Introduction To Solid State Relays

Definition:

A SSR (solid state relay) can perform many tasks that an EMR (electromechanical relay) can perform. The SSR differs in that it has no moving mechanical parts within it. It is essentially an electronic device that relies on the electrical, magnetic and optical properties of semiconductors, and electrical components to achieve its Isolation and relay switching function.

Over the last ten years many standards have been set regarding SSR packages, most notably the rectangular package introduced by us in the early 1970s which has now become an industry standard for power switching using SSRs, with models ranging from 1 to 125 A.

Applications:

Since its introduction the SSR, as a technology, has gained acceptance in many areas, which had previously been the sole domain of the EMR or the Contactor. The major growth areas have come from Industrial Process Control applications, particularly heat/cool temperature control, motors, lamps, solenoids, valves, transformers. The list of applications for the SSR is almost limitless.

The following are typical examples of SSR applications: manufacturing equipment, food equipment, security systems, industrial lighting, fire and security systems, dispensing machines, production equipment, on-board power control, traffic control, instrumentation systems, vending machines, test systems, office machines, medical equipment, display lighting, elevator control, metrology equipment, entertainment lighting.

The Advantages of the Solid State Relay:

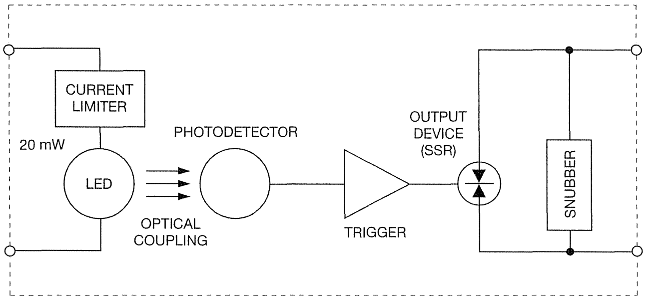
When utilized in the correct manner for the intended application, the SSR provides many of the characteristics that are often elusive in the EMR; a high degree of reliability, long service life, significantly reduced electromagnetic interference, fast response and high vibration resistance are significant benefits from SSRs.

In today's environment we have all come to demand, rather than to expect, improved performance from the components that we use. The SSR offers Designers, Engineers and Maintenance Engineers significant advantages over alternative technologies, further enhanced by the use of Surface Mount Solid State circuitry. These advantages are namely consistency of operation and longer usable lifetime. The SSR has no moving parts to wear out or arcing contacts to deteriorate, which are often the primary cause of failure within an EMR. The long term reliability of components used within SSRs has become well established throughout industry, and with no moving parts to become fractured, detached, or to resonate during operation, makes the SSR solution more robust when used in unfriendly environments.

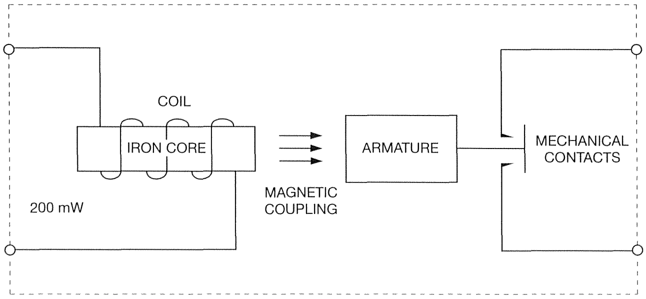
The Advantages of SSRs

- Zero voltage turn-on, low EMI/ RFI
- Random turn-on, proportional control
- Long life (reliability) > 10^9 operations
- No contacts – handles high inrush current loads
- No acoustical noise
- Microprocessor compatible
- Design flexibility
- Fast response
- No moving parts
- No contact bounce

In terms of internal design, the SSR and the EMR are fundamentally similar in that each has an input electrically isolated from the output that controls a load. Fig. 1 shows the basic configurations of both the SSR and EMR. In the case of the SSR, the isolation is achieved by photocoupling and transformer coupling, and in the EMR by means of a magnetic coupling.



(A) AC solid state relay (SSR).



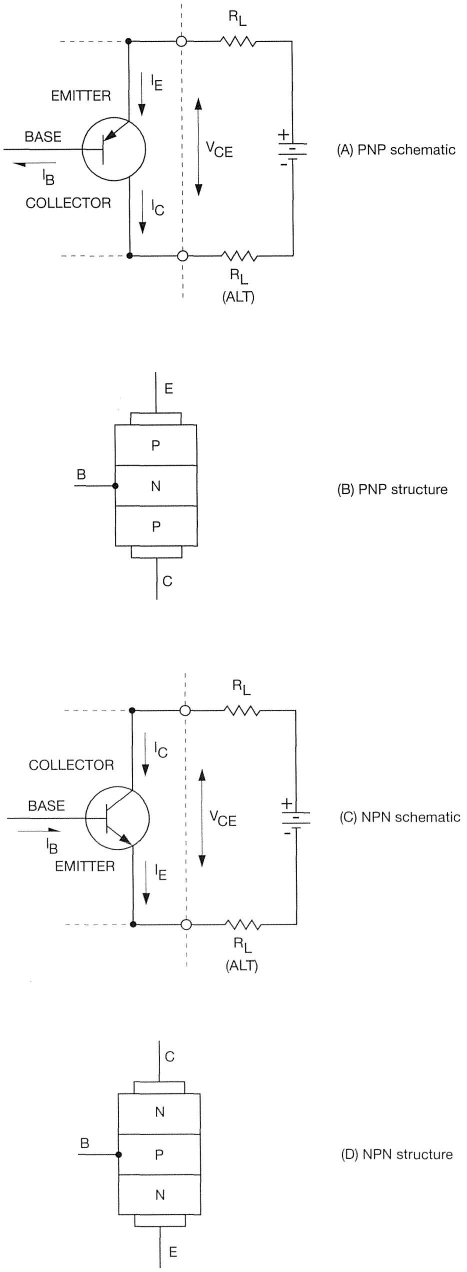
(B) Electromagnetic relay (EMR)

Fig. 1 Solid state relay and electromagnetic configurations.

Comparing the two technologies, the input control circuit of the SSR is functionally equivalent to the coil of the EMR, while the output device of the SSR performs the switching function of the EMR contacts. The operating speed of the EMR is dependent upon the time it takes for its mechanical mass to react to the application and removal of a magnetic field. Operating speed of the SSR is primarily determined by the switching speed of the output device, typically much faster – microseconds for DC SSRs compared to milliseconds for EMRs. In most AC SSRs, response time is related to phase angle and frequency of the line, and in the case of the zero voltage/current types, may be deliberately prolonged. In the case of AC input control, the operating speeds of both the EMR and SSR are similarly extended due to phase angle and filtering considerations.

Output Switching Devices

The AC or DC designation of an SSR generally describes its output switching capability as opposed to its input control voltage requirements, which can also be AC or DC.



(A) PNP schematic

(B) PNP structure

(C) NPN schematic

(D) NPN structure

Fig. 2 PNP and NPN transistor types.

DC Switches

The output of a DC SSR can be a bipolar power transistor, with the emitter and collector connected to the output terminals, or a power MOSFET. Fig. 2 illustrates the schematic and structure of the two bipolar transistors types, PNP and NPN, the choice of which is primarily a matter of economics, since relay isolation makes it impossible to tell the difference externally. Current flow in the transistors is described by the expression:

$$I_C = I_E - I_B$$

Referring to Fig. 3, a family of curves is shown indicating the relationship between base current I_B and collector I_C. Collector current increases as base current increases along a load line between points "A" and "B" defined as the active region and determined by the load resistance. In switching devices such as SSRs, this region is traversed very quickly (typically less than 10 microseconds), as the drive current from the preceding stage is either at I_{BO} for the off state, or in excess of I_{B6} for the on state. The transition is usually hastened by built-in positive feedback or hysteresis, which also prevents "hang up" and possible destruction in the high dissipation (active) region caused by the slow transition of an input signal.

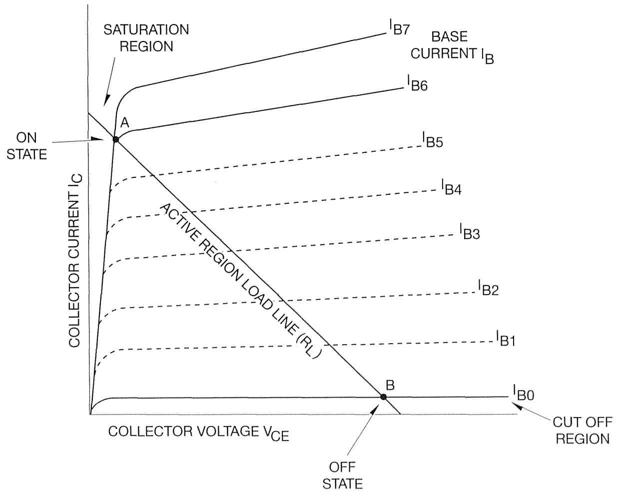
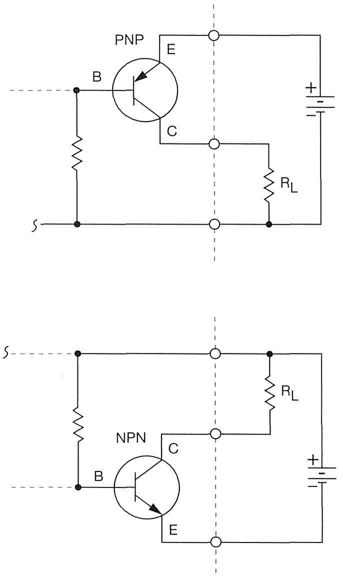


Fig. 3 Transistor voltage-current characteristic curves.

The ratio of base current to collector current is the gain or amplification factor of the transistor:

$$I_B : I_C = \text{Gain}$$

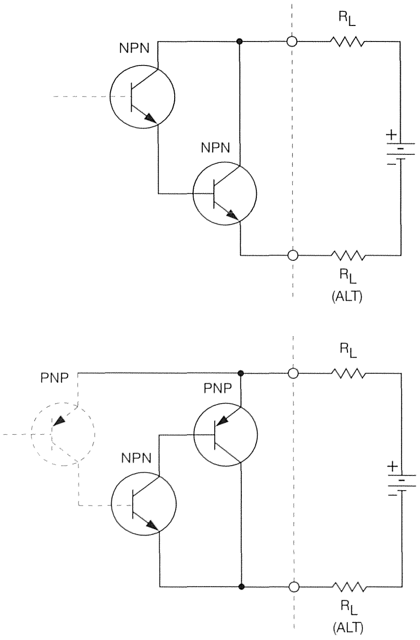
In DC SSRs the degree of amplification is directly related to the small available photocoupler current. As a result, the higher the output current rating, the more stages of gain are required. As long as polarity is observed, the load can be switched in series with either of the relay output terminals, as is the case for AC SSRs. This is true for any two terminal isolated switching device. However, there are three terminal DC output configurations where the load side of the power supply is connected to a separate terminal on the SSR, as shown in Fig. 4. The purpose of the third terminal may be to provide entry for additional internal power, or full base drive in order to saturate the output transistor and achieve a lower voltage drop (0.2 volt). The load is then dedicated to one terminal of the relay output, while the other is common to both drive and load circuits. The output transistor type, shown in what is described as the common-emitter configuration, also becomes a consideration – PNP for a ground referenced load (Fig. 4A), and NPN for a positive reference load (Fig. 4B). The transistor types could be reversed and used in the common-collector (emitter-follower) mode, but would defeat the purpose of achieving the lower (saturating) voltage drop.



(A) PNP with ground (-) referenced load

(B) NPN with positive (+) referenced load

Fig. 4 Three-terminal, DC output, common emitter configurations.



(A) NPN Darlington output

(B) Complementary output

Fig. 5 Two-terminal, gain compounding, DC output configurations.

To maximize signal gain with two-terminal outputs, the output transistor and its driver are usually wired in a Darlington or a complementary gain compounding configuration (Fig. 5) where the amplification factor is approximately the product of the two stages. In either case, the output forward voltage drop is in the region of 1.2 volt DC, which is similar to AC SSRs and considered acceptable for most applications. Since any number of alternating PNP/NPN stages can be added to increase gain with no increase in voltage drop, the complementary output of Fig. 5B is preferred. Where the lower voltage drop is required, the only alternatives are the previously described three-terminal outputs of Fig. 4, or by similarly adding an external transistor and driving it in the saturating mode. This technique can also be used to increase current or voltage switching capability in applications where no suitable SSR exist. The external transistor can, of course, be added for current gain in the two-terminal gain compounding mode; however, it will augment the existing 1.2 volt DC drop of the SSR by about another 0.6 volt.

In summation, the more common two-terminal output has the higher voltage drop of approximately 1.2 volts, but it provides the load flexibility of a true relay. The three-terminal output on the other hand, even with input/output isolation, polarizes the load with respect to the common power supply terminal, but it has the advantage of lower voltage drop (0.2 volt) and, in some cases, lower off state leakage current.

AC Switches

The most commonly used output devices in AC SSRs are Silicon Controlled Rectifiers (SCRs) and Triacs, generally known as thyristors (so named because of their similarity to the gas discharge thyratrons of the vacuum tube era). Thyristors are a family of semiconductor switches whose bistable state depends on regenerative feedback within a basic four-layer PNPN structure. Their attractiveness for SSR use lies in their ability to switch high power loads, with practical values up to 120 amperes and high AC line voltages, up to 480 volts RMS, with less than 50 mA of gate drive. In addition, they can withstand one-cycle peak-current surges in excess of ten times their steady-state ratings.

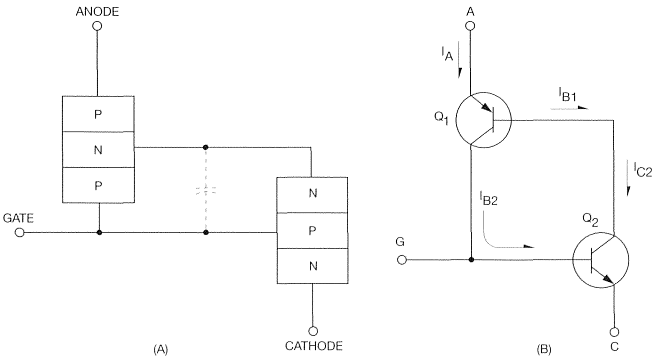
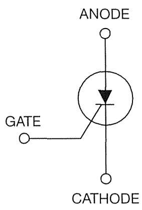


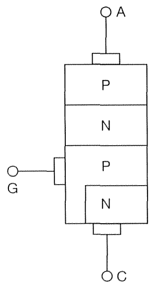
Fig. 6 Two-transistor analogy of SCR operation.

The SCR is a three-terminal unidirectional device that blocks current in both directions in its off state, and performs much like a rectifier in its on state, thus a "controlled" rectifier. The SCR is best illustrated by the two-transistor analogy shown in Fig 6. While the transistor can be used as an On/Off switch, it is essentially a continuously variable current device where the collector-emitter current flow is controlled by a small, but proportional, amount of base-emitter current. The SCR, on the other hand, has only two states, on or off. Once it is triggered on by a small briefly applied gate signal, it cannot be turned off by its gate. Only with a reversal or reduction of anode to cathode voltage and current below a critical level will the SCR revert to its blocking off state.

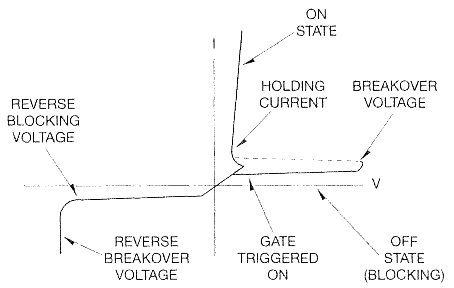
The regenerative (latching) characteristic of the thyristor provides its high current and surge capability, but it is also responsible for the thyristor's sensitivity to sharply rising voltages, a less desirable characteristic known as dv/dt, or rate effect. This phenomenon causes inadvertent turn-on, without the benefit of a gate signal. The capacitor shown in A of Fig. 6 represents the internal SCR capacitance through which a rising "anode" voltage can inject a turn-on signal into the gate, resulting in a dv/dt turn-on. In a SSR, the built-in snubber (RC) network, which limits the rate of rise of the applied voltage, largely controls this effect. The rate above which turn-on can occur, usually specified in the catalogue as minimum dv/dt, is expressed in terms of volts per microsecond, typically 500 volts per microsecond. The schematic symbol for the SCR and a typical SCR structure are shown in Figs. 7A and B. The structure represents a conventional "edge" or "center" gate fired device commonly used in SSRs.



(A) Schematic symbol



(B) PNPN structure

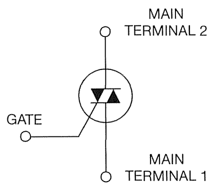


(C) Voltage-current characteristic

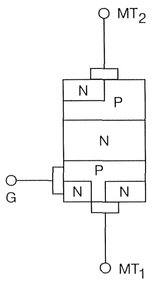
Fig. 7 Undirectional thyristor (SCR).

The triac is a three-terminal bidirectional device that blocks current in its off state; but, unlike an SSR, the triac conducts in either direction when triggered on by a single gate signal. As the schematic symbol implies (Fig. 8A) the triac is a true AC switch. Its structure (Fig. 8B) is essentially that of an inverse parallel pair of PNPN switches integrated into one device. Though the power terminals appear symmetrical, they are designated MT_1 and MT_2 for measurement purposes. The triac gate is associated with the MT_1 terminal similar to the gate-cathode relationship of the SCR. Apart from the uniqueness of a single gate controlling oppositely polarized switches with a common signal, the switching characteristics can be likened to those of a pair of SCRs, as can be seen from the voltage current characteristic of Fig. 8C. Even though the two switches are combined into one device, they still exhibit individual characteristics, such as different breakdown voltages, holding currents, and trigger levels.

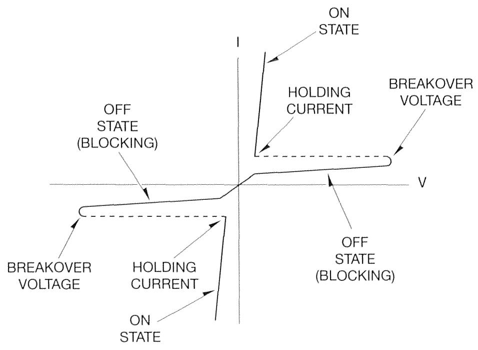
Triacs do have a limitation compared with a pair of SCRs in that the commutating dv/dt (the dv/dt applied to the switch at turn-off) can be as low as 5V/μS. For a switch consisting of a pair of SCRs, dv/dt capability at turn-off is the critical dv/dt rating, 500V/μS, so a 100 times improvement over a triac.



(A) Schematic symbol



(B) Parallel PNPN structures



(C) Voltage-current characteristic

Fig. 8 Bidirectional thyristor (triac).

SSR Operation

In a bid to increase the understanding of SSRs, an SSR Operational description is included. It has to be said that an in-depth understanding of the internal circuitry of an SSR and how it functions are not in themselves a prerequisite to the use of SSR in many applications.

Most SSRs in the higher current ranges are offered with either AC or DC control options. Indeed many have some form of current limiting at their input in order to provide a practical operating voltage range.

DC Inputs

Figs. 9A and B illustrate two typical DC input circuits for controlling current through the photocoupler LED. The low end of the input range is tailored to provide the minimum input current required to operate the SSR, at the specified turn-on (must on) voltage (typically 3 volts DC). The high end of the range is dictated by dissipation in the current limiting component (typically 32 Vdc).

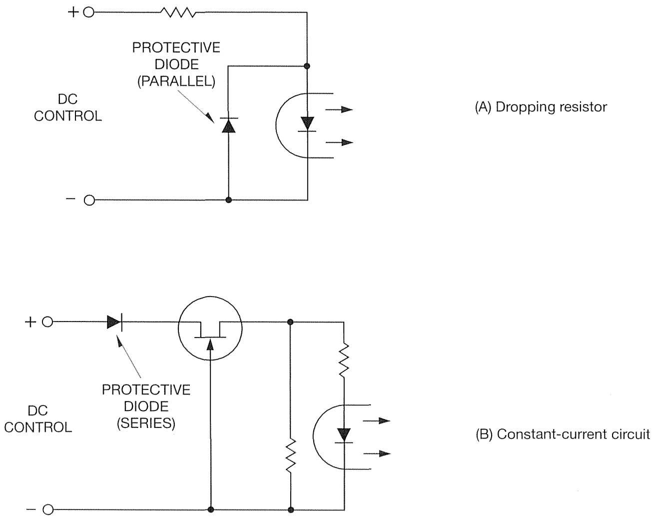


Fig. 9 Typical DC input circuits.

As a precaution against inadvertent voltage reversal, a series or inverse parallel diode is usually included in the input circuit. This protection prevents damage to the photocoupler LED and possibly the constant-current device. The series diode permits reversal up to the PIV rating of the diode with negligible reverse current flow. With an inverse parallel diode, the reverse protection is limited by dissipation in the dropping resistor, so brief voltage transients of a higher magnitude will not damage the diode or LED. However, the series diode is favored because it also raises the level of voltage noise immunity by a value equal to its forward voltage drop (0.6 V approx.)

AC Inputs

AC inputs models are usually suitable for both 120 and 240 Vac line voltages, with a typical operating range of 90 to 280 Vac and 60 K ohm input impedance. Full wave rectification is used, followed by capacitive filtering and dropping resistors, as shown in Figs. 10A and B. While both circuits work equally well, the circuit in Fig. 10B is favored as being more reliable and fail safe, since two or more components would have to fail to create an unsafe situation. In the circuit of Fig. 10A, a single diode breakdown would place a dead short across the incoming line, thus creating a possible heat hazard.

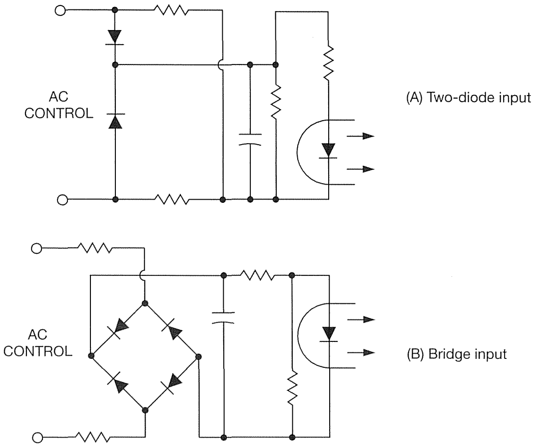


Fig. 10 Typical AC input circuits.

Either of the AC input circuits in Fig. 10A is also capable of operating from a DC source and, therefore, might be considered as AC-DC; however, SSR inputs are rarely characterized in that way. The circuit of Fig. 10B should operate with a DC control range similar to that of the AC (RMS) source. On the other hand, the circuit of Fig. 10A might have dissipation problems with the input resistors, since they would no longer operate at a 50% duty cycle. In both cases, the SSR would have the uniqueness of operating from a DC signal of either polarity.

Well designed AC input-output SSRs can operate from separate power sources operating at different frequencies, as long as they are both within the specified limits of voltage, frequency and isolation. Line frequency for both input and output is typically specified as 47 to 63 hertz, the upper limit of which is not critical for the input control power since the input is rectified and filtered. However, the upper frequency limit for an output is less flexible, especially for a triac, which has definite frequency limitations, related to its ability to commutate off. An SCR output pair is capable of operating at much higher frequencies. However, because of circuit time constraints in the drive circuitry, other SSR parameters become the limiting factors (e.g. the zero switching window may be extended and/or turn-on delayed each half cycle with eventual lock-on or lockout).

The Coupler

DC voltage is generally used to drive the coupling system regardless of the type. Even with transformer coupling, DC is used to drive an oscillator, which in turn converts the DC to AC.

Optical coupling is by far the most common means of achieving input-output isolation. With this method, the input element is generally a light emitting diode (LED) which converts the input control power into infrared light energy. This light is collected by a phototransistor or photo-SCR on the other side of the isolation gap and converted back into electrical energy.

The forward voltage drop of the LED is in the region of 1.2 to 1.8 volts at normal input currents of 2 – 20 mA. The LED reverse breakdown voltage is typically less than 3 volts and is usually protected by a series or (inverse) parallel standard diode, as previously described.

Hysteresis

Due to the wide variation in photocoupler sensitivities, the minimum voltage to guarantee “off”, which is also considered the SSR noise immunity level, is well below the forward bias threshold of the LED, typically 1 volt. This threshold can be higher where an additional diode is used in series with the LED. The 2 volt range between the “off” and the maximum operate voltage is an indeterminate state and not largely influenced by hysteresis as in the case for the pickup and dropout of an EMR. The transition is generally made rapidly in either direction, on or off, over a very narrow band, probably less than 0.1 volt, unless hysteresis is deliberately built in.

Hysteresis occurs where the input voltage required to sustain the output on state is reduced once the transition is made, lowering the turn-off voltage accordingly. Likewise, once the output returns to the off state, the input turn-on voltage is raised back to its initial level. The effect is to speed up the transition and separate the “pickup” and “dropout” control points. In doing so, any adverse threshold effects caused by a slowly ramped on control signal are minimized.

The hysteresis characteristic is not generally required in most SSR applications where the thyristors in AC relays have an inherent regenerative action of their own, and the control signals are derived from logic with clearly defined states, and rapid transition times, such as TTL. It would be of value, however, in high current, bipolar transistor, DC SSRs, where hesitation in the high dissipation, transitional region might be catastrophic to the output transistors, and the resultant “snap action” would reduce or eliminate this possibility.

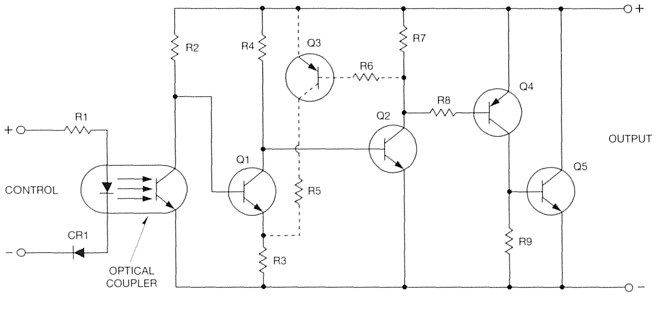


Fig. 11 Optically isolated DC SSR with hysteresis.

DC SSR

The circuit of Fig. 11 is an example of a high current DC bipolar transistor SSR incorporating hysteresis. The input control can be DC or rectified and filtered AC. R1 is a current limiting resistor to protect the LED in the photocoupler, and CR1 provides reverse voltage protection. With no input applied, the phototransistor in the optocoupler is in its off or high impedance state, and transistor Q1 is permitted to saturate. In this condition, Q2 through Q5 are off, and no power is applied to the load.

When a DC input above the threshold voltage of the LED is applied to the optocoupler, the phototransistor turns on, biasing off Q1. This allows Q2 through Q5 to turn on, and power is applied to the load. Should the turn-on signal be applied in a slowly ramped fashion, Q3 will apply a feedback voltage to the emitter of Q1, which will enhance the turn-off command at its base. This will speed up the turn-on process and thereby hasten the output transistor Q5 through its high dissipation region.

Unlike an AC SSR which has a latching function, current continues to flow in the drive circuit of a DC SSR, holding it on until the input signal is removed. The on state voltage is similar to that of an AC SSR, 0.8 volt to 1.6 volts, which gives rise to most of the package dissipation; therefore, heat sinking requirements are also similar.

The turn-off process is the reverse of the turn-on (Fig. 11). If the turn-off signal is slowly ramped down, the removal of the feedback voltage from Q3 will enhance the turn-on command at the base of Q1. This will speed up the transition to off, again preventing Q5 from hesitating in the high dissipation region.

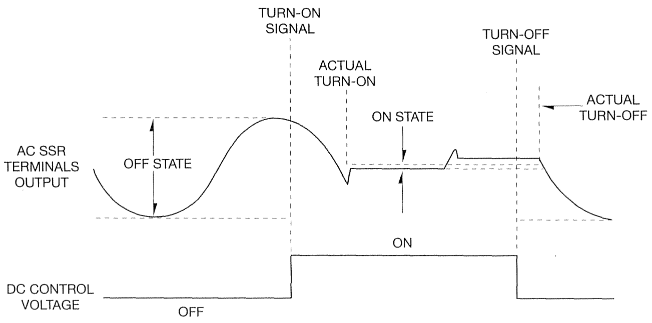


Fig. 12 Control and output terminal voltages for zero voltage turn-on relay.

Zero Switching

Zero voltage turn-on (or zero crossing), as illustrated in Fig. 12, is used in some AC SSRs to reduce electromagnetic interference and high inrush currents during initial turn-on. Without zero crossing, the load voltage is applied randomly to the load at any point in the line voltage cycle. With the zero crossing feature, the line voltage is switched to the load only when it is close to zero, typically specified with a maximum value of ± 15 volts peak. Thus, a very small change in power results, and proportionally lower EMI levels are generated. After zero crossing, the “Zero” switching voltage, which defines the switching window limits, may also be expressed in terms of phase angle, or time, converted as follows:

Voltage to phase angle (15 volts):

$$\phi = \sin^{-1} \frac{Z \text{ sw. max}}{\text{Line V RMS } (\sqrt{2})}$$

$$= \sin^{-1} \frac{15}{120 \times 1.41}$$

$$= 5^{\circ}$$

or

Phase angle to time (5°):

$$T = \frac{\frac{1}{2} \text{ cyc. ms}}{\frac{1}{2} \text{ cyc. deg}} \times \phi$$

$$= \frac{8.3}{180} \times 5$$

$$= 0.23 \text{ ms}$$

Zero current turn-off is an inherent characteristic of the thyristors used in AC SSRs, whether zero voltage is employed or not. Once triggered, the thyristor stays on for the balance of the half cycle, until switching load current drops below its "holding" level, where it turns off. For a resistive load, this point is also close to zero voltage, as shown in Fig. 12. With an inductive load, the amount of stored energy in the load is a function of the current flowing through it, which in this case is so small that inductive kickback is virtually eliminated. This is probably the most desirable feature of the SSR, when compared to the destructive effects of "arcing" contacts when switching inductive loads with an EMR.

AC SSR

The schematic of Fig. 13 illustrates a simplified optically coupled AC SSR circuit, which includes the zero turn-on feature, implemented by the inhibit action of Q1 as described in the following. The input control to the SSR can be DC or rectified and filtered AC. R1 is a current limiting resistor used to protect the LED portion of the optocoupler, and CR1 provides reverse voltage protection. With no input applied, the phototransistor in the optocoupler is in its off or high impedance state and transistor Q1 is permitted to saturate. In this condition, the pilot SCR is prevented from firing, thus the triac is off and no power is applied to the load.

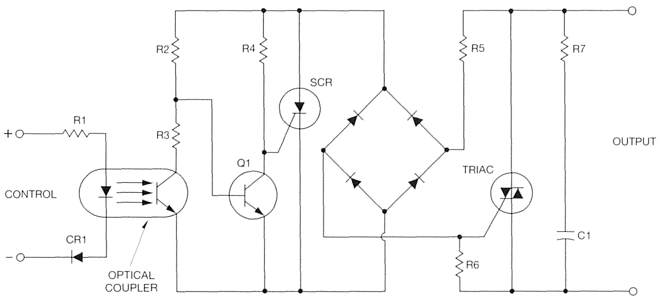


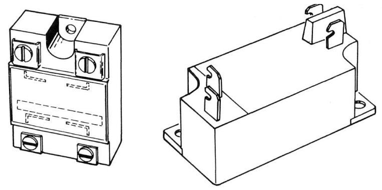
Fig. 13 Optically isolated AC SSR with zero crossing detector.

When a DC input greater than the threshold voltage of the LED is applied to the optocoupler, the phototransistor turns on. The values of R2 and R3 are such that Q1 will remain on if the instantaneous line voltage is above zero, thus holding the SSR off until the next zero crossing. When the line voltage is close to zero in either a positive or negative direction, the phototransistor holds Q1 out of saturation long enough for the pilot SCR to trigger, turning on the triac. The triac will remain on, being retriggered each half cycle, until the input control is removed and the AC line current goes through zero. The result is a continuous sine wave applied to the load, except for a small discontinuity at each zero line crossing, caused by the delay before turn-on. The snubber network of R7 and C1 is used to reduce the dv/dt applied at the output terminals of the SSR.

The minimum delay for turn-on after zero crossing depends largely on individual circuit design, while the zero detector circuit dictates the maximum delay. The initial turn-on point can occur anywhere within these allowable limits, referred to as the "window" or the "notch". Subsequent turn-on points are generally lower and fairly consistent in amplitude, with circuit gain being the primary controlling factor.

Once the output thyristor turns on, the drive circuit is deprived of power by the lower forward voltage drop of the thyristor, and current ceases to flow. This voltage, which is responsible for most of the package dissipation, varies from device to device and also as a function of the current through it, ranging from 0.8 volt to 1.6 volt. This is why the paralleling of two or more SSRs is difficult, necessitating the use of balancing resistors, etc. to preclude the possibility of current "hogging".

Solid State Relay Characteristics



Selecting the Ideal SSR

In a bid to specify the exact SSR for an application, it is important to consider the input drive requirements, output voltage, load or output current, isolation and installation requirement i.e. where is the SSR to be used and how it should be mounted. In many instances the load power will dictate whether the SSR is PCB, panel, or DIN rail mounted. In loads greater than 5 to 7 amps, a heat sink becomes necessary to remove heat from the SSR body. Certain designs include integral heat sinks, while others have dissipation characteristics that are inherently within the product.

General Parameters

The following parameters relate to isolation between parts of the SSR, namely input to output of the SSR, input to the outer case of the SSR, and the output to the outer case of the SSR.

Dielectric Strength Also referred to as "isolation voltage". Expressed as a voltage (RMS) at 50/60 hertz, that the isolated sections of the SSR can withstand without breakdown. Considered a minimum value.

Insulation Resistance The minimum resistive value (ohms) usually measured at 500 volts DC between the isolated sections of the SSR.

Maximum Capacitance Input to Output Maximum value of capacitive coupling between control and power output terminals.

Ambient Temperature Range The surrounding air temperature limits, usually given for both operating and storage conditions. The maximum operating temperature may require close consideration by the thermal dictates of heat dissipation and the possible requirement of a heat sink.

Input Parameters

Control Voltage Range The range of voltages which, when applied across the input terminals, will maintain an "on" condition across the output terminals. A negative voltage is stated separately as "Max Reverse Voltage".

Maximum Turn-On Voltage The voltage applied to the input at or above which the output is guaranteed to be in the on state. Also known as "must operate" or "pickup".

Minimum Turn-Off Voltage The voltage applied to the input at or below which the output is guaranteed to be in the off state. Also, known as "must release" or "dropout", it is often considered to be the SSR "noise immunity" level.

Maximum Input Current The maximum current drain on the driving source, usually specified at a nominal point within the control voltage range (the output is assumed to be in the on state unless "normally closed"). This defines the input power requirements, which can also be given in terms of input impedance at a given voltage.

Minimum Input Impedance Minimum impedance at a given voltage which defines input power requirements, as an alternative to, or in addition to, input current.

Maximum Turn-On Time The maximum time between the application of a turn-on control signal and the transition of the output device to its fully conducting (on) state.

Maximum Turn-Off Time The maximum time between the removal of the turn-on control signal and the transition of the output device to its blocking (off) state.

Output Parameters

Operating Voltage Range The range of voltage applied to the output, over which an SSR will continuously block or switch and otherwise perform as specified. Line frequency is either included or stated separately (AC).

Maximum Load Current The maximum steady-state load current capability of an SSR, which may be further restricted by the thermal dictates of heat sink and ambient temperature conditions.

Minimum Load Current The minimum load current required by the SSR to perform as specified. Sometimes combined with the maximum load current and given as the "operating current range".

Transient Overvoltage The maximum allowable excursion of the applied voltage that an SSR can withstand without damage or malfunction while maintaining its off state. Transients in excess of this value may turn on the SSR nondestructively if current conditions are met. The transient period, while not generally specified, can be in the order of several seconds, limited by dissipation in internal bias networks or by capacitor ratings.

Maximum Surge Current (non-repetitive) The maximum allowable momentary current flow for a specified time duration, typically one line cycle (16.6 milliseconds) for AC. Usually specified as a peak value and provided with current versus time curves. Relay control may be lost during, and immediately following, the surge.

Maximum Overcurrent (non-repetitive) Similar to the above, but typically expressed as a RMS value for one-second duration.

Maximum On State Voltage Drop The maximum (peak) voltage that appears across the SSR output terminals at full rate load current. Not to be confused with "Zero Voltage Turn-On" or "Peak Repetitive Turn-On", or used to calculate power dissipation.

Maximum I^2t Maximum non-repetitive pulse-current capability of the SSR; used for fuse selection. Expressed as "ampere squared seconds" (A^2s) with a stated pulse width, typically between 1 and 8.3 milliseconds.

Thermal Resistance, Junction to Case ($R_{\theta JC}$) Expressed as "degrees celsius per watt" (ºC/W), this value defines the temperature gradient between the output semiconductor junction (T_J) and the SSR case (T_C) for any given power dissipation. $R_{\theta JC}$ is necessary for calculating heat sink values and allowable current and temperature limits.

Power Dissipation (at Rated Current) The maximum average power dissipation (watts) resulting primarily from the effective voltage drop (power loss) in the output semiconductor. Sometimes provided in the form of curves over the current range.

Maximum Zero Voltage Turn-On The maximum (peak) off state voltage that appears across the output terminals immediately prior to initial turn-on, following the application of a turn-on control signal. Also referred to as the "notch" which defines the limits of the permissible turn-on window.

Maximum Peak Repetitive Turn-On Voltage The maximum (peak) off state voltage that appears across the output terminals immediately prior to turn-on at each subsequent half cycle following the initial half cycle, with a turn-on control signal applied. This parameter applies equally to SSRs with or without the "zero turn-on" feature.

Maximum Off State Leakage Current The maximum (RMS) off state leakage current conducted through output terminals, with no turn-on control signal applied. Usually specified at maximum rated voltage over the operating temperature range.

Minimum Off State dv/dt (Static) The rate of rise of applied voltage across the output terminals that the SSR (AC) can withstand without turning on in the absence of a turn-on control signal. Usually expressed as a minimum value at maximum rated voltage in terms of "volts per microsecond" (V/µs).

Mechanical Characteristics

Weight Is given in oz. and in gramms.

Encapsulation Specifies the material used as the SSR encapsulant.

Product Dimensions Are contained within the lines included in each product section.

Driving the SSR

To activate an SSR output, a voltage greater than that specified for maximum turn-on is applied to the input (3 volt DC typical). The off state occurs when zero or less than the minimum turn-off voltage is applied (1 volt DC typical). For an AC input type, the typical values would be 90 volts RMS for on, and 10 volts RMS for off. For an SSR designated as normally closed or form B, the previous on-off conditions would be reversed. Generally, normally open is the accepted, but undesignated, standard for the SSR.

DC is considered as being a steady-state DC voltage of one polarity, and AC is a reasonably well shaped sinusoidal waveform.

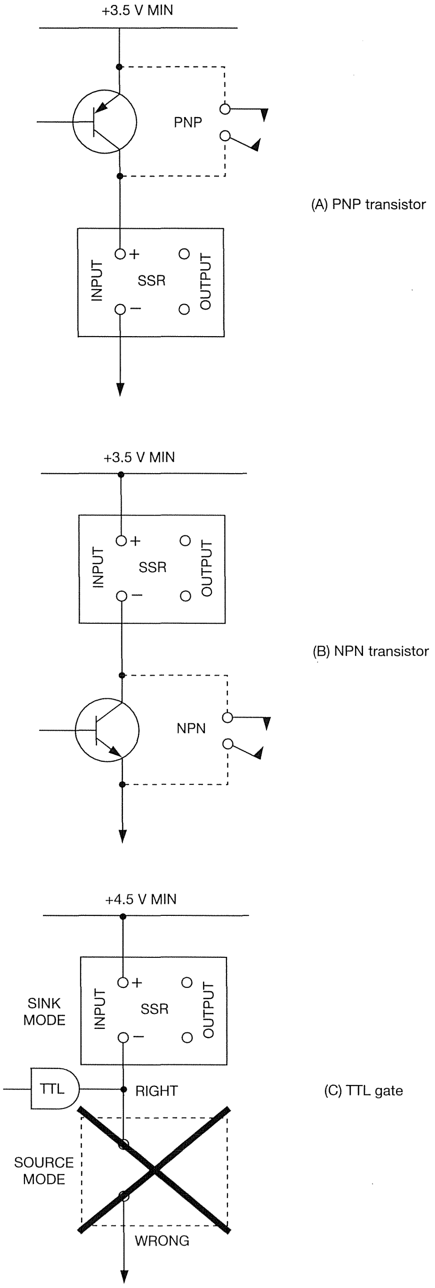
Due to consideration of input to output isolation, the switch controlling the input to an SSR can be placed in series with either of the two input terminals, assuming polarity is observed (DC). The same flexibility applies to the output side, where the load may also be placed in series with either output terminal. There are a few specialized types, usually with more than two input or output terminals, that have dedicated functions (i.e. V_{CC} logic input and common).

The activating signal may be derived from mechanical contacts or solid state devices such as those shown in Fig. 14. The minimum supply voltage through these contacts may be equal to the SSR turn-on voltage (3 volts DC typical), whereas the positively or negatively referenced transistors require a minimum supply voltage a few tenths of a volt above the specified turn-on threshold, say 3.5 volts DC. This is because of their approximate 0.2-0.4 volt on state voltage drop when driven in the grounded emitter (saturating) mode.

TTL Drive Methods

A standard TTL gate can drive most SSRs with its 16 mA sink capability, Fig. 14C. However, very few SSRs can be driven reliably with the gates' available source current of only 400 microamperes. Also, the SSR minimum voltage threshold requirements are not met in the source mode (i.e. gate output in the positive leg of the SSR).

The relationship of the TTL gate to an SSR is illustrated schematically in Fig. 15. In this configuration the SSR supply voltage and the gate V_{CC} should be common and comply with the TTL specified limits of say 5 volts ± 10%. It can be seen that with a positively referenced SSR and the gate at logical (0), Q2 is operating much like



(A) PNP transistor

(B) NPN transistor

(C) TTL gate

Fig. 14 SSR drive methods.

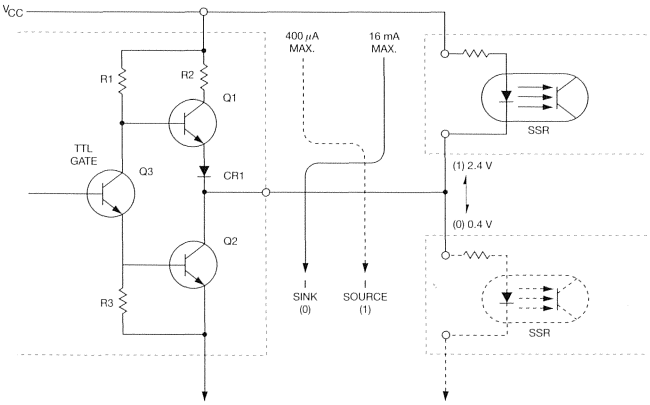


Fig. 15 Typical circuit of a TTL gate driving an SSR.

a discrete NPN transistor in the grounded-emitter saturated state. In this mode the gate can sink up to 16 mA with a maximum 0.4 volt drop. Subtracting 0.4 volt from the worst case V_{CC} of 4.5 volts, a minimum of 4.1 volts will appear across the SSR input terminals, which is sufficient to turn on most SSRs. For different supply voltage tolerances, the values would be adjusted accordingly.

With a negatively referenced SSR and the gate at logical (1), Q1 conducts, but does not saturate, since it is operating as an emitter follower (common collector). In this mode the gate can source up to 400 microamps; however, the accumulated voltage drops are:

$$R1_{(IR\ DROP)} + Q1_{VBE} + CR1_{VF}$$

The sum of these values subtracted from the worst case V_{CC} results in a minimum output voltage specified as 2.4 volts, which is 0.6 volt below the SSR turn-on threshold (assuming a 3 volt turn-on). Although some SSRs may operate satisfactorily in this mode, it is not recommended that this be done. Both the available current and the minimum voltage are considered inadequate for the typical optically isolated SSR.

It should be noted that the 2.4 volt gate output in the logical 1 state relates only to a negatively referenced load. It does not represent a voltage source to a positively referenced load (SSR), where it would appear to be greater than the off state voltage. Referring again to Fig. 15, Q2 would be off and CR1 is reverse biased, thus presenting essentially an open circuit with virtually zero potential across the SSR.

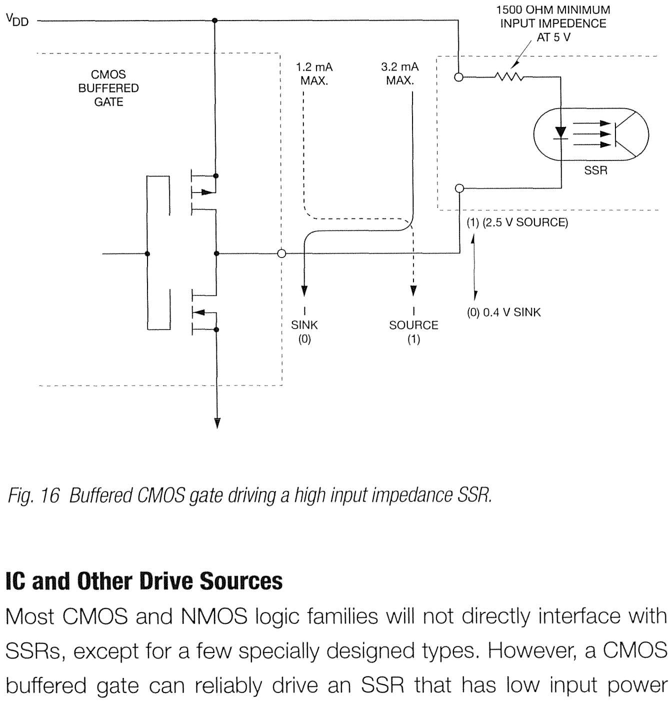


Fig. 16 Buffered CMOS gate driving a high input impedance SSR.

IC and Other Drive Sources

Most CMOS and NMOS logic families will not directly interface with SSRs, except for a few specially designed types. However, a CMOS buffered gate can reliably drive an SSR that has low input power requirements (i.e. >1500 ohms at 5 volts) and is also driven in the sink mode the same as TTL. Fig. 16 shows 1/6 of 4049 (inverting) or a 4050 (non-inverting) CMOS hex buffer driving such an SSR with a common 5 volt supply. CMOS can, of course, operate at higher voltages, but care must be taken not to overstress the gate with excessive dissipation.

Integrated circuits with open collector outputs are also commonly used to drive SSRs, as in Fig. 17. The open collector IC has an output transistor without an active (transistor) or passive (resistor) pull-up, and generally has enough power to drive an SSR directly. Open collector outputs can also be logically ORed like discretes, so that the SSR may be controlled by any one of the many outputs. Furthermore, the SSR supply voltage does not have to be the same as the IC V_{CC}, provided that one side is common, and the transistor and SSR maximum voltages and currents are not exceeded.

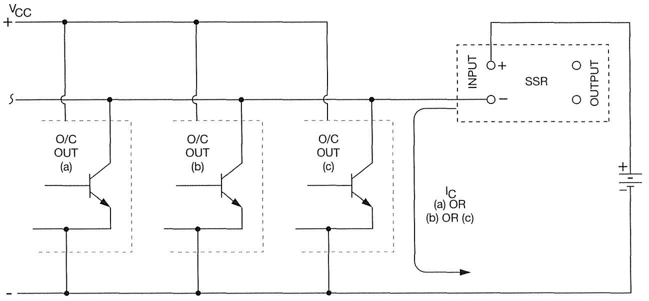


Fig. 17 Open collector IC outputs driving SSR in logically ORed configuration.

SSRs do not generally require pull-up or shunt resistors for noise reduction or any other functional reason. An open input, if not assigned to a particular logic level, produces an open or off state in the output (unless otherwise designated). Input lines would have to be extremely long and through noisy environments before noise of any significance would appear at the input terminals to cause the SSR to change state.

Some IC devices have “three state” (tristate) outputs. These have the normal high and low states as described for standard TTL, plus an additional high impedance state activated by an enable signal. In the high impedance state, no source or sink current flows, appearing as an open input to a driven SSR. The IC is essentially out of the circuit, thus permitting similar devices to be paralleled and enabled, as desired, without interacting with each other. For example, in this configuration a number of ORed driver stages can be individually polled as to their logic states by a sequentially applied enable signal. Only the drivers with outputs at logical 0 would activate the SSR.

Leakage from the Drive Source

The off state leakage current in the driving semiconductors shown in Figs. 14 to 17 is significant, just a few microamperes, which could not possibly turn on the SSRs. However, the off state (output) leakage current of any packaged solid state driving device (e.g. temperature controller, etc.) should first be checked for compatibility with the SSR. One method is to multiply the maximum leakage current (amps) by the maximum input impedance (ohms) of the SSR. This should result in a voltage that is less than the specified turn-off voltage. If it is not, a resistive shunt across the SSR input may be required.

Thermal Considerations

One of the major considerations when using a SSR, which cannot be stressed too strongly, is that an effective method of removing heat from the SSR package must be employed. The most common method is to employ a heat sink. SSRs have a relatively high "contact" dissipation, in excess of 1 watt per amp.

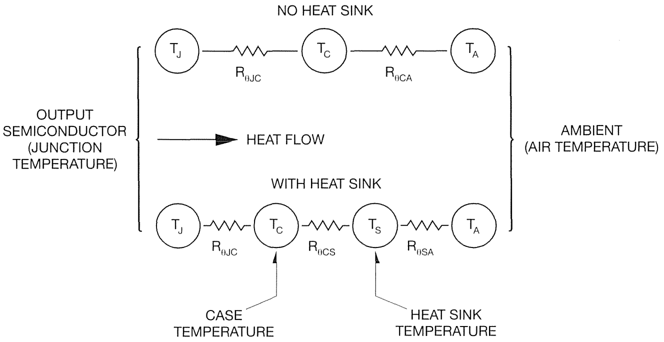


Fig. 18 A simplified thermal model.

With loads of less than 5 amps, cooling by free flowing air or forced air current around the SSR is usually sufficient. At higher currents it will become necessary to make sure the radiating surface is in good contact with a heat sink. Essentially this involves mounting the baseplate of the SSR onto a good heat conductor, usually aluminum; good thermal transfer between the SSR and the heat sink can be achieved with thermal grease or heat sink compound. Using this technique, the SSR case to heat sink thermal resistance ($R_{\theta CS}$) is reduced to a negligible value of 0.1°C/W (celsius per watt) or less. This is usually presumed and included in the thermal data. The simplified thermal model in Fig. 18 indicates the basic elements to be considered in the thermal design. The values that are determinable by the user are the case to heat sink interface ($R_{\theta CS}$), as previously mentioned, and the heat sink to ambient interface ($R_{\theta SA}$).

Thermal Calculations

Fig. 18 illustrates the thermal relationships between the output semiconductor junction and the surrounding ambient. $T_J - T_A$ is the temperature gradient or drop from junction to ambient, which is the sum of the thermal resistances multiplied by the junction power dissipation (P watts). Hence:

$$T_J - T_A = P\,(R_{\theta JC} + R_{\theta CS} + R_{\theta SA})$$

Where

T_J = Junction temperature, °C
T_A = Ambient temperature, °C
P = Power dissipation (I_{LOAD} X E_{DROP}) watts
$R_{\theta JC}$ = Thermal resistance, junction to case °C/W
$R_{\theta CS}$ = Thermal resistance, case to sink, °C/W
$R_{\theta SA}$ = Thermal resistance, sink to ambient, °C/W

To use the equation, the maximum junction temperature must be known, typically 125°C, together with the actual power dissipation, say 12 watts for a 10 amp SSR, assuming a 1.2 volt effective (not actual) voltage drop across the output semiconductor. The power dissipation (P watts) is determined by multiplying the effective voltage drop (E_{DROP}) by the load current (I_{LOAD}).

Assuming a thermal resistance from junction to case ($R_{\theta JC}$) of, say, 1.3°C/W and inserting the above typical values into the equation, solutions can be found for unknown parameters, such as maximum load current, maximum operating temperature, and the appropriate heat sink thermal resistance. Where two of these parameters are known, the third can be found as shown in the following examples:

(a) To determine the maximum allowable ambient temperature, for 1°C/W heat sink and 10 amp load (12 watts) with a maximum allowable T_3 of 100°C:

$$\begin{aligned} T_J - T_A &= P\,(R_{\theta JC} + R_{\theta CS} + R_{\theta SA}) \\ &= 12\,(1.3 + 0.1 + 1.0) \\ &= 28.8 \end{aligned}$$

hence,

$$\begin{aligned} T_A &= T_J - 28.8 \\ &= 100 - 28.8 \\ &= 71.2^\circ\mathrm{C} \end{aligned}$$

(b) To determine required heat sink thermal resistance, for 71.2°C maximum ambient temperature and a 10 amp load (12 watts):

$$\begin{aligned} R_{\theta SA} &= \frac{T_J - T_A}{P} - (R_{\theta JC} + R_{\theta CS}) \\ &= \frac{100 - 71.2}{12} - (1.3 + 0.1) \\ &= 1^\circ\mathrm{C/W} \end{aligned}$$

(c) To determine maximum load current, for 1°C/W heat sink and 71.2°C ambient temperature:

$$\begin{aligned} P &= \frac{T_J - T_A}{R_{\theta JC} + R_{\theta CS} + R_{\theta SA}} \\ &= \frac{100 - 71.2}{1.3 + 0.1 + 1.0} \\ &= 12 \text{ watts} \end{aligned}$$

hence,

$$\begin{aligned} I_{LOAD} &= \frac{P}{E_{DROP}} \\ &= \frac{12}{1.2} \\ &= 10 \text{ amperes} \end{aligned}$$

Regardless of whether the SSR is used on a heat sink or the case is cooled by other means, it is possible to confirm proper operating conditions by making a direct base plate temperature measurement when certain parameters are known. The same basic equation is used except that base plate temperature (T_C) is substituted for ambient temperature (T_A) and $R_{\theta CS}$ and $R_{\theta SA}$ are deleted. The temperature gradient now becomes $T_J - T_C$ that is the thermal resistance ($R_{\theta JC}$) multiplied by the junction power dissipation (P watts). Hence:

$$T_J - T_C = P\,(R_{\theta JC})$$

Parameter relationships are similar in that solutions can be found for maximum allowable case temperature, maximum load current, and required junction to case ($R_{\theta JC}$) thermal resistance. Again, where two parameters are known, the third can be found as shown in the following examples (using previous values):

(d) To determine maximum allowable case temperature, for $R_{\theta JC}$ = 1.3°C/W and 10 amp load (12 watts):

$$T_J - T_C = P\,(R_{\theta JC})$$

$$= 12 \times 1.3$$

$$= 15.6$$

hence,

$$T_C = T_J - 15.6$$

$$= 100 - 15.6$$

$$= 84.4^{\circ}\mathrm{C}$$

(e) To determine maximum load current, for $R_{\theta JC}$ = 1.3°C/W and 84.4°C case temperature:

$$P = \frac{T_J - T_C}{R_{\theta JC}}$$

$$= \frac{100 - 84.4}{1.3}$$

$$= 12 \text{ watts}$$

hence,

$$I_{LOAD} = \frac{P}{E_{DROP}}$$

$$= \frac{12}{1.2}$$

$$= 10 \text{ amperes}$$

(f) To determine required thermal resistance ($R_{\theta JC}$), for 84.4°C case temperature and 10 amp load (12 watts):

$$R_{\theta JC} = \frac{T_J - T_C}{P}$$

$$= \frac{100 - 84.4}{12}$$

$$= 1.3^{\circ}\mathrm{C/W}$$

In examples (a) through (c) SSR operating conditions are determined as they relate to ambient air temperature using a heat sink. Similarly, conditions can be determined for an SSR operating in free air without a heat sink, provided that a value is given for the radiating characteristics of the package ($R_{\theta CA}$). This value is rarely given and when it is, it is more commonly combined with ($R_{\theta JC}$) and stated as ($R_{\theta JA}$). The equation would appear as follows:

$$T_J - T_A = P\,(R_{\theta JC} + R_{\theta CA})$$

Or

$$T_J - T_A = P\,(R_{\theta JA})$$

Where

$R_{\theta CA}$ = Thermal resistance, case to ambient, °C/W

$R_{\theta JA}$ = Thermal resistance, junction to ambient, °C/W

The equation can be used to calculate maximum load current and maximum ambient temperature as before. However, the resultant values are inclined to be less precise due to the many variables that affect the case to air relationship (i.e., positioning, mounting, stacking, air movement, etc).

Generally, free air performance is associated with PCB or plug-in SSRs of 5 amps or less, which have no metallic base to measure. The question is often raised as to where the air temperature is measured. There is no clear-cut answer for this. Measurement is made more difficult when the SSRs are closely stacked, each creating a false environment for its neighbour. One suggested approach is to place a temperature probe or thermocouple in the horizontal plane approximately 1 inch away from the subject SSR. This technique is reasonably accurate and permits repeatability.

Ratings

The free air performance of lower powered SSRs is usually defined in the catalogue by means of a single derating curve, current versus ambient temperature based on the foregoing formulas, which is adequate for most situations.

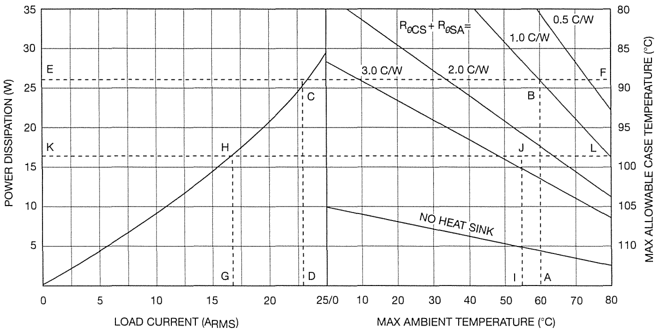


Fig. 19 Thermal derating curves (25 A SSR).

Heat Sinking

Under worst case conditions the SSR case temperature should not exceed the maximum allowable shown in the right hand vertical scales of Fig.19.

A typical finned section of extruded aluminum heat sink material is shown in outline form in Fig 20. A 2 inch length of this material would approximate the same thermal characteristics as curve (a) in Fig. 21, likewise, a 4 inch length would approximate curve (b). This is assuming the heat sink is positioned with the fins in the vertical plane, with an unimpeded air flow.

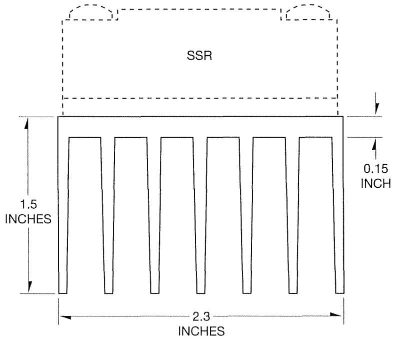


Fig. 20 Typical light duty aluminum heat sink extrusion (end view).

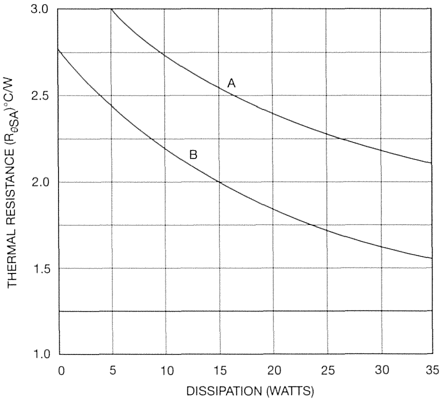


Fig. 21 Typical heat sink characteristics.

As a general rule, a heat sink with the proportions of the 2 inch length of extrusion (curve(a)) is suitable for SSRs rated up to 10 amps, while the 4 inch length (curve (b)) will serve SSRs rated up to 20 amps. For power SSRs with ratings greater than 20 amps, a heavy duty heat sink of the type shown in Fig. 22 becomes necessary. The performance of a 5.5 inch length of this extrusion would approximate the characteristics shown in Fig. 23.

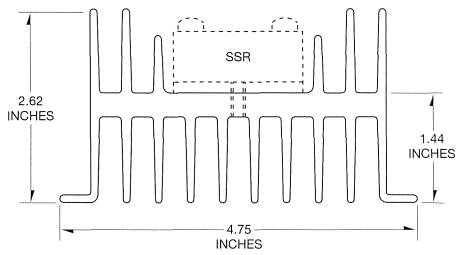


Fig. 22 An end view of a typical heavy duty aluminum heat sink extrusion.

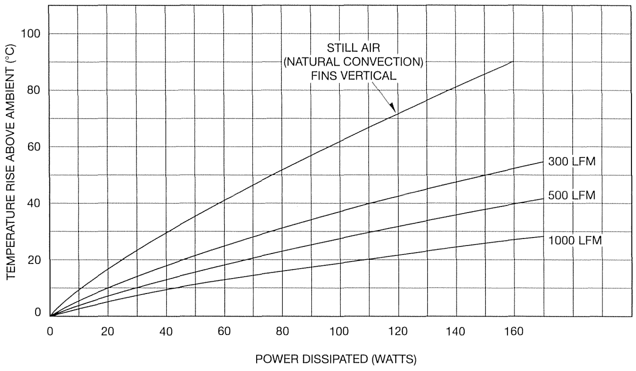


Fig. 23 Typical free-moving air characteristics of a heavy duty heat sink, temperature rise versus power dissipated.

Not all heat sink manufacturers show their characteristics in terms of degrees C per watt (ºC/W); some show them as a temperature rise above ambient, as shown in Fig. 23. In this case, a value for $R_{\theta SA}$ is found by dividing power dissipation (watts) into the temperature rise (ºC). For example, taking the 60 watt point on the dissipation scale, the free air curve would indicate a 40 degree rise. Hence:

$$R_{\theta SA} = \frac{T_{Rise}}{P}$$

$$= \frac{40}{60}$$

$$= 0.66^\circ C/W$$

In many applications, the SSR is mounted to a panel or base plate, which may also be more than adequate as a heat sink. By ensuring flatness, using thermal compound, and removing paint to maximize effectiveness, a base plate (SSR) temperature measurement at maximum ambient may be all that is necessary to confirm proper operation as previously mentioned.

If an SSR installation does not provide an adequate heat sink, a selection is made from the wide variety of commercial heat sink types that are available. Each configuration has its own unique thermal characteristics and are usually well documented with manufacturers' performance curves and applications data.

Surge Ratings and High Inrush Current Loads

After improper heat sinking, surge current is one of the more common causes of SSR failure. Overstress of this type can also seriously impair the life of the SSR. Therefore, in a new application it would be wise to carefully examine the surge characteristics of the load.

There are very few completely surgeless SSR loads. Resistive loads, such as heating elements and incandescent lamps, can prove problematic. Capacitive loads can also prove equally problematic because of their initial appearance as short circuits. High surge currents can occur while charging, limited only by circuit resistance. Inductive loads, on the other hand, tend to impede high inrush currents; in fact, inductance is often inserted into a circuit for the express purpose of limiting high fast rising peak currents (e.g. EMI filters, chokes, etc.). However, inductive loads can give rise to high inrush currents.

Inductive loads have traditionally created more problems on turn-off rather than turn-on due to stored energy and "back EMF". The inherent zero current turn-off characteristics of thyristors used in AC SSRs is most beneficial in this regard.

Surge Ratings

The highest surge current rating of an SSR is typically 10 times the steady-state RMS value, and it is usually given as the maximum nonrepetitive peak current for one line cycle. It should be noted that a surge of this magnitude is allowable only 100 times during the SSR lifetime. The preceding cautionary notes would tend to reduce the attractiveness of the high surge capability (100%) of the AC SSR; however, they apply only to the extreme limits where the SSR should not be designed to operate anyway. When a reasonable surge safety margin is used, conditions rapidly improve.

Generally, DC SSRs do not have an overcurrent surge capability, since the output transistors (nonregenerative) are usually rated for continuous operation at their maximum capacity. The tendency is for the DC SSR to cut off (current limit), thus impeding the flow of excessive current. However, the resultant over-dissipation may destroy the relay if the surge is prolonged. If overcurrent carrying capacity is required, as may be the case when designing fuse protection, the SSR could be over specified (have a higher current capability).

To aid in the proper design of SSR fusing, an I^2t rating is usually given. This parameter expressed in ampere-squared seconds is useful since it can relate directly to the published fuse characteristics. It is generally derived from the peak surge (one cycle) output thyristor rating as follows:

$$I^2t = \frac{I^2_{PK}t}{2}$$

Where

Ipk = peak surge current – (sinusoidal)

t = duration of surge (normally 8.3 μS) (.0083 seconds in the formula)

For example, for a 25 amp SSR with a 250 amp one-cycle surge rating, the value would be 260 amp-squared seconds.

Inductive Loads

High inrush lamp and capacitive loads sometimes include a series inductor such as a choke or transformer. This will tend to limit the initial inrush current, but the combination will primarily be seen by the SSR as an inductive load. While most SSR loads, even lamps, include some inductance, its effect with resistive loads is usually negligible. Only those loads that utilize magnetics to perform their function, such as transformers and chokes, are likely to have any significant influence on SSR operation.

The majority of SSRs will operate inductive loads with power factors as low as 0.3, especially if they are switching medium to high current loads relative to their rating. When a load rating is close to the minimum current rating of the SSR, the off state leakage may become significant when compared to the load current. The leakage may have a deleterious effect on certain loads such as small solenoids that fail to drop out, or motors that buzz or even continue to run. The solution is to reduce the load impedance by means of a shunt or parallel impedance, thus reducing this voltage below the drop out or off threshold of the load.

A saturating inductive load can also cause switching problems with the SSR. The AC impedance of such a load is relatively high under normal conditions. However, when saturation occurs the inductance falls to a very low value, resulting in a fall in impedance close to that of the Copper resistance of the coil winding. This can cause several cycles of surge currents in excess of 30 times the steady-state value, which may seriously affect the lifetime.

Transformer Switching

Extremely high current surges are commonly associated with transformers, especially those with a penchant for saturation. The zero voltage turn-on feature of standard SSRs can increase this possibility and might require that special precautions be taken.

At the instant turn-on, transformer current is essentially zero, with the highest peak usually occurring within a half cycle, depending on the line phase angle, load power factor, and magnetic state of the core. When the SSR is energized at the ideal phase angle, as dictated by power factor, a maximum back EMF is generated that will tend to counter the magnetizing current, thereby reducing or eliminating the surge.

However, when switched on at, or near, zero voltage, the back EMF is reduced, allowing an increase in magnetizing current that can be further enhanced by residual magnetism in the core, which almost always exists since ferromagnetic core material has a natural tendency to remain magnetized at turn-off.

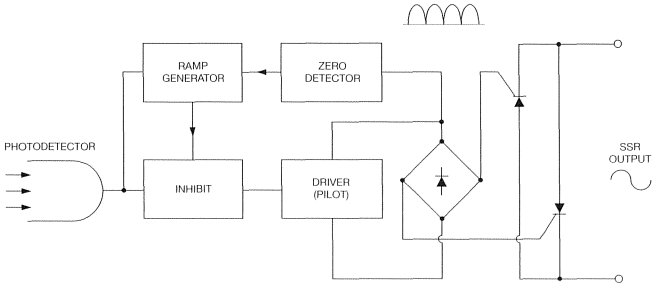
If a random turn-on SSR is used to switch transformer loads, the likelihood of transformer core saturation is greatly reduced.

Switching

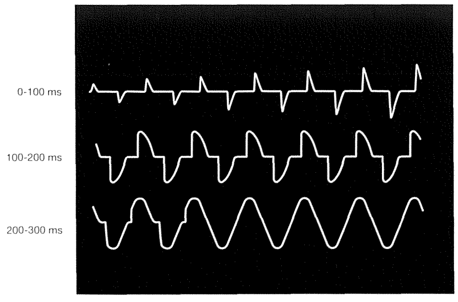
Dynamic loads, such as motors and solenoids, etc., can create special problems for SSRs, in addition to those discussed for passive inductors. High initial surge current is drawn because their stationary impedance is usually very low. For example, after the initial surge, a solenoid core will pull in and "seal" at a much lower steady-state current, possibly by dropping to less than 25%. With motors, the change in current from stall to run can be even greater, possibly dropping to less than 20%, depending on the type.

As a motor rotor rotates, it develops a back EMF that reduces the flow of current. This same back EMF can also add to the applied line voltage and create "overvoltage" conditions during turn-off. Mechanical loads with a high starting torque or high inertia, such as fans and flywheels, will, of course, prolong the start-up surge period, which should be taken into account when selecting the driving SSR. When the mechanical load is unknown, as may be the case with a power tool, worst case conditions should apply.

One of the best surge reducing techniques is the soft start shown with a typical waveform on an expanded scale in Fig. 24. With this system, once the control signal is applied, the SSR is ramped on by internal circuitry that advances the turn-on phase angle over several half cycles. The slow transition to full line voltage virtually eliminates the problems associated with zero, random, peak, and integral cycle turn-on. This is also beneficial for lamps and capacitive loads and could be applied in most general applications.



(A) Circuit



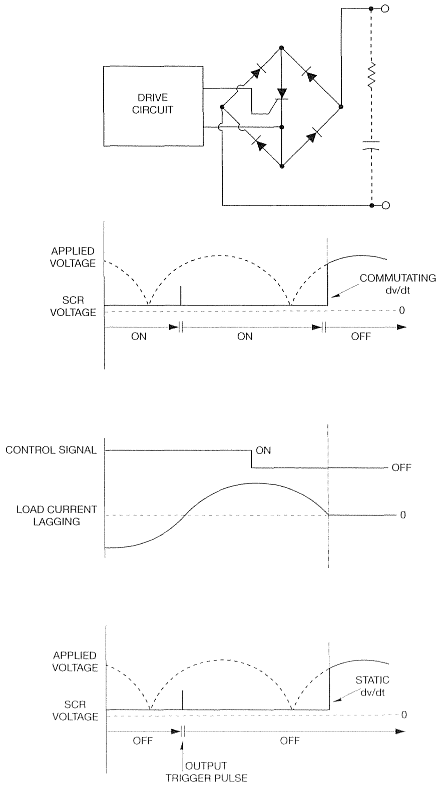
(B) Voltage waveform

Fig. 24 Typical circuit configuration and voltage waveform of soft start, with phase angle ramped on over 14 cycles.

While soft start spreads the inrush current over many cycles, thus reducing stress, it also prevents the occurrence of enormous saturating currents. Due to its phase control nature, it can produce a brief burst of EMI noise during the ramp up period; possibly a small sacrifice for the added benefits.

The inrush current characteristic of tungsten filament (incandescent) lamps is somewhat similar to the surge characteristic of the thyristors used in AC SSR outputs, making them a good match. The typical ten times steady-state ratings which apply to both parameters from a cold start allow many SSRs to switch lamps with current ratings close to their own steady-state ratings. Some lamps have even higher instantaneous inrush currents. This is rarely seen in practice, since line and source impedances and filament inductance become significant at higher currents, all of which tend to limit the peak current. Generally the ten times steady-state rating is considered a safe number for lamps.

Protective Measures



(A) SCR as output switch (dv/dt from conducting to forward blocking)

Fig. 25 Turn-off conditions for SCRs in full-wave bridge circuits switching inductive loads.

Noise Susceptibility

Noise, or more properly defined as Electromagnetic Interference (EMI), does not generally cause SSRs to fail catastrophically. Some of the techniques used to reduce noise in the coupler and drive circuits are also effective against false triggering caused by voltage transients on the input lines. When a capacitor is added, for example, the response time which is not critical for AC SSRs may be lengthened, possibly from a few microseconds to tenths of milliseconds. Due to the induced delay, voltage transients or bursts of shorter duration are rejected, thus improving noise immunity.

Most AC SSRs use thyristors in their drive and output circuits which, due to their regenerative nature, can latch on for a whole half cycle when triggered by a brief voltage transient, thus acting as a pulse stretcher. In addition to responding to the amplitude of the transient, a thyristor can also mistrigger when the rate of rise (dv/dt) of a transient or applied voltage exceeds certain limits. Transient suppressors are effective against the former, and the RC snubber improves the tolerance of an SSR to the latter.

dv/dt (Rate Effect)

The expression dv/dt defines a rising voltage versus time expressed in volts per microsecond (V/μS). When applied to an AC SSR as “static” or “off state” dv/dt, it is a parameter that defines the minimum dv/dt withstand capability of the SSR or, in other words, the maximum allowable rate of rise of voltage across the output terminals that will not turn on the SSR (typically 500 V/μS).

Snubber

The internal RC network (snubber) used in AC SSRs is a major factor in transient voltage and dv/dt suppression. It deals effectively with two facets of a voltage transient. Not only does the network slow down the rate of rise as seen by the output thyristors and sensitive drive circuits, but it also limits the amplitude to which it can rise.

While the typical internal snubber value and the typical dv/dt specification are adequate for most applications, they may not prevent what is commonly referred to as the “blip” or “bleep” problem which occurs during start-up. That is, when power is initially applied to the SSR/load combination usually by means of a mechanical switch, the resultant fast rising transient may mistrigger the SSR and possibly “let through” a half cycle pulse. Fortunately, most loads are not troubled by this pulse.

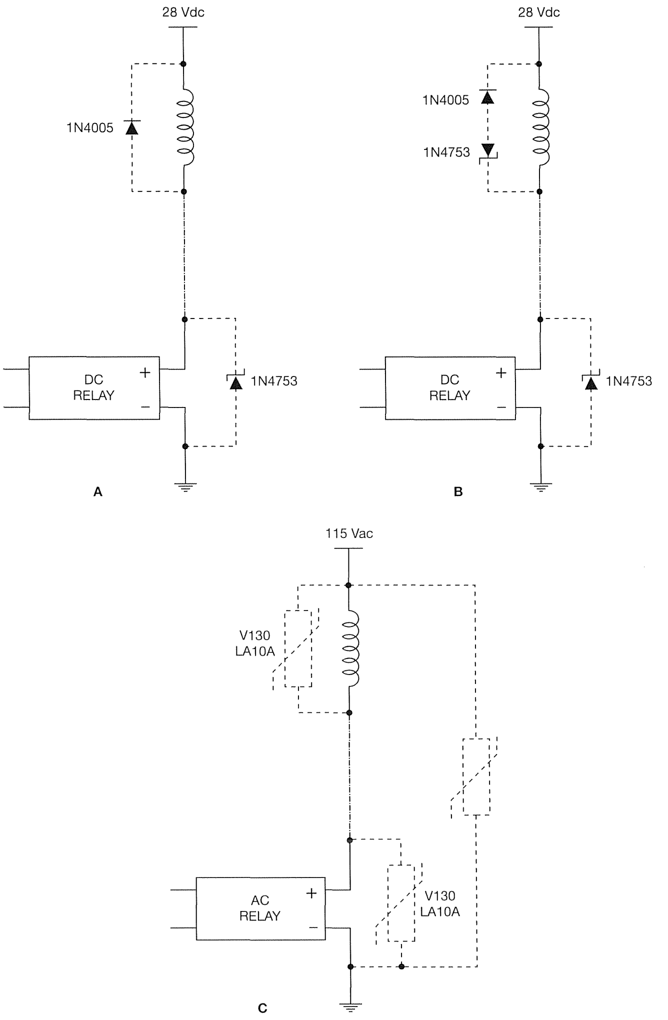


Fig. 26 Transient suppression techniques.

Suppressors

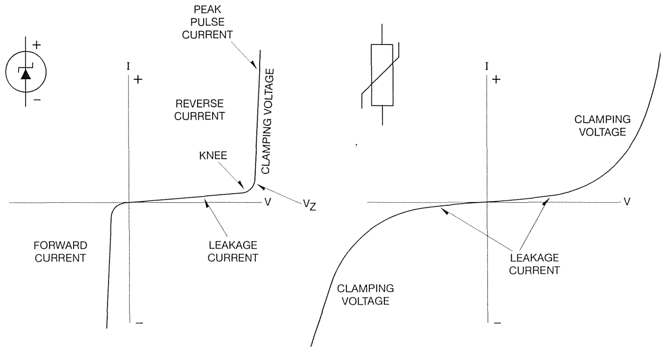
When overvoltage transients occur, another form of suppression may be required beyond the capabilities of the snubber. One popular technique is to add a clamping device across the SSR terminals that will absorb the transient energy above a predetermined level.

Devices, such as zeners and MOVs, will conduct only at the predetermined level and above, thereby sharing the transient with the load. If it is unacceptable for the load to receive any transient energy, the only solutions may be suppression of the transient source, or an SSR with a blocking capability higher than the transient.

Fig. 26 illustrates typical methods of suppressing transients across the SSR output “contacts”, as well as suppression of transients at the source, which can be the load itself for DC inductive type loads.

Diodes and Zeners

The diode shown across the load in A of Fig. 26 is the most effective way of suppressing the possibly hundreds of volts of back EMF that can be generated by the coil at turn-off. The disadvantages of this method are the SSR is not protected from other transient sources, and the dropout time of the load may be extended by several milliseconds.



(A) Zener diode V-I characteristic

(B) MOV V-I characteristic

Fig. 27 Comparison of zener diode and MOV characteristics.

The general rule in the selection of protective diodes and zeners is that their peak nonrepetitive (pulse) current ratings (Fig. 27) should be equal to, or greater than, the minimum load current. Conservative steady-state power ratings for these devices may be ascertained from the following equation:

$$P_{\text{watts}} = \frac{I_L^2 L}{t_r}$$

where

I_L = load current in DC amperes

L = load inductance in henrys

t_r = on/off repetition rate in seconds

Example: A load with a resistance of 4 ohms and an inductance of 0.0025 henry is driven from a 28 volt DC supply while being switched on and off 5 times a second:

$$I_L = \frac{28 \text{ volts}}{4 \text{ ohms}}$$

$$= 7 \text{ amperes}$$

$$t_r = \frac{1}{5} = 0.2 \text{ second}$$

$$P = \frac{7^2 \times .0025}{0.2}$$

$$= 0.613 \text{ watt}$$

A protective diode or zener with a 3/4 watt rating would suffice.

The zener diode is the ideal choice for protecting low voltage DC SSRs (less than 100 volts DC) used in parallel with the output. In the forward current mode (reverse for the SSR), the zener diode typically clamps as a single diode would at approximately one volt, thereby providing added reverse-voltage protection. When two zeners are used back-to-back (in series) with equal standoff voltages, they can be used to protect SSR outputs bidirectionally when switching AC loads. At higher voltages (greater than 100 volts) AC or DC, economics versus performance may suggest another transient protective device such as the MOV (metal oxide varistor) being the most popular.

MOVs

For more hostile environments, the MOV can be used as follows: across the incoming line to suppress external transients before they can enter the system; across the load to suppress load generated transients; or, more frequently, across the SSR to protect it from all transient sources. In the latter case, the MOV can be conveniently mounted to the same SSR output terminals as the load wiring. With the impedance of the load in series with the MOV to limit current, a 30 joule unit is usually adequate for brief spikes and also small enough to be supported by its own leads.

If a MOV is connected directly across the power line, the current limiting impedance will only be that of the power generating source plus the wiring. In order to absorb the possibility of high energy line transients from such a low impedance source, the larger panel mount (300 – 600 joule) variety of MOV may be required. The greater expense of such a device might be justified in that suppression across the line is required in one place only.

Individual MOV specifications should be consulted for precise information regarding energy absorption, clamping properties and physical size, since the relationships of these parameters will vary from one manufacturer to the next.

Fuses

Semiconductor fuses are usually used in conjunction with SSRs and are specialist fuses designed to protect while operating at close to their full ratings. They are sometimes referred to as current limiting fuses, providing extremely fast opening, while restricting let through current far below the available fault current that could destroy the SSR. Although these fuses are not low cost, they do provide a means of protecting SSRs against high current overloads where survival of the SSR is of prime importance.

The following are the main parameters used in the selection of a semiconductor fuse:

- Fuse voltage rating
- Fuse current rating
- Available system fault current
- Fuse peak let through current
- Fuse total clearing (or let through)
- Surge withstand capability of the SSR

SSR Applications

The diagrams in this section are conceptual illustrations of just a few typical SSR applications. They are intended as design guides to steer the user in the right direction and to stimulate further design ideas. Some of the diagrams provide problem solving or circuit protection and others enhance relay operation.

Latching SSR

Momentary push-button control allows the SSR to self-latch for on-off, stop-start operations. It may be similarly configured for DC in/DC out type SSRs.

Resistor R1 (10,000 ohms) is required to prevent line short only if alternate (N O) switch is used.

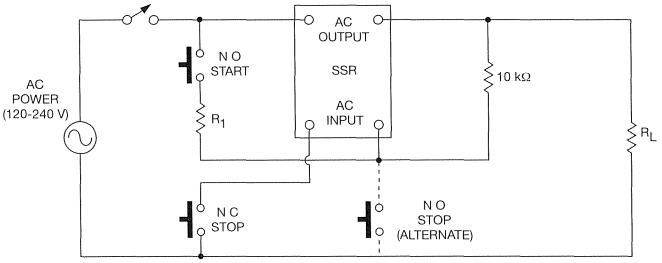


Fig. 28 Latching SSR circuit.

Latching SSR with Short-Circuit Protection

Push-button control as in the previous example, but R2 is tailored to limit the load shorting current to SSR surge rating (for turn-off time), thus preserving SSR while the control signal is removed. Latching characteristic permits lock-out until the circuit is reset.

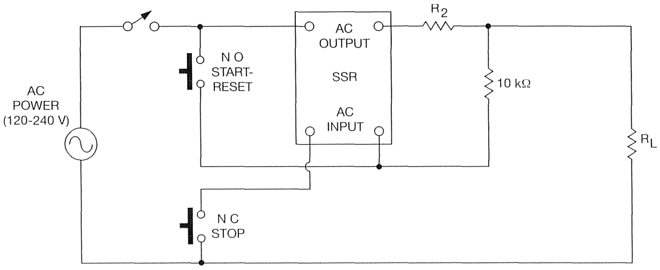


Fig. 29 Latching SSR with short-circuit protection.

Motor Starter Switch

Initial locked rotor current flowing through R1 creates a voltage that, when rectified and filtered, turns on the SSR, which in turn activates the start winding. As the motor comes to speed, the voltage across R1 is reduced until the start winding is de-energized.

The SSR should have a voltage rating approximately twice that of the applied line to withstand overvoltage generated by the current LC.

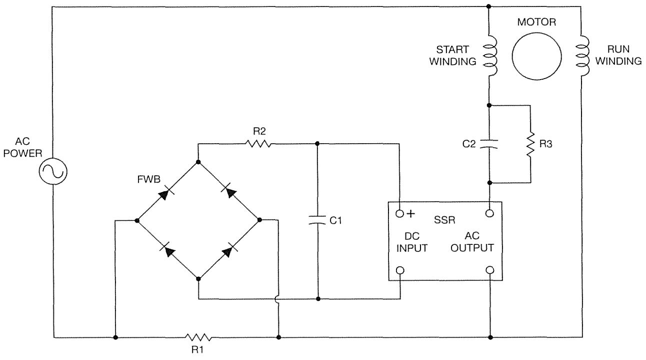


Fig. 30 Motor starting switch.

Functional Three-Phase Switch for Three-Wire System

Two SSRs may be used to control a Y or a delta load in a three-wire system. A third SSR would be required in phase C if the center of the Y load were grounded, as in a four-wire system. SSR voltage rating must be greater than line to line voltage for three-wire systems and line to ground voltage for four-wire systems (with neutral ground).

SSRs are most commonly used in three-phase applications to control motors, where their current ratings depend as much on locked motor current as they do on normal run current and proper heat sinking. Where a motor rating is not given, a minimum SSR current value can be estimated from the device surge curves, using the general rule of six times the motor run current for one second. This value must also be commensurate with thermal and lifetime requirements.

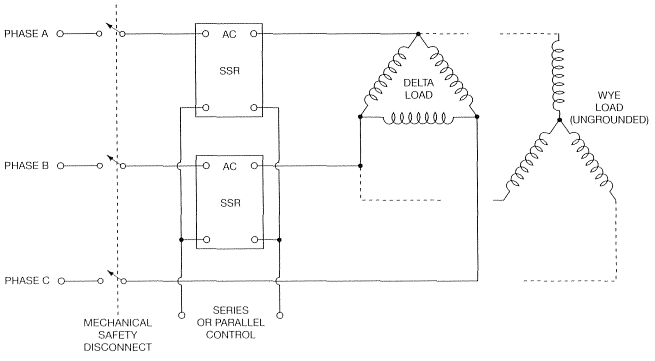


Fig. 31 Functional three-phase switch for three-wire system.

Phase-Controlled Dimming

A 555 timer and a photocoupler may be used with a non-zero switching (instant-on) SSR to provide isolated lamp dimming.

The IC is operating as a one shot, triggered by a negative pulse from the output of the zero detector circuit (Q1). Once triggered, the timing interval begins and the SSR is off. Upon time out, dependent on the time constant of R1C1, IC output (pin 3) goes low and the SSR turns on for the balance of the half cycle. Simultaneously, C1 is discharged through a transistor in the IC (pin 7), and the process repeats every half cycle.

The phase angle firing point is independent of DC control voltage. However, at the higher DC voltages and shorter firing angles (full on), the IC may over-dissipate due to the repetitive discharge of C1, and possibly require a small heat sink.

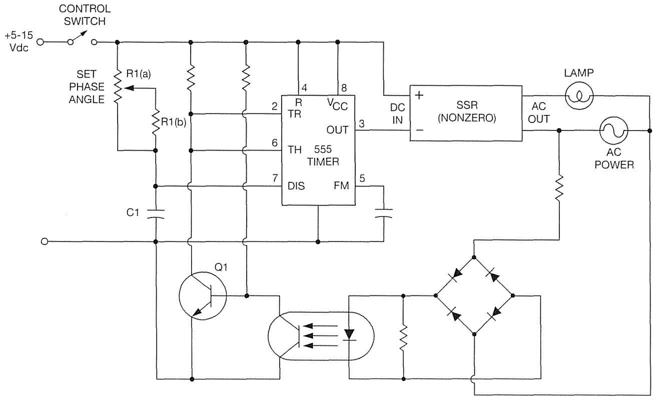


Fig. 32 Phase-controlled dimming.

Three-Phase Motor Reversal

Four AC SSRs can provide a reversing function for a three-phase motor, using the drive logic suggested. The half cycle time delay before enabling the drive, in either direction, prevents make before break which would result in a line to line short. Two opposing SSRs (nos. 1 and 4, or 2 and 3) could still mistrigger simultaneously due to dv/dt or high voltage transients; therefore, resistors R1 through R4 are inserted to limit the resultant surge current. The sum of any two resistors plus the source impedance should limit the shorting current to less than the peak one cycle surge rating of each relay. Semiconductor type fuses should be chosen to permit such a condition for one cycle and open as soon as possible thereafter. SSRs should have a transient (blocking) rating equal to twice the line to line voltage to withstand the combined line and back EMF generated at the moment of reversal.

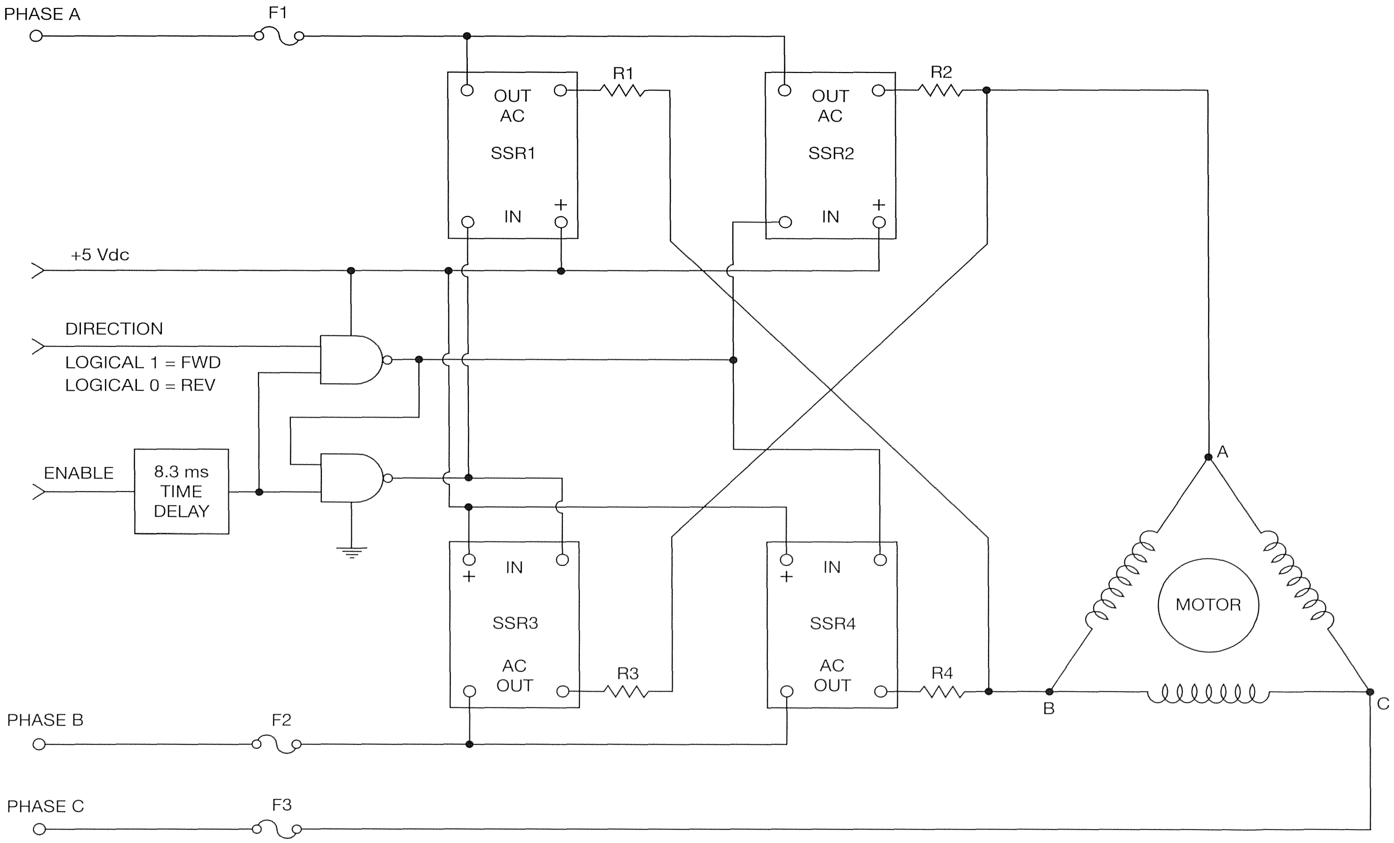
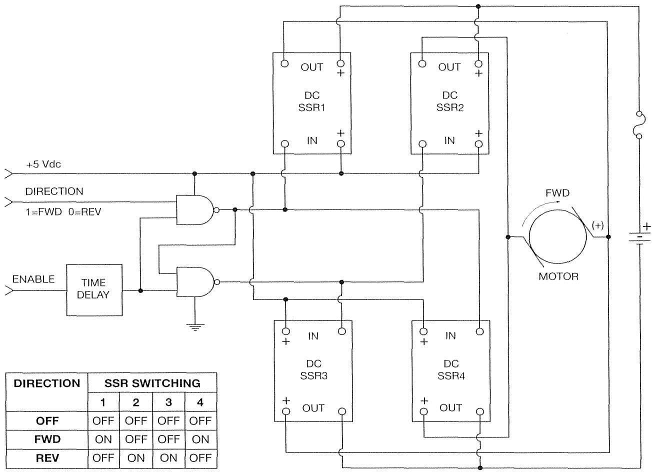


Fig. 33 Three-phase motor reversal.

Reversing Motor Drive for DC Motors

In this configuration, four DC SSRs are used for motor reversal from a single power supply. The time delay before enabling the drive in either direction must be greater than the SSR turn-off time to preclude the possibility of a hazardous make before break condition.

Internal reverse diodes or zeners in the SSRs will suppress inductive transients across the low impedance of the power supply. If no internal suppressors exist, a reverse diode should be installed across each SSR output or, alternatively, SSRs with blocking ratings at least twice that of the supply voltage may be used. The circuit should be current limited or fused to protect the wiring in the event of a short circuit.



DIRECTION	SSR SWITCHING			
	1	2	3	4
OFF	OFF	OFF	OFF	OFF
FWD	ON	OFF	OFF	ON
REV	OFF	ON	ON	OFF

Fig. 34 Reversing motor drive for DC motors.

Paralleling SSRs

SSRs with MOSFET outputs are self balancing and easily paralleled, whereas most others with bipolar or thyristor outputs require special attention. Ideally, the forward voltage drops should be matched to achieve thermal balance and lowest dissipation; alternatively, balancing resistors (R_X) are used to force current sharing as shown. For example, with 40 amps allowed through SSR1, SSR2 must carry 32 amps.

Assuming V1 = 1.3 volts and V2 = 1.5 volts (worst case).

$$R_X = \frac{\Delta V}{\Delta I}$$

or

$$\frac{V2 - V1}{I1 - I2} = \frac{1.5 - 1.3}{40 - 32}$$

$$= 0.025 \text{ ohm}$$

Thus producing a total voltage drop of 2.3 volts.

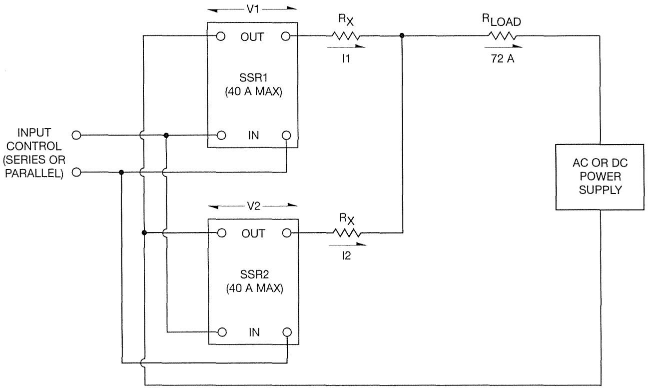


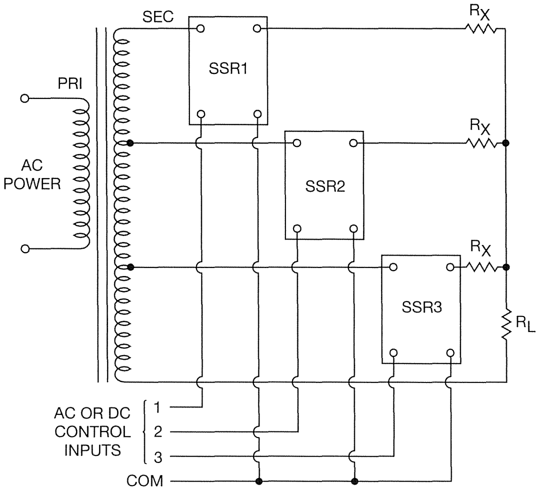
Fig. 35 Paralleling SSRs.

For zero voltage turn-on thyristor types, either one of the SSRs must be capable of handling the initial full load surge alone because of a possible half cycle mismatch. Thyristor SSRs have additional turn-on problems that can prevent paralleling.

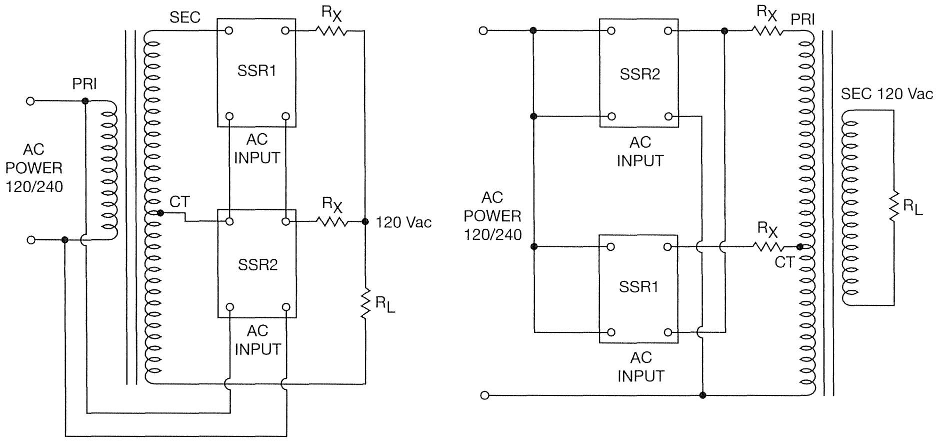
Transformer Tap Switching

If a momentary interruption in power is acceptable, a time delay on operate is suggested to prevent overlap and the resulting high current surge from a shorted winding. Two times Rx plus the winding resistance must be sufficient to limit the surge current to the one cycle surge rating of the SSRs.

As an additional precaution, the SSR blocking (breakdown) voltage should exceed the main winding voltage plus the highest tap voltage. For multi-tap switching the SSRs are generally logic driven DC controlled AC output types without special requirements. For Figs. 36B and C, they are 240 Vac output with 120 Vac input for SSR1 and 240 Vac input for SSR2 in each case. An important requirement of SSR2 is that it must be off below the highest expected 120 Vac line swing, say 150 Vac. When SSR2 is off, SSR1 will be on and vice versa, thus activating the appropriate winding.



(A) Multitap switching



(B) Autotap selection (secondary)

(C) Autotap selection (primary)

Fig. 36 Transformer tap switching.

Testing the SSR

Many of the tests required to verify SSR performance are inherently hazardous and caution should be excercized, using adequate safeguards for the personnel conducting such tests.

Possibly the simplest of all field tests that can be made to determine proper function of an AC SSR is by means of a 3 volt battery, a light bulb, and a piece of insulated wire. This simple go/no-go test is illustrated by Fig. 37.

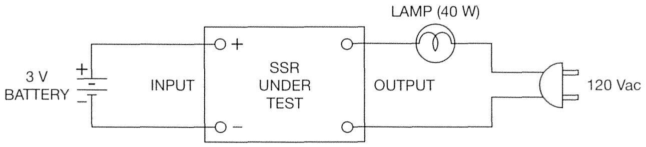


Fig. 37 Simple go/no-go SSR test.

A more complete performance check might include operating the SSR in position with its actual load, while exercising the system installation functionally through all of its specified environmental and power combinations.

When connecting test equipment directly to the power circuit of an SSR output, protective fusing would be a wise precaution. Also, remember that with some equipment such as an oscilloscope, the case must be “floated” (ungrounded) and may be at line potential. In some test circuits an isolated current probe or an isolation transformer can be used to avoid this hazard. The output functions of an SSR should not ever be checked by a multimeter in the ohms mode, since the minimum voltages and bias currents necessary for proper SSR operation are not present, thus producing erroneous readings.