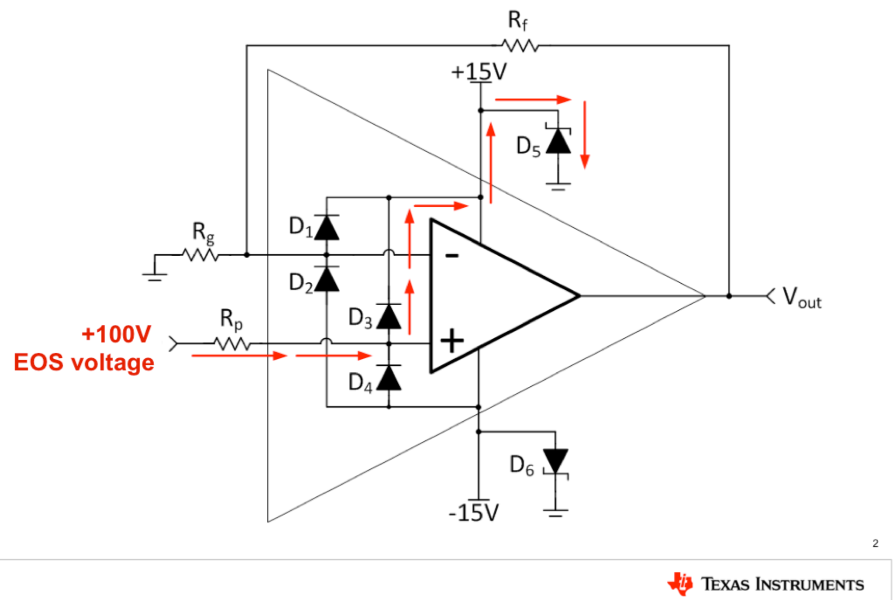
Hello, and welcome to the video for the TI Precision Lab discussing electrical overstress, or EOS, part 3. In this video we'll show how to select components for EOS protection. We will use the op-amp data sheet absolute maximum specifications and application circuit operating conditions to select the appropriate TVS diode and current-limiting resistors.

Choosing TVS Diodes and R_P

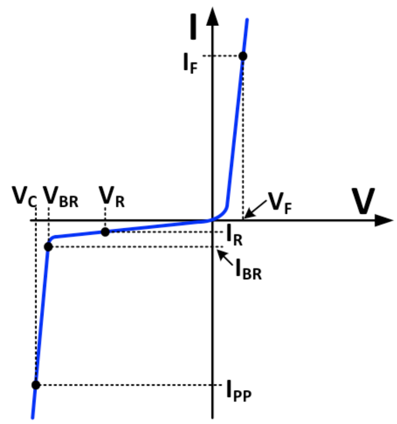


The objective in selecting the TVS diode is to make sure that the diode is off and has minimal leakage during normal operation, but turns on and limits the supply voltage under overstress conditions. The objective in selecting the resistor is to limit the input current to less than 10mA.

TVS Diode V_R – Reverse Standoff Voltage

Set $\mathbf{V_R}$ = maximum operating supply voltage
Note: leakage current I_R is specified at V_R

Symbol	Parameter
V_{BR}	Breakdown voltage
V_R	Stand-off voltage
V_C	Clamping voltage
V_F	Forward voltage drop
I_{BR}	Breakdown Current @ V_{BR}
I_R	Reverse Leakage @ V_R
I_F	Forward Current @ V_F
I_{PP}	Peak Pulse current @ V_C



Let’s review some of the characteristics of TVS diodes given in EOS 1. The most critical spec for TVS selection is the reverse standoff voltage, or V_R. Looking at the I-V characteristic on the right, we see that Vr is the highest operating voltage of the TVS where it still has low leakage current I_R, typically around 1 µA. This is the “off” stage for the TVS. If higher voltages are applied, the TVS will reach its reverse breakdown voltage, where it will turn on and limit voltage as well as conduct significant current. Finally, the clamping voltage V_C is the voltage across the TVS where the peak pulse current, or I_{PP}, is flowing.

These three points on the I-V curve are what we’ll use to select a TVS.

Set V_R for the Example

ELECTRICAL CHARACTERISTICS **OPA192 Data Sheet**

At T_A = +25C, VCM = VOUT = VS/2, and RLOAD = 10kΩ connected to Vs/2, unless otherwise noted.

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
POWER SUPPLY						
VS	Specified voltage range		±2.25		±18	V
IQ	Quiescent current per amplifier	I_O = 0A		1	1.2	mA
		T_A = -40°C to 125°C, I_O = 0A			1.5	mA

TVS Diode Specifications

Part Number	Reverse Standoff Voltage V_R	Leakage I_R @ V_R	Breakdown Voltage V_{BR}		Breakdown Current I_{BR}	Maximum Clamping Voltage V_C	Maximum Peak Pulse Current I_{PP}	Peak Power P_{PP}
			Min	Max				
SMAJ18A	18V	5µA	20.0V	22.1V	1mA	29.2V	13.7A	400W

4

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Both the amplifier operating conditions and the TVS diode specifications need to be considered when selecting the TVS diode. First let's consider the amplifier specifications. The specified power supply range is the range under which the device can be used while maintaining its specified datasheet performance. In this example, the OPA192 specified power supply range is from ±2.25V to ±18V. If a supply voltage of ±18V is used for the amplifier, then the TVS diode needs to remain off and have low leakage.

Remember that the reverse standoff voltage specification on the TVS diode, or V_R, is the maximum voltage that can be applied to a TVS diode where the maximum reverse leakage current is valid. This example diode was selected to match the maximum specified supply voltage from the amplifier. V_R is specified at 18V and the associated maximum reverse leakage is 5µA. This means that if the reverse voltage applied across the TVS diode is 18V or less the leakage current will never be above 5µA. Normally, the standoff voltage is selected according to the maximum operating conditions of the circuit. So, if the amplifier was operated at a lower voltage the reverse standoff voltage would need be selected accordingly.

Please note the difference between the "specified voltage range" and "absolute maximum range" of an op amp's power supply. The **specified** voltage range is the range where the specifications are valid and the range under which the device is designed to operate. The **absolute maximum** range is the range that can be applied to the device before damage is caused. In this example we are discussing the specified range of ±18V. The absolute maximum for this device is ±20V.

Fault Voltage < Absolute Maximum

Fault voltage = voltage across the TVS at maximum fault current

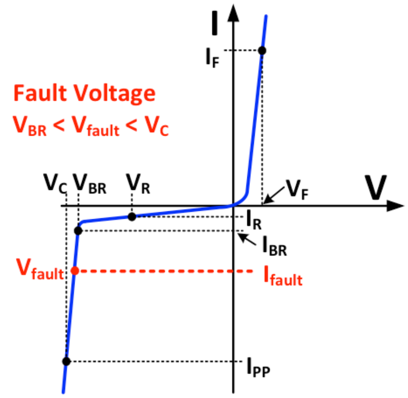
In this example:
Vs operating maximum = **±18V**
Vs absolute maximum = **±20V**
Ideally: **18V < TVS Fault Voltage < 20V**

OPA192			VALUE	UNIT
Supply voltage			±20 (+40, single supply)	V
Signal input terminals	Voltage	Common-mode	(V-) - 0.5 to (V+) + 0.5	V
		Differential	(V+) - (V-) + 0.2	V
	Current		±10	mA
Output short circuit			Continuous	
Operating temperature			-55 to +150	°C
Storage temperature			-55 to +150	°C
Junction temperature			+150	°C
Electrostatic discharge (ESD) ratings	Human Body Model (HBM)		4	kV
	Charged device model (CDM)		1	kV

Let’s take a look at the absolute maximum specifications for the OPA192. Recall from the last slide that the OPA192’s operating voltage is ±18V. The absolute maximum for this device is ±20V. So, if the amplifier supply is normally at ±18V, then the TVS diode must be fully off at 18V. However, the TVS needs to turn on to protect the amplifier before the supply reaches the absolute maximum of ±20V.

The fault voltage is the voltage across the TVS diode when it is turned on and protecting the device. The fault voltage is dependent on the current that flows during the overvoltage fault condition. Ideally, this fault voltage should be kept lower than the absolute maximum voltage. Lets look again at the TVS diode I-V curve to better understand this concept.

Find the Fault Voltage on the I-V Curve



Symbol	Parameter
V_{BR}	Breakdown voltage
V_R	Stand-off voltage
V_C	Clamping voltage
V_F	Forward voltage drop
I_{BR}	Breakdown Current @ V_{BR}
I_R	Reverse Leakage @ V_R
I_F	Forward Current @ V_F
I_{PP}	Peak Pulse current @ V_C
I_{fault}	Fault current
V_{fault}	Voltage across TVS diode during fault

Note: You will have to estimate the fault current based on your application.

6

Texas Instruments

In our example, we are targeting 18V as the reverse standoff voltage because this is the normally operating voltage that will be applied to the op amp. V_{BR} is the breakdown voltage, the point at which the device is just beginning to turn on. Typically, 1mA of current flows at the breakdown voltage. The clamp voltage, V_C, is the voltage across the TVS diode with maximum reverse current flowing through it. Depending on the current expected during the fault condition, the fault voltage will be somewhere between V_{BR} and V_C. One way to estimate the fault current is to consider the maximum supply current and add margin. In this example we will estimate the fault current at 2A. Since V_C and V_{BR} are specified it is possible to interpolate between the two points to determine the fault voltage at a specific fault current, or 2A in this example.

Interpolate to Find V_{FAULT}

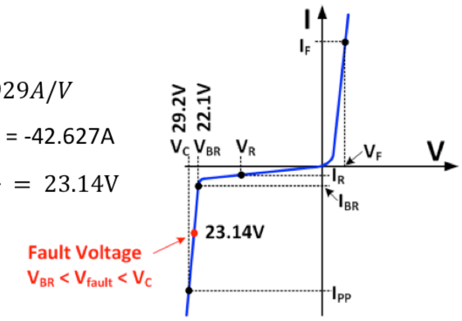
Part Number	Reverse Standoff Voltage V_R	Leakage I_R @ V_R	Breakdown Voltage V_{BR}		Breakdown Current I_{BR}	Maximum Clamping Voltage V_C	Maximum Peak Pulse Current I_{PP}	Peak Power P_{PP}
			Min	Max				
SMAJ18A	18V	5uA	20.0V	22.1V	1mA	29.2V	13.7A	400W

$$I = m \cdot V + b$$

$$m = \frac{(I_C - I_{BR})}{(V_C - V_{BR})} = \frac{(13.7A - 0.001A)}{(29.2V - 22.1V)} = 1.929A/V$$

$$b = I_C - m \cdot V_C = 13.7\text{A} - (1.929\text{A/V})(29.2\text{V}) = -42.627\text{A}$$

$$V_{fault} = \frac{(I_{fault} - b)}{m} = \frac{(2A - [-42.627A])}{1.929A/V} = 23.14\text{V}$$



7

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Here we show how to use linear interpolation to find the fault voltage across the example TVS diode for 2A of fault current. The equation is the standard straight line in the form I = m V + b. Solving for the slope, m, we divide the change in current over the change in voltage for the breakdown and clamp points. In this example, we use the maximum values for these points so that the solution is conservative. After solving for the slope, we rearrange the equation and solve for the y-axis intercept, or b. Finally, we substitute this information back into the equation and solve for the fault voltage at 2A. In this case, the fault voltage is 23.14V.

TVS Comparison – V_{FAULT} and V_R

Option 1: SMAJ18A			
TVS Voltages		**Amplifier Voltages**	
Reverse Standoff	V_R = 18V	Operating Maximum	18V
Fault Voltage	V_{FAULT} = 23.14V	Absolute Maximum	20V

Option 1: Fault voltage is greater than the absolute maximum.

Option 2: SMAJ15A			
TVS Voltages		**Amplifier Voltages**	
Reverse Standoff	V_R = 15V	Maximum Supply	15V
Fault Voltage	V_{FAULT} = 19.2V	Absolute Maximum	20V

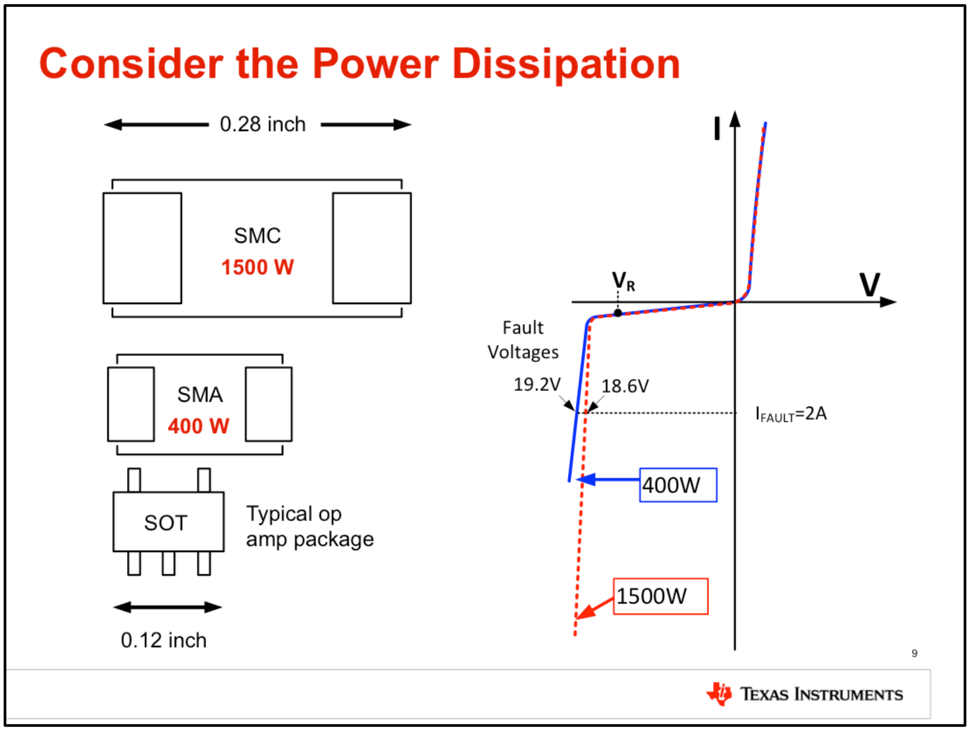
Option 2: Fault voltage is less than the absolute maximum.

8

TEXAS INSTRUMENTS

We now must compare the TVS voltages to the op-amp specifications. Recall that the TVS reverse standoff of 18V was selected to match the op amp operating supply voltage of 18V. We determined that the fault voltage is actually 23.14V using linear interpolation between known points on its I-V curve. For best protection, the fault voltage should be less than the op amp absolute maximum voltage, unfortunately, this TVS fault voltage is above the op amp absolute maximum of 20V.

In the second option, the op amp supply voltage is reduced to 15V. This gives more margin between the maximum supply and the absolute maximum voltage. A new TVS is selected with a 15V reverse standoff, which results in a fault voltage of 19.2V - less than the op amp absolute maximum. Thus, this TVS diode will effectively protect against EOS events. It should be noted that in some cases it is not possible to find a TVS diode that meets both the operating and absolute maximum conditions. In this case, it is recommended to still use the TVS in spite of the fact that it will not limit the fault voltage to a EOS safe level. The reason is that some protection is always better than no protection.



Ideally the TVS reverse standoff voltage and fault voltage would be very close to each other, since op amps often have operating conditions which are near the absolute maximum voltage. However, this isn't always the case. Thankfully we can consider TVS diodes with different power ratings. Increasing the power rating increases the slope of the curve in the reverse breakdown region, which will move the fault voltage closer to the reverse standoff voltage.

Note that the power rating refers to the peak power dissipated during a 1ms pulse. In this example we compare a 1500W TVS diode to a 400W TVS diode. You can see from the curve on the right that at 2A, the 400W device has a fault voltage of 19.2V while the 1500W device has a fault voltage of only 18.6V. This reduction can be very helpful when selecting a TVS. However, there is a disadvantage to high-power TVS diodes. They are quite large compared to most op amp packages. The diagram on the left compares the size of an op-amp in a 5-pin SOT package, a 400W TVS in a SMA package, and a 1500W TVS in a SMC package.

TVS Comparison – V_{FAULT} and Power

Option 1: SMAJ15A (400W)			
TVS Voltages		**Amplifier Voltages**	
Reverse Standoff	V_R = 15V	Maximum Supply	15V
Fault Voltage @ 2A	V_{FAULT} = 19.2V	Absolute Maximum	20V

Option 2: SMCJ15A (1500W)			
TVS Voltages		**Amplifier Voltages**	
Reverse Standoff	V_R = 15V	Maximum Supply	15V
Fault Voltage @ 2A	V_{FAULT} = 18.6V	Absolute Maximum	20V

Note: Option 1 and option 2 have the same reverse standoff voltage. The fault voltage at 2A is lower for the option 2. This makes option 2 a better choice in cases where the maximum supply and absolute maximum are closer together.

10

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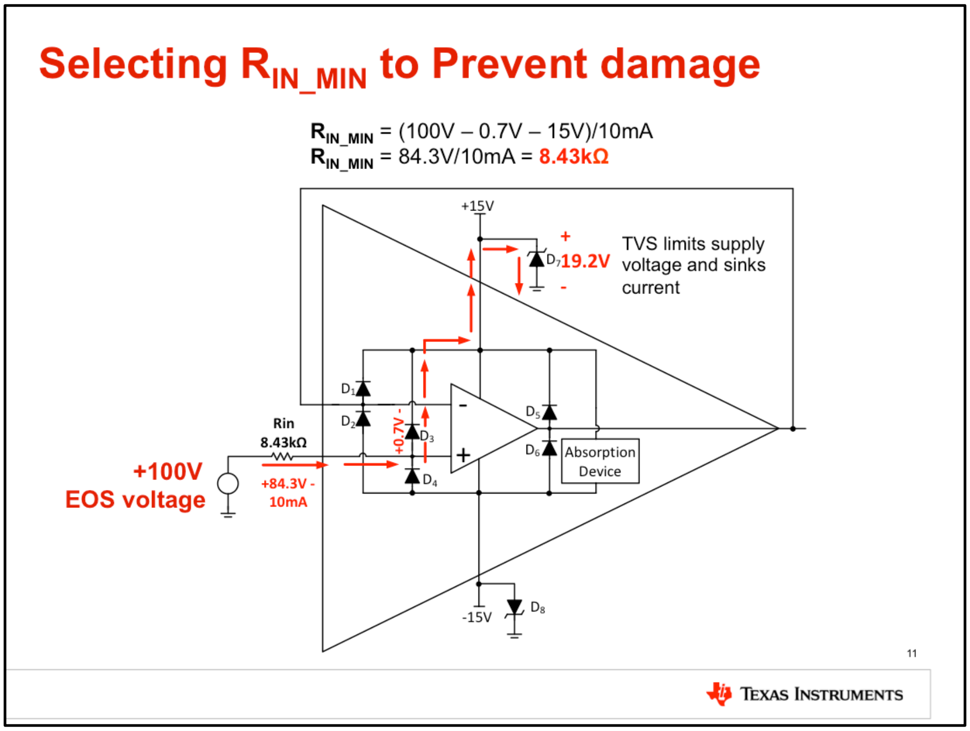
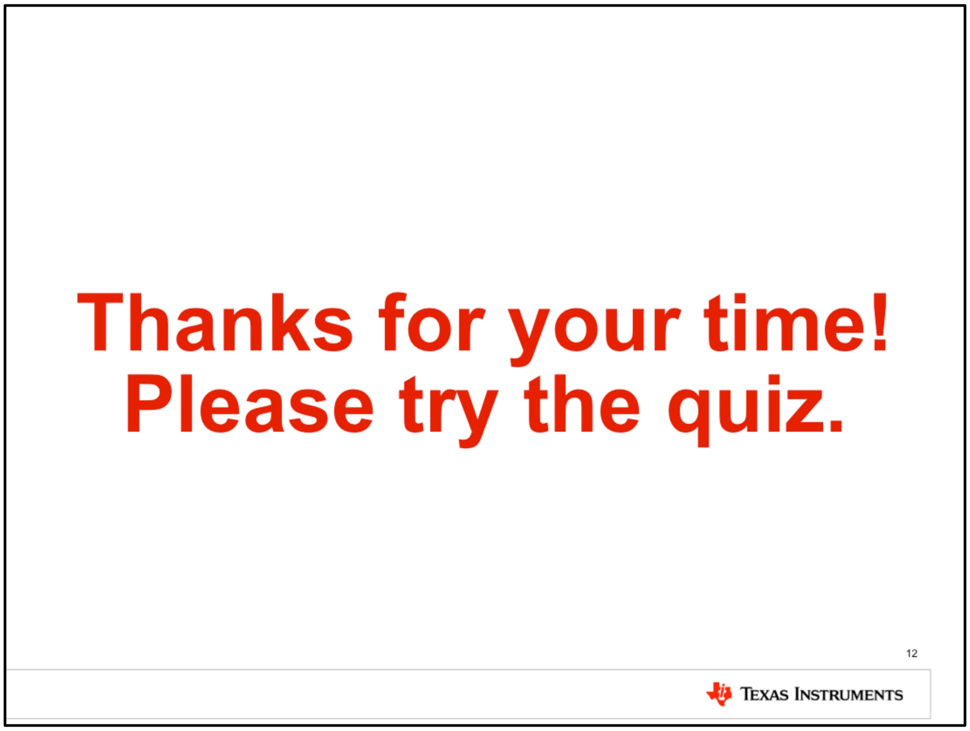
Comparing the results for TVS diodes with different power ratings, we clearly see that the fault voltage is significantly lower for the higher power TVS diode in option 2. In this case both options will protect against EOS because the fault voltage is lower than the absolute maximum of the op amp. However, the higher power option has additional margin. Furthermore, if operating conditions were closer to the absolute maximum conditions, this might be the only option.



The last step to developing effective EOS protection is to choose the current limiting resistance in series with the input. First, pick a worst-case EOS voltage, 100V in this example. Second do a "voltage walk" through the path of current flow to determine the voltage drop across the resistor. In this example, the 100V is distributed across R_{IN}, D3, and D7. D3 has about 0.7V of voltage drop and D7 has a 19.2V drop based on its fault voltage, so 84.3V remains across the resistor. The absolute maximum current flow into the amplifier before EOS damage is 10mA. Use Ohm's law to calculate the minimum resistor value based on the voltage of 84.3V and maximum current of 10mA, which results in 8.43 kΩ. Note that increasing the resistance will improve the protection, but may cause other performance tradeoffs.



That concludes this video – thank you for watching! Please try the quiz to check your understanding of the video's content.

Electrical Overstress – 3

Multiple Choice Quiz

TI Precision Labs – Op Amps

Quiz: Electrical Overstress – 3

1. Which specification on a TVS diode is matched to the amplifier's operating voltage?

a. Clamp voltage
b. Reverse breakdown voltage
c. Forward voltage drop
d. Reverse standoff voltage

2. What is the typical current flow through a TVS diode at the reverse breakdown voltage?

a. 1uA
b. 1mA
c. 1A
d. 10A

3. What is the typical current flow through a TVS diode at the reverse standoff voltage?

a. 1uA
b. 1mA
c. 1A
d. 10A

Quiz: Electrical Overstress – 3

4. In cases where the operating voltage and absolute maximum voltage are near each other, it can be difficult to find a TVS diode that will have low leakage at the operating voltage but will fully turn on before the absolute maximum voltage. Which parameter on the TVS diode can help resolve this?

a. Turn on time
b. Temperature rating
c. Power rating

5. In a particular amplifier design, the operating voltage is 10V and the absolute maximum is 12V. No TVS diode is available that will be off at 10V and on before 12V. What can be done to resolve this?

a. If possible, reduce the operating supply voltage to a lower level.
b. Use the best TVS available. Some protection is better than none.
c. Use a Schottky diode instead of a TVS diode.
d. Use a ferrite bead on the power supply instead of a TVS diode.
e. Option a & b
f. Option c & d

Electrical Overstress – 3

Multiple Choice Quiz: Solutions

TI Precision Labs – Op Amps

Quiz: Electrical Overstress – 3

1. Which specification on a TVS diode is matched to the amplifier's operating voltage?

a. Clamp voltage
b. Reverse breakdown voltage
c. Forward voltage drop
d. Reverse standoff voltage

2. What is the typical current flow through a TVS diode at the reverse breakdown voltage?

a. 1uA
b. 1mA
c. 1A
d. 10A

3. What is the typical current flow through a TVS diode at the reverse standoff voltage?

a. 1uA
b. 1mA
c. 1A
d. 10A

Quiz: Electrical Overstress – 3

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b. Temperature rating
c. Power rating

5. In a particular amplifier design, the operating voltage is 10V and the absolute maximum is 12V. No TVS diode is available that will be off at 10V and on before 12V. What can be done to resolve this?

a. If possible, reduce the operating supply voltage to a lower level.
b. Use the best TVS available. Some protection is better than none.
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d. Use a ferrite bead on the power supply instead of a TVS diode.
e. Option a & b
f. Option c & d

Electrical Overstress – 3

Exercises

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1. Below is a specifications table for several different TVS diodes. Also below is the absolute maximum table for the OPA192. Assuming the OPA192 is being run with ±12V supplies, choose the best TVS diode. Assume a fault current of 10A.

Part Number	Reverse Standoff Voltage V_R	Leakage I_R @ V_R	Breakdown Voltage V_{BR}		Breakdown Current I_{BR}	Maximum Clamping Voltage V_C	Maximum Peak Pulse Current I_{PP}	Peak Power P_{PP}
			Min	Max				
SMAJ12A	12V	1µA	13.3V	14.7V	1mA	19.9V	20.1A	400W
ESD12VD5	12V	0.02µA	14.1V	-	1mA	25V	9.6A	240W
1PMT12AT1G	12V	1µA	13.3V	14.7V	1mA	19.9V	10.1A	200W
SMCJ12A	12V	1µA	13.3V	14.7V	1mA	19.9V	75.4A	1500W

OPA192			VALUE	UNIT
Supply voltage			±20 (+40, single supply)	V
Signal input terminals	Voltage	Common-mode	(V-) - 0.5 to (V+) + 0.5	V
		Differential	(V+) - (V-) + 0.2	V
	Current		±10	mA
Output short circuit			Continuous	
Operating temperature			-55 to +150	°C
Storage temperature			-55 to +150	°C
Junction temperature			+150	°C
Electrostatic discharge (ESD) ratings	Human Body Model (HBM)		4	kV
	Charged device model (CDM)		1	kV

2. Below is a specifications table for several different TVS diodes. Also below is the absolute maximum table for the OPA192. Assuming the OPA192 is being run with ±15V supplies, choose the best TVS diode. Assume a fault current of 0.1A.

Part Number	Reverse Standoff Voltage V_R	Leakage I_R @ V_R	Breakdown Voltage V_{BR}		Breakdown Current I_{BR}	Maximum Clamping Voltage V_C	Maximum Peak Pulse Current I_{PP}	Peak Power P_{PP}
			Min	Max				
5.0SMDJ13A	13V	1µA	14.4V	15.9V	1mA	21.5V	69.8A	1500W
5.0SMDJ16A	16V	1µA	17.8V	19.7V	1mA	26.0V	57.7A	1500W

OPA192			VALUE	UNIT
Supply voltage			±20 (+40, single supply)	V
Signal input terminals	Voltage	Common-mode	(V-) - 0.5 to (V+) + 0.5	V
		Differential	(V+) - (V-) + 0.2	V
	Current		±10	mA
Output short circuit			Continuous	
Operating temperature			-55 to +150	℃
Storage temperature			-55 to +150	℃
Junction temperature			+150	℃
Electrostatic discharge (ESD) ratings	Human Body Model (HBM)		4	kV
	Charged device model (CDM)		1	kV

Electrical Overstress – 3

Solutions

TI Precision Labs – Op Amps

1. **Below is a specifications table for several different TVS diodes. Also below is the absolute maximum table for the OPA192. Assuming the OPA192 is being run with ±12V supplies, choose the best TVS diode. Assume a fault current of 10A.**

Part Number	Reverse Standoff Voltage V_R	Leakage I_R @ V_R	Breakdown Voltage V_{BR}		Breakdown Current I_{BR}	Maximum Clamping Voltage V_C	Maximum Peak Pulse Current I_{PP}	Peak Power P_{PP}
			Min	Max				
SMAJ12A	12V	1μA	13.3V	14.7V	1mA	19.9V	20.1A	400W
ESD12VD5	12V	0.02μA	14.1V	-	1mA	25V	9.6A	240W
1PMT12AT1G	12V	1μA	13.3V	14.7V	1mA	19.9V	10.1A	200W
SMCJ12A	12V	1μA	13.3V	14.7V	1mA	19.9V	75.4A	1500W

Matches the supply
Good

As long as the supply stays at 12V and less the leakage from the TVS will be at or below this level.

Need to use this info to calculate the reverse voltage when conducting the 10A fault current. Shown on next slide.

1. Continued. Which TVS is the best option.

Part Number	Breakdown Voltage V_{BR}		Breakdown Current I_{BR}	Maximum Clamping Voltage V_C	Maximum Peak Pulse Current I_{PP}	Peak Power P_{PP}	Vfault at 10A
	Min	Max					
SMAJ12A	13.3V	14.7V	1mA	19.9V	20.1A	400W	17.3V
ESD12VD5	14.1V	-	1mA	25V	9.6A	240W	-na-
1PMT12AT1G	13.3V	14.7V	1mA	19.9V	10.1A	200W	19.8V
SMCJ12A	13.3V	14.7V	1mA	19.9V	75.4A	1500W	15.4V

Example:
Vfault Calculation
SMAJ12A

$V_{br} := 13.3 \quad I_c := 20.1$

$I_{br} := .001 \quad V_c := 19.9$

$I_{fault} := 10$

$$m_1 := \frac{I_c - I_{br}}{V_c - V_{br}} = 3.045$$

$$b := I_c - m_1 \cdot V_c = -40.502$$

$$V_{fault} := \frac{(I_{fault} - b)}{m_1} = 16.583$$

Part Number	Peak Power P_{PP}	Vfault at 10A	Note
SMAJ12A	400W	17.3V	Vfault (17.3V)<<Absolute Max (20V) Medium Size **Best Option** – Lots of Margin and ok size
ESD12VD5	240W	-na-	Max Current Ipp (9.6A) < Ifault(10A) **Worst option**
1PMT12AT1G	200W	19.8V	Vfault (19.8V)<Absolute Max (20V) Small Size Not enough Margin
SMCJ12A	1500W	15.4V	Vfault (15.4V)<<Absolute Max (20V) Large Size The amount of margin is probably overkill. Too big and costly for this application.

2. Below is a specifications table for several different TVS diodes. Also below is the absolute maximum table for the OPA192. Assuming the OPA192 is being run with ±15V supplies, choose the best TVS diode. Assume a fault current of 0.1A.

Part Number	Reverse Standoff Voltage V_R	Leakage I_R @ V_R	Breakdown Voltage V_{BR}		Breakdown Current I_{BR}	Maximum Clamping Voltage V_C	Maximum Peak Pulse Current I_{PP}	Peak Power P_{PP}
			Min	Max				
5.0SMDJ13A	13V	1µA	14.4V	15.9V	1mA	21.5V	69.8A	1500W
5.0SMDJ16A	16V	1µA	17.8V	19.7V	1mA	26.0V	57.7A	1500W

Part Number	Reverse Standoff Voltage V_R	Leakage I_R @ V_R	Comment
5.0SMDJ13A	13V	1µA	VR < V_{supply} to assure leakage I_R < 1µA V_R(13V) > V_{supply} (±15V) so high leakage is a possibility **Bad option**
5.0SMDJ16A	16V	1µA	V_R < V_{supply} to assure leakage I_R < 1µA V_R(16V) < V_{supply} (±15V) so leakage should be low This may work . Let's check the fault voltage (next slide)

2. Below is a specifications table for several different TVS diodes. Also below is the absolute maximum table for the OPA192. Assuming the OPA192 is being run with ±15V supplies, choose the best TVS diode. Assume a fault current of 0.1A.

Part Number	Reverse Standoff Voltage V_R	Leakage I_R @ V_R	Breakdown Voltage V_{BR}		Breakdown Current I_{BR}	Maximum Clamping Voltage V_C	Maximum Peak Pulse Current I_{PP}	Peak Power P_{PP}
			Min	Max				
5.0SMDJ16A	16V	1µA	17.8V	19.7V	1mA	26.0V	57.7A	1500W

$V_{br} := 19.7$ $\quad I_c := 57.7$

$I_{br} := .001$ $\quad V_c := 26$

$I_{fault} := .1$

$$m_1 := \frac{I_c - I_{br}}{V_c - V_{br}} = 9.159$$

$$b := I_c - m_1 \cdot V_c = -180.423$$

$$V_{fault} := \frac{(I_{fault} - b)}{m_1} = 19.711$$

Ok. Solution

V_{fault} (19.7V) < Absolute Max (20V)

So this option works but not much margin. Note that the relatively low fault current of 0.1A caused the fault voltage to be close to V_{BR} max. With larger fault currents the fault voltage would increase. Note that choosing a similar TVS diode with a 15V standoff voltage would have more margin.