

# Solid-State Relays for Control

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## ABSTRACT

**S**OLID-STATE relays (SSRs) offer improved reliability and performance over that of electromechanical relays (EMRs) in applications requiring large numbers of contact closures, interfacing to low power solid-state circuits, maximum speed and control of contact closure, and minimum production of radio-frequency interference. SSRs may not be used as a direct replacement for EMRs in many circuits, however, and a number of the important factors required for satisfactory SSR application and performance are considered.

## INTRODUCTION

Electromechanical relays (EMRs) or contactors have been a primary method of switching and power control for many years. They have, however, been subject to a number of problems and limitations, particularly in the hostile environments often found in farm applications.

Although solid-state relays (SSRs) offer possible solutions to many of the EMR disadvantages, SSRs may not be used to directly replace EMRs in many circuits. The basic differences between SSRs and EMRs must be carefully considered if satisfactory application and performance are to be obtained as a number of authors have indicated (Arnett 1967; Andreiev 1973; and Dowdell 1974).

As part of a project for improving farmstead electrical equipment, advantages and limitations of solid-state relays for control applications have been investigated.

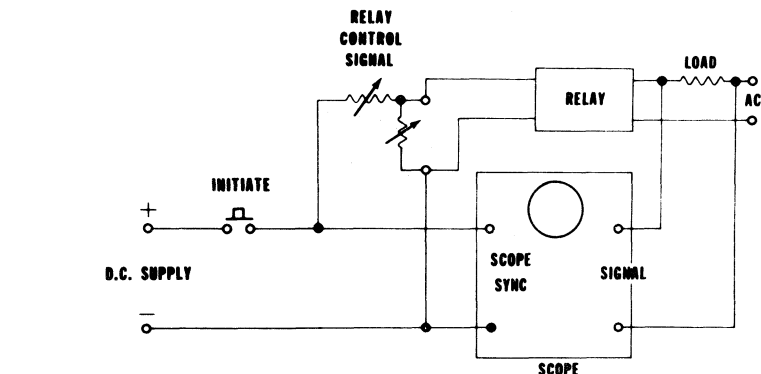


FIG. 1 Relay test circuit.

## MATERIALS AND METHODS

Solid-state relays have been tested both in the laboratory and in control applications for determination of their performance and their limitations. The circuit shown in Fig. 1 was used to evaluate speed of response, turn-on characteristics, and performance of a number of solid-state relays. A storage-type oscilloscope was used to record relay response time, and measurements were made of both turn-on and turn-off characteristics from the oscilloscope trace.

Because most controlled circuits encountered in farm applications operate on ac, the four basic types of relays considered were the electromechanical relay (EMR), the hybrid solid-state relay (HSSR), the totally solid-state relay (SSR), and the triac switch as shown in Fig. 2.

## RESULTS

Typical characteristics of control circuit relays as determined from both manufacturers' and experimental data are shown in Table 1. Operational characteristics of SSRs vary over a wide range as shown and are dependent on the exact type and model of relay. The following discussion gives a number of major considerations that were found to be important in control circuit relay selection and use.

## Electromechanical Relays

For conventional applications requiring multiple poles and for normal environments, the EMR is generally the most cost effective choice. EMRs offer a closed resistance that is essentially zero (in the order of milliohms) and an extremely high open circuit resistance that is limited only by the insulation used in the relay. EMRs are insensitive to voltage transients on their load side and can operate at high temperatures.

Disadvantages of EMRs, however, are limited contact life, slow speed of operation, contact bounce, electrical spark hazard, and opening upon momentary low coil voltage. EMRs may also produce radio frequency interference (RFI) that can interfere with other control circuits because of their unpredictable time of contact opening and closure in power control circuits.

## Solid-State Relays

In control circuits involving solid-state logic or other low-level applications and in many types of hostile environments, the SSR and the HSSR have characteristics unobtainable in the normal EMR. Solid-state relay characteristics and the intended application must be thoroughly understood, however, to obtain proper performance and to prevent malfunctions.

Article was submitted for publication in August 1975; reviewed and approved for publication by the Electric Power and Processing Division of ASAE in March 1976. Presented as ASAE Paper No. 75-3008.

Journal Paper No. J-8199 of the Iowa Agriculture and Home Economics Experiment Station, Ames, IA. Project 1867.

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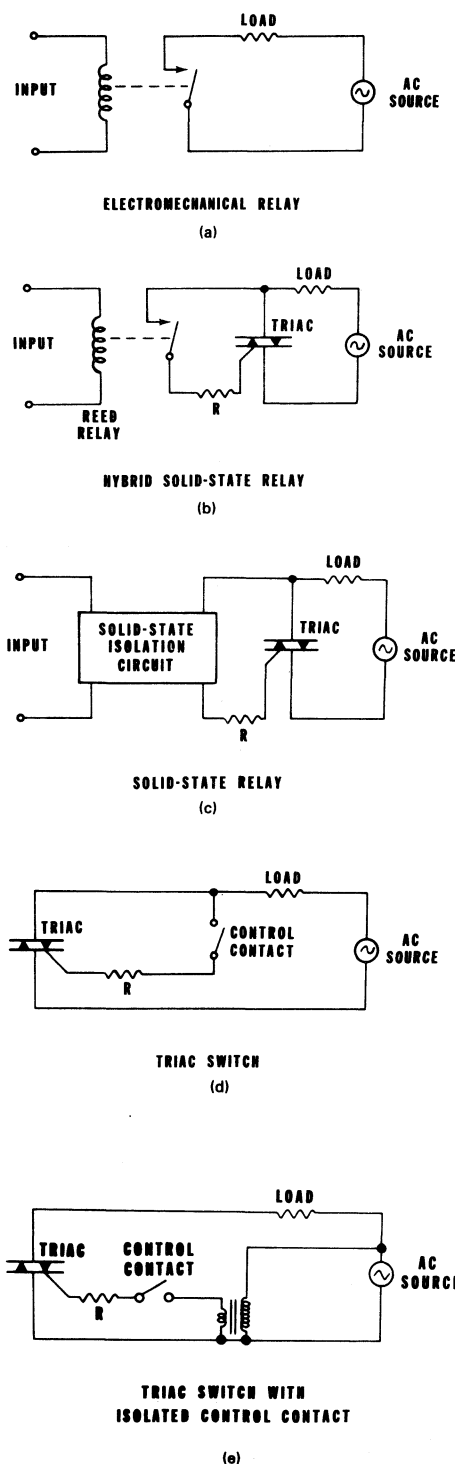


FIG. 2 Basic relay types.

Proper initial selection of SSRs was found to be the most important factor in the successful application of SSRs to control circuits. When the operating parameters specified in Table 1 and the application considerations were properly followed, all SSRs tested gave very satisfactory performance.

The only problem observed was the possible safety hazard presented by the lack of isolation between the control contact and the load circuit for the triac switch circuit of Fig. 2(d).

This may be easily overcome by using some means of control contact isolation as shown in Fig. 2(e).

The true SSR uses all-semiconductor circuitry to trigger the output switching element (Sahm III, 1974), but the HSSR uses a mechanical contact such as a reed relay to provide the trigger signal. Both methods of triggering can provide isolation of 1,000 V or more between the input and output circuits, but the HSSR has an advantage over the SSR in its integration of noise transients on the input. Because the reed relays used in the HSSR generally take 1 to 2 ms to operate, short duration transients at the input usually will not cause unwanted operation. This slow response, however, generally prevents the use of HSSRs for fast switching.

Measurements made of the turn-on characteristics of a typical HSSR are shown in Fig. 3. A random closure at  $\pi/2$  in the ac cycle is indicated, as well as a typical delay in turn-on of 2 ms.

Because the reed relay in the HSSR has definite limits on input voltage (similar to limits on input voltage for the EMR), it must be selected for specific input conditions. SSR inputs,

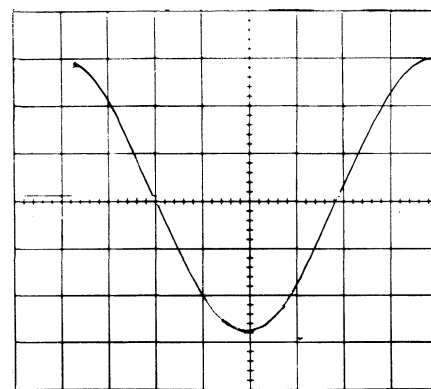


FIG. 3 Typical HSSR turn-on characteristics for a 60 Hz, 120 V circuit. Time base 2ms/Division.

on the other hand, usually accept a wider range of input voltage; 3 to 32 V dc or 90 to 280 V ac are not uncommon. Turn-on occurs at the minimum voltage of the SSR voltage range, however, and the upper value of specified voltage indicates only the maximum voltage that they can accept without damage.

Many solid-state relays are opto-isolated. That is, a light-emitting diode (LED) is optically coupled to a photo-sensitive semiconductor. The input signal activates the LED and its emitted light is picked up by the photo-sensitive transistor or silicon-

TABLE 1. TYPICAL CHARACTERISTICS OF CONTROL CIRCUIT RELAYS.

Comparison	Type of relay		
	Electromechanical	Hybrid	Solid-state
Operating frequency	1-10 Hz	1-100 Hz	1 Hz to 1 kHz
Minimum load current	No general limitation (Dry circuit types available)	10-100 mA, common	10-100 mA, common
Contact resistance			
Closed	10-100 mΩ	100 mΩ to 2 ohms	100 mΩ to 2 ohms
Open	500 GΩ	>20 MΩ	>20 MΩ
Synchronous operation and zero voltage turn-on	No	Possible, generally no	Yes
Coil voltages, ac	6,12,24,48,115,230, 460 V		3-280 V
dc	6,12,24,110,220 V	Generally the same as for EMRs	3-200 V
Speed, turn-on	1-20 ms	1-20 ms	5 μs
turn-off	2-20 ms	100 μs to 8.3 ms	100 μs to 8.3 ms
Input power	As low as 400 mW, typically 1-3 W	As low as 400 mW	As low as 6 mW
Life cycles	100,000 to 1 million	100 million (limited primarily by the reed relay)	Virtually unlimited (limited primarily by solid-state device life)
Contact bounce	Yes	No	No
Electrical spark hazard	Yes	No	No
RFI/EMI	Yes, unless suppressed with auxiliary components	Generally yes, unless specifically switched at zero crossover or otherwise suppressed	None if switched at zero crossover
Vibration/shock	Susceptible	Highly resistant	Highly resistant
Can exhibit unwanted closure	Can exhibit unwanted closure	Generally resistant to unwanted closures from shock	No unwanted closures from shock
Transient immunity (dv/dt)	Not susceptible	100 V/μs	100 V/μs

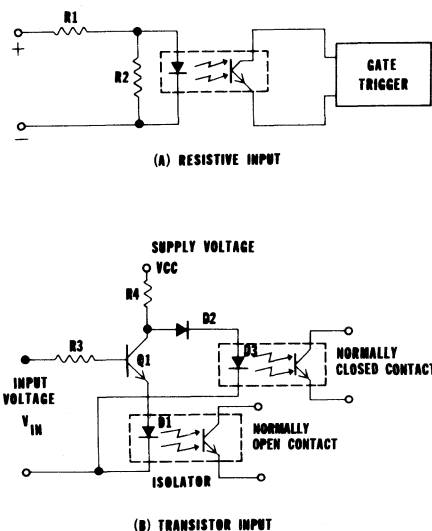


FIG. 4 Typical solid-state relay input circuits.

controlled rectifier. The input current required to drive the LED must be supplied from the control circuitry. An important design consideration is, therefore, the interface compatibility between the controlling device and the relay input requirements, particularly in relation to pull-in and drop-out voltages and currents.

Variation of LED light output also must be considered in critical applications. Light output and rate of decrease in output with age vary between units. Such variation may produce a change in turn-on parameters and cause system failures, particularly when analog signals are applied and relay hysteresis becomes important.

Two input circuits are commonly used. Both have isolation provided by an optical photocoupler as shown in Fig. 4. The light-emitting diode (LED) in Fig. 4(A) with a resistive input is the simplest. Resistors  $R_1$  and  $R_2$  are selected to provide the proper current through the LED for the control signal used and for the desired turn-on and turn-off thresholds of the SSR. Operating current is supplied by the input control signal, and variations in the LED over its operating life must be compensated for by control of the input signal. The circuit of Fig. 4(B) uses a transistor to obtain the equivalent of single-pole, double-throw switching. Values of  $R_3$  and  $R_4$  may be determined by the following relationships:

$$R_3 = \frac{\text{Input voltage, } V_{IN} - (\text{Voltage drop in } Q_1) - (\text{Voltage drop in LED, } D_1)}{\text{LED current, } I_{D_1} (1/\text{Gain } Q_1)}$$

$$R_4 = \frac{\text{Supply voltage, } V_{CC} - (\text{Voltage drop in diode } D_2) - (\text{Voltage drop in LED, } D_3)}{(\text{LED current, } I_{D_3})}$$

For a typical application:

Saturated voltage drop of transistor

$$Q_1 = 0.7 \text{ V}$$

LED voltage drop

$$= 1.3 \text{ V}$$

Gain of  $Q_1$

$$= 20$$

Required current of LED

$$= 0.05 \text{ A}$$

$$R_3 = \frac{V_{IN} - 0.7 - 1.3}{0.05/20} = 400 (V_{IN} - 2.0 \text{ V})$$

and

$$R_4 = \frac{V_{CC} - 0.7 - 1.3}{0.05} = 20 (V_{CC} - 2.0)$$

Solid-state relays, however triggered, use solid-state output devices to close the circuit. Power control devices in all the SSRs tested were either back-to-back SCRs or a triac (a bidirectional device named from the construction of TRIode AC semiconductor switch).

Triacs or SCRs are capable of switching ac loads, but dc control usually is not obtained because the load current must be reduced below the holding current of the SCR or triac for turn-off.

When contact chatter, arcing, or hesitation must be avoided, or when a load must be switched in synchronization with power or control timing, SSRs offer definite superiority to EMRs. In control applications where potentially explosive atmospheres are encountered, the advantage of the SSR arcless operation becomes obvious. Zero-voltage turn-on of SSRs offers less obvious advantages but can be extremely important in preventing the malfunctioning of other control circuits or adjacent equipment by eliminating power line surges and RFI due to mid-cycle turn-on (McLendon 1974).

Generally, the power required to turn on an SSR is lower than that for an EMR. Typically this may be as low as 100 mW as compared with

3 W or more for a power control EMR. Measured values have been found as low as 0.1 mW.

## APPLICATION CONSIDERATIONS

Low-cost SSRs may use a single SCR for control and have a rectified dc output suitable only for heating or lighting loads. Even ac SSRs using back-to-back SCRs, a single SCR in a diode bridge or a triac may partly fail and produce dc. Circuits and use should be planned to accept inadvertently produced dc.

SSR open circuit contacts are not the same as open EMR contacts. SSR contacts are never really open and always have some value of leakage current through them. In the off-state, an SSR presents a high impedance but still may apply an appreciable voltage across a load. When SSRs are used to control unloaded transformers or other high impedance loads, some provision, such as a dummy load resistor, should be used for reducing the off-state voltage.

Transient voltage spikes or over-voltage conditions can turn on an SSR without a trigger signal and result in conduction for the remainder of the voltage cycle. Although this may not be a destructive condition, it can result in unwanted or unexpected power-on conditions. Power line transients usually are more serious with SSRs than with EMRs. Transient voltage surges of up to 10 times the nominal line voltage are often encountered on power lines, and provision must be made to prevent unwanted application of power to the load when SSRs are used.

Transient problems also may be caused by the steep wave fronts or the high frequency oscillations produced by phase-controlled loads or high current switching of other loads by EMRs. A high rate of rise of forward applied voltage ( $dv/dt$ ) can cause thyristors to switch into the "on" or low impedance forward conducting state even though break-over voltage has not been exceeded.

Snubber networks consisting of a small resistor in series with a capacitor as shown in Fig. 5 can be placed across the SSR output terminals to prevent  $dv/dt$  triggering. The capacitor limits the rate of voltage rise across the open SSR contacts, and the

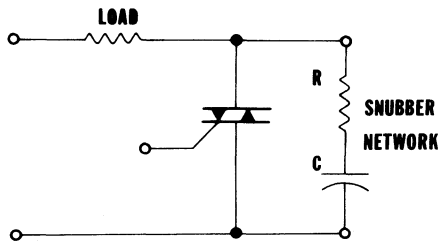


FIG. 5 Snubber network for suppressing  $dv/dt$  triggering.

resistor prevents ringing and limits the discharge current of the capacitor.

Snubber currents combine with semiconductor leakage currents to produce minimum off-state currents that may affect high impedance circuits. The maximum leakage current that the load can stand and still be considered off determines the relay and snubber network selection. The size of the snubber capacitor must be chosen with care because snubber capacitor current usually is the major portion of the total leakage current.

Solid-state relays are much faster than EMRs but do not have unlimited speed. They operate well at 60 Hz and may perform well at 400 Hz. At frequencies of 1,000 Hz or greater, however, the zero-voltage time window in which the thyristor can be triggered, decreases and susceptibility to  $dv/dt$  turn-on increases.

Several additional factors must be considered in using SSRs. The importance of each is dependent on the application, but a user of SSRs must be aware of their possible effect.

The EMR is usually free from thermal heat buildup problems, but devices using semiconductors are not. Voltage drops across semiconductor junctions are on the order of 0.5 to 1.5 V. For every ampere of current, therefore, 0.5 to 1.5 W of heat are created that must be conducted away. Heat buildup must be limited so that the junction temperature of the solid-state device stays within its ratings. Otherwise, the relay may not turn off. This necessitates heat sinks for con-

ducting the heat away and requires derating the power with temperature as indicated in the typical derating curve of Fig. 6.

Care must be taken in mounting an SSR to be sure that it is mounted to a heat sink and not to a heat source. Increased ambients caused by heat buildup within enclosures or the mounting of a solid-state device to a surface that is above normal ambient may cause turn-off failure. In enclosed cabinets and wall boxes, additional heat sinking is often required to use SSRs at full ratings.

Brownout conditions also may cause problems in SSRs because of the reduced voltage conditions. Load current of controlled motors will increase and the load on-time of heater loads may increase, causing increased dissipation and possible overheating of the SSR. Low voltage also may cause problems in SSR turn-on because of insufficient trigger energy. Some SSR designs have been found that will not operate below 75 percent of nominal line voltage.

Surge current ratings are an important consideration in SSR applications. For short-period overcurrents, thyristors behave essentially like a resistance with a fixed thermal capacity and no power dissipating means. Although the surge currents that may be applied to SSRs are generally greater than those that may be applied to EMRs and have less effect on relay life, they must be limited. Typically a 1,000 percent surge current may be safely applied to an SSR for one ac cycle (16 ms) or 650 percent for up to 10 cycles, as shown in Fig. 7.

The maximum forward non-recurring overcurrent for very short durations (generally 8.3 ms or less) must also be limited to prevent thyristor damage in SSRs. This current capability is expressed as the  $I^2t$  rating where  $I$  is the rms current value over the interval  $t$ .

Care must also be taken in burst firing of SSRs so that half-cycle firing or unidirectional grouping of the pulsed ac power does not occur when magnetic cores are involved. This prevents the addition of a dc bias to the magnetic circuit which may cause saturation and nonlinear operation.

The holding current required to keep a thyristor conducting may be an important consideration in some applications; SSRs that use triacs or SCRs require a minimum load current to stay turned on after they have

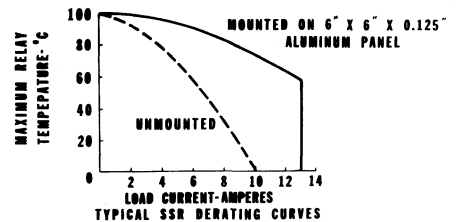


FIG. 6 Typical SSR derating curve.

been triggered. If load current drops below a minimum value, the SSR will shut off. Typical values for this minimum current may vary from 200 mA for a 25-amp rated SSR to 500 mA or more for a 75-amp rating.

When highly inductive loads are encountered, additional circuitry may be required to compensate for the fact that zero voltage and zero current do not occur at the same time, thus creating timing problems. Current limiting also may be required to keep the SSR within its  $I^2t$  rating or it may be destroyed.

For pulsed applications, SSR average power ratings must not be exceeded by pulsing too often. Pulsed operation may also cause thermal fatigue at the thyristor mounting junction because of temperature gradients and uneven expansion.

Noise immunity is also a consideration in applying SSRs because of their sensitivity and ability to operate at high speeds. If a relay is specified to close at 3 V at worst case and open at 1 V at worst case, and the actual operating voltage is 2 V for a specific unit, then only 1 V of noise immunity is obtained as shown in Fig. 8.

Most SSRs have build-in hysteresis to prevent chatter when driven by analog marginal or noisy signals. Best noise immunity is obtained by using a relay with a low dynamic input impedance and a large hysteresis. Noise problems on input circuits require more care in the application of SSRs than of EMRs. Techniques such as single-point grounding, push-pull driver circuits, and twisted and shielded input lines may be required to achieve the desired noise immunity.

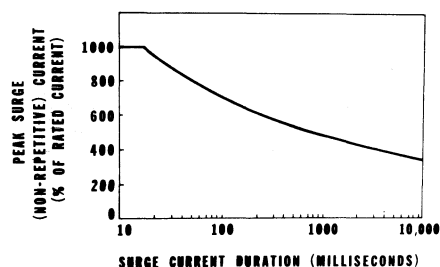


FIG. 7 Surge handling capability of typical SSR [one minute maximum repetition rate].

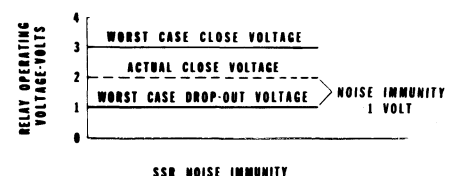


FIG. 8 Noise immunity of an SSR in relation to operating specifications.

## CONCLUSIONS

Solid-state relays are most useful for applications requiring maximum reliability for many contact closures and minimum RFI. Principal uses of SSRs at present are control of heaters, motors, or lighting where their contactless switching and zero voltage turn-on properties may be used to advantage.

A given set of EMR contacts can switch dc, ac, or control signals, but an SSR generally may be used for only a single task and many can only switch ac power into relatively low impedance loads. The fast and controlled con-

tact closures of an SSR, however, allow operations to be performed in a way that would be impossible with EMRs. Power turn-on for as little as one ac cycle or for a controlled number of ac cycles becomes possible.

The most important factor in the use of SSRs in control circuits is to recognize that SSRs may not be used as a direct replacement for EMRs in most circuits. Although SSRs and EMRs have some common performance characteristics, each has capabilities that the other cannot match. Both knowledge of solid-state relay characteristics and the intended application are essential to

obtain proper performance and prevent malfunctions.

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