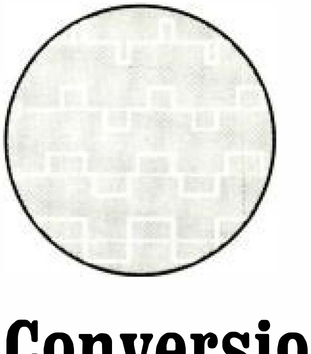


Switching-Mode Power Conversion

Description of new technique that can cut the size, weight, and cost of conventional power supplies and, at the same time, considerably increase efficiency.

By DONALD E. LANCASTER

THERE is an interesting paradox in present-day power supplies. While the rectifiers and regulating components are becoming almost vanishingly small, the over-all size and weight of most power supplies has stayed nearly the same. No matter how small the rectifiers become, as long as power conversion is to take place at 60 Hz, we are essentially stuck with large, heavy, iron transformers and filter chokes as well as bulky and expensive capacitors. Furthermore, as long as conventional regulation methods, such as series or shunt zeners or transistors, are used, bulky and expensive heatsinking is required to remove the heat that is produced during regulation. This heat is also reflected in very poor power-supply efficiency, requiring much more input power than is usefully converted.

The sheer bulk and weight of equipment using present power conversion techniques multiplies itself, for heavy chassis and rugged construction are required in order to support and to protect this type of supply.

New Circuits & Techniques

Some new circuits and some significant new techniques have appeared that can drastically slash the size, weight, and cost of conventional power supplies while at the same time substantially increasing their efficiency. The size improvement attainable with these techniques is remarkable. Today's 1N4005 is about half the size of one base pin on yesterday's 5U4G. Tomorrow's power supplies will provide the same dramatic space and weight reductions when compared with present-day supplies.

These techniques are quite simple and have been known for some time. To a certain extent, they are in use in some power supplies today. Only the lack of suitable components to date has prevented the widespread use of these techniques. New components now make this transition possible.

The techniques are simply stated: (1) Go to a high frequency instead of 60 Hz for power conversion. (2) Use square waves instead of sine waves. (3) Operate all regulators in the switching mode so that they are always either off or on and thus, at least in theory, they never dissipate any power. Let us investigate the consequences of these new techniques.

Using a Higher Frequency

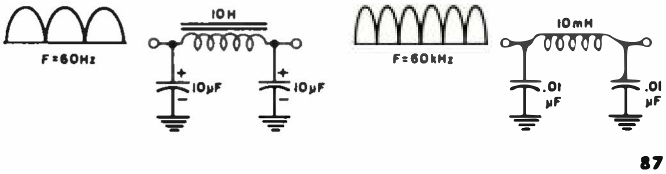
Just going to a higher supply frequency is not new. Aircraft electronics systems are based upon a 400-Hz power system to reduce the amount of copper and iron required in supplies, motors, and generators. Many automotive vibrator-type supplies also ran at this frequency. Today's transistorized power converters run at a slightly higher frequency, usually between 1 and 2.5 kHz. New techniques at present set typical operating frequencies between 50 and 200 kHz; in the near future, this will likely be upped into the megahertz region.

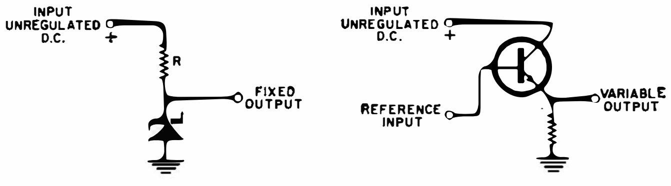
Fig. 1 compares two power-supply filters, one operating at a 60-Hz frequency and the other at a 60-kHz frequency. Both filters provide identical output ripple. Note that the values of all components in the 60-kHz filter are 1/1000 the size of the 60-Hz units. This means a .01-μF, 600-volt Mylar capacitor may be used in place of a 10-μF, 600-volt electrolytic. The size, cost, and weight savings are obvious. More subtle is the gain in reliability. All but the finest electrolytics eventually change their value and need to be replaced, but a failure in an ordinary Mylar capacitor is practically unknown. A second gain comes about when the capacitor is mounted on the supply chassis. Large brackets are required for an electrolytic, while the Mylar can safely support itself on its own leads.

The effect upon the inductance is even more marked. Instead of a 10-henry choke, we need a 10-millihenry one. One is a heavy, expensive, iron-core device, while the other is a low-cost air- or lightweight ferrite-core device. Again, the latter is self-supporting on its own leads, while the 10-henry unit requires a rugged chassis mounting. Inductance is never obtained free. There is always a copper and a core loss to contend with. The core loss is negligible in air-core and ferrite chokes but is quite significant in power-frequency iron-core units. The lower inductance value also means fewer turns of wire and thus less d.c. resistance. Because of this, the 10-millihenry choke is considerably more efficient. This reduces the input power required for the same output power and at the same time eliminates a source of heat that limits the minimum possible size of the supply.

The same dramatic reduction in size and weight is reflected in the power transformers. A 60-kHz transformer is usually a compact, lightweight toroidal unit. The toroidal

Fig. 1. Power-supply filters for different operating frequencies.





(A) SHUNT ZENER (B) SERIES TRANSISTOR

Fig. 2. Conventional regulators such as these are quite inefficient and convert much of the input power into useless heat.

design contains the field within the core, and very little shielding is required. By the same token, a toroidal transformer is relatively immune to external magnetic fields, eliminating hum and coupling problems normally encountered in conventional supplies.

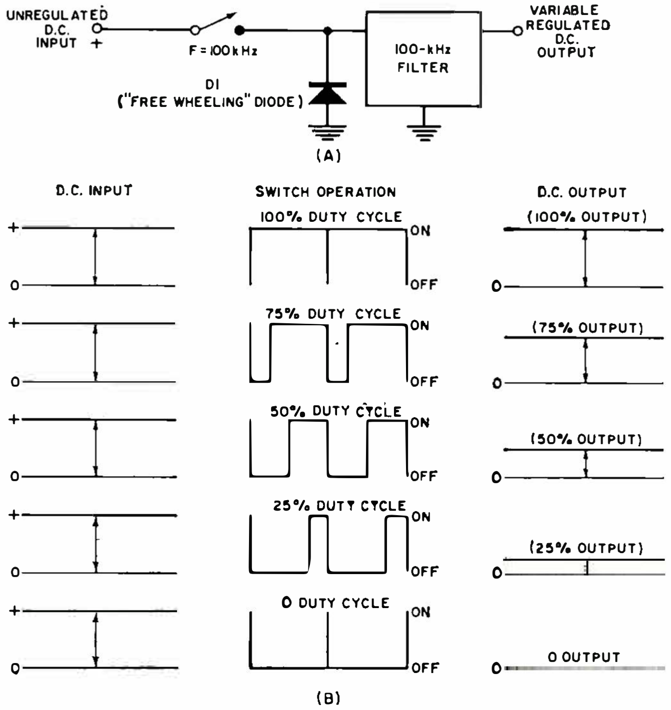
In certain cases, we can go one step further and replace the 60-kHz sine wave with a 60-kHz square wave. In a full-wave rectifier that is driven by an ideal square wave, no filter at all is needed, for there is never a time when a filter would be required to store energy. Unfortunately, in the real world of finite rise times, overshoot, and transients, some filtering is required to fill in and smooth out the transitions between the cycle halves. But in a properly designed circuit, the filtering required is quite small, even when compared with that needed for 60-kHz sine-wave filtering.

By going to a high frequency, the requirements for filtering are realized with much smaller, lower cost components. By going to square-wave operation, these small components may be replaced with even smaller components.

Regulator Circuits

Fig. 2 shows some ordinary regulators. Fig. 2A shows a zener diode connected as a shunt regulator. Constant power is always drawn from the supply, regardless of whether zero or full-load current is being drawn. The output power is proportioned between the load and zener in such a manner as to maintain constant load voltage. The efficiency of this circuit is quite low and approaches zero for small loads. In a 1-ampere, 100-volt supply, the zener employed must dissipate 100 watts of power. Resistor *R* will add at least 10 watts of dissipation. If these two dissipating components could be removed from the supply, while at the same time retaining the same regulation, the size of the supply could be substantially reduced and operation would be considerably cooler. At the same time, supply efficiency would be markedly improved.

Fig. 3. Lossless, 100-percent efficient variable regulator.



The series transistor circuit of Fig. 2B is somewhat more efficient and allows adjustment of the output voltage, but the transistor is still asked to dissipate considerable power. As long as the difference between the available supply power and the required power is made up by a lossy element, be it a resistor, transistor, zener, tube, or any other dissipative device, the problem of supply inefficiency and heat removal remains and must of necessity add to supply size and cost.

Switching Circuits

Suppose, instead, that the supply were switched off and on at a 100-kHz rate by a perfect switch, perhaps as in Fig. 3. If the "on" time of the switch equalled the "off" time, one-half the available supply voltage would be present at the output, with not a watt lost as heat. Since the output is a 100-kHz square wave, it is readily filtered to obtain a smooth, low-ripple d.c. output. Diode *D1* is called a "free-wheeling diode." It automatically provides a path for filter reactive energy during the switch "off" time. The diode *D1* is essential for efficient operation. The ratio of the switch "on" time to "off" time determines the output voltage. The greater the fraction of a period that the switch is "on," the higher will be the output voltage, and *vice versa.* This regulator is 100% efficient and requires no heatsinking and no heat removal.

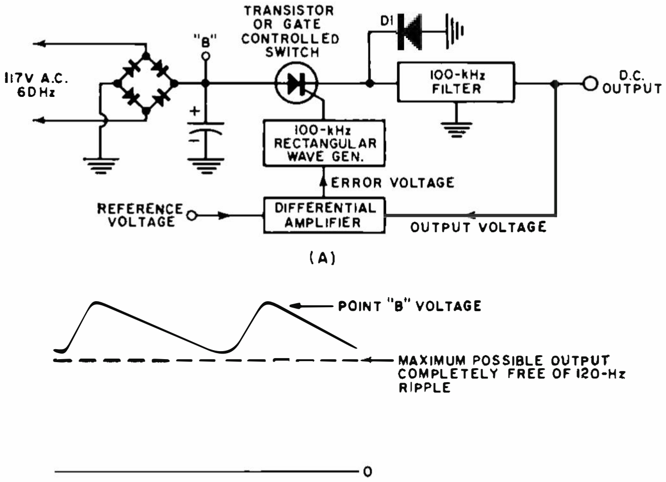


Fig. 4. Block diagram of practical switching-mode supply.

A gate-controlled switch (GCS), a silicon controlled rectifier (SCR), or a power switching transistor is not quite perfect, but if it can switch much more rapidly than 100 kHz, only the small saturated forward voltage drop need be taken into account. For a silicon device, this is around .6 volt. In the 1-ampere, 100-volt supply, the semiconductor switch has to dissipate only .6 watt, and then only during the "on" time of the switch. When this .6-watt loss is compared with the 110-watt loss of a zener circuit, the advantages of switching-mode regulation become apparent.

A typical circuit operating off a.c. power is shown in Fig. 4. The a.c. line is rectified by four power diodes in a full-wave bridge configuration. The output is then crudely filtered by a single filter capacitor, perhaps to a 15 or 20% ripple level. Although a large capacitor is required, the loose tolerance on the ripple allows a substantially smaller unit than normal to be used. To perform the regulation, a precision voltage reference is compared to the output voltage by a differential amplifier. The output of this amplifier is used to alter the duty cycle of a 100-kHz rectangular-wave generator which provides the switching pulses for the GCS regulator. The ratio of "on" to "off" time determines the output voltage. The output filter sees only a 100-kHz waveform, for the response of the differential amplifier extends well beyond 60 Hz and adjusts the duty cycle exactly to eliminate any 60-Hz ripple in the output. Any increase in output voltage is immediately converted into a shorter "on" time, which returns the output voltage to its normal value, and *vice versa*.

This circuit may be used as three distinct switching-mode power converters. As shown, it converts 60-Hz a.c. line voltage to any desired lower d.c. voltage, smoothly filtered and precisely regulated both against line and load variations. If a d.c. input is provided instead of the rectifier and first filter, the circuit serves as a nearly lossless d.c.-to-d.c. voltage down-converter. Finally, the circuit may be used as a high-efficiency regulator that automatically removes any low-frequency ripple from the output. No transformers are required.

Although more parts are required for this type of circuit than for a conventional supply, the over-all power-supply cost is actually reduced due to a lower component cost, a lighter chassis, and simplified assembly.

New Switching Devices

The concept of switching-mode power conversion is only now possible because of the previous lack of economical high-frequency power semiconductors. Devices have recently become available that make these circuit techniques practical. Of foremost importance are new silicon power rectifiers with recovery times short enough to allow their operation into the megahertz region at average current levels between one and ten amperes. New three-terminal semiconductors are now available with high gain, fast switching time, and low cost. Where low voltages are prevalent, the power transistor may be used to advantage. Transistors have high speed as a big advantage but have no internal feedback mechanism to allow them to remain in a saturated state. Because of this, they require a continuous base drive signal. The traditional low-voltage limitations are being seriously challenged, for some newer power transistors are pushing the kilovolt level.

Silicon controlled rectifiers are low in cost and can handle quite substantial currents combined with very high breakdown voltages. SCR's may be turned on with a brief pulse and may not require continuous drive. On the debit side, the switching time is somewhat slow. Typical are turn-on times of a fraction of a microsecond and turn-off times of several microseconds. This limits SCR inverters to a maximum of 60 kHz or so at the present time. SCR's must also be turned "off" by removal or reversal of the main current. This limits the utility of the SCR in regulators.

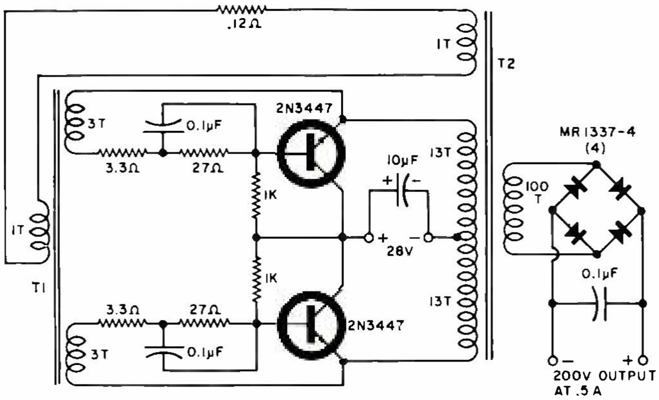
The gate-controlled switch overcomes two objections of the SCR—it turns "off" an order of magnitude faster, and it may be turned "off" as well as "on" by a gate pulse of the proper polarity. These new devices are still rather expensive.

The choice of device depends upon the economics of the required power conversion. At present, transistors are favored for low-voltage, high-frequency operation, while the SCR's and GCS's find favor in high-current, high-voltage converters, usually operating at lower frequencies, *e.g.*, between 20 and 60 kHz.

Addition of a transformer to the basic circuit of Fig. 4 allows voltage step-up as well as high current and voltage step-down. The transformer also isolates input from output and allows an output of reverse polarity if desired.

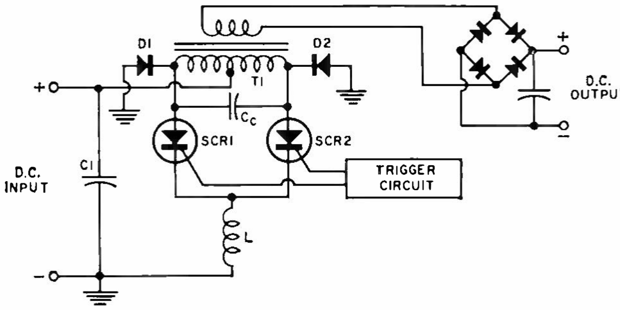
Typical Switching Circuits

Typical circuits are those of Fig. 5. Fig. 5A is a conventional d.c.-to-d.c. transistorized push-pull converter, except that the choice of components gives a 100-kHz operating frequency with an over-all efficiency of nearly 85% at a 100-watt output level. The d.c. output is 200 volts at half an ampere. The second transformer (*T*1) reduces both the transients and the core loss in the main transformer (*T*2). As shown, the circuit is not self-regulating. A regulator may be added to the input or the output, or else circuit modifications may be used to make the circuit self-regulating.

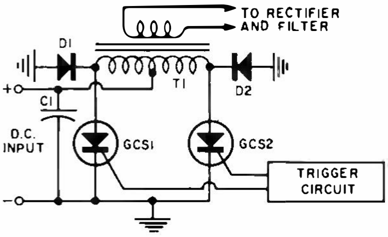


T1–FERROXCUBE 213T125 3C CORE T2–FERROXCUBE 528T500 3C5 CORE

(A) 100-kHz 100-W TRANSISTORIZED D.C. SUPPLY



(B) SILICON CONTROLLED RECTIFIER D.C CONVERTER



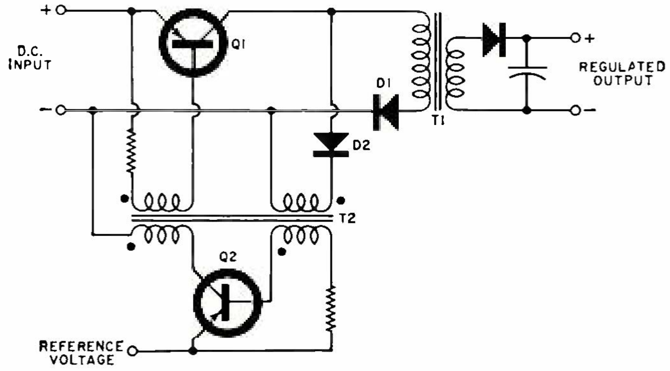
(C) ADJUSTABLE, REGULATED SUPPLY USING GATE CONTROLLED SWITCHES

Fig. 5. A number of switching-mode power supplies, converters.

Fig. 5B shows the general configuration used in an SCR inverter. This push-pull circuit operates between 20 and 50 kHz and allows supply voltages as high as 600 volts.

Every half period during circuit operation, a turn-on

Fig. 6. Single-ended supply with adjustable, regulated output.



pulse is alternately routed to each SCR. Assume *SCR*1 has just turned on. This connects the left end of commutating capacitor C_c to ground and causes current to flow in the left half primary of *T*1. The right end of C_c will charge up to twice the supply voltage. When *SCR*2 is turned on by its gate pulse half a period later, the charge on C_c cannot instantaneously change. This forces the anode of *SCR*1 negative by twice the supply voltage, turning *SCR*1 off. The circuit has changed state, current now flows through the right half primary of *T*1, and C_c begins charging in the opposite direction. This happens every half period.

As a result of the above, the secondary winding produces a square wave of magnitude determined by the turns ratio. The output square wave is then full-wave rectified and filtered. Diodes *D*1 and *D*2 are transient eliminating clamps, while filter capacitor *C*1 and the small inductor *L* provide reliable transitions between the two operating states.

GCS Circuit

If we replace the SCR's with gate-controlled switches, we can adjust the circuit operation in such a manner that there will be times when *neither* GCS is conducting. No commutating capacitor is used and the GCS is always turned off by a properly delayed gate pulse. By varying the ratio of the conduction *vs* the non-conduction time, the output may be regulated and adjusted both against the line and the load variations.

At lower voltages, a transistor may be used in place of the GCS. In one ingenious single-ended circuit, the same transistor is used both for rectangular-wave generation *and* power switching. The circuit is shown in Fig. 6. This is not a simplified schematic, for all required parts are shown. The circuit is self-regulating against changes in input voltage and may be adjusted by simply adjusting the reference voltage. *Q*1 and *Q*2 form a rectangular output multivibrator with a variable duty cycle. It can be shown that this circuit's output voltage is determined by the reference voltage only, and *not* the input voltage, as long as the input voltage is above some minimum value. Large changes in output load will have a small effect on the output voltage because of the drops in *Q*1 and *D*1, but this change is quite small. Because of this, the circuit is also self-regulating against changes in output load.

The self-regulating characteristics of these last two circuits mean that high-ripple d.c. may be used, which allows the 60-Hz line to be rectified, crudely filtered, and used as a d.c. supply source. No 60-Hz ripple will appear at the output because of the regulation against input-voltage variations. The amount of high-frequency ripple present can be made arbitrarily small by suitable output filtering.

Applications

The applications for these new techniques are numerous. With the advent of practical, economical microelectronic circuits, the bulk of the entire system size and weight is now in the power supplies. It is reasonable to assume that, as components become available, the majority of supplies for these circuits will use these high-frequency techniques, most likely at frequencies ultimately in the 1- to 10-MHz region.

The new techniques find favor in vehicular and airborne applications where weight, size, and efficiency are perpetual design headaches. This is particularly true of satellites where every ounce of payload is reflected as so many more pounds of thrust required for orbiting.

An extremely interesting application lies in television sets. If the set power conversion were to take place at 15,750 Hz, the power supply and horizontal output stage could be combined into one small, compact, low-cost circuit. This could significantly reduce the size and cost of what today are the largest and most expensive circuits in the set.

Along these lines, many all-transistor television receivers operating from a 12-volt battery, rectify a portion of the horizontal-oscillator output to provide high voltage for the video amplifiers and the cathode-ray tube.

Another natural application for switching-mode conversion lies in circuits requiring very high current at very low voltage. Fuel cells and thermoelectric cooling devices are in this category. The sizes for filters required for 60 Hz in these applications are horrendous. Furthermore, the high currents cause any inductors to be highly inefficient due to I^2R heat loss.

A present application is in portable equipment, such as transceivers, transmitters, and similar systems. There are at present gains in efficiency and output power to be made by operating r.f. and audio power stages in the 24- to 72-volt collector-supply region, but the available power is usually 12 volts from a lead-acid or nickel-cadmium battery. ▲

Editor's Note: The circuits that have been shown and described in this article are not intended as construction projects but rather illustrate circuit operating principles. We are sorry that neither we nor the author can supply further information on the availability of the semiconductors, transformers, or any other special components that may be required for these circuits.