15. Variable-Voltage Devices

If you ever design a high-voltage dc system for a microwave tube, make sure it has a mechanism for varying the voltage, preferably from zero on up. This is true even for microwave tubes like TWTs and crossed-field devices, which have narrow ranges of actual operating voltages. The commissioning of almost every component in the high-voltage loop is a gradual affair, and it is all but impossible to commission a system without being able to control the high voltage over nearly its complete range. It is also important that the variability be low-loss because we are usually dealing with large amounts of average power.

15.1 The phase-controlled rectifier

One way to achieve variable high voltage is by the use of phase-controlled rectifiers in the ac-dc converter. Indeed, this is the basic application of the SCR, which has already been discussed. Before the advent of solid-state components, however, devices such as thyratrons and ignitrons were also used as phase-controlled rectifiers in variable-output high-voltage supplies. A full-control rectifier system, illustrated in Fig. 15-1 as a six-pulse rectifier, requires nothing more complicated than the replacement of the rectifier diodes with SCRs. A half-control rectifier involves the replacement of only half of the rectifiers, but a complication arises in the gate-firing circuits.

The electronic strategy used to produce less than the full-output voltage for a given ac input is to delay the gating of the controllable rectifiers until after the normal commutation point (in time) has passed, as shown in Fig. 15-2. The conduction angles of the six "CRs"—they do not have to be silicon—are the same, but they are less than the normal 60° intervals that produce maximum-output voltage. The waveforms to the left in the figure would apply under no-load conditions for different retardation angles, which are the amounts by which the rectifier turn-on points are delayed from the "natural" commutation points. On the right side of the figure are the waveforms that are obtained under load

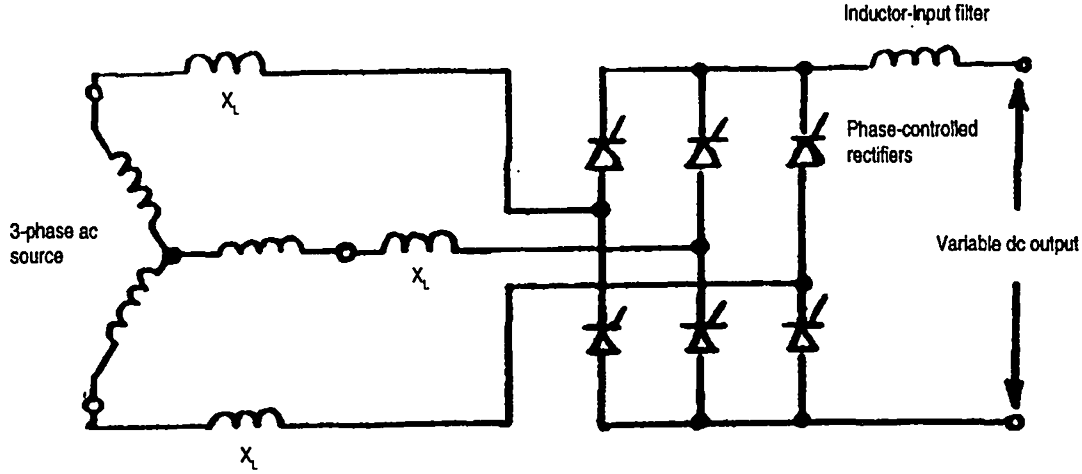

Figure 15-1. The phase-controlled rectifier variable-output dc power supply.

and with finite three-phase source inductance, giving rise to a commutation angle as well as a retardation angle. Note that the output-voltage waveform with retardation includes an instantaneous jump upward halfway between the outgoing- and incoming-phase voltages. This is followed by downward-tracking segment that is also midway between the phase voltages. Finally, when the stored energy in the source inductance has been overcome, another step upwards occurs to meet the instantaneous voltage of the incoming phase. This complex voltage waveform has a lower average value than the full-conduction waveform. It also requires a rectifier load having a high-variational input impedance, such as an inductor-input filter, in order to support the voltage.

The ratio of partial-conduction output to full-conduction output is the cosine of the angle of retardation (ignoring the effect of commutation delay). For the case of 60° ($\pi/3$ radians) retardation, the waveform looks like a sine wave traveling between 0 and $\pi/3$ radians, but backwards. The integral of this waveform is 1/2. Its average value is $3/\pi \times 1/2$. The full-voltage output has an average value, as previously discussed, that is $6/\pi \times \sin(\pi/6)$. But the sine of $\pi/6$ is 1/2. This gives $6/\pi \times 1/2$, which is twice as great as the average value for 60° retardation. We would expect this result because the cosine of 60° is 1/2. For 90° retardation, the waveform at the input to the inductor is finite, comprising positive and negative 30° segments. But their average value is zero, as would be expected

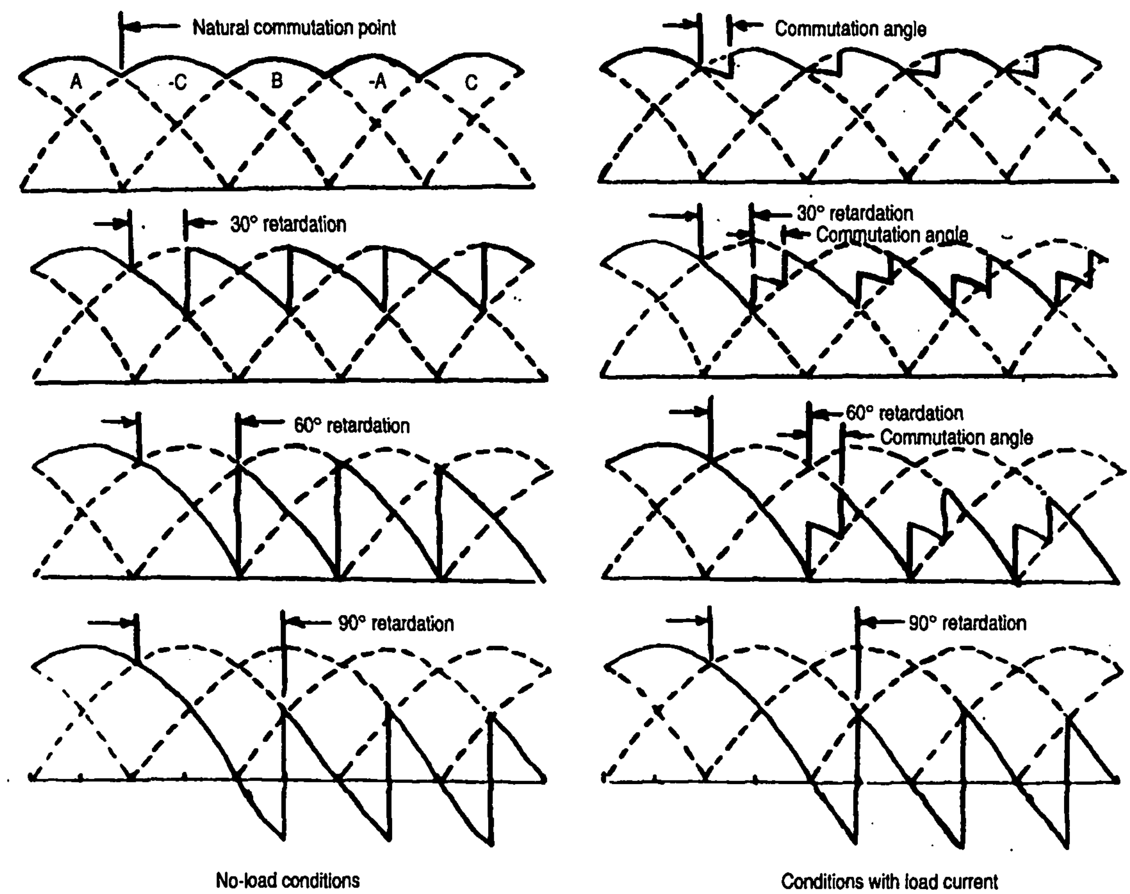

Figure 15-2. Phase-controlled rectifier waveforms for different output voltages.

because the cosine of 90° is 0.

Note that this is a true switch-mode application of an inherently lossless device, the half-control switch. In order for there to be dc output, the rectifiers must be gated "on" during each and every conduction interval. They will block forward and reverse voltage unless they are gated into conduction in the forward direction. Although this arrangement implies that there be considerably more electronic complexity than for a more conventional dc power supply, it also provides the mechanism for the highest-speed load disconnect following fault conditions: simply blocking the low-level SCR gating signals. Gate-signal timing strategies can also produce such desirable features as voltage or current regulation, soft-start (or ramped-up turn-on), and output current-limiting.

High-voltage variable-output power supplies using phase-controlled rectifiers are relatively rare, but they are by no means unheard of. A new installation, part of a test facility for the microwave-tube group of the French corporation Thomson, uses phase-controlled SCRs to vary the output of a 30-kV dc power supply to charge pulse-forming networks in a highly versatile line-type modulator. (This installation was designed by the same engineers who produced France's high-speed train. Experience helps.)

15.2 The primary SCR controller

A far more popular application of the half-control switch in the role of a variable-voltage device is as the active element of the primary-voltage controller. Because the SCR is the device that predominates in this area—although it is by no means the only one—the primary-voltage controller is universally referred to as the primary SCR controller. It differs from the phase-controlled rectifier in that what is varied is the amplitude of the alternating voltage applied to the primary winding of the rectifier transformer. It works in much the same fashion as the

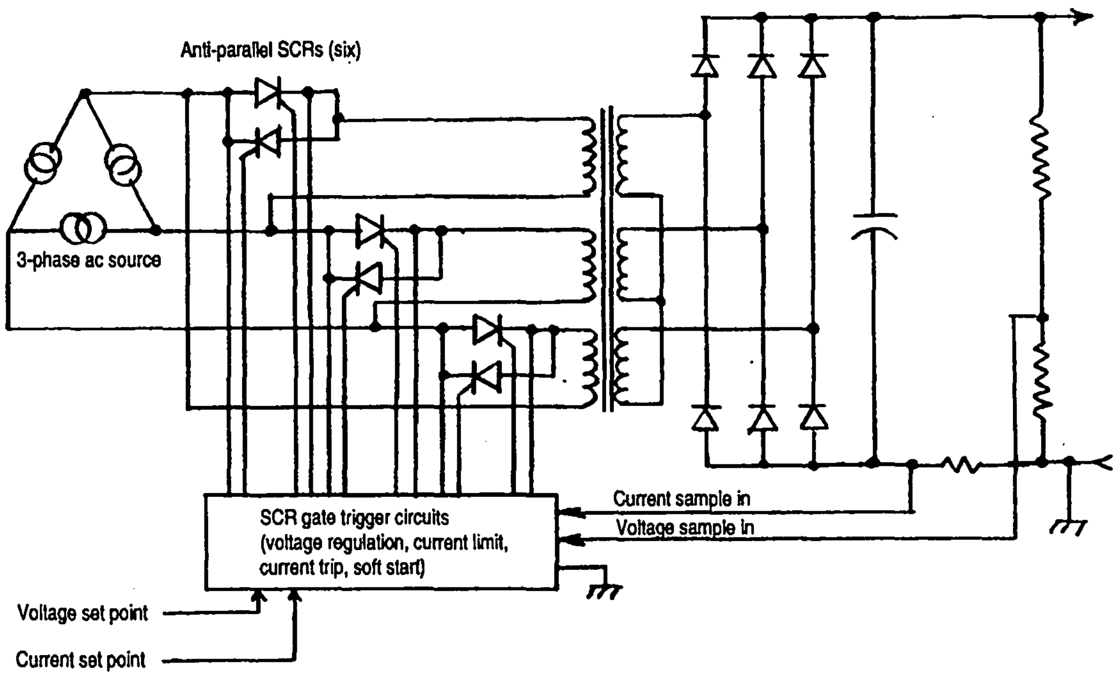

Figure 15-3. Primary phase control of variable dc output voltage using SCRs.

household full-wave light-bulb dimmer. Of course, primary current is bidirectional, which is why the control devices, as shown in Fig. 15-3, must be provided in pairs connected in anti-parallel configuration (parallel, but of opposite polarities).

At first glance it is apparent that many more devices are now required to produce the same voltage variability of the phase-controlled rectifier. Not only are a minimum of six primary half-control devices required, but rectifiers on the secondary side must be provided as well. The great advantage of this design is that the primary voltage can be selected to match the voltage-handling capability of a single device, even if it must often have prodigious current-handling ratings. Primary voltages rarely exceed 600 Vac, even for power supplies rated in megawatts of dc output and hundreds of kilovolts of output voltage. The gate-control circuits, although not simple, are by no means as complicated as the comparable gating circuits required by series-connected SCRs in a high-voltage phase-controlled-rectifier supply. Integrated low-level controls, comprising voltage and/or current regulators and "proportional" SCR gating circuits, can accomplish all of the same functions described earlier. (The gating circuits are called proportional because the effective primary voltage is proportional to the low-level dc input signal to the trigger board.)

High-speed disconnect from the ac source and current-limiting into a short-circuited load are important features of proper gate-control strategy. These are not the only design considerations, however. SCRs can and do fail, especially when they are subjected to transient source overvoltage, such as from a lightning strike (or near miss), power-line switching transients, etc. When SCRs fail, they take on all of the characteristics of bus bars. So transient suppression in the source is not an option; it is a necessity. Also, the SCR controller must always be backed up by an air-insulated contactor. Even though it is slow-acting, it can ensure positive disconnect from the ac source. SCR control on the primary side is much more susceptible to loss of control than phase-controlled rectification. Ironically, this is partly due to one of the phase-controlled-rectifier's disadvantages when used at high-voltage: many rectifiers may be needed in series to handle the full voltage. In such circuits, the failure of one or two phase-controlled rectifiers may not cause immediate failure of the entire series string. (In fact, periodic checks of series strings of conventional high-voltage solid-state rectifiers regularly indicate that as many as 10% of the individual junctions are short-circuited at any given time.) But the failure of one or more SCR primary-control devices, however, means immediate loss of control.

The possibility of short-circuit SCR failure is but one reason why the maximum dc output voltage from the system should correspond closely to the full-conduction angle of the primary SCRs. If a range of output voltages is required, it is a good idea to have a transformer tap-changing switch. The very real possibility of seriously overvoltaging the load could result from a design that operates normally with significant SCR phase-back.

As mentioned earlier, the SCR is not the only high-power half-control switch. Figure 15-4 shows the simplified schematic of a 2.25-MW, 150-kVdc primary phase-controlled power supply that first went into service with ignitrons as the control devices. (This power supply still exists as part of a high-power micro-

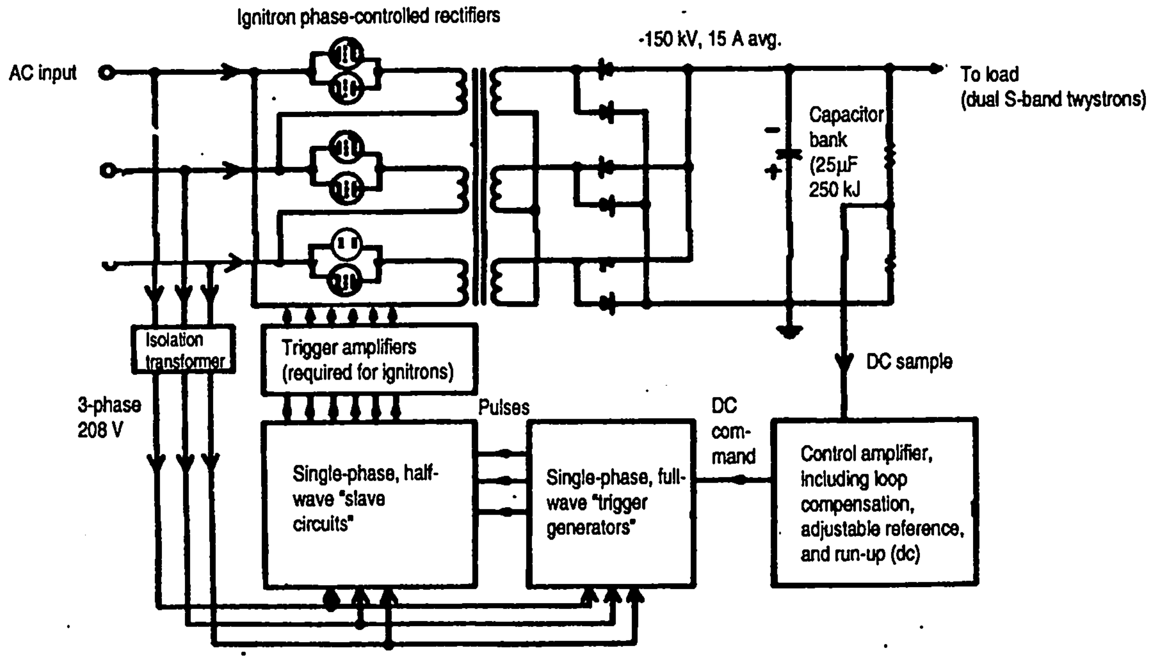

Figure 15-4. High-power variable dc power supply with primary phase control using ignitrons.

wave-tube test facility, but its original ignitrons have been replaced with SCRs.)

In the circuits of both Figs. 15-3 and 15-4, the half-control switches are shown connected within an "open-delta" transformer primary connection. This is used because the stress on individual switches is lower in this connection than if they were outside of the delta in series with each input line. They handle only the current in each delta leg, which is smaller by a factor of $\sqrt{3}$ than the line current. On the other hand, they must handle the full line voltage. If the delta winding is closed and the SCRs are in series in the line, two switches will be in series to block the line voltage at any given time. Having two switches in series, however, is less of a factor than it might appear because the sharing of reapplied voltage between the two may not be perfect.

Most primary phase controllers are outside of the delta of the rectifier transformer so that they can be part of an assembly that is completely separate from the transformer/rectifier. In fact, complete high-power, high-voltage dc systems often comprise three completely separate assemblies:

1. A full-power transformer that steps down whatever the subtransmission line voltage might be (4160 V, 13.2 kV, etc.) to the ~600 V that is compatible with single-device (per phase) controllers;
2. The primary phase controller itself; and
3. The high-voltage transformer/rectifier, which is often mounted in an oil-filled enclosure.

The waveforms of Fig. 15-5 show how the output voltage of the controller (transformer primary voltage) grows to resemble more and more the input line voltage as the conduction angle is increased. For small conduction angles, neither the output voltage nor the line current is especially sinusoidal in wave

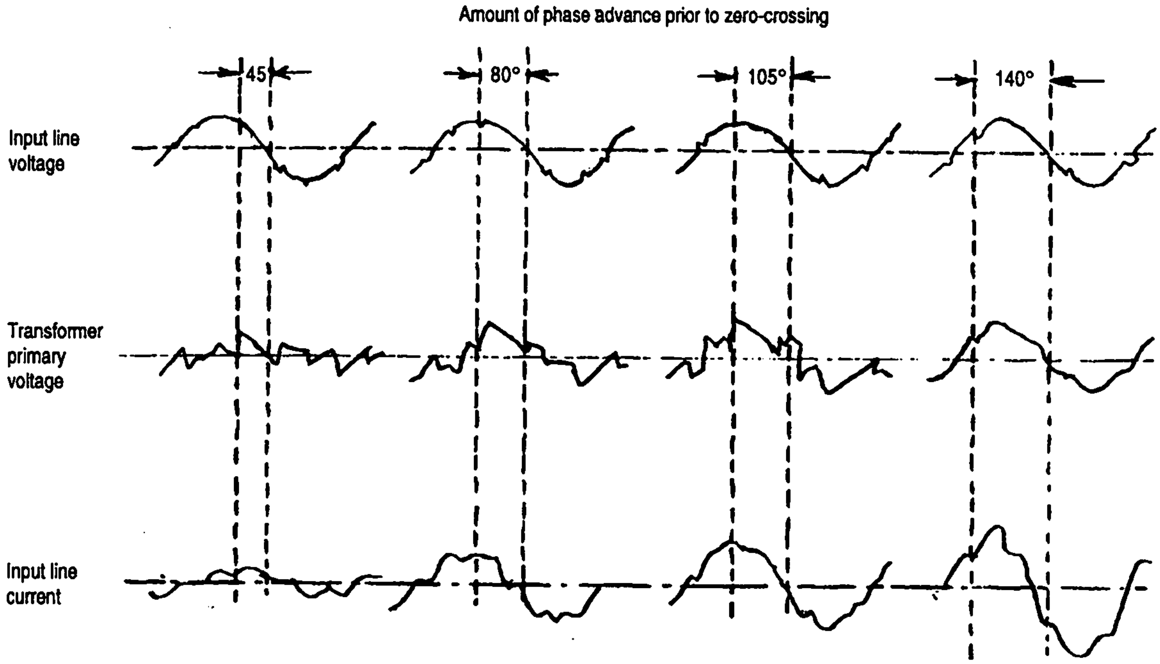

Figure 15-5. Wave shapes of primary phase-control circuit as conduction angle is varied.

shape. The fundamental-frequency component of line current is also displaced in phase from the line voltage. Figure 15-6 shows the effect on the input-power factor as the output voltage is varied through phase-control alone. The figure illustrates why it is a good idea to have the useful range near the maximum

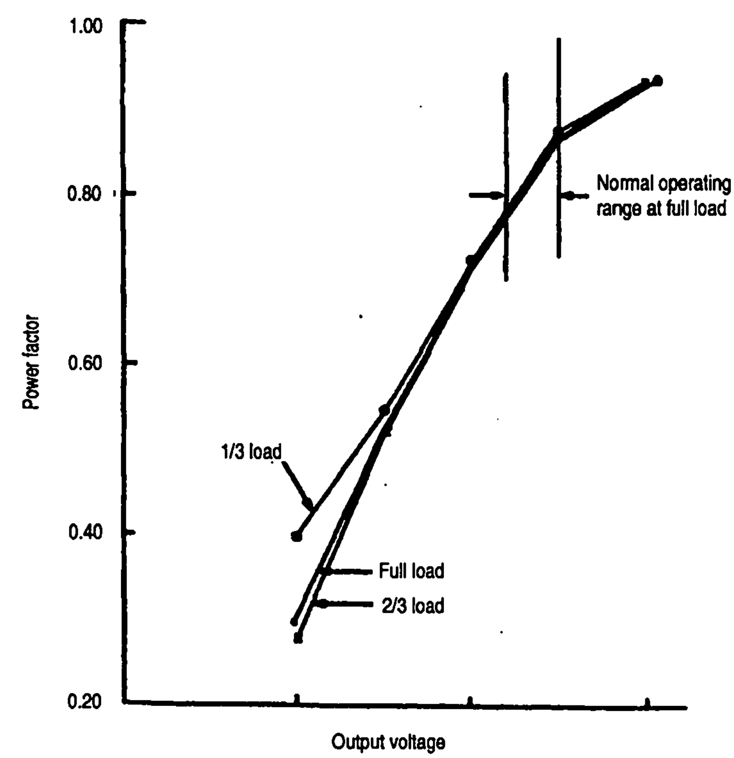

Figure 15-6. Effect on input-power factor as output voltage is varied.

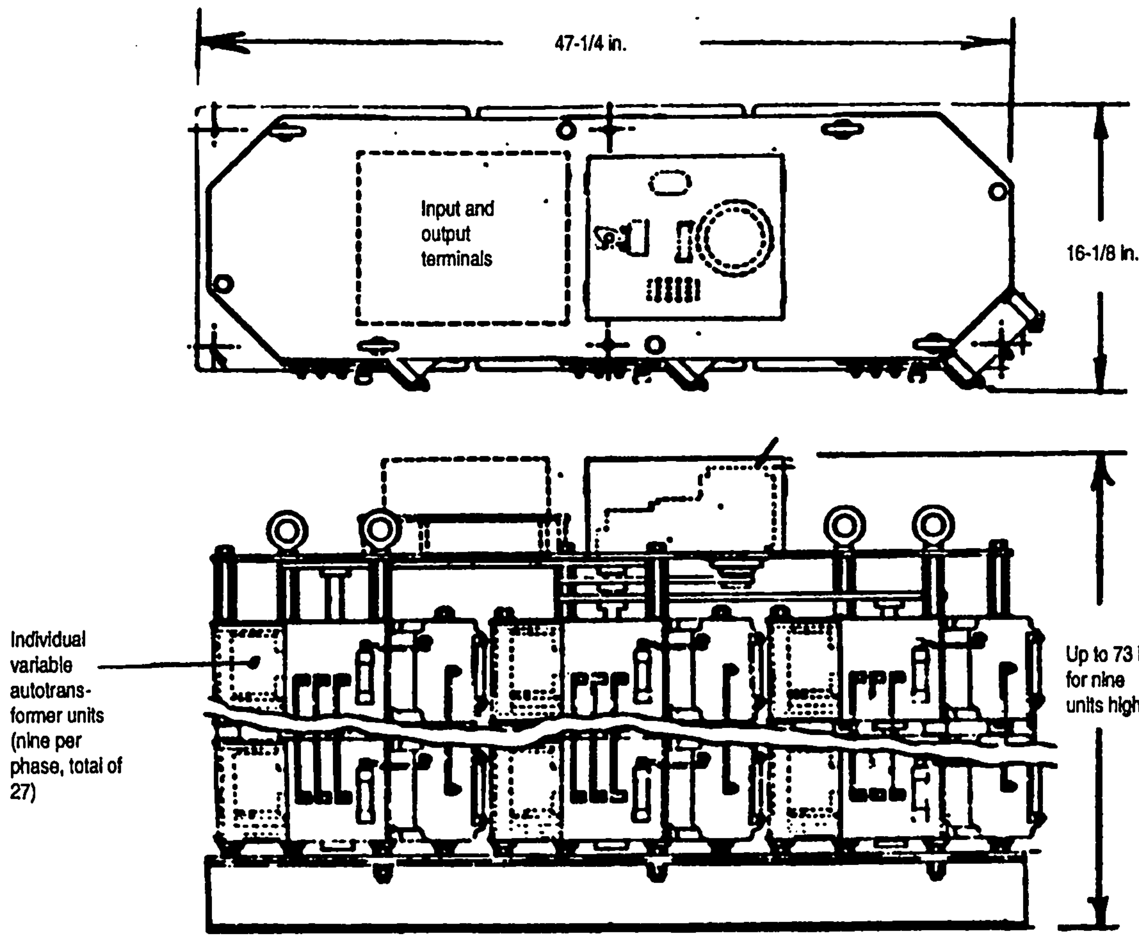

Figure 15-7. Multiple-gang, three-phase (nine per pulse) variable autotransformer, rated at 244 kVA.

output value.

Despite some very real shortcomings—including circuit complexity, line-current harmonic pollution, and the ever-present possibility of catastrophic failure—the SCR-type primary controller of high-voltage power supply is presently the most popular design by far. Almost all new requirements specify this type of controller. The popularity of designs based on the SCR is due partly to the electronic agility of SCRs and partly to its low cost and small physical size.

15.3 The variable autotransformer

At the other end of the technological spectrum, and sharing none of the advantages (or disadvantages) of the fully electronic voltage control methods discussed, is the archetype of all ac variable-voltage devices: the variable autotransformer. (It is known to many by the non-generic term "Variac," which is no more than a contraction of the terms "vary" and "ac.") In applications where the input volt-ampere demand is less than 100 kVA, the variable autotransformer, or suitable arrays of multiple autotransformers, can be quite economically competitive. Figure 15-7 shows just such a multiple-gang, three-phase array. All of its pickup-arms are driven by a single reversible motor by means of a chain drive. The outline drawing is of a 27-gang unit rated at 244 kVA. It has nine transformers connected in parallel for each of the three phases. Because there can be no assurance that the tap voltage will be precisely the same for each unit, the outputs are collected through paralleling transformers, as shown in Fig. 15-8, that losslessly produce equalizing voltages so that there are no circulating currents.

Whether the variable autotransformer is technologically competitive with electronic control devices depends upon what is important for the particular application. If line-current harmonic distortion matters, this device produces none (or only a small amount due to non-sinusoidal magnetizing current of the core). If there is a fear that components downstream might suddenly be exposed to maximum-output voltage as a result of a catastrophic short-circuit failure in an active control device, this device won't do that. If the speed of response is not important, these devices can be incorporated in voltage- or current-control closed-loop regulators. (There have actually been electronic phase-control, high-voltage systems that have been retrofitted with autotransformers because of the problems associated with electronic control devices.)

15.4 The variable-voltage transformer

The variable-voltage transformer, or VVT, logically extends the circular-format variable autotransformer to higher current capabilities (up to 1 MVA). As shown in Fig. 15-9, the winding has been uncoiled and made flat. The advantages to this are obvious. When the winding is flat, its wires can be made flat, thus greatly increasing the pickup-brush surface area and even making dual-brush-pickup assemblies practical, as shown. If this is such a great idea, why haven't all variable autotransformers been made this way? The answer is leak-

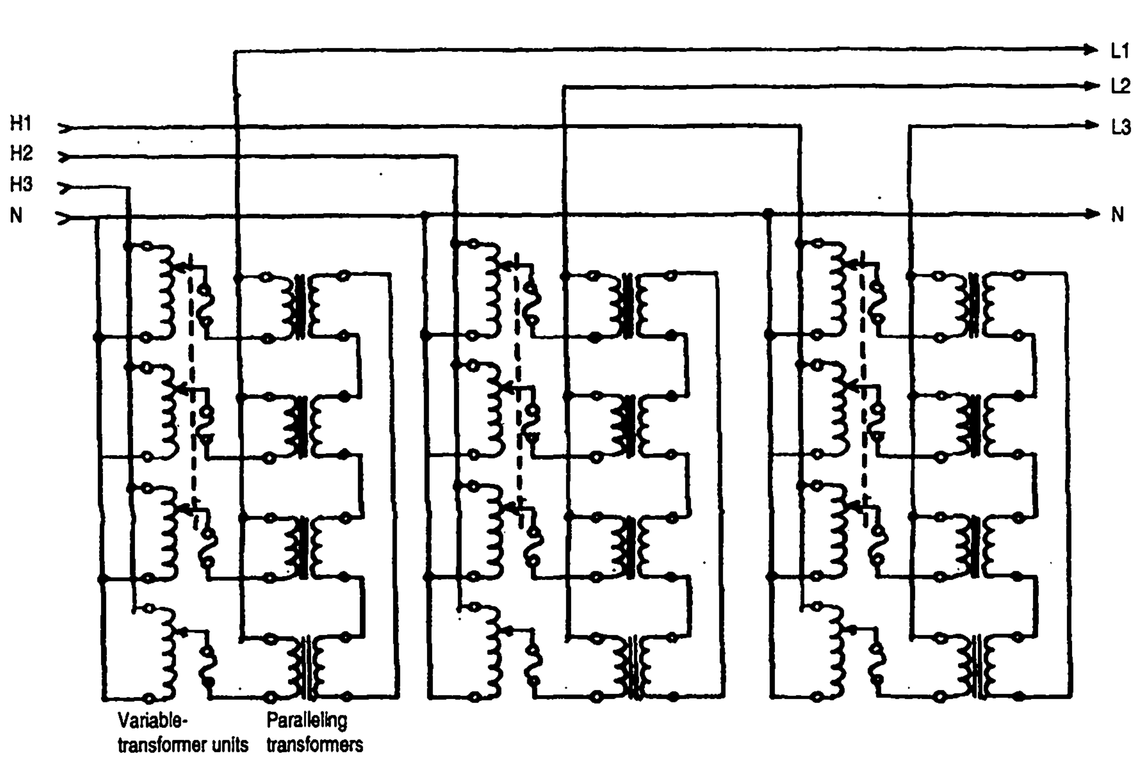

Figure 15-8. Electrical schematic of multiple-gang variable autotransformer showing use of paralleling transformers to avoid circulating currents.

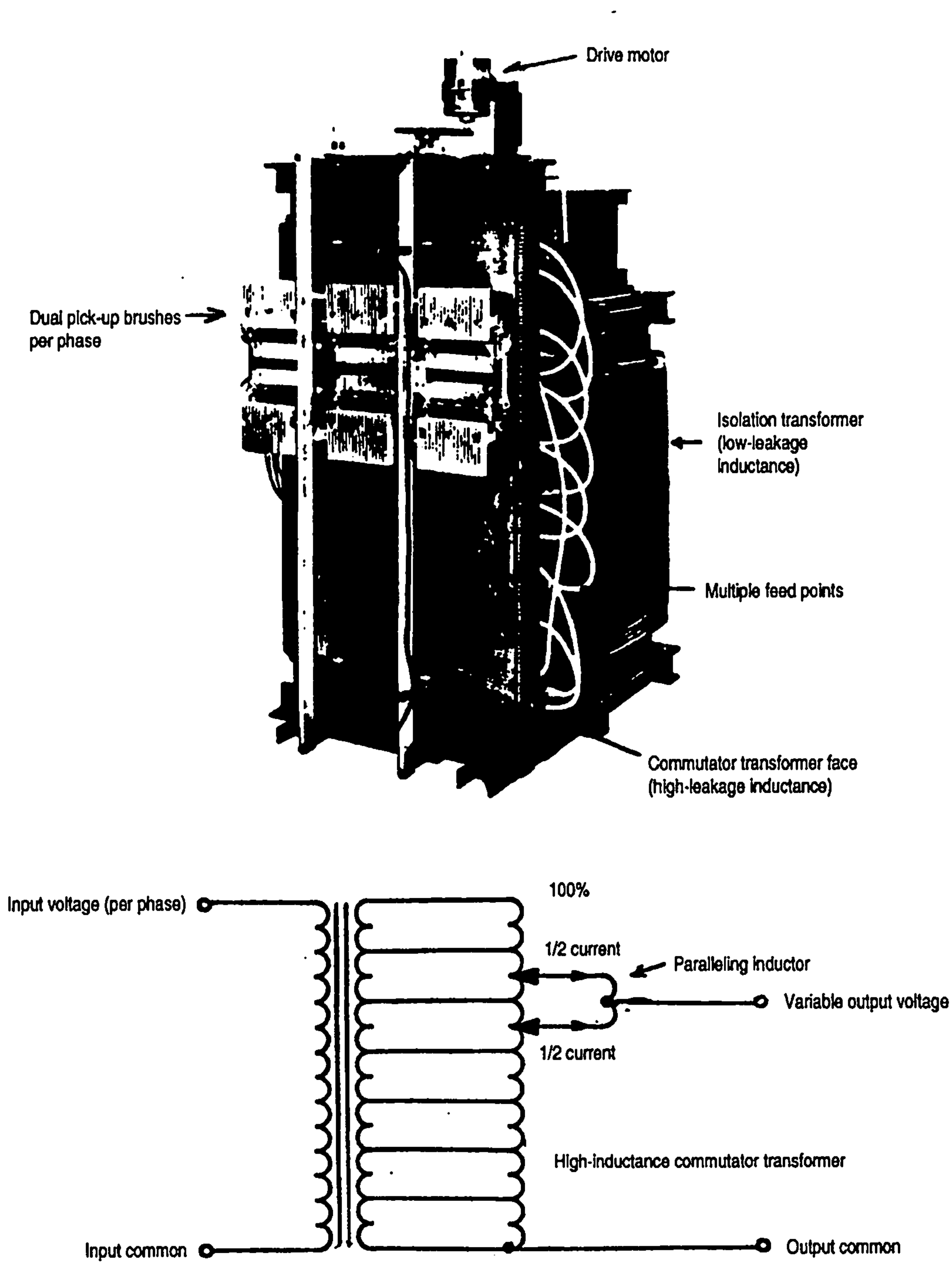

Figure 15-9. The variable-voltage transformer (VVT).

age inductance. The lack of tight magnetic coupling to the entire length of a linear winding is much greater with a flat-winding format than with the toroidally wound circular format.

Fortunately, this problem has been solved. (The solution has been patented, making this a unique device.) A conventional isolation transformer, but one with multiple secondary voltage taps, has been added to the linear winding. These tap points are connected to the corresponding voltage points along the linear winding, in effect short-circuiting the leakage inductive reactance and greatly improving the voltage regulation over the entire range of output voltages. With dual brushes contacting adjacent conductors, there will be a small voltage difference between, of course. This voltage difference is equalized in the patented design by means of a balancing transformer, which rides along with the brushes. (This problem was handled differently in a competitor's linear-format variable transformer. It placed a pair of anti-parallel-connected silicon rectifiers in series with each brush and the common point. Because the contact voltage of the rectifiers is slightly greater than the turn-turn winding voltage, there was no circulating current.)

The motor control of these variable-voltage devices is no more complicated than that required for the circular-format transformers, and manually operated versions with hand cranks have been built for the absolute minimum of system complexity.

15.5 The step regulator

In the realm of very-large-power, variable-voltage devices is the under-load step regulator. Its output is not continuously variable, as was the case with all of the previous devices. It also differs in that its output is not a variable portion of the input voltage over the range from zero to 100%. Note from the schematic diagram shown in Fig. 15-10 that the typical step regulator comprises a trans-

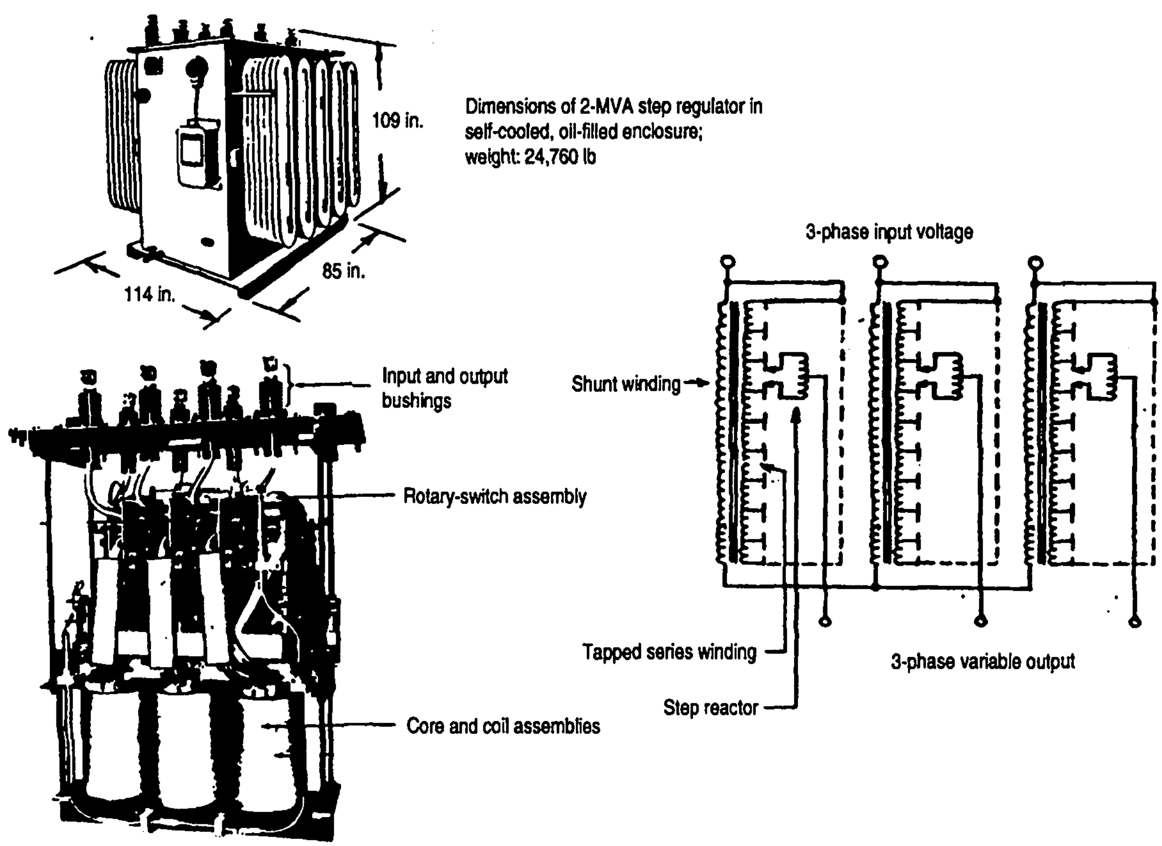

Figure 15-10. The 32-step (16 buck and 16 boost) voltage regulator.

former with primary, or exciting, windings, which shunt the incoming line, and multi-tapped secondary windings, not unlike those of the VVT, called the series windings. Either one end or the other of each series winding is connected to the high side of each incoming line by means of a reversing switch (not shown in the schematic). When the winding is in one polarity, the voltage induced in it will add to, or "boost," the incoming line voltage. In the other polarity it will subtract from, or "buck," the incoming line voltage.

The taps on the windings are connected to contacts of a double-brush, make-before-break, tap-selector rotary switch (shown linearly in the schematic). One of the two brushes is always in contact with the source winding. At every other step, the two brushes will be connected across the entire voltage between tap points. A balancing, or "step," reactor produces an output that is the mid-point voltage. Typically there are 16 steps in each polarity, or 32 steps altogether. A common industrial application of the step regulator is as a line-voltage corrector that can buck or boost capability by 10% in discrete steps of 5/8 of a percent. The regulator itself handles only 10% of the connected volt-amperes. A device rated at 2000 kVA (or 2 MVA), as illustrated in the figure, will regulate a 20-MVA system.

However, for the high-power transmitter service that we are interested in, full-range control is usually required—which means 100% buck or boost. Note that 100% buck will only be zero volts if the full series-winding voltage is precisely equal to the incoming line voltage, which it may not be. Also note that the maximum output voltage (100% boost) will be very nearly twice the incoming line voltage, not 100% of it, as was the case for the previous devices. (There are precious few things more embarrassing than designing a full-range control system with a buck/boost device to feed a rectifier transformer whose maximum-output voltage corresponds to the nominal line voltage. But it has happened. And more than once.) Even with full-range control, the step-regulator VA rating is only half the maximum-system VA rating because it only processes half of the maximum voltage.

With a standard 32-step device, there will be granularity in the stepped output of approximately 3% per step. For a dc power supply of 100-kVdc output, this amounts to about 3 kV/step. The rate at which the regulator will slew from minimum to maximum output is user-selectable, with 30-s run-up time being fairly typical. In systems where automatic return-to-zero is implemented, the run-down time can be made more rapid, such as 15 s. If such granularity is too great or the speed not great enough for a particular application, the step regulator is not the device to use. Nevertheless, the step regulator is the least expensive means of obtaining voltage variability at very high VA ratings. (Although the word "is" should probably be replaced with "was" in the last sentence; it is not known if there is a domestic source for such devices at this time.)

15.6 The induction voltage regulator

The induction voltage regulator, or IVR, is often referred to by the non-generic name of "Inductrol." It is also a buck/boost device, but it has continuously variable output voltage. If the step regulator were a Chevy, the IVR would be a Cadillac. Like the step regulator, it has shunt and series windings, as illustrated

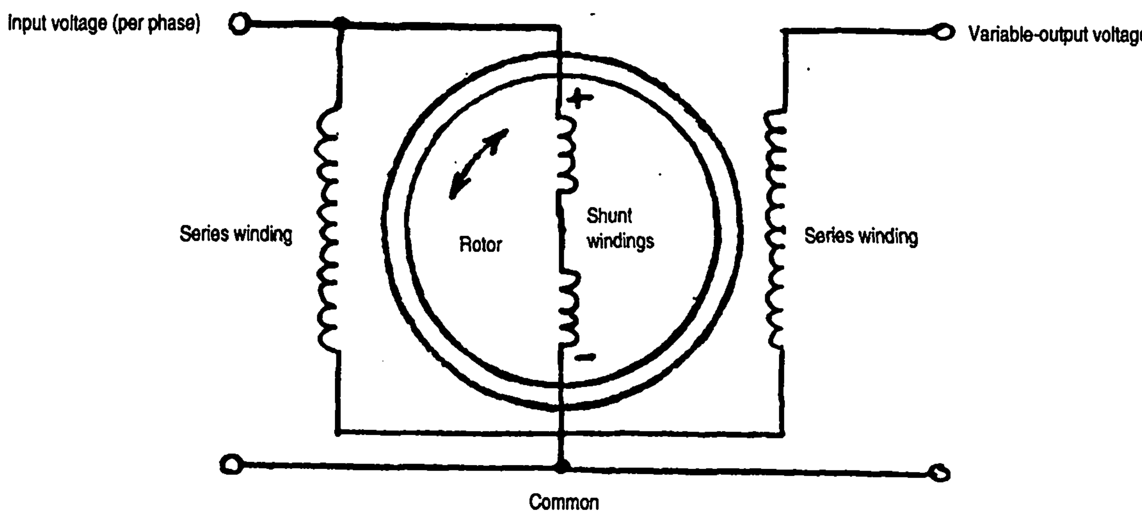

Figure 15-11. The induction voltage regulator (IVR).

in the schematic diagram of Fig. 15-11. The shunt windings, however, are part of a rotor assembly that can be rotated with respect to fixed, or stator, series windings. One end of each series winding is permanently connected to the high-side of each incoming line.

Depending upon the angular orientation of the rotor with respect to the stator, the voltage induced in the series windings will vary in amplitude and polarity. One complete revolution of the rotor will generate every condition from maximum buck to maximum boost. The turns ratio of the shunt and series windings will determine the degree of output buck and boost, from 100% buck/boost for full-range control, down to 10% buck/boost for line-voltage correction or filament-voltage regulation, as indicated in Table 15-1. Still, obtaining true zero-voltage minimum is even trickier with the IVR than with the step-regulator. Not only must the series-winding voltage exactly match the incoming-line voltage, but the rotor must be stopped at exactly the proper spot. Mechanical stops must be perfectly positioned and then never be budged—neither of which is entirely likely. (Electronic return-to-zero circuits have been built with non-linear dynamics that greatly exaggerate IVR output voltage as zero is approached. This method does as well as any in achieving minimum, if not zero, voltage.)

Both the IVR and the step regulator can be incorporated in closed-loop voltage- or current-control servo systems. Both require "bandwidth" compromises to avoid continuous "hunting." (Bandwidth here refers to a voltage band rather

Table 15-1. Characteristics of the induction voltage regulator.

Device buck/boost ratio	Ratio of minimum and maximum output voltages to input	Ratio of load VA to device VA
10%	0.9/1.1	10
20%	0.8/1.2	5
50%	0.5/1.5	3
100%	0.0/2.0	2

than a frequency-response band.) Experience with large IVRs has shown that the rotor setting is not completely insensitive to mechanical vibration. (When operating in its "killer" 50%-duty mode at a 10 pps rate, the Haystack Hill LRIR transmitter, which has been referred to several times already, produced sufficient floor vibration to cause very gradual but very noticeable walk-off of the output of the IVR that fed the high-voltage dc power supply.)

In external physical appearance, there is little difference between the IVR and the step regulator. At the highest VA levels, both devices are enclosed in oil-filled tanks for electrical insulation and cooling. Some IVRs, however, have been built for lower VA service, where they are competitive with variable autotransformers and VVTs, even though they are most costly. At these lower power levels, they are air-insulated and convection-cooled.

Like the step regulator, the IVR, or at least the type that goes by the trade name "Inductrol," is no longer available domestically. However, a form of it is still being manufactured abroad.