Application Report
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System-Level Protection for High-Voltage Analog Multiplexers

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ABSTRACT

Analog multiplexers (MUXs) form an essential part of modern day measurement systems. MUXs are used in a variety of applications such as multichannel data acquisition systems, test and measurement equipment, and process control systems. In many data acquisition systems, multiplexer input is interfaced with remotely placed sensors. In such applications, an overvoltage fault condition is possible on the multiplexer input. In an overvoltage condition, a significantly high current can flow through the internal circuit of the multiplexer, which can damage the device and the circuit interfaced to its output.

This application report explains the most common overvoltage fault conditions, and ways to protect the multiplexer in these conditions. The experimental results with TI's recently introduced high-voltage analog multiplexer, MUX36S08, are also included to provide clarity on how the protection scheme works.

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1 Basic Construction of the CMOS Switch

The CMOS switch is formed by connecting N-channel MOSFET and P-channel MOSFET in parallel, as shown in Figure 1. This particular arrangement lets users switch positive and negative voltage at the input with equal ease. Logic high enables NMOS and thus switches negative input voltage to output, while logic low enables PMOS and allows positive voltage at the output. Therefore, the logic high input turns on both transistors or turns off both with a logic low input. Several CMOS can be combined with some simple logic control to create a multiplexer. Although the CMOS switch input pin and output pin are interchangeable, for simplicity we assume the source pin as the input and the drain pin as the output of the CMOS switch.

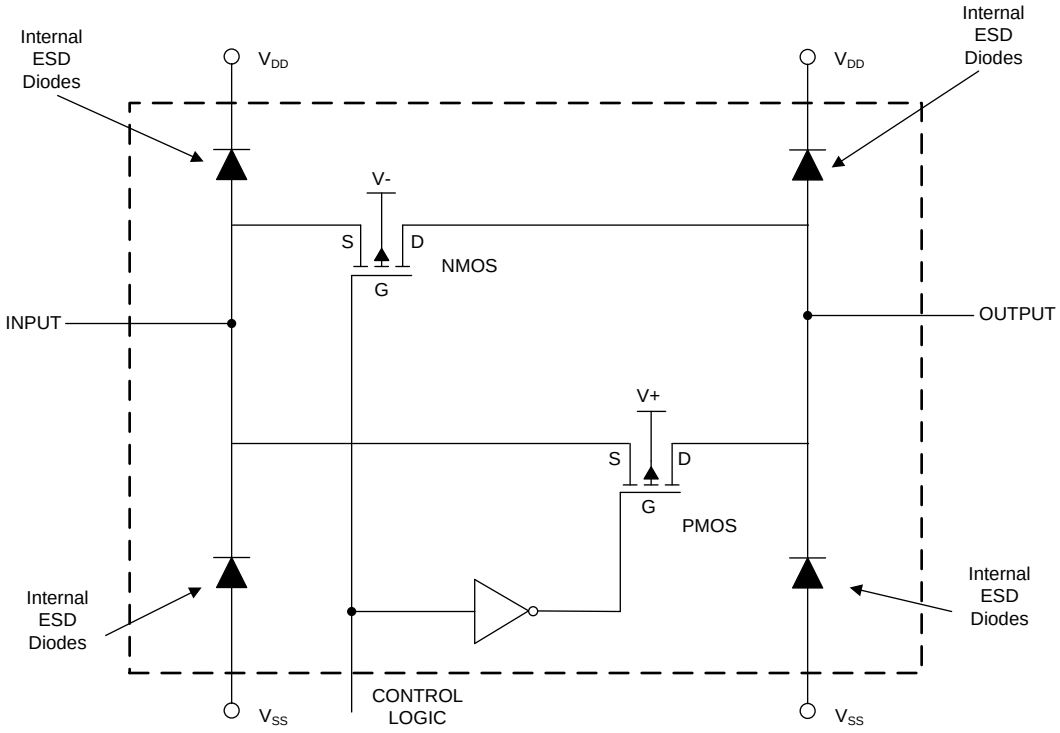

Figure 1. Basic Construction of CMOS Switch

In almost all semiconductor devices, the inputs and outputs have internal ESD diodes clamped to either V_{DD}, V_{SS}, or both. The primary function of these internal ESD diodes is to protect against HBM and CDM ESD events. These diodes typically have forward voltage in the range of 0.4 V to 0.7 V, and a current carrying capacity of a continuous 10 mA to 30 mA. These diodes connected between the input and output pins, as well as V_{DD} and V_{SS}, are reverse-biased under normal operating conditions, but they become forward-biased as the inputs rise above the positive supply voltage or fall below the negative power supply voltage.

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2 Overvoltage Condition and Its Effects

Usually multiplexers are at the front end of the data acquisition system. Inputs to multiplexers can come from various sensors, which are placed remotely. It is possible for a multiplexer input channel to be exposed to an overvoltage transient. Figure 2 shows a typical overvoltage condition that can occur in the real world.

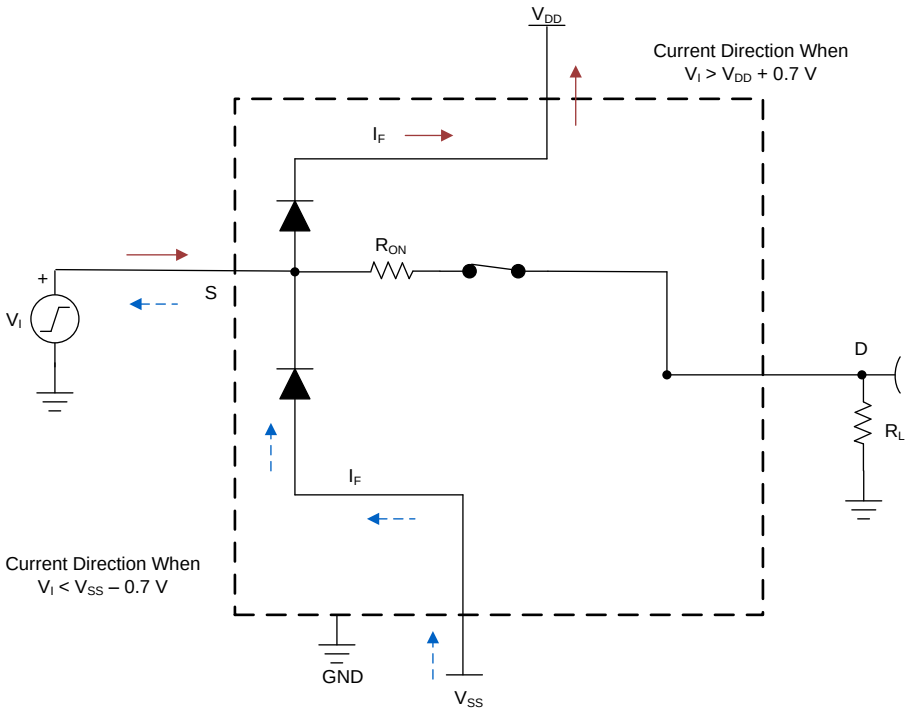

Figure 2. Overvoltage Condition at Input of the Multiplexer

If the input voltage, V_I, is more positive than the supply voltage, V_{DD} (typically 0.7 V higher than V_{DD}), or more negative than the supply voltage, V_{SS} (typically 0.7 V lower than V_{SS}), then the internal ESD diodes get forward-biased. Users can expect a high-current drawn from the input source into the supply voltage V_{DD}/V_{SS} of the multiplexer. If this current exceeds the absolute maximum rating of the internal ESD diodes, then the multiplexer internal ESD structure can fail, leading to device failure. Also, it is important to understand that multiplexers are powered from a DC-DC converter, or a linear regulator, which are generally not designed to sink current. The overvoltage condition on the input is directed through the ESD diodes to the supply. Because the supply cannot sink current, directing the overvoltage from the input to the supply can cause the supply to rise to an overvoltage level. An overvoltage condition at the input of the multiplexer damages not only the multiplexer, but also other devices connected to the supply of the multiplexer. The multiplexer must be protected under such conditions.

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3 Protection Scheme 1: On Channel Protection Against an Overvoltage Fault Using a Series Resistor

3.1 Theory of Operation

Figure 3 shows overvoltage protection at the input of the multiplexer with a series resistor.

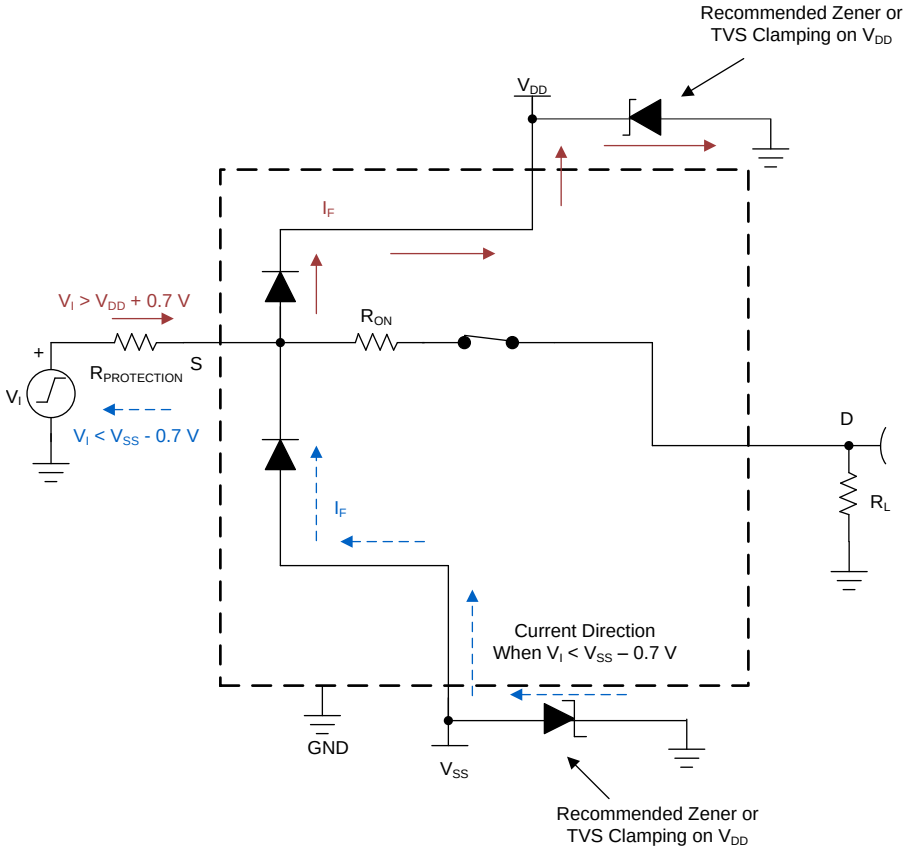

Figure 3. Input Series Resistor Protection Against Overvoltage Condition

During an overvoltage condition, internal ESD diodes trigger and clamp the output voltage at V_{DD} and V_{SS} based on the signal swing. A simple series resistor ($R_{PROTECTION}$) in the input path can limit the current during an overvoltage condition. A voltage drop occurs across the series resistor ($R_{PROTECTION}$) which is approximately equal to the difference between input voltage and supply rail V_{DD} and V_{SS}.

Internal ESD diodes are typically rated to handle 10 mA to 30 mA of continuous current. Pay careful attention when selecting the value of the input series resistor. Series resistors should be selected so that the maximum current through the ESD diodes is less than 20% of the absolute maximum current limit of ESD diodes. This selection is to keep power dissipation, due to internal ESD diode conduction, to a minimum if the device is subjected to an overvoltage condition for longer periods.

In most cases, the multiplexer is powered by a switching regulator or a linear regulator. These supplies are not meant to sink current, as is the case during an overvoltage condition. A Zener diode or TVS clamping must be introduced at the supply pins (V_{DD} and V_{SS}) to avoid any reverse current flowing into the circuit powering these pins. This precaution ensures that the overstress voltage problem is not just moved from the input to the supply. Also, this precaution protects the biasing circuit and components connected to the multiplexer supply from overstress damage.

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3.2 Example Calculation of Input Series Resistor ($R_{PROTECTION}$)

Equation 1 shows how to calculate the value of the input series resistor ($R_{PROTECTION}$).

V_{DD} = 15 V (1)

V_{SS} = –15 V

$V_{OVERVOLTAGE}$ at Input Channel = ±20 V

For example, internal ESD diodes are rated for 30 mA of absolute maximum forward current. Therefore, the current must not exceed 6 mA. Thus I_{LIMIT} = 6 mA (see Equation 2).

$R_{PROTECTION} = (V_{IN} – V_{DD} – V_{BE}) / I_{LIMIT}$ (2)

$R_{PROTECTION}$ = (20 V – 15 V – 0.7 V) / 6 mA = 716 Ω.

Choose 750 Ω – standard value

3.3 Experimental Results With the MUX36S08

Figure 4 provides experimental results carried out with the MUX36S08 device from TI. MUX36S08 is a 8-channel, single-ended, high-voltage multiplexer. A series resistor of 1 kΩ was used at the input for protection against an overvoltage condition. The test conditions follow.

Multiplexer power supplies:

- V_{DD}: 15 V, V_{SS}: –15 V
- Input signal swing: 40 V_{PP} (100-Hz sine wave)
- Channel 1: input (blue)
- Channel 2: output (magenta)

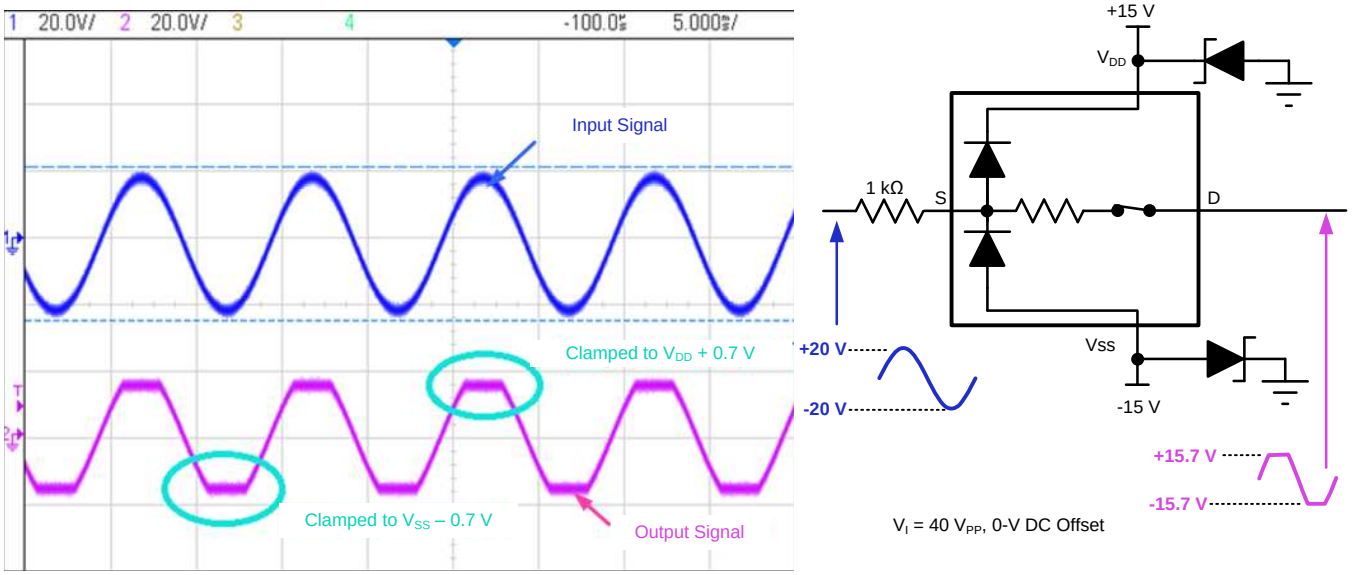

Figure 4. MUX36S08 Overvoltage Performance With Input Series Resistor Protection

The MUX36S08 device is powered with a ±15-V supply. A 40-V_{PP} sine wave is applied at the input of the MUX36S08. Therefore, input is allowed to swing 5 V higher than the V_{DD} rail and 5 V lower than the V_{SS} rail. It can be seen that an input series resistor of 1 kΩ restricts current through internal ESD diodes below 5 mA, and clamps the voltage at the output of multiplexer to either V_{DD} + 0.7 V or V_{SS} – 0.7 V, based on the input signal swing. Because the current is limited and the input voltage is also within absolute maximum ratings of the device, the MUX device does not get damaged.

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3.4 External Schottky Diode Clamping

During an overvoltage condition, one drawback of relying on the conduction of internal ESD diodes is self-heating of the device, due to power dissipated across ESD diodes. These ESD diodes are also rated for smaller forward current (typically a few 10s of mA). To avoid self-heating of the device, users can clamp the input of the multiplexer to supply rails using external Schottky diodes as shown in Figure 5.

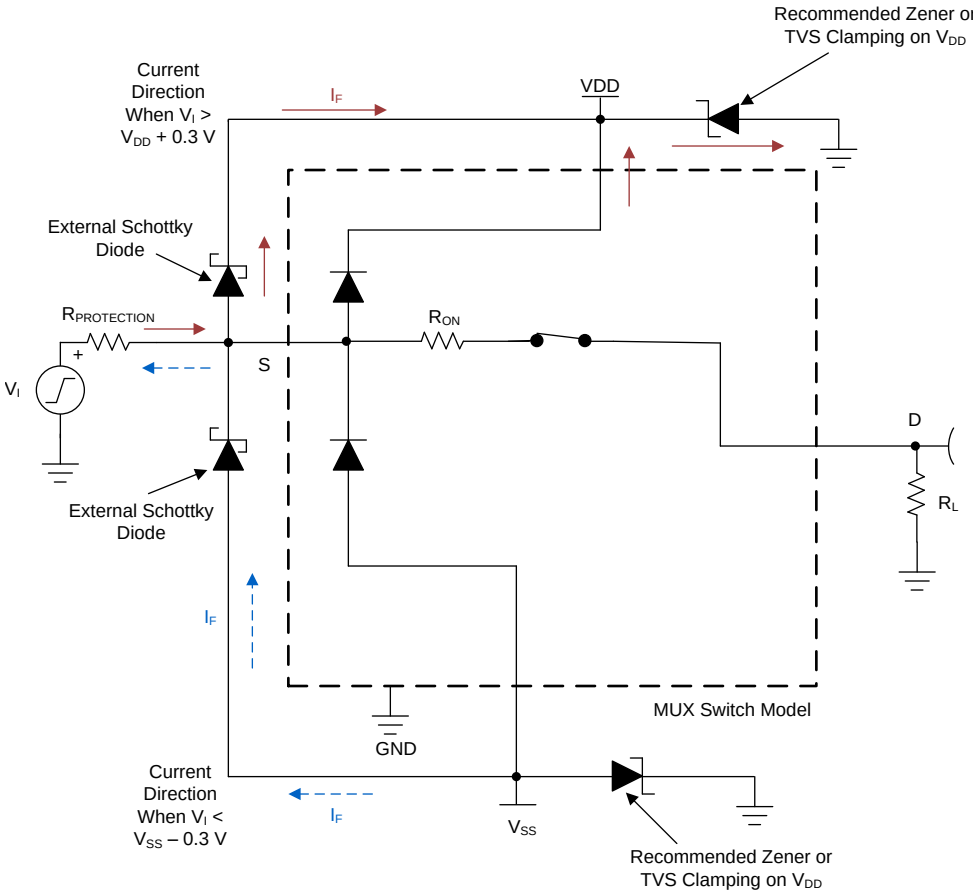

Figure 5. Input Series Resistor Protection With External Schottky Diode Clamping

When selecting a schottky diode, the forward voltage drop of the schottky diode must be lower than the forward voltage drop of the internal ESD diode. Schottky diodes have typical forward voltage drop of 0.2 V to 0.3 V. Generally, device internal ESD diodes have forward voltage in the range of 0.4 V to 0.7 V. The external schottky diodes also have higher current carrying capacity compared to internal ESD diodes. The schottky diodes effectively clamp inputs to the supply rails thereby protecting the device in an overvoltage condition. The series resistor ($R_{PROTECTION}$) limits the current flowing through schottky diodes. A Zener or TVS clamp at V_{DD} and V_{SS} should be considered to clamp the maximum supply voltage within data sheet specifications.

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4 Protection Scheme 2: Off Channel Protection Against an Overvoltage Fault

Often, there are situations when the multiplexer channel that is on does not see an overvoltage condition, but the channel that is off has an overvoltage event occurring on it. Figure 6 shows a typical use case where the overvoltage fault occurs on an adjacent channel that is not selected, or off.

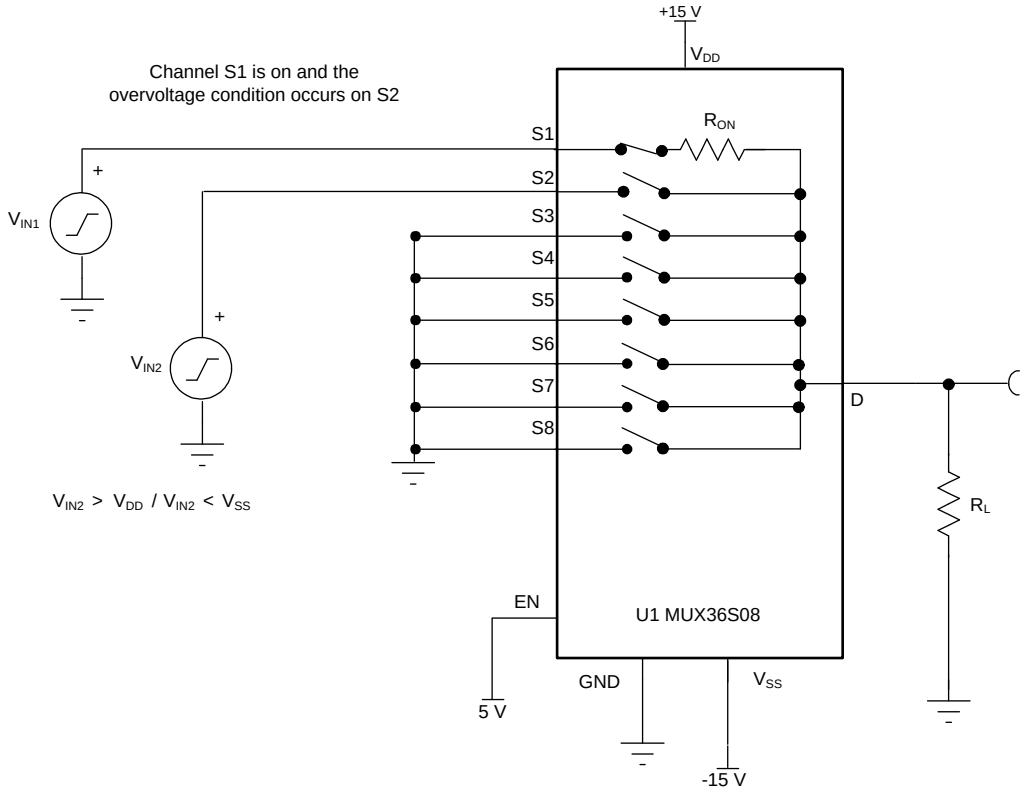

Figure 6. Overvoltage Fault Condition on the Off Channel

In Figure 6, we can see the multiplexer channel, S1, is selected and the overvoltage condition appears on channel S2, which is off. Because the voltage V_{IN2} is greater than the device absolute maximum specification, it introduces an undesired effect at the output of the multiplexer, and affects system measurement accuracy.

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Figure 7 shows that a Zener diode or TVS clamping at the input channel which is prone to overvoltage conditions as a simple solution. The Zener diode or TVS clamping voltage is selected to effectively clamp the faulty channel voltage so that it does not exceed V_{DD} and V_{SS} applied to the device. The series resistor ($R_{PROTECTION}$) acts as a current limiting resistor and limits the breakdown current flowing through the clamping device.

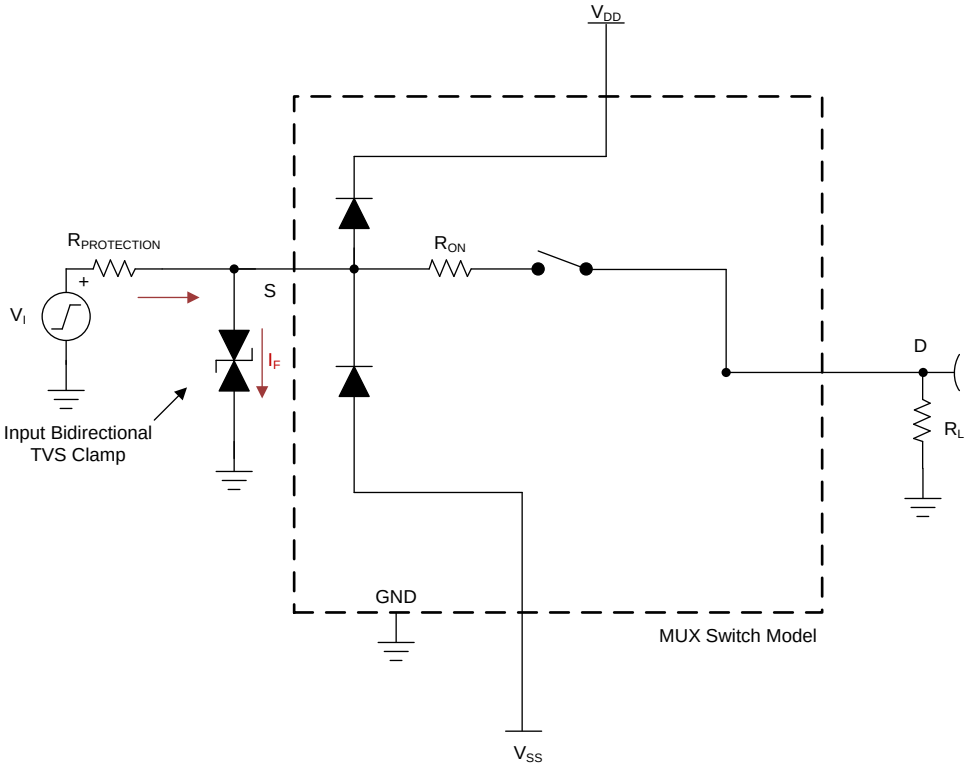

Figure 7. Zener or TVS Clamping at Input of the Multiplexer

4.1 Experimental Results With the MUX36S08

Figure 8 provides experimental results carried out with the MUX36S08 from TI, an 8-channel, single-ended, high-voltage multiplexer when an overvoltage condition appears on the off channel. The test conditions follow.

Multiplexer power supplies:

- V_{DD}: 18.5 V, V_{SS}: GND
- Channel S1: 5-V DC (channel S1 is on)
- Channel S2: 16 V_{PP} with 12-V DC offset (channel S2 is off)
- $R_{PROTECTION}$: 1 kΩ
- Zener diode clamp at S2: 18 V

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Oscilloscope Capture:

- Channel 1: input channel S2 of MUX36S08 (blue) – 16 V_{PP} with 12-V DC offset
- Channel 2: input channel S1 of MUX36S08 (magenta) – 5-V DC
- Channel 3: output channel D of MUX36S08 (yellow) – 5-V DC

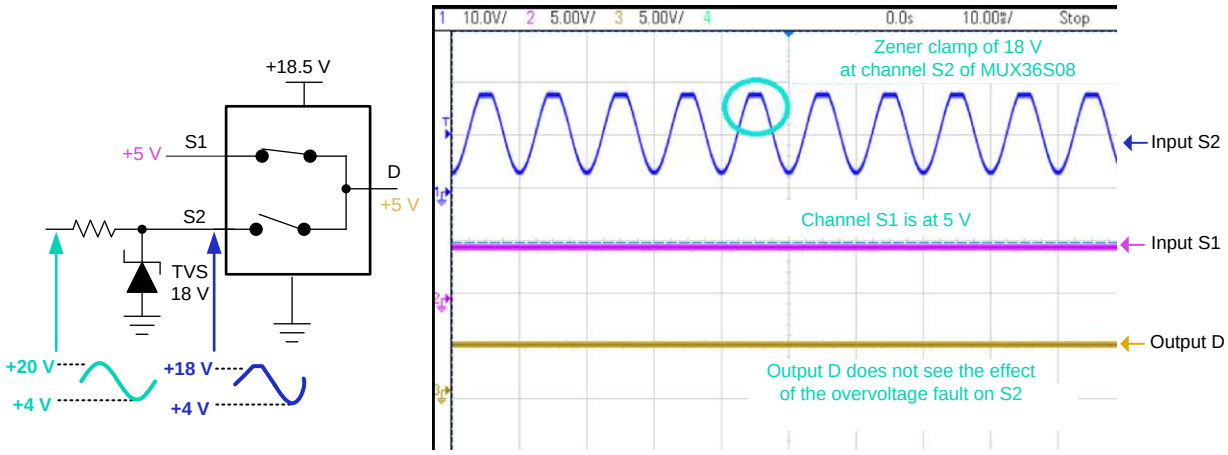

Figure 8. MUX36S08 Overvoltage Performance With Input Series Resistor Protection and Zener Clamping on the Off Channel

Figure 8 shows how the Zener diode on the input can be used to prevent an overvoltage condition on the off channel from impacting the operation of the on channel. This example uses a single-supply configuration with an 18.5-V supply. The input overvoltage signal applied to the off channel S2 is a 16-V_{PP} sinusoidal wave with a 12-V offset, so that the input ranges from 4 V to 20 V. The on channel S1 is connected to a 5-V DC signal. Zener diode clamping is used at channel S2 because it is a single-supply configuration. In this case, any negative voltage causes the diode to be forward bias and limit the input signal to about –0.7 V. The reverse breakdown voltage of the Zener diode should clamp the input channel to a voltage that is less than supply rail V_{DD} (18.5 V). The reverse breakdown is set at 18 V, so if the input signal exceeds 18 V the Zener diode clamps the input signal to 18 V. The measured waveforms show the overvoltage signal on the off channel is clamped to 18 V. The signal on the on channel is 5 V DC and this signal is coupled through to the output unaffected by the overstress signal applied to the off channel.

The Zener diode and TVS clamping protection scheme previously mentioned can also be applied to on channels, provided we select a Zener diode and TVS clamping voltage less than the supply rails of the multiplexer (V_{DD} and V_{SS}).

5 Conclusion

Most data acquisition applications have a multiplexer placed at the front end of the system. The possibility of overvoltage events on the multiplexer channel in these systems exists. If there is no protection against overvoltage, it can possibly damage a multiplexer and the devices used to bias and interface with the multiplexer. Some of the overvoltage protection systems such as use of series resistor, clamping diodes at supply rails, Zener and TVS clamping at input of multiplexers proves to be effective in overvoltage conditions. The cost impact of suggested solutions on overall system cost is also minimal and can be easily implemented in the system.

6 Resources

1. *MUX36xxx 36-V, Low-Capacitance, Low-Leakage-Current, Precision, Analog Multiplexers*, Data Sheet (SBOS705)
2. TI Precision Labs – Op Amps: Basic of Multiplexers

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