Robust Design of ADC System Inputs for EOS Immunity

Dale Li
Applications Engineer
Data Converters – Precision ADC
Agenda

• EOS and Fault Conditions
  – EOS vs ESD
  – Fault Conditions

• ADC Input Structures
  – Internal Protection on Precision ADC
  – Internal Protection on ADC with AFE

• Diode - Type and Characteristic
  – Schottky vs PN diode
  – TVS vs Zener diode

• Protection Techniques
  – Protection for Precision ADC:
    ✓ Common protection solution
    ✓ Settling improved solution
  – Protection for ADC with AFE:
    ✓ Protection solutions
    ✓ Protection for ADC with SCR input
ESD vs. EOS – What’s the Difference?

**ESD**
- Electrostatic discharge
- Short duration event (1-100ns)
- High voltage (kV)
- Fast edges
- Both “in-circuit” and “out-of-circuit”

**EOS**
- Electrical overstress
- Longer duration event
  - Milliseconds or more
  - Can be continuous
- Lower voltage
  - May be just beyond absolute maximum ratings
- “In-circuit” event only
EOS from Fault or Overdriven

–Fault Conditions

✓ Harsh electrical environment
✓ High voltage circuit in the system
✓ Improper power up sequencing
✓ Hot-swap connection and disconnection
✓ Loss of power supply but input signal is applied
✓ Apply bipolar signal to unipolar input ADC
✓ Miswiring
✓ Other conditions violating the absolute maximum specifications
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Internal Clamp/Protection on Data Converters

1. Input Steering diodes:

2. Back-to-Back Zener diode:

3. SCR-Based input:

*Bi-directional SCR example
SCR-Based ESD Structure and Latch-up

SCR (silicon controlled rectifier) is a parasitic structure. Overshoot and undershoot outside the normal operating voltage and current levels can cause Latch-up and damage the device.

- **Trigger Latch-up:**
  - Applied voltage > \( V_H \) and applied current > \( I_H \)

- **Terminate Latch-up state:**
  - A latch-up remains even after applied signal has been removed and requires a **power supply shut down** to remove the low impedance path.

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Why use SCR-Based ESD protection

- Input Signal Voltage > Power Supply.
- SCR is used as effective input ESD protection element to sustain a higher ESD level within a smaller layout area because:
  - Lower holding voltage
  - Significantly lower power dissipation
  - Robust ESD protection

* Electrostatic Discharge Protection Circuit for High-Speed Mixed-Signal Circuits by Hossein Sarbishaei.
Input Diode to REF/AVDD

**ADS8860 Input Stage:**
- Internal diodes are connected to REF: ADS8860, ADS9110, ADS8900B...
- Internal diodes are connected to AVDD: ADS9224R, ADS8168...
- Absolute Maximum Input Range:
  - Analog input voltage is limited to -0.3V to REF+0.3V (or AVDD+0.3V)
  - Input current is generally limited to -10mA to 10mA
When input signal is overdriven, a disturbance is found on REF signal (or AVDD) which can degrade the performance if the REF (or AVDD) is shared.

The higher overdriven signal, the worse disturbance impact.
Typically 5V supply voltage and ±10/12V input range, so ESD diode to supply will not work

Clamp is implemented with back-to-back Zener diodes or SCR input.

ABS MAX Input voltage limit: ±15V on ADS8588S, and ±20V on ADS8681/8688

ABS MAX Input current Max Limit = ±10mA
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Schottky Diode vs PN Diode

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Schottky Diode</th>
<th>PN Junction Diode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Junction Type</td>
<td>Metal-semiconductor</td>
<td>Semiconductor-semiconductor</td>
</tr>
<tr>
<td>Forward Voltage</td>
<td>Small - typically 0.3V</td>
<td>Large - typically 0.7V</td>
</tr>
<tr>
<td>Capacitance and Variation</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Reverse Leakage Current</td>
<td>Higher current but less temperature dependence</td>
<td>Lower current, but greater temperature dependence</td>
</tr>
<tr>
<td>Reserve Voltage</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Switching speed and Recovery time</td>
<td>Faster because of majority carrier transport</td>
<td>Limited by the recombination time of injected minority carriers</td>
</tr>
</tbody>
</table>
Unidirectional TVS Diode
(Transient Voltage Suppressor)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_{BR})</td>
<td>Breakdown voltage</td>
</tr>
<tr>
<td>(V_R)</td>
<td>Stand-off voltage</td>
</tr>
<tr>
<td>(V_C)</td>
<td>Clamping voltage</td>
</tr>
<tr>
<td>(V_F)</td>
<td>Forward voltage drop</td>
</tr>
<tr>
<td>(I_{BR})</td>
<td>Breakdown Current @ (V_{BR})</td>
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<tr>
<td>(I_R)</td>
<td>Reverse Leakage @ (V_R)</td>
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<tr>
<td>(I_F)</td>
<td>Forward Current @ (V_F)</td>
</tr>
<tr>
<td>(I_{PP})</td>
<td>Peak Pulse current @ (V_C)</td>
</tr>
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TVS_Uni
Bidirectional TVS Diode (Transient Voltage Suppressor)

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<tr>
<td>$I_{BR}$</td>
<td>Breakdown Current @ $V_{BR}$</td>
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<td>Forward Current @ $V_F$</td>
</tr>
<tr>
<td>$I_{PP}$</td>
<td>Peak Pulse current @ $V_C$</td>
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TVS_Bi
**TVS vs. Zener**

- **TVS Diode**
  - Solid state PN junction
  - Designed for operation in reverse-breakdown region only during over-voltage events
  - Junction area sized to conduct significant current and absorb significant power
  - Specifically designed for large transients such as ESD
  - Can react to overvoltage in pico-seconds

- **Zener**
  - Solid state PN junction
  - Designed for full-time operation in reverse-breakdown region
  - Ideal for voltage regulation
  - Slower reaction time
  - Lower current/power capability

![Zener Diode Diagram]
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Common Data Acquisition System in industrial application

Precision amplifier with HV power supply

Driving Circuit:
- Proper $R_{filt}$ and $C_{filt}$ in charge bucket filter will optimize signal settling.
- Achieve final settling of 0.5LSB or better settling error at end of tacq (acquisition time).

Sample and Hold Capacitor Settling During Acquisition

$V_{in \pm 0.5\text{LSB}}$
Based on Precision labs training, build SAR Model and find proper RC with amp to drive:

- High Bandwidth OPA828 is selected to drive ADS8860.
- Rfilt ≤ 15Ω to achieve settling error less than 0.5LSB.
Settling Error Check (Rflt=15Ω, Cflt=1.1nF)

At end of Vacq, Verror = -23.3μV -> 0.305 LSB (Rflt=15Ω) !

Note: <1/2 LSB is expected.
Hardware Performance Check

(R_{flit}=15\Omega, C_{flit}=1.1nF, OPA828+ADS8860 at 1Msps sampling rate)

### Spectral Analysis

![Spectral Analysis Graph]

**ADS8860 Data Sheet (1Msps)**

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<th>Max</th>
<th>Unit</th>
</tr>
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<td>93</td>
<td>dB</td>
</tr>
<tr>
<td>THD</td>
<td>-108</td>
<td></td>
<td></td>
<td>dB</td>
</tr>
</tbody>
</table>

**Measured:**

- SNR = 93.29dB
- THD = -112.9dB

![OVP Test Board (Overvoltage Protection)]

![Plabs-SAR-EVM with PHI controller]

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Input Protection – External Diode

Note:

$R_{flt}$ forces $I_2 << I_3$, which ensures that the majority of the surge Energy is diverted by external Diodes rather than by the IC’s internal protection diodes.

### ADS8860 Absolute Maximum Ratings:

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>AINP to GND or AINN to GND</td>
<td>-0.3</td>
<td>REF+0.3</td>
<td>V</td>
</tr>
<tr>
<td>Input Current</td>
<td>-10</td>
<td>+10</td>
<td>mA</td>
</tr>
</tbody>
</table>
Understanding the Protection Scheme

- **Normal Operation:**
  - D₁ and D₂ are Reverse-Biased.

- **Positive EOS:** \( V_A > 5V \)
  - Forward-Biased on D₁ for positive EOS.
  - Reverse-Biased state on D₂.

- **Negative EOS:** \( V_A < 0V \)
  - Forward-Biased on D₂ for negative EOS.
  - Reverse-Biased state on D₁.

- **\( R_P \) considerations**
  - Limiting total current \( I_1 \).
  - Lower \( I_1 \) keeps \( V_D \) lower.
  - Watch the power in \( R_P \) and the Amp.

- **\( V_D \) is smaller to keep:**
  - Lower \( V_B \).
  - Lower \( V_C \) (Better \( \leq +5.3V \)).

- **\( I_2 \) should be less than 10mA.**

- **Impact to settle signal on ADC’s \( C_{SH} \):**
  - Larger \( R_P \) and Rflt degrade settling.
  - Diode’s capacitance.
  - Diode’s leakage current.
Select $R_P$ and $R_{flt}$

Parameters known:

1. $I_1$ (OPA828) $\pm 50mA$ (Short current, $I_{SC}$)
2. $V_A$ (OPA828) $\pm 12V$ (Maximum, $V_O$)
3. $I_2$ (ADC Input) $\pm 10mA$ (Maximum, $I_{ADC_{in, Abs}}$)
4. $V_C$ (ADC Input) $+5.3V$ (Maximum, $V_{ADC_{in,max}}$) $-0.3V$ (Minimum, $V_{ADC_{in,min}}$)

Select $R_P$ and $R_{flt}$ (for negative EOS):

1. $I_3$ $I_{3\text{(min)}} = I_1 - I_2 = 40mA$
   $I_{3\text{(max)}} = I_1 - 0 = 50mA$
2. $V_D$ (BAT54) $V_D = 0.42V$ (Selected $V_F$)
3. $V_B$ $V_B = -0.42V$
4. $R_P$ $R_P > \frac{(12 - 0.42)V}{50mA} > 232\Omega$
5. $R_{flt}$ $R_{flt} \geq \frac{0.42 - 0.3)V}{10mA} \geq 12\Omega$
6. Select $R_{flt} = 15\Omega$, $R_P = 249\Omega$
## Diode Comparison Chart - Schottky

### Electrical Characteristics:

<table>
<thead>
<tr>
<th>Part Numbers</th>
<th>Manufacturer</th>
<th>Reverse Breakdown Voltage ($V_{BR}$) V</th>
<th>Forward voltage ($V_F$) mV</th>
<th>Leakage current ($I_R$) μA</th>
<th>Total Capacitance ($C_T$) pF</th>
<th>Forward continuous current ($I_F$) mA</th>
<th>Repetitive peak forward current ($I_{FSM}$) A</th>
<th>Power Dissipation ($P_D$) mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1N5712</td>
<td>Avago</td>
<td>20</td>
<td>580@10mA</td>
<td>0.15</td>
<td>1.2</td>
<td>35</td>
<td></td>
<td>250</td>
</tr>
<tr>
<td>BAT54</td>
<td>Diodes</td>
<td>30</td>
<td>400mV@10mA</td>
<td>2.0</td>
<td>10</td>
<td>200</td>
<td>0.3</td>
<td>200</td>
</tr>
<tr>
<td>BAT60</td>
<td>Infineon</td>
<td>10</td>
<td>150mV@10mA</td>
<td>1000</td>
<td>35</td>
<td>3000</td>
<td>5</td>
<td>1350</td>
</tr>
<tr>
<td>BAS70</td>
<td>Infineon</td>
<td>70</td>
<td>750mV@10mA</td>
<td>0.1</td>
<td>2</td>
<td>70</td>
<td>0.1</td>
<td>250</td>
</tr>
<tr>
<td>1PS70SB82</td>
<td>NXP</td>
<td>15</td>
<td>340mV@1mA</td>
<td>0.2</td>
<td>1@typ</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DB2S20500L</td>
<td>Panasonic</td>
<td>20</td>
<td>390mV@200mA</td>
<td>50</td>
<td>30</td>
<td>200</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>VS-10BQ015- M3/5BT</td>
<td>Vishay</td>
<td>15</td>
<td>330 @1A</td>
<td>500</td>
<td>390</td>
<td>1000</td>
<td></td>
<td>140</td>
</tr>
</tbody>
</table>

BAT54 has the best trade off for forward voltage, leakage, and capacitance.
Using Diode V-I Curves

- BAT54 from “Diodes Inc.” manufacture has better forward voltage (V = 0.42V)
- Same current (I_F = 50mA)
- Same temperature (+25°C).
Power Dissipation on Rp

- Voltage drop across Rp may not be acceptable.
- Power Dissipation on Rp may be a challenge:

|   |  
|---|---|
| 1 | $V_O$ (OPA828) | $\pm 12V$ (Choose -12V for worst case across Rp) |
| 2 | $V_B$ | $V_B = -0.42V$ |
| 3 | $V_P$ (Volts on Rp) | $V_P = V_O - V_B = -12V - (-0.42V) = -11.58V$ |
| 4 | $I_1$ (Current through Rp) | $I_1 = \frac{V_P}{R_P} = \frac{-11.58V}{249\Omega} = -38.6mA$ |
| 5 | $P_P$ (Power Dissipation on Rp) | $P_P = I_1^2 \times R_P = (38.6mA)^2 \times 249\Omega = 371mW$ |

**Note:**
1. Actual resistor should have at least double power dissipation ability which requires larger package size.
2. Higher $V_O$ or power supply to amplifier will require higher power dissipation on Rp.
Driving circuit with Schottky diode - Simulation

The settling error target is less than 38µV, so 97mV is a large error and poor THD and SNR is expected.

1. 1Msps ADC sampling rate.
2. At end of Vacq, Verror = -97mV -> 1271 LSBs II

ADS8860_OPA828_BAT54_1Msps.TSC
Hardware Performance Check with Schottky diode

(BAT54 Schottky diode, $R_p=249\,\Omega$, $R_{flt}=15\,\Omega$, $C_{flt}=1.1\,nF$, OPA828+ADS8860 at 1Msps sampling rate)

Measured with BAT54:
SNR = 76.6dB
THD = -65.1dB
Large series resistance impacts settling

- Need longer time to settle the signal with $R_P$ and $R_{filt}$
- Reducing $F_S$ can extend ADC’s acquisition time to meet the requirement.

* $C_P$ is parasitic capacitance.
Limitation on Protection Solution – Hardware Check

Sampling rate ≤ 400ksps can achieve the performance specified in ADS8860 datasheet.

Note: Real test results with 2kHz sinewave and $R_p=200\Omega$, $R_{\text{filt}}=15\Omega$, $C_{\text{filt}}=1.1\text{nF}$ on OVP card and Plabs-SAR-EVM hardware.
Solution to Improve Settling

\[ Z_{Out}(R_p) = \frac{R_p}{1 + \beta A_{ol}} \]

R\textsubscript{p} value can be larger:

- Better to limit current and clamp the signal.
- No impact to settle the signal on sample-hold capacitor of ADC.
- Small size and lower power dissipation resistor can be used.
The settling error target is less than 38µV, so -23µV meets the requirement.
Hardware Performance Check for Improved Solution

(BAT54, $R_{iso}=1k\Omega$, $C_{comp}=100nF$, $R_{flt}=15\Omega$, $C_{flt}=1.1nF$, OPA828+ADS8860 at 1Msps sampling rate)

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<td></td>
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**Measured Performance:**
- **SNR** = 93.3dB
- **THD** = -113.7dB

HV Sinewave Input Signal Clamped:
OPA828 Stability Check - Improved Solution

\[ A_{OL\_LOADED} = \frac{V_o}{V_{fb}} \]
\[ \frac{1}{\beta} = \frac{1}{V_{fb}} \]
\[ A_{OL} = V_o \]

Texas Instruments
01/2019 - DL
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Solution 1: Protection with Internal Back-to-Back Zener Diode

Select \( R_{flt} (\pm 40V EOS): \)

\[
R_{flt} \geq \frac{40V - 15V}{10mA} \geq 2.5 \text{ k}\Omega
\]

Select \( R_{flt} = 3k\Omega \) in this example.

A simple resister in series with input limits the current to ADC.
Back-to-Back Zener diode Protection on Device – Hardware Performance

(R_{\text{filt}}=3k\Omega, C_{\text{filt}}=1nF, ADS8588S at 200ksps maximum sampling rate)

Measured with 3k\Omega R_{\text{filt}}:
- SNR = 92.2dB
- THD = -109.7dB

(Tested on ADS8588SEVM)

Performance without external diode
Measured on ADS8588SEVM (200ksps):

<table>
<thead>
<tr>
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<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>91</td>
<td>92</td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td>THD</td>
<td>-110</td>
<td>-95</td>
<td></td>
<td>dB</td>
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(ADS8588SEVM at 200ksps maximum sampling rate)
THD vs Source Impedance ($R_{\text{flt}} + R_g$) with ADS8588S

- Nonlinear capacitance associated with input clamp on device causes the degradation with external resistors.

- The larger value resistor ($R_{\text{flt}}$):
  - Smaller current to ADC.
  - Small package size and less Power dissipation.
  - Less risk for continuous EOS.

  But can lead to worse THD:
  - $3k\Omega \rightarrow -109.7\text{dB THD}$
  - $15k\Omega \rightarrow -98.9\text{dB THD}$
  - $24.9k\Omega \rightarrow -95.1\text{dB THD}$

(ADS8588S-200ksps EVM board with 1kHz sinewave input).

Note: Continuously turning on internal diode may affect device’s lifetime.

Source: ADS8588S Datasheet.
Wrong Protection for ADC with SCR-Based Input

- Do not use this solution because EOS signal may trigger Latch-up.
- External diode is needed to protect ADC.
Solution 2: External TVS Diode Protection

- $V_{\text{drop}}$: +28V - Rp
- $V_C$: (+12V)
- $V_{\text{in}\_\text{Abs}}$: (+15V, or ±20V)
- ±10V Linear Range
- SCR or Back to back Zener Clamp not turned on!
- External diodes are turned on for overdriven EOS signal.
TVS Diode V- I Curve

Set $V_R \geq V_{in}$ Maximum voltage of normal input signal

**Note:** leakage current $I_R$ is specified at $V_R$

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Bidirectional TVS
Set $V_R$ and $V_{BR}$ to select TVS diode

Set $V_R \geq V_{in}$ Maximum voltage of normal input signal.
Set $V_{BR} < V_{in\_Abs}$ Absolute maximum input range of ADC.

### ADS8588S Data Sheet

#### Absolute Maximum Ratings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MIN</th>
<th>TYP</th>
<th>MAX</th>
<th>UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog Input to AGND ($V_{in_Abs}$)</td>
<td>-15</td>
<td></td>
<td>+15</td>
<td>V</td>
</tr>
<tr>
<td>Normal Input Signal (Range Pin=1, $TA = -40^\circ C \text{ to } +125^\circ C$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$AIN_{nP}$ Signal ($V_{in}$)</td>
<td>-10</td>
<td></td>
<td>+10</td>
<td>V</td>
</tr>
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</table>

#### TVS Diode Specifications

<table>
<thead>
<tr>
<th>Part Number</th>
<th>MFG</th>
<th>Reverse Standoff Voltage ($V_R$)</th>
<th>Breakdown Voltage ($V_{BR}$)</th>
<th>Reverse Leakage ($I_R@V_R$)</th>
<th>Breakdown Current ($I_{BR@V_{BR}}$)</th>
<th>Peak pulse Current ($I_{PP}$)</th>
<th>Peak Power Dissipation ($P_{PP}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMCJ10CA</td>
<td>Bourns</td>
<td>10V</td>
<td>11.1 12.3</td>
<td>17V</td>
<td>5uA</td>
<td>1mA</td>
<td>88.3A</td>
</tr>
</tbody>
</table>
Choose Rp to limit power on Rp and TVS

<table>
<thead>
<tr>
<th>Part Number</th>
<th>MFG</th>
<th>Reverse Standoff Voltage (VR)</th>
<th>Breakdown Voltage (VBR)</th>
<th>Clamping Voltage Max (VC@IPP)</th>
<th>Reverse Leakage Max (IR@VR)</th>
<th>Breakdown Current (IBR@VBR)</th>
<th>Peak pulse Current (IPP)</th>
<th>Peak Power Dissipation (PP)</th>
<th>Steady State Power Dissipation (PP)</th>
</tr>
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<td>SMCJ10CA</td>
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<td>11.1 - 12.3</td>
<td>17V</td>
<td>5μA</td>
<td>1mA</td>
<td>88.3A</td>
<td>1500W</td>
<td>5.0W</td>
</tr>
</tbody>
</table>

1. \[ R_P \geq \frac{(V_{EOS,Max} - V_{BR,Min})^2}{P_{RP,max}} = \frac{(40V - 11.1V)^2}{1W} = 835\Omega \] (choose 1kΩ)

2. \[ I_{max} = \frac{V_{EOS,Max} - V_{BR,Min}}{R_P} = \frac{40V - 11.1V}{1k\Omega} = 28.9mA \]

3. \[ P_{TVS,max} = I_{max} \cdot V_C = (28.9mA)(17V) = 491.3mW \]
Selecting $R_{\text{filt}}$ for Abs Ratings to Prevent damage

### Parameters known:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$V_{\text{in_Abs}}$ (ADC)</td>
</tr>
<tr>
<td>2</td>
<td>$I_{\text{in_Abs}}$ (ADC)</td>
</tr>
<tr>
<td>3</td>
<td>$V_{C\text{_Max}}$ (TVS)</td>
</tr>
<tr>
<td>4</td>
<td>$I_{pp}$ (TVS)</td>
</tr>
</tbody>
</table>

### Select $R_{\text{filt}}$:

1. $R_{\text{filt}} \geq \frac{(17 - 15)V}{10mA} \geq 200\Omega$

2. Select $R_{\text{filt}} = 1k\Omega$
External TVS (SMCJ10CA) – Hardware Performance

(TVS - SMCJ10CA, $R_p=1\,\text{k}\Omega$, $R_{\text{flt}}=1\,\text{k}\Omega$, $C_{\text{f}}=1\,\text{nF}$, ADS8588S at 200ksps sampling rate)

Performance without external diode
Measured on ADS8588SEVM (200ksps):

<table>
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<tr>
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<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>91</td>
<td>92</td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td>THD</td>
<td>-110</td>
<td>-95</td>
<td></td>
<td>dB</td>
</tr>
</tbody>
</table>

Measured with TVS:
SNR = 92.3dB
THD = -69.6dB
Capacitance Variation Causes Worse THD

- Capacitor($C_T$) is viewed as a capacitor(frequency) controlled resistor with a $1/Z_c$ variation in impedance as capacitor(frequency) value variation.

$$Z_{C_{\text{min}}} = \frac{1}{2\pi \cdot f_{\text{in}} \cdot C_{T_{\text{max}}}} = \frac{1}{2\pi \cdot 1\,\text{kHz} \cdot 10\,\text{nF}} = 15.9\,\text{k}\Omega$$

$$Z_{C_{\text{max}}} = \frac{1}{2\pi \cdot f_{\text{in}} \cdot C_{T_{\text{min}}}} = \frac{1}{2\pi \cdot 1\,\text{kHz} \cdot 2.3\,\text{nF}} = 69.2\,\text{k}\Omega$$

**Texas Instruments**
THD improved for lower input frequency

Performance without external diode
Measured on ADS8588SEVM (200ksps):

<table>
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<th>Min</th>
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<th>Unit</th>
</tr>
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</tr>
<tr>
<td>THD</td>
<td>-110</td>
<td>-95</td>
<td></td>
<td>dB</td>
</tr>
</tbody>
</table>

Note: Real test results $R_p = 60.40\Omega$ and SMBJ12CA TVS diode, $R_{flt} = 1k\Omega$, $C_{flt} = 1nF$ and ADS8588S at 200ksps on EVM.
# TVS Diodes

## TVS Diodes: Electrical Characteristics and Performance Measurement Result

<table>
<thead>
<tr>
<th>Part Numbers</th>
<th>MFG</th>
<th>Reverse Standoff Voltage (V&lt;sub&gt;R&lt;/sub&gt;)</th>
<th>Breakdown Voltage (V&lt;sub&gt;BR&lt;/sub&gt;)</th>
<th>Clamping Voltage Max (V&lt;sub&gt;C&lt;/sub&gt;)</th>
<th>Capacitance Variation (C&lt;sub&gt;T&lt;/sub&gt;) **</th>
<th>Reverse Leakage Max (I&lt;sub&gt;R&lt;/sub&gt; @ V&lt;sub&gt;R&lt;/sub&gt;)</th>
<th>Breakdown Current (I&lt;sub&gt;BR&lt;/sub&gt; @ V&lt;sub&gt;BR&lt;/sub&gt;)</th>
<th>Peak pulse Current (I&lt;sub&gt;PP&lt;/sub&gt;)</th>
<th>Measured THD (dB)</th>
<th>Peak Power Dissipation (P&lt;sub&gt;PP&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMCJ10CA</td>
<td>Bourns</td>
<td>10V</td>
<td>11.1 - 12.3</td>
<td>17V</td>
<td>2.3nF - &gt;10nF*</td>
<td>5µA</td>
<td>1mA</td>
<td>88.3A</td>
<td>- 69.6</td>
<td>1500W</td>
</tr>
<tr>
<td>SMA6J10A</td>
<td>TSM</td>
<td>10V</td>
<td>11.1 - 12.3</td>
<td>15.7V</td>
<td>200~400pF</td>
<td>5µA</td>
<td>1mA</td>
<td>38.2A</td>
<td>- 79.5</td>
<td>600W</td>
</tr>
<tr>
<td>PGSMAJ10CA</td>
<td>TSM</td>
<td>10V</td>
<td>11.1 - 12.3</td>
<td>17V</td>
<td>80~160pF</td>
<td>5µA</td>
<td>1mA</td>
<td>23.5A</td>
<td>- 81.8</td>
<td>400W</td>
</tr>
</tbody>
</table>

* The datasheet does not directly show the capacitance at 0V, it is much larger than 10nF regarding the trend.

** These are estimated value from the capacitance curve in the datasheet.

Note: the ADS8588S specified typical THD = -110dB
# Low Capacitance TVS diode - Select $R_P$

<table>
<thead>
<tr>
<th>Part Number</th>
<th>MFG</th>
<th>Reverse Standoff Voltage ($V_R$)</th>
<th>Breakdown Voltage Min ($V_{BR}$)</th>
<th>Clamping Voltage Max ($V_C$) @ $I_C=1A$</th>
<th>Reverse Leakage Max ($I_R@V_R$)</th>
<th>Typical Capacitance (0V,1MHz)</th>
<th>Breakdown Current ($I_{BR@V_{BR}}$)</th>
<th>Peak pulse Current ($I_{PP}$)</th>
<th>Peak Power Dissipation ($P_{PP}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDSOD323-T12C</td>
<td>Bourns</td>
<td>12V</td>
<td>13.3</td>
<td>19V</td>
<td>1uA</td>
<td>3pF</td>
<td>1mA</td>
<td>11A</td>
<td>350W</td>
</tr>
</tbody>
</table>

1. \[ R_P \geq \frac{(V_{EOS\_Max} - V_{BR\_min})^2}{P_{RP\_max}} = \frac{(40V - 13.3V)^2}{1W} = 712\Omega \] (choose $1k\Omega$)

2. \[ I_{max} = \frac{V_{EOS\_Max} - V_{BR\_min}}{R_P} = \frac{40V - 13.3V}{1k\Omega} = 26.7mA \]

3. \[ P_{TVS\_max} = I_{max} \cdot V_C = (26.7mA)(19V) = 507mW \]
The larger value resistor ($R_p$):

- Smaller current to TVS/ADC.
- Small package size and more choices in the market.
- Less risk for continuous EOS.

**But:**

- Worse THD.

- Test Data with CDSOD323-T12C and ADS8588SEVM.
PTC Fuse - Characteristics and Terminology

**PTC (Positive Temperature Coefficient) Fuse** is placed in series with the circuit protects the circuit by changing from a low-resistance to a high resistance state in response to an overcurrent.

- **$V_{\text{max}}$**: Maximum continuous voltage the device can withstand without damage at rated current ($I_{\text{max}}$).
- **$I_{\text{max}}$**: Maximum fault current the device can withstand without damage at rated voltage ($V_{\text{max}}$).
- **$I_{\text{hold}}$**: Maximum current device will pass without tripping at T°C.
- **$I_{\text{trip}}$**: Minimum current that the device will trip and transition from low resistance to high resistance at T°C.
- **$P_{\text{d}}$**: Power dissipated from device when in tripped state at T°C.
- **$R_{\text{i}}$**: Minimum resistance of device in initial (un-soldered) state.
- **$R_{1}$**: Maximum resistance of the device when measured one hour post reflow at T°C.

* Note for T°C: certain temperature room temperature still air
PTC Solution to Resolve the Challenges (THD vs Power Dissipation)

PTC selection for

SMCJ10CA 2.3nF to 10nF TVS Diode:

- $V_{\text{fault}} (40V) \leq V_{\text{max}}$ of PTC
- $I_{\text{fault(min)}} = 0.6A > I_{\text{trip}}$ of PTC
- $I_{\text{fault(max)}} = 8A < I_{\text{max}}$ of PTC

(see excel file for $I_{\text{fault}}$ calculation)

---

**Eaton:**

<table>
<thead>
<tr>
<th>Part Number</th>
<th>$V_{\text{qu}}$ (V)</th>
<th>$I_{\text{max}}$ (A)</th>
<th>$I_{\text{hold}}$ (A)</th>
<th>$I_{\text{trip}}$ (A)</th>
<th>$P_{\text{d}}$ (W)</th>
<th>$\text{Time to trip (maximum)}$ (Seconds)</th>
<th>$\text{Initial (R)}$</th>
<th>$\text{Post trip (R)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTS120660V005</td>
<td>60</td>
<td>100</td>
<td>0.05</td>
<td>0.15</td>
<td>0.4</td>
<td>0.25</td>
<td>1.5</td>
<td>3.6</td>
</tr>
<tr>
<td>PTS120660V010</td>
<td>60</td>
<td>100</td>
<td>0.10</td>
<td>0.25</td>
<td>0.4</td>
<td>0.5</td>
<td>1.0</td>
<td>1.6</td>
</tr>
<tr>
<td>PTS120630V012</td>
<td>30</td>
<td>100</td>
<td>0.12</td>
<td>0.29</td>
<td>0.5</td>
<td>1</td>
<td>0.2</td>
<td>1.4</td>
</tr>
<tr>
<td>PTS120630V016</td>
<td>30</td>
<td>100</td>
<td>0.16</td>
<td>0.37</td>
<td>0.5</td>
<td>1</td>
<td>0.3</td>
<td>1.1</td>
</tr>
<tr>
<td>PTS120624V020</td>
<td>24</td>
<td>100</td>
<td>0.20</td>
<td>0.42</td>
<td>0.6</td>
<td>8</td>
<td>0.1</td>
<td>0.65</td>
</tr>
</tbody>
</table>

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Microsoft Excel Worksheet
PTC with Regular TVS (SMCJ10CA) – Hardware Performance

ADS8588S at 200ksps sampling rate:

<table>
<thead>
<tr>
<th>TVS</th>
<th>Rp</th>
<th>Measured</th>
<th>Typ</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ADS8588S Data Sheet Spec.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SNR</td>
<td>92</td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td></td>
<td>THD</td>
<td>-110</td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td>SMCJ10CA</td>
<td>1kΩ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>1kΩ Resistor</strong></td>
<td>SNR</td>
<td>92.3</td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td></td>
<td>THD</td>
<td>-69.6</td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td>PTS120660V005 (PTC Resettable Fuse)</td>
<td>SNR</td>
<td>92.0</td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td></td>
<td>THD</td>
<td>-96.8</td>
<td></td>
<td>dB</td>
</tr>
</tbody>
</table>

Input Signal

60Vpp

Clamped Signal

25Vpp
Solution 3: External Protection with Schottky diode

Additional Power Supply is required.

External diodes are turned on.

Internal diodes are never turned on.

- This solution can be used for SCR-Based input ADC.

![Diagram of ADS8588S amplifier with protection diodes](image-url)
Selecting $R_P$ for Abs Ratings to Prevent damage

<table>
<thead>
<tr>
<th>Absolute Ratings – Schottky Diode - Diodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part Number</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>BAT42WS</td>
</tr>
</tbody>
</table>

1. $I_{fault} \approx 0.1 \cdot I_F = 20mA$
2. $V_P = V_g - V_C = V_g - (V_F + 12V) = 40 - (0.4+12) = 27.6V$
3. $R_P \ge \frac{V_P}{I_{fault}} = \frac{27.6V}{20mA} = 1380\Omega$
4. $R_P \ge \frac{V_P^2}{P_D} = \frac{(27.6)^2}{0.5W} = 1523.5\Omega$ (may use 1W with margin)
5. Select $R_P = 1.54k\Omega$

* $P_D$ is power dissipation of $R_P$. 

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400mV

20mA
External Schottky Diode (BAT42) – Hardware Performance

(Schottky – BAT42WS, \(R_{p}=1.54\,k\Omega\), \(R_{f}=1k\Omega\), \(C_{f}=1nF\), ADS8588S at 200kspi sampling rate)

- Measured with BAT42:
  - SNR = 92dB
  - THD = -104dB

Performance without external diode

Measured on ADS8588S at 200kspi:

<table>
<thead>
<tr>
<th>Parameter</th>
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<td>-110</td>
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<td></td>
<td>dB</td>
</tr>
</tbody>
</table>

Signal Clamping Check (±30V sinewave input):

- 24.8V_{pp}
PTC with Schottky Diode (BAT42) – Hardware Performance

(Schottky – BAT42WS, PTS120660V005, Rp=1kΩ, Cf=1nF, ADS8588S at 200ksps sampling rate)

Performance without external diode
Measured on ADS8588SEVM (200ksps):

<table>
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</table>

Measured with BAT42 and PTC:
SNR = 92.1dB
THD = -111dB

Signal Clamping Check (±30V sinewave input):

25.2Vpp
Thank you!!

**TI Precision Labs – ADCs videos:** Electrical Overstress on Data Converters