The Lenkurt Demodulator

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New Techniques in Power Conversion

Transistors and related semi-conductor components have brought revolutionary changes to the design of power supplies, just as they have to more "glamorous" types of equipment. Semiconductor or "solid-state" components are noted for having far greater reliability than electron tubes, which they are gradually displacing. Nowhere is this additional reliability more vital than in power supplies. Some of the recent techniques used to enhance the performance and reliability of modern power supplies are described in this article.

In the sometimes exotic field of communications, power supplies rarely receive credit as being among the most important elements in a system. So humdrum and routine the subject of power supplies may seem, that new contributions toward reliability made by power supply engineering may go unnoticed.

No matter how cleverly engineered the transmission equipment, or how ingenious the modulation plan, the system goes "off the air" if the power supply fails for any reason. The source of power and the means of converting it to a useful form comprise the vital heart of any communications system.

Obviously, the prime requisite must be *reliability*; the power supply must be engineered so that there is hardly *any* chance whatsoever that it can fail. To achieve this end, components and circuit techniques are employed which, of themselves, have little or no chance of failure. For instance, communications power supplies should avoid the use of electron tubes. Instead, voltage regu-

Figure 1. Reliability is the most important consideration in designing communications power supplies, followed by stability, regulation, and freedom from hum and ripple. Microwave power supply shown employs semiconductor rectifiers, magnetic amplifiers for voltage regulation. Plug-in construction permits each unit to be replaced instantly, provides superior access to internal components.

lation may be achieved with magnetic amplifiers, rugged, passive devices which fail only by burning out a winding.

A second important quality of power supplies is that they must be efficient. As always in communications, economics must enter the picture. A high degree of reliability is not difficult to obtain if bulkiness, weight, and cost are of no concern. Under these conditions, savings gained in reliability might be more than offset by high operating costs or excessive plant facilities. Since power supplies may handle and modify *all* the power used in the equipment, relatively small differences in power supply efficiency may make a large difference in the total power consumed by the system. The wasted energy appears as heat which may be costly to control or dissipate in large installations.

Last, but hardly least, the power supply must be well-disciplined, delivering the exact voltages and currents demanded by the equipment—not approximations or variations of these needs. Transmission equipment may be "finicky" or relatively sensitive to such external variables as temperature and operating voltages. Some equipment might exhibit frequency drift or vary its signal power as a result of such factors. Accordingly, the power supply must not magnify this difficulty by adding to it with its own sensitivity to ambient conditions.

Transmission equipment has enough difficulty combatting unavoidable noise and interference in the transmission path. If the power supply introduces ripple, hum, or noise, it is like sabotage. Fortunately, most hum and ripple are easily controlled by various conventional filtering techniques, such as described in a previous issue (DEMODULATOR, *April*, 1958).

Converters and Inverters

The most important recent changes in power supply design have occurred in converters and inverters which have a d-c input. Direct-current conversion has always presented an engineering problem, the solution of which has usually been far short of ideal. This problem has been greatly increased with the rapid growth of electronics. Most electronic circuits must operate from d-c power. In many applications, the most logical source of power provides only dc, but at the wrong voltage for use by the equipment. To cope with this problem, many types of converters and inverters have been developed.

The terms converter and inverter are often used in different and inconsistent ways. In general, a *converter* is a device or circuit for changing d-c power to a different voltage, or a-c power to a different frequency—the latter device being mostly used in the power transmission industry. A converter does not change ac to dc or dc to ac; thus, a dc-dc converter might convert 24-volt d-c power to 500 volts dc.

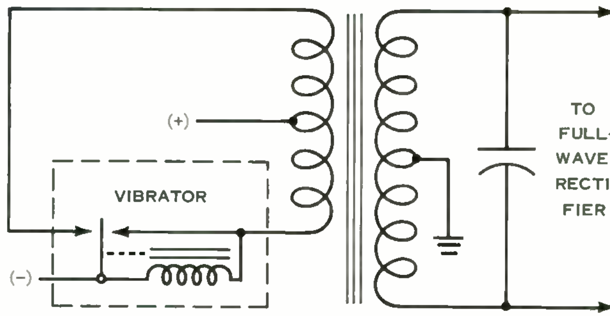
An *inverter* does change one type of power (ac or dc) to the other. Thus, an inverter is a device for changing direct current to alternating current, regardless of the voltage involved. By convention, the term "inverter" is not usually applied to devices which change alternating current to direct current. Such units are usually called "power supplies" or "rectifiers" in the United States. The term "inverter" normally is applied to any device used to produce a-c power from a direct-current source.

The simplest and most reliable device for converting a low voltage to a higher voltage is the transformer. Unfortunately, however, a transformer will not function unless the applied voltage is constantly or periodically changing. This requirement is satisfied by alternating current, of course, but not by direct current of a constant voltage.

In order to use a transformer with direct current, some means must be found for varying it periodically. One way of accomplishing this is to use some sort of interrupter or "chopper" to break the smooth direct current into a series of intermittent pulses. When one of these pulses is applied to a winding of a transformer, the flow of current causes a magnetic field to build up in the transformer core. When the pulse ends, this field collapses. The changing magnetic flux causes a current to be induced in the various windings of the transformer—flowing in one direction during the flux build-up, then reversing direction when the field collapses. The secondary windings in the transformer thus yield an alternating current, the voltage of which is determined by the turns ratio of the primary and secondary windings.

One way of interrupting the direct current is to use an electro-mechanical vibrator. The contacts are so arranged that the energized magnet opens the contacts and de-energizes itself. The contacts again close, energizing the mag-

Figure 2. Typical vibrator inverter circuit, simplified. Vibrator circuits exhibit poor regulation, low reliability.



net, which again opens the circuit. Figure 2 shows a diagram of such an arrangement. Until quite recently, this method of power inversion was very widely used in commercial automobile radios because of its low cost.

An important objection to vibrator inverters is that they are relatively inefficient and highly unreliable. In addition, they exhibit poor voltage regulation. Since the interrupted dc is applied directly to the primary winding of the power transformer—a highly inductive load—considerable arcing occurs at the vibrator contacts. The arcing, in turn, generates a particularly troublesome type of electrical radio noise which is difficult to filter from the output power. In addition, arcing rapidly erodes the vibrator contacts, and builds up oxides and other impurities on the contact surface, increasing its resistance. As the surface of the contact becomes rougher, its effective area may be reduced (because electrical contact may occur only at the high points of the surface). Eventually, contact surface may be so reduced that the contacts weld together due to the high current density through the limited area of conduction. If this occurs, the contacts stick and may cause the electromagnetic coil to burn out or cause other damage in the power supply.

Another method of d-c conversion that has been widely used is the *dynamotor*. In principle, a dynamotor consist of a d-c motor driving a d-c generator to produce the desired voltage. In practice, both motor and generator share a common field winding, powered from the input power, and a common armature. Input and output circuits have separate armature windings and commutators, however. In fact, each different output voltage obtained from the dynamotor requires its own armature winding and commutator.

Although the dynamotor is simple, it is heavy and requires considerable maintenance. Bearings, commutators, and brushes suffer continuous wear and require inevitable repair. Like the vibrator, commutator arcing introduces noise which may be difficult to eliminate.

Still another way of achieving dc-dc conversion is the use of an RF oscillator. In a resonant circuit, such as the tank circuit of an RF oscillator, voltage and current are out of phase; where current is low, voltage is high. If there is little loss in the resonant circuit, very high a-c voltages may be obtained by tapping the resonant circuit at a high-voltage point. After rectifying and filtering the high voltage, it may be used for powering portable radiation detectors, providing accelerator voltage for television picture tubes, or in other applications where high voltage and little current are required.

Solid-State Inverters

With the invention of transistors, a new and better type of power inverter was made possible. The transistor proved to be an excellent switch, had no problems of mechanical wear, operated very nicely on low voltages (unlike the electron tube), and was quite efficient. Accordingly, many types of transistorized power inverters have been developed. Two basic types predominate: the *self-oscillating* push-pull inverter, and the *driven* push-pull inverter. Both are usually symmetrical. Although many single-transistor and other unbalanced circuits have been developed, these are not generally as efficient as the symmetrical arrangements.

In the driven inverter, two transistors arranged in a push-pull circuit are alternately turned on and off by an external control circuit. The control circuit may itself be controlled externally, or it may be independent. If tuning fork or crystal oscillators are used to provide the control, a very high degree of frequency stability may be obtained regardless of load variations. For this reason, driven inverters are widely used in missile and aircraft applications where variations in the a-c power frequency may affect the accuracy of gyroscopes powered by the alternating current.

Self-oscillating push-pull inverters are more commonly used in communications equipment than the driven inverters because they are simpler, and therefore more reliable. The typical inverter consists of two or more power transistors (or controlled rectifiers) connected in a symmetrical arrangement such as shown in Figure 4. As in the case of a vibrator inverter, the transistors act only as switches to turn the d-c power on and off. Unlike the vibrator, transistors have no mechanical wear, and

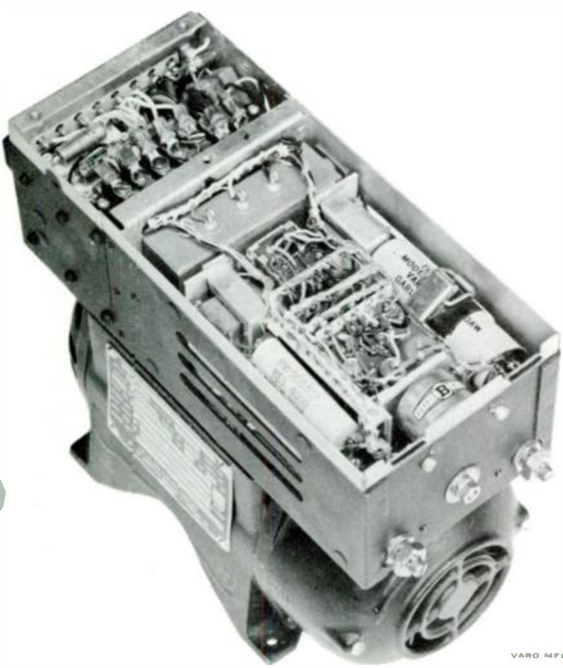


Figure 3. Typical rotary inverter such as used in some aircraft and missile applications. Cover has been removed to show circuitry required to stabilize output voltage and frequency. Newer solid state inverters eliminate mechanical problems inherent in rotating machinery, permit quicker response to regulating signals.

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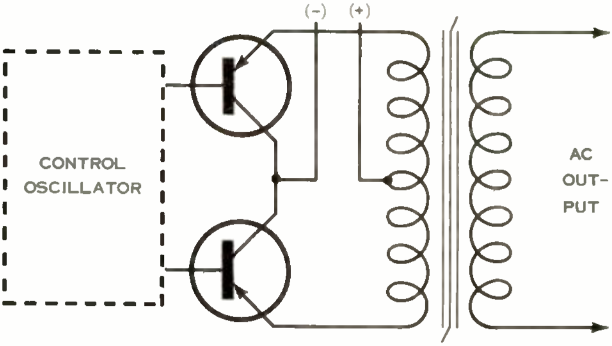


Figure 4. Simplified diagram of transistor inverter using external driving or control circuit.

are obviously free from such mechanical problems as contact arcing. They are fast, efficient, and have a life expectancy virtually unlimited, unless abused.

In the circuit shown in Figure 6, power is applied to the center tap of the transformer primary winding. From there it flows through the two transistors, Q1 and Q2, back to the power source. Because the two halves of the circuit cannot be *exactly* alike, one half of the primary winding will carry somewhat more current than the other. This

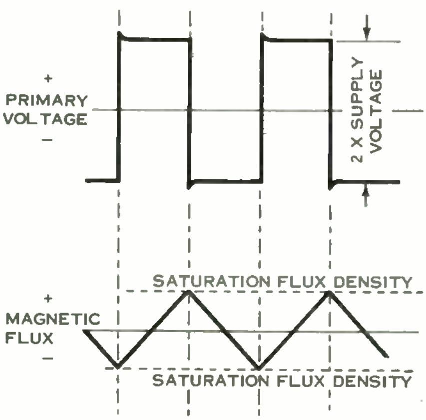


Figure 5. Comparison of voltage across primary winding of inverter transformer, and the change in flux through the saturable core.

causes a small voltage to be induced across the feedback winding. The polarity of this voltage is such as to bias the less conductive transistor Q1, for instance to conduct even less, and Q2 to conduct more. This biasing effect is self-amplifying, with the result that Q1 is rapidly cut off and Q2 conducts the maximum current permitted by the circuit impedance.

Since the transistor bias is obtained by inductive coupling in the transformer, it can be maintained only while the magnetic flux is building up in the transformer core. When the core reaches magnetic saturation, the bias voltage on the two transistors disappears. Transistor Q1 begins to conduct again moderately, while Q2 has its conductivity reduced. This change causes the established flux to diminish. The changing flux again induces a voltage across the feed-back winding, but of the opposite polarity to that before. Now Q2 is rapidly cut off and the Q1 conducts heavily, thus building up the magnetic field in the opposite direction, and this alternating action continues automatically. As a result of this regular "flip-flop" action, a square-wave alternating current is induced in the secondary winding.

Note that the frequency of oscillation is determined by how long it takes to saturate the transformer core. This is largely a function of the applied voltage, transformer characteristics, and the load across the secondary. The lower the input voltage or the larger the load on the inverter, the lower the frequency of oscillation.

Since the inverter output is usually rectified and filtered in communications applications, output frequency is not very critical.

The Controlled Rectifier

Within the past two years, a new class of semiconductor component has appeared which is quite superior to transistors for power switching and inversion. The new device, called a *controlled rectifier* or *silicon controlled rectifier* (after the principal substance from which it is made), is capable of handling tremendous currents for its size. Like a thyratron, the silicon controlled rectifier, or SCR, is a rectifier which, when "turned on", conducts freely in *one* direction, but will not conduct in *either* direction unless triggered by a control "gate." (SCR's will conduct without a gate signal if their forward "breakover" voltage is exceeded.) Once the SCR is conducting, the gate has no further effect, and cannot be used to turn the device off. To return the SCR to the non-conducting state, the applied voltage must be interrupted or reversed. To date, commercially available SCR's small enough to fit in the palm of a hand can switch currents up to 100 amperes, at peak inverse voltages of 400 volts.

Although SCR's are like thyratrons in that they can be turned on but not off by a control signal, they are far more efficient than thyratrons. For example, whereas a typical thyratron will exhibit a voltage drop between cathode and anode of about 10 to 15 volts when conducting, the SCR exhibits a voltage drop of one volt or less. This is very important when controlling power at lower voltages. At 24 volts, the thyratron would be only about 50% efficient, whereas the SCR is 95% efficient. Another point of superiority is the speed with which the SCR operates. The typical thyratron has an ionization and de-

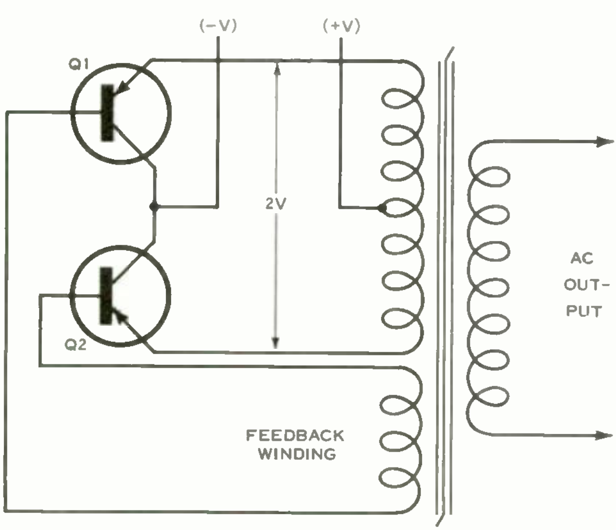


Figure 6. Simplified self-oscillating inverter circuit. Device functions as a "flip-flop" square-wave oscillator. Oscillation frequency is quite sensitive to load and input voltage.

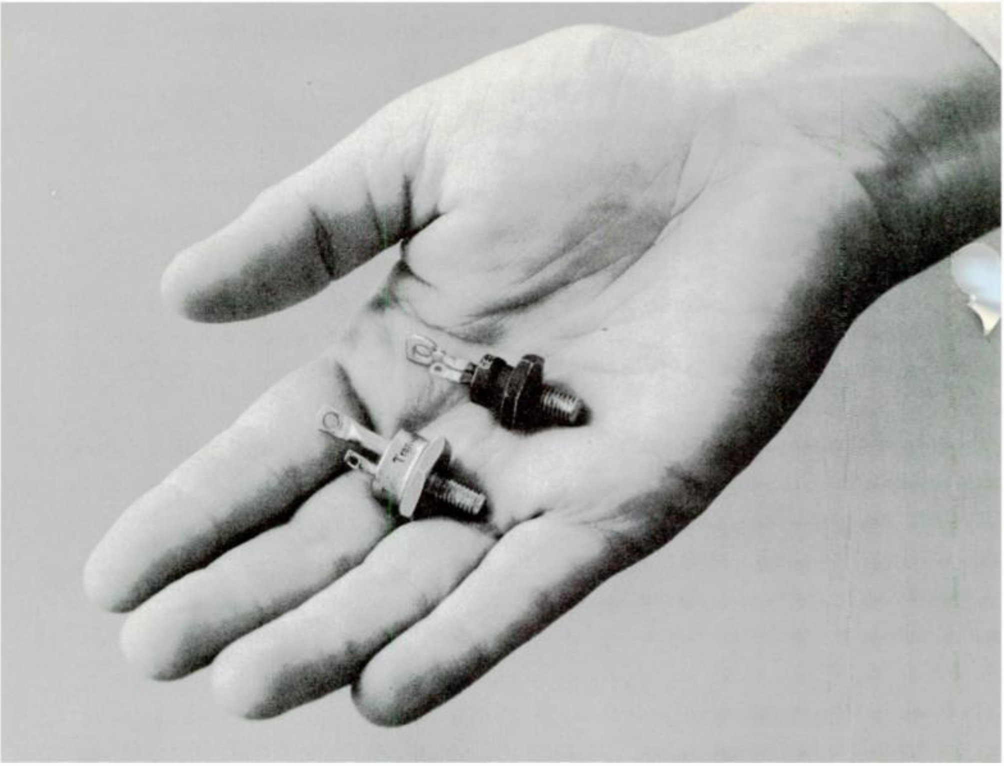


Figure 7. Tiny silicon controlled rectifiers can control surprising amounts of power. The smaller unit is able to switch 16 amperes at 400 peak inverse volts; larger unit is rated at 20 amperes. Parallel operation permits control of much larger currents.

ionization time (time required to establish or destroy conductivity) in the order of milliseconds, but the typical SCR turns on within a microsecond and turns off within one to twenty microseconds, depending on the size of the unit, and other conditions, such as the temperature of the unit.

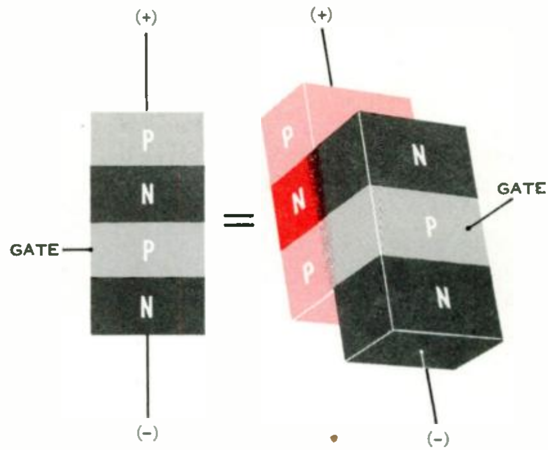
How It Works

The controlled rectifier is a new version of a relatively old semiconductor device—the four-layer transistor. As indicated in Figure 8, it is made up of alternate *p* and *n* layers.* The SCR may be regarded as two separate transistors —a *npn* and a *pnp* which, in effect, overlap so that the center *n* and *p* layers are common to both. The center *p* section may then be regarded as the base of the *npn* transistor, and the center *n* section as the base of the *pnp* transistor. When "forward" voltage is applied to the SCR, conduction is blocked by the center junction, which acts like a back-biased diode.

If current is injected at either of the center sections (positive at the *p* layer or negative at the *n* layer), the center junction becomes conductive by transistor action, permitting the flow of current carriers through the device. In addition, this conduction biases the other center layer so that it also provides

* See DEMODULATOR, *May*, 1960 for a general discussion of semiconductors.

Figure 8. Four-layer controlled rectifier is analagous to two transistors sharing common layers. Injecting current at base of one "transistor" permits conductivity, and turns other transistor "on." Each biases the other to full conduction.



transistor-like current amplification. Because these two functions are self-supporting once started, the SCR reaches full conductivity very rapidly and the gate by which the process was started loses control.

One difficulty encountered with transistor inverters is that they have poor tolerance to voltage irregularities. Few transistors are available which can safely operate with more than 100-125 peak inverse volts across the transistor. However, in some communications installations where the local battery is nominally 48 volts, battery output may actually reach 60 volts. In the typical push-pull inverter where d-c power is applied to the center tap of a choke or transformer, the actual voltage applied to the transistors will be twice the battery voltage because the transformer winding acts as an auto-transformer, doubling the applied voltage. Thus, peak inverse voltages applied to the switching transistors

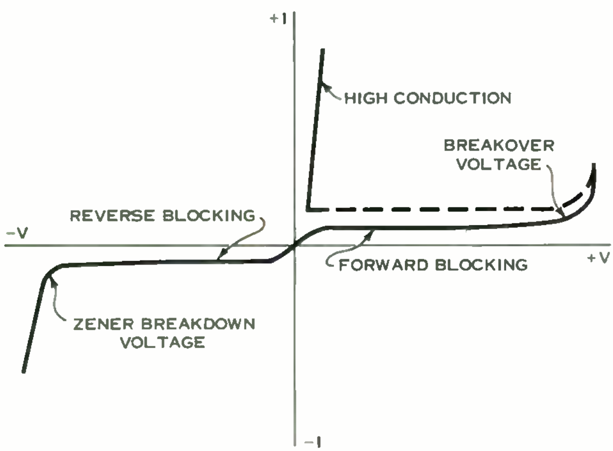


Figure 9. Typical controlled rectifier voltage-current characteristic. In absence of gate current, device will not conduct unless breakover voltage or zener breakdown voltages are exceeded. Gate current reduces breakover voltage, permitting forward conductivity.

will range from 96 to 120 volts—equal to or greater than their maximum ratings! Although some transistors are now becoming available which have higher voltage ratings, even these don't provide the performance reserve demanded by conservative engineering practice.

The silicon controlled rectifier provides an immediate solution to this problem because of its excellent voltage characteristics. An additional bonus provided by the SCR is that it requires much less driving power than a typical power transistor. Where a transistor might require half an ampere of driving current in order to conduct five amperes, a controlled rectifier requires a gate current of under 0.1 ampere to start conduction of fifteen amperes or more.

Practical SCR Circuit

The main difficulty in the use of SCR's is that they cannot be turned off

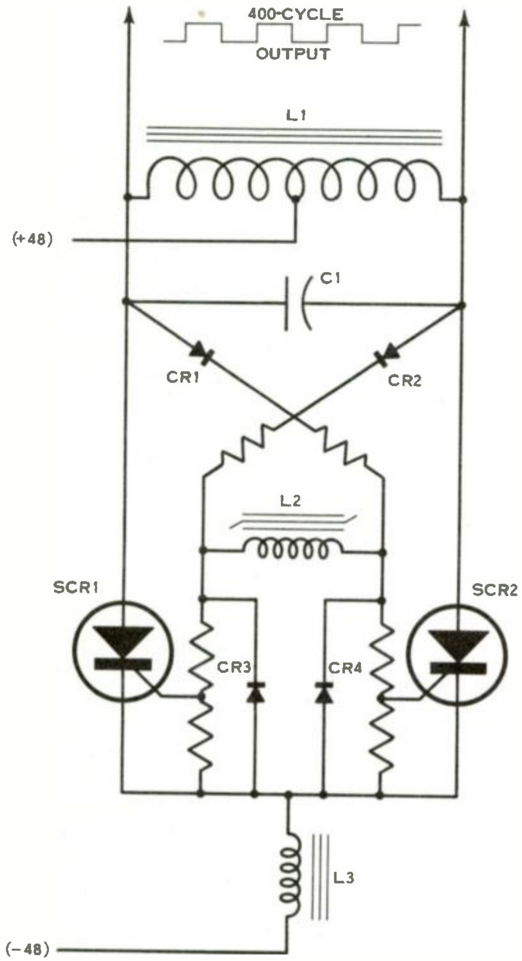


Figure 10. Simplified diagram of Lenkurt SCR inverter. Both SCR's are nonconductive until gate current from voltage divider causes SCR1 to conduct. When L2 saturates, gate current of SCR2 "fires" SCR2. Stored voltage in C1 surges through SCR2, is blocked by high impedance of L3, is applied to bottom of SCR1. Since C1 voltage is twice the forward voltage on SCR1, SCR1 is turned off. When L2 saturates in reverse direction, process reverses and continues automatically.

Table 1. Power supply weight vs. frequency (from Ref. 2)

	60~	400~	800~
TRANSFORMERS......	61.0	19.0	8.6
FILTER CHOKE........	20.2	1.8	0.8
CAPACITORS...........	20.0	4.7	2.2
HOUSING................	8.0	5.0	4.0
TOTAL...................	109.2	30.5	15.6

by the control gate, as can the transistor. Normally, current flow through the SCR must be interrupted long enough for the non-conductive condition to be restored, or the flow of current must be reversed briefly. Figure 10 shows a simplified schematic diagram of a practical inverter now used in Lenkurt's dc-dc converter for powering microwave equipment from battery sources. This circuit is self-oscillating and does not vary its frequency appreciably with variations in load or input voltage. The frequency of the square-wave output is approximately 400 cycles per second, thus permitting the use of small but efficient transformers, magnetic amplifiers (for voltage regulation), and filter components.

It may be interesting to note how much the weight and size of equipment decreases as the frequency of the a-c power is increased. The comparison in Table 1 was compiled on the basis of airborne communications equipment, where weight savings are particularly important. As frequency increases, weight and size of the reactive components needed for control and filtering is reduced, but electrical losses begin to increase, so that eventually diminishing benefits result from higher frequencies unless special core materials are used for the cores of inductive components. Normally, this is only worthwhile in aircraft or missile applications.

Future Trends

We can expect power equipment to continue to become smaller, lighter, and more efficient as improved components and ways of using them are developed. The increasing use of transistors and other semiconductor components in all types of communication equipment is changing power requirements. Because of the steadily increasing reliability available from semiconductor components, power supplies may make more use of such techniques as active or electronic filtering instead of reactive filtering, thus reducing the size and weight of power supplies. •

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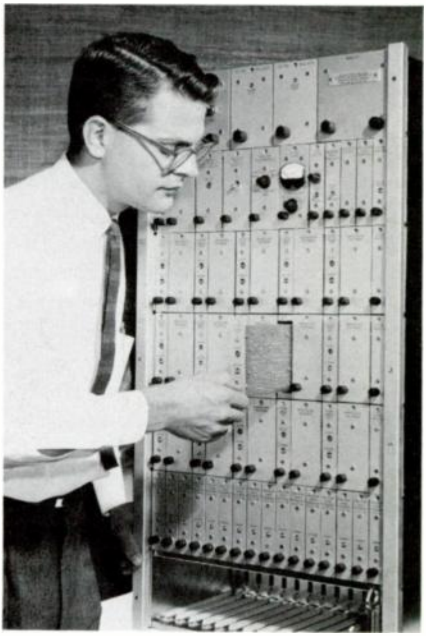
Under contract to *NASA*, Lenkurt designed and built the ground demultiplexing system (shown) and helped design the rocket-borne portion.



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