Agilent Technologies
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Small Signal Solid State Relays

Application Note 1036

Introduction

Traditionally, isolated control of signal paths has been provided by the Electro-Magnetic Relay (EMR). The purpose of this application note is to present an alternative, the Solid State Relay (SSR), and to describe some of the ways in which the SSR can be used.

An SSR, as the name implies, is entirely composed of solid state devices—no mechanical movement takes place in its operation. An LED on the control side converts the electrical input into optical power. On the contact side, the optical power is converted back into an electrical signal that supplies power for a switch driver to energize a solid state switch. In some classes of SSR a small fraction of the power from the circuit being switched is used to operate the solid state switch (e.g. thyristor), but in others the power for switch operation comes exclusively from the optical signal (e.g. HSSR-8200) making the contacts completely passive.

Some of the relative merits of SSRs and EMRs are immediately seen in the schematic comparison of Figure 1. On the CONTROL side, the EMR presents an inductive load that may suffer from or radiate magnetic disturbances; the collapse of the magnetic field, when it is de-energized, may produce transient voltages requiring suppression. The SSR control is simply an LED that neither suffers from nor causes magnetic disturbances; and the low voltage change at turn-on or turn-off seldom requires transient suppression. While the EMR can usually be energized by either polarity of voltage and current, the SSR requires current in the direction shown. Either-polarity operation of the SSR is easily accomplished with a bridge rectifier.

On the CONTACT side, SSRs are of three general classes: ac only, dc only, and bi-directional (ac or dc). Bi-directional types, like the EMR, can pass current in either direction when closed, and can withstand voltage of either polarity when open. In some types of EMR, a single control circuit can operate more than one set of contacts, and these contacts could be form A (normally open), form B (normally closed), form C (double throw), or any combination of these options. Most SSRs offer form A contacts but form B and form C can also be made. Also, in most SSRs a single control operates a single set of contacts, but multi-function operation of SSRs can be achieved easily with simple circuits, as shown later.

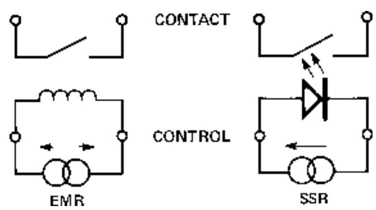


Figure 1. Schematic Comparison of EMR and SSR.

The IMPORTANT differences between SSRs and EMRs do not appear schematically, but functionally. In SSRs there are no mechanical movements and consequently they enjoy four distinct advantages over EMRs:
1. No contact bounce—closure is always clean
2. No problems with shock, vibration, or mounting position
3. No wearout mechanism limiting the number of operations
4. No minimum contact “wetting” current

In EMRs, the contact bounce problem can be addressed with mercury-wetted contacts, but this may impose a restriction on mounting orientation relative to gravity; SSRs can be mounted and operated in any position. In environments of heavy shock and vibration, SSRs provide clean operation—unless the mechanical abuse causes physical damage. A particularly important advantage of SSRs is the unlimited number of operations. EMRs typically function reliably for only about one billion operations; at 1,000 operations per second such EMRs are good for only two weeks and should then be replaced.

Summary of Characteristics

Some features of the SSR from Agilent Technologies, the HSSR-8200, can be described relative to the circuit diagram in Figure 2 and the approximate equivalent circuit of Figure 3.

First, notice the construction is in 8-pin DIP size, but of course only four pins are needed. Agilent uses the four corner pins 1, 4, 5, and 8, to make handling easier, especially by machinery for automatic insertion.

Next, consider the control side. Polarity is defined in Figure 2.

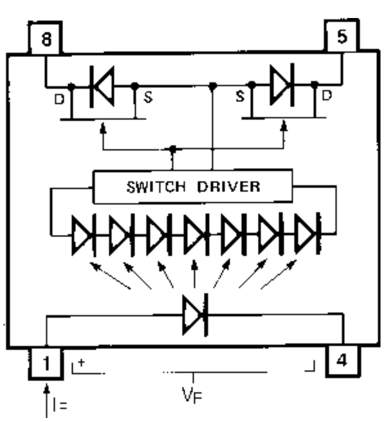


Figure 2. Circuit Diagram of HSSR-8200.

The HSSR-8200 is energized (contacts closed) with I_F as low as 1.0 mA at V_F only slightly more than 1.0 V (some SSRs may have higher I_F and V_F requirements). In some applications it may be desirable to operate with higher current, but since the current varies exponentially as the voltage this would require only a slightly higher voltage. Operation at higher current causes faster closure of the contacts. and reduces $R_{(ON)}$ slightly; it also increases the offset voltage, $V_{O\ (OS)}$. To de-energize the SSR (contacts open) requires a lower current, but a more reliable assurance of the de-energized condition is to make the forward voltage less than 0.8 V. A complete switching of the contacts from open to closed requires a voltage change usually less than 0.4 V, and seldom more than 0.9 V.

In the energized condition, optical radiation from the LED is converted by a photodiode array into sufficient voltage and current to operate the SWITCH DRIVER (Fig. 2) and also to drive the gate-source electrodes of the two FETs. It is important to notice here that all the power to operate the switch comes from the photodiode array—no power is required from the circuit being operated by the switch.

The contact side appears complicated, but in most applications it is possible to ignore some or all of the extraneous circuit elements. It is therefore worthwhile to give some thought to the equivalent circuit of Figure 3, and check the data sheet values to see if they can indeed be ignored. In many situations the values of $R_{(ON)}$ are so low and $R_{(OFF)}$ so high that they can be ignored, and the same may

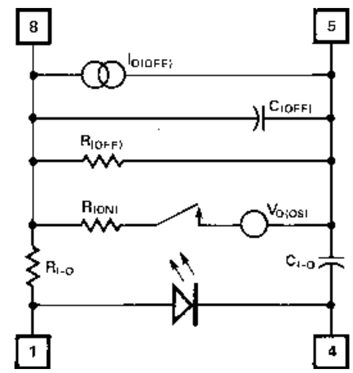


Figure 3. Approximate Equivalent Circuit of HSSR-8200.

be true of the other parameters as well. For the HSSR-8200, $R_{(ON)}$ is less than 0.00025 megohms and $R_{(OFF)}$ is more than 50,000 megohms; consequently, in circuits having few-megohms impedances they may be regarded as short and open, respectively, with error of only a few parts per million. For circuits having variable impedances, the ratio of $R_{(OFF)}$ to $R_{(ON)}$ is significant as it relates to the ratio of impedances, relative to which the error may be ignored.

The HSSR-8200 is distinguished relative to other SSRs and mechanical relays by its high speed of operation, low offset voltage $V_{O\ (OS)}$, low offset current $I_{O(OFF)}$, and small value of off-capacitance.

Where very low signals are to be switched, $V_{O\ (OS)}$ and $I_{O\ (OFF)}$ should be considered. With voltage applied to the open contacts, part of the resulting current $I_{O\ (OFF)}$ is flowing in $R_{O\ (OFF)}$, and part is the reverse current in whichever of the two diodes in the contact circuit (see Figure 2) is reverse biased. When the LED is turned on and the switch closes, the magnitude of $V_{O\ (OS)}$ initially rises, then falls as heat from the LED spreads through the contact circuit and largely balances out thermocouple voltages. The data sheet values for $V_{O\ (OS)}$ are taken at peak, occurring a few seconds after the control LED is energized, and the polarity is consistent.

Although $C_{(OFF)}$ is extremely small, at 1,000 Hz the reactance of $C_{(OFF)}$ is below 100 megohms; consequently, to switch signals having frequencies even as low as the audio range it may be necessary to employ special techniques to deal with $C_{(OFF)}$. Such techniques might be as simple as lowering the circuit impedances, but could also require series-shunt combinations of form A and form B switching, or applying neutralization.

Another consideration is the range of circuit currents with which the SSR contacts can be used. At the low end, there is the leakage current, $I_{O\ (OFF)}$. At the high end, the current may be limited only by the maximum rating of $I_{O\ (ON)}$, (40 mA for HSSR-8200), or it may be limited by the linearity of $R_{(ON)}$. Notice in Figure 2 that the contact consists of two FETs in anti-series to provide bidirectional symmetry. Across each FET there is a source-to-drain diode. Since each FET has a channel resistance approximately equal to half $R_{(ON)}$, this diode begins to turn on when the contact current rises to a level at which the voltage drop across the contact is approximately two diode drops. Above this level, the dynamic resistance has approximately half the value it has at contact currents below this level.

In the de-energized condition the open contacts of the HSSR-8200 can withstand voltages up to 200 V of either polarity. In some applications these contacts may be exposed to harmfully high transient voltages. The FET drain electrodes may require that external means be provided to protect them from such transients. Similarly, in the energized condition there is a limit on how much current can be permitted to flow through the closed switch without damaging it.

Between the control side and the contact side are the unavoidable parasitics $R_{I\text{-}O}$ and $C_{I\text{-}O}$ seen in Figure 3. Having a value of more than a million megohms, $R_{I\text{-}O}$ can usually be ignored. $C_{I\text{-}O}$ can usually be disregarded with respect to large transient voltages relative to the contact circuit. Transients with sufficient amplitude could couple enough charge through $C_{I\text{-}O}$ to cause a temporary improper condition of the contacts. However, as seen in the data sheet, the values given for Control-Contact Transient Rejection are so high that it is extremely unlikely that common-mode transients of such magnitude could occur. Even if large transients are not present, there could be a situation in which the control and contact circuits have line voltages be tween their common points. At 115 V rms, 60 Hz, a capacitance of 1.0 pF couples a current of approximately 50 nA rms, and in a 1-megohm load this would produce a 50-mV rms “hum” voltage.

Applications Suggestions

In the arrangements suggested here, only the contacts and their intended closure sequences are shown. Later on, the details of how to obtain such sequences are described.

The signals $E_1 \ldots E_n$ in Figure 4 might come from sources in which the levels are too low to permit processing directly; that is, they may require amplification or impedance conversion. A/D converters and amplifiers are costly, so one motivation for multiplexing is to have the amplifier cost shared among a number of sources. Another, and perhaps more important, consideration is the desirability of having precisely the same gain applied to each of several signals so that ratios of the amplified levels $V_1 \ldots V_n$ will relate to ratios of their unamplified counterparts, $E_1 \ldots E_n$.

Figure 5a shows a configuration that takes advantage of the low offset and negligible nonlinearity of the closed contacts. Without

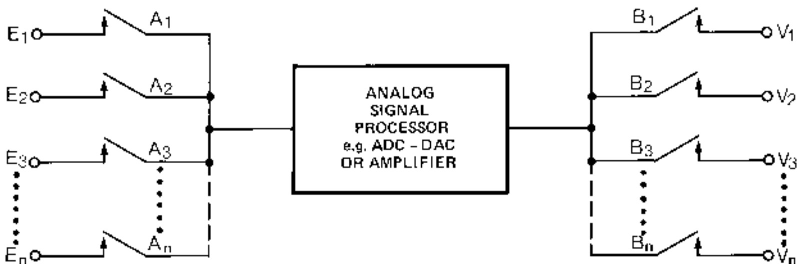
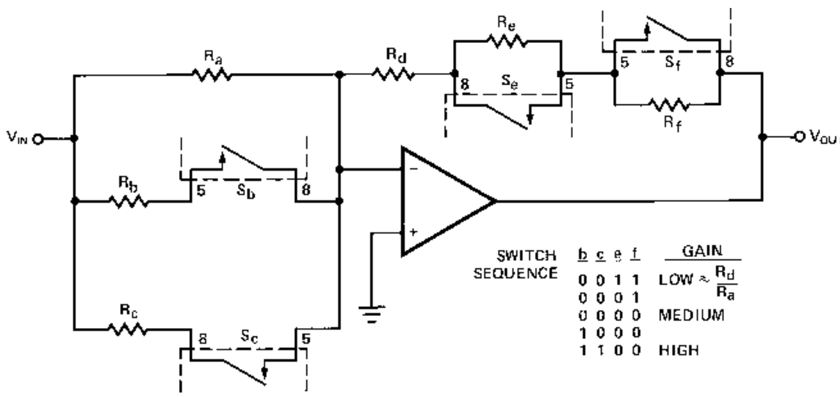


Figure 4. Multiplexing and Demultiplexing.



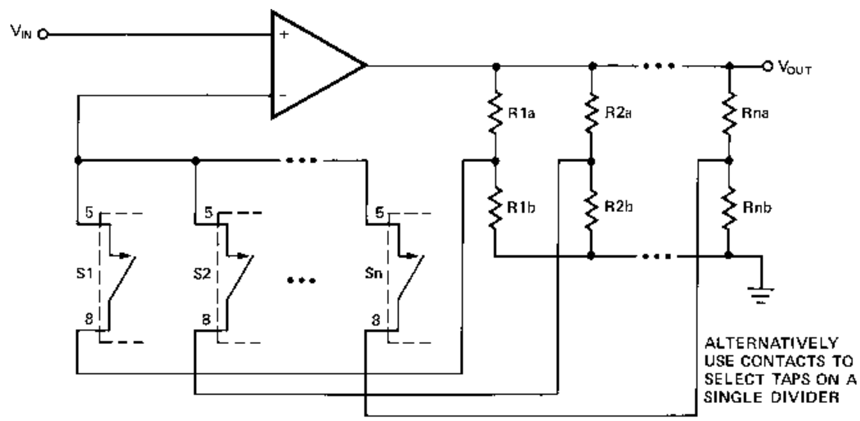
$$\text{VOLTAGE GAIN} = \frac{V_{OUT}}{V_{IN}} \approx -\left(\frac{1}{R_a}+\frac{1}{R_b+\frac{R_{ON}}{S_b}}+\frac{1}{R_c+\frac{R_{ON}}{S_c}}\right)\left(R_d+\frac{1}{\frac{1}{R_e}+\frac{S_e}{R_{ON}}}+\frac{1}{\frac{1}{R_f}+\frac{S_f}{R_{ON}}}\right)$$

$$\text{EACH SWITCH, } R_{eq,n} = \frac{R_{ON}}{S_n+\frac{R_{ON}}{R_{OFF}}} \approx \frac{R_{ON}}{S_n} \qquad \text{OPEN, } S_n\ 0 \quad \text{CLOSED, } S_n = 1$$

Figure 5a. Inverting Amplifier Gain Switching.

encountering serious error at either a high or a low signal level this arrangement can perform inverting gain selection over a four-decade range. Another possibility is shown in Figure 5b; here On-Resistance of the closed contacts is even less significant than in the arrangement of Figure 5a.

Where speed of operation is unimportant, the SSR can be operated at a much lower control current than is required for usual applications. This would be useful in an application such as the battery-powered alarm system shown in Figure 6. Here the alarm circuit, which would be a relatively heavy drain on the battery, is disconnected until the sensor circuit energizes the control circuit of the SSR. At that point, as the contacts begin to close, the control circuit current is augmented, and latches the alarm.



$$\text{VOLTAGE GAIN} \quad \frac{V_{OUT}}{V_{IN}} \approx \left(1+\frac{R_{na}}{R_{nb}}\right)$$

Figure 5b. Non-Inverting Amplifier Gain Switching.

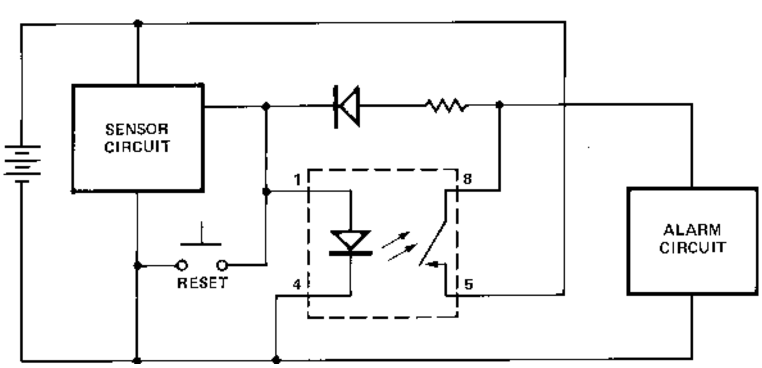


Figure 6. Low-Control-Current Battery Saver.

Control Drive Circuit Suggestions

Operation of the HSSR-8200 control requires a forward current for the energized (ON) condition to close the contacts; for the de-energized (OFF) condition the forward voltage must be less than 0.8 volts. $R_{(ON)}$ is specified for forward current of 1.0 mA, and operation at higher forward current does not reduce $R_{(ON)}$ very much. On the other hand, increasing the control current increases the offset voltage – almost linearly. The only benefit from operation at control current greater than 1.0 mA is

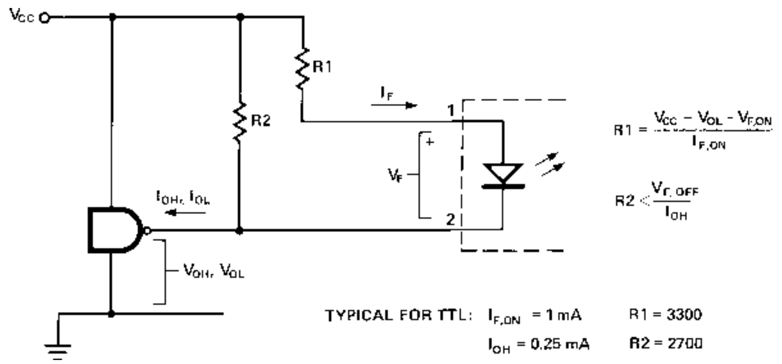


Figure 7. Logic-Driven Control Circuit.

the better-than-linear reduction in turn-ON time; there is also a slight reduction in turn-OFF time. A simple circuit for obtaining the desired ON current and OFF voltage is shown in Figure 7. The logic series used can be almost anything; any of the TTL logic family, open-collector or totem pole, will work in the arrangement shown. The same is true for CMOS, provided only that the current-sinking capability is adequate. R1 sets the level of forward current, independent of R2. The purpose of R2 is to bypass logic-high leakage current with sufficiently small voltage drop to ensure an OFF-voltage less than 0.8 V. In some cases R2 is not required; some logic outputs have internal pullup circuits that are able to satisfy the OFF-voltage requirement without the external pull-up provided by R2. With open-collector TTL outputs, R2 is always required because the HSSR-8200 can actually be operated (though at higher ON resistance) with just a few microamperes of forward current.

In computing the resistor values for this and other drive circuits a useful approximation for the relationship between the forward voltage and the forward current is given by: The circuit in Figure 7 is basically a series-drive type because the active current is

$$V = Va + (dV/dT)*(25 - T) + Vb*\log(I)$$

V in volts, T in degrees Celsius, I in milliamperes

where $1.1 < Va < 1.5$ volts
$0.07 < Vb < 0.12$ volts
$0.0015 < (dV/dT) < 0.002$ volts/degree Celsius

switched by a device in series with the LED. As will be seen later, this type of drive circuit has a great deal of flexibility in achieving other design objectives. It can be used with TTL having either active pull-up (totem-pole) output or open-collector output. If open collector TTL is available for driving the control, a simpler alternative is the shunt switching of Figure 8. It requires only a single resistor, and the logic-low voltage does not influence the ON current. The OFF voltage requirement is inherently satisfied by the logic-low voltage.

As mentioned earlier, turn-ON time is influenced by the level of forward current. As forward current is increased, the turn-ON time becomes shorter. However, it may not be desirable to operate with a high steady-state forward current because that would increase the offset voltage due to heat transferred from the LED control to the

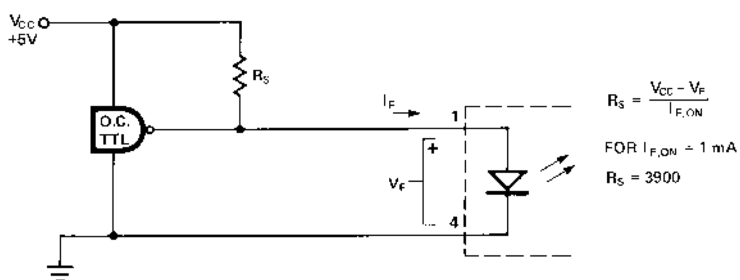


Figure 8. Shunt-Driven Control.

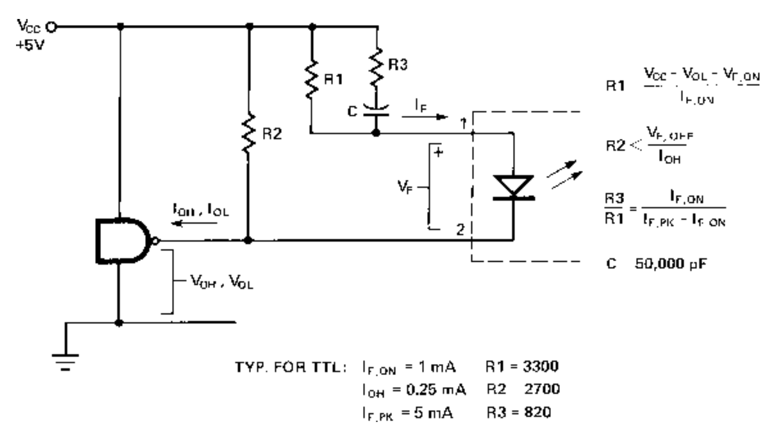


Figure 9. Peaking to Shorten Turn-On Time.

contact side. In situations requiring fast turn- ON but low offset, a peaking circuit can be used, like that in Figure 9. When the logic output is high, R2 assures that the current through the LED is so small that the capacitor is completely discharged. Then when the logic output goes low, there will be a surge of current through both R1 and R3 until the capacitor is charged to the voltage across R1, and thereafter the steady-state current is set by R1 only. Thus peaking permits fast turn-ON as well as low steady-state current (low offset in the contact circuit).

Closing the contacts requires charging the capacitances in the SWITCH DRIVER circuit (Figure 2). This charge is the time-integrated photocurrent from the photodiode array, and translates into a certain amount of charge that must pass through the LED (of the order of 200 nanocoulombs). That amount of charge is set by the value of the peaking capacitor and the voltage across R1. For this reason it is not necessary to change the value of the capacitor when other (higher) values of peak current are desired; it is necessary only to reduce the value of R3 and make sure that the logic output is capable of sinking the higher current.

Figure 10 shows a combination of series-shunt drive. The column drivers do the series switching and the row drivers operate in shunt mode. With the ENABLE input high, selection is made of desired row and column (high true) but the selected LED remains OFF until the ENABLE goes low. This provision is necessary to ensure "break-before make" operation of the contacts. With turn-OFF time longer than turn-ON time, there must be a "dead" time of 0.2 milliseconds or more to prevent overlapping contact closure. The values of R1 and R2 are selected as described for the circuits of Figures 7 and 9, and, if desired, the R3,C peaking may be added in parallel with each R1.

The matrix arrangement in Figure 10 is worth considering only if a very large number of switches are to be selectively operated. To make a selection from a smaller number of switches, a much simpler circuit is shown in Figure 11, where a decoder/demultiplexer IC is used. The values of the resistors R1 and R2 are NOT computed in the same way as for the circuits of Figures 7 and 9. Here the principle is to select a ratio R1/R2 such that the forward voltage across the LED is less than 0.8 volts when the 74154 output is high, then establish this ratio with resistor values small enough to allow adequate forward current when the 74154 output is low. Actual selection of resistor values is most easily done by first selecting R1 with a large margin in the inequality to provide a wide range for selection of R2 to fit within the two sided inequality. If peaking is desired on any or on all three of the anode bus lines, the R3,C peaking circuit may be added with no effect on the choice of R1 and R2 values. The peaking circuit may be connected either to V_{CC} or to ground. An important concern is operation of the ENABLE inputs of the 74154 decoder. Both of these must be low to make the output (selected by the address) go low. It is recommended that at least one of the ENABLE inputs be

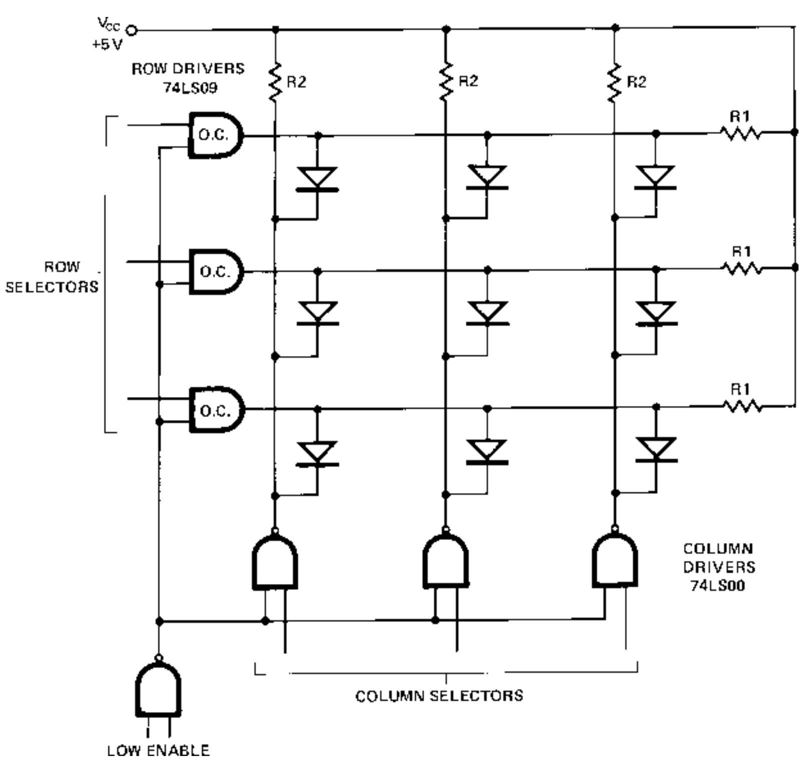


Figure 10. Matrix-Driven Control Circuit.

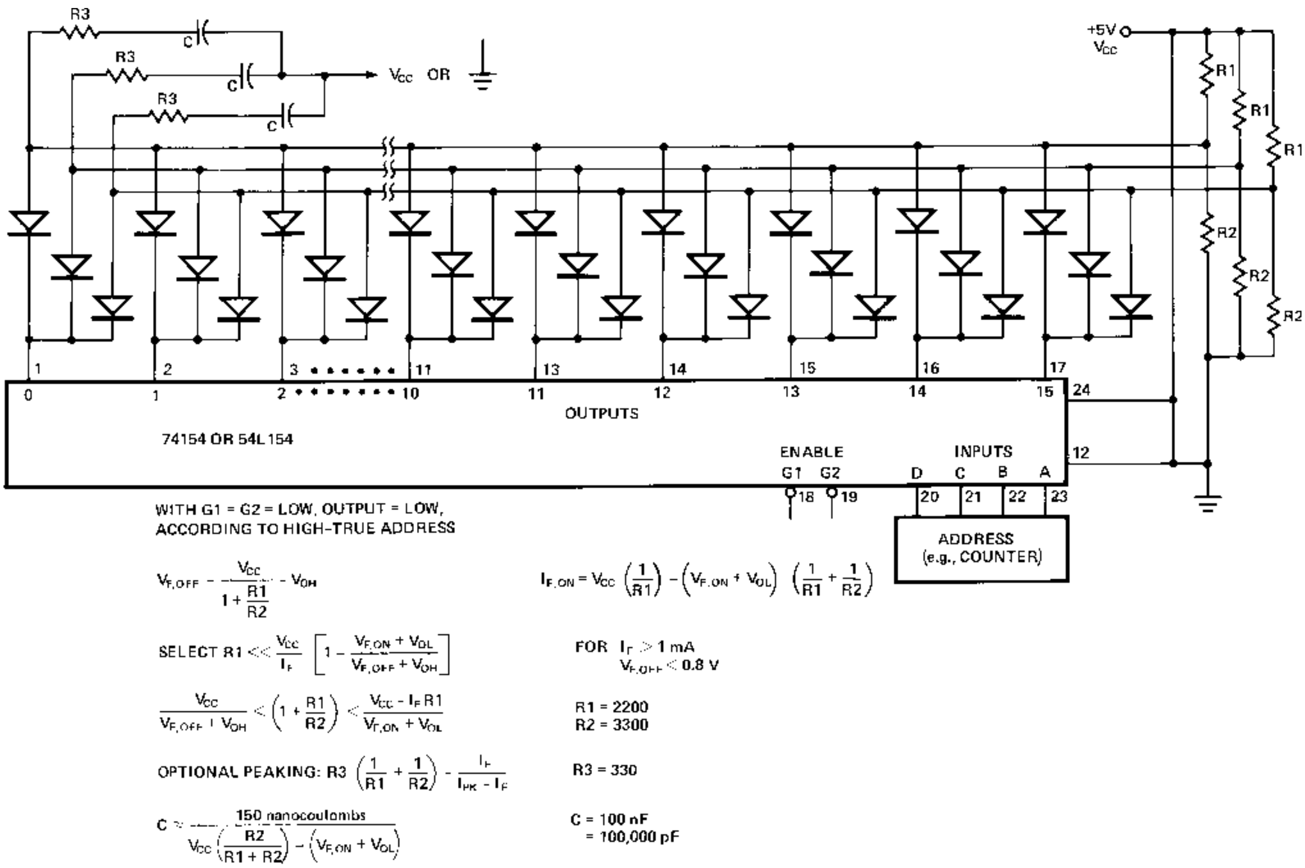


Figure 11. Control Circuit for 16-Channel Multiplexer.

made high for an interval of 0.2 milli- seconds or more, following address selection, to prevent overlapping contact closure.

In Figure 11 (also in Figure 10) the length of time that any individual contact is held closed may depend on how fast the contact circuit can respond to the contact closure. It depends also on the offset voltage property of the HSSR-8200 as a function of time following application of control current, shown in Figure 13. At the initial closure, heat from the LED produces a thermal gradient in the contact drive IC, causing the offset voltage to begin increasing (negative polarity); after a few seconds, the offset voltage reaches a peak and then decreases as the thermal gradient disperses. The polarity of the offset voltage is consistent, however, so two sets of contacts in a differential arrangement will cause the offset voltage (either in steady state or during the transient) to be partially cancelled. For this reason the contacts should be arranged as in Figure 12, and the control LEDs should be driven in triplets, as in Figure 11. Two of the contacts perform differential signal selection while the third connects the "guard" driver to the appropriate shield.

Overvoltage Protection

In some applications there is a possibility that the contacts may be exposed to destructively high voltages. One such situation is partially illustrated in Figure 12, where the HSSR-8200 is being used to select one set of inputs from among several and present this set to the Signal Processor. The differential inputs (H and L) are shielded by a guard (G) driven by the Processor. When open, the

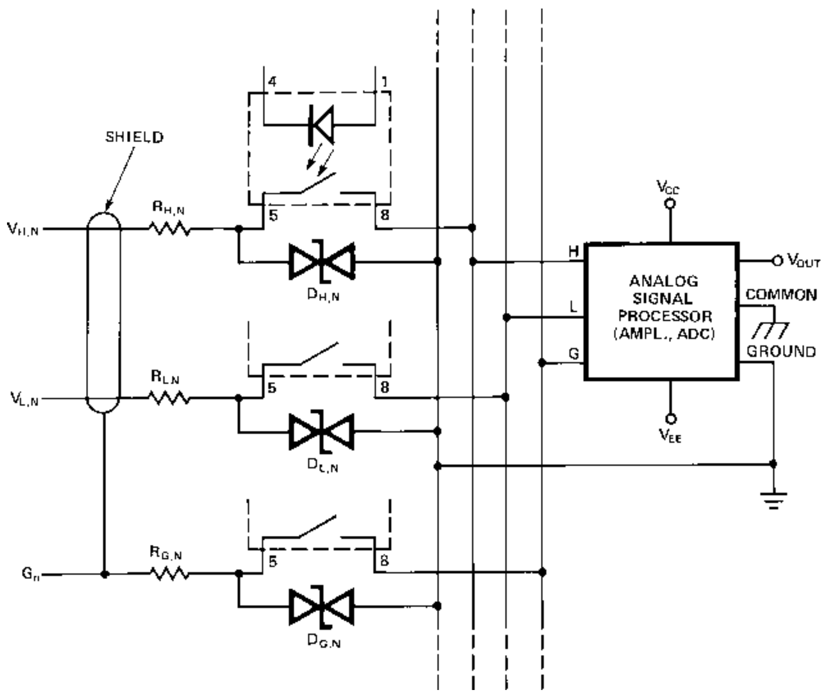


Figure 12. Contact Circuit for One Triplet of Several in Multiplexing.

contacts of the HSSR-8200 can withstand 200 volts, positive or negative. Protection against damage due to exceeding 200 volts is provided by the breakdown devices shown. These devices may be either General Semiconductor TransZorbs™ or GE/RCA MOVs™ (Metal Oxide Varistors). They break down and conduct heavily when the voltage across them rises above a design level. As indicated by the symbol, the breakdown voltage is of either polarity, but single-polarity devices are also available. TransZorbs can tolerate more blows but MOVs have lower shunt capacitance. Both types fail "short" so protection does not fail even if operation does. The series resistors must be large enough to limit surge current to values specified for the protection devices.

Selection of the breakdown voltage of the protection devices may depend on the particular situation. To see this more clearly consider Figure 13, illustrating just one of the three signal buses and the contacts connecting it to one of several signal sources. If one of the contacts is closed, the voltage appearing across the open contacts is the DIFFERENCE between the voltage at the closed contact and the voltage at the open contact. Consequently, if voltages of either polarity are allowed at the inputs, the breakdown device must be selected to protect at less than HALF the withstand voltage rating of the open contacts, and dual-polarity breakdown is required. On the other hand, if the voltages at the inputs are all of the same polarity, a unipolar breakdown device can be used up to the FULL withstand voltage of the open contacts.

For either polarity of protection, a series resistor should be used to limit the current to the level for which the protection device is rated. The relationships between input voltages and the characteristics of the breakdown device and its series resistance are summarized in Figure 13.

TM MOV is a registered trademark of GE/RCA Solid State

TransZorb is a registered trademark of General Semiconductor

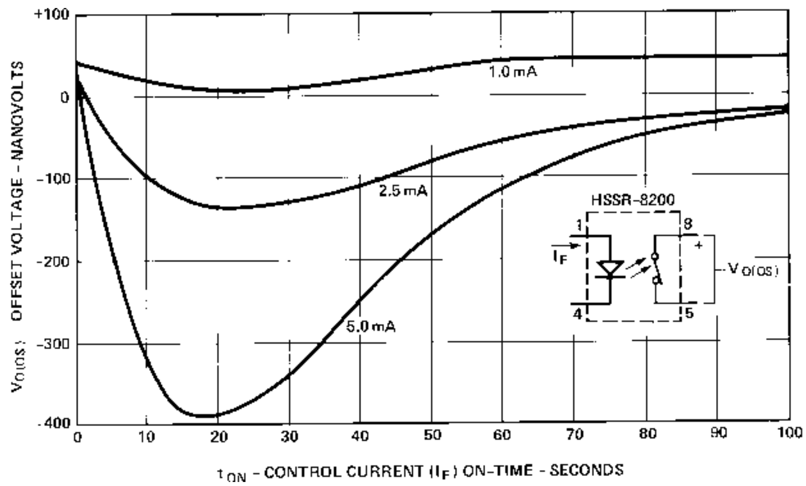


Figure 13. Typical Contact Offset Voltage.

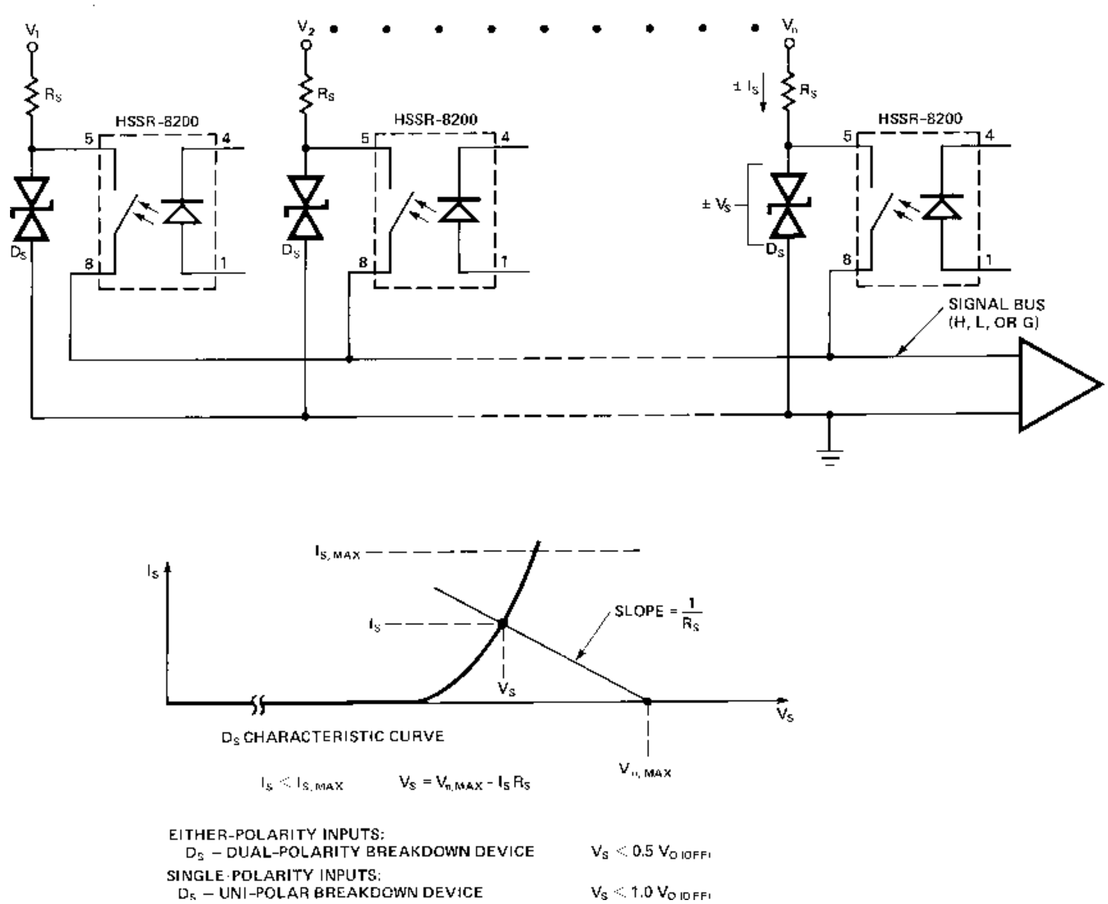


Figure 14. Over-Voltage Protection in Multiplexer Application.

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