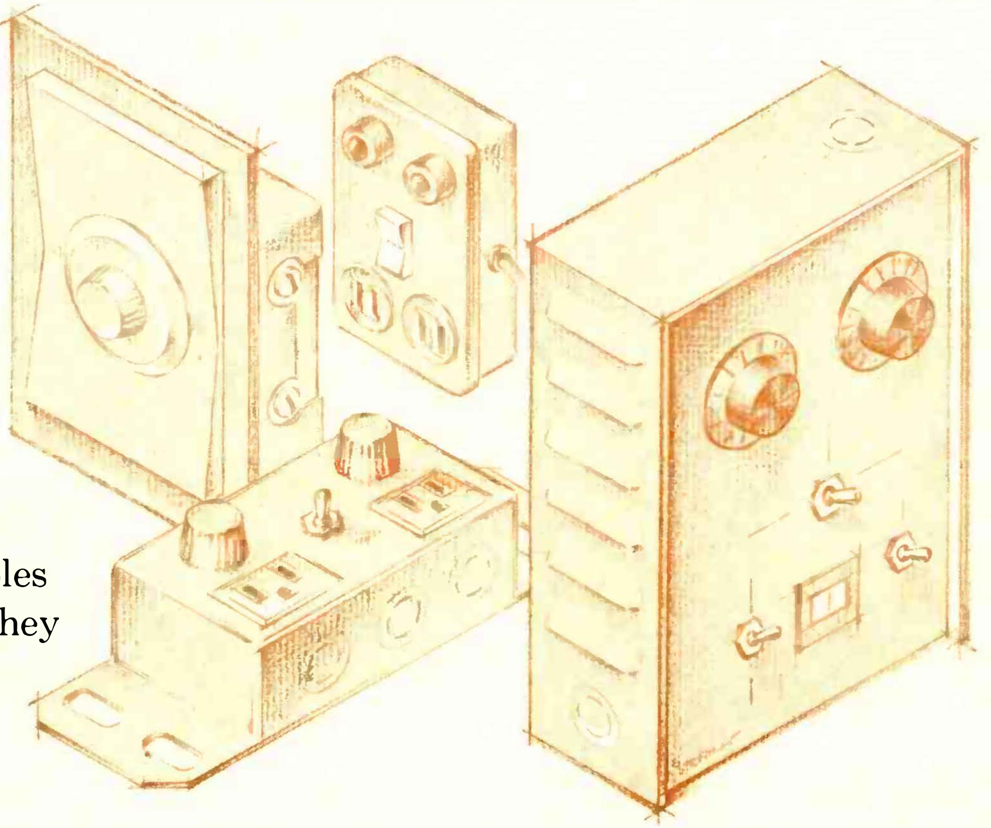
Solid-State Dimmers & Power Controls

By DONALD LANCASTER



Part 1. Roundup of new controls, their capabilities and their limitations. Basic operating principles and the types of load they can handle are covered.

IT is a rare home indeed that has water faucets than can only be turned "off" or "on," with no possibility of adjustment. Yet for years people have been putting up with single-brightness lamps; single-speed power tools; single-heat driers, soldering equipment, and heaters; and a wide variety of other appliances that can only be turned "on" or "off." The little control equipment that did exist was limited to inefficient rheostats, bulky autotransformers, switching and tapping schemes, and mechanical adjustments such as pulleys, transmissions, and multiple belts. To change the amount of light in a room, you had to change the number or size of the bulbs in use.

There is a quiet revolution going on in the power semiconductor field that will relegate many of these crude control devices to the museum. New semiconductor power controls that give instant and precise control of virtually any lamp, appliance, power tool, or heating device are rapidly becoming available. These controls are small in size and low in cost. They can control 117-volt a.c. power far in excess of most home requirements, typical units being capable of 600 or 1000 watts of power control, with industrial units going as high as several hundred kilowatts.

Today the large-quantity manufacturing cost of adding a dimmer to an ordinary table lamp is under three dollars; it will ultimately fall below a dollar as component prices drop with increased usage. From a component standpoint, one variety of control circuit requires only four low-cost electronic parts to give full-range, symmetric, 1-kilowatt a.c. control.

It would be rather foolish to run a comparison of the capabilities of dimmer "A" *versus* power-tool control "B," comparing the makes and models currently available. Some of these circuits are already obsolete or unnecessarily complex. Some use parts that are expensive and give only a limited control range. This is due to the rapid pace at which new components and control techniques have become available, particularly in the past year or so. There is keen competition among manufacturers of components to promote their particular components and control schemes to the power-control market.

Of more interest are the basic principles behind these controls, the loads which they can and cannot control. There is a wide variety of packages for these controls, some of which are highly specialized. This determines the utility of the control from a user's standpoint. There is a large number of power-control semiconductors in use, many of which are based on the silicon controlled rectifier (SCR). A wide spread of control circuitry exists, ranging anywhere from a single neon lamp to exotic multiple semiconductor circuitry. Finally, there are the special circuit capabilities; controls that handle fluorescents; tool controls that use feedback to maintain constant torque or speed despite a varying load; and controls that are designed to respond to external input information such as light, a d.c. control signal, or audio.

Principles of Operation

The basic problem is simple. You must vary the amount of power reaching a load. As Fig. 1 shows, there are two possible ways of doing this. Either you can vary the voltage or you can rapidly switch the load on and off, either applying full voltage or no voltage for a certain percentage of the time. The greater the ratio of on-to-off, the greater the power reaching the load. This "on-off-on-off" sequence is carried out so rapidly that the load can only respond to the average value, resulting in a smooth power flow. The inertia of the load, whether thermal or mechanical, accounts for this smoothing. This particular switching mode is invariably employed in the semiconductor power controls.

The big advantage with switching mode is that it is lossless, at least theoretically. The device doing the switching is either "off" or "on"; in neither state does the switching element consume power.

Compare this with a rheostat adjusted so that the load receives half voltage. The efficiency of this setting would be only 50% since the dissipation in the rheostat is *equal* to the dissipation in the load. This heat costs money and must be dissipated in some manner—which is not a simple problem at the kilowatt power level. Obviously, the rheostat must also be physically large to have a power dissipation in excess of that required at high levels. By the same token, an autotransformer must also be large and bulky, if it is to be used for voltage adjustment, because of the amount of iron and copper required for efficient power conversion at high power levels.

Actually, the semiconductor switches used are not quite perfect, but typical losses amount to less than one percent of the total load power rating, giving a power-control efficiency in excess of 99 percent. Because of this small heat loss and the temperature limitations of all semiconductors, a small heatsink is essential for any control rated above 250 watts.

Twice each a.c. cycle, the a.c. line goes through zero volts. It is most convenient to use these "zeros" to turn the switch that is producing the "on-off-on-off" sequence "off." In fact, some of the semiconductors **must** be turned off in this manner; there is no other convenient way. This means that the switch turn-on must somehow be synchronized to the a.c. line. If this were not so, the output power would be quite random as more or less of each half cycle was passed to the load. (There are several electronic novelty items which make use of this random non-synchronous operation to simulate candle and flame effects. The power variations flicker at about the same rate with the same random brilliance.)

Let us see what happens as we delay the turn-on time of the switch with respect to the a.c. "zeros" (Fig. 2). Assume that the switch is turned on very shortly *after* each a.c. zero, and then stays on for the remainder of the a.c. half cycle. The switch is "on" most of the time and nearly full power reaches the load. Next suppose the turn-on was delayed only about half the way between zeros. The switch is now on half the time and about half-power reaches the load. Similarly, a very late turn-on means that very little average power reaches the load. Obviously, if the turn-on is delayed so long that it never occurs during a half cycle, no power at all reaches the load and the circuit is essentially "off."

This basic control principle is called "a.c. phase control" and is common to all of the currently popular power controls. Back in the days of thyratrons, this same technique was used to give similar control of power in certain industrial controls.

It probably has occurred to the reader that there might be an easier way to do this—perhaps by turning entire cycles of voltage on and off or by operating only on one-half of each a.c. cycle and either allowing the entire other half-cycle to reach, or not reach, the load. This can be done and has led to some interesting and economical circuits, but there are serious drawbacks. Skipping cycles (called "skip cycling") causes an annoying flicker in any lamp as it goes on and off at a rate below the persistence of vision. This lamp operation is completely unacceptable. Skip cycling is quite useful in heating devices and other resistive loads that have a long thermal time-constant which can average out over a burst of many cycles.

This technique also has uses in certain motor controls where the counter-e.m.f. of the motor is used as a reference voltage for the next cycle, giving a smooth, constant-torque operation. The mechanical inertia of the load must be high enough to average out the power bursts. This technique is often used in industrial applications, but finds little use in the home power-control field.

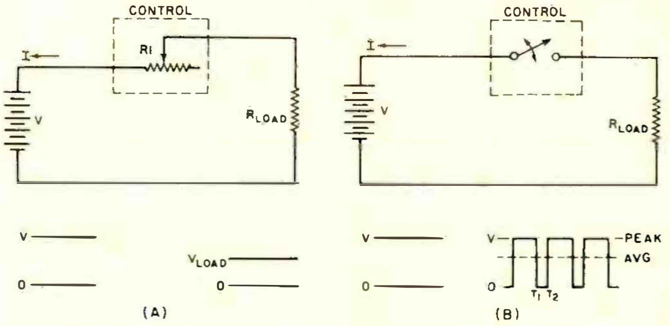


Fig. 1. Methods of controlling the amount of power reaching a load. (A) Resistive-loss method. (B) Switching duty cycle method which is employed by all the solid-state control units.

The concept of working only on one-half of each a.c. cycle and passing or not passing the other half in its entirety, is currently very popular. However, there is a big disadvantage to this mode of control. There is invariably a d.c. component in the output waveform. Feed this to a transformer or other inductance and no current limiting can be provided, resulting either in damage to the control or to the load. This d.c. component limits the utility of such circuits and has a devastating effect on fluorescent lights.

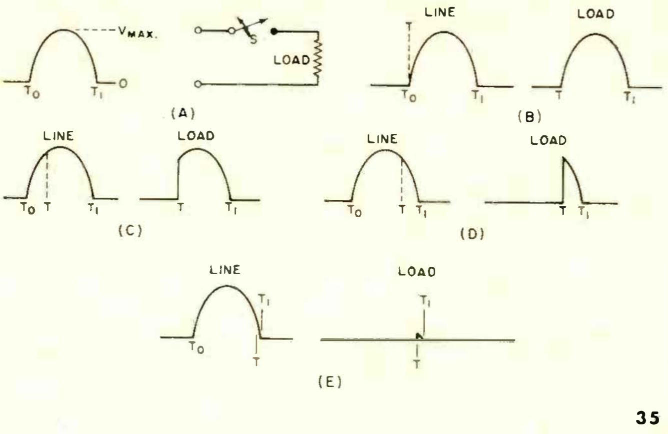
Any control that provides the same delayed turn-on in each alternate half-cycle is called a "symmetrical" control, while those that don't are called "asymmetric" controls. To date, the symmetrical controls have been more expensive than the asymmetric ones, but have a considerably wider range of acceptable loads, as we shall see shortly. Fig. 3 shows the differences in a symmetric and asymmetric control waveform.

Types of Loads

Just what loads will these power controls handle? Normal power levels may range from 10 watts to 2 kilowatts, typically 600 watts or 1 kilowatt maximum power level. Certain loads can be permanently damaged or can ruin the control if they are used incorrectly or on the wrong control. There are several classes of load which *can* or *cannot* be used with these controls:

Incandescent Lamps: All of the controls can handle any incandescent lamp within their ratings. This includes all desk, table, and overhead lamps; three-way lamps; and photofloods. Very tiny bulbs (3 watts or less) might not operate properly unless enough of them are used to meet the minimum load rating of the control. There are two special effects which could be annoying in certain circumstances. Certain very large bulbs (driveway spots, etc.) will tend to buzz at a 60- or 120-cycle rate at very low brilliance levels. This is due to the sudden expansion and gradual contraction of the large

Fig. 2. (A) A.c. phase control with a semiconductor being used as a switch that may be turned on any time from T_0 to T_1 but always turns off at the a.c. zero. (B) If S closes immediately after T_0, practically all the available power reaches load. (C), (D) As the closing times are delayed, less power reaches the load. (E) If S is closed very near to T_1, very little power gets to load. Finally, if T does not occur between T_0 and T_1, then the circuit is off and no power at all reaches the load.



filament. Also, as the brilliance of any incandescent bulb is reduced, the spectral output shifts from a fairly uniform white to an output favoring the orange and red spectrum. This can cause a shift in colors of all objects being illuminated by the lamp. Photographers would have to correct for the lower color temperature of the bulbs, especially on color shots.

Neon, Electroluminescent Panels: These devices consume far too little current and have a very non-linear volt-ampere characteristic to give any sort of smooth or predictable control. Sometimes, adding an ordinary 25-watt incandescent bulb to provide a minimum load for the control will smooth out operation to the point where it will be useful.

Fluorescents: Assymetric power controls will cause permanent damage to fluorescent lights as the ballast cannot limit a d.c. current. Symmetric controls will operate fluorescents over a limited range. Special fluorescent-only dimmers are available which permit full-range operation by means of waveform distortion. Some of the power-factor correction circuitry in expensive (corrected) fluorescents can damage some of the older symmetrical controls.

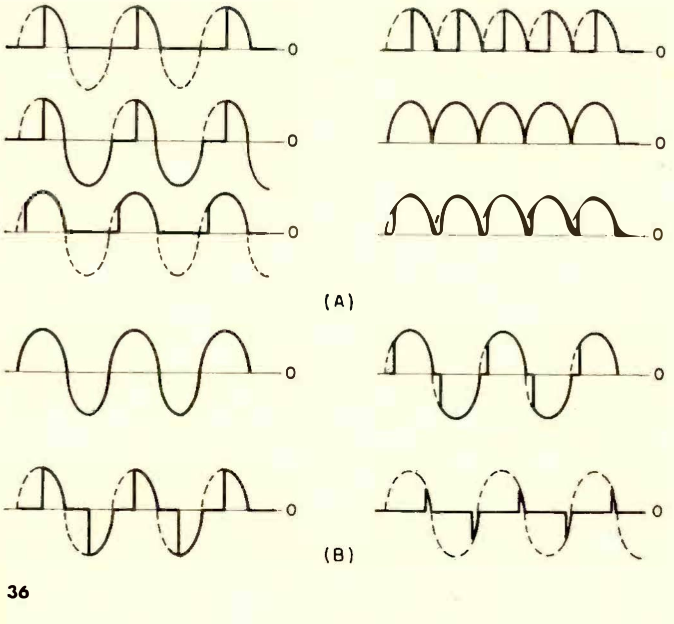
Heaters: The controls are ideal for any resistive device within control ratings. Thermostats or thermistors may be added for stable temperature control. This application includes dryers that have universal motors and soldering irons that have no transformers.

Soldering Guns and Transformer-Type Soldering Irons: Any symmetrical control with enough power rating will give ideal control. *Permanent damage can result from operating a soldering gun with an asymmetric control.* This also applies to transformer-operated soldering irons and, incidentally, to those new high-intensity lamps that have a transformer in the base.

Capacitive Loads: Never use controls for such loads. Suddenly switching a capacitor across a voltage source can produce current transients large enough to permanently ruin the control. Under certain circumstances, a small noise-filtering capacitor across a resistive or inductive load is permissible, especially if some current limiting is provided.

Inductive Loads: As any inductance cannot block direct current, only symmetrical controls may be used with highly inductive loads. If the power factor is more than 0.8, either control type may be used. Less than 0.8 means that only the symmetrical type may be used. Certain turn-on circuitry may have its range restricted by highly inductive loads. An important problem in some applications is the tremendous reverse kick produced if the current in an inductance is suddenly stopped. This could happen due to a power failure or if the main switch were turned off. Newer, symmetrical devices simply turn on when reverse-biased, protecting themselves and the rest of the circuit. This is also true of the recent controlled avalanche devices. It is *not* true of ordinary SCR's and some sort of protection must be provided. This is especially important in solenoid drives and similar highly inductive applications.

Fig. 3. (A) Typical waveforms produced by asymmetric controls. These controls add a d.c. term to the load waveform which can damage transformer-operated or inductance-limited loads. (B) Symmetric controls produce these typical waveforms. These can be used with any type of load. Note waveform "balance."



Transformer Input Power Supplies: These may be used with symmetric controls, *but permanent damage can result if asymmetric controls are used.* Best results are obtained when the transformer is run fully loaded or nearly so, otherwise the control range might be restricted or non-linear. Obviously, if the transformer is of the self-regulating type, no control over its operation is possible.

Motors: Here is where the trouble comes in. As a general rule, if the motor has brushes and a wound armature, either type of control may be used. This applies to all a.c.-d.c. "universal" motors, such as found on electric drills, sewing machines, hand-held power tools, etc. *Any motor that does not have brushes will be permanently damaged by either type of control.* The control may also be ruined if this is tried.

There is a definite reason for this. The no-load speed of a.c.-only motors (synchronous, repulsion-induction, squirrel-cage induction, hysteresis-synchronous, etc.) is determined only by the motor geometry and the line *frequency* and *not* the line voltage. This also applies to the "washing machine" or electric-saw type of ¼-horsepower motor, usually rated at 1725 rpm, as well as all other a.c.-only motors of this type. Other examples are clock, phonograph, and tape-recorder motors, as well as certain sanders and other vibrating type power tools. Reducing the applied voltage of these motors simply reduces the available torque. If the voltage (or the voltage duty cycle) is reduced too much, the motor either breaks synchronization or goes into a stall. Either of these high-current modes can cause motor burnout.

The only way to change the speed of this type of motor is to change the operating frequency. This is why electric clocks keep perfect time—their speed is precisely controlled by the frequency standard at the power company. Even changing frequency can only provide a limited speed range since the reactance of the winding will increase or decrease with frequency, changing the currents in the motor.

There are, of course, exceptions to any rule and certain obscure industrial or surplus motors without brushes might be controllable but the rule holds good for virtually any motor that is likely to be found in home appliances.

Control Packages

The choice of a control package can have a major influence on the utility of a control. Some current types of packages are illustrated at the beginning of this article.

One type is an "in-the-box" dimmer, intended for permanent installation as a replacement for an ordinary light switch. This is the oldest form of control package. The major advantage is its built-in control of room lights, replacing the older, bulkier, and more expensive autotransformer control. There are some disadvantages to this package. Few living rooms have ceiling fixtures these days. The installation is expensive, unless you do it yourself, and once installed the control cannot be "borrowed" for a drilling job in the workshop or a spot-dimming application for a night light.

Other new designs just plug in and mount directly on an electric outlet. The beauty of this design is its inconspicuous appearance and its portability. It is ideal for desk and table lamps and can also be used in kitchens and workshops for mixers, heaters, and tools. The small package, which is also the heatsink, limits power to 600 watts at most. One drawback of this control is the location of some outlets very near the floor or behind furniture,

(*Continued on page* 85)

Solid-State Power Controls

(*Continued from page* 36)

making continuous adjustment of such a control rather difficult.

Most kitchen and shop outlets, however, are at counter height so this is not a problem when the control is used with appliances.

The conventional tool control consists of a control box equipped with a long, heavy-duty line cord. This type is intended for the home workshop and is usually equipped with 3-prong plugs and outlets for safety grounding. They may also include fuses or circuit breakers for control protection. This type of control is not suitable for use on table lamps because it is far from decorative and often the required 3-prong outlets are not available in such locations.

The industrial version of this home tool control is extremely rugged and specifically designed to operate a single motor or tool. The torque and speed may be controlled independently while internal feedback circuits automatically adjust for changing load and line-voltage variations.

Also available is a special double dimmer intended for photoflood control. The adjustment gives precise shadow control and balance on black-and-white photography and control of color temperatures for color work. A very important feature of this control is that it can substantially extend the life of normal six-hour photofloods. Photofloods almost always fail on the turn-on current surge. By starting in an "off" position and bringing the bulb voltage up to full brilliance slowly, the bulb life can be greatly prolonged.

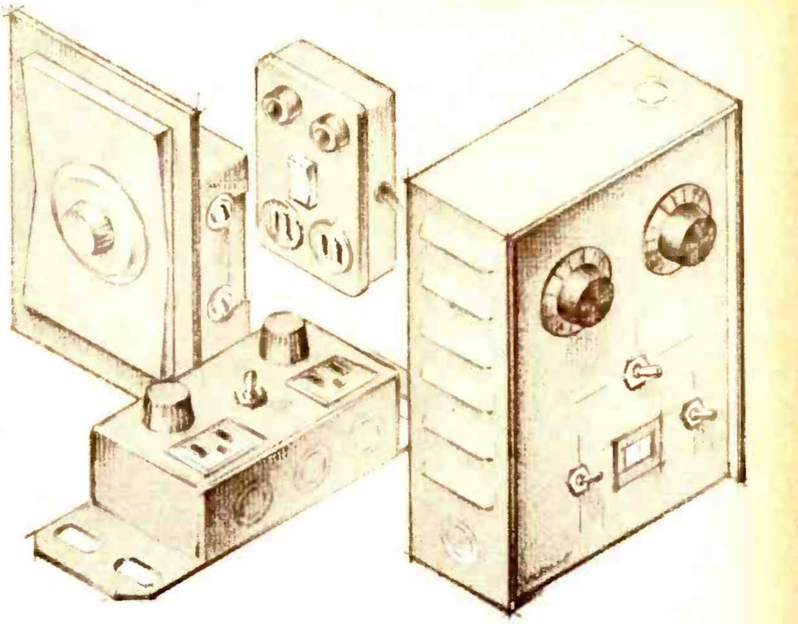
There is also a built-in control integrated into the trigger of an electric drill. As more pressure is exerted on the trigger, the speed of the drill increases steadily. The circuit is built right into the tool itself during original manufacture.

Other built-in controls are included in an ordinary desk or end-table lamp during initial manufacture. The advantage of these latter two controls is their integral, built-in circuitry. The low additional cost of these controls means that ultimately many lamps and power tools will incorporate them. As these see more and more use, other types of controls will be displaced—with integral control spotlighted in the marketing of many appliances.

Next month, we will investigate the specific control circuitry common to all these types of units, considering what power semiconductors are used, how they are controlled, and how the special circuits that use fluorescents, feedback, or external inputs for control operate. Parts values will be included wherever possible.

(*Concluded Next Month*)

Solid-State Dimmers & Power Controls



By DONALD LANCASTER

Part 2. Specific circuits and their characteristics. Included is operation of circuits for fluorescent lamps, tool controls that use feedback for constant torque, and special controls for light, d.c., and audio input.

LAST month we looked at solid-state power controls from a user's standpoint; considering what they are, their basic operating principles, the loads they can and cannot handle, and the various available packages with their individual advantages and disadvantages. This month, we will look at these controls from a different angle, considering how they work, and then going into specific circuits. There are many approaches to these new power controls, differing primarily in economy and utility.

All solid-state power controls make use of the a.c. phase-control principle to chop up the a.c. line into bursts of energy fed the load. The greater the fraction of each cycle that reaches the load, the greater the average load power. The load smoothes the "off-on-off-on" sequence into a uniform average value of load power with its inertia, be it thermal or mechanical. There are two basic switching schemes: the symmetric and the asymmetric. The asymmetric controls, although lower in cost, invariably produce a d.c. term in the output waveform which prevents their use on fluorescents, soldering guns, and any transformer-operated loads.

Common Control Circuits

Fig. 1 shows a family of dimmer and tool control circuits which illustrate the common control schemes in use today. Each control consists of two parts—the power control itself and the turn-on circuitry. Although we have shown complete circuits, look at them initially only from their power-control aspects.

Fig. 1A is the simplest control and consists of a three-position switch and a single silicon rectifier. In the "Off" position, no power reaches the load. In the "Dim" position, only the negative half cycles reach the load since the diode blocks the positive halves. In the "Bright" position, the diode is removed and both cycle halves reach the load. The circuit is asymmetric and has no continuous adjustment. It is suitable only for incandescent lamps and two-speed electric drills. Its main features are economy and simplicity. The maximum load current is twice the diode rating, since the diode is "on" only half the time. An ordinary 750-ma., 200 p.i.v. diode is good to 1500 ma. or almost 200 watts of load. A diode with a somewhat higher current rating can be used for loads of 600 watts or more.

The next simplest configuration is that of Fig. 1B. Here the silicon rectifier is replaced by a silicon controlled rectifier (SCR). The turn-on of the SCR is delayed each half cycle until it receives a turn-on pulse from the control circuit. Varying the 10,000-ohm pot varies the time of the turn-on pulse, and the SCR gives continuous adjustment from "off" to half power. Note that the range of this control is restricted and that, once again, the waveform is asymmetric. A silicon controlled rectifier, just like an ordinary diode, works only one way and conducts current only when forward biased. The SCR is turned "on" by a gate pulse and "off" by the first a.c. zero.

By combining the circuits of Figs. 1A and 1B, a full-range asymmetic circuit results (Fig. 1C). If the switch is open, the SCR controls from "off" to half power, since the negative cycle halves aren't passed. With the switch closed, the diode passes the negative half cycles and control of half power to full "on" is achieved. Usually the switch is combined with the delay pot in the turn-on circuit, so that two turns of the pot are required to go from full "off" to full "on." This circuit is commonly used in the dimmer and tool controls now being offered by distributors and hardware stores, but the newer symmetrical circuits will soon match it in parts cost. The disadvantages of this circuit are two-fold: an asymmetric output waveform and the two-turn control. Power rating is determined solely by the current ratings of the SCR and shunt diode.

The only thing that can be said for asymmetric circuits is their economy, for they are capable of handling only a limited number of useful loads and plugging in the wrong load can cause permanent damage to both control and load. This economy will shortly be matched by the newer circuits, and this form of circuit will ultimately disappear.

Symmetrical Controls

There are two approaches to symmetrical control, either using unilateral (one current direction only) components in pairs, or using bilateral components only. The bilateral components are quite new, while the unilateral SCR circuits have been around for some time.

An SCR is unilateral. It works in one current direction only. So why not use two SCR's, one going in each direction? This is the approach of the circuit of Fig. 1D. The SCR's each operates in its own forward direction and provides full-range symmetric control. The diodes in the control circuitry do not handle the load current and can be quite small. The turn-on circuit for this configuration must be bilateral, as it must provide a turn-on pulse of the proper polarity each half cycle, properly routed to the right SCR.

But a unilateral turn-on circuit may be preferable, particularly when using the special circuits that require input signals. The shorted bridge configuration of Fig. 1E allows symmetric power control with a unilateral turn-on circuit. This requires two SCR's and two power diodes. The current flow is always in the forward direction of one of the SCR's and the opposite diode. This circuit has recently become quite attractive due to the availability of reverse-polarity SCR's and diodes. By a proper combination, one uninsulated heatsink may be used as the common connection for all four components.

The circuit of Fig. 1F uses a full-wave bridge rectifier and a single SCR. This might be preferable if you were using one of the new insulated full-wave bridge assemblies, either molded or stud mount. Also, the SCR never has reverse voltage applied to it. This is a protective advantage, important on older type SCR's.

There is an interesting variant of this circuit. If the load is brought inside the bridge circuit, the same bridge may be used on a multiple SCR arrangement. Of course, this puts a strong d.c. component in the output waveform, but this doesn't matter with incandescent bulbs. Each SCR may be independently controlled. This is quite useful for theater lighting, color organs, and variable color advertising displays. Fig. 1G shows this extension. Its advantage is that only a single bridge assembly is needed for *all* the SCR's and control circuits.

There must be an easier way. Why not a single bilateral semiconductor directly in series with the load and a simple bilateral turn-on circuit? *Transitron* and *General Electric* have very recently come up with *bilateral* power-switching devices, *e.g.*, ones that operate equally well in either direction. Typical ratings of these semiconductors are 600 watts, 1 kw., and 5 kw. They can provide complete symmetrical control with either four or five components. These devices are so new that they are not priced competitively with the SCR systems. There is another disadvantage to these new devices, which may be important in some applications. The circuits *must* be driven by a bilateral turn-on circuit. In cases where control is to be by d.c. or other external signal, the available turn-on circuitry is quite limited. This limitation will almost certainly be overcome in the near future, but at present it limits the use of the new bilaterals in external-signal controls.

The *G-E* bilateral, called the "Triac," is similar to an SCR except that either polarity gate pulse may be used to turn on the device. (One particular combination of gate pulse and load current at present requires excessive current. Because of this, forward gate polarity with respect to the main current is almost always used.) A "Triac" power control is shown in Fig. 1H. Operation is just like the circuit of Fig. 1B, except that turn-on occurs each half cycle, giving symmetrical, full-range control.

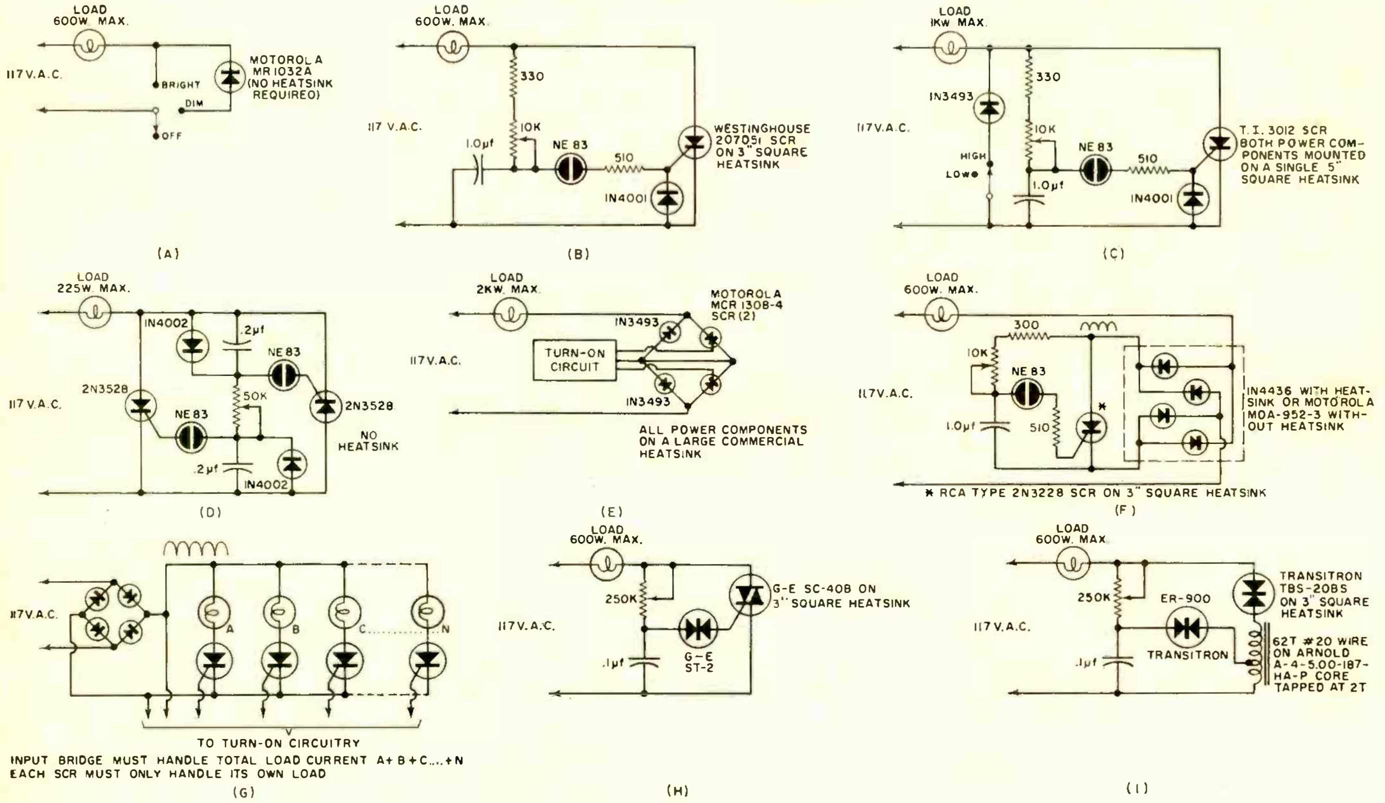
The *Transitron* bilateral, called a "Biswitch," has no gate. It is turned on by exceeding the forward breakover voltage and avalanching the five-layer silicon structure into conduction. To do this, a small transformer steps up the turn-on pulse to a 400-volt spike which breaks down the "Biswitch." This transformer has a very low 60-cycle reactance and does not affect the main current flow. The circuit of Fig. 1I is similar in operation to the "Triac" circuit with the transformer replacing the gate connection. The "Biswitch" has a lower unit price than the "Triac" but the need for a transformer largely offsets this price advantage.

Ultimately, the circuits of Figs. 1H and 1I, because they require fewer parts and are easier to manufacture, may replace the rest as the price of bilateral switching devices drop and the external control problem is solved.

Turn-On Circuitry

Fig. 2A shows a circuit consisting of a resistor and a capacitor connected to the gate of an SCR. This is a phase-shifting circuit in which the current leads the voltage. As an a.c. zero

Fig. 1. A wide variety of solid-state dimmers and power-control circuits are being presently employed.



comes up, *R* will start to charge *C*. When *C* gets up to the forward turn-on voltage of the SCR (about 0.6 volt), the SCR turns "on," discharges *C*, and removes the source of charging current for *R* by shorting out the *RC* network. A large value of *C* is needed and the turn-on is temperature-dependent, due to the changing turn-on level of the SCR. This can cause a time drift in the control settings which can be quite severe. This circuit is not used in any but the lowest priced controls. It is bilateral and is shown because it is the basis for the more practical circuits that follow.

The main objections to the *RC* turn-on circuit are the loading of the SCR gate on capacitor *C* and the absence of a discrete turn-on pulse. Both these objections are overcome by adding a neon lamp to the circuit, as shown in Fig. 2B. *R* charges *C* until the breakdown level of the neon is reached. At this instant, the neon ionizes and briefly conducts a turn-on pulse into the SCR gate. The precision of the turn-on is determined entirely by the neon characteristics and not by the SCR. In practice, a high-current neon, typically a low-cost NE-83, is used to provide sufficient current to guarantee SCR turn-on. The circuit is bilateral and operates equally well unilaterally.

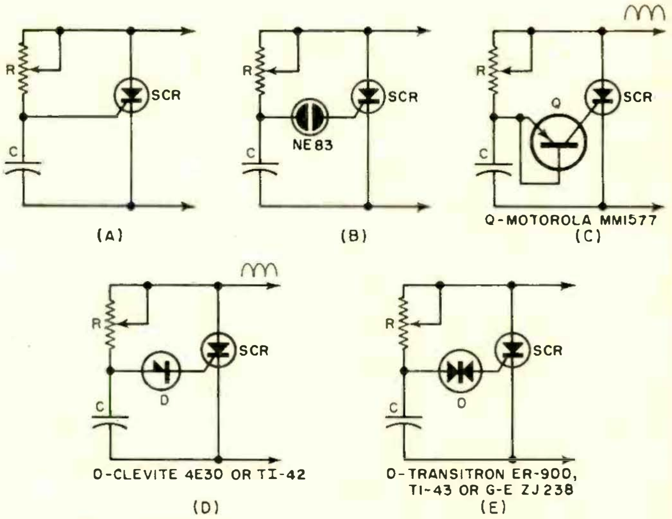
There are several limitations to this improved circuit. The first is the intrinsic "orneriness" of neon lamps with regard to their firing levels and pulse capabilities. This is largely overcome by painting the neon black, using a fixed, short geometry, and by using only neons that have radioactive tracers added to stabilize their operating points. A second, and major, disadvantage is that a neon will not turn on at less than about 80 volts. This means that no matter how small *R* is, the circuit cannot turn on the SCR *until the a.c. line has reached at least 80 volts,* and cannot provide turn-on any later than after the a.c. line has dropped below 80 volts. This results in a reduced control range. Starting with "off," no control can be obtained until a jump to a low brilliance is achieved at 80 volts. From there, smooth control exists up to the setting at which the first 80 volts occurs. *There can never be full power applied to the load.*

What is needed is a neon lamp that breaks down at 20 or 30 volts. There is very little power in the "corners" of half a sine wave, since power is proportional to voltage squared. The missing parts of the control range would be quite small and of no consequence. Gaseous discharges at such low potentials simply do not occur, and no neon or argon device will break down at these low potentials. But any small-signal transistor has an avalanche breakdown voltage. The breakdown characteristic of a transistor may be used to provide the turn-on pulse.

This is the circuit of Fig. 2C. The turn-on pulse is produced by the voltage on *C* exceeding the avalanche voltage of transistor *Q*. *Q* avalanches at this point and produces a turn-on pulse. The SCR then resets the circuit by discharging *C* through *Q* and shorting out the source of current for *R*. This is a quite practical circuit. Transistor *Q* is a special inexpensive one, optimized for safe avalanche breakdown very near 25 volts. This circuit is unilateral and will not drive the bilateral controls unless a double configuration is used. The circuit smoothly controls output power between 3 and 97 percent of maximum available power from the line. This corresponds to very nearly "off" and very nearly full brightness.

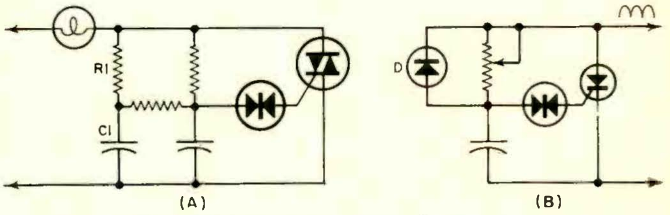
Instead of using a transistor, any avalanche diode may be used, such as a four-layer diode or a *p-n-p* avalanche diode. These are shown in Fig. 2D and are simply alternates to Fig. 2C.

By going to a *five*-layer *p-n-p-n-p* trigger diode, as in Fig. 2E, bilateral operation may be obtained over the same range as the circuits of Figs. 2C and 2D. This is a very good circuit and, except for critical applications, is well suited to all home-power-control needs.



(A) (B) (C) (D) (E)

Fig. 2. Turn-on circuits arranged in order of increasing cost.



(A) (B)

Fig. 3. Circuits employed to eliminate "jump-start" effect.

There is a minor annoyance in connection with this circuit that is corrected by the addition of a phase-shift network, consisting of a fixed resistor and capacitor. In bringing the bilateral control up from zero, a sudden jump occurs to about one-quarter brightness or speed. From this point, the control may be smoothly varied, either up or down in intensity. The jump is caused by capacitor *C* failing to discharge through *R* fast enough for settings so low that *C* never reaches 30 volts, SCR turn-on never happens, and at each zero, *C* must begin charging, not from zero but from some reverse bias. As soon as initial turn-on is achieved, *C* always starts charging from zero bias, which shifts the settings so that a full control range may be realized. The new resistor and capacitor provide enough additional phase shift at extremely low brightness (or speed) settings to minimize this effect. Fig. 3A shows the circuit.

In unilateral turn-on circuits, the addition of a diode and a resistor across the line may be used to eliminate this effect. This is detailed in Fig. 3B. Diode *D* is always reversed biased *except* when the charge on *C* exceeds the line voltage. This insures zero capacitor charge at the beginning of each half cycle, whether or not the SCR has turned on during that cycle. This effect is called the "jump-start" effect and is of importance only in critical light-dimming applications.

All of the firing circuits shown are somewhat line-voltage dependent. If it is necessary to precisely control the load power totally independent of line variations, a regulated charging supply for the timing capacitor must be used. This usually takes the form of a zener diode. A very old combination is to use a zener and a unijunction transistor as the avalanche device. This circuit is quite expensive when compared to the others, but provides stable operation despite varying line voltage, a feat that the other circuit cannot match. The unijunction circuit is shown in Fig. 4. It is strictly unilateral and must be driven from an inverted (positive-going half cycles only) a.c. source. A pulse transformer may be added to provide gate signals for two or more SCR's. The circuit finds little use in home and shop applications due to its expense and the large number of parts, but is widely used in precision regulators and servos.

There is much confusion over the use of solid-state power controls on fluorescent lights. Any symmetrical control will

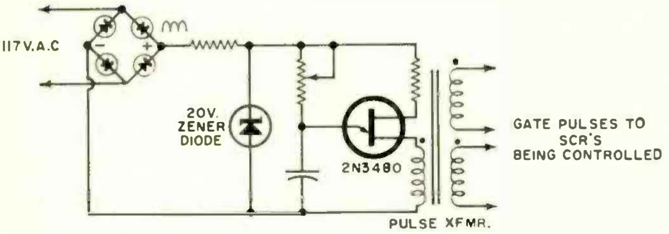


Fig. 4. Unijunction turn-on circuit is stable under varying line voltage but is more complex and is much more expensive.

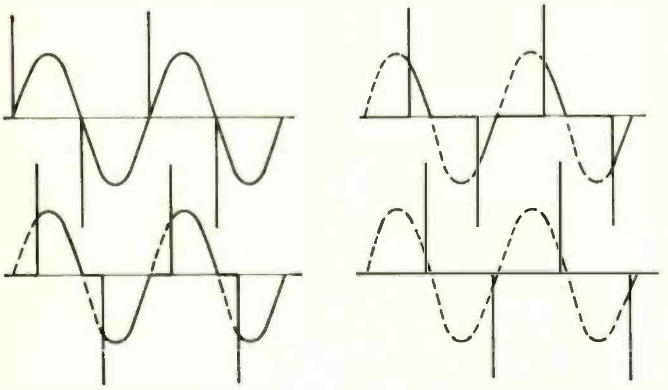


Fig. 5. Typical waveforms for fluorescent-lamp dimmers.

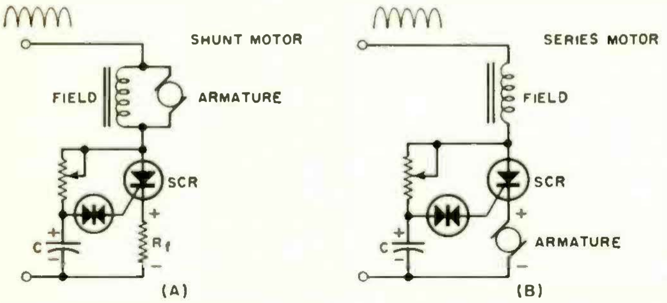


Fig. 6. Techniques using feedback for constant motor speed.

* 200-VOLT CADMIUM SULFIDE LIGHT-DEPENDENT RESISTOR—DELCO LDR25, SIGMA OED5HC2, RAYTHEON EM1502, IEC201

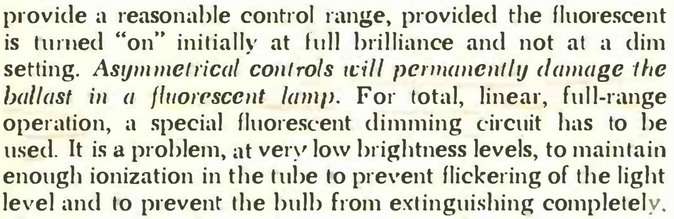


Fig. 7. Light-sensitive turn-on circuits. Thermistors may be used in (A) and (B) to produce temperature-sensitive controls.

provide a reasonable control range, provided the fluorescent is turned "on" initially at full brilliance and not at a dim setting. *Asymmetrical controls will permanently damage the ballast in a fluorescent lamp.* For total, linear, full-range operation, a special fluorescent dimming circuit has to be used. It is a problem, at very low brightness levels, to maintain enough ionization in the tube to prevent flickering of the light level and to prevent the bulb from extinguishing completely. There are a number of dimmer circuits that overcome this, by use of waveform distortion. A *spike* is always applied to the fluorescent just as SCR turn-on would normally occur. This "restrikes" the discharge in the tube every time, insuring enough ionization to maintain a uniform low brilliance. Typical waveforms are shown in Fig. 5. The actual circuits employed vary with the size and types of lamps in use.

It has been assumed all along that these circuits are to operate on 60-cycle a.c. To the SCR, the operating frequency does not matter, as long as the a.c. zeros are available. But the delay circuit must be changed each time to "fit" the time length of each half cycle of the particular supply frequency in use. Time constants must be lengthened for 50-cps operation and shortened for the 400-cps aircraft lines. If d.c.-only operation is attempted with the controls shown, they will simply lock at full brilliance very soon after power is applied and stay "on" until the power is disconnected, hence, these circuits are totally unsuitable for d.c. operation. Similar control functions may be provided on d.c. by using a gate controlled switch (an SCR that can be turned *off* as well as on by a gate pulse). Another alternative is the use of pairs of SCR's in various capacitor commutation schemes.

Constant-Speed Arrangements

The controls shown provide constant power to a load. If the load is a motor or a tool (electric drill, etc.), it would be preferable to provide constant *speed* in light of a varying mechanical load. A mechanical load reflects itself as an increase or decrease in motor current. Feedback is used to advance or retard the turn-on time of the control as the load increases or decreases. This is done by sensing the output current or using the induced back-e.m.f. of the motor to alter the biasing of the turn-on circuit. As motor current increases (corresponding to a heavier load that would try to decrease speed), a feedback signal is produced that shifts the turn-on earlier in the half cycle (corresponding to more power that tries to increase speed).

Two typical circuits are those of Fig. 6. (A) shows a resistor R_f in series with the SCR whose voltage drop adds to the normal 30 volts to which the timing capacitor C must charge. As the load varies, the drop across R_f follows, producing a feedback voltage according to Ohm's Law. R_f must be a high wattage unit since the total load power flows through it. Fig. 6B replaces resistor R_f with the armature of the motor. This is only applicable to series motors. The *IR* drop of the armature is directly proportional to motor current which, in turn, is directly proportional to the mechanical load. This *IR* drop forms the correction voltage which is again used to shift the turn-on time to maintain constant speed. There are considerably more elegant schemes for providing constant torque or constant speed, but these two simple methods are indicative of the general principles behind all controls of this type. These circuits are usually unilateral.

Light-Sensitive Controls

Light-sensitive power controls involve one of the three methods shown in Fig. 7. A photoresistor, usually cadmium sulfide or selenide with a 200-volt rating, is added to shunt the timing capacitor or to replace the timing resistor. If the capacitor is shunted, as in Fig. 7B, *increasing* light causes *decreasing* load power. Or, as in Fig. 7A, if the photoresistor is used as the timing resistor, increasing the light decreases the photoresistance, which increases the load power. The latter method is considerably more linear. Both circuits are bilateral. There are also available SCR's which are directly light sensitive. Here the presence of light simply turns the SCR on, resulting only in "on-off" and *not* proportional control.

A final large group of these controls makes use of external control signals, whether d.c., low-voltage 60 cps, or audio. These are useful for temperature controls, feedback and logic systems, color organs, displays, and other audio-driven devices. An important advantage of this type of operation is that low-voltage "doorbell" circuits may be used instead of the conduit runs that are normally required for direct 117-volt proportional control circuitry.

D. C. and Audio Controls

A new and rather obvious means of d.c. control consists of placing a light bulb (incandescent or neon) in front of the photoresistors in either light control circuit (Figs. 8A and 8B). Commercial optical links (*Continued on page* 75)

Solid-State Power Controls

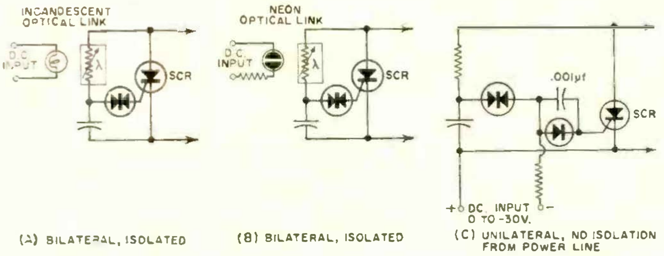
(*Continued from page* 44)

(four-terminal light-photocell pairs), which enhance this possibility, are newly available. An obvious advantage is the complete isolation between input and output signals. These circuits are not too linear and not overly sensitive. A second possibility, shown in Fig. 8C, is to bias the breakdown diode by a varying 0 to −30 volt d.c. control signal. This method is quite linear and extremely sensitive (gains of 10,000 and up are possible) since the control signal does nothing but bias an already reverse-biased diode and does not have to provide power for the SCR turn-on. This method is unilateral and provides no isolation for the control signal.

There seems to be a myth prevailing that it is possible to "feed" random audio signals to the gate of an SCR and expect the load to precisely follow the input signal. Unless the audio consists of a precisely synchronized, phase-shiftable, 60-cps control signal, this concept is incorrect. Audio control may be effected by two means, shown in Fig. 9. The optical links do not care whether the light source is excited by d.c. or a.c. and the slow rise time of the photoresistor integrates the audio signal into a constant resistance value proportional to the audio input power. This method is very economical and provides complete isolation. It is bilateral. It is also non-linear and not too sensitive. Pre-biasing schemes at the light source partially overcome these objections. Linear control is obtained by isolating, rectifying, and filtering the audio as shown in Fig. 9. This method is extremely sensitive.

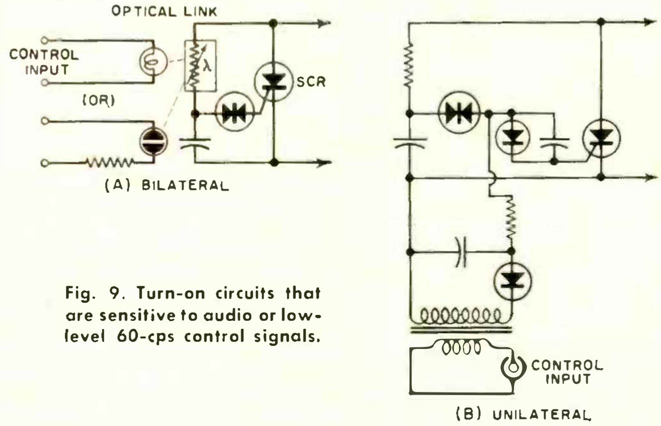
There are most certainly other solid-state power control circuits and control schemes, but most of the ones omitted are either of little current interest or are simply mutations of those we have covered. The surface of this vast field has barely been scratched. The control techniques are so new, at least on an economically practical level, that the controls incorporating such techniques are only beginning to appear commercially.

In addition, the potential of these new techniques is practically limitless. In the not too distant future, we may find that all our electric tools, appliances, and lights will be completely controllable as to speed and brightness rather than simply being turned on and off. ▲



(A) BILATERAL, ISOLATED (B) BILATERAL, ISOLATED (C) UNILATERAL, NO ISOLATION FROM POWER LINE

Fig. 8. Turn-on circuits sensitive to d.c. control voltage.



(A) BILATERAL (B) UNILATERAL

Fig. 9. Turn-on circuits that are sensitive to audio or low-level 60-cps control signals.