

Input protection for high-voltage ADC circuit with TVS Diode

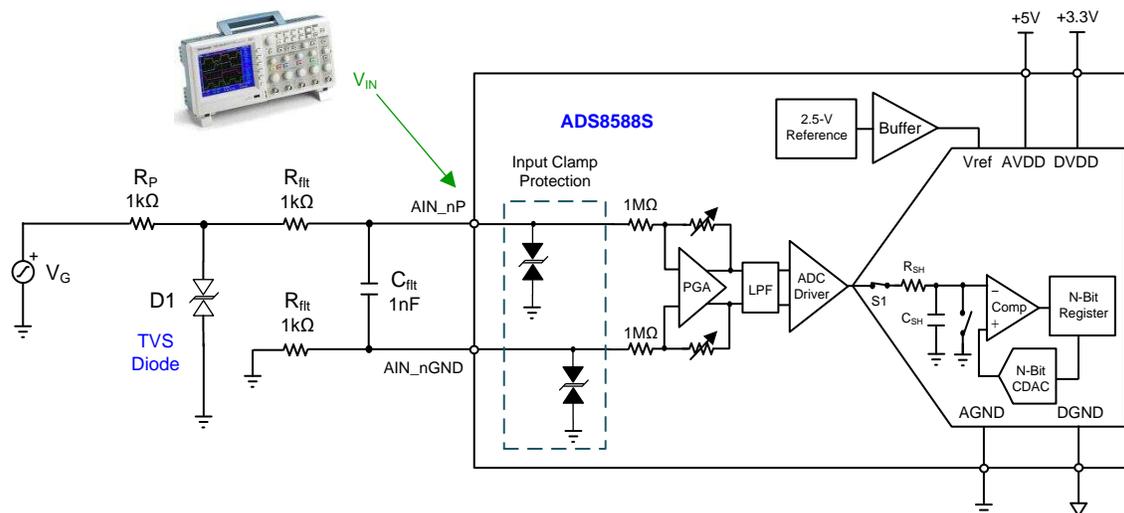
Dale Li

Input	ADC Input	Digital Output ADS8588S
$V_{inMax} = +10V$	CH_nP = +10V	7FFFF _H
$V_{IN} = 0V$	CH_nP = 0V	0000 _H
$V_{inMin} = -10V$	CH_nP = -10V	8000 _H

Power Supplies and Input				
AVDD	DVDD	Normal Input V_{IN}	Absolute Maximum Input Voltage Rating (V_{in_Abs})	Absolute Maximum Input Current Rating (I_{in_Abs})
+5V	+3.3V	±10V	±15V	±10mA

Design Description

This circuit describes a solution to protect high-voltage SAR ADCs with integrated analog front end (AFE) from electrical overstress. The protection is implemented with an external transient voltage suppressor (TVS) diode, current-limiting resistors, and an RC filter. This document shows the impact that the external protection clamp has on system performance and introduces how to improve the performance. This circuit is useful in the following end equipment: [Multifunction relays](#), [AC analog input modules](#), and [Train control and management systems](#). For protecting low-voltage SAR ADC from electrical overstress, see [Circuit for protecting low-voltage SAR ADC from electrical overstress with minimal impact on performance](#).



Specifications

Specification	Goal	Measured
Maximum continuous fault voltage	±40V	No damage with 40-V peak sinusoidal wave applied
SNR (ADS8588S)	91.0dB (±10-V range)	92.0dB
THD (ADS8588S)	-114dB	-81.8dB

Design Notes

1. The TVS diode is usually used as an electrical overstress protection for high-voltage SAR ADCs with integrated AFE because this kind of ADC only requires a single +5-V analog power supply but supports high-voltage analog input. For example, the ADS8588S device supports ±10V on a 5-V analog supply. The TVS diode turns on and clamps the input voltage at its breakdown voltage.
2. R_p is used to limit the current into the TVS diode and the ADC, this resistor is helpful to clamp the input fault signal with TVS diode together. The component selection in the external protection circuitry depends on the absolute maximum input voltage and current ratings on the particular ADC and the fault signal. See the [component selection](#) section for the details.
3. Select a C0G type capacitor for C_{filt} to minimize the distortion.
4. See the [Electrical Overstress on Data Converters](#) video in the [TI Precision Labs](#) video series for a theoretical explanation of overstress on data converters. This series discusses the details on protection solutions for different types of ADCs including diode selection and current-limiting resistor selection.

Component Selection

- Select a bidirectional TVS diode according to the following guidelines:
 - $V_R \geq V_{IN}$ (V_R is the standoff voltage of the TVS diode, V_{IN} is the normal input voltage of the ADC that is $\pm 10V$ on the ADS8588S device)
 - $V_{BR} \leq V_{in_Abs}$ (V_{BR} is the breakdown voltage of the TVS diode, V_{in_Abs} is the absolute input voltage ADC that is $\pm 15V$ on the ADS8588S device)
- Also, select a bidirectional TVS diode according to the following restrictions:
 - Low-leakage current, since the leakage current is translated into an offset voltage error when it flows through a series resistance.
 - Low capacitance as the capacitance has a strong voltage coefficient and distorts the input signal.
 - The TVS diode can dissipate the maximum power during fault condition. The steady-state power dissipation of the TVS diode should be higher than the maximum power from the fault signal.

Based on these guidelines, the PGSM AJ10CA bidirectional TVS diode from Taiwan Semiconductor Manufacturing Company, Ltd. (TSMC®) is used in this design to protect the ADS8588S device which is a widely-used TVS diode. The specifications for three different TVS diodes are given later in this document to compare all the pertinent parameters.

- The following equation finds a minimum value of R_P to limit its power dissipation to a specified level during a fault condition. The equation uses the maximum fault voltage (V_{EOS_Max}), the minimum breakdown voltage (V_{BR_Min}), and the maximum power dissipation (P_{RP_Max}). In this design, the maximum electrical overstress signal was selected to be $\pm 40V$ because this is a common requirement for industrial systems. The minimum breakdown voltage of the PGSM AJ10CA diode is 11.1V, and the maximum resistor power is set to 1W. In this example, the minimum value of R_P is 835 Ω , and R_P is rounded up to 1k Ω . It is important to note that the resistor power rating must have margin to operate safely over temperature. A typical guideline is to double the power rating (2W, in this example).

$$R_P \geq \frac{(V_{EOS_Max} - V_{BR_Min})^2}{P_{RP_Max}} = \frac{(40V - 11.1V)^2}{1W} = 835\Omega \text{ (round up to 1k}\Omega\text{)}$$

The following equation shows the maximum current in R_P during an electrical overstress fault event:

$$I_{Max} = \frac{V_{EOS_Max} - V_{BR_Min}}{R_P} = \frac{40V - 11.1V}{1k\Omega} = 28.9mA$$

Using the maximum current (I_{Max}) and maximum clamping voltage (V_{C_Max}) on the PGSM AJ10CA TVS diode, calculate the maximum power dissipated on the diode during an electrical overstress fault event. The objective of this equation is to make sure that the correct power rating of TVS diode is used. For the PGSM AJ10CA diode, the steady-state power rating is 1W. Thus, there is margin in this design as we do not expect more than 491mW of continuous power.

$$P_{TVSmax} = I_{Max} \cdot V_{C_Max} = (28.9mA)(17V) = 491mW$$

- The resistor R_{fit} acts as a filter with the capacitor C_{fit} and also to limit the current to the ADC input under a fault condition. The absolute maximum input voltage (V_{in_Abs}) of the ADS8588S device is $\pm 15V$ and the maximum input current (I_{in_Abs}) is $\pm 10mA$. The PGSM AJ10CA TVS diode has 17-V maximum clamping voltage (V_{C_Max}) when 23.5-A peak current (I_{PP}) are flowing it for a brief period of time. Hence, the minimum value of R_{fit} can be determined by:

$$R_{fit} \geq \frac{V_{C_Max} - V_{in_AbsMax}}{I_{in_AbsMax}} = \frac{17V - 15V}{10mA} = 200\Omega \text{ (round up to 1k}\Omega\text{)}$$

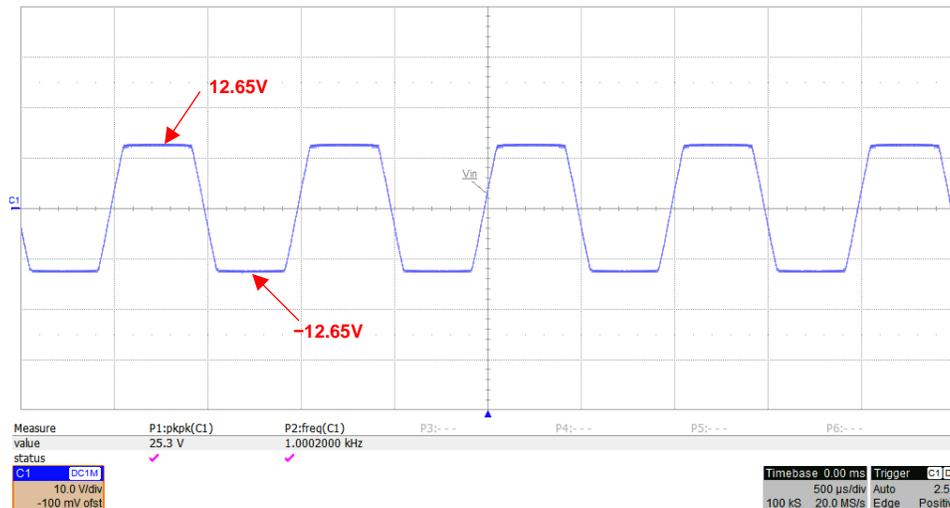
The equation calculated R_{fit} to be 200 Ω . In this design, the 200 Ω is rounded up to 1k Ω to add significant design margin. R_{fit} can be adjusted to set the cutoff frequency of the filter as step 5 shows.

- The capacitor C_{fit} in parallel with R_{fit} is used to filter the noise from the front-end circuit. The equation for the cutoff frequency based on the input resistors and capacitors follows. The exact value may not be critical, so a standard value of 1nF is used in this design.

$$f_c = \frac{1}{2\pi(R_P + 2R_{fit})C_{fit}} = \frac{1}{2\pi(3k\Omega)(1nF)} = 53kHz$$

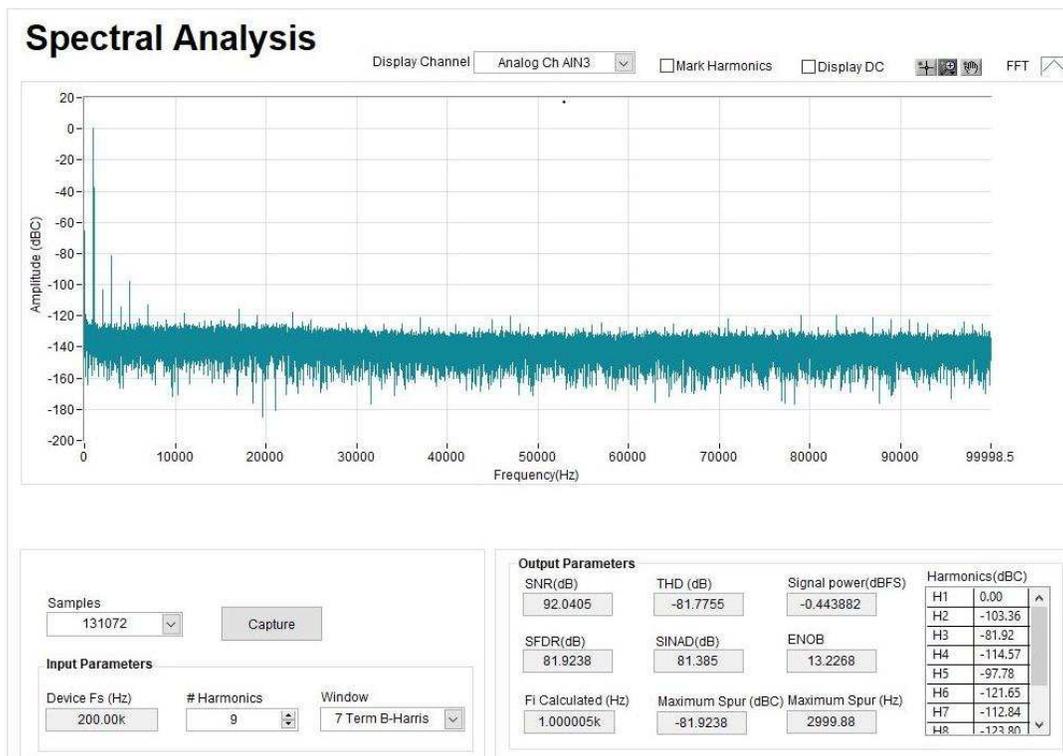
ADC Input (AIN_P) Overvoltage Condition

The following figure shows the ADC input voltage when a high-voltage continuous overvoltage sinusoidal wave signal (60Vpp) is applied. Note that the external bidirectional TVS diode is turned on and the overvoltage sinusoidal wave signal has been clamped to $\pm 12.5V_{\text{peak}}$, which is less than $\pm 15\text{-V}$ absolute maximum input voltage ($V_{\text{in_Abs}}$) on the ADS8588S device, so the ADC device is protected from the overvoltage signal.



AC (SNR and THD) Performance Checked on Hardware

The following spectral analysis is measured using the [ADS8588SEVM-PDK](#) and overvoltage protection (OVP) board specifically designed for this test. The measured THD performance with all the protection circuitry including the TVS diode is worse than the typical specification in the [ADS8588S 16-Bit, High-Speed, 8-Channel, Simultaneous-Sampling ADC With Bipolar Inputs on a Single Supply Data Sheet](#) (measured SNR = 92dB, THD = -81.8dB).



Capacitance Variation on TVS Diode Causes Worse THD

The previous test result shows that the measured SNR performance meets the specification in the ADS8588S data sheet; however, the measured THD performance is worse than the specification in the data sheet. The key reason to cause the worse THD performance is the large capacitance variation which is changed with the voltage applied on the TVS diode, see the [Electrical Overstress \(EOS\) and Electrostatic Discharge \(ESD\) on Analog-to-Digital Converters \(ADC\)](#) video (part of the *TI Precision Labs* video series) for detailed theory and analysis on this subject.

There are two solutions to improve the system THD performance: use a low-capacitance variation bidirectional TVS diode, reduce input signal frequency with less impact from the capacitance and variation on the TVS diode, if this is acceptable in the system.

Low Capacitance Variation TVS Diode

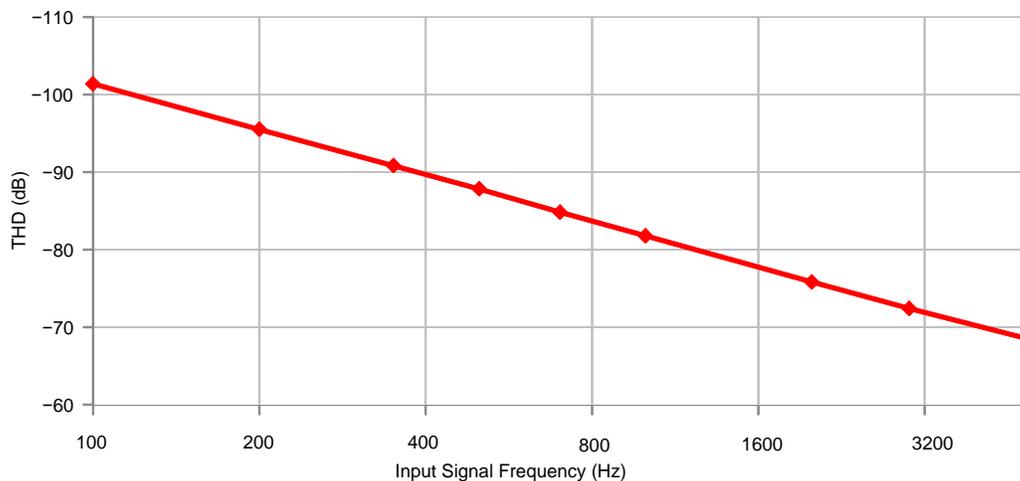
The capacitance of the TVS diode has a strong impact on distortion, and the following table compares the measured results for TVS diodes with different capacitance specifications. This table shows improved THD performance with decreasing capacitance on the TVS diodes. The low-capacitance bidirectional TVS diode, PG SMAJ10CA, from TSMC shows a better THD performance (–81.8dB) with the same protection circuitry. To achieve a better THD performance, use the TVS diode with further lower capacitance and variation.

Part Numbers	Reverse Standoff Voltage (V_R)	Breakdown Voltage (V_{BR})		Clamping Voltage MAX (V_C)	Capacitance Variation (C_T)	Reverse Leakage MAX (I_R at V_R)	Peak Pulse Current (I_{PP})	Measured THD (dB)	Clamped Voltage ($1\text{k}\Omega R_p$, $V_{IN} = 40\text{V}$)
		MIN	MAX						
SMCJ10CA	10V	11.1	12.3	17V	2.3nF to 10nF	5 μ A	88.3A	–69.6	$\pm 12.6\text{V}$
SMA6J10A	10V	11.1	12.3	15.7V	200 to 400pF	5 μ A	38.2A	–79.5	$\pm 12.6\text{V}$
PG SMAJ10CA	10V	11.1	12.3	17V	80 to 160pF	5 μ A	23.5A	–81.8	$\pm 12.6\text{V}$
CDSOD323-T12C ⁽¹⁾	12V	13.3		19V	3pF	1 μ A	11A	–102.1	$\pm 15.6\text{V}$

- ⁽¹⁾ The PG SMAJ10C is selected in this design because it is effective in protecting the ADS8588S device. The clamp voltage of this diode is 12.6V under a 40-V fault condition with a 1-k Ω current-limiting resistor. The 12.6-V clamp voltage is below the ADS8588S absolute maximum input voltage of $\pm 15\text{V}$, so it is effective at protecting the ADC. An optional TVS diode that can be used for the ADS8688 and ADS8681 devices is the CDSOD323-T12C diode. This diode is low capacitance (3pF) and significantly improves THD performance (THD = –102.1dB). This diode has a clamp voltage of 15.6V with a 40-V fault condition and a 1-k Ω current-limiting resistor, so it cannot be used with devices that have an absolute maximum input voltage of $\pm 15\text{V}$ (ADS8588S). The ADS8688 and ADS8681 devices have an absolute maximum input voltage of $\pm 20\text{V}$, so the 15.6-V clamp voltage on the CDSOD323-T12C protects the device and also allows for very good THD performance.

Lower Input Signal Frequency

The following figure shows that the measured THD performance is improved by reducing input signal frequency. This graph was measured with the PG SMAJ10CA TVS diode, $R_p = 1\text{k}\Omega$, $R_{fit} = 1\text{k}\Omega$, $C_{fit} = 1\text{nF}$ and ADS8588S at 200kSPS on the EVM.



Design Featured Devices and Alternative Parts

Device	Key Features	Link	Other Possible Devices
ADS8588S	16-bit, 200-kSPS, 8-channel simultaneous-sampling, single-supply bipolar-input SAR ADC	http://www.ti.com/product/ADS8588S	http://www.ti.com/adcs
ADS8688	16-bit, 500-kSPS, 8-channel non-simultaneous-sampling, single-supply with bipolar-input SAR ADC	http://www.ti.com/product/ADS8688	http://www.ti.com/adcs
ADS8681	16-bit, 1-MSPS, single-channel, single-supply with bipolar-input SAR ADC	http://www.ti.com/product/ADS8681	http://www.ti.com/adcs

Design References

See [Analog Engineer's Circuit Cookbooks](#) for TI's comprehensive circuit library.

1 Trademarks

TSMC is a registered trademark of Taiwan Semiconductor Manufacturing Company, Ltd.. All other trademarks are the property of their respective owners.

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES "AS IS" AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, or other requirements. These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI's products are provided subject to TI's Terms of Sale (www.ti.com/legal/termsofsale.html) or other applicable terms available either on ti.com or provided in conjunction with such TI products. TI's provision of these resources does not expand or otherwise alter TI's applicable warranties or warranty disclaimers for TI products.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2019, Texas Instruments Incorporated