9 (b). (a) Leading and (b) lagging reactive current is drawn from ac system. AC system frequency: 60 Hz. HF base frequency: approximately 450 Hz.

load condition. Thus the total reactive power supplied to the ac system is essentially circulated within the UDFFC. However, as was mentioned, the operation of a static frequency changer always results in harmonic (extrabasal) input current components having frequencies different from the input frequency, which flow through the input source. Thus, when considering the use of a UDFFC in such a system, the input current wave is entirely composed of harmonic components which have to flow through the HF base. Thus the main requirement for the HF base is to provide input voltages, but no reactive power to the UDFFC, at a fixed base frequency, and to provide a low-impedance path for the harmonic current components. The required rating of the *LC* tank circuit to be used with a UDFFC, just to provide essentially the "harmonic" power, is thus theoretically considerably smaller than that required for an NCC, where both reactive and "harmonic" power must be provided.

The operation of the static var generator using a conventional naturally commutated cycloconverter is not detailed here but is illustrated by the oscillograms in Fig. 10, which were taken in an experimental 30-kvar system comprising a simple three-pulse NCC, and a three-phase HF base employing three *LC* tuned tank circuits. Typical output voltage and current waveforms of the NCC, together with the corresponding HF base (input) voltage and current waveforms, when the NCC supplies leading vars to the ac system, are shown in Fig. 10(a). Similar waveforms, when the NCC provides lagging vars to the ac system, are shown in Fig. 10(b).

The operation of the static var generator employing a special unity displacement factor frequency changer, composed of one naturally and one force-commutated cycloconverter, each rated for one-half of the output var, is illustrated in Fig. 11. As shown at the top of the figure, both converters are operated from a common high-frequency base. The force-commutated cycloconverter (FCC) is controlled to complement its naturally commutated counterpart; that is to say, it is controlled to produce, under all operating conditions, a fundamental input current that is opposite to that of the NCC. This means, of course, that the FCC is controlled to produce a *leading* fundamental input current with the same magnitude as that of the lagging fundamental input current of the NCC. In consequence, the resultant fundamental input current of the two converters is zero and, since the HF base absorbs only a small amount of real current from the ac system to replenish the internal losses, there is practically no fundamental current (i.e., current with the HF base frequency) flowing through the HF base.

At the output terminals (i.e., at the ac system) the two converters are connected in parallel via an interphase reactor to share the total output current.

Theoretical waveforms illustrating the operation of a var generator comprising a six-pulse NCC and a six-pulse FCC are

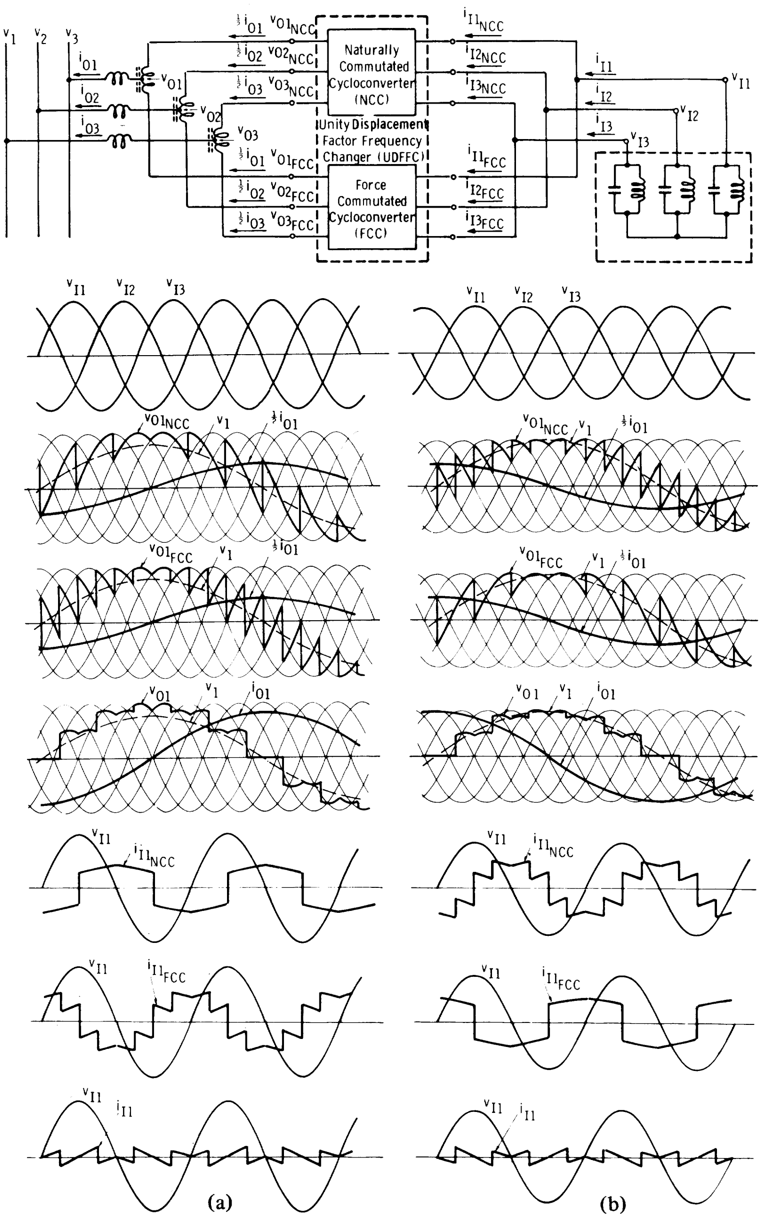

Fig. 11. Voltage source type var generator employing unity displacement factor frequency changer. Waveforms at (a) illustrate operation for generating leading vars, at (b) for generating lagging vars.

shown in Fig. 11 for the cases of generating leading (a) and lagging (b) vars. It may be observed that the FCC produces complementary [6] output voltage and input current waveforms during both operating modes. That is to say, the output voltage and input current waveforms of the FCC with *lagging* output currents are the same as those of the NCC with *leading* output currents, and vice versa.

When compared with a more conventional type of static controllable var generator using, for example, shunt capacitors and inductors in conjunction with thyristor switches, the HF base scheme generally has the potential advantage of reduced size and possibly reduced cost, because the reactive elements operate at a frequency higher than that of the ac system. In addition, when the UDFFC is employed, the total rating of the reactive elements may be substantially less than that required for the more conventional approach, (though the requirement for forced commutation may offset this advantage). The system is free from the problem of energizing large capacitor banks directly from the ac system and from possible problems caused by such banks resonating with the ac system. Also, the output currents supplied by the HF base scheme have little distortion and thus require little or no filtering. The major disadvantage of this approach is the relative complexity; further appreciable effort would be required to develop such a system for high-power applications.

Hybrid (Voltage and Current Source) Type var Generators Employing ac/ac Frequency Changers

A unique static var generator which theoretically uses no reactive components—capacitors or inductors—can be realized with the so-called "power doubling" scheme [6]. Such a scheme uses the frequency changer's output as a voltage source and its input as a current source.

In the "power doubling" arrangement the input and output sides of the frequency changer are *both* connected to the ac system, and thus both the input and output frequencies are equal to the system frequency. The main function of the frequency changer is to reflect the same phase angle at both its input and output terminals, as viewed by the common ac system voltage applied to both sets of terminals. This operating mode makes it possible to provide *twice* as much reactive VA for the ac system as the actual VA rating of the frequency changer. Thus, a frequency changer of 1/2 per unit (pu) VA rating (throughput) can supply 1 pu reactive VA to the ac system.

The operation of the "power doubling" scheme is explained conceptually with reference to Fig. 12. Consider first Fig. 12(a), where a static frequency changer converts the three-phase ac system voltages (v_1, v_2, v_3) to three-phase output voltages (v_{O1}, v_{O2}, v_{O3}). Let it be assumed that the frequency changer can be operated under the following conditions.

1) The generated angular output frequency ω_O is equal to the angular input frequency ω_I.
2) The wanted sinusoidal components v_{O1w}, v_{O2w}, and v_{O3w} of the generated output voltages v_{O1}, v_{O2}, and v_{O3} are in phase with the respective ac voltages v_1, v_2, and v_3.
3) The amplitude of the wanted components of the generated output voltage waves is variable with respect to the nominally fixed amplitude of the input voltages, i.e., $V_O = kV_I$.
4) The input displacement angle ϕ_I, between the input phase voltage and the fundamental component of the input current, is the negative of the output phase angle ϕ_O, between the wanted components of the output voltage and current. Thus, $\phi_I = -\phi_O$.

Assume now that the outputs of the frequency changer are connected to a three-phase external voltage source (e_1, e_2, and e_3)—which could be another ac power system—via three small inductors, the values of which are theoretically unimportant. The arrangement is shown in Fig. 12(b). Assume further that the three voltages of the external source are in fact replicas of the input voltages—that is, $e_1 = v_1$, $e_2 = v_2$, and $e_3 = v_3$. The frequency changer, whose output voltages are stipulated to be proportional to the input voltages, thus can be made to supply either lagging or leading vars to this external source. That is to say, if $k > 1$,[2] the frequency changer supplies lagging current to (i.e., it draws leading current from) the external source, and if $k < 1$, the frequency changer supplies leading current to (i.e., it draws lagging current from) the external source. In the first case the output currents of the frequency changer *lag* the corresponding wanted output voltages, which means that the frequency changer is *inductively* loaded, while the external source is *capacitively* loaded. In the second case the output currents of the frequency changer *lead* the output voltages, which means that the frequency changer is *capacitively* loaded, while the external source is *inductively* loaded. Of course, when $k = 1$, no current of fundamental frequency flows. To proceed further with the explanation of the "power doubling" concept, it is necessary to consider the fundamental input currents i_{I1F}, i_{I2F}, and i_{I3F} drawn by the frequency changer from the ac system for the three cases of $k > 1$, $k < 1$, and $k = 1$.

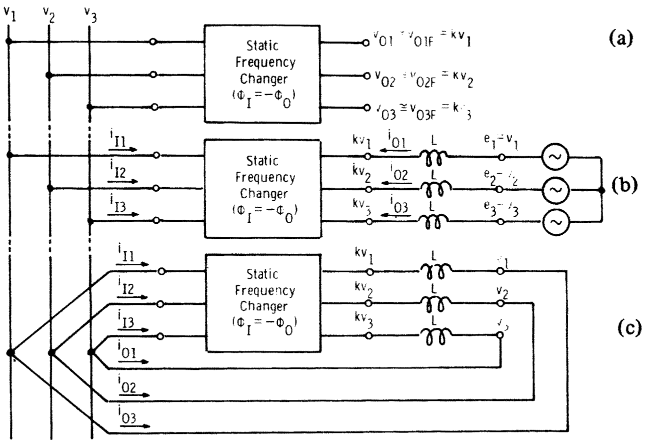

Fig. 12. Conceptual explanation of notion of "power doubling."

As was explained, if $k > 1$, the wanted output currents of the frequency changer *lag* the corresponding wanted output voltages, that is, the output phase angle ϕ_O is $-90°$. It was stipulated at the outset that the frequency changer has the characteristic of reflecting the negative of the output phase angle to the input. Thus, $\phi_I = -\phi_O = -(-90°) = 90°$. Consequently, the fundamental input currents lead the corresponding ac system voltages, by 90°. Similarly, if $k < 1$, the fundamental output currents lead the output voltages of the frequency changer; that is, the output phase angle, ϕ_O, is $+90°$. The input currents now *lag* the input voltages by 90°; that is, $\phi_I = -90°$. At $k = 1$ the fundamental components of the input currents are, of course, zero since the frequency changer supplies no output currents.

On the basis of the above deductions it can be concluded that whenever $k > 1$, the currents flowing from the ac system to the input terminals of the frequency changer, *as well as* those flowing from the external source to the output terminals of the frequency changer, *lead* the corresponding voltages by 90°. Similarly, whenever $k < 1$ the currents flowing from the ac system, *as well as* those flowing from the external source, *lag* the corresponding voltages by 90°.

These conclusions lead directly to the essence of the power doubling concept. Since the voltages of the three-phase external source were stipulated to be perfect replicas of the ac system voltages, it follows that the above-described current/voltage relationships will not change if the outputs of the frequency changer are removed from the external source (which was introduced only to aid the explanation) and connected instead to the ac system, as shown in Fig.

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[2] It should be noted that k can be greater than 1 only if an input or output transformer is employed in the frequency changer.

12(c). Since both the input and output currents of the frequency changer can simultaneously be made to lead or lag the ac system voltages, it is evident that the total reactive current supplied to the ac system will be the sum of these currents, thus, $i_1 = i_{I1} + i_{O1}$, $i_2 = i_{I2} + i_{O2}$, and $i_3 = i_{I3} + i_{O3}$. Therefore, the total reactive power supplied to the ac system is

$$P_Q = 3V_{I,\mathrm{rms}}(I_{I,\mathrm{rms}} + I_{O,\mathrm{rms}})$$

where

$V_{i,\mathrm{rms}}$ rms input (ac system) voltage,

$I_{I,\mathrm{rms}}$ rms value of the fundamental input current,

$I_{O,\mathrm{rms}}$ rms value of the fundamental component of the output current.

If the inductance L is relatively small, the input and output currents will be approximately equal; therefore, the total reactive power may be expressed by

$$\begin{aligned} P_Q &= 3V_{I,\mathrm{rms}} \times 2I_{I,\mathrm{rms}} \\ &= 3V_{I,\mathrm{rms}} \times 2I_{O,\mathrm{rms}}. \end{aligned}$$

The VA rating (throughput) of the frequency changer (FC), on the other hand, is

$$\begin{aligned} (\mathrm{VA})_{\mathrm{FC}} &= 3V_{I,\mathrm{rms}} \times I_{I,\mathrm{rms}} \\ &= 3V_{I,\mathrm{rms}} \times I_{O,\mathrm{rms}} \\ &= \frac{P_Q}{2}. \end{aligned}$$

Thus, the VA rating (throughput) of the static frequency changes only one-half of the maximum leading or lagging vars supplied to the ac system.

The principle of the "power doubling" has been based upon the assumption of a frequency changer having special characteristics—that is to say, $\phi_I = -\phi_O$, and $\omega_I = \omega_O$. A particular force-commutated cycloconverter called the unrestricted frequency changer [6] meets, unreservedly, these requirements. However, a naturally commutated cycloconverter can also be employed in this scheme if the objective is only to provide continuously lagging reactive power. A particular embodiment of the "power doubling" scheme employing a three-phase bridge-type unrestricted frequency changer is shown in Fig. 13, and its operation is described with reference to Fig. 14.

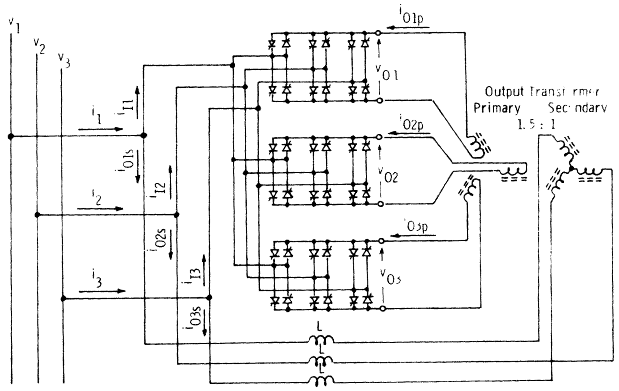
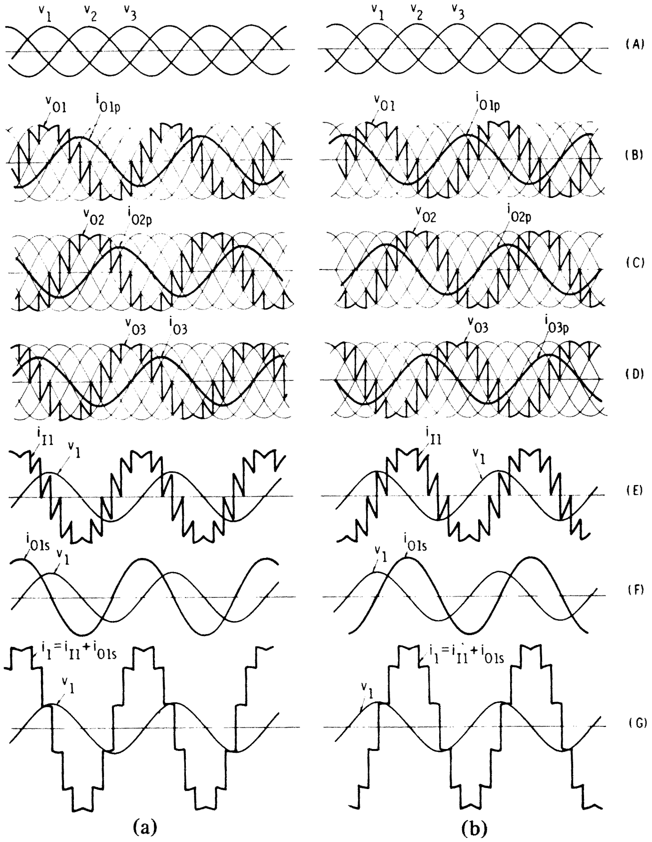


Fig. 13. Schematic of "power doubling" var generator employing three-phase six-pulse bridge-type frequency changer.



(a) (b)

Fig. 14. Waveforms illustrating operation of static var generator using unrestricted frequency changer in "power doubling" arrangement shown in Fig. 13. (a) Generating leading vars. (b) Generating lagging vars.

The line-to-neutral voltages of the ac system v_1, v_2, and v_3 are illustrated in Fig. 14(a). The frequency changer is operated so that its output voltages v_{O1}, v_{O2}, and v_{O3} [shown at (B), (C), and (D)] are in phase with v_1, v_2, and v_3, respectively. This can be accomplished by appropriately synchronizing the operation of the thyristors of the power circuit to the ac system voltages as indicated in the figure.

Consider first the case where the amplitude of the wanted components of the three output voltage waves, at the secondary winding of the transformer, are somewhat greater than those of the line-to-neutral ac system voltages. Then, a lagging current will flow from each output phase of the frequency changer to the corresponding phase of the ac system. In other words, the frequency changer constitutes a corresponding leading load on the system. The three output currents, i_{O1}, i_{O2}, and i_{O3}, are shown on the left side of Fig. 14 at (B), (C), and (D). The three input currents, i_{I1}, i_{I2}, and i_{I3} can be derived graphically from the output current waveforms shown at (B), (C), and (D). One input current waveform, I_{I1}, is illustrated together with the corresponding voltage v_1 at (E), on the left side, for the case under consideration. As can

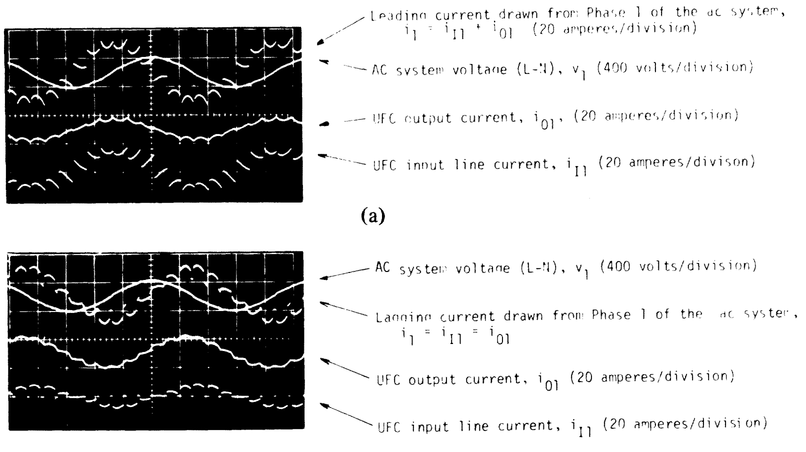


Fig. 15. Oscillograms illustrating operation of "power doubling" var generator shown in Fig. 13. (a) Leading and (b) lagging reactive current is drawn from ac system.

be seen, the input current i_{I1} leads the corresponding voltage v_1. One output current, i_{O1s}, flowing into the secondary of the transformer from phase 1 of the ac system, is shown together with the corresponding voltage v_1 at (F).

The total current flowing from line 1 of the system into the frequency changer $(I_{I1} + i_{O1s})$ is shown at (G). Evidently, this total current "flows through" the frequency changer, and it leads the corresponding system voltage.

The operation of the scheme when drawing lagging current from the system is similar. In this case the amplitude of the output voltages of the frequency changer at the secondary side of the output transformer must be lower than those of the system voltages. The operation under this condition is illustrated in a self-explanatory manner on the right side of Fig. 14.

The operation of an actual static var generator employing an unrestricted frequency changer in the "power doubling" configuration is illustrated by the oscillograms in Fig. 15. These oscillograms are appropriate to a model system using a 6-kVA frequency changer with gate-controlled switches in the arrangement shown in Fig. 13. The output voltage of the frequency changer is controlled by the technique of pulse-width modulation. As can be seen, the practical waveforms are quite similar to the ideal ones shown in Fig. 14.

Considering now the possibility of using a naturally commutated cycloconverter in this type of scheme, inspection of Fig. 14 indicates that when the frequency changer consumes *lagging* reactive power from the ac system $(k < 1)$ then the requirements for natural commutation of the switches of the power circuit are satisfied. Thus, the output waveforms at (B), (C), and (D), on the right side, show that the "incoming" voltage is always more positive than the "outgoing" one during the positive current half-cycles, and that this relationship reverses during the negative current half-cycles. Consequently, a naturally commutated cycloconverter with $\frac{1}{2}$ pu VA rating could be employed to consume variable lagging reactive power up to 1 pu from the ac system.

Since the naturally commutated cycloconverter cannot be operated in the manner illustrated by the waveforms on the left side of Fig. 14, this arrangement as it stands cannot consume leading vars from the system. It can, however, be used in conjunction with a fixed capacitor to consume controllable leading vars from the system.

The "power doubling" scheme represents an elegant solution to static var generation which, in principle, requires virtually no reactive storage components. The major disadvantage of this scheme is that it can be used only to generate controllable lagging vars when the thyristors are naturally commutated; the generation of controllable leading vars requires forced commutation.

SUMMARY

Considerable progress has been made in the development and application of controllable static var sources in the last few years. The variable impedance approach employing high-power thyristor switches to control current in reactive circuit elements (capacitors and inductors) is gaining widespread acceptance both in industrial and utility applications. Recent developments indicate that the characteristics of an "ideal" synchronous condenser are attainable with static approaches using thyristor circuits suitable for high-power applications. The unique "power doubling" scheme shows that an "all solid-state" realization of static var sources, in which passive storage elements theoretically are not needed, is a practical reality. Although these new approaches have not yet been developed for commercial use, their performance characteristics and adaptability for high-power applications make them strong potential candidates for future applications.

ACKNOWLEDGMENT

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Laszlo Gyugyi, for a photograph and biography please see page 429 of the July/August 1979 issue of this TRANSACTIONS.

A New Controlled Current Type Inverter with Improved Performance

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Abstract—**A new current-commutating method applying the action of the mutually coupled inductances is described and is termed the coupled reactor commutating (CRC) method. With this method a unique self-excited controlled current type inverter is constructed. The CRC inverter not only gives an efficient voltage adjustment function, but it also liberates men from the task of treating reactive powers. An example of the application to the induction motor drives is described in which an overall efficiency as high as 85 percent has been reached. The troublesome problem of parasitic torque pulsation in the low-revolution range, which is inherent in the controlled current type inverters, is also resolved by the torque-smoothing current control method with the CRC inverter.**

INTRODUCTION

INVERTERS used in the control of ac motors can generally be divided into two categories: the controlled voltage inverters such as the bridge inverter with the pulsewidth modulation (PWM) control and the controlled current or current source inverters [1]. Both methods, however, have proven unsatisfactory when both smooth running and uniform motor performance is desired. The problems inherent in the PWM inverter control of ac motors arise from the necessity of using a step-down dc–dc chopper converter which allows the output voltage of the inverters to be adjusted. The best performance can be obtained from the voltage step-down chopper converter when a very large inductance appears in its output circuit. From the standpoint of the inverter, however, this would result in excessive reactive power that is not in keeping with the nature of ac circuits. Usually only the motor inductance itself is used. The results of such a compromise are threefold. First, fluctuating output currents along with high-current transients during switching necessitate the use of higher current-rating choppers; second, higher-order harmonics in the output result, which cause heating in the motor and therefore require a higher design factor for motor specification; and third, the overall efficiency is reduced due to chopper loss from high currents and high chopping frequencies over and above the motor loss [2], [3].

The case presented by currently used current source inverters is not much better. Their main disadvantage is their parasitic pulsating torque, making steady drive in the low-revolution range impossible [4], [5]. They still require some form of voltage level adjustment, and quite often a variable voltage source is required. Other undesirable features are self-oscillation while driving the induction motor, higher impressed voltages placed on main thyristors, and so on [6]. These difficulties could be overcome if there were a more efficient and more suitable method.

A unique magnetically coupled commutating method has been reported previously by the author [7]. This current-commutating method has since been developed and is termed the coupled reactor commutating (CRC) method. The theory and operation of such a method are quite simple and will be described.

THE CRC METHOD

The circuits in Fig. 1 are used to illustrate the principle of the CRC method. The solid-line circuits represent the output circuits of the dc–dc chopper converters; in this case two smoothing reactors magnetically coupled with each other tightly are used. Initially we assume a current I_0 to be flowing in the first circuit and no current to be flowing in the second. In order to commutate the current from the first to the second circuit one must either apply a positive voltage in the second circuit, or a negative voltage in the first circuit, or both.

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