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# AN-755
**Application Note**

# SOLID-STATE RELAYS FOR AC POWER CONTROL

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Solid-State Relays (SSRs) using both SCRs and Triacs are examined in detail. The advantages and disadvantages of SSRs compared with electromechanical relays are discussed. Inductive loads are reviewed and snubbing suggestions made. Parts lists are given for SSRs for voltages of 120 and 240 V rms and currents from 5 to 113 A rms. Also described are circuits to give ac and CMOS compatibility.

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## INTRODUCTION

AC solid-state relays are being used in applications such as traffic control equipment, furnace heater controls and motor controls. This note describes some typical circuits and discusses the application of these comparatively new devices.

### What Is It? – Some Definitions

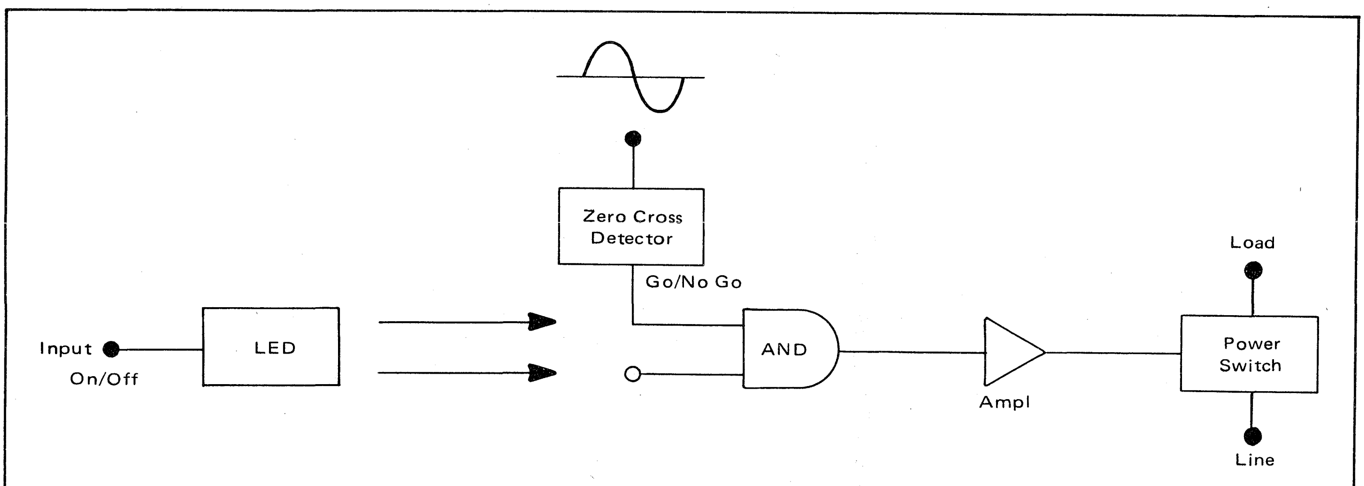
The Solid-State Relay (SSR) as described below, is a relay function with:

a. Four Terminals (Two Input, Two Output)
b. DC or AC Input
c. Optical Isolation Between Input and Output
d. Thyristor (SCR or Triac) Output
e. Zero Voltage Switching Output (Will Only Turn On Close to Zero Volts)
f. AC Output (50 or 60 Hz)

Figure 1 shows the general format and waveforms of the SSR. The input ON/OFF signal is conditioned (perhaps only by a resistor) and fed to the Light-Emitting-Diode (LED) of an optoelectronic-coupler. This is ANDed with a GO signal that is generated close to the zero-crossing of the line, typically ≤ 10 Volts. Thus, the output is not gated ON via the amplifier except at the zero-crossing of the line voltage. The SSR output is then re-gated on at the beginning of every half-cycle until the input ON signal is removed. When this happens, the thyristor output stays on until the load current reaches zero, and then turns off.

### The Hybrid Relay

Historically the first "solid-state" relay, the hybrid relay, has a thyristor output, as in the SSR, but uses a reed relay to provide input-to-output isolation and amplification. As the reed relay is a comparatively slow switching component, synchronization with line zero-crossing is difficult. Figure 2 shows a typical Hybrid Relay circuit. Higher current relays (shown later in this note) may use an amplifying SCR.



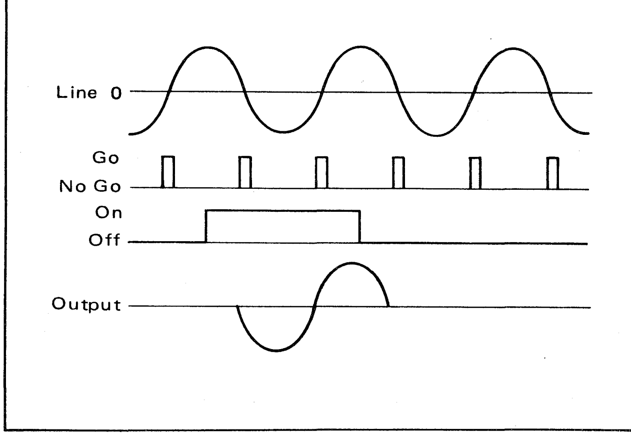




FIGURE 1 – SSR Block Diagram

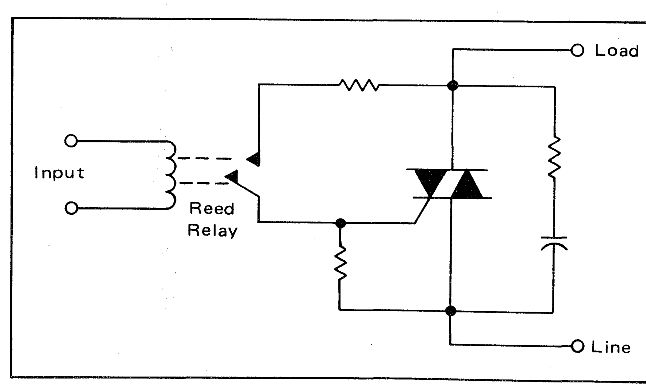



FIGURE 2 – Example of Hybrid Relay

Circuit diagrams external to Motorola products are included as a means of illustrating typical semiconductor applications; consequently, complete information sufficient for construction purposes is not necessarily given. The information in this Application Note has been carefully checked and is believed to be entirely reliable. However, no responsibility is assumed for inaccuracies. Furthermore, such information does not convey to the purchaser of the semiconductor devices described any license under the patent rights of Motorola Inc. or others.

### Advantages of SSRs

The SSR has several advantages that make it an attractive choice over its progenitor, the Electromechanical Relay (EMR) although the SSR generally costs more than its electromechanical counter-part. These advantages are:

1. No Moving Parts – the SSR is all solid-state. There are no bearing surfaces to wear, springs to fatique, assemblies to pick up dust and to rust. This leads to several other advantages.
2. No Contact Bounce – this in turn means no contact wear, arcing, or Electromagnetic Interference (EMI) associated with contact bounce.
3. Fast Operation – usually less than 10 $\mu$s. Fast turn-on time allows the SSR to be easily synchronized with line zero-crossing. This also minimizes EMI and can greatly increase the lifetime of tungsten lamps, of considerable value in applications such as traffic signals.
4. Shock and Vibration Resistance – the solid-state contact cannot be "shaken open" as easily as the EMR contact.
5. Absence of Audible Noise – this devolves from the lack of moving mechanical parts.
6. Output Contact Latching – the thyristor is a latching device, and turns off only at the load current zero-crossing, minimizing EMI.
7. High Sensitivity – the SSR can readily be designed to interface directly with TTL and CMOS logic, simplifying circuit design.
8. Very Low Coupling Capacitance Between Input and Output. This is a characteristic inherent in the optoelectronic-coupler used in the SSR, and can be useful in areas such as medical electronics where the reduction of stray leakage paths is important.

This list of advantages is impressive, but of course, the designer has to consider the following:

### Disadvantages of SSRs

1) Voltage Transient Resistance – the ac line is not the clean sine wave obtainable from a signal generator. Superimposed on the line are voltage spikes from motors, solenoids, EMRs (ironical), lightning, etc. The solid-state components in the SSR have a finite voltage rating and must be protected from such spikes, either with RC networks (snubbing), zener diodes, MOVs or selenium voltage clippers. If not done, the thyristors will turn on for part of a half cycle, and at worst, they will be permanently damaged, and fail to block voltage. For critical applications a safety margin on voltage of 2 to 1 or better should be sought.

   The voltage transient has at least two facets – the first is the sheer amplitude, already discussed. The second is its frequency, or rate-of-rise of voltage (dv/dt). All thyristors are sensitive to dv/dt to some extent, and the transient must be snubbed, or "soaked up," to below this level with an RC network. Typically this rating ("critical" or "static" dv/dt) is 50 to 100 V/$\mu$s at maximum temperature. Again the failure mode is to let through, to a half-cycle of the line, though a high energy transient can cause permanent damage. Table I gives some starting points for snubbing circuit values. The component values required depend on the characteristics of the transient, which are usually difficult to quantify. Snubbing across the line as well as across the SSR will also help.

| Load Current A rms | Resistance $\Omega$ | Capacitance $\mu$F |
|---|---|---|
| 5.0 | 47 | 0.047 |
| 10 | 33 | 0.1 |
| 25 | 10 | 0.22 |
| 40 | 22 | 0.47 |

**TABLE I – Typical Snubbing Values**

2) Voltage Drop – The SSR output contact has some offset voltage – approximately 1 V, depending on current, causing dissipation. As the thyristor has an operating temperature limit of +125°C, this heat must be removed, usually by conduction to air via a heat sink or the chassis.
3) Leakage Current – When an EMR is open, no current can flow. When an SSR is open however, it does not have as definite an OFF condition. There is always some current leakage through the output power switching thyristor, the control circuitry, and the snubbing network. The total of this leakage is usually 1 to 10 mA rms – three or four orders of magnitude less than the on-state current rating.
4) Multiple Poles – are costly to obtain in SSRs, and three phase applications may be difficult to implement.
5) Nuclear Radiation – SSRs will be damaged by nuclear radiation.

### Triac SSR Circuit

Many SSR circuits use a triac as the output switching device. Figure 3 shows a typical Triac SSR circuit. The control circuit is used in the SCR relay as well, and is defined separately. The input circuit is TTL compatible. Output snubbing for inductive loads will be described later.

A sensitive-gate SCR (SCR1) is used to gate the power triac, and a transistor amplifier is used as an interface between the optoelectronic-coupler and SCR1. (A sensitive-gate SCR and a diode bridge are used in preference to a sensitive gate Triac because of the higher sensitivity of the SCR.)

### Control Circuit Operation

The operation of the control circuit is straightforward. The AND function of Figure 1 is performed by the wired-NOR collector configuration of the small-signal transistors Q1 and Q2. Q1 clamps the gate of SCR1 if optoelectronic-coupler OC1 is off. Q2 clamps the gate if there is sufficient

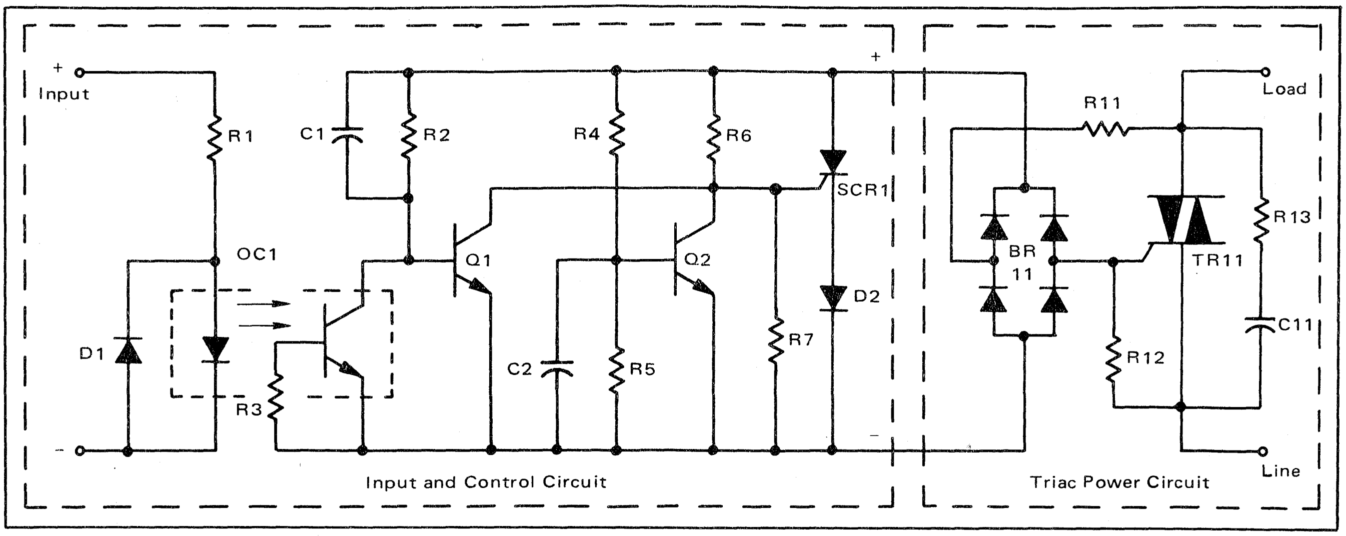



**FIGURE 3 — Triac SSR Circuit**

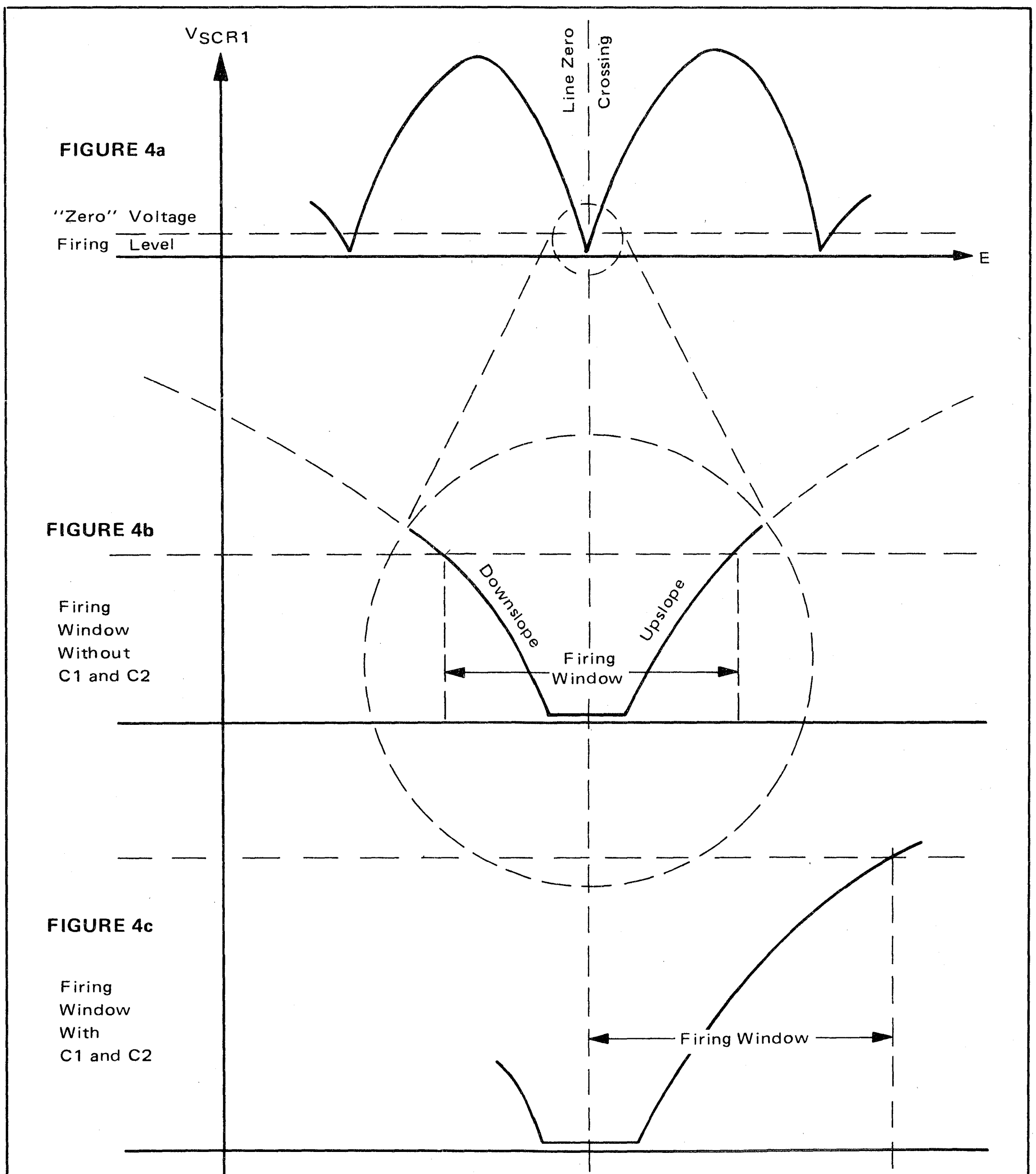



**FIGURE 4 — Firing Windows**

voltage at the junction of the potential divider R4, R5 to overcome the $V_{BE}$ of Q2. By judicious selection of R4 and R5, Q2 will clamp SCR1's gate if more than approximately 5 Volts appear at the anode of SCR1; i.e., Q2 is the zero-crossing detector.

If OC1 is on, Q1 is clamped off, and SCR1 can be turned on by current flowing down R6, only if Q2 is also off – which it is only at zero crossing.

The capacitors are added to eliminate circuit race conditions and spurious firing, time ambiguities in operation. Figure 4a shows the full-wave rectified line that appears across the control circuit. The "zero" voltage firing level is shown in Figure 4a and 4b, expanded in time and voltage. A race condition exists on the up-slope of the second half-cycle in that SCR1 may be triggered via R6 before Q1 has enough base current via R2 to clamp SCR1's gate. C1 provides current by virtue of the rate of change of the supply voltage, and Q1 is turned on firmly as the supply voltage starts to rise, eliminating any possibility of unwanted firing of the SSR; thus eliminating the race condition.

This leaves the possibility of unwanted firing of the SSR on the down-slope of the first half cycle shown. C2 provides a phase shift to the zero voltage potential divider, and Q2 is held on through the real zero-crossing. The resultant window is shown in Figure 4c.

### Control Circuit Components

The parts list for the control circuit at two line voltages is shown in Table II.

R1 limits the current in the input LED of OC1. The input circuit will function over the range of 3 to 33 Vdc.

D1 provides reverse voltage protection for the input of OC1.

D2 allows the gate of SCR1 to be reverse biased, providing better noise immunity and dv/dt performance.

R7 eliminates pickup on SCR1's gate through the zero-crossing interval.

SCR1 is a sensitive gate SCR; the 2N5064 is a TO-92 device, the 2N6240 is a Case 77 device.

Alternatives to the simple series resistor (R1) input circuit will be described later.

| | LINE VOLTAGE | |
|---|---|---|
| Part | 120 Vrms | 240 Vrms |
| C1 | 220 pF, 20%, 200 Vdc | 100 pF, 20%, 400 Vdc |
| C2 | 0.022 μF, 20%, 50 Vdc | 0.022 μF, 20%, 50 Vdc |
| D1 | 1N4001 | 1N4001 |
| D2 | 1N4001 | 1N4001 |
| OC1 | MOC1005 | MOC1005 |
| Q1 | MPS5172 | MPS5172 |
| Q2 | MPS5172 | MPS5172 |
| R1 | 1 kΩ, 10%, 1 W | 1 kΩ, 10%, 1 W |
| R2 | 47 kΩ, 5%, 1/2 W | 100 kΩ, 5%, 1 W |
| R3 | 1 MΩ, 10%, 1/4 W | 1 MΩ, 10%, 1/4 W |
| R4 | 110 kΩ, 5%, 1/2 W | 220 kΩ, 5%, 1/2 W |
| R5 | 15 kΩ, 5%, 1/4 W | 15 kΩ, 5%, 1/4 W |
| R6 | 33 kΩ, 10%, 1/2 W | 68 kΩ, 10%, 1 W |
| R7 | 10 kΩ, 10%, 1/4 W | 10 kΩ, 10%, 1/4 W |
| SCR1 | 2N5064 | 2N6240 |

**TABLE II – Control Circuit Parts List**

### Power Circuit Components

The parts list for the Triac power circuit is shown in Table III for several rms current ratings, and two line voltages. The metal Triacs are in the half-inch pressfit package in the isolated stud configuration; the plastic Triacs are in the TO-220 Thermowatt package. R12 is chosen by calculating the peak control circuit off-state leakage current and ensuring that the voltage drop across R12 is less than the $V_{GT}$(min) of the Triac.

C11 must be an ac rated capacitor, and with R13 provides some snubbing for the Triac. The values shown for this network are intended more for inductive load commutating dv/dt snubbing than for voltage transient suppression. Consult the individual data sheets for the dissipation, temperature, and surge current limits of the Triacs.

### Triacs and Inductive Loads

The Triac is a single device which to some extent is the equivalent of two SCRs inverse parallel connected; certainly this is so for resistive loads. Inductive loads however, can cause problems for Triacs, especially at turn-off.

A Triac turns off every line half-cycle when the line current goes through zero. With a resistive load, this coincides with the line voltage also going through zero. The

| Voltage | | 120 Vrms | | | | 240 Vrms | | | |
|---|---|---|---|---|---|---|---|---|---|
| RMS Current Amperes | | 8.0 | 12 | 25 | 40 | 8.0 | 12 | 25 | 40 |
| BR11 | | MDA102 | MDA102 | MDA102 | MDA102 | MDA104 | MDA104 | MDA104 | MDA104 |
| | C11, μF (10%, line voltage ac rated) | 0.047 | 0.047 | 0.1 | 0.1 | 0.047 | 0.047 | 0.1 | 0.1 |
| | R11 (10%, 1 W) | 39 | 39 | 39 | 39 | 39 | 39 | 39 | 39 |
| | R12 (10%, 1/2 W) | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 |
| | R13 (10%, 1/2 W) | 620 | 620 | 330 | 330 | 620 | 620 | 330 | 330 |
| TR11 | Plastic | 2N6342 | 2N6342A | – | – | 2N6343 | 2N6343A | – | – |
| | Metal | – | MAC40799 | 2N6163 | MAC4688 | – | MAC40800 | 2N6164 | MAC4689 |

**TABLE III – Triac Power Circuit Parts List**

Triac must regain blocking state before there are more than 1 or 2 Volts of the reverse polarity across it – at 120 Vrms, 60 Hz line this is approximately 30 μs. The Triac has not completely regained its off-state characteristics, but does so as the line voltage increases at the 60 Hz rate.

Figure 5 indicates what happens with an inductive or lagging load. The on signal is removed asynchronously and the Triac, a latching device, stays on until the next current zero. As the current is lagging the applied voltage, the line voltage at that instant appears across the Triac. It is this rate-of-rise of voltage, the commutating dv/dt, that must be limited in Triac circuits, usually to a few volts per microsecond.

SCRs have less trouble as each device has a full half-cycle to turn off and, once off, can resist dv/dt to the critical value of 50 to 100 V/μs.

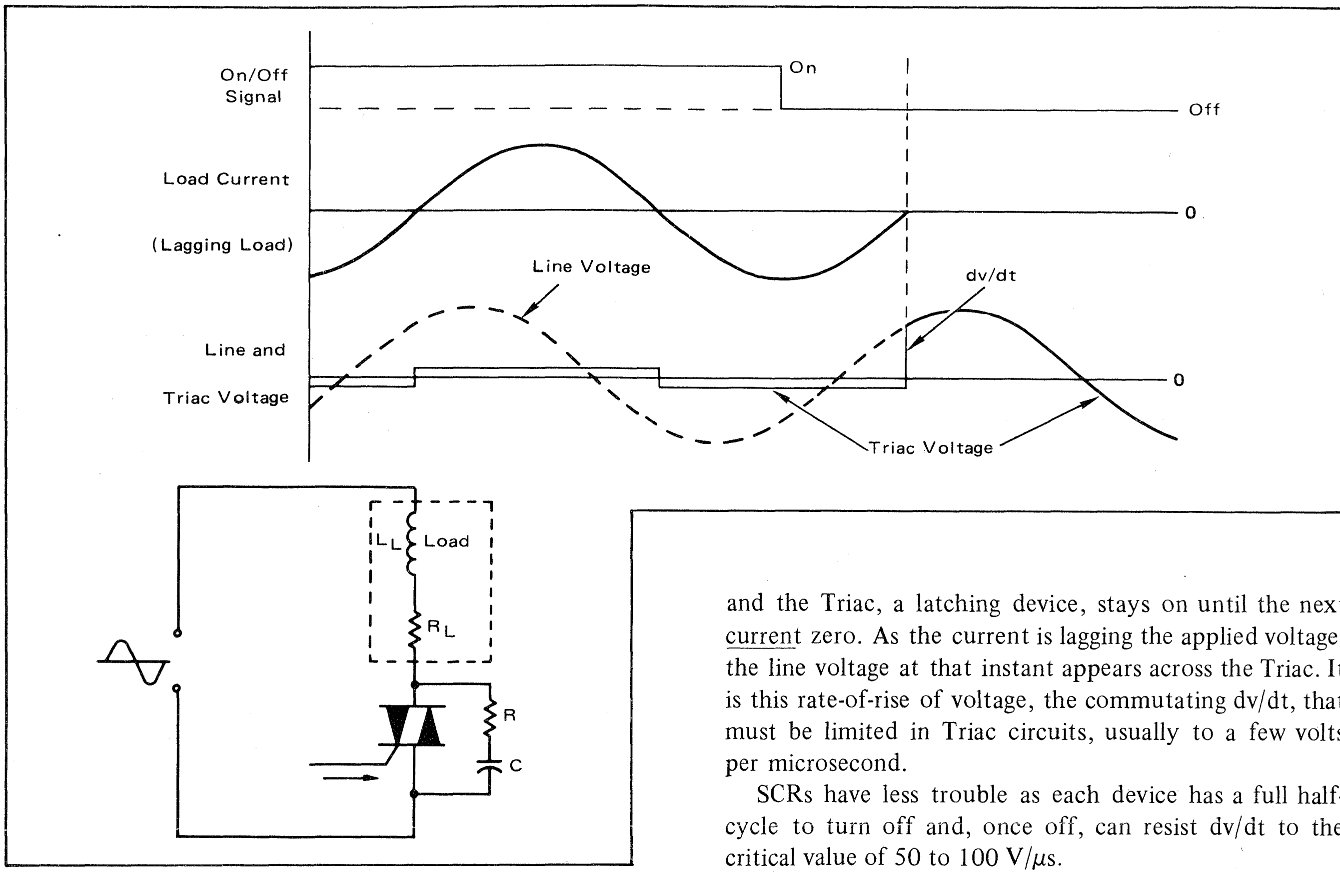



**FIGURE 5 – Commutating dv/dt**

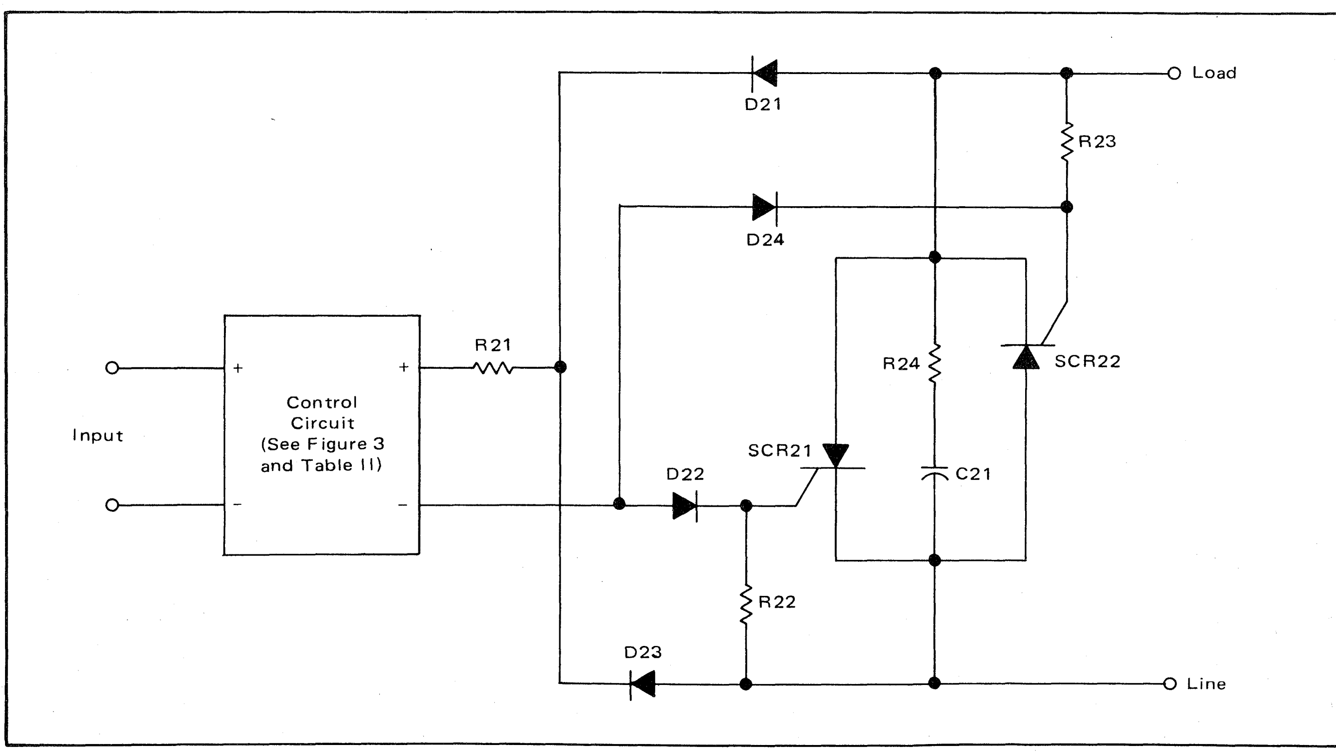



**FIGURE 6 – SCR SSR Circuit**

### Choosing the Snubbing Components

There are no easy methods for selecting the values of R and C in Figure 5 required to limit commutating dv/dt. The circuit of Figure 5 is a damped tuned circuit comprised by R, C, $R_L$ and $L_L$, and to a minor extent the junction capacitance of the Triac. At turn-off this circuit receives a step impulse of line voltage which depends on the power factor of the load. Assuming the load is fixed, which is normally the case, the designer can vary R and C. C can be increased to decrease the commutating dv/dt; R can be increased to decrease the resonant over-ring of the tuned circuit – to increase damping. This can be done empirically, beginning with the values for C11 and R13 given in Table III, and aiming at close to critical damping and the data sheet value for commutating dv/dt. Reduced temperatures, voltages, and off-going di/dt (rate-of-change of current at turn-off) will give some safety margin.

### SCR SSR Circuit

The inverse parallel connected Silicon Controlled Rectifier (SCR) pair (shown in Figure 6) is less sensitive to commutating dv/dt. Other advantages are the improved thermal and surge characteristics of having two devices; the disadvantage is increased cost.

The SCR power circuit can use the same control circuit as the Triac Circuit shown in Figure 3. In Figure 6, for positive load terminal and when the control circuit is gated on, current flows through the load, D21, R21, SCR1, D22, the gate of SCR21 and back to the line, thus turning on SCR21. Operation is similar for the other line polarity. R22 and R23 provide a path for the off-state leakage of the control circuit and are chosen so that the voltage dropped across them is less than the $V_{GT}$(min) of the particular SCR. R24 and C21 provide snubbing and line transient suppression, and may be chosen from Table I or from the C11, R13 rows of Table III. The latter values will provide less transient protection but also less off-state current, with the capacitor being smaller. Other circuit values are shown in Table IV.

Consult the individual data sheets for packages and dissipation, temperature, and surge current limits.

While the SCRs have much higher dv/dt commutation ability, with inductive loads, attention should be paid to maintaining the dv/dt below data sheet levels.

## ALTERNATE INPUT CIRCUITS

### CMOS Compatible

The 1 kΩ resistor, R1, shown in Figure 3 and Table II, provide an input that is compatible with the current that a TTL gate output can sink. The resistor R1 must be changed for CMOS compatability, aiming at 2 mA in the LED for adequate performance to 100°C. At 2 mA do not use the CMOS output for any other function, as a LOGIC 0 or 1 may not be guaranteed. Assume a forward voltage drop of 1.1 V for the LED, and then make the Ohm's Law calculation for the system dc supply voltage, thus defining a new value for R1.

### TTL/CMOS Compatible

To be TTL compatible at 5 Volts and CMOS compatible over 3 to 15 Volts, a constant current circuit is required, such as the one in Figure 7. The current is set by

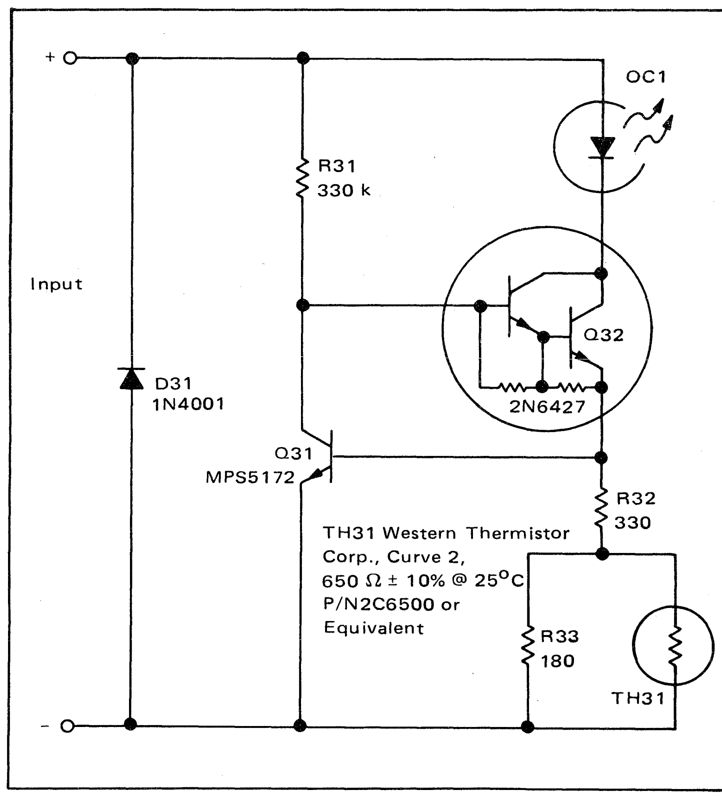



**FIGURE 7 — TTL/CMOS Compatible Input**

| Voltage | | 120 Vrms | | | | | 240 Vrms | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| RMS Current Amperes | | 5.0 | 11 | 22 | 49 | 113 | 5.0 | 11 | 22 | 49 | 113 |
| C21 (10%, line voltage ac rated) | | ◄ SEE TEXT ► | | | | | | | | | |
| D21-24 | | 1N4003 | 1N4003 | 1N4003 | 1N4003 | 1N4003 | 1N4004 | 1N4004 | 1N4004 | 1N4004 | 1N4004 |
| R21 (10%, 1 W) | | 39 | 39 | 39 | 39 | 39 | 39 | 39 | 39 | 39 | 39 |
| R22, 23 (10%, 1/2 W) | | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 |
| R24 | | ◄ SEE TEXT ► | | | | | | | | | |
| SCR21, 22 | Plastic | 2N6239 | 2N4442 | 2N6402 | – | – | 2N6240 | 2N4443 | 2N6403 | – | – |
| | Metal | – | 2N4170 | 2N6168 | 2N6172 | MCR82-20 | – | 2N4172 | 2N6169 | 2N6173 | MCR82-40 |

**TABLE IV — SCR Power Circuit Parts List**

the $V_{BE}$ of Q31 and the resistance of the R32, R33, and thermistor TH31 network, and is between 1 and 2 mA, higher at high temperatures to compensate for the reduced transmission efficiency of optoelectronic-couplers at higher temperature. The circuit of Figure 7 gives an equivalent impedance of approximately 50 kΩ. The circuit performs adequately over 3 to 33 Vdc and -40 to +100°C. Note that though the SSR is protected against damage from improperly connected inputs, the external circuit is not, as D31 acts as a bypass for a wrongly connected input driver.

### AC Line Compatible

To use SSRs as logic switching elements is inefficient, considering the availability and versatility of logic families such as CMOS. When it is convenient to trigger from ac, a circuit such as shown in Figure 8 may be used. The capacitor C41 is required to provide current to the LED of OC1 through the zero-crossing time. An in-phase input voltage gives the worst case condition. The circuit gives 2 mA minimum LED current at 75% of nominal line voltage.

### REFERENCES


1. Solid-State Relays – A Guide To Their Design and Applications. Phillip Johnson. *EDN*, 10/5/73.

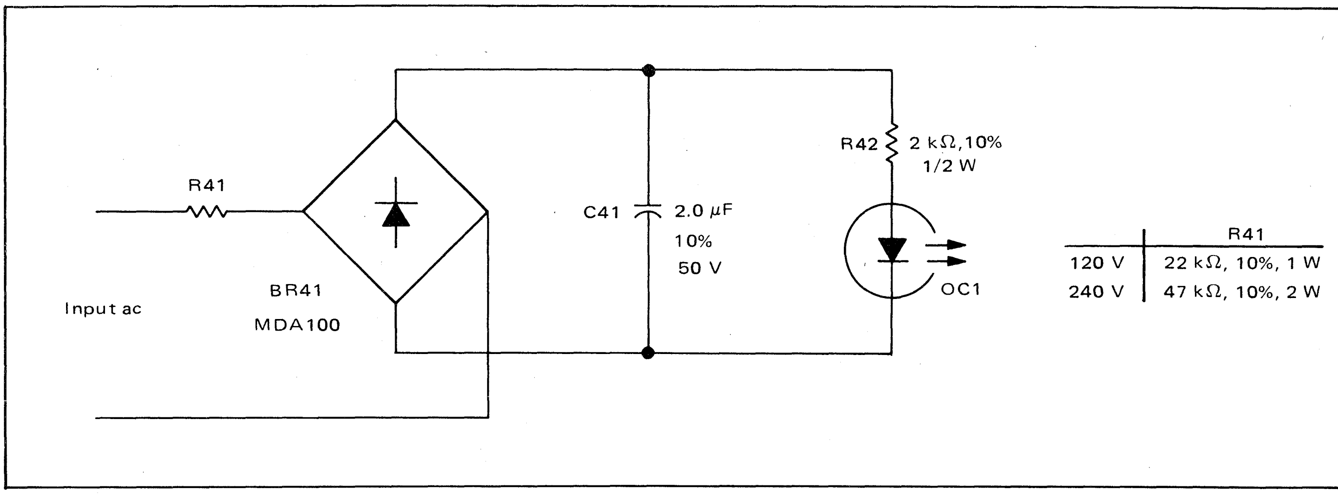




**FIGURE 8 — AC Compatible Input**