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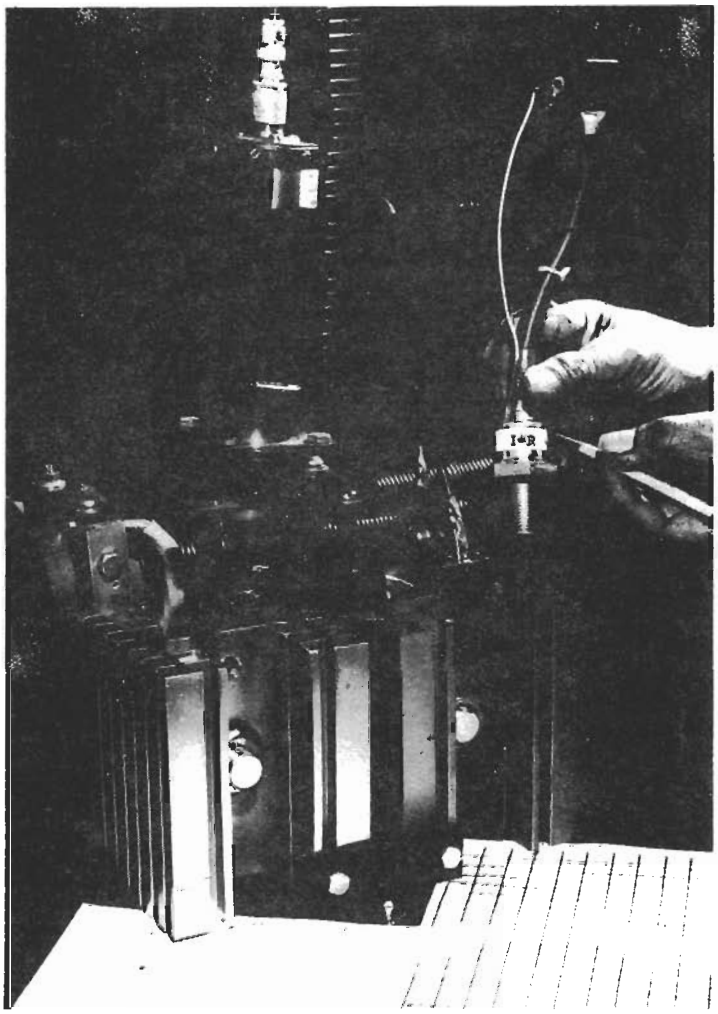
Need a triac for 200 amps at 1,000 volts? It's available now. Here's a look at this startlingly different device, and some examples of how it can be used.



Applying the power-logic triac

BY DAVE COOPER
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El Segundo, Calif.

THE ADVENT of silicon-controlled rectifiers that handle many kilowatts of power with high control gain and low power circuit losses has had a sharp impact on industrial controls.

This activity, coupled with an increasing demand for more accurate and sophisticated control functions, has forced the development of more advanced control and logic devices, including integrated circuits. It was only a matter of time before this same drive for design of multiple-control functions in a single package was extended to higher power devices. The development of the silicon bidirectional thyristor (silicon symmetrical switch, diac, triac, etc.) was the first step in extending the principle to a-c power semiconductors. However, the power-handling capability of the first devices was not great enough to enable their use in heavy industrial systems.

A new epitaxial logic-triac is now available which overcomes these deficiencies. It can control more than 140 kw of a-c power. The power logic-triac (IR series 200AC) is capable of carrying 200 amp rms current and has a main terminal peak operating voltage rating of up to 1,000 v. The 1,000-v rated device has a guaranteed minimum breakover voltage of 1,100 v. *(This unit will control more than 20 times the power of any other existing triac.)* In addition, by incorporating a selective gate characteristic, the logic-triac becomes a uniquely versatile power-control device.

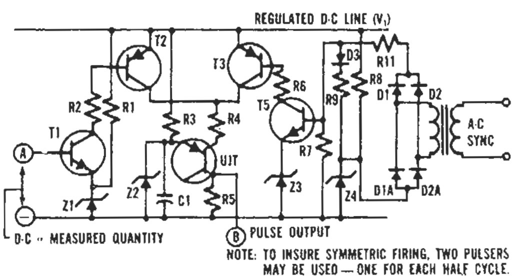
Applications for the logic-triac include:

- Heating controls.
- D-C motor drives.
- D-C motor reversing drives.
- Light flashers.
- Transformer static tap changers.
- Chopper drives with dynamic braking for d-c motors.
- Bridge inverters.

The logic-triac can switch to the ON state when a signal is applied to a single-gate connection. It can be made to conduct in either direction by applying either a unidirectional gate signal or a properly phased bidirectional gate signal.

With one polarity of gate bias the logic-triac can be characterized as a pnpn switch in parallel with an npnp switch, both devices having a common gate.

ZERO CROSSOVER FIRING



A BRIEF EXPLANATION OF THE DRIVING CIRCUIT TO TRIGGER THE LOGIC-TRIAC

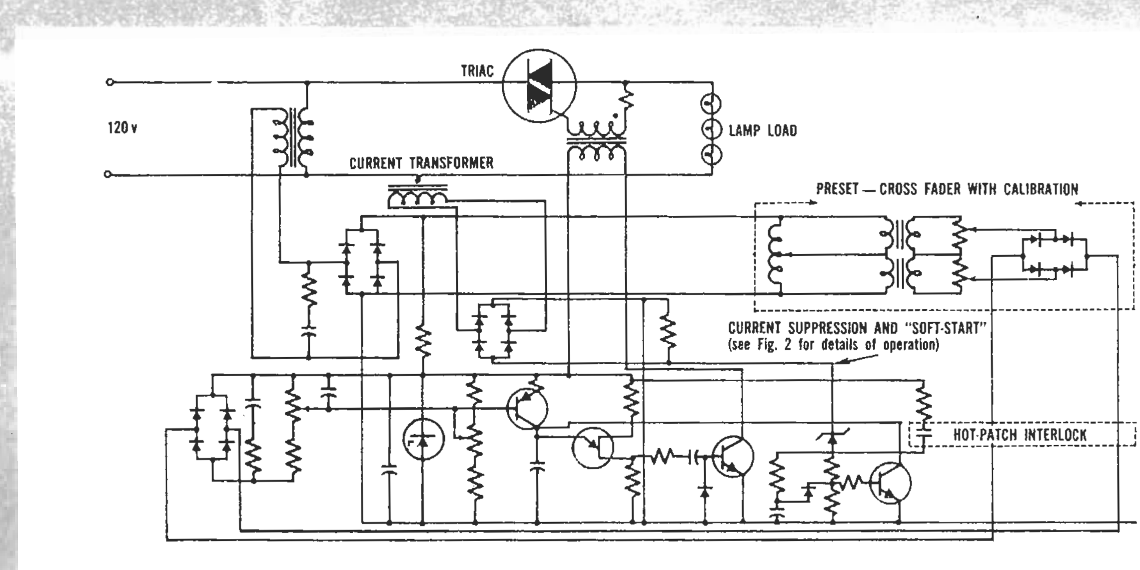
Transistor T1 and zener diode Z1 comprise the reference amplifier which establishes an error signal. If the measured quantity is greater than the reference, T2 will turn ON pulling the upper base of the UJT (unijunction transistor) to the regulated d-c line voltage. The zener diode across C1 is chosen so that it clamps the emitter of the UJT to a low enough voltage so that if the UJT upper base is at V1 the UJT cannot fire. Thus, regardless of what else is happening in the circuit, if the measured quantity is above the reference, the load current will be cut off when the UJT stops pulsing.

Examining the right side of the circuit, we see that the output of a small transformer (12 v output is suitable) is rectified and added to a zener voltage (Z4). The sum of these two voltages is compared to a reference zener (Z3). Should this sum exceed the reference level (indicating a line voltage far from crossover), transistors T5 and T3 are turned on pulling the upper base of the UJT to V1 and also preventing the UJT from firing.

Therefore, if the line voltage is considerably greater than zero or if the measured quantity exceeds the reference, no firing can take place.

On the other hand, if the measured quantity is low and the line voltage is near zero, the UJT will fire and supply power to the load. Values of R3 and C1 must be selected so that the pulse from the UJT will bridge the crossover from the declining edge of the sine wave to the increasing edge of the sine wave. This can be somewhat alleviated by connecting a small capacitor from the junction of R11 and D3 to the negative of V1.

Fig. 1. Power lamp dimmer and cross fader controls four 5-kw spot lights. Current-suppression circuit limits inrush currents.



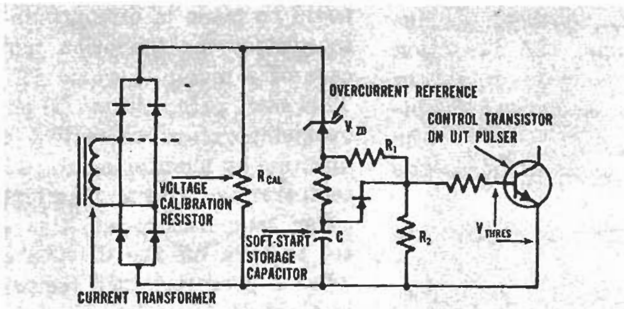


Fig. 2.

Fig. 2. The soft-start circuit. Here's how it works: When current $I_{primary}$ in current transformer satisfies

$$I_{primary} \times a \times R_{cal} \quad V_{ZD} - \left(\frac{V_{thres} \times R_1 - R_2}{R_2} \right)$$

where a = current transformer turns ratio, then the UJT control transistor begins to turn on — shunting the pulser capacitor in the UJT relaxation oscillator, reducing the pulse rate at the same rate as C charges. When the current transformer output decreases, C discharges through the base to the emitter of the control transistor delaying it from turning off and providing soft restoration of the full output to the lamps.

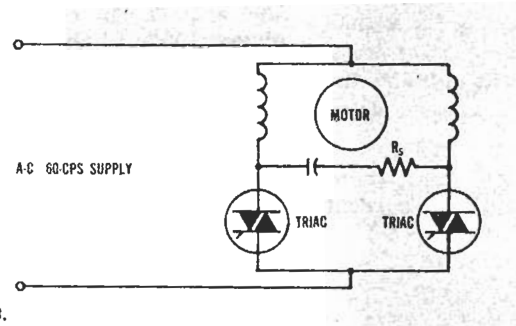


Fig. 3.

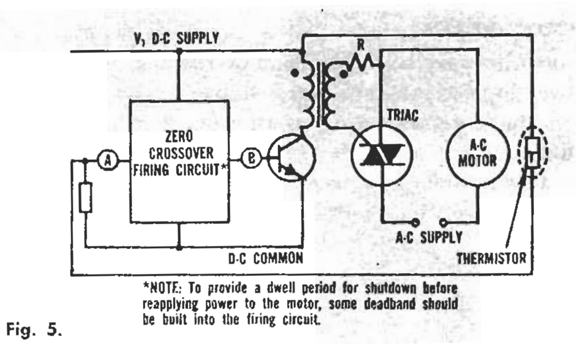


Fig. 5.

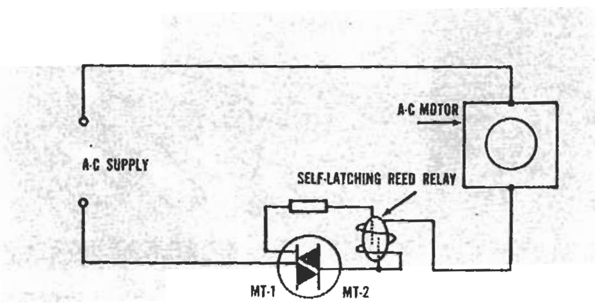


Fig. 4.

Fig. 3. Single-phase induction motor drive uses two triacs. With this circuit, the motor can be made to turn in either direction.

Fig. 4. Overcurrent protection for an induction motor is provided by this triac circuit. It can also be used for overtemperature protection.

Fig. 5. Overtemperature protection requires monitoring the winding temperature of the motor with a thermistor.

With the opposite gate bias polarity the device acts as a single pnpn controlled rectifier. Due to separation of conduction areas, the carriers of conduction in one direction do not influence the blocking capabilities of the device in the other direction. The 200AC power logic-triac has a guaranteed dv/dt capability of 20 v/μsec and a di/dt limit of 50 amp/μsec. Because of the epitaxial process and the ability to maintain good process control, all 200AC power logic-triacs may be turned on in either direction by overvoltage or high dv/dt without causing damage to the device (assuming no other ratings are exceeded).

A-C control applications

The logic-triac provides simple control of large amounts of a-c power and the selective gate characteristic enables control of d-c by simply reversing the gate bias. The following circuit description illustrates the a-c control characteristics of the logic-triac.

A power lamp dimmer and cross fader circuit is shown in Fig. 1. The power circuit consists of a single triac controlling four 5-kw spot lights. In this type of circuit, lamp inrush currents must be limited. Theoretically, inrush currents are limited only by the cold filament resistance of the lamps. Also, the line impedance may act as a limitation. These currents should be within the allowable peak current rating of the triac. This can be done by incorporating a current limit control (for soft start of the firing circuit) and a timed phase advance indicated by "A" in Fig. 1. In practice, the short time overcurrent capability of the triac should not visibly detain the lamp load starting, especially compared to older types of installations (magnetic amplifiers or motor-driven variable autotransformers).

The advantages of using the logic-triac as opposed to magnetic devices for lamp brilliance control are basically the same as for other applications. And the 8-oz logic-triac offers a considerable weight and size advantage over the many pounds of saturable reactors that would be needed to do the same job.

If some lamps are already operating on the dimmer and a cold lamp is suddenly connected into the load, the inrush current is superimposed on the existing steady-state load current. To protect the triac, the "soft-start" current should be activated (perhaps by an interlock on the "hot-patch" switch shown in Fig. 1). Details of the soft-start circuit are shown in Fig. 2.

When lamp filament resonance is a problem because of the steep wavefront presented by phase-control waveshapes, line inductive reactance can be inserted to reduce harmonics in the filaments. This inductance will also minimize inrush currents.

Motor drives

Another circuit application of the power logic-triac is in motor drives. It is made attractive by the unique single-control characteristic of the a-c power-control device. A single-phase induction motor reversing drive can be developed, for instance, by using two triacs as shown in Fig. 3. By properly phasing the signal with the line, the induction motor can be made to rotate in either direction. Because of the bidirectional characteristics of the triacs, both can be mounted on the same heat sink.

When size and reliability are paramount in a particular a-c motor-drive application, it is possible to drive a 10-hp motor using the 200AC logic-triac with no external means of limiting the inrush current to the motor. With external means of limiting this current, the 200AC power logic-triac can drive considerably larger motors.

If the motor current were monitored by a self-latching current relay (a reed switch relay would be ideal), the triac driving circuit could be made to discontinue firing to protect the induction motor in case of a motor overload (Fig. 4). This same principle can be used for overtemperature protection of the machine by monitoring the winding temperature. Use a thermistor or other temperature-sensitive device set to turn off the driving circuit when a predetermined temperature is reached (Fig. 5). Used in conjunction with zero crossover firing, this system can keep the triac on almost 100% of the time.

A list of potential applications for the logic-triac was presented earlier. This list will grow rapidly as engineers find new ways to solve their problems with this device. ⊕

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Controlling ac loads with C-MOS bilateral switches

by Arthur Johnson
Darlington, Md.

Power to an ac load can be efficiently controlled by an integrated complementary-MOS quad bilateral switch and a capacitively triggered sensitive-gate triac. The necessary gate-triggering current comes, not from the low-voltage C-MOS power supply, but from the ac line.

Capacitor-triggering is best for firing the triac because it produces the maximum current (at 90° phase shift) when the ac voltage crosses the zero-voltage level. Therefore, the fullest possible use is made of gate-triggering current. Also, the triac is switched into conduction at a low voltage to reduce switching transients, and maximum power is delivered to the load.

The driver circuit for ac loads is drawn in the diagram. Because the on-resistance of each C-MOS bilateral switch is several hundred ohms, circuit voltages could falsely trigger the triac. The triac gate therefore needs to be isolated by the series switch, which, in turn, needs to be protected in its nonconducting state by the shunt switch from possibly damaging high voltages.

Two power-supply voltages, +7.5 volts and -7.5 v, are needed to control both positive and negative ac voltage excursions. This may prove to be a minor inconvenience. But since the necessary gate-triggering current does not have to come from these supplies, they may be simple half-wave-rectified high-resistance sources.

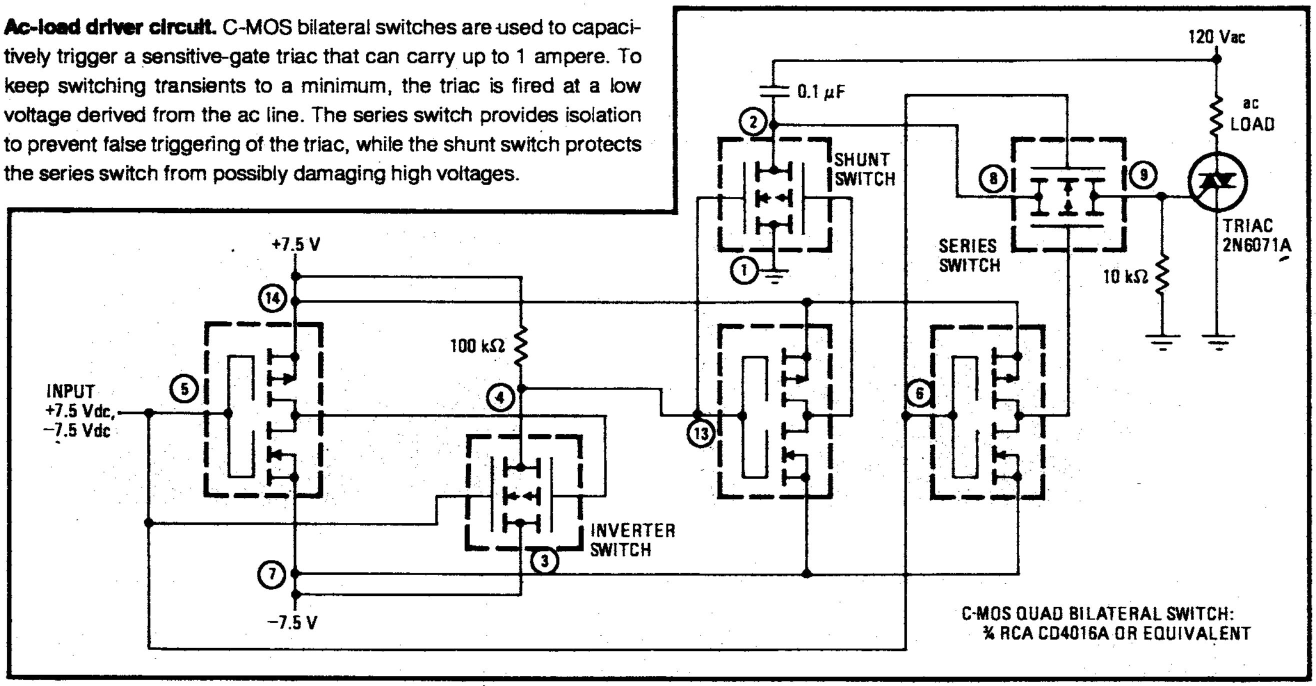
The sensitive-gate triac used here has a maximum current-carrying capacity of 1 ampere. If a larger load must be handled, a triac with higher ratings can be controlled by the smaller triac. In this way, a large load can be controlled without wasting a large amount of energy.

The capacitor value is chosen to provide the required triac-triggering current of 5 milliamperes maximum:

$$C = (5\ mA)/2\pi f E_{max}$$

where f is the ac frequency and e_{max} is the zero-to-peak ac voltage level. □

Ac-load driver circuit. C-MOS bilateral switches are used to capacitively trigger a sensitive-gate triac that can carry up to 1 ampere. To keep switching transients to a minimum, the triac is fired at a low voltage derived from the ac line. The series switch provides isolation to prevent false triggering of the triac, while the shunt switch protects the series switch from possibly damaging high voltages.



POWER LOGIC-TRIAC... the inside story

by John Gault, Project Manager, Research and Development

Introduction

An examination of the construction of International Rectifier's new power logic-triac might lead one to believe that except for a modification of the gating in one portion of the device, the logic-triac could be viewed as two anti-parallel silicon controlled rectifiers constructed in one wafer of silicon. This similarity is illustrated by Figure 1(a), a block diagram of two SCR's connected in anti-parallel, and Figure 1(b), a block diagram of a logic-triac. If the gating on the right hand SCR were changed and the control PNP regions connected as illustrated in Figure 1(c) the similarity would be complete.

Gating

As might be expected, the gating characteristics of the logic-triac are different from those of the anti-parallel SCR's. For the anti-parallel SCR's, a gate signal is applied between Gate 1 and Terminal 1 when Terminal 1 is negative, and between Gate 2 and Terminal 2 when Terminal 2 is negative. This method of operation requires two separate gate circuits.

In the logic-triac, Gate 1 and Gate 2 are connected together and operated from a single gate circuit connected between the gates and Terminal 1. The easiest firing mode for AC control is achieved by biasing the gates positive when Terminal 1 is negative, and negative when Terminal 1 is positive. Triggering for AC control is also possible with negative bias on the gates during both half cycles. For DC control, a positive bias will result in an operation similar to an SCR. This type of operation was made possible by a design in which a positive gate bias will not fire the device when Terminal 1 is positive.

When Terminal 1 is negative, triggering takes place in the same manner as in an SCR. The positive bias at Gate 1 with respect to the top N type cathode, causes injection of electrons from this cathode into the P type region as shown in Figure 2. A large percentage of these injected electrons are collected by junction J-2 which is reversed biased. This collector current in turn induces a forward bias across junction J-3 which results in injection of holes into the central N type region. Some of these holes recombine with electrons but a small percentage of them are collected by reverse biased junction J-2. This hole injection occurs over a larger area of junction J-3 than the area of the initial electron injection from J-1. The ratio of the areas is a function of the diffusion length of electrons in the upper P region and the resistivity of the central N region.

The collected holes induce an additional injection of electrons from J-1 over an even larger area than the hole injection area. This counter injection continues until the entire area under the upper N type region or cathode is conducting and the reverse bias across J-2 has collapsed. Although the counter injection has been described as a stepwise process, since collection is not an abrupt occurrance, the growth of the conduction area is a fairly smooth continuous process.

Since Terminal 1 is also connected to the upper P type region some shunting of the gate signal will occur. This shunt current is, however, minimized by judicious placement of Gate 1. The same type of shunting occurs in an SCR with a shorted emitter construction.

As shown in Figure 3 when Terminal 1 is positive, a negative bias on Gate 2 will cause injection from the N type gate region. Many of these injected electrons will recombine with holes. This current can be considered to be as a parasitic diode current between Gate 2 and Terminal 1 since it has no useful function. Some of the injected electrons, however, will be collected by J-2 in the vicinity of

COVER

The environmental oven shown on the cover has been modified to use IR's 200 Amp logic-triac in a three phase A.C. power control system.

A variety of applications has been developed in the past as designers applied the attributes of new semiconductors to their circuitry. The power triac will undoubtedly nurture the development of circuits which have never before been technically or economically achievable. The list of applications is expected to grow as the more aggressive manufacturers begin designing the power triac into the end product.

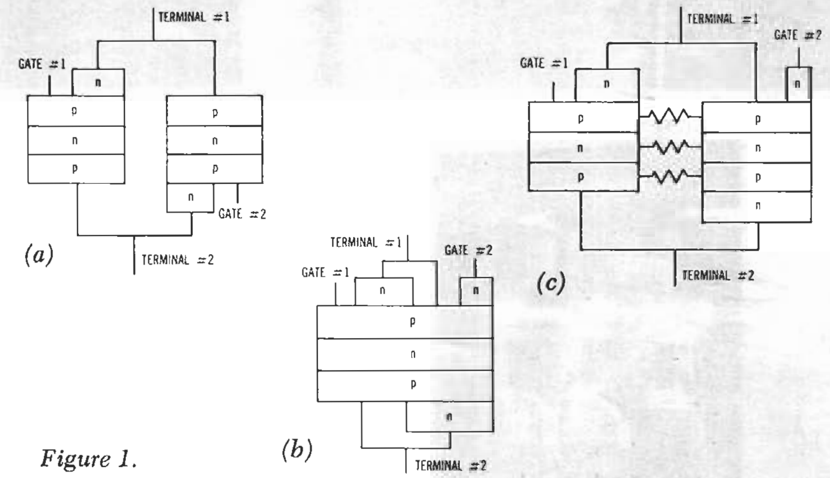


Figure 1.

Gate 2 and cause J-2 to become forward biased. Since Terminal 1 is positive with respect to Gate 2, J-2 at point (1) will have a greater forward bias than at point (2). This forward bias will cause an injection of holes primarily at point (1) into the central N type region. Some of these injected holes will be collected by junction J-3 which is now reversed biased. This will induce injection of electrons from J-4 into the lower P type region which in turn will be collected by J-3. Here again the counter injection will continue until the entire area over the lower N type region or cathode is turned on.

As long as the current through the device is maintained above a certain minimum level (holding current) this positive feedback will continue and the device will continue to conduct.

Turn-Off Time

Except for gating, the logic-triac is a symmetric device. The turn-off mechanism, when the device has been conducting in one direction is virtually the same as turn-off in the other direction.

Consider the case depicted in Figure 4 where Terminal 1 is negative with respect to Terminal 2 and the left hand portion of the device is conducting. Region P-1 and region N-2 in the left hand portion are flooded with minority carriers. Majority carriers are not shown.

When the polarity of the device is reversed some of these minority carriers will recombine with majority carriers and most of the others will be collected by junctions J-1 and J-3. The collection of these stored minority carriers results in the reverse recovery current. This current causes the injection of additional minority carriers from junction J-2. Both electrons are injected into P-1 and holes are injected into N-2 by junction J-2. The primary effect is the injection of holes into N-2. This additional injection prolongs the recovery process but since the α of the P-1, N-2, P-2 section is quite low at these current densities only a small percentage of them ever reach J-3.

If a sufficient number of holes are collected at section R of J-3 to induce injection of electrons by J-4 into P-2 section R (See Figure 5) the device will turn on. This can only occur if a large number of holes have diffused into section R from section L of N-2 or if a sufficient number of holes are injected into section R of N-2 by J-2 during the recovery phase of section L.

This problem is minimized by constructing the device with a horizontal separation between N-1 and N-3 of several minority carrier diffusion lengths and obtaining a high enough sheet resistance of N-2 to minimize injection of carriers from J-2 into section R of N-2.

The development of International Rectifier's new 200 ampere power logic-triac is the result of the continuous research effort at IR, in order to provide engineers with the design tools necessary for our industry.

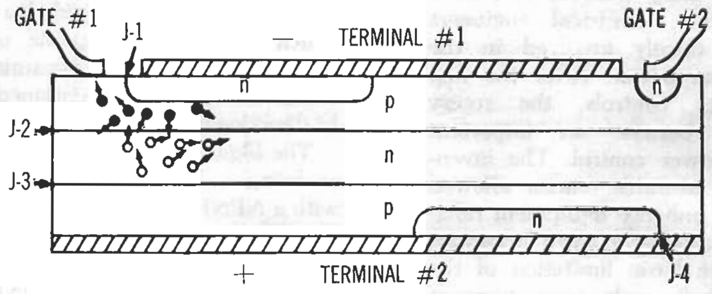


Figure 2.

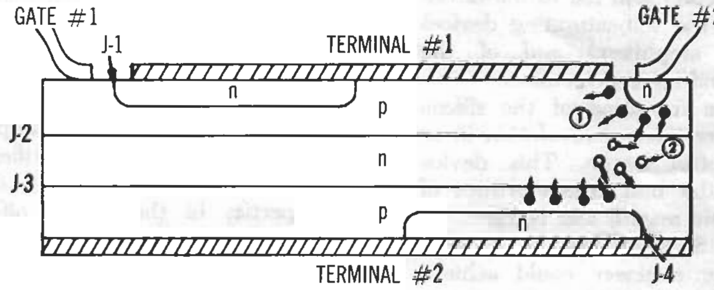


Figure 3.

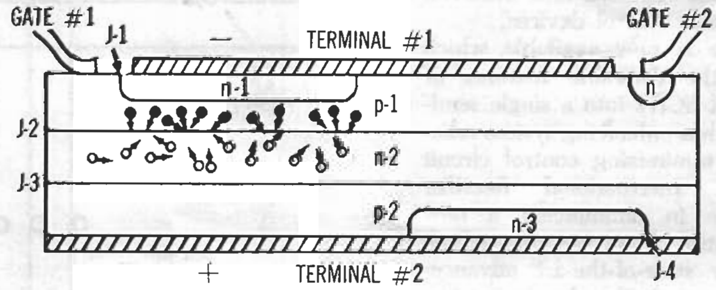


Figure 4.

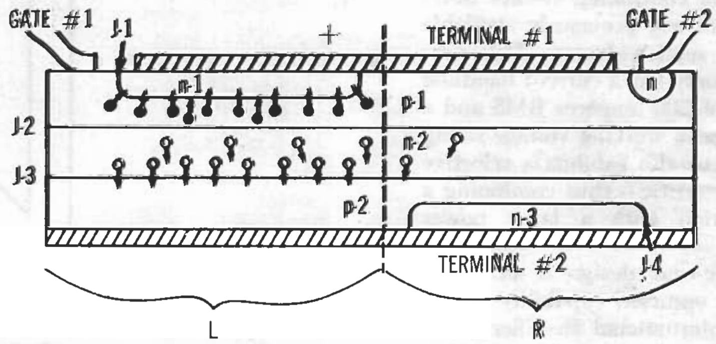


Figure 5.

AC & DC POWER CONTROL with a single semiconductor

by Dave Cooper
Manager, Special Projects Engineering

Since the early work of Heaviside and Steinmetz, electrical engineers have been deeply involved in the control of ac power. After the first potentiometer controls, the rotory transformer became an important means of power control. The invention of the saturable reactor allowed designers to enhance equipment reliability and improve control accuracy. However the basic limitation of the device to half cycle time response limited the figure of merit (gain-time constant factor) and led to the development of the self-saturating devices (magnetic amplifiers) and of the thyration and ignitron rectifiers.

With the invention of the silicon controlled rectifier, a revolution in ac power control began. This device combined the best characteristics of the saturable reactor and rectifier. By using two SCR's connected in anti-parallel the engineer could achieve control of large amounts of ac power with a figure of merit orders of magnitude greater than the best achieved with magnetic control devices.

A device is now available which combines the desirable features of anti-parallel SCR's into a single semiconductor thus enhancing system reliability and minimizing control circuit complexity. International Rectifier takes pride in announcing a new power control semiconductor which is a major state-of-the-art advancement in ac control — the logic-triac. The International Rectifier logic-triac is capable of controlling twenty times the power of any previously available ac control semiconductor. This new device not only has a current handling capability of 200 amperes RMS and a maximum peak working voltage rating of 1000V but also exhibits a selective gate characteristic — thus combining a logic function with a large power capability.

The logic-triac design is an extension of the epitaxial capability developed by International Rectifier in its power SCR technology. The stability of the device has been established by extensive blocking life tests at elevated temperatures, considerably above the maximum specified operating temperature. The epitaxial structure with no area overlap has yielded a device which is not only capable of long term stability but has dynamic properties never before combined in a bi-directional thyristor.

The logic-triac can be characterized as being a PNPN device in parallel with a NPNP device — both being triggered from a single source. By applying a positive gate signal with respect to main terminal one, the device will only conduct with main terminal two positive and main terminal one negative. By applying a negative gate signal with respect to main terminal one the device will conduct with either polarity of main terminal voltage.

With the large area control provided by the International Rectifier logic-triac design, the excellent dynamic properties of the device offer considerable flexibility to the circuit designer. The IR device (200AC100, 200AC80, 200AC60 and 200AC40) has an allowable di/dt of 50 amperes per microsecond and a guaranteed dv/dt of 20 volts per microsecond.

Control of almost 140 kw of ac power is now attainable with a single semiconductor. In order to illustrate the inherent advantages of the logic-triac to the Circuit Designer we will examine a few applications of the device.

A.C. Motor Control

For years the control of ac motors has been a major challenge to engineers. With the announcement of the International Rectifier logic-triac, a powerful new tool is available to circuit designers.

Speed control of dc motors has long been possible with a variety of control devices. The cumbersome proportions of the dc motor, its high control losses and required periodic maintenance have served as an incentive in the search for better and more versatile methods of ac motor speed control. With the advent of controlled

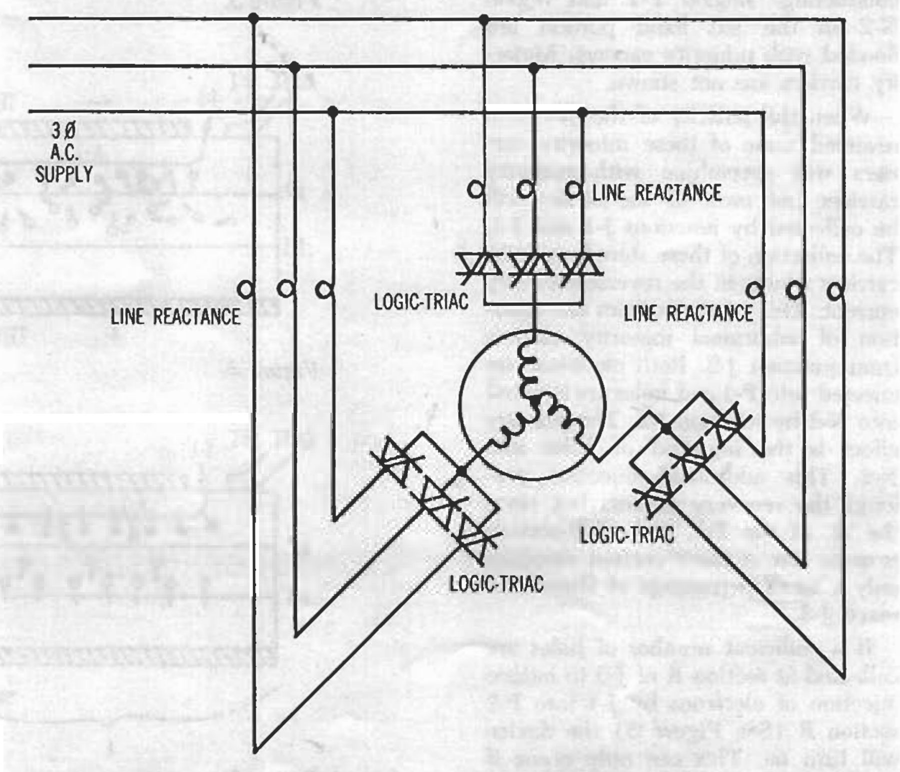


Figure 1. Triac Cycloconverter.

power tubes, new circuits were devised to provide controlled variable frequency for excitation of induction machines. Inverters were constructed with good characteristics but had extremely limited frequency range due to the response limitations of the tubes. Cycloconverters were devised which provided means of obtaining variable ratio frequency changers, but when using power tubes they were somewhat inefficient and required large amounts of control power. Methods were also devised to vary the effective resistance between slip rings of the three phase motor thus altering the effective slip of the machine to achieve a degree of speed control. All of these techniques have yielded successful controls for various applications in industry. Two SCR's connected in anti-parallel have been applied with a great degree of success to many of these circuits. With the availability of a high-power logic-triac, a new era of ac speed control system simplification is at hand.

Consider the cycloconverter of Figure 1. The circuit diagram shown using 9 triacs rather than the 18 SCR's normally required in this circuit presents a clear picture through use of this new power control device. This system could be mounted on three heat sinks with no interface insulation necessary. Under the same conditions, an SCR system would require 12 heat sinks.

As previously mentioned, another method of speed control for a three phase machine is achieved by means of varying the effective resistance between slip rings.

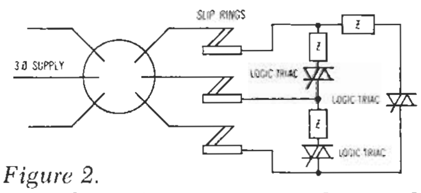


Figure 2.
Three Phase Motor Speed Control.

As shown in Figure 2, this can be implimented by properly phase controlling 3 logic-triacs rather than by use of anti-parallel SCR's and a similar savings in driving circuitry as well as heat sinks can be achieved as in the case of the cycloconverter.

It is sometimes desirable to periodically cause reversal of induction motors in drive systems. This has previously been done by means of ac contactors or by controlling two sets of anti-parallel SCR's. Using the logic-triac as shown in Figure 3, a 20 h.p. motor can be driven without any special precautions for surge protection. The system can be constructed using only one heat sink and two triacs, rather than the three heat sinks and four SCR's previously required.

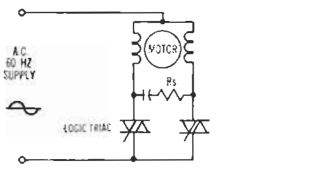


Figure 3.
Induction Motor Reversing Drive.

The circuit shown in Figure 4 is ideal for use as an automatic starter for a single phase ac motor. Up to the present time, the circuit has been restricted to a small ac motor application. With the 200 ampere International Rectifier logic-triac, this system has far greater potential and becomes economically feasible in many more applications.

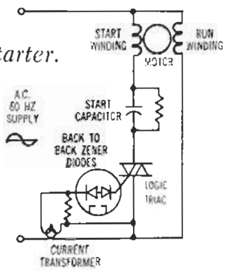


Figure 4.
Static Motor Starter.

Phase control has long been a powerful tool in the design of control equipment. However, the steep wave fronts generated by ordinary phase control, propagate system electrical noise, radio frequency interference (r.f.i.) and power systems line voltage disturbance. The technique of firing the power control semiconductors at near zero supply voltage virtually elimininates these disturbances. Stress levels of insulation in machines or transformers driven by control systems utilizing this technique are greatly reduced. This is known as pulse burst modulation or zero cross-over firing (See Appendix I). The resulting wave shapes of this control technique are illustrated in Figure 5.

By gating the logic-triac in the various ways shown by these waves shapes, the three types of logic-triac control can be explained. In the first full cycle shown, the logic-triac is first driven by a bi-directional gate signal and made to conduct in each direction successively; thus conducting the full supply to the load. In the second cycle of supply voltage shown in Figure 5 the logic-triac is gated positive with respect to main terminal one and conducts in only one direction, thus providing half-wave control to the load. The logic-triac will not conduct if the main terminal two (MT2) voltage is negative with respect to main terminal one (MT1) and if the gate signal is positive with respect to MT1. The third cycle shown of the supply voltage is controlled by a uni-directional gate signal to the logic-triac which is

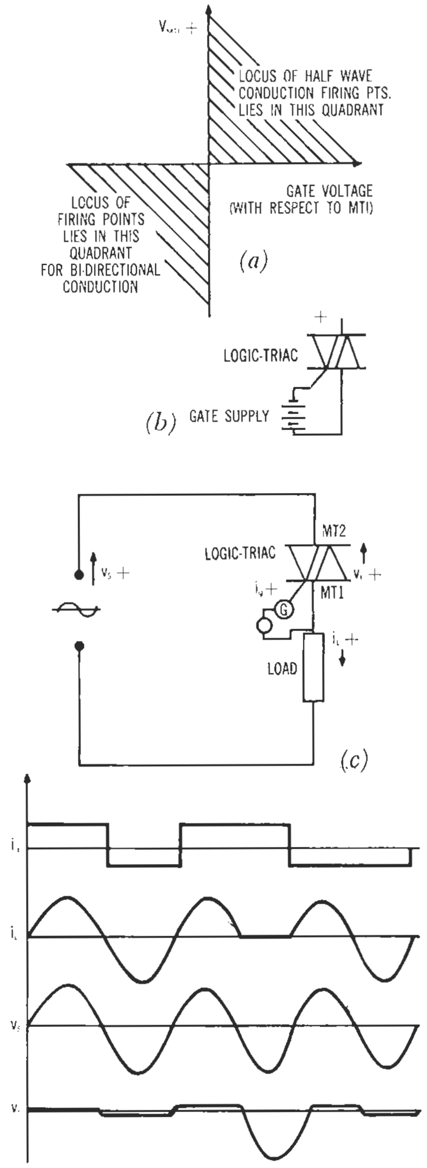


Figure 5. Power Triac Gate Firing

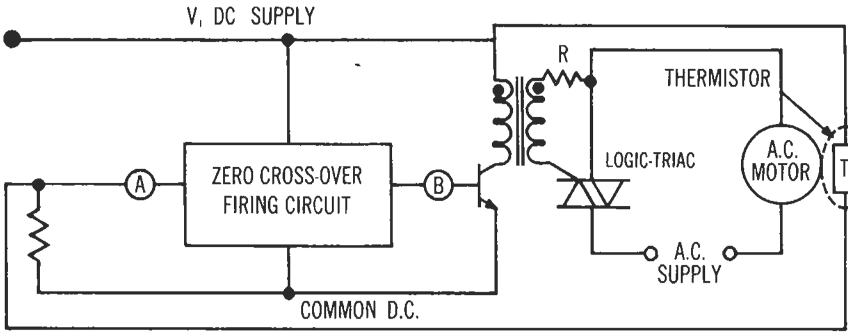


Figure 6. Over Temperature Protection

negative to the gate with respect to MT1 of the device. These versatile control characteristics of the logic-triac will simplify control design and provide considerable latitude to the circuit designer.

Utilizing this zero cross-over technique in ac motor circuits, yields some interesting applications for the logic-triac. For instance, shown in Figure 6 is a combination for over temperature protection of a single phase motor without use of electromechanical devices. With a thermistor located in proximity with the motor windings, the circuit can be designed to stop pulsing the logic-triac at a predetermined temperature and with some dead band designed into the system, the power will be removed from the machine until the temperature is considerably reduced.

A system for over current protection of an ac machine is illustrated

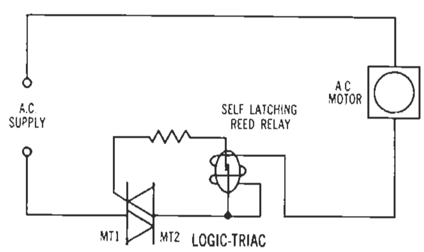


Figure 7. Over Current Protection

in Figure 7. By using a latching reed relay, activated by the motor current, the logic-triac can be made to turn off when the motor current becomes excessive. With the overload capabilities of the 200AC logic-triac and its 200 ampere steady state rating, some sizable motors can be protected with simplicity and reliability.

Heating Controls

Although individual room control of electric power in the home has become increasingly popular, the advantages of central forced air heating are often desirable. In many areas — with long periods of extreme cold — the advantage of a central heating system through which the air in the home is circulated, filtered and humidified are undeniable. The availability of a logic-triac operating on a 220V line and carrying 200 amperes makes a simple, reliable central heating system possible. When used in conjunction with pulse burst modulation, the system can be designed without the r.f.i. resulting from ordinary phase control or electro-mechanical control. In figure 8 a typical circuit for a heating system is shown, requiring no relays, contactors, or thermostat contacts. A temperature sensitive resistor can be used as the sensor and a potentiometer as the control. This design has advantages of extreme accuracy, with a temperature error of less than 1°F. By eliminating the temperature sensor in the drive circuit, this same principle can be applied to welding equipment which may be operated manually or automatically.

The fan used in a forced air heating system can be controlled in this same manner. By reversing the positions of the thermostat (potentiometer) and temperature sensor (negative temperature coefficient resistor) shown in Figure 8 and locating the resistor near the heat source, the fan can be turned on (as shown in figure 9) when the air becomes warm enough to circulate. This technique serves equally well in industrial heating and other fan control applications.

Lighting Circuit Applications

Another very active area for appli-

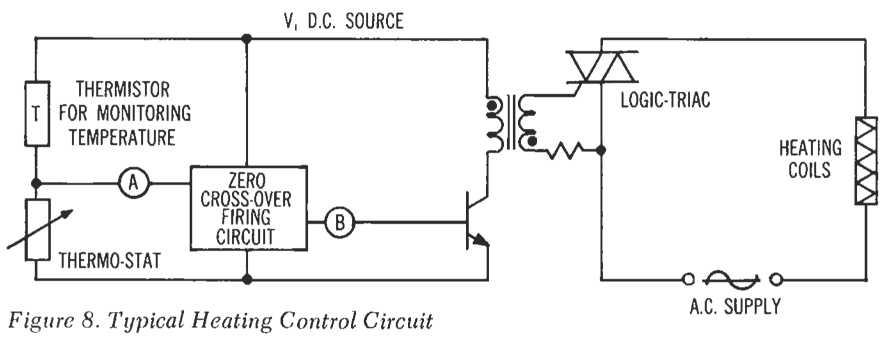


Figure 8. Typical Heating Control Circuit

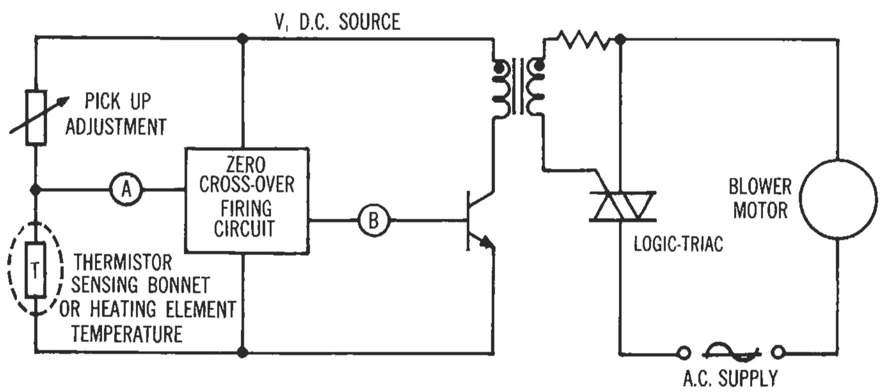


Figure 9. Typical Blower Fan Control

cation of ac static control is in various types of lighting systems. By phase controlling the logic-triac, the light intensity of banks of incandescent lamps can be adjusted with a single device. Thus, large theater light dimming systems can be greatly simplified by using a single logic-triac rather than anti-parallel SCR's. In figure 10, a

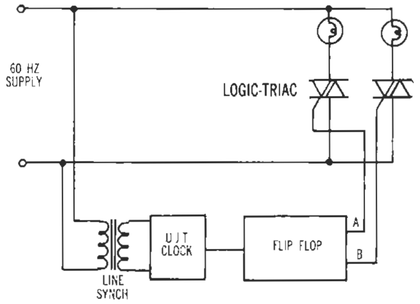


Figure 10. Light Flasher.

configuration for a light flasher is shown requiring two logic-triacs and one heat sink rather than the four SCR's and three heat sinks previously required.

When motor loads are switched on to an ac line which is also supplying fluorescent lamps – there is often a visible flicker in the lamps due to the surge loading of the line. This can often be objectionable especially when the motor starting is frequent. For example, compressor motors are often required to start frequently and run a relatively short time. One method of minimizing the effect of such flicker is by automatically correcting the line voltage during high surge currents. This is done by inserting a section of step up transformer to boost the line voltage temporarily until the surge disappears.

The logic-triac is an excellent device for this purpose because of the simplicity of the driving function and ease of heat sinking. A tap change similar to that shown in Figure 11 can

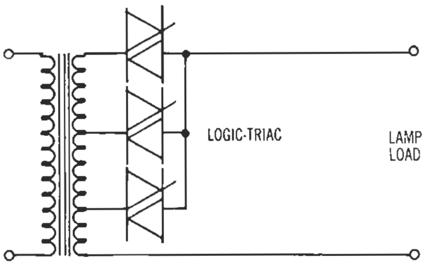


Figure 11. Static Tap Changer for Discrete Load Steps.

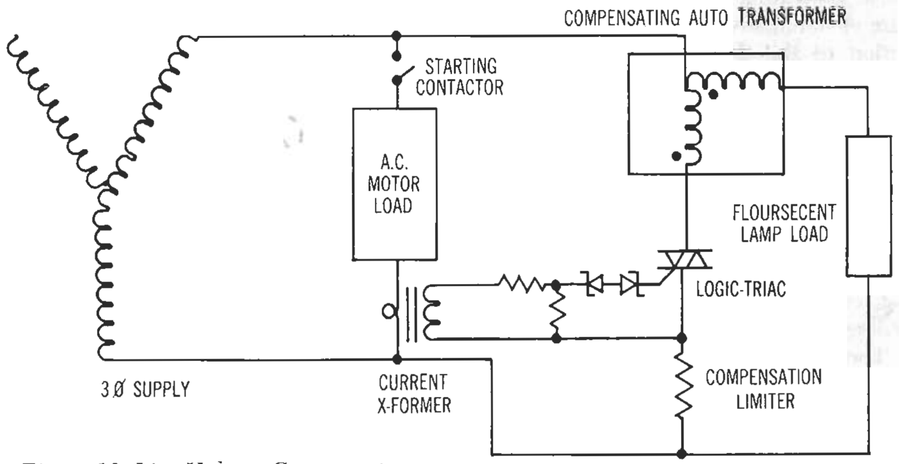


Figure 12. Line Voltage Compensator.

be used as a line compensator. Line compensation can also be accomplished by using a logic-triac and a current transformer as shown in Figure 12. As the starting contactor, in series with the motor load, is closed, the motor surge current begins to flow. This current is generally three to six times the running current of the machine. The surge causes a voltage drop on the line inductance and transient inductance of the supply alternator which causes the line voltage, as seen by the fluorescent lamps, to drop. If the surge current is sensed by a current transformer as shown in Figure 12 and caused to fire the logic-triac into a compensating auto-transformer, the flicker resulting from motor starting can be greatly minimized.

The degree of compensation can be adjusted by the resistor in series with the logic-triac, while the surge current at which compensation takes place can be changed by adjusting the resistor divider across the secondary of the current transformer. By utilizing this circuit across each line, the three phase system can be automatically compensated.

High Current DC or AC Supplies

In the electro chemical industry, power supply outputs range into hundreds of killowatts at extremely high currents but often at quite low voltages. System cost generally dictates use of a multi-phase step down transformer with rectified output and phase controlled input. Many rectifier-transformer configurations are useful depending upon the load requirements and the power source available. Some transformer control arrangements are shown in Figures 13, 14 and 15.

AC control, on the primary of the transformer, yields worthwhile savings in semiconductor cost and system efficiency. Use of the logic-triac for this application is ideal from the standpoint of control circuit simplification and reduction in the number of heat sinks. The circuit of Figure 13

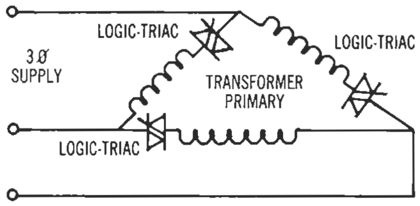


Figure 13. Delta Connected Transformer Phase Control

is attractive from the standpoint of semiconductor rating but requires careful volt-second balance to avoid high circulating currents. In all cases, load short circuits can cause semiconductor damage unless sufficient limiting inductance is provided somewhere in the system. It is often wise to provide some sort of system in the primary side of the transformer to

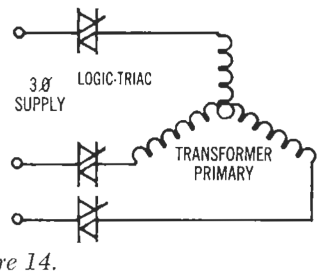


Figure 14. Y Connected Transformer Line Control

sense individual logic-triac current in case of unbalance and apply corrective action to the driving circuits.

The circuits shown provide an introduction to the many applications of the logic-triac to ac control. These controls have applications in many industries such as elevator drives, mill drives, electric transmission for rapid transit vehicles, large earth moving equipment, ac welding machines, plating, chemical process control, oil well drilling equipment, etc.

The ac control story for the International Rectifier logic-triac is certainly

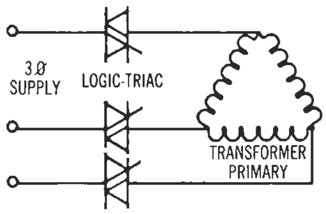


Figure 15. Delta Connected Transformer Line Control

the most logical to be written first, but can be considered only the first chapter in what is sure to be a long and valuable series of applications. The device can be utilized for instance in D.C. choppers, inverters, no break

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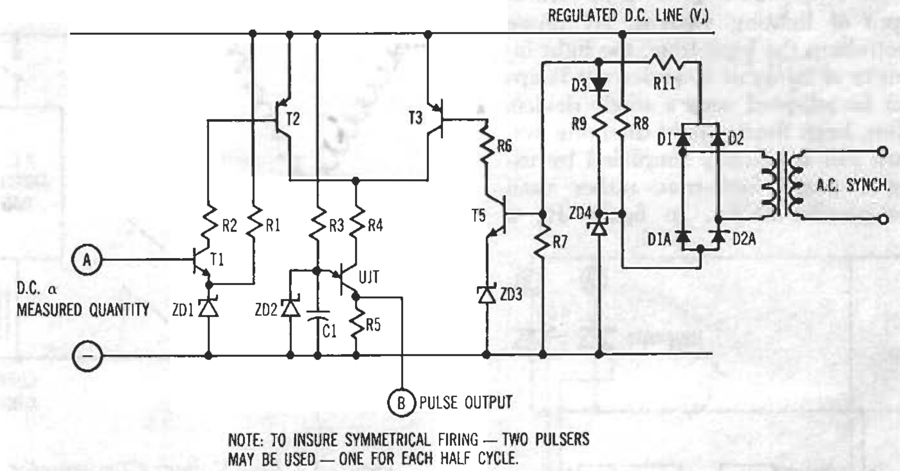

Figure I-A. Driving Circuit

power supplies and numerous other systems.

APPENDIX I
Zero Cross-over Firing

A brief explanation of type of zero cross-over driving circuit follows: (See Figure I-A)

Transistor T1 and zener diode ZDI comprise the reference amplifier which establishes an error signal. If the measured quantity is greater than the reference, T2 will turn on, pulling the upper base of the UJT to the regulated D.C. line voltage. The zener diode across C_1 is chosen so that it clamps the emitter of the UJT to a low enough voltage so that if the UJT upper base is at V_1 the UJT cannot fire. Thus, regardless of what else is happening in the circuit, if the measured quantity is above the reference, the load current will be cut off by virtue of the cessation of UJT pulsing.

Now examining the right side of the circuit, we see that the output of a small transformer (12v output is suitable) is rectified and added to a zener voltage (ZD4), the sum of which is compared to a reference zener (ZD3). Should this sum exceed the reference level (indicating a line voltage far from cross-over) the transistors T5 and T3 are turned on pulling the upper base of the UJT to V_1 and also preventing the UJT from firing.

We can see then that if either the line voltage is considerably greater than zero or if the measured quantity exceeds the reference, no firing can take place.

If on the other hand the measured quantity is low and the line voltage is near zero, the UJT will fire and supply power to the load. Caution should be exercised in choosing the values of R3 and C1 so that the pulse from the UJT will bridge the cross-over from the declining edge of the sine wave to the increasing edge of the sine wave. This can be somewhat alleviated by connecting a small capacitor from the junction of R11 and D3 to the negative V_1.

Triacs Bid for Ac Power Control

With the ability to handle hundreds of amperes, bidirectional thyristors are moving speedily into the high-power areas of heating, lighting, and motor control.

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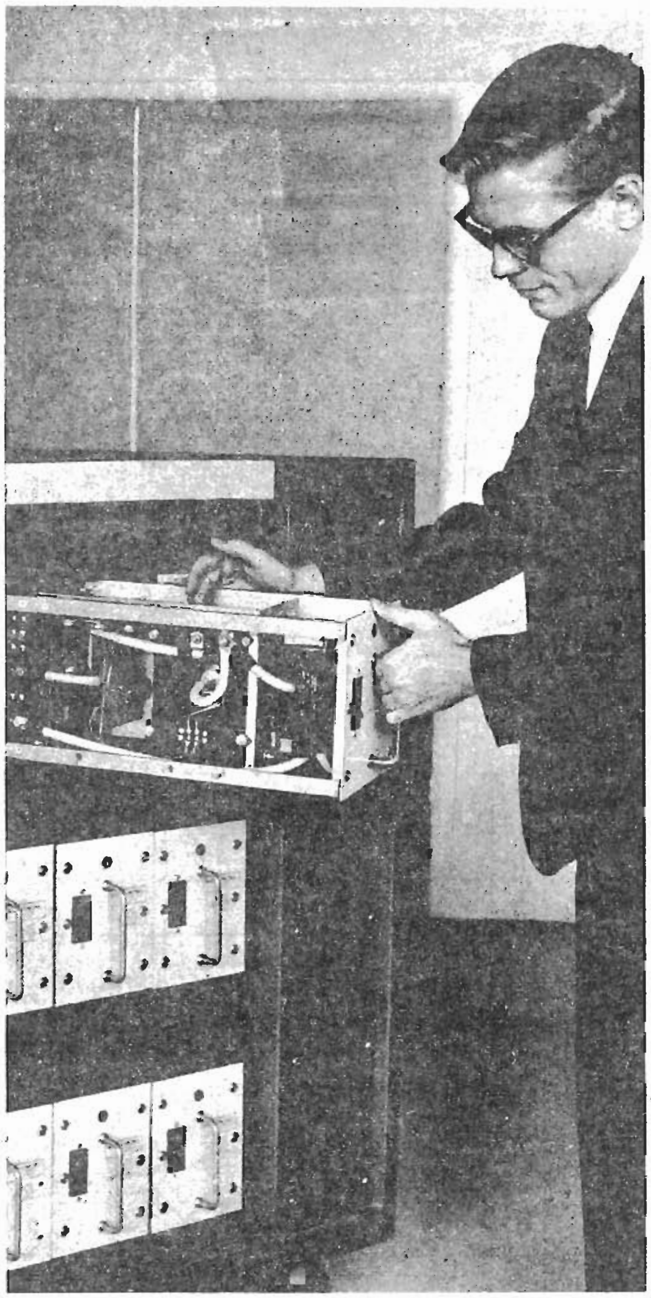
• Only a little more than ten years after its introduction, the thyristor is now firmly established as the key to smooth, efficient control of large power loads. The growing family of thyristor devices, which includes the unidirectional silicon controlled rectifier (SCR) and the bidirectional triac, provides the industrial equipment designer with all the inherent advantages of solid-state technology—reliability, relatively low cost, and design flexibility.

With the advent of the SCR and its low on-state voltage drop, high power gain, and fast switching response, static control of large dc power loads rapidly became a wide-spread, well developed technique. Solid-state control of large amounts of ac power, however, did not progress as rapidly, because of some limitations of SCR's when pressed into ac service.

It is possible to connect two SCR's in antiparallel for bidirectional current control, and indeed this has been successfully applied to heating, lighting, and induction-motor control, but the method has some disadvantages. Unlike conventional power rectifiers, power SCR's are generally available with only one polarity—that is, the device cathode is common to the stud mount of the case. Thus, for SCR's to be connected in antiparallel, each device must be provided with its own heat sink, or alternatively, an electrical insulator must be placed between one of the devices and the heat sink to preserve the electrical integrity of both devices.

The required insulator must also be a good thermal conductor to allow heat dissipated by the semiconductor to flow to the heat sink. Interface materials like mica, beryllium oxide, and boron nitride, which are commonly used for this purpose, display acceptable thermal and electrical characteristics, but are generally expensive or difficult to work with in equipment manufacture.

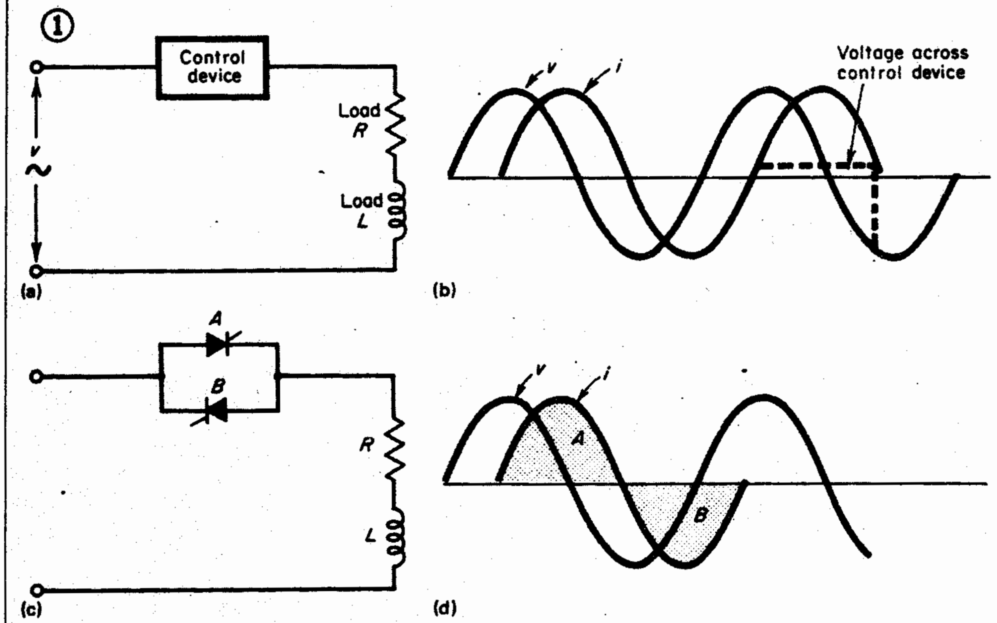


Heart of this lighting control system designed by Sicodim Inc. for theaters and television studios is a 200-ampere logic triac.

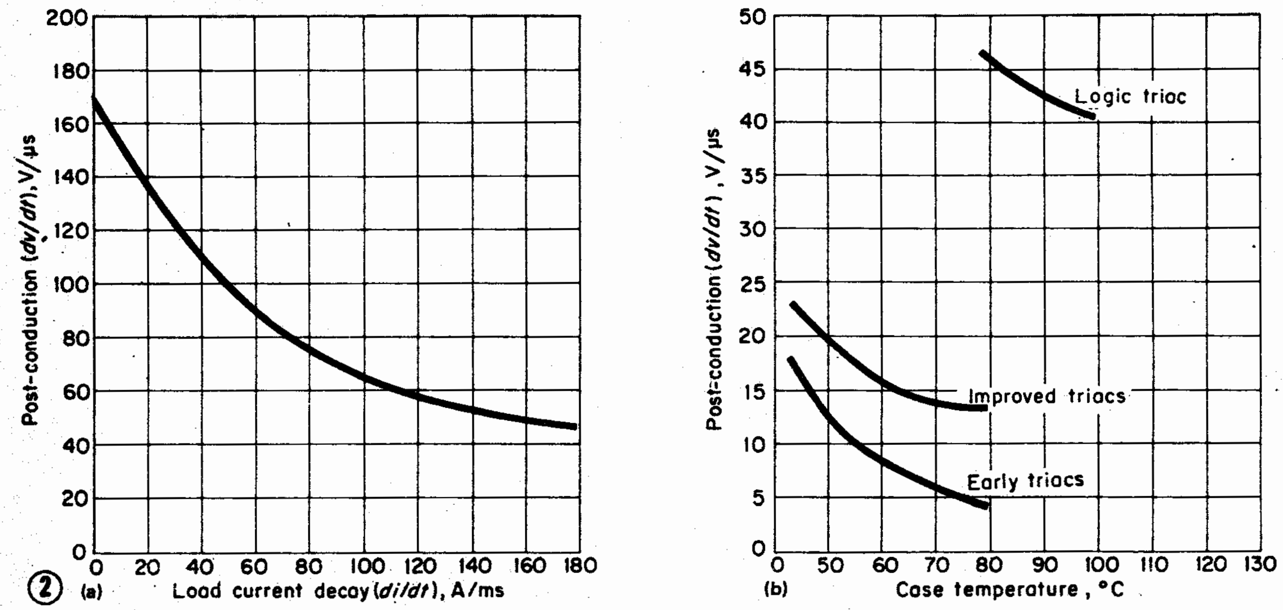
Fortunately, advances in semiconductor technology and device fabrication have now been able to overcome these limitations. With epitaxial deposition, shorted-emitter construction, surface contouring, and multigate geometry, it is possible to provide the function of an antiparallel combination of SCR's on a single semiconductor wafer. Thus, the triac was born.

Critical Parameters

The triac promised substantial simplification of ac control, but early triacs were limited by their construction in their ability to handle high power. To understand why, consider a case in which an ac load with a lagging power factor must be controlled. A simple

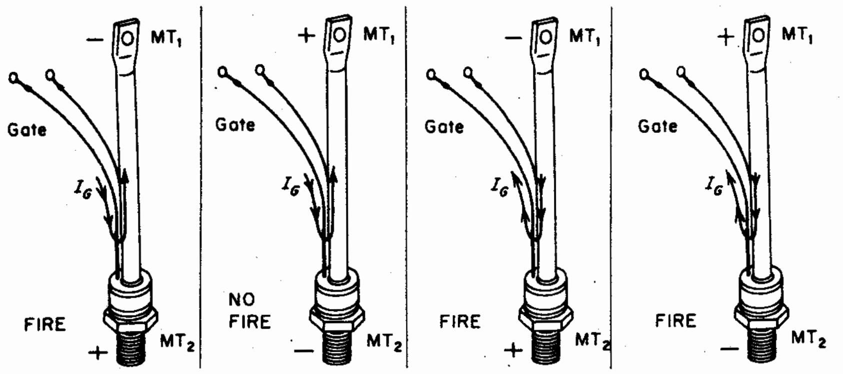


Lagging power factor of load is typical of thyristor applications. Simple control circuit (a) produces waveforms represented in (b). If SCR's in anti-parallel are used for control as in (c), shaded sections of waveform (d) represent conducting half-cycles of the devices.

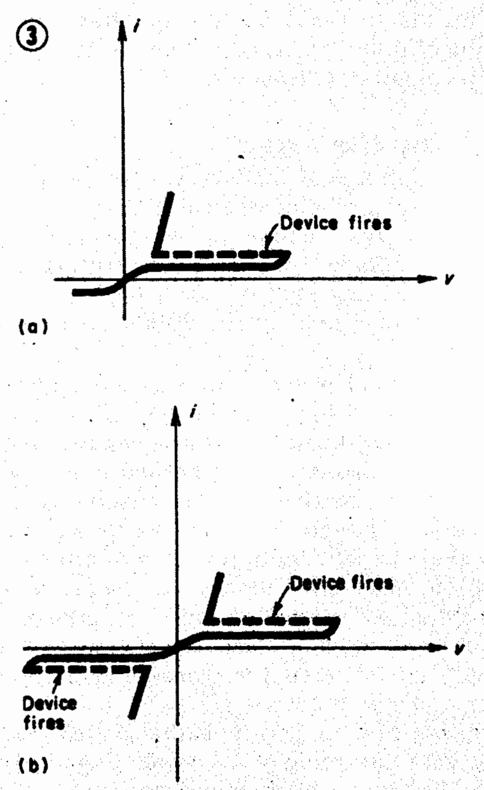


Charts indicate limitations of first-generation triac family. In (a), plotted at junction temperature of 105°C, the devices are seen to be sensitive to rapid changes in load current. Chart (b) shows evolution of triac design to point where available devices can withstand much higher *dv/dt* stress at elevated temperatures.

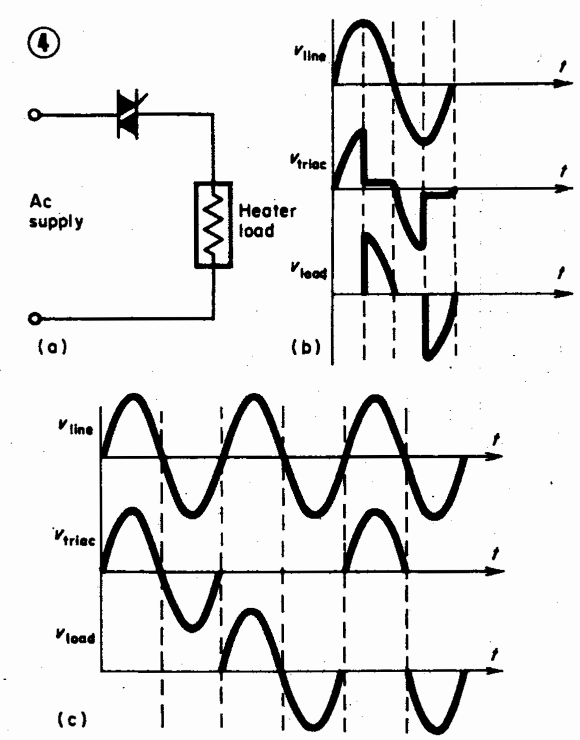
THREE WAYS TO FIRE THE LOGIC TRIAC



The selective gating characteristic of the logic triac provides flexibility in the control of ac power loads. By changing relative polarities of the gate and main terminal (MT) voltages, several firing or blocking modes are possible with a single trigger source. The gates can be connected together and operated from a single trigger circuit connected between them and MT_1. When there is a positive gate bias with respect to MT_2, the device is in a blocking condition. When MT_2 is positive with respect to MT_1, either polarity of gate bias will fire the triac. If a gate signal that is negative with respect to MT_1 is applied, the device will conduct with either polarity of MT voltage.



Triac gating characteristic resembles combination of gating characteristic of single SCR (a) with its mirror image (b).



Conventional phase control of ac heater loads (a) can produce radio-frequency interference due to rapid changes in current (b). Zero-crossover firing (c) produces smoother current transitions, reduces rfi.

circuit for this purpose is shown in Fig. 1(a) with the associated waveforms of the voltage and current [Fig. 1(b)].

For control purposes, let's insert into the circuit a device (like a thyristor) capable of interrupting current flow at the beginning of any half-cycle. The device must hold off or block the supply voltage instantaneously when the load current passes through zero. In an inductive circuit, this condition results in the application of a blocking voltage with a very high rate of rise. If the control device is a pair of SCR's connected in antiparallel [designated *A* and *B* in Fig. 1(c)], the respective conducting half-cycles of each device are related as indicated by the shaded portions of the waveform [Fig. 1(d)]. Suppose SCR *A* is conducting; when the current through it reaches zero, a certain amount of supply voltage exists which appears as a forward voltage across SCR *B*. The rate of change of this voltage can be very high, depending on the amount of inductance in the load. It can cause a device to conduct in the forward direction even though the gate has not been signaled.

The ability of an SCR to withstand such a rate of forward applied voltage is called its critical *dv/dt* rating. If antiparallel SCR's are used, each device has a full half-cycle for recombination of the carriers before it is required to block the forward voltage. With a triac, however, the problem is greatly magnified by the fact that the carriers required for conduction in either direction can interact within the same structure and interfere with the ability of the device to block.

Early triacs featured a coaxial construction which failed to provide the necessary carrier isolation, and thus were greatly limited in their power-handling capability. Typical plots of postconduction *dv/dt* as functions of the rate of decline of forward current and temperature are shown in Fig. 2.

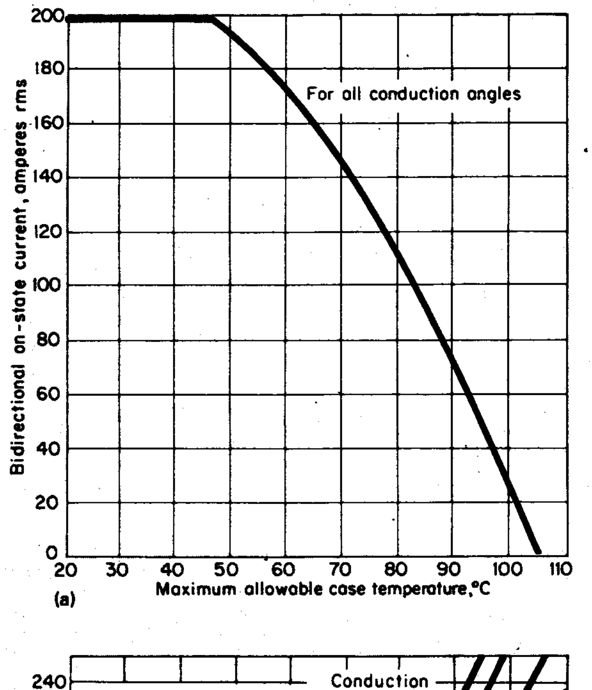
Recent device technology has been brought to bear on this problem, and the result has been the development of a triac capable of withstanding postconduction *dv/dt* values of more than 30 v/μs. Called a logic triac, it features epitaxial construction of the emitter areas, permitting precise manufacturing control of large areas of the semiconductor crystal and resulting in a current-carrying capacity of 200 amperes rms, at a peak working voltage of 1000 v. Excellent critical *dv/dt* rating is provided by the device's shorted-emitter construction. The cathode is designed to avoid overlapping of active areas, thereby reducing the interaction of carriers on one side with the blocking capabilities of the other.

The epitaxial structure and contoured junction of the logic triac incorporate overvoltage protection without the aid of external devices. By comparison, when SCR's in an antiparallel connection are used, the forward breakover voltage of one SCR must be lower than the reverse breakover point of the other. A common way of assuring nondestructive breakover in the forward direction is by using an auxiliary rectifier to protect the SCR from inverse overvoltage.

The firing characteristic of a triac can be represented as the combination of an SCR firing characteristic with its inverted mirror image, as shown in Fig. 3. As in the case of the antiparallel SCR circuit, nondestructive conduction in either direction can be triggered by several methods:

- Increasing the terminal voltage beyond the blocking voltage of the device.
- Applying terminal voltage with a high rise rate.
- Biasing the gate.

The logic triac's unique selective gating characteristic, illustrated in the accompanying panel, lends it considerably more control flexibility than that provided by the nonselective four-quadrant firing characteristic of other triacs, or by the limited firing characteristic of antiparallel SCR's.



These curves, typical of high-power triacs, are used for design of appropriate heat sinks to establish operating conditions within device ratings.

Applying the Triac

The availability of 200-ampere triacs now makes possible simple, reliable control of large central heating systems that eliminate relays, contactors or thermostat contacts. A single power triac is capable of handling a heating load of up to 88 kw on a 440-v single-phase line, and up to 190 kw in a three-phase configuration.

If conventional phase control of a heating load is used, as shown in Fig. 4(a), sharply rising currents in the circuit can generate radio-frequency interference. However, the inherently long thermal time constant of heater elements renders them insensitive to instantaneous current changes. It is possible to take advantage of this characteristic by applying zero-crossover techniques with pulse-burst modulation to firing the triac. The resultant waveforms of Fig. 4(c) indicate the absence of rfi-producing steep wavefronts. The same technique can be used for controlling a three-phase heating load with three triacs.

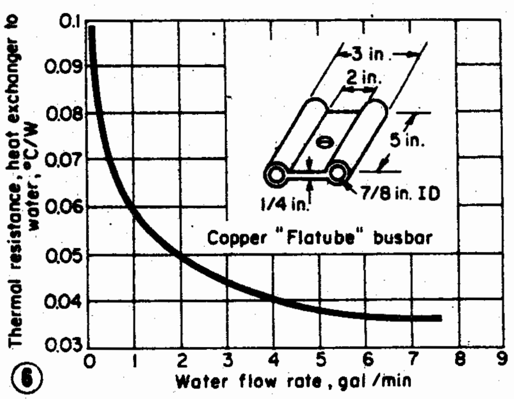
Operating-case temperatures that match the steady-state rms current rating of the device [Fig. 5(a)] can be achieved by using a water-cooled heat sink. A suitable heat sink can be selected by using the curve of Fig. 5(b). At 143 A, for 180° conduction, the curve shows that the device will dissipate 225 w. From Fig. 6, a water-cooled heat sink has a thermal efficiency of 0.0425 at a flow rate of 3.5 gal/min with full-cycle conduction. This keeps the sink rise below 9.7°C. Assuming for this size case an efficiency of 0.06°C/w between heat sink and case, the total temperature rise between the cooling water and the triac case is 23.2°C.

Thus, if the cooling water is at 45°C, the maximum allowable junction temperature of the triac will not be exceeded and approximately the full load of 190 kw can be delivered. Additional control of heating loads can be achieved by adding a simple gate-reversing arrangement to the circuit of Fig. 7. For the gate bias polarity shown, the circuit delivers full power to the heater. If the dc bias polarity is reversed, half-wave rectification takes place, and the power to the load is reduced to 0.707 of its former value.

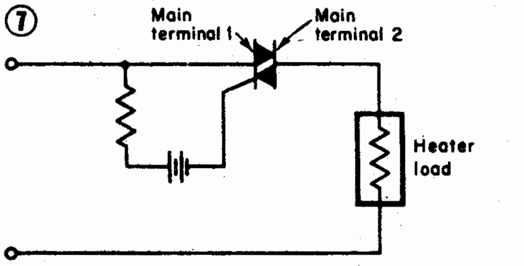
In heating applications, transients that result in high rates of rise of the main terminal voltage (dv/dt) or that cause the breakover voltage rating of the devices (V_{BO}) to be exceeded are not generally a problem with triacs. An occasional transient power pulse to the load is usually of little consequence. Since the power triac can be broken over nondestructively, considerable circuit complexity is avoided by choosing a properly voltage-rated device so that "false firing" does not occur frequently and the need for overvoltage protection and dv/dt suppression is minimized. A triac with a rating of 1000 v, for example, will generally suffice for an application in a 440-v rms line.

Speed Control

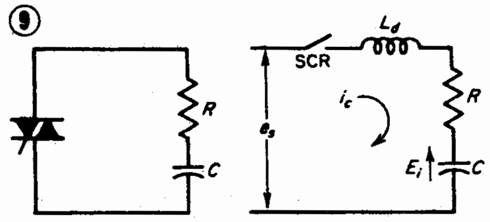
A second major application of solid-state ac power devices is in speed control of wound induction motors. These machines can be controlled either by varying the applied voltage or by changing their effective rotor re-



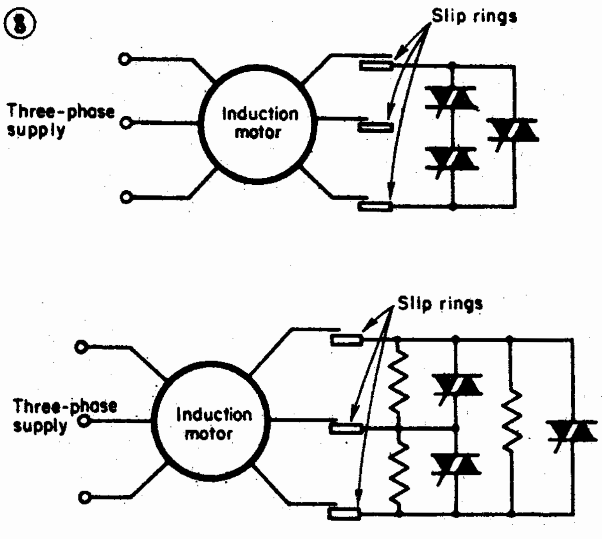
Design curves for a liquid-cooled heat exchanger provide values of thermal resistance as a function of water flow rate.



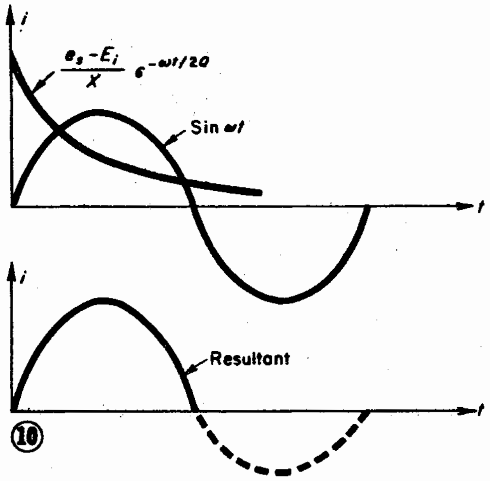
Simple polarity-sensitive gate control. Under conditions shown, full power is delivered to heater. If bias polarity is reversed, load power is cut in half.



Snubber circuit is required to protect triacs from dv/dt stress due to inductive characteristic of motor.



Alternate methods of controlling the speed of polyphase wound-rotor induction motors by varying the effective resistance between slip rings. Here, phase control of triac firing must be used. Triacs require less heat sinking and drive circuitry than antiparallel SCR's.



Analysis of control circuit with snubber permits estimation of di/dt stress from resultant instantaneous current and its components.

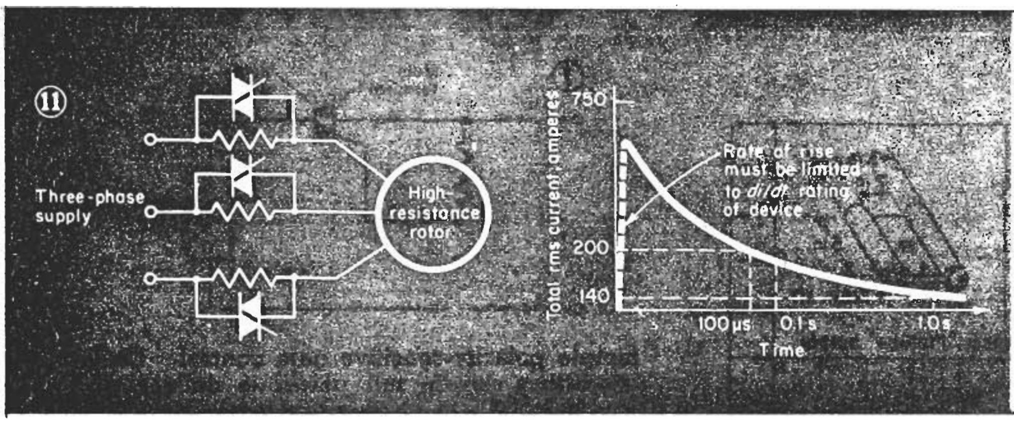
sistance. The latter method can be achieved through slip rings with triacs located as shown in Fig. 8.

In this application, the zero-crossover technique is not usable, and proportional phase control is required. However, this type of control subjects the triac to very high dv/dt due to the inductive nature of the machine. False firing is normally suppressed by connecting a simple RC network, called a "snubber," across the triac as shown in Fig. 9.

The action of the snubber may be analyzed by deriving the current equation from the equivalent circuit shown in Fig. 9. For this purpose the thyristor is represented as a switch (neglecting its forward drop and distributed capacitance), and the other circuit parameters are lumped. The differential equation for this circuit, when the switch is closed, is

$$e_s = L_d \frac{di_c}{dt} + \frac{1}{c}\int i_c dt + i_R - I_i R \qquad (1)$$

where e_s is instantaneous source voltage, L_d is circuit inductance, i_c is instantaneous current, C is capacitance, E_i is the initial voltage charge on the capacitor, and R is circuit resistance (ohms). The approximate



Inrush current is the limiting factor in stator voltage control of a polyphase machine. Here is a simplified circuit for this type of control, which subjects the triac to current inrush values shown here for a one-second period at start-up.

solution for i_c (for the underdamped case) is

$$i_c \approx \left[\frac{e_s - E_i}{X}(\sin \omega t) + I_i(\cos \omega t)\right] \epsilon^{-(\omega t/2Q)} \qquad (2)$$

where X is the characteristic impedance of the circuit $\sqrt{L/C}$, ω is $1/\sqrt{L_d C}$, Q is $\omega L_d/R$, E_i is capacitor charge at t_o, t_o is the time when the forward voltage across the switch begins to drop following gating, and I_i is the initial current flowing in the circuit before $t = t_o$.

The initial circuit current I_i can be neglected since it is at most only a few milliamperes of leakage through the semiconductor switch. Thus Eq (2) becomes

$$i_c \approx \left[\frac{e_s - E_i}{X}(\sin \omega t)\right] \epsilon^{-(\omega t/2Q)} \qquad (3)$$

Equation (3) indicates two current components, the product of which yields the resultant instantaneous current in the circuit as shown in Fig. 10.

The solution of Eq (3) for the underdamped case can be used to determine the *di/dt* stress imposed on the device. To determine stress due to *dv/dt*, the solution for the overdamped case can be applied.

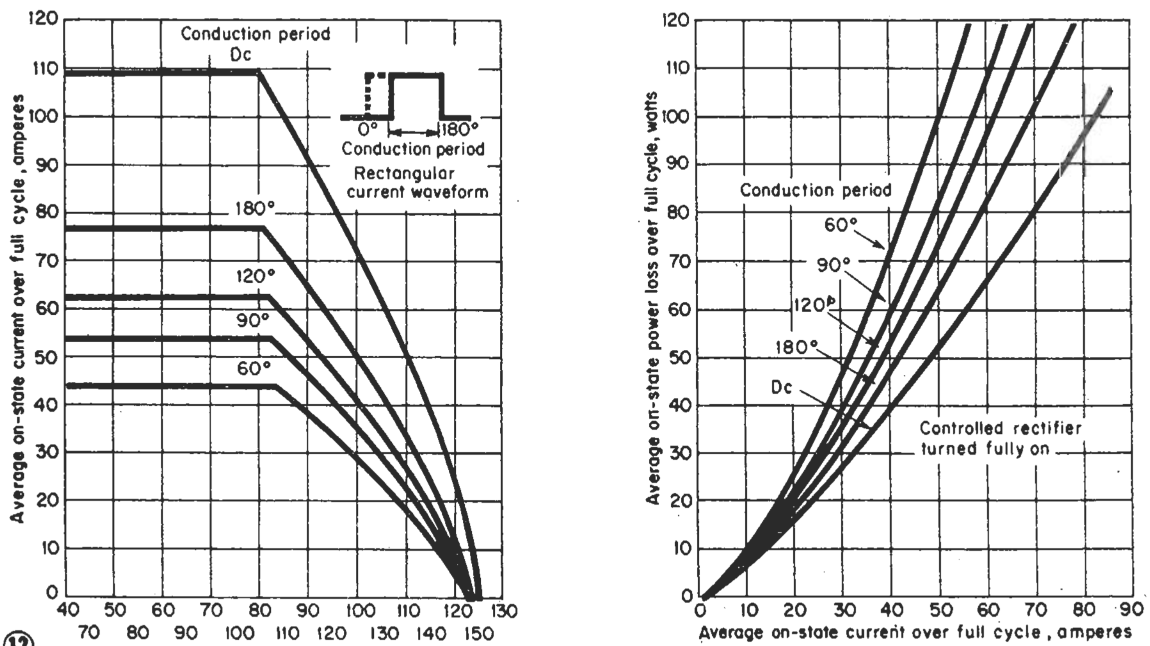
The worst condition of *dv/dt* occurs when power is switched on at peak supply voltage. The circuit must therefore also satisfy the relationship

$$LC > \frac{4V^2_{pk}}{(dv/dt)^2_{max}}$$

Inrush Current

In stator voltage control of a polyphase machine (as shown in Fig. 11), the inrush current is a limiting factor in applying the triac, or any other power rectifier, from the standpoint of *di/dt* and long-term overload.

Should the inrush last for more than a few cycles (which is normal on induction-motor applications), it may be necessary to apply a ramp function to the



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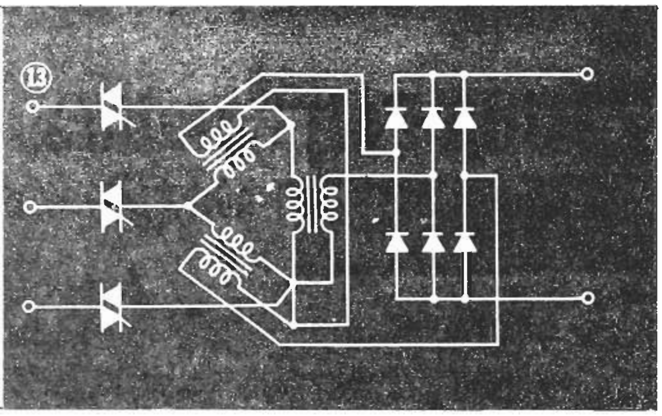
Case temperature and power dissipation curves for representative 70-ampere units are used to evaluate antiparallel connection of six SCR's in motor starter application (see text). To compare performance of triacs, curves of Fig. 5 are used for the same load conditions.

For bidirectional primary polyphase transformer control, firing angle of three triacs must be closely balanced to equalize currents. This insures against device overheating when transformer saturates.



pulser driving the triacs to advance the phase of the units slowly, thus limiting this inrush. The current during the initial period can be as much as six times the normal current drawn by the machine. With a 100-hp, 440-v, three-phase motor, this current could be $6 \times (100 \times 746)/(3 \times 440) = 340$ A rms.

The triac must be capable of withstanding this starting transient, and the device selected must be rated accordingly.

Typical Design Problem

Suppose we wanted to build a static three-phase, 440-v, 60-Hz starter for frequent operation—which would prohibit using a short-life contactor or electromagnetic motor starter. The induction motor has a running current of 520 A rms and an inrush current as shown in Fig. 11.

As one possible solution, we might select a circuit using six SCR's. For a unidirectional device, bidirectional rms values must be converted to full-cycle average values by the relationship:

$$\text{full-cycle average} = \text{full-cycle rms} \times 0.577$$

(assuming a 120° square current waveform).

At a running current of 140 A rms, the full-cycle average current of the SCR with a 120° conduction angle is 40.3 A. From manufacturer's curves of allowable case temperature and power dissipation as a function of current (Fig. 12), we find the allowable case temperature at this current level is 100°C and the dissipation is 58 w.

Referring to the data for a liquid-cooled sink having a typical thermal efficiency of 0.1 (as in the previous example) and a water temperature of 45°C,

$$T_{case} = 0.1 \times 58 + 45 = 51°C$$

which is within the value established by Fig. 12.

As an alternate, three triacs may be used to perform the same function, cutting the heat-sink problem in half. Figure 5(a) shows that at 140 A rms the allowable case temperature is 72°C. From Fig. 5(b), the dissipation at this current level is approximately 200 w. The case temperature rise for the triac, then, is $T_{case} = 20°C$ (with the same heat sink). Maximum case temperature will be 65°C, which is within the value specified by Fig. 12. The motor surge current is well below the maximum limits for the device.

In this application, post-conduction dv/dt becomes an important consideration; to prevent false firing of the device, an appropriate snubber network should be included. Stress due to di/dt must also be minimized.

Transformer Control

Another important application for a bidirectional device is primary transformer control. The design calculations involved for choosing a properly rated device in transformer-fed power-supply applications are the same as those for motor control. But there are some unique ramifications of the problem. For example, at first glance the typical high-current dc supply shown in Fig. 13 appears to be straightforward. However, should the transformer go into saturation, the primary currents can become inordinately high and overheat the thyristors. It becomes obvious that secondary or dc current-sensing is not sufficient for protection. The circuit should be designed to insure proper balance of triac currents by using feedback to the driving circuits. Balance among firing angles of the three line controls should be close enough to insure good current equalization under normal balanced load conditions. Several manufacturers of packaged firing modules guarantee a maximum interphase unbalance within a specified tolerance.

Lighting Control

Static power devices are finding a major niche in ac lighting control. A 200-A triac is obviously not destined for application in consumer lamp dimmers (typically rated 600 to 1200 w), but since most theater lighting applications are in the 6- to 12-kw class, the device appears to have a bright future in the entertainment industry. Under steady-state conditions, this application is no different from a heating load supply design. However, the triac can be subjected to high transient currents due to the extremely low cold resistance of lamp filaments. This starting current condition can be minimized by either

- Providing a ramp-type function to heat the filaments at start-up without allowing full phase advance on the triac, or
- Providing a limiting inductor in series with the triac. For a one-cycle surge on the triac, ignoring line reactance and assuming zero filament resistance from a 120-v, 60-Hz source, the required inductive reactance would be

$$X_L = 120/1000 = 0.120\,\Omega$$

The power triac gives the designer greater freedom than he ever enjoyed with such other static control devices as magnetic amplifiers. As a result, solid-state control will undoubtedly become commonplace in such applications as elevator drives, electric transmission for rapid-transit vehicles, earth-moving equipment, ac welding, plating, and many types of processing equipment.

Triac trigger sets firing point over 0° to 360°

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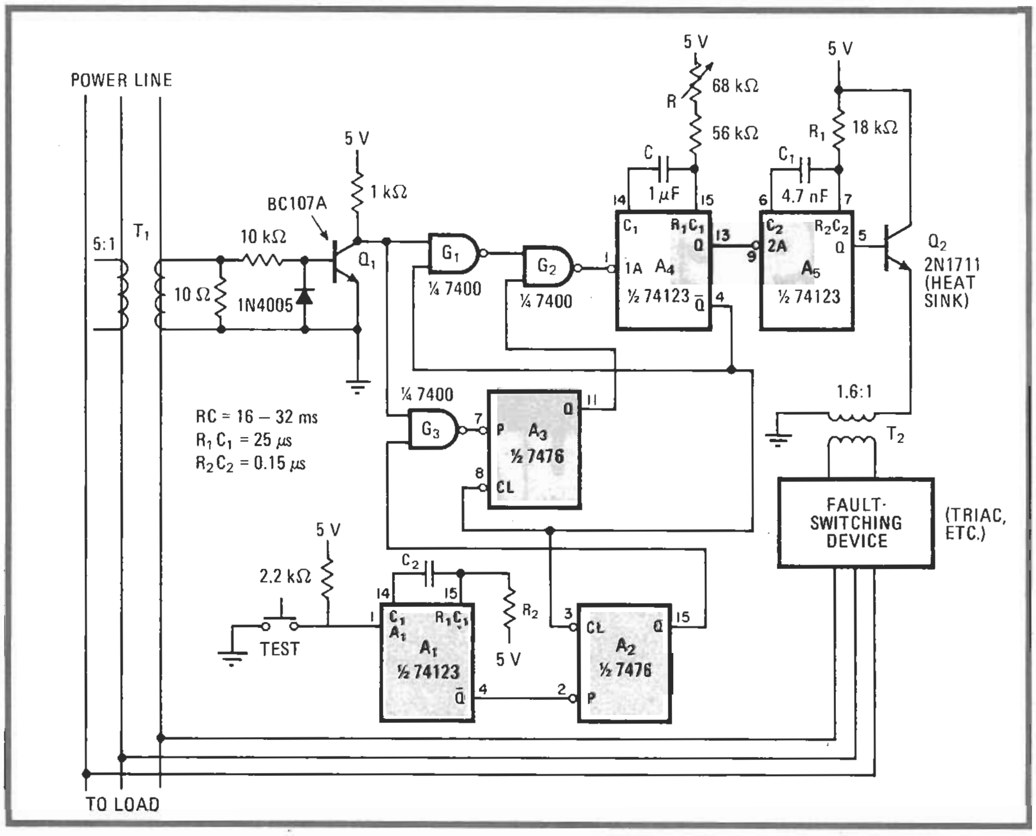
Because it selects the point on the cycle at which a 60-hertz line input will fire a triac, this circuit is very useful for checking the transient response of overload protection systems and in many other power-control applications. Standard TTL elements are used here to switch the triac on when commanded, over any point in the range of 0° through 360°.

Generally, the 60-Hz voltage on the secondary winding (T_1) of the current transformer turns transistor Q_1 on and off at every positive and negative transition of the power-line input, respectively, as shown in the figure. During these times, the output of gate G_2 is always high.

When the test button is depressed, one-shot A_1 fires to set flip-flop A_2. The resulting low output from G_3 that occurs when Q_1 is off then sets A_3, so that Q_1's output passes through to G_2 and one-shot A_4.

A_5 turns on when the Q output of A_4 moves low. The delay between the positive-going transition of the input wave and the firing of the fault-switching device may be selected by adjusting R. Note that because the time constant of A_4 is slightly greater than the period of the input waveform, the triac will not be pulsed until after the passage of one cycle.

A calibrated potentiometer for R is suggested. The trigger-point markings will be accurate to within a few degrees throughout the range if an oscilloscope is used to calibrate the circuit. □



Power angle. Trigger circuit sets point on ac cycle at which triac or other power-controlling device turns on. Using standard TTL elements, including a simple monostable multivibrator for selecting fire angle, it has a range that is adjustable over 0°-360°.