

Circuit for protecting ADC with TVS diode and PTC fuse



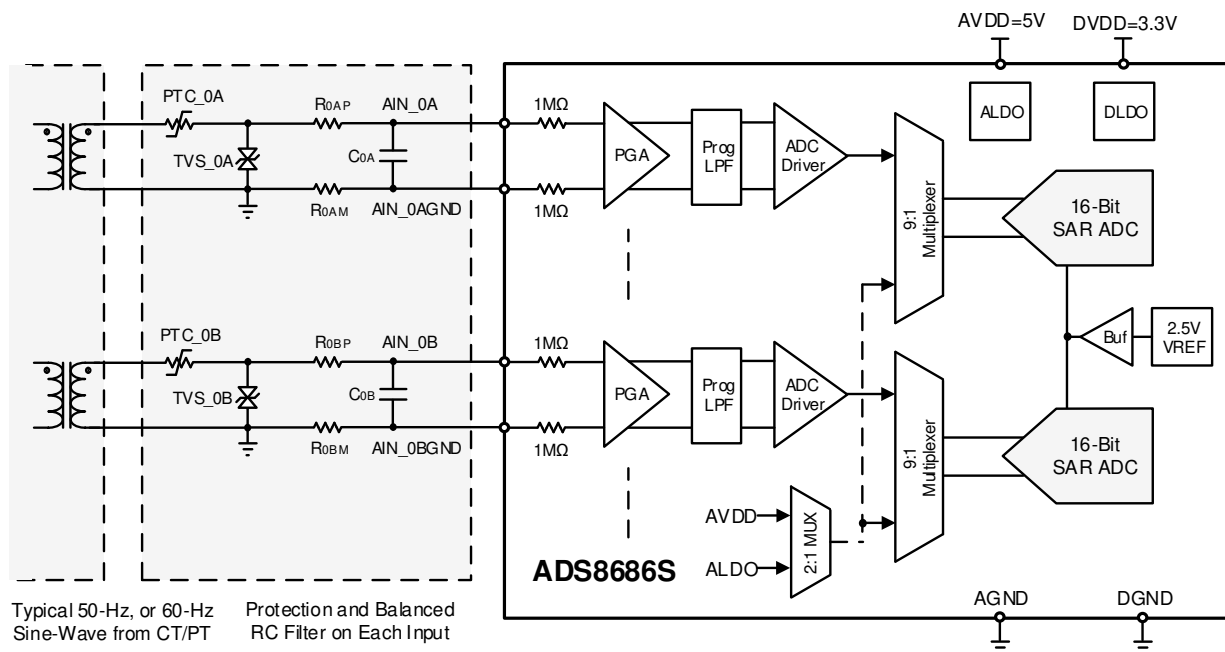
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Design Goals

AVDD	DVDD	Normal Input V_{IN} (No Overrange)	Absolute Maximum Input Voltage Rating (V_{in_Abs})	Absolute Maximum Input Current Rating (I_{in_Abs})
5V	3.3V	$\pm 10V$	$\pm 15V$	$\pm 10mA$

Design Description

This circuit shows an external 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 and a Positive Temperature Coefficient (PTC) fuse. This document shows how the PTC fuse can be used to replace the large value and regular current-limiting resistor to implement the external protection clamp with TVS diode for overstress signal and improve the performance especially *total harmonic distortion* (THD). This circuit is useful in end equipment such as: [Multi-Function Relays](#), [AC Analog Input Module in Protection Relay](#), [Train control & management systems](#), and [Factory automation & control](#). For protecting high-voltage SAR ADC from electrical overstress with regular current-limiting resistor and TVS diode, see [Input Protection for high-voltage ADC circuit with TVS Diode](#). 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:
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Specification	Goal	Measured
Maximum continuous overstress voltage (V_{EOS_Max})	$\pm 40V$	No damage with 40-V peak sinusoidal wave signal
SNR on ADS8686S (± 10 -V range)	89.0dB	90.7dB
THD on ADS8686S	-105dB	-105.5dB

Design Notes

1. A TVS diode is usually used as an electrical overstress protection for high-voltage SAR ADCs with integrated Analog Front-End (AFE) because this kind of ADC only requires single 5-V analog power supply but supports high-voltage analog input. For example, ADS8686S device supports ± 10 -V input on a 5-V analog supply. The external TVS diode turns on and clamps the input overstress signal at its breakdown voltage with proper current-limiting.
2. Select C0G type capacitor for C_{0x} in the front-end RC filter to minimize the distortion.
3. See the [Electrical Overstress on Data Converters](#) video in the [TI Precision Labs - ADCs](#) 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, current-limiting resistor selection and PTC fuse selection.

Design Steps

- Select a bidirectional TVS diode according to the following guideline:
 - $V_R \geq V_{in}$. V_R the standoff voltage of TVS diode, is the normal input voltage of the ADC that is $\pm 10V$ without overrange on the ADS8686S device.
 - $V_{BR} < V_{in_Abs}$. V_{BR} is the breakdown voltage of TVS diode, is the absolute input voltage of the ADC that is $\pm 15V$ on the ADS8686S device.
 - Based on these guidelines, the PGSM AJ10CA bidirectional TVS diode from Taiwan Semiconductor Co., Ltd. (TSC[®]) is used in this design to protect the ADS8686S from electrical overstress.
- Also, select a bidirectional TVS diode according to the following restrictions:
 - Low leakage current as the leakage current will be translated into an offset voltage error when it flows through a series resistance.
 - Low capacitance as the capacitance is not constant and large capacitance variation which is related to the signal voltage applied to the diode can distort the input signal and lead to a distortion.
 - 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.
- In this design, the maximum electrical overstress signal is $\pm 40V$ that is common in industrial systems, the minimum breakdown voltage of PGSM AJ10CA is 11.1V (V_{BR_Min}), the maximum breakdown voltage of PGSM AJ10CA is 12.3V (V_{BR_Max}). The following table lists the key parameters for PTC fuses from Eaton Corporation (Eaton[®]).

Item	Part Numbers	$V_{max_PTC}(V)$	$I_{max_PTC}(A)$	$I_{hold}(A)$	$I_{trip_PTC}(A)$	$R_{min_PTC}(\Omega)$	$R_{max_PTC}(\Omega)$
1	PTS120660V005	60	100	0.05	0.15	3.6	50
2	PTS120660V010	60	100	0.10	0.25	1.6	15
3	PTS120660V005	30	100	0.12	0.29	1.4	6
4	PTS120660V005	30	100	0.16	0.37	1.1	4.5
5	PTS120660V005	24	100	0.20	0.42	0.65	2.6

- The first criteria to consider when choosing the PTC fuse is the maximum fault voltage. Applying this criteria to the table eliminates items 3–5, as their maximum operating voltage is lower than the fault voltage.

$$V_{fault} \leq V_{Max_PTC}$$

- The next criteria, is to check that the maximum fault current is lower than the PTC maximum rating.

$$I_{fault_max} < I_{max_PTC}$$

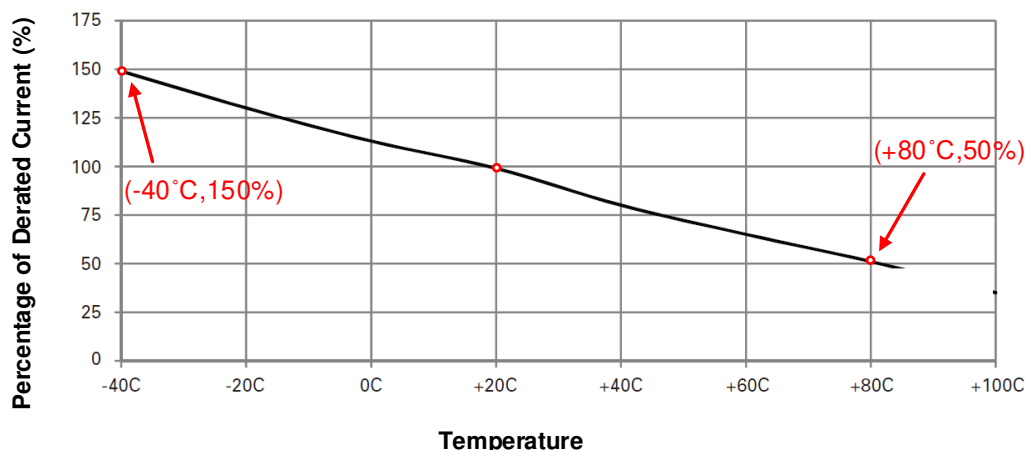
$$I_{fault_max} = \frac{V_{EOS_Max} - V_{BR_Min}}{R_{min_PTC}} = \frac{40V - 11.1V}{R_{min_PTC}} = \frac{28.9V}{R_{min_PTC}}$$

- c. The next criteria, is to make sure that the minimum fault current is greater than the hold current rating. This assures that the PTC fuse will remain tripped under a fault condition. For this criteria, the temperature derating curve should be used to find the highest hold current.

$$I_{fault_min} > I_{hold}$$

$$I_{fault_max} = \frac{V_{EOS_Max} - V_{BR_Min}}{R_{min_PTC}} = \frac{40V - 12.3V}{R_{min_PTC}} = \frac{27.7V}{R_{min_PTC}}$$

$$I_{hold(-40C)} = I_{hold(20C)} \cdot 150\% = 0.05A \cdot (1.5) = 0.075A$$



- d. Finally, select the device with lowest trip current that meets all other criteria. Selecting a device with a low trip current provides better protection, as it trips at a lower current level. For this example, the PTS120660V005 was selected.

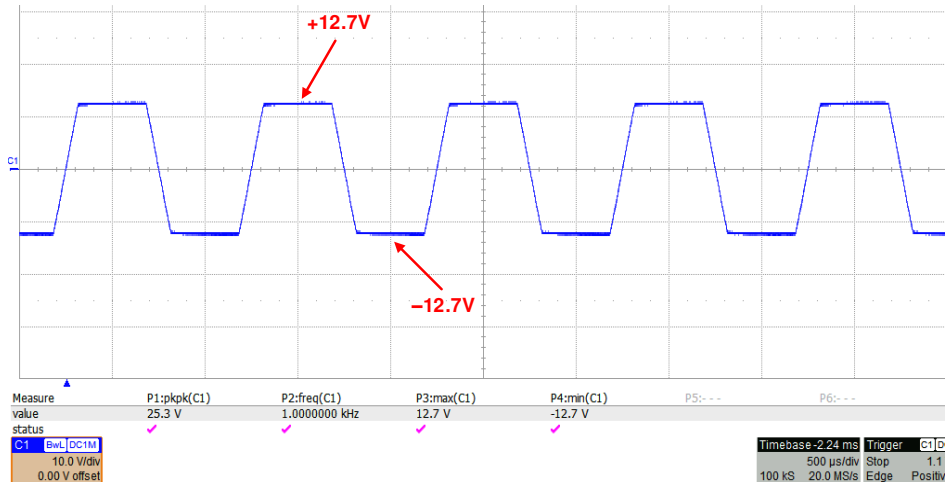
4. The resistor R_{0XP} acts as a filter with the capacitor C_{0X} and also to limit the current to the ADC input under a fault condition. The absolute maximum input voltage (V_{in_Abs}) of ADS8686S is $\pm 15V$ and the maximum input current (I_{in_Abs}) is $\pm 10mA$. The PGSM AJ10CA TVS diode has 17-V maximum clamping voltage (V_{C_Max}) when 23.5A peak current (I_{PP}) is flowing it for a brief period of time. Hence, the minimum value of can be determined by:

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

5. The capacitor C_{0X} in parallel with R_{0XP} is used to filter the noise from the front-end circuit. The exact value may not be very critical so we use a standard value of 1nF in this design.

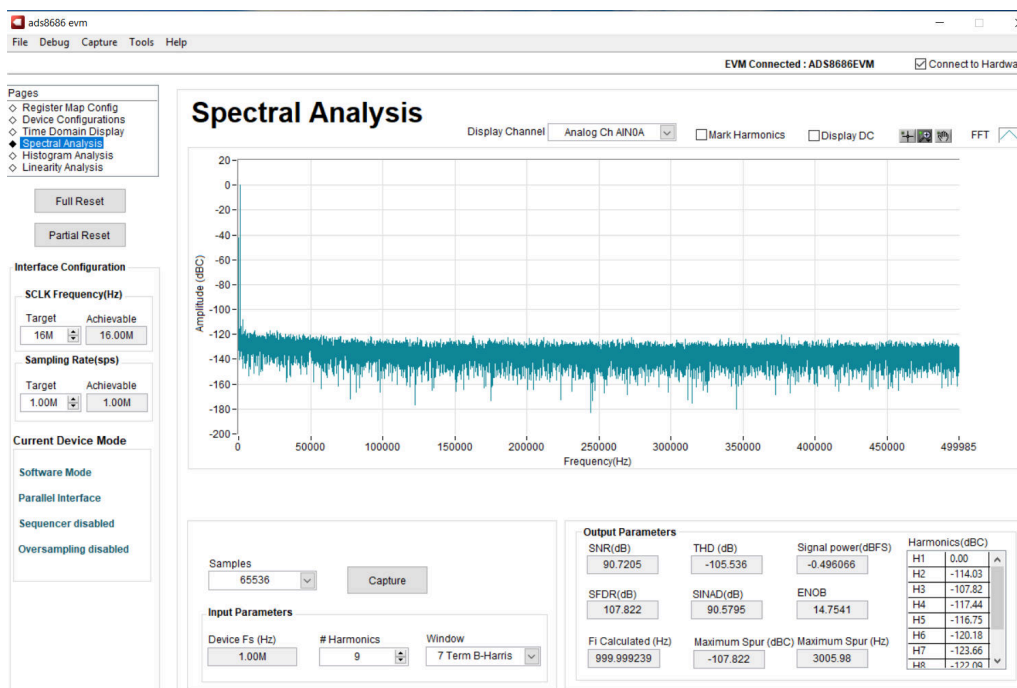
ADC Input Overvoltage Condition

The following figure shows the ADC input voltage when a high voltage continuous overvoltage sinusoidal wave signal ($60V_{pp}$) is applied. Note that the external bidirectional TVS diode PGSMJ10CA is turned on and the overvoltage sinusoidal wave signal has been clamped to $\pm 12.7V_{pk}$ which is less than $\pm 15V$ absolute maximum input voltage (V_{in_Abs}) on the ADS8686S, so the ADC device is successfully protected from overvoltage signal.



AC (SNR and THD) Performance Checked on Hardware

The following spectral analysis is measured using [ADS8686SEVM-PDK](#) with PTC fuse (PTS120660V005) and bidirectional TVS diode (PGSMJ10CA). The measured THD and SNR performance with all the protection circuitry including TVS diode meets the typical specification in the [ADS8686S 16-Channel, 16-Bit, 1-MSPS, Dual, Simultaneous Sampling ADC with Integrated Analog Front-End Data Sheet](#) (Measured SNR = 90.7dB, THD = -105.5dB with 1kHz sinusoidal wave input at 1Msps sampling rate). Also, the PTC fuse solution has significantly improved THD performance on regular resistor with TVS diode shown in [Circuit Input Protection for high-voltage ADC circuit with TVS Diode](#).



Capacitance Variation on TVS Diode and Impact to THD Performance

The capacitance on TVS diodes commonly used in the market has a strong voltage coefficient, this large capacitance variation which is changed with the voltage applied on the TVS diode and the input protection resistance form a low pass filter. The attenuation of this input filter changes according to the input voltage because the diode capacitance changes according to the input signal and this distorts the input signal and can significantly degrade the THD performance, See [Electrical Overstress on Data Converters](#) video (part of the [TI Precision Labs - ADCs](#) video series) for detailed theory and analysis on this subject.

There are two solutions to improve the system THD performance: use 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. However, it is hard to find an ultra-low capacitance variation bidirectional TVS diode to achieve the performance specified in ADC data sheet. The PTC fuse is a device that shows a low resistance under normal condition and a high resistance for an overcurrent condition, hence this characteristic is useful for ADC input protection as the series resistance will be low in the normal un-tripped state and it will keep the distortion relatively low, also the series resistance will be high in the tripped state to limit the fault current and power dissipation.

The following table compares the measured result for PTC fuse (PTS120660V005) and the TVS diodes with different capacitance specifications. The test result shows that the measured THD performance with PTC fuse and TVS diode SMCJ10CA is improved and it is better than the performance with regular resistor and SMCJ10CA TVS diode shown in [Circuit Input Protection for high-voltage ADC circuit with TVS Diode](#), however the measured THD (-96.8dB) is still worse than the specification in ADS8686S data sheet because of large capacitance and variation on SMCJ10CA TVS diode. Conversely, the measured THD performance with PTC fuse and PGSM AJ10CA TVS diode is significantly improved and better than the performance with regular resistor and same TVS diode shown in [Circuit Input Protection for high-voltage ADC circuit with TVS Diode](#), the measured THD performance (-105.5dB) meets the typical specification in ADS8686S data sheet because of lower capacitance and variation on the PGSM AJ10CA TVS diode. To achieve a better performance in the ADC system design, the TVS diode with further lower capacitance and variation should be selected and used even when PTC fuse is used to improve the performance.

Part Numbers	MFG	Reverse Standoff Voltage (VR)	Breakdown Voltage (VBR)		Clamping Voltage Max (VC)	Capacitance Variation (CT) ⁽⁴⁾	Reverse Leakage Max (IR@VR)	Peak pulse Current (IPP)	Measured THD (dB) With PTC ⁽²⁾	Peak Power Dissipation (PPP)
			MIN	MAX						
SMCJ10CA	Bourns	10V	11.1	12.3	17V	2.3nF - >10nF ⁽¹⁾	5μA	88.3A	-96.8	1500W
SMA6J10A ⁽³⁾	TSC	10V	11.1	12.3	15.7V	200 to 400pF	5μA	38.2A	-103.4	600W
PGSM AJ10CA	TSC	10V	11.1	12.3	17V	80 to 160pF	5μA	23.5A	-105.5	400W

(1) The TVS data sheet does not directly show the capacitance at 0V, it is much larger than 10nF regarding the trend.

(2) The performance is measured on ADS8686SEVM-PDK ($R_{0XP} = 1k\Omega$, $R_{0XM} = 1k\Omega$, $C_{0X} = 1nF$, 1Msps throughput).

(3) SMA6J10A is a unidirectional TVS diode, two diodes are used to measure the performance.

(4) The capacitance values are estimated from the capacitance curve in the data sheet.

Design Featured Devices:

Device	Key Features	Link	Other Possible Devices
ADS8686S	16-Bit, 2 x 1Msps, 16-Channel, Dual Simultaneous-Sampling, Single Supply, SAR Analog-to-Digital Converter	http://www.ti.com/product/ADS8686S	http://www.ti.com/adcs
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, 1MSPS, 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.

For similar reference designs, see:

[Input Protection for high-voltage ADC circuit with TVS Diode](#)

[Circuit for protecting low-voltage SAR ADC from electrical overstress with minimal impact on performance](#)

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