Application Report

ESD Diode Current Specification

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ABSTRACT

This document explains the maximum ESD diode current specified for GPIOs on MSP microcontrollers. Sometimes signals on specific pins exceed the supply voltage range of the MSP MCU, causing an overvoltage or negative voltage condition. In such a case, the ESD diodes provide some protection to the device, but the ESD diode specification must be considered during application design. The items to be considered are described in this document.

Note

Many of the specifications and figures in this application report are from the MSP430FR5969 microcontroller data sheet as an example. However, the same theory and understanding applies to all MSP430™ MCUs, which all have similar specifications in each device-specific data sheet.

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1 Important Side Effects of the ESD Diodes During Power Cycling

The methods described in this application report do not apply when the main supply (typically DVCC) is unpowered and a voltage is applied on a GPIO pin. This condition can cause unintended power sourcing to the MCU through the ESD structures on the GPIOs. This is a concern in both the power up and power down scenarios. If the main supply and a GPIO are powered at the same time, ensure that delays in the main supply (due, for example, to inline capacitance or LDO delays) are accounted for and that a GPIO is not powered before the main supply.

Due to the physical architecture of the ESD diodes, which is explained in the following sections, other secondary side effects can appear if the MSP microcontroller is not properly powered. Improper power scenarios include sensors that are sourced by a different supply or communication lines that are driven by other ICs in the application, if these signals are connected to the MCU while the main supply of the MCU is off. During the power-down scenario, a side effect is that the device can be back powered through the ESD diodes. However, this is not the intended powering scheme for the MSP microcontroller and can lead to erroneous and unpredictable behavior, due to the current limitations of the ESD diodes and the bypassing of the intended power path. In worst case scenarios, this can lead to physical damage to the device, unexpected execution, or memory corruption causing a malfunction in the application.

2 Introduction and Clarification of the Specification

Most MSP microcontrollers specify the maximum ESD diode current in the *Absolute Maximum Ratings* section (see Figure 2-1). The diode current specified as ±2 mA is a constant current that flows through the ESD structure to the supply rails to protect the device. These ESD structures are triggered if a signal is applied that exceeds the maximum or minimum supply voltage specifications of the device. To follow the specification, the application must protect the device pin externally so that a signal does not exceed the ±2-mA specification.

In other words, voltages greater than the actual device supply (DVCC and AVCC) or lower than VSS can be applied, but the current that flows through the ESD diodes must be controlled.

5 Specifications

5.1 Absolute Maximum Ratings(1)

over operating free-air temperature range (unless otherwise noted)

	MIN	MAX	UNIT
Voltage applied at DVCC and AVCC pins to V_{SS}	–0.3	4.1	V
Voltage difference between DVCC and AVCC pins(2)		±0.3	V
Voltage applied to any pin (3)	–0.3	V_{CC} + 0.3 V (4.1 Max)	V
Diode current at any device pin		±2	mA
Storage temperature, T_{stg}(4)	–40	125	°C

(1) Stresses beyond those listed under *Absolute Maximum Ratings* may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under *Recommended Operating Conditions* is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.
(2) Voltage differences between DVCC and AVCC exceeding the specified limits may cause malfunction of the device including erroneous writes to RAM and FRAM.
(3) All voltages referenced to V_{SS}.
(4) Higher temperature may be applied during board soldering according to the current JEDEC J-STD-020 specification with peak reflow temperatures not higher than classified on the device label on the shipping boxes or reels.

Figure 2-1. Absolute Maximum Ratings of MSP430FR5969

While the current is specified as ±2 mA, the ESD structure can withstand much higher current levels, such as those that appear during typical ESD events according HBM or CDM. The cells are made to pass standard ESD tests like HBM or CDM as shown in Figure 2-2. During this high-voltage stress, current peaks in the range of several amperes flow through the ESD structures.

5.2 ESD Ratings

			VALUE	UNIT
$V_{(ESD)}$	Electrostatic discharge	Human-body model (HBM), per ANSI/ESDA/JEDEC JS-001(1)	±1000	V
		Charged-device model (CDM), per JEDEC specification JESD22-C101(2)	±250	

(1) JEDEC document JEP155 states that 500-V HBM allows safe manufacturing with a standard ESD control process. Pins listed as ±1000 V may actually have higher performance.
(2) JEDEC document JEP157 states that 250-V CDM allows safe manufacturing with a standard ESD control process. Pins listed as ±250 V may actually have higher performance.

Figure 2-2. ESD Ratings of MSP430FR5969

However, the duration of the high-current pulse is quite short (in the range of several nanoseconds), which leads to less thermal stress and much less heating compared to a long-term high-current event. This is the main reason why the constant current through the ESD diodes is limited to ±2 mA for longer or constant operation.

3 Considerations During Application Design

When considering the ESD diode current specification of the device data sheet during the development of an application, first analyze if signals connected to the GPIO pins can exceed the actual supply. One example would be the output of analog sensors, which might go above the MSP MCU supply for a longer period of time (several milliseconds). In such a case, the maximum voltage levels that can be seen by the MSP MCU must be defined or evaluated, and a current-protection mechanism must be developed. This protection mechanism is important to prevent permanent damage on the ESD structure of the MSP microcontroller caused by high current beyond the allowed level. This protection also prevents the secondary effect of increasing the supply voltage due to energy introduced through the ESD diodes.

In most cases, the current limitation can be implemented as a simple series resistance that is sized based on the maximum expected current. However, in some cases, this might not be enough to fulfill all aspects of a reliable working application. Even if the current limitation specification of the ESD diodes is met, the supply of the MSP microcontroller might be disturbed. This is because the ESD structures draw the current to the supply rail of the MSP MCU, which boosts the supply as long as current is flowing. If the supply connected to the MSP MCU cannot sink current, the maximum DVCC specification of the MSP MCU might be violated over time. This high supply voltage can cause permanent damage that can lead to malfunction of the device or high current consumption. The high supply voltage can also cause wear-out effects that lead to functional and parametric failures over time.

The principle of supply voltage increase can be explained using a principle I/O schematic (see Figure 3-1). The external serial resistors R1 and R2 limit the current that flows through the ESD diodes D1 and D2 when an overvoltage is applied. Protecting the CMOS devices against this kind of overvoltage is the essential function of the internal ESD diode. Assuming that the rating for the continuous current through the diode of ±2 mA is considered, no physical damage occurs. At the same time, the current of ±2 mA maximum flows to the supply potential through the ESD diodes and raises the potential by providing "extra" current. If this "extra" current is larger than the current that is consumed by a load connected to the supply, the voltage increases. If more than one GPIO adds current to the supply, the sum of "extra" currents added to the V_{CC} potential flowing through all protection diodes must be considered. Figure 3-1 shows this case, when two GPIOs experience overvoltage at the same time. If the sum of currents exceeds the maximum current consumption of the whole system connected to V_{CC}, additional protection mechanisms must be considered. The whole system is defined by the supply architecture itself which can have current sink capability but also by the microcontroller and connected loads to the microcontroller. If the microcontroller is running in active mode and driving some LEDs, it is probable that the energy provided by the ESD diodes during overvoltage condition will be consumed. However, if the microcontroller is in low-power mode and consuming only a few nanoamperes, the supply voltage will increase due to the extra current from the ESD diodes.

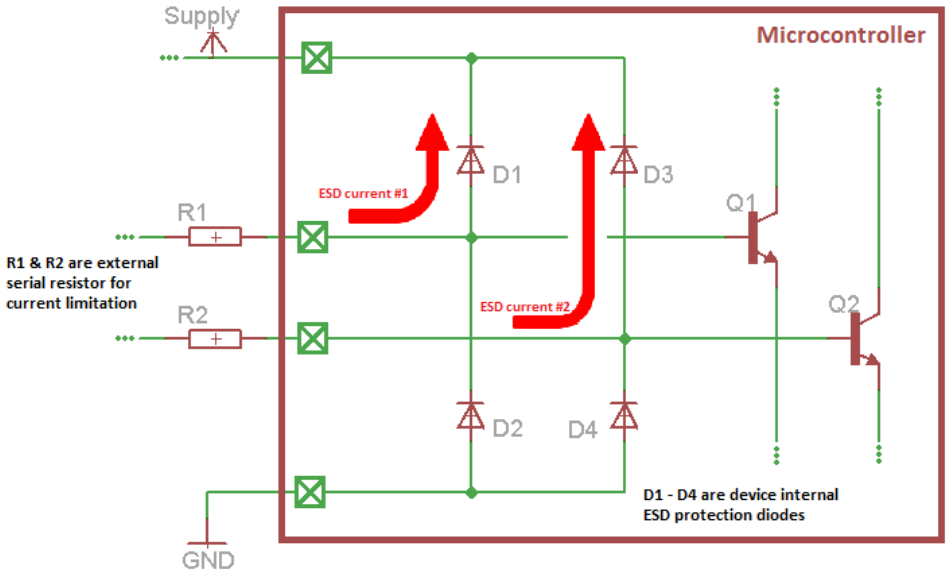

Figure 3-1. Principle Schematic of an I/O in overvoltage condition

A similar principle applies if a voltage lower than VSS is applied to a GPIO; however, current would flow through D2 and D4. This condition can cause an adverse effect on the device ground, depending on the capabilities of the supply.

To remove this adverse effect on the supply's voltage and ground, TI recommends consideration of the best choice of the regulator to fit the application requirements. In addition to form factor, performance parameters, cost, and power consumption, the impact on the whole system must also be considered. Section 3.1 describes the advantages and disadvantages of regulator circuits with good current sinking capabilities, and also lists alternative solutions to prevent the supply increase effect.

A similar effect to the overvoltage condition appears if the device is powered down and no voltage is applied to V_{CC}. In this case, a voltage greater than 0.3 V can result in backward supply through the ESD diodes. Section 1 provides more details on this scenario.

WARNING

In battery-supplied applications, the supply voltage boosting effect due to overvoltage on I/O pins can cause the battery to explode or burn.

3.1 Consideration of the Correct Supply Circuit

3.1.1 Power Supplies With Good Current-Sinking Capability

Figure 3-2 shows an example of a power supply with good current-sink capability if the ESD diodes raise the supply voltage through the 2-mA path. The main reason for the good sinking property of this circuit is the relatively high feedback current drawn by the R1 and R2 combination for this specific regulator. As described in the figure, the feedback current is approximately 10 mA, which is much higher than the 2 mA that is allowed by the MSP microcontroller ESD diodes. Therefore, the energy can be dissipated by the feedback path of the voltage regulator, and no increase of the supply will be seen. The significant disadvantage of this power supply on the system level is the relatively high static power dissipation.

9.2 Typical Application

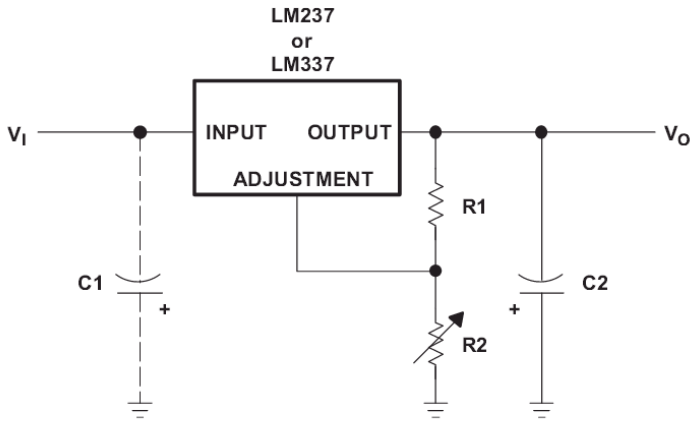

Figure 3. Adjustable Negative-Voltage Regulator

9.2.1 Design Requirements

- 1-µF solid tantalum on the input pin if the regulator is more than 10 cm from the power supply filter capacitor
- 1-µF solid tantalum or 10-µF aluminum electrolytic capacitor is required on the output pin for stability.
- R1, which is usually 120 Ω as part of the resistor divider.
- R2, which can be varied to change the value of V_O.

9.2.2 Detailed Design Procedure

V_O is determined by the values of R1 and R2. Choosing R1 = 120 Ω means that about 10.42 mA of current will flow through R1. The ~10 mA of current satisfies the minimum operating current and renders I_{REF} negligible. Since the current is coming from ground, the same amount of current will flow through R2. Therefore, the size of R2 will be the dominant factor in adjusting V_O. The relationship between R1, R2, and V_O is as follows:

$$R2 = R1\left(\frac{V_O}{-1.25} - 1\right) \quad (1)$$

where V_O is the output in volts.

Figure 3-2. Typical Example for a Current-Sink LDO

3.1.2 Power Supplies With Limited Current-Sinking Capability

Figure 3-3 shows an example of a power supply with limited current sinking capability. In comparison to the regulator in Figure 3-2, the feedback divider R1 and R2 of the power supply with limited current sink capability draws a static current of approximately 7 µA.

As soon as the ESD diodes of the MSP MCU connected to V_O are operated with the maximum current of 2 mA, the output voltage of the power supply in Figure 3-3 increases. This increase in V_O may lead to overvoltage stress on the MSP microcontroller or the power supply itself.

output voltage programming

The output voltage of the TPS77001 adjustable regulator is programmed using an external resistor divider as shown in Figure 22. The output voltage is calculated using:

$$V_O = V_{ref} \times \left(1 + \frac{R1}{R2}\right) \quad (1)$$

where

V_{ref} = 1.224 V typ (the internal reference voltage)

Resistors R1 and R2 should be chosen for approximately 7-µA divider current. Lower value resistors can be used but offer no inherent advantage and waste more power. Higher values should be avoided as leakage currents at FB increase the output voltage error. The recommended design procedure is to choose R2 = 169 kΩ to set the divider current at 7 µA and then calculate R1 using:

$$R1 = \left(\frac{V_O}{V_{ref}} - 1\right) \times R2 \quad (2)$$

OUTPUT VOLTAGE PROGRAMMING GUIDE

OUTPUT VOLTAGE (V)	DIVIDER RESISTANCE (kΩ)‡	
	R1	R2
2.5	174	169
3.3	287	169
3.6	324	169
4.0	383	169
5.0	523	169

‡1% values shown.

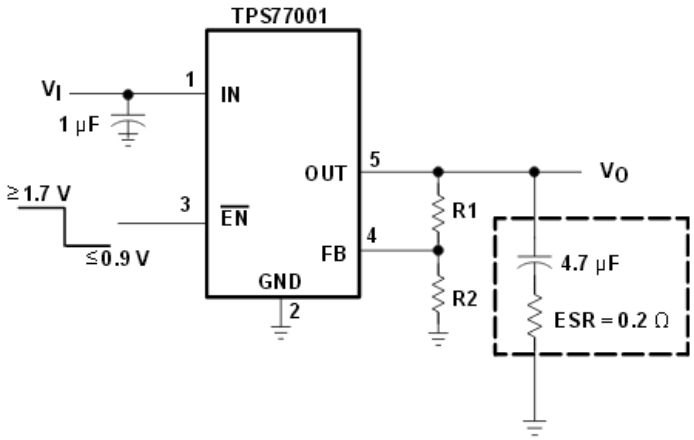

Figure 22. TPS77001 Adjustable LDO Regulator Programming

Figure 3-3. Typical Example for a LDO Circuit With Limited Current-Sinking Capability

An example for ultra-low-power supplies is the TPS7A16, which recommends large resistor values in the feedback path (see Figure 3-4) to keep the overall quiescent current of the system low. This approach is well suited for ultra-low-power applications where no overvoltage can be introduced through the MSP MCU internal ESD diodes. In systems where the ESD diodes of the MSP MCU increase the supply rails, this power supply can cause overvoltage on the MSP MCU, due to the limited current-sink capability.

Table 3. Selected Resistor Combinations

V_{OUT}	R_1	R_2	$V_{OUT}/(R_1 + R_2) \ll I_Q$	NOMINAL ACCURACY
1.194 V	0 Ω	∞	0 µA	±2%
1.8 V	1.18 MΩ	2.32 MΩ	514 nA	±(2% + 0.14%)
2..5 V	1.5 MΩ	1.37 MΩ	871 nA	±(2% + 0.16%)
3.3 V	2 MΩ	1.13 MΩ	1056 nA	±(2% + 0.35%)
5 V	3.4 MΩ	1.07 MΩ	1115 nA	±(2% + 0.39%)
10 V	7.87 MΩ	1.07 MΩ	1115 nA	±(2% + 0.42%)
12 V	14.3 MΩ	1.58 MΩ	755 nA	±(2% + 0.18%)
15 V	42.2 MΩ	3.65 MΩ	327 nA	±(2% + 0.19%)
18 V	16.2 MΩ	1.15 MΩ	1038 nA	±(2% + 0.26%)

Figure 3-4. Selected Resistor Combinations for TPS7A16

3.1.3 Bidirectional Power Supplies

In addition to the unidirectional regulators previously introduced, there are also bidirectional LDOs with a built-in reverse current operation. A typical bidirectional power supply is the TPS715A. The reverse current operation is realized by a built-in back-gate diode of the LDO pass device. When the input voltage V_{IN} drops below the output voltage V_{OUT} minus the forward voltage of the back-gate diode, current flows from the output to the input. The bidirectional operation lets the power-up and power-down sequences enable a certain SVS functionality of the LDO. Figure 3-5 shows the power-up and power-down behavior of the TPS715A. This is only a recommended power cycle scenario for the MSP MCU, and this operation should not be confused with the actual current-sink capability.

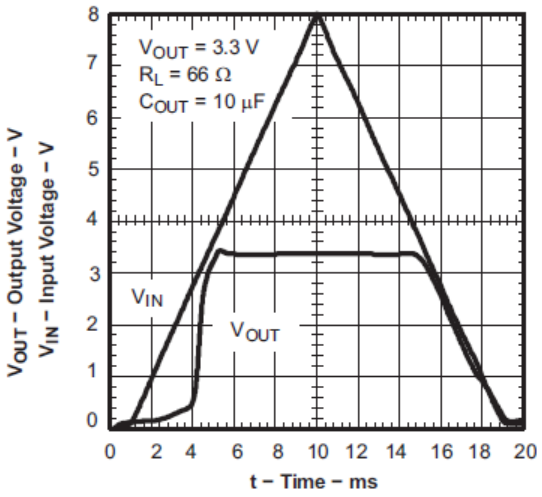

Figure 3-5. Power-Up and Power-Down Behavior of TPS715A

3.2 Alternative Solutions

Due to system requirements, a power supply with limited current-sink capability might be required by the application. Hence, the risk of constant overvoltage at the I/O pins with respect to the ESD diode current specification must be evaluated. In this special application, an alternative solution must be implemented to protect the MCU from voltage stress.

3.2.1 Zener Diodes

A common solution is the use of a Zener diode connected to the supply (see Figure 3-6). This diode can dissipate the additional energy introduced by the MSP MCU internal ESD diodes and clamps the voltage to the desired domain. The Zener diode does not draw static current, so that the advantage of the low-power LDO combined with the current-sink capability of the Zener diode offers a reasonable protection and supply to the MSP MCU.

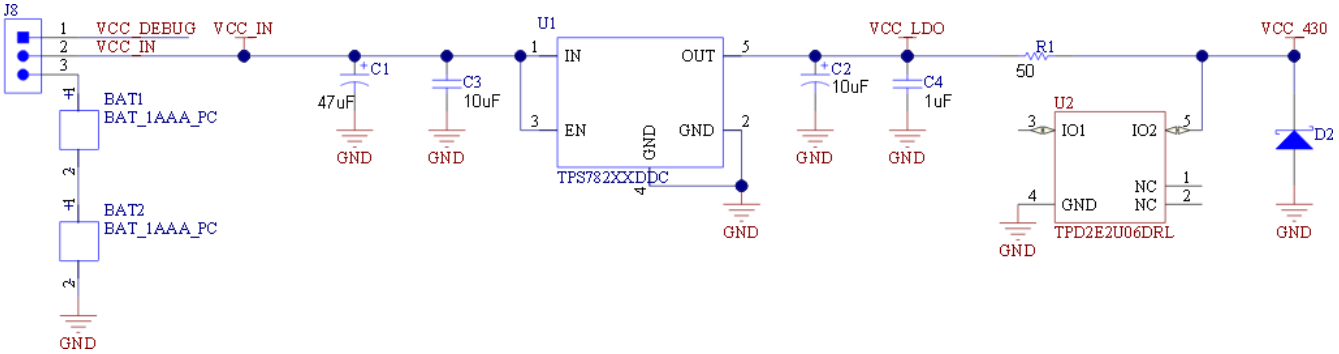

Figure 3-6. Alternative Solution Using a Zener Diode

When using this alternative approach, the selection of the correct Zener diode depends on the application. Consider characteristics like overall power consumption, power dissipation, and overall clamping behavior to

protect against overvoltage conditions caused by the MSP MCU internal ESD diodes during overvoltage stress. One of the main items be considered is the constant current that is drawn by the Zener diode even when it has not started to protect the MCU. The second parameter is the clamping voltage itself, which should be above 4.1 V, which is the absolute maximum rating for MSP MCUs. Therefore, a Zener diode that provides a good comprise between clamping voltage and current consumption in nonprotection modes must be found.

3.2.2 Shunt Regulators

Shunt regulators like the ATL431 are offered as Zener diode replacements and are a good alternative to a real Zener diode to address the use case described in this application report. The clamping voltage is adjustable by using external resistors, and the regulators have a very low operating current when they are not in clamping state. The most important function is the steep characteristic of the I-V curve at the clamping point. Figure 3-7 is an extract from the ATL431 data sheet that clearly shows the fast increase in current when the clamping voltage of 2.5 V is reached, while the regulator operates at low current below this clamping threshold.

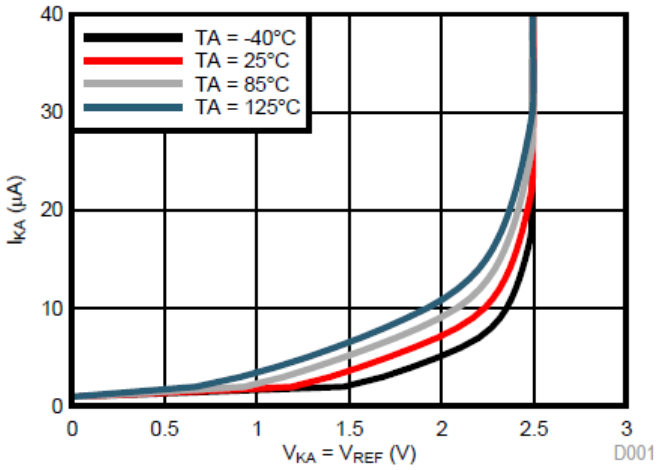

Figure 3-7. Cathode Current vs Cathode Voltage

Experiments using the TPS77033 in combination with the ATL431 prove the concept of protecting the supply for continuous overvoltage caused by extra currents through the ESD diodes. In this example, the supply voltage of 3.3 V for the MSP430 MCU is provided by the TPS77033 (see Figure 3-8).

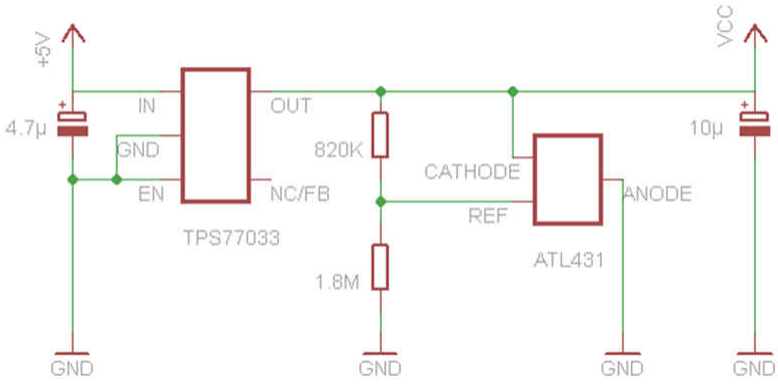

Figure 3-8. Schematic Example Using ATL431

For test purposes, an MSP430F6638 MCU was programmed to stay in LPM3 with a timer active and causing interrupts every 10 ms. At the same time, P1.4 was configured as an input pin and overvoltage (4.4 V with limited current) was applied to this GPIO. This was done so that the current driven to the input pin activates the current path through the ESD diodes to the supply rail. Without the ATL431, an increase of the supply voltage to 3.8 V was observed on the DVCC pin and also on P1.0, which was driven in the timer interrupt service routine.

To calculate the external resistor combination connected to the ATL431, use Equation 1.

$$V_{OUT} = \left(\frac{1 + R1}{R2}\right) \times Vref - Iref \times R1 \quad (1)$$

To consider the reference current specification (*Iref*) of the ATL43x for output voltage (V_{OUT}) variation, the following equations can be used to calculate the minimum and maximum clamping voltages:

$$V_{OUT}min = \left(\frac{1 + 820\ k\Omega}{1800\ k\Omega}\right) \times 2.5\ V - 150\ nA \times 820\ k\Omega = 3.52\ V \quad (2)$$

$$V_{OUT}typ = \left(\frac{1 + 820\ k\Omega}{1800\ k\Omega}\right) \times 2.5\ V - 30\ nA \times 820\ k\Omega = 3.61\ V \quad (3)$$

$$V_{OUT}max = \left(\frac{1 + 820\ k\Omega}{1800\ k\Omega}\right) \times 2.5\ V - 0\ nA \times 820\ k\Omega = 3.64\ V \quad (4)$$

When the ATL431 was configured for clamping at approximately 3.6 V, no increase above this voltage was seen. This simple experiment proves the principle concept of the proposed protection methodology.

However, if resistor combinations in the range of MΩ are used, the risk of leakage caused by external contamination must be considered during application development.

4 Clarification on ESD Diode Current and I/O Output Drive Capability

This section clarifies the meaning of the GPIO output voltage specification to prevent any confusion with the ESD diode current specification in the maximum ratings section.

The output voltage specification (see Figure 4-1) describes the driver capability of the I/Os. An I/O can drive high output at a certain load with a certain loss in the voltage level. For example, an I/O can drive a load of –0.6 mA, but the voltage level in this case may be as much as 0.6 V lower than the actual supply voltage. The same is true if an I/O drives a zero level. In such a case, the low-level voltage might raised by 0.6 V, maximum, if a current of 6 mA flows into the I/O.

However, these specifications are not related to the 2-mA ESD diode current specification, which describes the maximum current that is allowed to flow through the ESD protection circuit when a voltage higher than the MSP microcontroller supply or lower than VSS is applied to an I/O.

Table 5-12. Digital Outputs

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)

PARAMETER		TEST CONDITIONS	V_{CC}	MIN	TYP	MAX	UNIT
V_{OH}	High-level output voltage	$I_{(OHmax)}$ = –1 mA(1)	2.2 V	V_{CC} – 0.25		V_{CC}	V
		$I_{(OHmax)}$ = –3 mA(2)		V_{CC} – 0.60		V_{CC}	
		$I_{(OHmax)}$ = –2 mA(1)	3.0 V	V_{CC} – 0.25		V_{CC}	
		$I_{(OHmax)}$ = –6 mA(2)		V_{CC} – 0.60		V_{CC}	
V_{OL}	Low-level output voltage	$I_{(OLmax)}$ = 1 mA(1)	2.2 V	V_{SS}		V_{SS} + 0.25	V
		$I_{(OLmax)}$ = 3 mA(2)		V_{SS}		V_{SS} + 0.60	
		$I_{(OLmax)}$ = 2 mA(1)	3.0 V	V_{SS}		V_{SS} + 0.25	
		$I_{(OLmax)}$ = 6 mA(2)		V_{SS}		V_{SS} + 0.60	

(1) The maximum total current, $I_{(OHmax)}$ and $I_{(OLmax)}$, for all outputs combined should not exceed ±48 mA to hold the maximum voltage drop specified.
(2) The maximum total current, $I_{(OHmax)}$ and $I_{(OLmax)}$, for all outputs combined should not exceed ±100 mA to hold the maximum voltage drop specified.
(3) The port can output frequencies at least up to the specified limit - it might support higher frequencies.
(4) A resistive divider with 2 × R1 and R1 = 1.6 kΩ between V_{CC} and V_{SS} is used as load. The output is connected to the center tap of the divider. C_L = 20 pF is connected from the output to V_{SS}.
(5) The output voltage reaches at least 10% and 90% V_{CC} at the specified toggle frequency.

Figure 4-1. GPIO Port Output Specification of MSP430FR5969

5 Conclusion

This document describes how to interpret the ESD diode current specification of the MSP microcontroller data sheets. In addition, it clarifies the differences between LDOs without and with current sinking capability. The conditions and requirements of the whole application are important aspects to select the correct supply circuit for the MSP microcontroller.

The best way to remove supply issues due to ESD diode current is to prevent the overvoltage or negative voltage conditions at the GPIO. If the system architecture can limit the overvoltage or negative voltage at the entry point, the considerations about the correct supply circuit are less critical.

6 References

1. *MSP430FR59xx Mixed-Signal Microcontrollers*
2. *LMx37 3-Terminal Adjustable Regulators*
3. *TPS770xx Ultra Low-Power 50-mA Low-Dropout Linear Regulators*
4. *TPS7A16 60-V, 5-µA Iq, 100-mA, LDO Voltage Regulator With Enable and Power-Good*
5. *TPS715A High Input Voltage, MicroPower SON Packaged, 80mA LDO Linear Regulators*
6. *ATL43x 2.5-V Low Iq Adjustable Precision Shunt Regulator*
7. Thermostat Implementation With FRAM Microcontroller Reference Design

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from July 11, 2019 to August 20, 2021	Page
• Updated abstract to account for negative voltage	1
• Updated Section 2 to account for negative voltage	2
• Updated Section 3 to account for negative voltage condition	3
• Updated Section 4 to account for negative volatge condition	9
• Updated Section 5 to account for negative voltage condition	10

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