AN1003

Phase Control Using Thyristors

Introduction

Due to high-volume production techniques, thyristors are now priced so that almost any electrical product can benefit from electronic control. A look at the fundamentals of SCR and triac phase controls shows how this is possible.

Output Power Characteristics

Phase control is the most common form of thyristor power control. The thyristor is held in the off condition — that is, all current flow in the circuit is blocked by the thyristor except a minute leakage current. Then the thyristor is triggered into an “on” condition by the control circuitry.

For full-wave AC control, a single triac or two SCRs connected in inverse parallel may be used. One of two methods may be used for full-wave DC control — a bridge rectifier formed by two SCRs or an SCR placed in series with a diode bridge as shown in Figure AN1003.1.

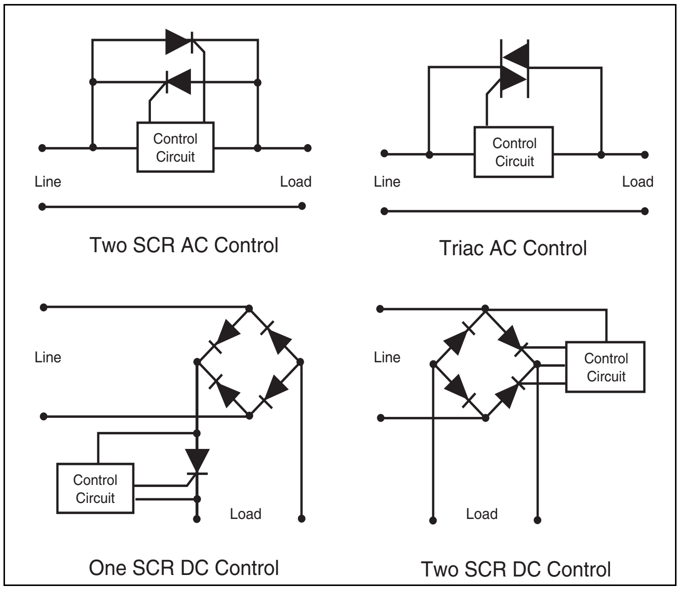


Figure AN1003.1 SCR/Triac Connections for Various Methods of Phase Control

Figure AN1003.2 illustrates voltage waveform and shows common terms used to describe thyristor operation. Delay angle is the time during which the thyristor blocks the line voltage. The conduction angle is the time during which the thyristor is on.

It is important to note that the circuit current is determined by the load and power source. For simplification, assume the load is resistive; that is, both the voltage and current waveforms are identical.

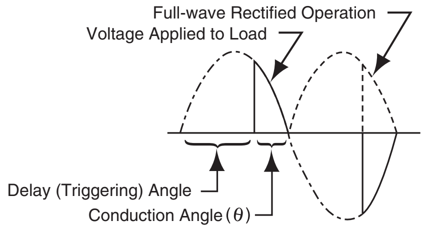


Figure AN1003.2 Sine Wave Showing Principles of Phase Control

Different loads respond to different characteristics of the AC waveform. For example, some are sensitive to average voltage, some to RMS voltage, and others to peak voltage. Various voltage characteristics are plotted against conduction angle for half- and full-wave phase control circuits in Figure AN1003.3 and Figure AN1003.4.

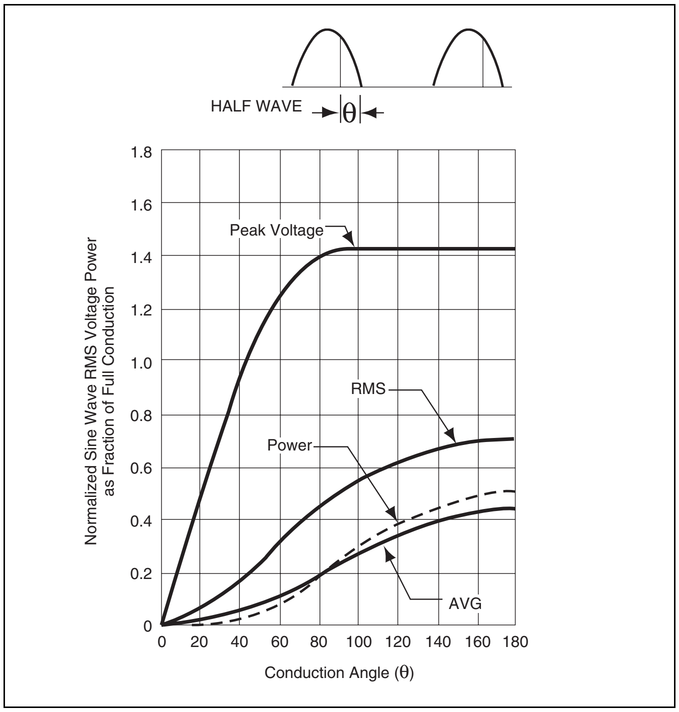


Figure AN1003.3 Half-Wave Phase Control (Sinusoidal)

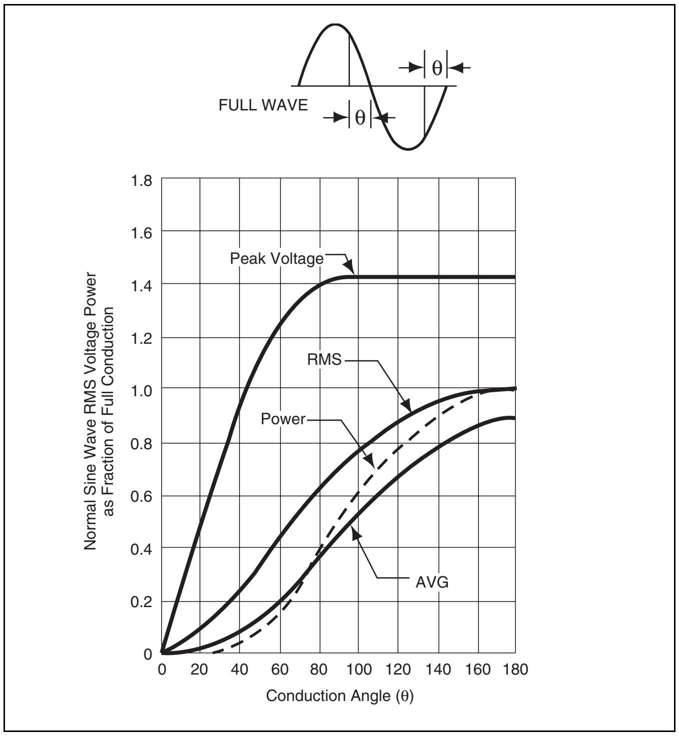


Figure AN1003.4 Symmetrical Full-Wave Phase Control (Sinusoidal)

Figure AN1003.3 and Figure AN1003.4 also show the relative power curve for constant impedance loads such as heaters. Because the relative impedance of incandescent lamps and motors change with applied voltage, they do not follow this curve precisely. To use the curves, find the full-wave rated power of the load, and then multiply by the ratio associated with the specific phase angle. Thus, a 180° conduction angle in a half-wave circuit provides 0.5 x full-wave conduction power.

In a full-wave circuit, a conduction angle of 150° provides 97% full power while a conduction angle of 30° provides only 3% of full power control. Therefore, it is usually pointless to obtain conduction angles less than 30° or greater than 150°.

Figure AN1003.5 and Figure AN1003.6 give convenient direct output voltage readings for 115 V/230 V input voltage. These curves also apply to current in a resistive circuit.

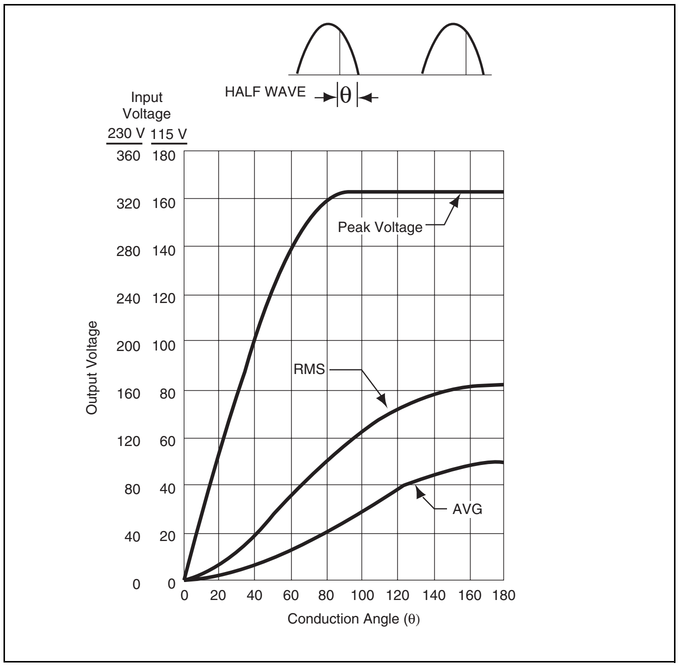


Figure AN1003.5 Output Voltage of Half-wave Phase

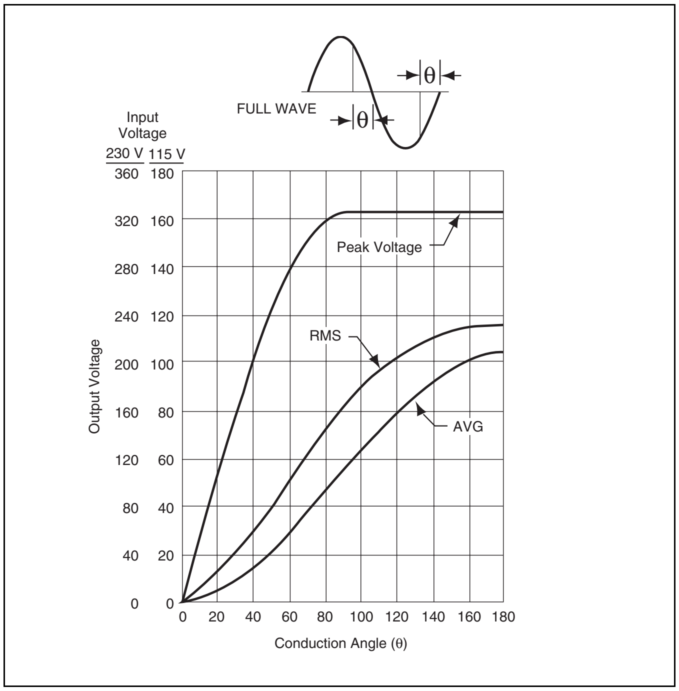


Figure AN1003.6 Output Voltage of Full-wave Phase Control

Control Characteristics

A relaxation oscillator is the simplest and most common control circuit for phase control. Figure AN1003.7 illustrates this circuit as it would be used with a thyristor. Turn-on of the thyristor occurs when the capacitor is charged through the resistor from a voltage or current source until the breakover voltage of the switching device is reached. Then, the switching device changes to its on state, and the capacitor is discharged through the thyristor gate. Trigger devices used are neon bulbs, unijunction transistors, and three-, four-, or five-layer semiconductor trigger devices. Phase control of the output waveform is obtained by varying the RC time constant of the charging circuit so the trigger device breakdown occurs at different phase angles within the controlled half or full cycle.

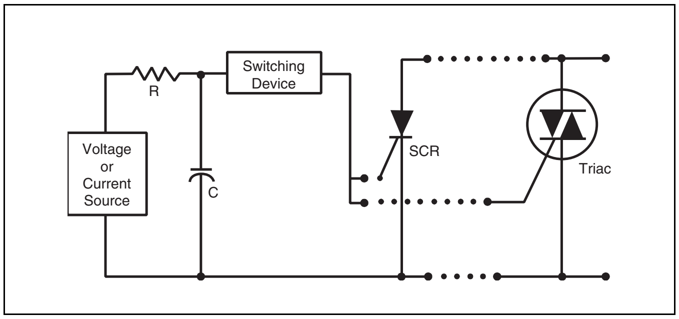


Figure AN1003.7 Relaxation Oscillator Thyristor Trigger Circuit

Figure AN1003.8 shows the capacitor voltage-time characteristic if the relaxation oscillator is to be operated from a pure DC source.

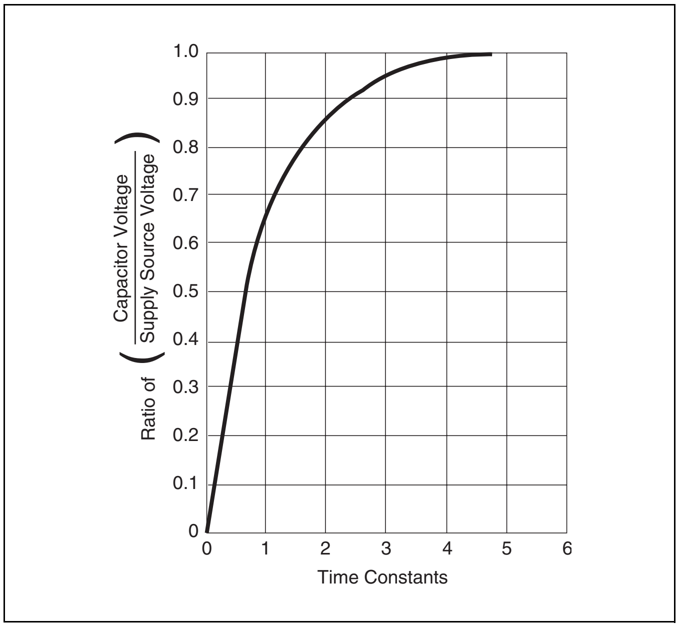


Figure AN1003.8 Capacitor Charging from DC Source

Usually, the design starting point is the selection of a capacitance value which will reliably trigger the thyristor when the capacitance is discharged. Trigger devices and thyristor gate triggering characteristics play a part in the selection. All the device characteristics are not always completely specified in applications, so experimental determination is sometimes needed.

Upon final selection of the capacitor, the curve shown in Figure AN1003.8 can be used in determining the charging resistance needed to obtain the desired control characteristics.

Many circuits begin each half-cycle with the capacitor voltage at or near zero. However, most circuits leave a relatively large residual voltage on the capacitor after discharge. Therefore, the charging resistor must be determined on the basis of additional charge necessary to raise the capacitor to trigger potential.

For example, assume that we want to trigger an S2010L SCR with a 32 V trigger diac. A 0.1 µF capacitor will supply the necessary SCR gate current with the trigger diac. Assume a 50 V dc power supply, 30° minimum conduction angle, and 150° maximum conduction angle with a 60 Hz input power source. At approximately 32 V, the diac triggers leaving 0.66 V_{BO} of diac voltage on the capacitor. In order for diac to trigger, 22 V must be added to the capacitor potential, and 40 V additional (50-10) are available. The capacitor must be charged to 22/40 or 0.55 of the available charging voltage in the desired time. Looking at Figure AN1003.8, 0.55 of charging voltage represents 0.8 time constant. The 30° conduction angle required that the firing pulse be delayed 150° or 6.92 ms. (The period of 1/2 cycle at 60 Hz is 8.33 ms.) To obtain this time delay:

6.92 ms = 0.8 RC
RC = 8.68 ms

if C = 0.10 µF

then, $R = \frac{8.68\times10^{-3}}{0.1\times10^{-6}} = 86{,}000\ \Omega$

To obtain the minimum R (150° conduction angle), the delay is 30° or

(30/180) x 8.33 = 1.39 ms
1.39 ms = 0.8 RC
RC = 1.74 ms

$$R = \frac{1.74\times10^{-3}}{0.1\times10^{-6}} = 17{,}400\ \Omega$$

Using practical values, a 100 k potentiometer with up to 17 k minimum (residual) resistance should be used. Similar calculations using conduction angles between the maximum and minimum values will give control resistance versus power characteristic of this circuit.

Triac Phase Control

The basic full-wave triac phase control circuit shown in Figure AN1003.9 requires only four components. Adjustable resistor R_1 and C_1 are a single-element phase-shift network. When the voltage across C_1 reaches breakover voltage (V_{BO}) of the diac, C_1 is partially discharged by the diac into the triac gate. The triac is then triggered into the conduction mode for the remainder of that half-cycle. In this circuit, triggering is in Quadrants I and III. The unique simplicity of this circuit makes it suitable for applications with small control range.

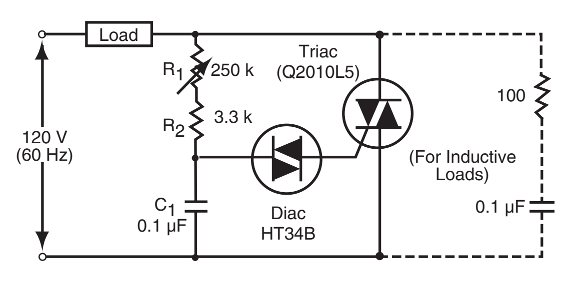


Figure AN1003.9 Basic Diac-Triac Phase Control

The hysteresis (snap back) effect is somewhat similar to the action of a kerosene lantern. That is, when the control knob is first rotated from the off condition, the lamp can be lit only at some intermediate level of brightness, similar to turning up the wick to light the lantern. Brightness can then be turned down until it finally reaches the extinguishing point. If this occurs, the lamp can only be relit by turning up the control knob again to the intermediate level. Figure AN1003.10 illustrates the hysteresis effect in capacitor-diac triggering. As R_1 is brought down from its maximum resistance, the voltage across the capacitor increases until the diac first fires at point A, at the end of a half-cycle (conduction angle θ_i). After the gate pulse, however, the capacitor voltage drops suddenly to about half the triggering voltage, giving the capacitor a different initial condition. The capacitor charges to the diac, triggering voltage at point B in the next half-cycle and giving a steady-state conduction angle shown as θ for the triac.

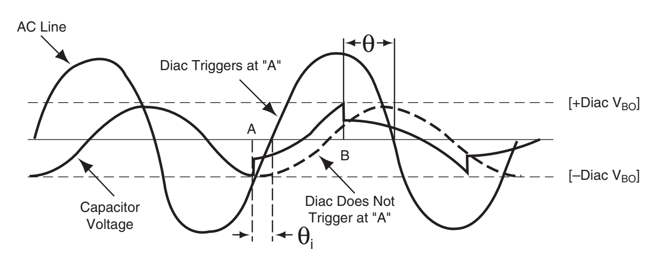


Figure AN1003.10 Relationship of AC Line Voltage and Triggering Voltage

In the Figure AN1003.11 illustration, the addition of a second RC phase-shift network extends the range on control and reduces the hysteresis effect to a negligible region. This circuit will control from 5% to 95% of full load power, but is subject to supply voltage variations. When R_1 is large, C_1 is charged primarily through R_3 from the phase-shifted voltage appearing across C_2. This action provides additional range of phase-shift across C_1 and enables C_2 to partially recharge C_1 after the diac has triggered, thus reducing hysteresis. R_3 should be adjusted so that the circuit just drops out of conduction when R_1 is brought to maximum resistance.

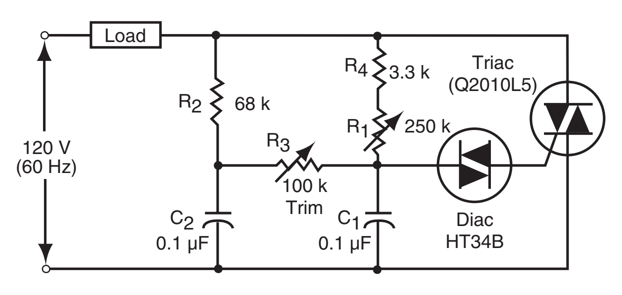


Figure AN1003.11 Extended Range Full-wave Phase Control

By using one of the circuits shown in Figure AN1003.12, the hysteresis effect can be eliminated entirely. The circuit (a) resets the timing capacitor to the same level after each positive half-cycle, providing a uniform initial condition for the timing capacitor. This circuit is useful only for resistive loads since the firing angle is not symmetrical throughout the range. If symmetrical firing is required, use the circuit (b) shown in Figure AN1003.12.

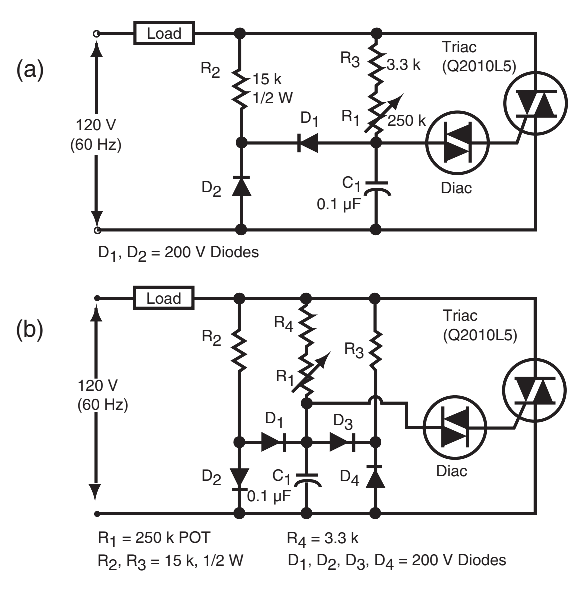
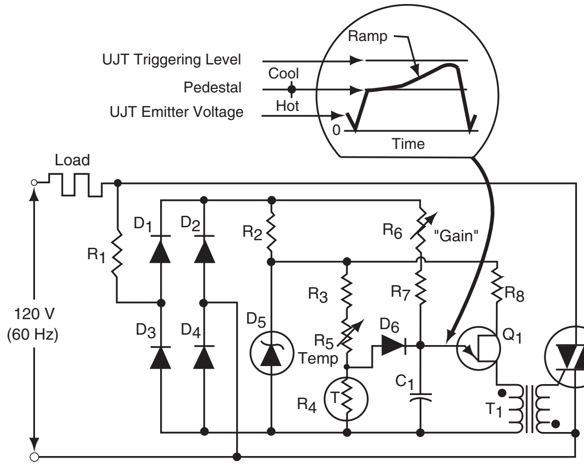


Figure AN1003.12 Wide-range Hysteresis Free Phase Control

For more complex control functions, particularly closed loop controls, the unijunction transistor may be used for the triggering device in a ramp and pedestal type of firing circuit as shown in Figure AN1003.13.

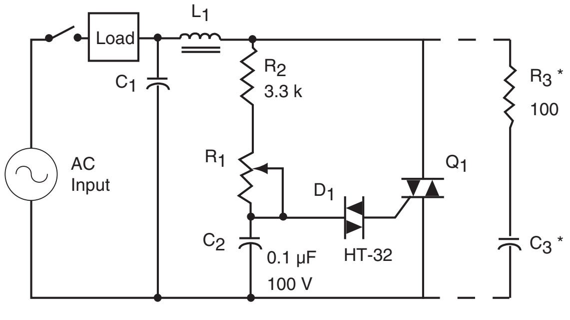


R_1, R_2 = 2.2 k, 2 W
R_3 = 2.2 k, 1/2 W
R_4 = Thermistor, approx. 5 k at operating temperature
R_5 = 10 k Potentiometer
R_6 = 5 M Potentiometer
R_7 = 100 k, 1/2 W
R_8 = 1 k, 1/2 W
Q_1 = 2N2646
Q_2 = Q2010L5
T_1 = Dale PT 10-101 or equivalent
$D_{1\text{-}4}$ = 200 V Diode
D_5 = 20 V Zener
D_6 = 100 V Diode
C_1 = 0.1 µF, 30 V

Figure AN1003.13 Precision Proportional Temperature Control

Several speed control and light dimming (phase) control circuits have been presented that give details for a complete 120 V application circuit but none for 240 V. Figure AN1003.14 and Figure AN1003.15 show some standard phase control circuits for 240 V, 60 Hz/50 Hz operation along with 120 V values for comparison. Even though there is very little difference, there are a few key things that must be remembered. First, capacitors and triacs connected across the 240 V line must be rated at 400 V. Secondly, the potentiometer (variable resistor) value must change considerably to obtain the proper timing or triggering for 180° in each half-cycle.

Figure AN1003.14 shows a simple single-time-constant light dimmer (phase control) circuit, giving values for both 120 V and 240 V operation.



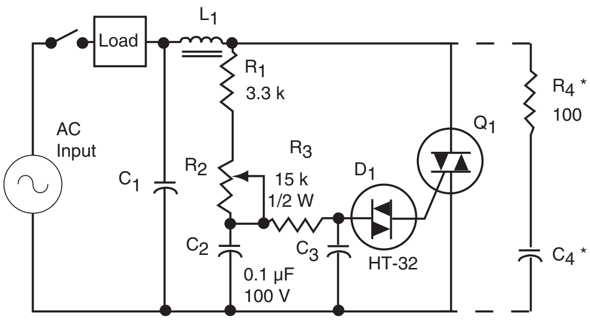
Note: L_1 and C_1 form an RFI filter that may be eliminated

* dv/dt snubber network when required

AC Input Voltage	AC Load Current	R_1	C_1, C_3	L_1	Q_1
120 V ac 60 Hz	12 A	250 k	0.1 µF 200 V	100 µH	Q2015L9
240 V ac 50/60 Hz	3 A	500 k	0.1 µF 400 V	200 µH	Q4004L4

Figure AN1003.14 Single-time-constant Circuit for Incandescent Light Dimming, Heat Control, and Motor Speed Control

The circuit shown in Figure AN1003.15 is a double-time-constant circuit which has improved performance compared to the circuit shown in Figure AN1003.14. This circuit uses an additional RC network to extend the phase angle so that the triac can be triggered at small conduction angles. The additional RC network also minimizes any hysteresis effect explained and illustrated in Figure AN1003.10 and Figure AN1003.11.



Note: L_1 and C_1 form an RFI filter that may be eliminated

* dv/dt snubber network when required

AC Input Voltage	AC Load Current	R_2	C_1, C_2, C_4	L_1	Q_1
120 V ac 60 Hz	8 A	250 k	0.1 µF 200 V	100 µH	Q2010L5
240 V ac 50 Hz	6 A	500 k	0.1 µF 400 V	200 µH	Q4008L4
240 V ac 60 Hz	6 A	500 k	0.1 µF 400 V	200 µH	Q4008L4

Figure AN1003.15 Double-time-constant Circuit for Incandescent Light Dimming, Heat Control, and Motor Speed Control

Permanent Magnet Motor Control

Figure AN1003.16 illustrates a circuit for phase controlling a permanent magnet (PM) motor. Since PM motors are also generators, they have characteristics that make them difficult for a standard triac to commutate properly. Control of a PM motor is easily accomplished by using an alternistor triac with enhanced commutating characteristics.

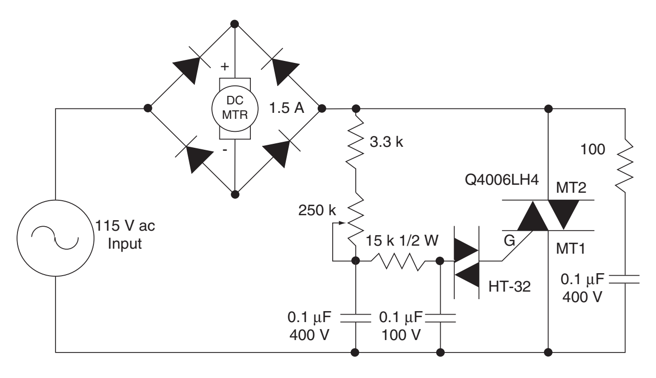
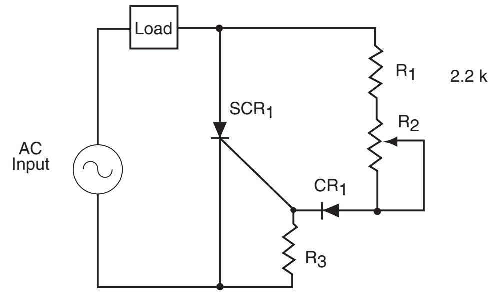


Figure AN1003.16 Circuit for Phase Controlling a Permanent Magnet Motor

PM motors normally require full-wave DC rectification. Therefore, the alternistor triac controller should be connected in series with the AC input side of the rectifier bridge. The possible alternative of putting an SCR controller in series with the motor on the DC side of the rectifier bridge can be a challenge when it comes to timing and delayed turn-on near the end of the half cycle. The alternistor triac controller shown in Figure AN1003.16 offers a wide range control so that the alternistror triac can be triggered at a small conduction angle or low motor speed; the rectifiers and alternistors should have similar voltage ratings, with all based on line voltage and actual motor load requirements.

SCR Phase Control

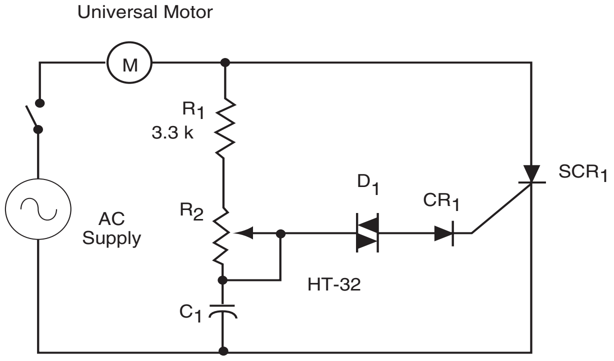
Figure AN1003.17 shows a very simple variable resistance half-wave circuit. It provides phase retard from essentially zero (SCR full on) to 90 electrical degrees of the anode voltage wave (SCR half on). Diode CR_1 blocks reverse gate voltage on the negative half-cycle of anode supply voltage. This protects the reverse gate junction of sensitive SCRs and keeps power dissipation low for gate resistors on the negative half cycle. The diode is rated to block at least the peak value of the AC supply voltage. The retard angle cannot be extended beyond the 90-degree point because the trigger circuit supply voltage and the trigger voltage producing the gate current to fire are in phase. At the peak of the AC supply voltage, the SCR can still be triggered with the maximum value of resistance between anode and gate. Since the SCR will trigger and latch into conduction the first time I_{GT} is reached, its conduction cannot be delayed beyond 90 electrical degrees with this circuit.



AC Input Voltage	AC Load Current	R_2	CR_1	SCR_1	R_3
120 V ac 60 Hz	0.8 A	500 k	IN4003	EC103B	1 k
120 V ac 60 Hz	8.5 A	100 k	IN4003	S2010F1	Not Required
240 V ac 60 Hz	0.8 A	1 M	IN4004	EC103D	1 k
240 V ac 60 Hz	8.5 A	250 k	IN4004	S4010F1	Not Required
240 V ac 50Hz	2.5 A	1 M	IN4004	T106D1	1 k

Figure AN1003.17 Half-wave Control, 0° to 90° Conduction

Figure AN1003.18 shows a half-wave phase control circuit using an SCR to control a universal motor. This circuit is better than simple resistance firing circuits because the phase-shifting characteristics of the RC network permit the firing of the SCR beyond the peak of the impressed voltage, resulting in small conduction angles and very slow speed.



AC Input Voltage	AC Load Current	R_2	CR_1	SCR_1	C_1
120 V ac 60 Hz	8 A	150 k	IN4003	S2015L	0.1µF 200 V
240 V ac 60 Hz	6.5 A	200 k	IN4004	S4008L	0.1µF 400 V
240 V ac 50 Hz	6.5 A	200 k	IN4004	S4008L	0.1µF 400 V

Figure AN1003.18 Half-wave Motor Control

Phase Control from Logic (DC) Inputs

Triacs can also be phase-controlled from pulsed DC unidirectional inputs such as those produced by a digital logic control system. Therefore, a microprocessor can be interfaced to AC load by using a sensitive gate triac to control a lamp's intensity or a motor's speed.

There are two ways to interface the unidirectional logic pulse to control a triac. Figure AN1003.19 illustrates one easy way if load current is approximately 5 A or less. The sensitive gate triac serves as a direct power switch controlled by HTL, TTL, CMOS, or integrated circuit operational amplifier. A timed pulse from the system's logic can activate the triac anywhere in the AC sinewave producing a phase-controlled load.

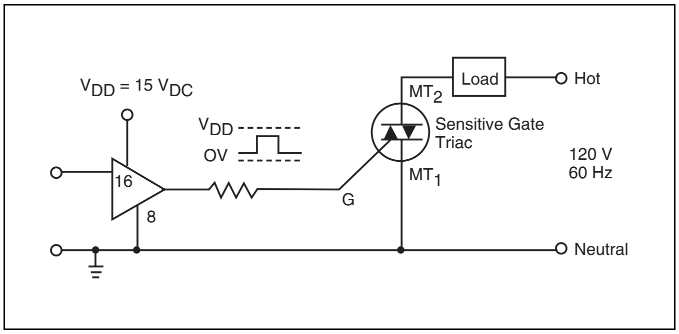
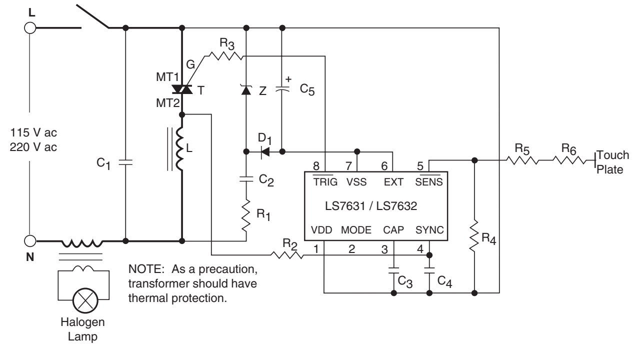


Figure AN1003.19 Sensitive Gate Triac Operating in Quadrants I and IV

The key to DC pulse control is correct grounding for DC and AC supply. As shown in Figure AN1003.19, **DC ground and AC ground/neutral must be common** plus **MT1 must be connected to common ground**. MT1 of the triac is the return for both main terminal junctions as well as the gate junction.

Figure AN1003.20 shows an example of a unidirectional (all negative) pulse furnished from a special I.C. that is available from LSI Computer Systems in Melville, New York. Even though the circuit and load is shown to control a Halogen lamp, it could be applied to a common incandescent lamp for touch-controlled dimming.



115 V ac		220 V ac	
C_1 = 0.15 µF, 200 V	R_3 = 62, ¼ W	C_1 = 0.15 µF, 400 V	R_3 = 62, ¼ W
C_2 = 0.22 µF, 200 V	R_4 = 1 M to 5 M, ¼ W	C_2 = 0.1 µF, 400 V	R_4 = 1 M to 5 M, ¼ W
C_3 = 0.02 µF, 12 V	(Selected for sensitivity)	C_3 = 0.02 µF, 12 V	(Selected for sensitivity)
C_4 = 0.002 µF, 12 V	R_5, R_6 = 4.7 M, ¼ W	C_4 = 0.002 µF, 12 V	R_5, R_6 = 4.7 M, ¼ W
C_5 = 100 µF, 12 V	D_1 = 1N4148	C_5 = 100 µF, 12 V	D_1 = 1N4148
R_1 = 270, ¼ W	Z = 5.6 V, 1 W Zener	R_1 = 1 k, ¼ W	Z = 5.6 V, 1 W Zener
R_2 = 680 k, ¼ W	T = Q4006LH4 Alternistor	R_2 = 1.5 M, ¼ W	T = Q6006LH4 Alternistor
	L = 100 µH (RFI Filter)		L = 200 µH (RFI Filter)

Figure AN1003.20 Typical Touch Plate Halogen Lamp Dimmer

For a circuit to control a heavy-duty inductive load where an alternistor is not compatible or available, two SCRs can be driven by an inexpensive TO-92 triac to make a very high current triac or alternistor equivalent, as shown in Figure AN1003.21. See ”Relationship of IAV, IRMS, and IPK’ in AN1009 for design calculations.

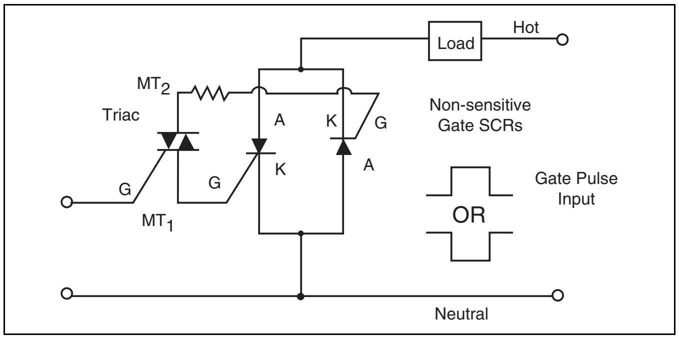


Figure AN1003.21 Triac Driving Two Inverse Parallel Non-Sensitive Gate SCRs

Figure AN1003.22 shows another way to interface a unidirectional pulse signal and activate AC loads at various points in the AC sine wave. This circuit has an electrically-isolated input which allows load placement to be flexible with respect to AC line. In other words, connection between DC ground and AC neutral is not required.

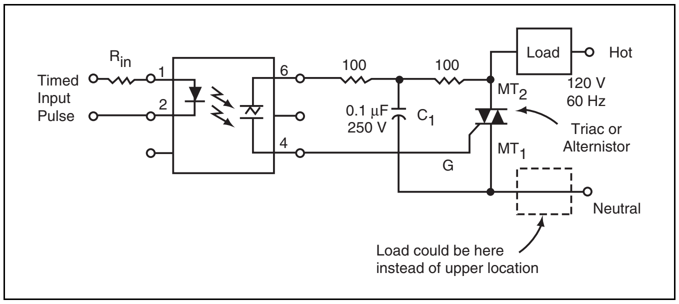


Figure AN1003.22 Opto-isolator Driving a Triac or Alternistor

Microcontroller Phase Control

Traditionally, microcontrollers were too large and expensive to be used in small consumer applications such as a light dimmer. Microchip Technology Inc. of Chandler, Arizona has developed a line of 8-pin microcontrollers without sacrificing the functionality of their larger counterparts. These devices do not provide high drive outputs, but when combined with a sensitive triac can be used in a cost-effective light dimmer.

Figure AN1003.23 illustrates a simple circuit using a transformerless power supply, PIC 12C508 microcontroller, and a sensitive triac configured to provide a light dimmer control. R_3 is connected to the hot lead of the AC power line and to pin GP_4. The ESD protection diodes of the input structure allow this connection without damage. When the voltage on the AC power line is positive, the protection diode form the input to V_{DD} is forward biased, and the input buffer will see approximately V_{DD} + 0.7 V. The software will read this pin as high. When the voltage on the line is negative, the protection diode from V_{SS} to the input pin is forward biased, and the input buffer sees approximately V_{SS} - 0.7 V. The software will read the pin as low. By polling GP_4 for a change in state, the software can detect zero crossing.

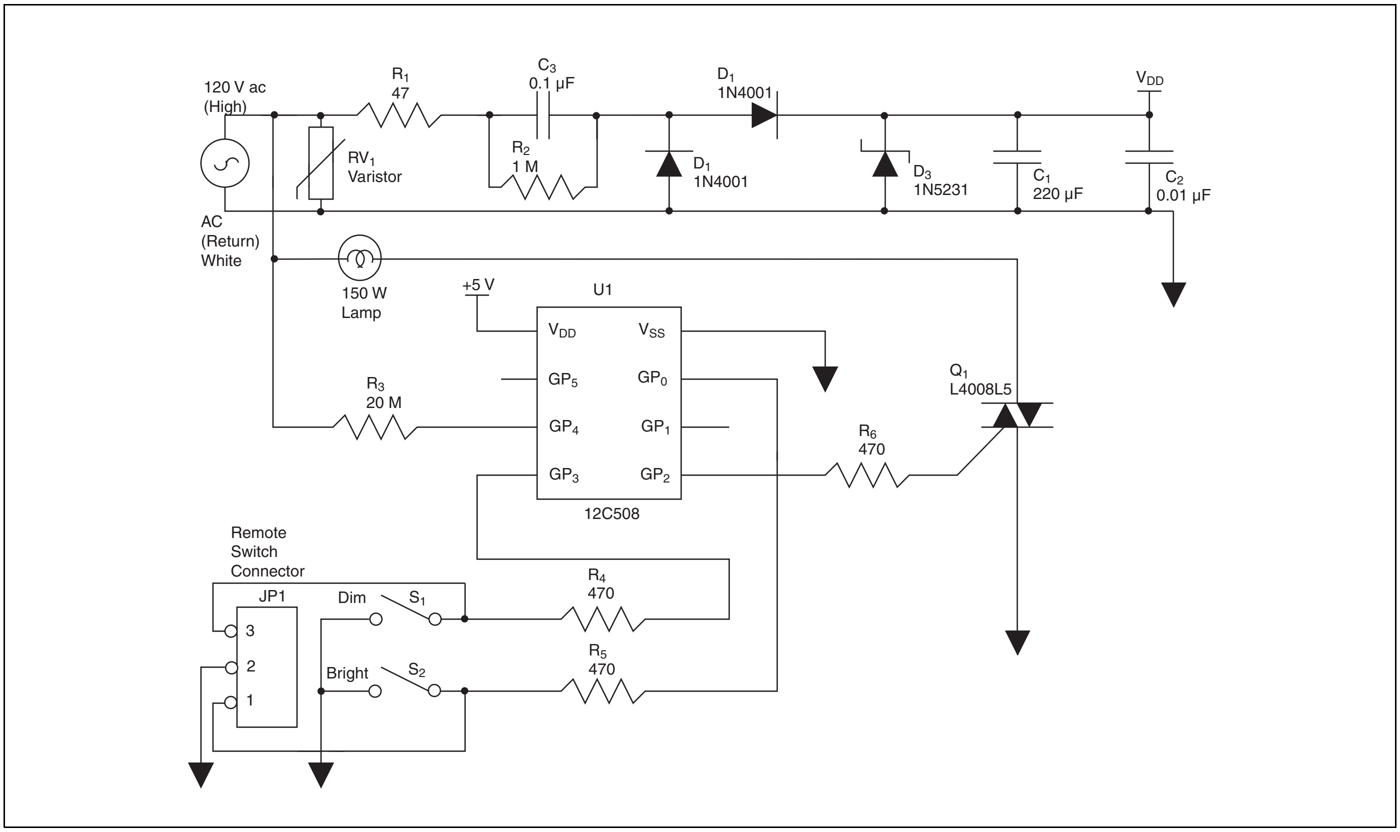


Figure AN1003.23 Microcontroller Light Dimmer Control

With a zero crossing state detected, software can be written to turn on the triac by going from tri-state to a logic high on the gate and be synchronized with the AC phase cycles (Quadrants I and IV). Using pull-down switches connected to the microcontoller inputs, the user can signal the software to adjust the duty cycle of the triac.

For higher amperage loads, a small 0.8 A, TO-92 triac (operating in Quadrants I and IV) can be used to drive a 25 A alternistor triac (operating in Quadrants I and III) as shown in the heater control illustration in Figure AN1003.24.

For a complete listing of the software used to control this circuit, see the Microchip application note PICREF-4. This application note can be downloaded from Microchip's Web site at www.microchip.com.

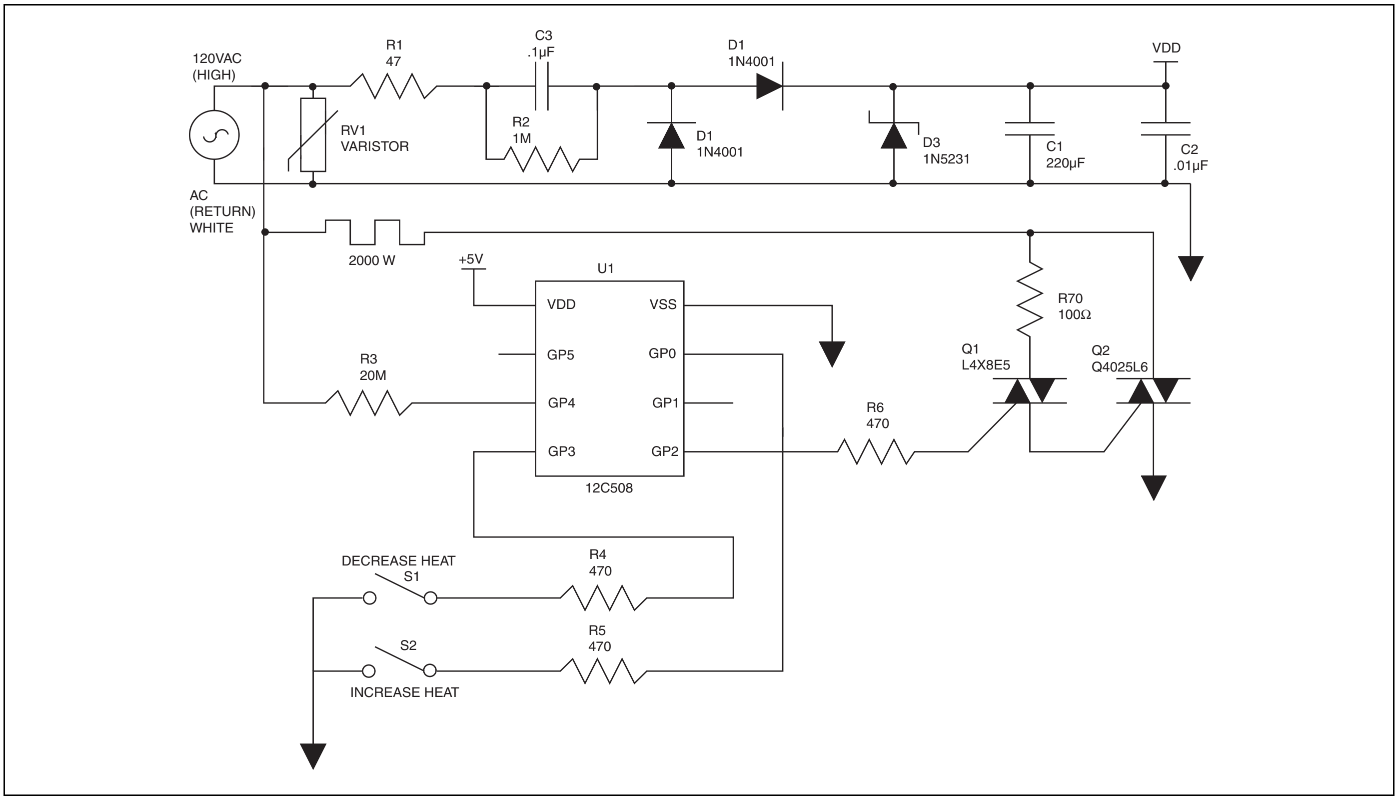


Figure AN1003.24 Microcontroller Heater Control

Summary

The load currents chosen for the examples in this application note were strictly arbitrary, and the component values will be the same regardless of load current except for the power triac or SCR. The voltage rating of the power thyristor devices must be a minimum of 200 V for 120 V input voltage and 400 V for 240 V input voltage.

The use of alternistors instead of triacs may be much more acceptable in higher current applications and may eliminate the need for any dv/dt snubber network.

For many electrical products in the consumer market, competitive thyristor prices and simplified circuits make automatic control a possibility. These simple circuits give the designer a good feel for the nature of thyristor circuits and their design. More sophistication, such as speed and temperature feedback, can be developed as the control techniques become more familiar. A remarkable phenomenon is the degree of control obtainable with very simple circuits using thyristors. As a result, industrial and consumer products will greatly benefit both in usability and marketability.

Notes