AN69

External Over-current Shutdown for High Current Op Amps

INTERNAL CURRENT LIMIT

Many of Apex's power op-amps include a built-in current limit feature. To utilize this feature, the user sets the current limit with an external resistor. The resistor's value is proportional to the desired current limit based on an equation that is supplied in the datasheet. The purpose of the current limit is to protect the op-amp from exceeding the Safe Operating Area (SOA). When the current limit is exceeded, the op-amp output stage switches from a voltage source to a constant current source. When the demanded output current drops below the set current limit, the output stage switches back to a voltage source. More about the op-amp current limit function can be found in AN09.

Although the built-in current limit feature protects the amplifier in many situations, it's still possible to exceed the SOA.

A direct short to ground will force the amplifier to dissipate power equal to the product of the voltage drop across the amplifier ($V_{supply} - V_{out}$) and the set current limit. At lower current limits this isn't an issue, but as the set current limit increases the risk of exceeding the SOA will also increase.

EXTERNAL CURRENT LIMIT

An external current limit can provide greater output current and reduce the op-amp's internal power dissipation. The external current limit consists of a series pass device placed between the power supply and the op-amp supply terminal or in series with the output terminal and the load. More about this can be found in AN53.

This approach shifts the power dissipation from the amplifier's output stage to the pass element and subsequently reduces the risk of the amplifier exceeding its SOA. Consideration of power dissipation for the pass element is required. When current limit is engaged, proper attention to thermal management is required to control the pass device junction temperature.

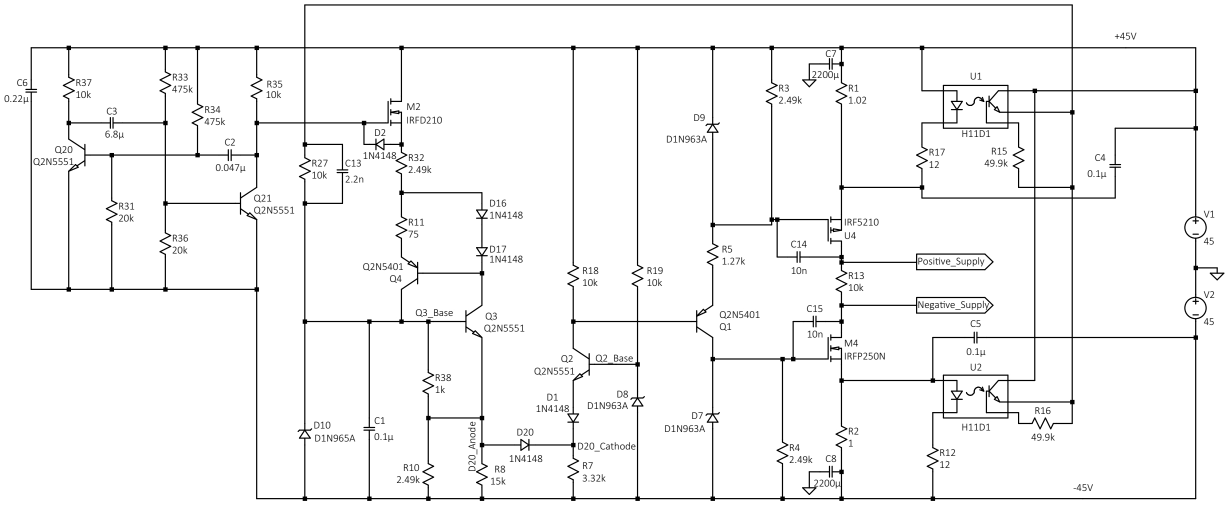
EXTERNAL OVER-CURRENT SHUTDOWN

The current limit techniques in AN09 and AN53 throttle the current but do not shut it off. As a result, there will still be power dissipated and the need for proper power management. The over-current shutdown discussed in this application note disconnects the op-amp from the power supply when the current limit is exceeded. This approach eliminates the power dissipation in over-current situations since there is no output current once the op-amp is disconnected. This method provides for adequate op-amp protection, a compact assembly, and a much simpler power management scheme.

THEORY OF OPERATION

Figure 1 presents a functional over-current shutdown circuit for high-current amplifiers like the PA50 and PA52. This circuit monitors the supply current into the positive pins(+Vs) and from the negative pins(-Vs). If the current limit is exceeded, the amplifier will be disconnected from both power supplies. About 60ms later the circuit will automatically reconnect the amplifier to the supply rails. If the fault hasn't been addressed, the amplifier will be disconnected from the power supplies again. The automatic reconnecting of the power supplies can be replaced with a manual reset. Refer to Section 1.4 for more information.

Figure 1: Over-Current Shutdown Circuit for High Current Amplifiers



1.2 HIGH CURRENT PATH

Identifying the high-current path is key to understanding the circuit. The positive supply current flows from R1 and U4 to the op-amp. The negative current flows from the op-amp through M4 and R2. R1 and R2 are sense resistors that set the current limit. As current flows through R1 or R2, a voltage will develop across each resistor. The current limit will be activated when the voltage-drop across either resistor is equal to the forward voltage of the optocoupler's, U1 or U2, internal LED. The current limit is set using the equation[1] below:

1.

$$I_{Lim} = \frac{V_F}{R_{Lim}}$$

Since the load current flows through the high-current path, power management of the sense resistors, U4, and M4 needs to be carefully considered. These components will likely require heatsinking.

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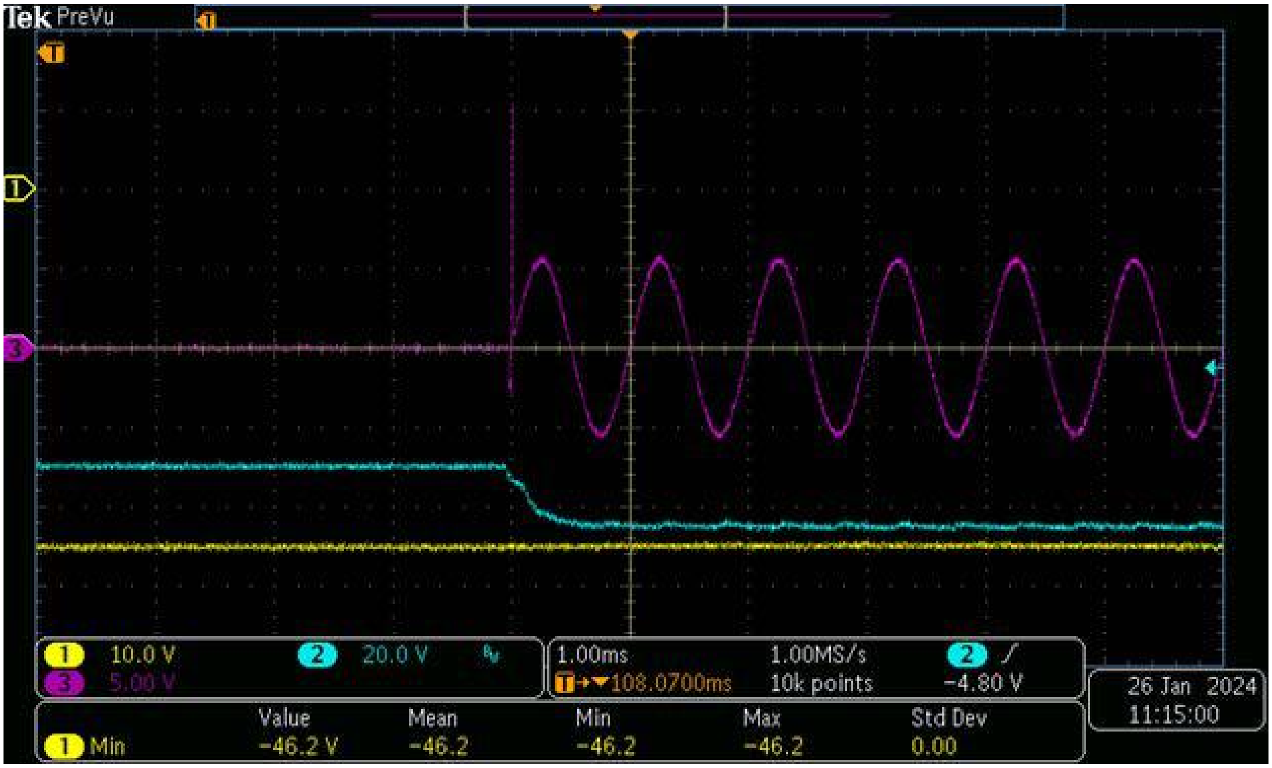
[1] Equation 1 is an approximation. See analysis section for more information.

1.3 ENTERING CURRENT LIMIT

During normal operation, the voltage at the base of Q3 is equal to the negative supply rail since the optocouplers are off and there is no current through R27. Subsequently Q3 and Q4 are also off. When I_{Lim} is exceeded, U1 or U2 will turn on and allow current to flow through R27. The 15V Zener, D10, sets the voltage at the base of Q3 to -Vs +15V. Transistor Q3 is now operating in the linear region and conducting current. The current through Q3 flows from M2, R32, D16 and D17. The voltage-drop across D16 and D17 turn transistor Q4 on. Transistor Q4 also begins conducting current. The current through Q3 keeps Q4 on, and the current through Q4 keeps Q3 on.

Transistors Q3 and Q4 form a silicon-controlled rectifier (SCR). An SCR is needed because R27 only conducts current for a brief amount of time. The SCR latches the circuit in its shutdown mode, after the optocouplers turn off.   Section 1.5 explains how turning on Q3 quickly disconnects the amplifier from the power supplies.

Figure 2: Relationship Between the Base of Q3, V_{out}, and $-V_s$

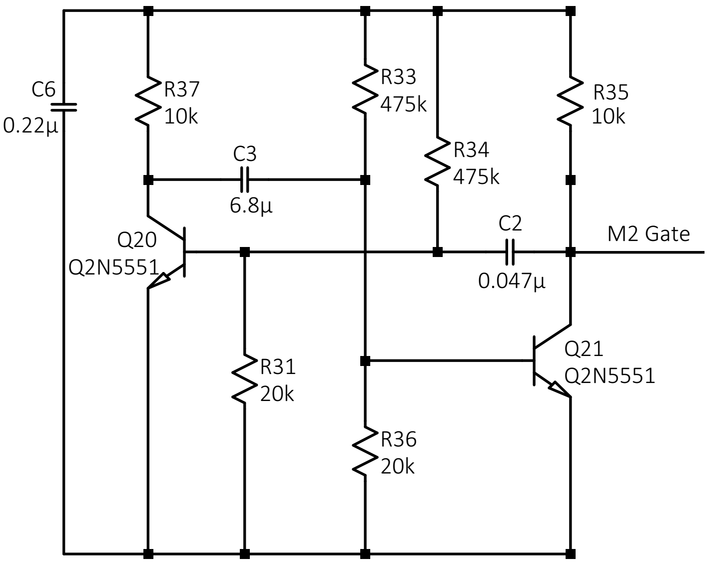


In the oscilloscope screen-capture of *Figure 2* the circuit is in shutdown mode for the first 4ms and then enters normal operation. Channel three (purple) is the amplifier's output, channel two (blue) is the voltage at the base of Q3, and channel one (yellow) is the negative supply rail.

1.4 THE OSCILLATOR

Figure 3 shows the oscillator used in this circuit. The Astable Multivibrator circuit consists of two switching transistors, a cross-coupled feedback network, and two time delay capacitors which allows oscillation between the two states with no external triggering to produce the change in state. This results in one stage conducting "fully-ON" (saturation) while the other is switched "fully-OFF" (cut-off) giving a very high level of mutual amplification between two transistors. Conduction is transferred from one stage to the other by the discharging action of a capacitor through a resistor.

Figure 3: The Oscillator

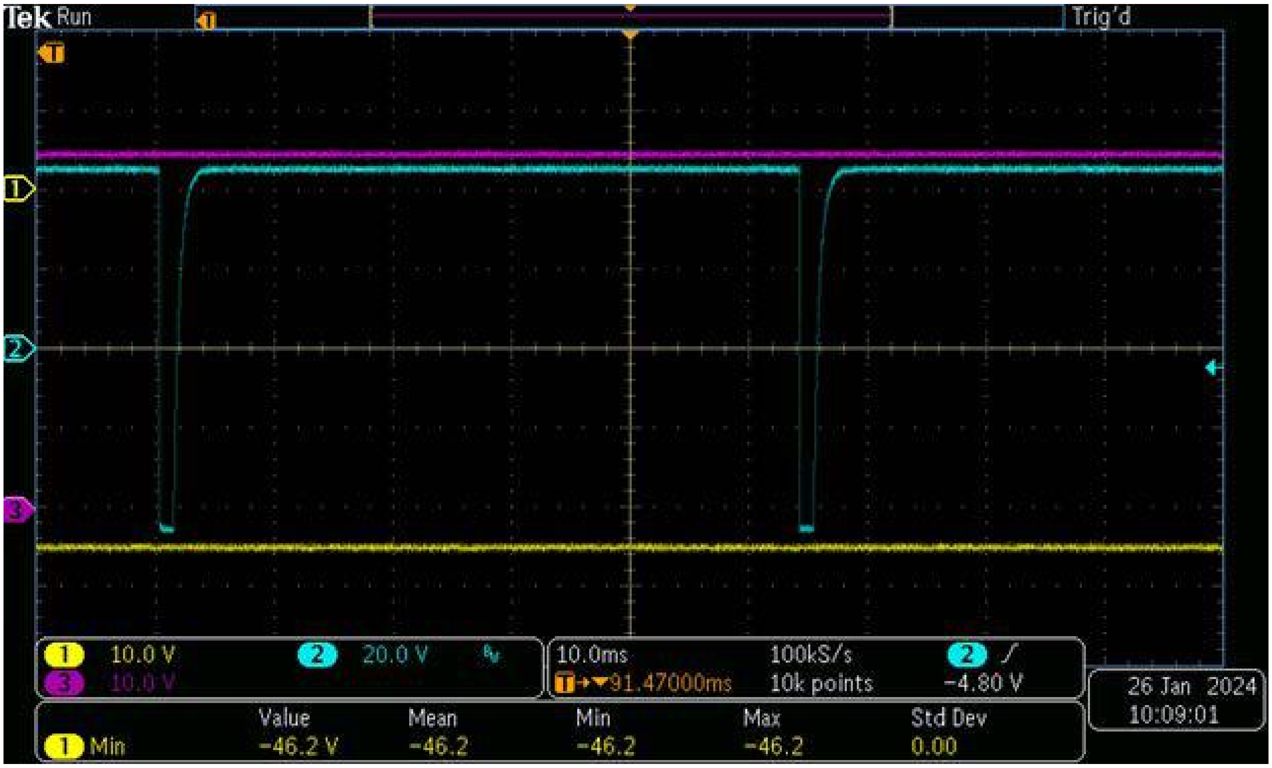


The oscillator and M2, an N-channel MOSFET, are used to reset the circuit. The gate of M2 is connected to the collector of Q21. When the voltage at the collector of Q21 is equal to the negative supply rail, M2 will turn off. Turning M2 off also turns off the SCR because the current flow has stopped. By turning off the SCR, the circuit is reset, and the amplifier is reconnected to the power supplies. The SCR will turn back on when the current limit is exceeded.

The oscillator, M2, and D2 can be replaced with a normally closed push button switch to act as a manual reset. The switch will supply current to the SCR once it has been turned on. Pressing the button will have the same effect as turning off M2.

In the oscilloscope screen-capture of *Figure 4*, channel three (purple) is the positive supply rail, channel two (blue) is the voltage at the gate of M2, and channel one (yellow) is the negative supply rail.

Figure 4: Voltage at the Gate of M2 with ±45V Supplies



Channel	Scale
1	10.0 V
2	20.0 V
3	10.0 V

10.0ms
T→▼91.47000ms
100kS/s
10k points
2 ∕ -4.80 V

	Value	Mean	Min	Max	Std Dev
1 Min	-46.2 V	-46.2	-46.2	-46.2	0.00

1.5 DISCONNECTING AND RECONNECTING THE AMPLIFIER

To understand how the circuit quickly turns U4 and M4 off there must be an understanding of Q2 and Q1. The 12V Zener, D8, keeps the base of Q2 twelve volts above the negative supply rail.

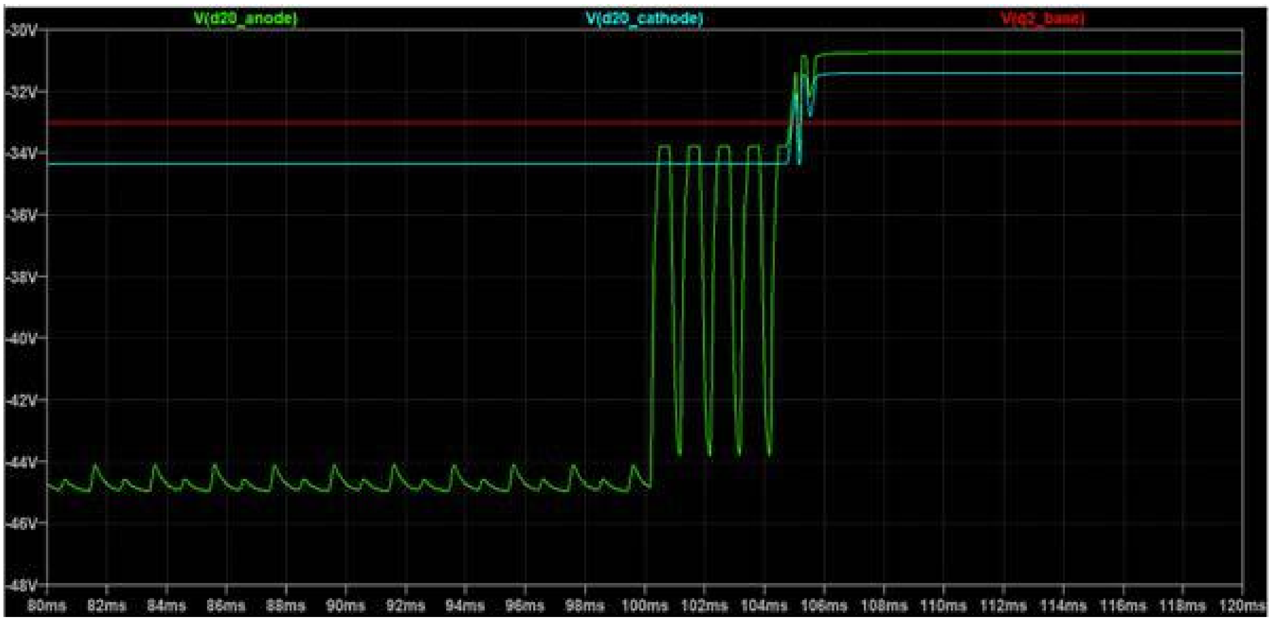
We can assume the supply voltages are ±45V. That means the voltage at the base of Q2 is -33V. There is a 0.7V drop across the base-emitter junction of Q2 and another 0.7V drop across D1. That means during normal operation the voltage at the cathode of D1 and D20 is -34.4V. D20 is reversed biased because Q3 is off and the voltage at the anode is equal to -45V.

Since the base of Q1 is directly connected to the collector of Q2, Q1 is only on if Q2 is conducting current. It's easy to see that Q1 is used to biased the high-current transistors U4 and M4. In conclusion, if Q2 is on then so is Q1 and subsequently U4 and M4 are also on, thus the amplifier is connected to the power supplies. If Q2 is off, the opposite is also true.

As explained in Section 1.3, when the set current limit is exceeded Q3 begins conducting current. During shutdown the voltage at the base of Q3 is -30V. With the 0.7V drop across Q3's base-emitter junction the voltage at the anode of D20 is -30.7V, so D20 is now forward biased. The 0.7V drop across D20 makes D1 reverse biased and turns off Q2. The technique of using the current through Q3 to quickly turn Q2 off is called current steering.

Figure 5 shows simulation results using ±45V supplies and showing the voltage at the base of Q2, cathode of D20, and anode of D20. The simulation was set to operate normally for the first 100ms, and after 100ms the current limit is activated.

Figure 5: Voltages Across D20 During Normal Operation and Current Limit with ±45V Supplies



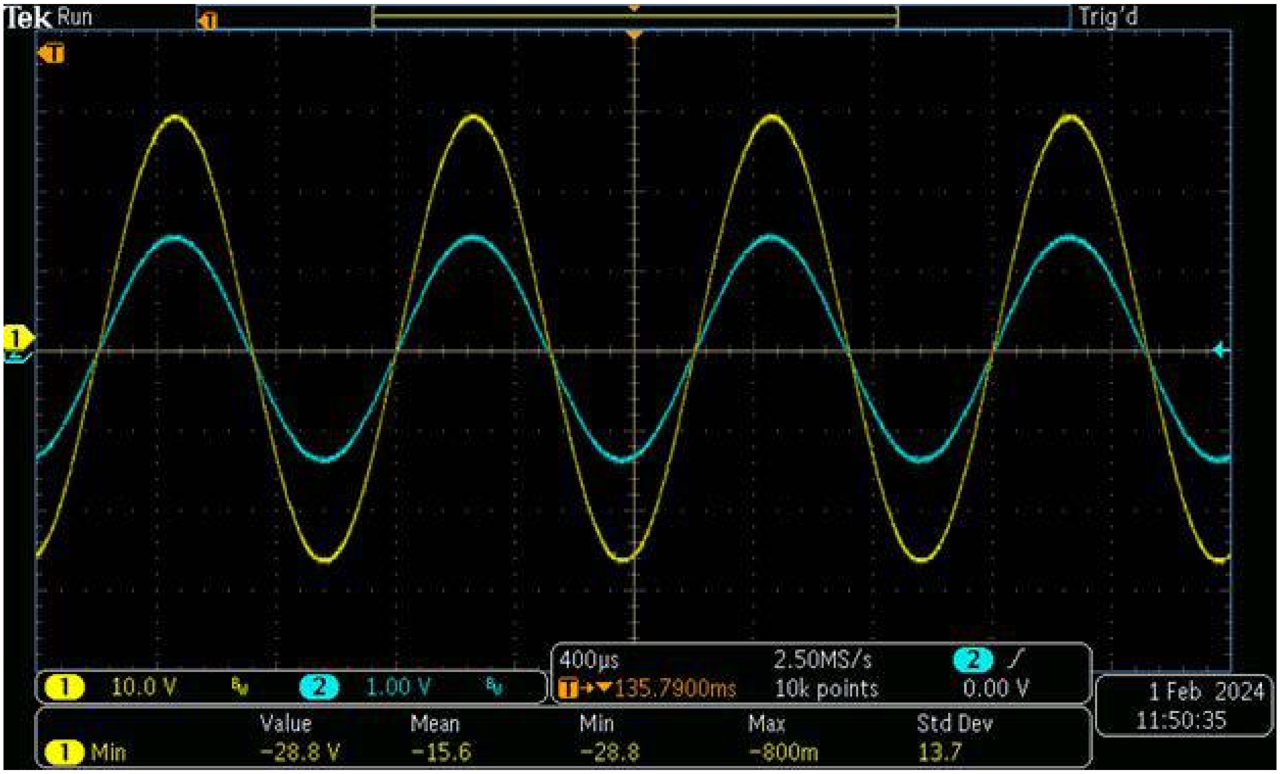
LAB RESULTS

The circuit of *Figure 1* was tested with the current limit set to 12A at different input frequencies. The amplifiers, PA50 and its high voltage counterpart PA52, were set in a noninverting configuration with a gain of 20. In every test the load consisted of four separate 300W-10Ω resistors connected in parallel for a total load of 2.5Ω. The amplifier's boost feature was not used on these tests. For each test, the oscilloscope screen-captures show the amplifier output (channel one, yellow), the amplifier's input (channel two, blue), and the gate voltage of M2 (channel three, purple). The test results are shown below.

TEST 1:

- Frequency: 1kHz
- Vsupply: ±38V
- Peak Shutoff Current: 11.6A
- Vout_max: 57.8Vpp
- Amplifier: PA50

Figure 6: Normal Operation at 1kHz



In *Figure 7*, the PA50 is in shutdown mode for the first 21ms, and there is no output from the amplifier. When the gate voltage of M2 is equal to -Vs, the amplifier is reconnected to the power supplies and the op-amp is back on. If the over-current situation has been addressed, the op-amp will continue to operate normally. In *Figure 7* the over current situation was not addressed and the op-amp reentered shutdown mode.

Figure 8 is a detailed oscilloscope screen-capture of the M2's gate voltage equal to -Vs. During this period the amplifier's output is not oscillating but amplifying the input signal. Also during this period, the circuit is checking whether the over-current situation has been addressed and normal operation can continue or if shutdown mode will be reentered.

Figure 7: Over-Current Shutdown Activated with a 1kHz Input

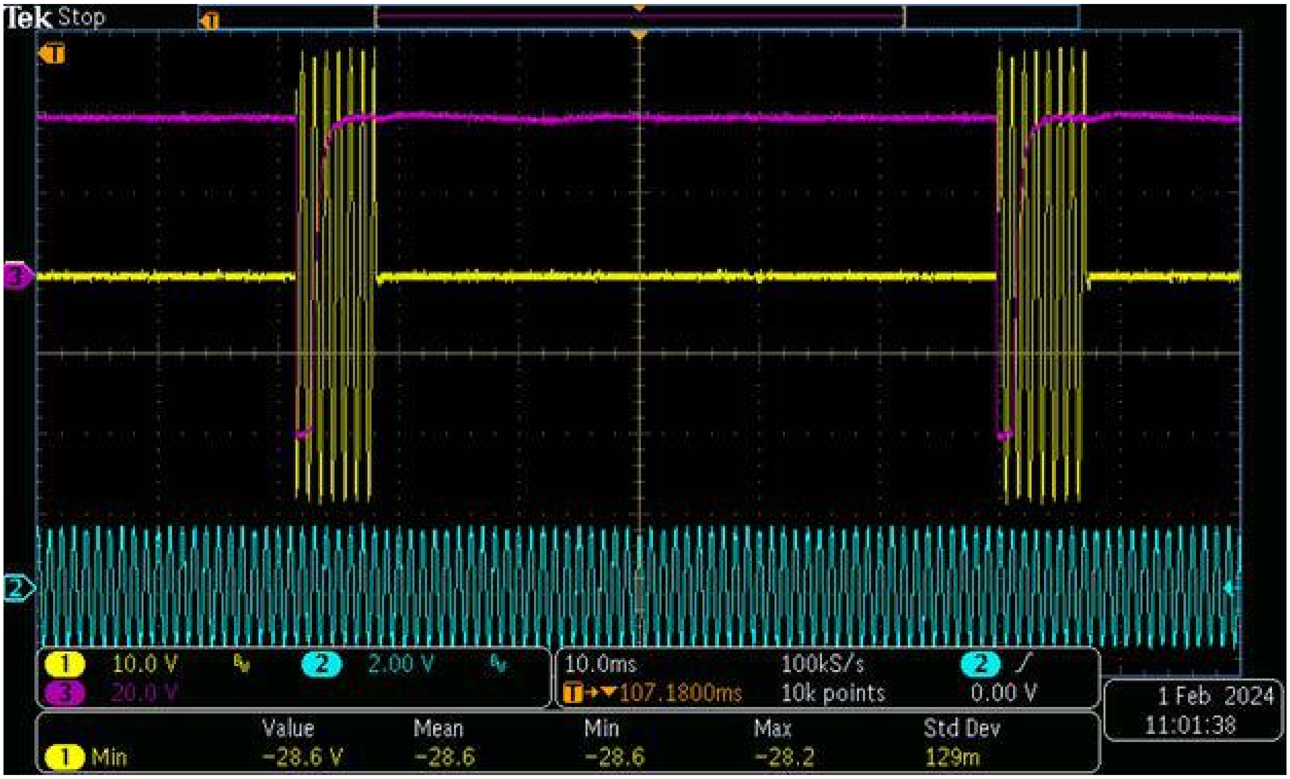
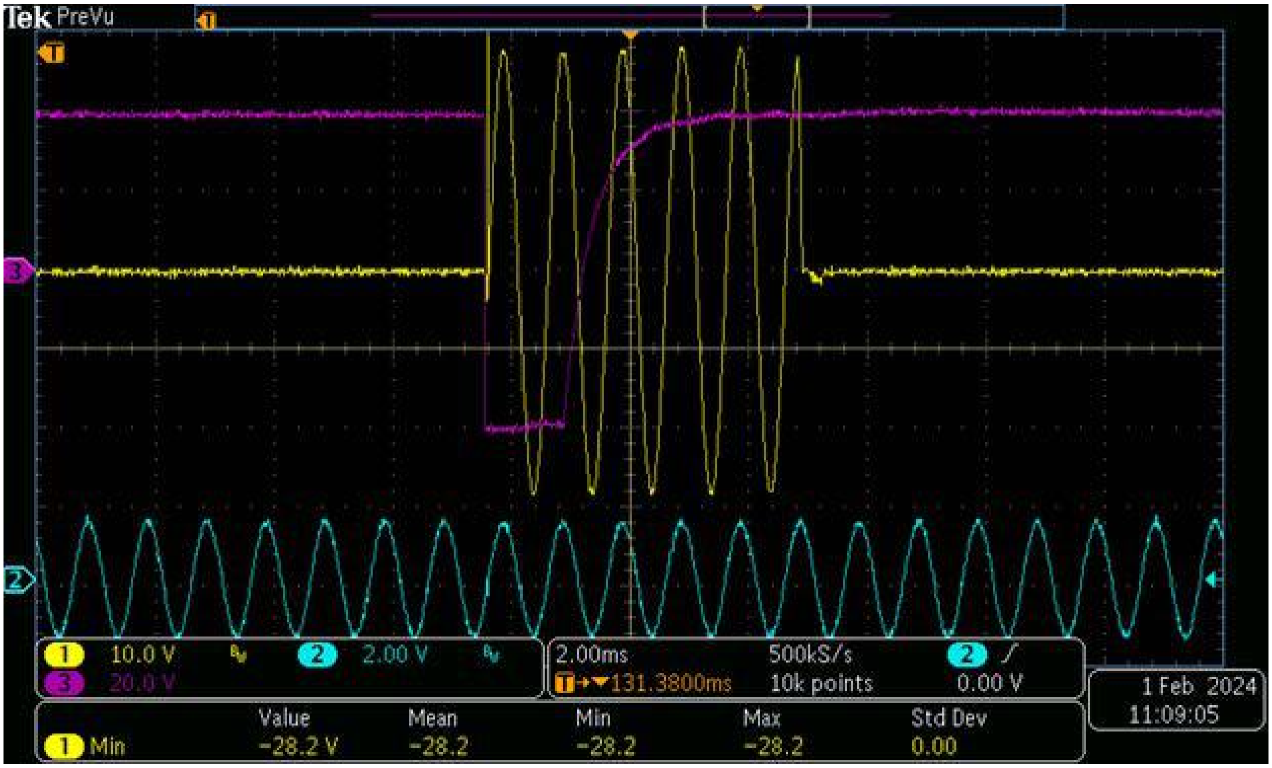


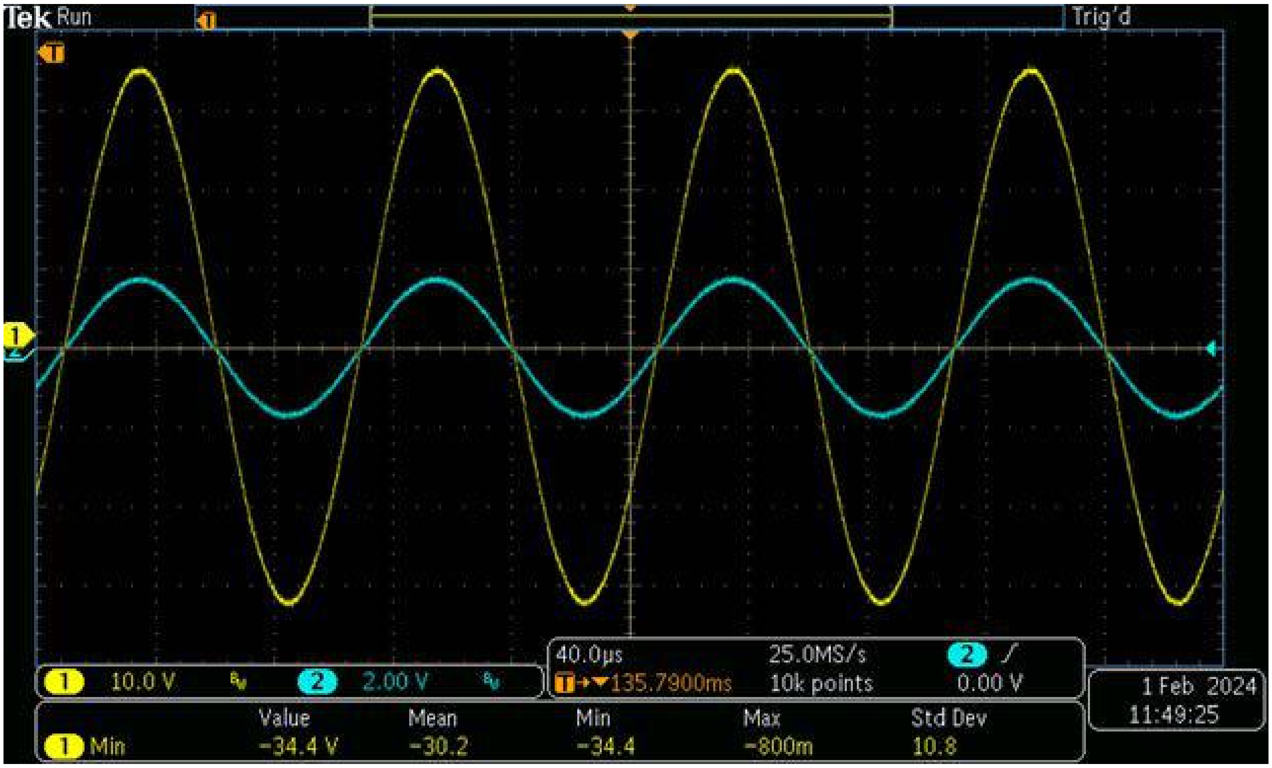
Figure 8: Close-up of the SCR Reset Period with a 1kHz Input



TEST 2:

- Frequency: 10kHz
- Vsupply: ±45V
- Peak Shutoff Current: 14.16A
- Vout_max: 70.6Vpp
- Amplifier: PA50

Figure 9: Normal Operation at 10kHz



	Value	Mean	Min	Max	Std Dev
1 Min	-34.4 V	-30.2	-34.4	-800m	10.8

Figure 10: Over Current Shutdown Activated with a 10kHz Input

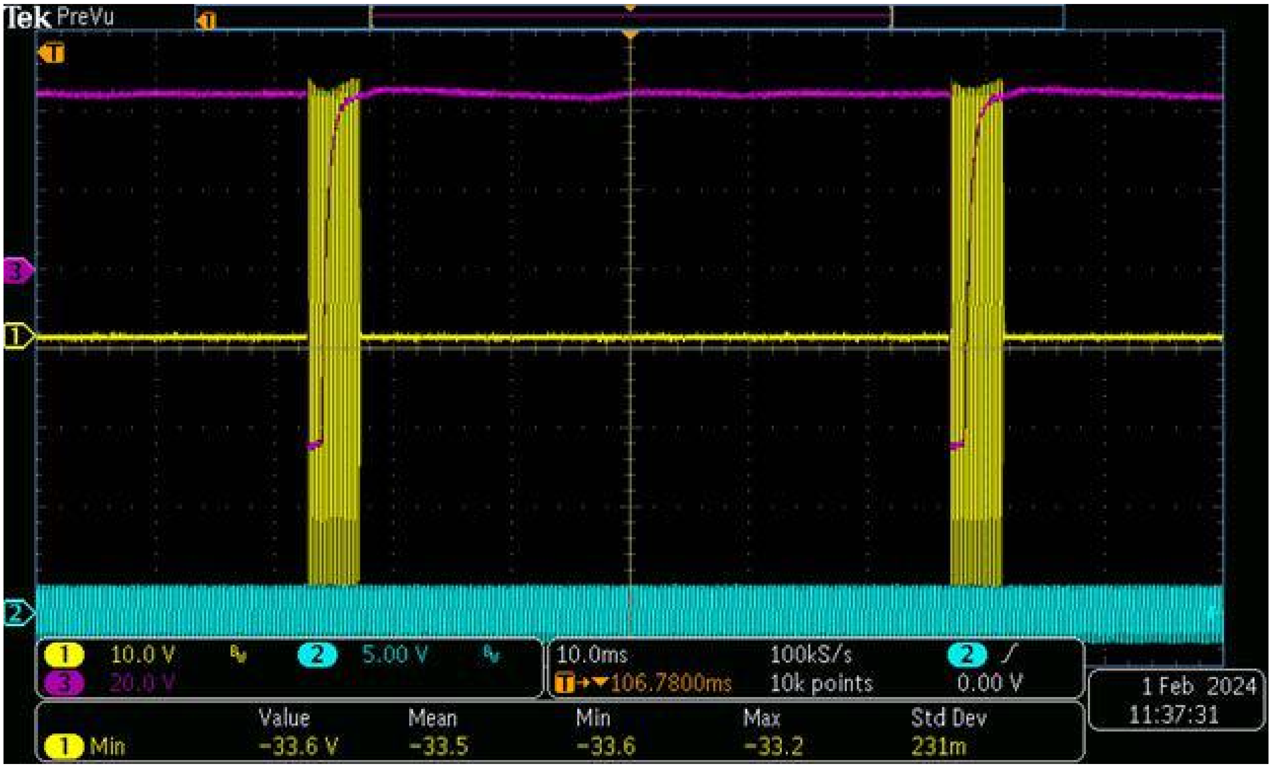


Figure 11: One Period of the SCR Reset with a 10kHz Input

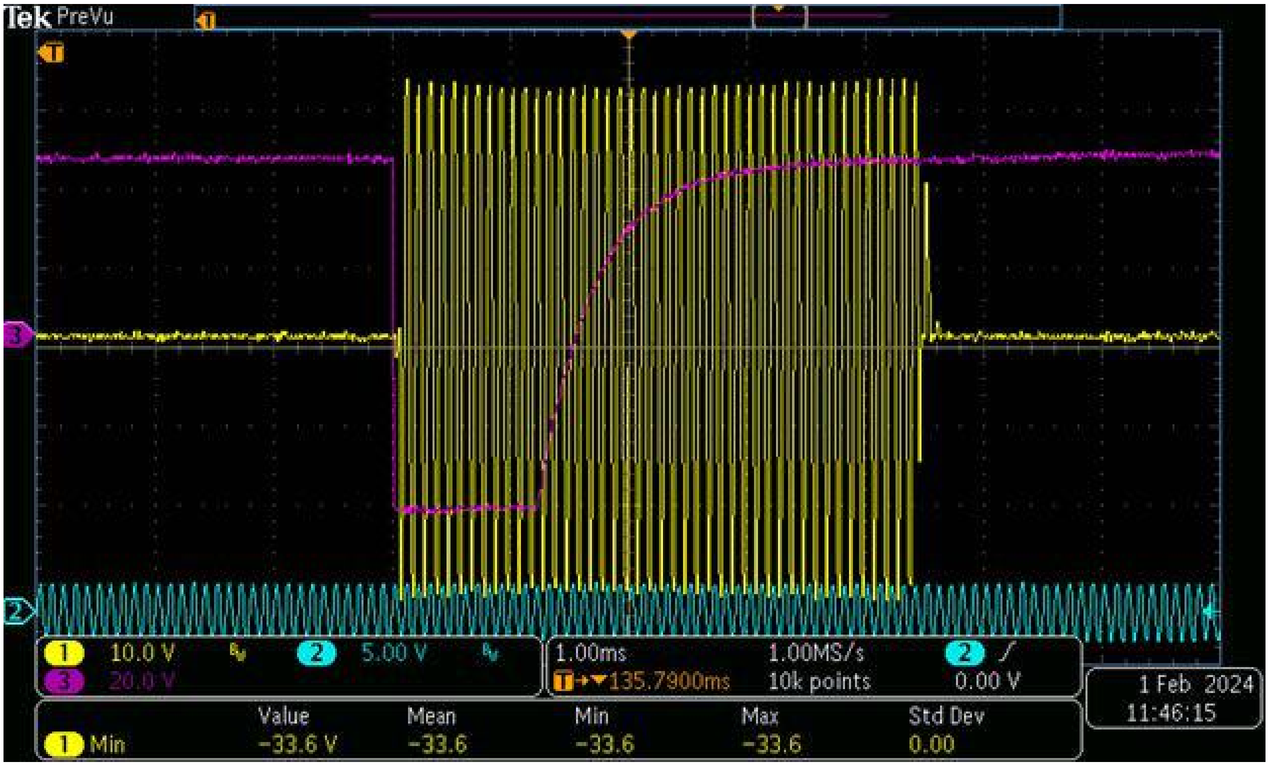
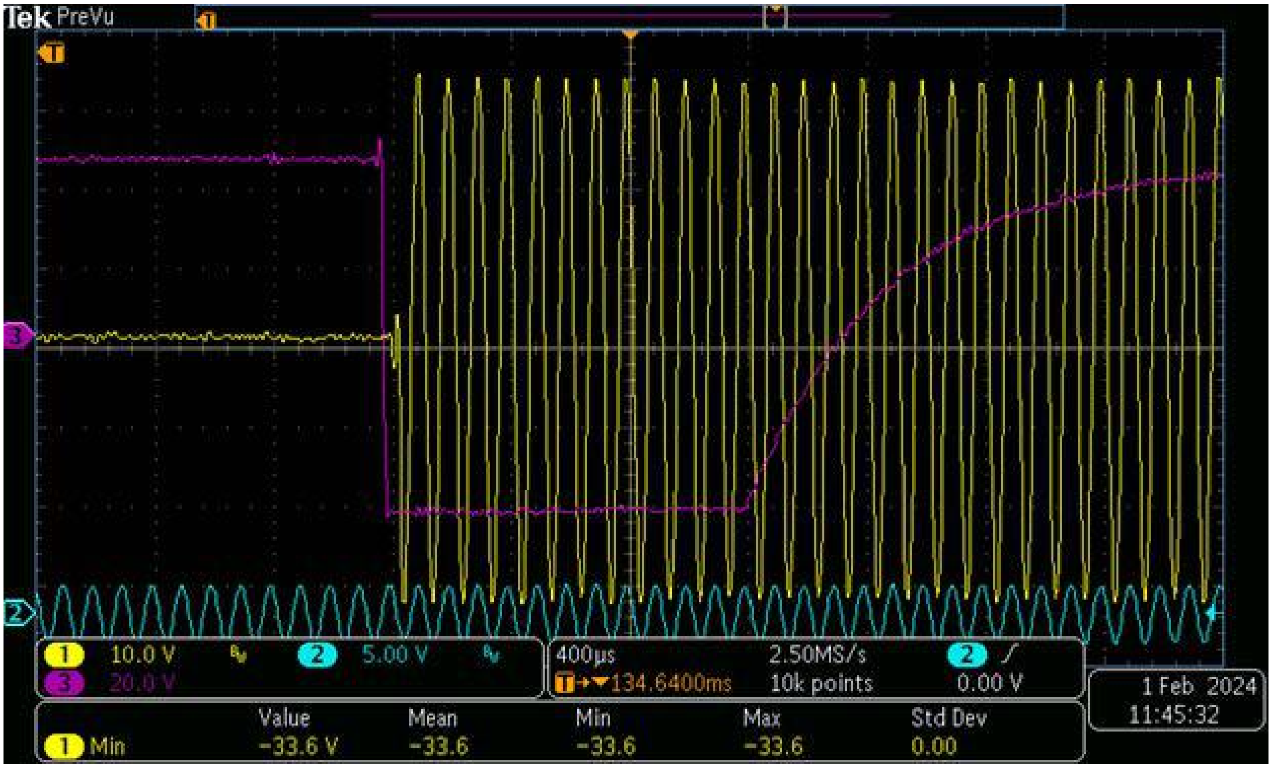


Figure 12: Close-up of the SCR Reset Period with a 10kHz Input



	Value	Mean	Min	Max	Std Dev
1 Min	-33.6 V	-33.6	-33.6	-33.6	0.00

TEST 3:

- Frequency: 50kHz
- Vsupply: ±80V
- Peak Shutoff Current: 25.8A
- Vout_max: 128.8Vpp
- Amplifier: PA52

Figure 13: Normal Operation at 50kHz

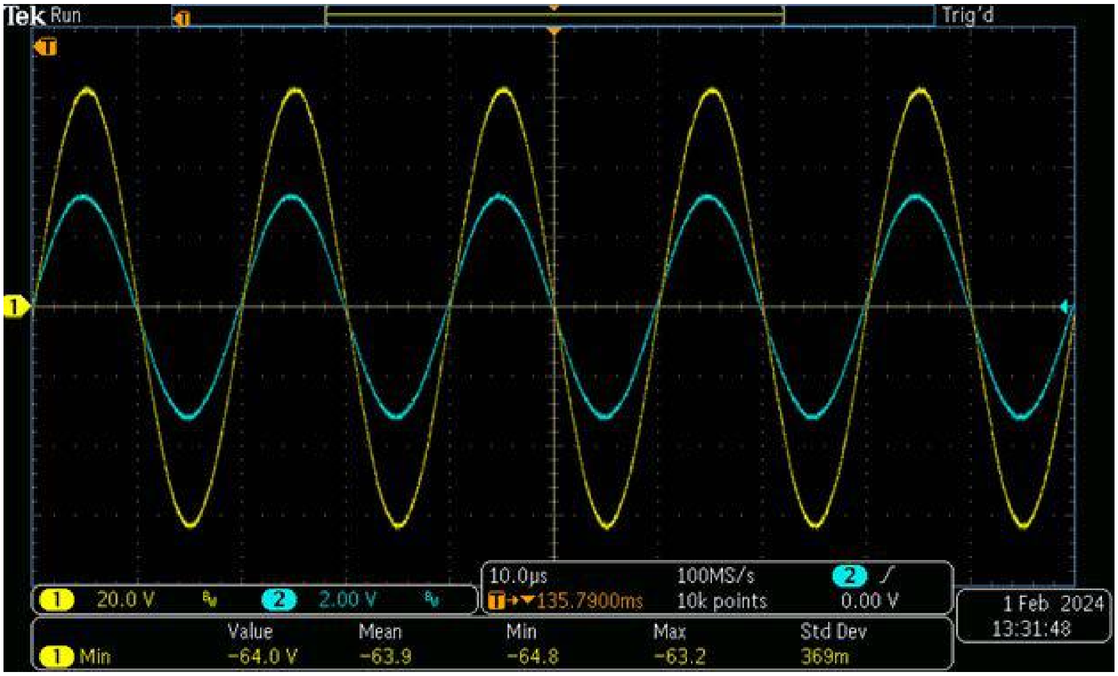


Figure 14: Over Current Shutdown Activated with a 50kHz Input

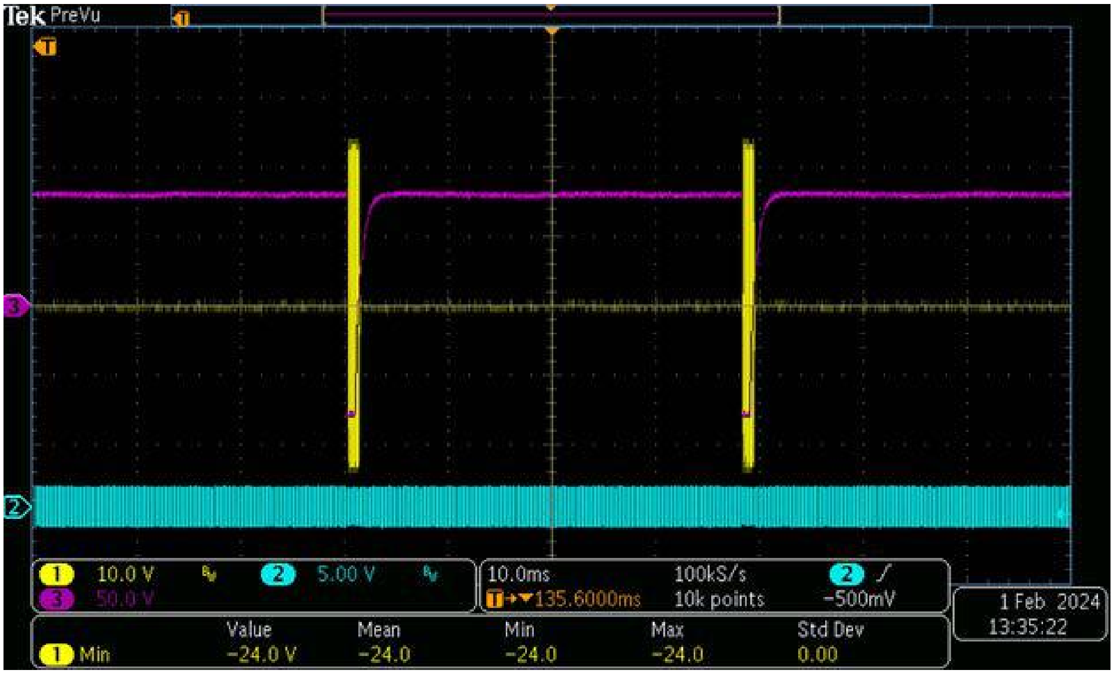


Figure 15: One Period of the SCR Reset with a 50kHz Input

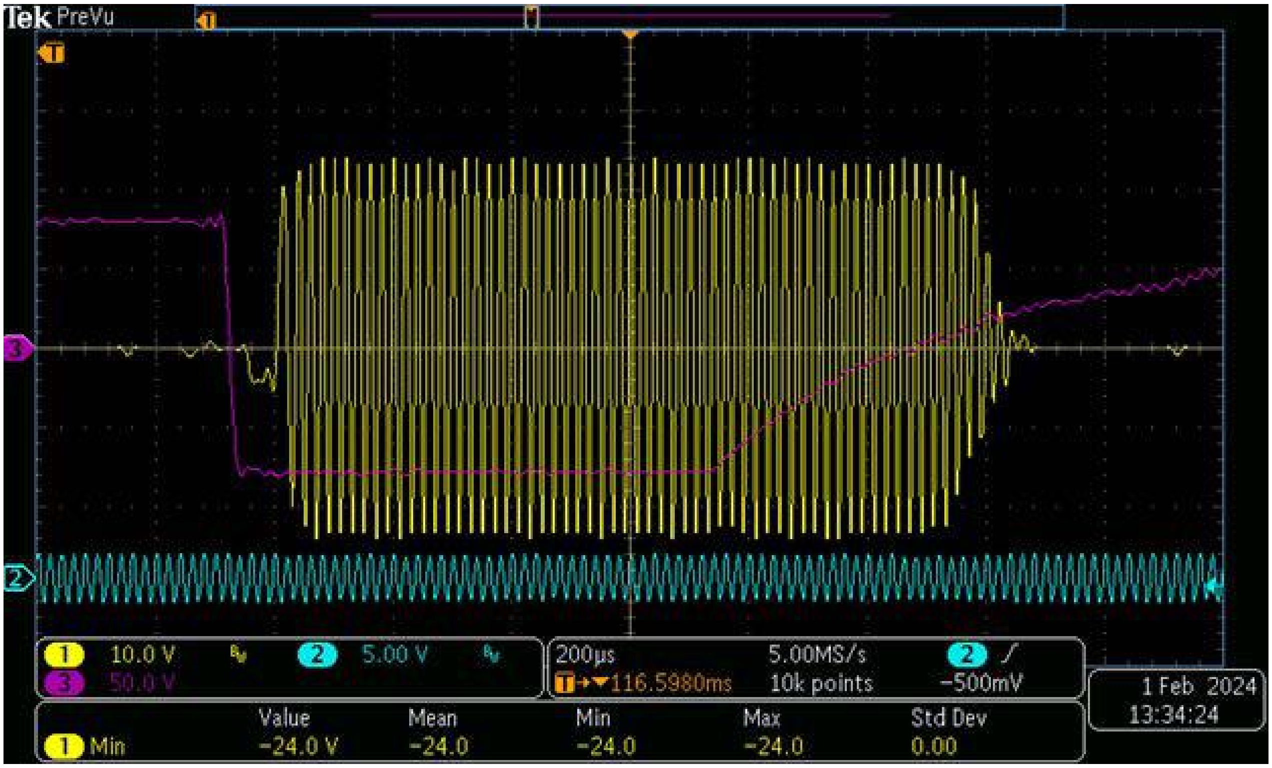
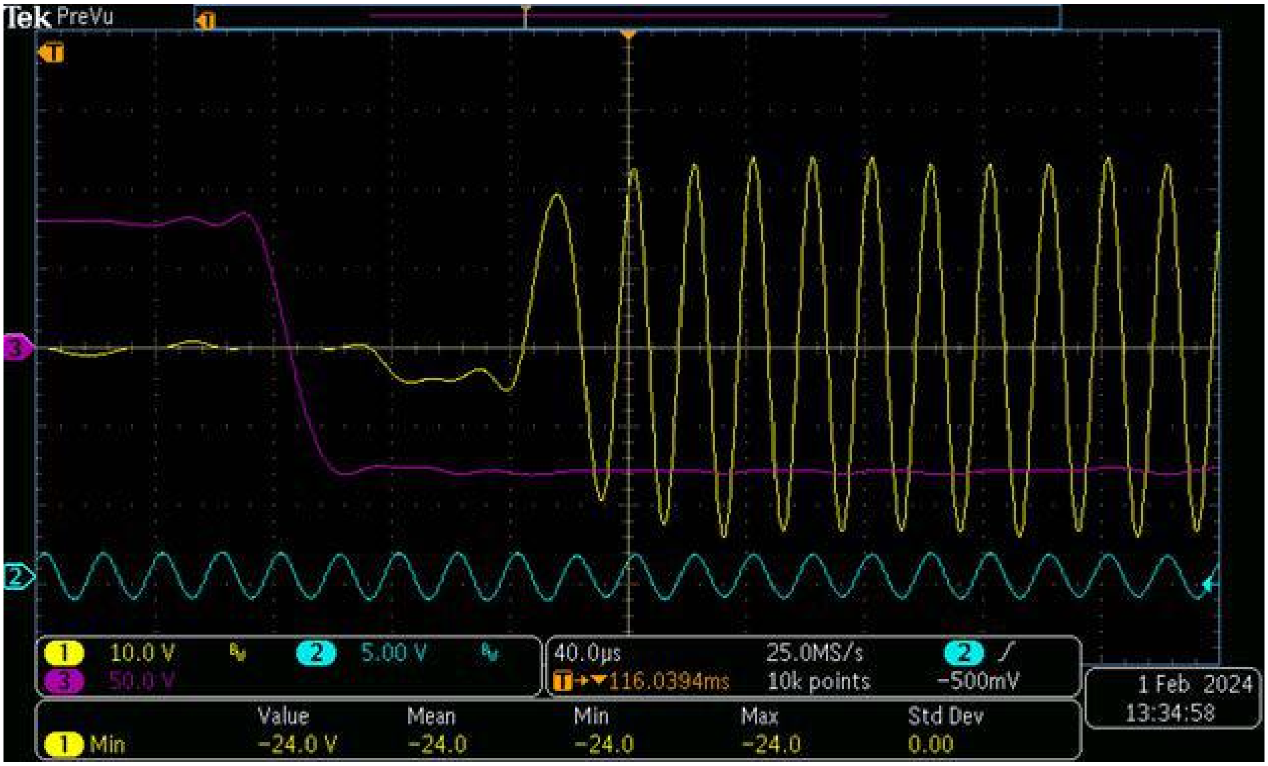


Figure 16: Close-up of the SCR Reset Period with a 50kHz Input



ANALYSIS

Earlier it was stated that the current limit is set by:

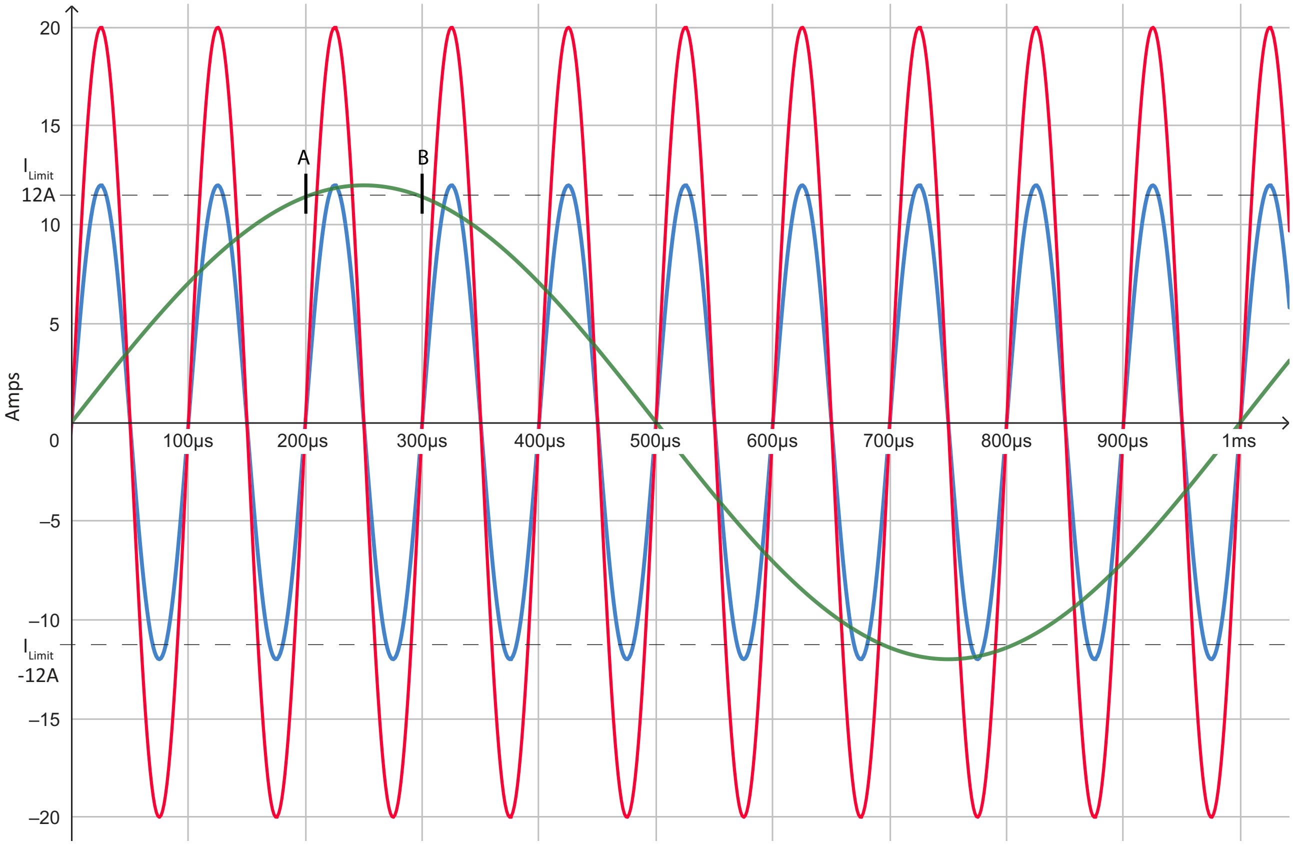
$$I_{Lim} = \frac{V_F}{R_{Lim}}$$

But the test results show that the peak current increased as frequency increased. With an input frequency of 1kHz the peak output current was 11.6A. The 400mA difference between the expected peak current of 12A and the actual peak current can be attributed to the forward-voltage of the H11D1. The typical forward-voltage of the optocoupler is 1.2V, so this value was used to set the current limit. Rearranging our current limit equation and solving for the actual forward voltage, the optocoupler's forward voltage is 1.16V.

It's easy to understand the discrepancy at 1kHz and its relationship to variations in forward voltages, but this does not explain the peak currents at 10kHz and 50kHz that far exceed 12A. To understand this phenomenon a closer look at Equation 1.0 is needed. Although Equation 1.0 seems to apply at low frequencies, the equation does not account for the optocoupler's turn on time. The peak current needs to be above the set current limit for a "certain amount of time" for the optocoupler to detect it. The "certain amount of time" can be called the detection time or $t_{detection}$.

At low frequencies $t_{detection}$ accounts for a very small portion of the sinusoidal period. Since the total period is significantly larger than $t_{detection}$, the optocoupler has enough time to turn on as soon as the op-amp's supply current is equal to the set current limit. Another way to think about this is that at lower frequencies the sine wave passes through its peak value a lot slower than it would at high frequencies, so there is enough time to detect this peak. Inversely, at higher frequencies the sine wave passes through its peak value faster and the optocoupler is not able to detect it. As a result, as frequency increases the peaks must be higher to allow the circuit enough time to detect an over-current situation.

Figure 17: Period of Time Exceeding I_{limit} vs Frequency and Amplitude



In *Figure 17* the green waveform is a 1kHz sine wave with a 12.5A peak. The blue sine wave is at a frequency of 10kHz with a 12.5A peaks, while the red is also at 10kHz but with 20A peaks. Although the green and blue waveforms have the same peak amplitude, the 1kHz signal exceeds the 12A current limit for a longer period. *Figure 17* illustrates how increasing the peak amplitude at 10kHz increases the amount of time the signal exceeds the 12A current limit.

Table 1: Detection Times Across Frequency with Current Limit set to 1.2A

Frequency (kHz)	$V_{in\ trip}$ (V_{pp})	$V_{out\ trip}$(V_p)	Peak Current (A)	$t_{detection}$ (µs)
2	1.12	11.2	1.12	42.67
3	1.14	11.4	1.14	31.68
4	1.16	11.6	1.16	29.73
5	1.18	11.8	1.18	26.39
6	1.2	12	1.2	23.93
7	1.22	12.2	1.22	22
8	1.25	12.5	1.25	20.99
9	1.27	12.7	1.27	19.6
10	1.29	12.9	1.29	18.42
15	1.43	14.3	1.43	15.17
20	1.59	15.9	1.59	13.11
25	1.76	17.6	1.76	11.59
30	1.96	19.6	1.96	10.48
35	2.16	21.6	2.16	9.52
40	2.36	23.6	2.36	8.71
45	2.59	25.9	2.59	8.06
50	2.82	28.2	2.82	7.49

Table 2: Detection Times Across Frequency with Current Limit set to 12A

Frequency (kHz)	$V_{in\ trip}$ (Vpp)	$V_{out\ trip}$(Vp)	Peak Current (A)	$t_{detection}$ (µs)
2	2.95	29.5	11.8	41.55
3	2.98	29.8	11.92	31.46
4	3.05	30.5	12.2	28.97
5	3.12	31.2	12.48	26.67
6	3.19	31.9	12.76	24.72
7	3.26	32.6	13.04	23.06
8	3.34	33.4	13.36	21.83
9	3.43	34.3	13.72	20.87
10	3.54	35.4	14.16	20.21
15	3.98	39.8	15.92	16.4
20	4.42	44.2	17.68	13.85
25	4.68	46.8	18.72	11.67
30	4.76	47.6	19.04	9.86

Detection times were measured starting at 2kHz up to 30kHz for a 12A peak and up to 50kHz for a 1.2A peak. The detection times were within 2µs of each other even though the set current limits were an order of magnitude different. As frequency increased the detection time became shorter. This implies that there's a second variable besides $t_{detection}$ that equation 1.0 does not consider.

When the voltage across the optocoupler's internal LED is greater than the LED's forward voltage the optocoupler turns on. The higher peaks that result from higher frequencies translate to a greater forward voltage. This turns on the optocoupler harder and reduces $t_{detection}$.

Precisely setting the current limit for this circuit is not as straight forward as equation one suggests and would require an in-depth analysis of the optocoupler that is far beyond the scope of this application note, but even without precisely setting the current limit the op-amp is still protected for two reasons. The PA50 and PA52 can handle peak currents up to 100A for 1.0ms. As shown in tables one and two, the circuit is shut off within 10's of microseconds, so the power amplifiers are protected against peak-transient-currents. Secondly, the introduction of this application note discussed the power dissipation issue that arose from conventional current limit techniques. The power that is generated using conventional current limit techniques can pose a threat to power amplifiers overheating. The technique covered in this application note does not pose a thermal threat to power amplifiers.

APPENDIX A: CALCULATING DETECTION TIME

The value of a sine wave at any point in time can be calculated with the following equation

2. 0

$$I_{instantanious} = I_{peak} \times \sin(\omega \times t)$$

ω = angular frequency = 2π*f
t = time (seconds)

For any sinusoidal wave the first peak always occurs at T/4 where T is the period. Referring to *Figure 17*, the sine wave exceeds I_{Limit} at some point before T/4 and crosses below I_{Limit} after T/4. If the peak current occurs at half the detection time or $t_{detection}/2$, then points A and B in *Figure 17* are equal distance from T/4. By rearranging equation 2.0 it is possible to know the time that point A occurs. This is shown below:

2.1

$$t_{pointA} = \frac{arc\sin\left(\frac{I_{Limit}}{I_{peak}}\right)}{\omega}$$

Since the time between point A and T/4 is equal to half the detection time, $t_{detection}$ can be found using equation 3.0

3.0

$$t_{detection} = 2\left(\frac{T}{4} - t_{pointA}\right)$$

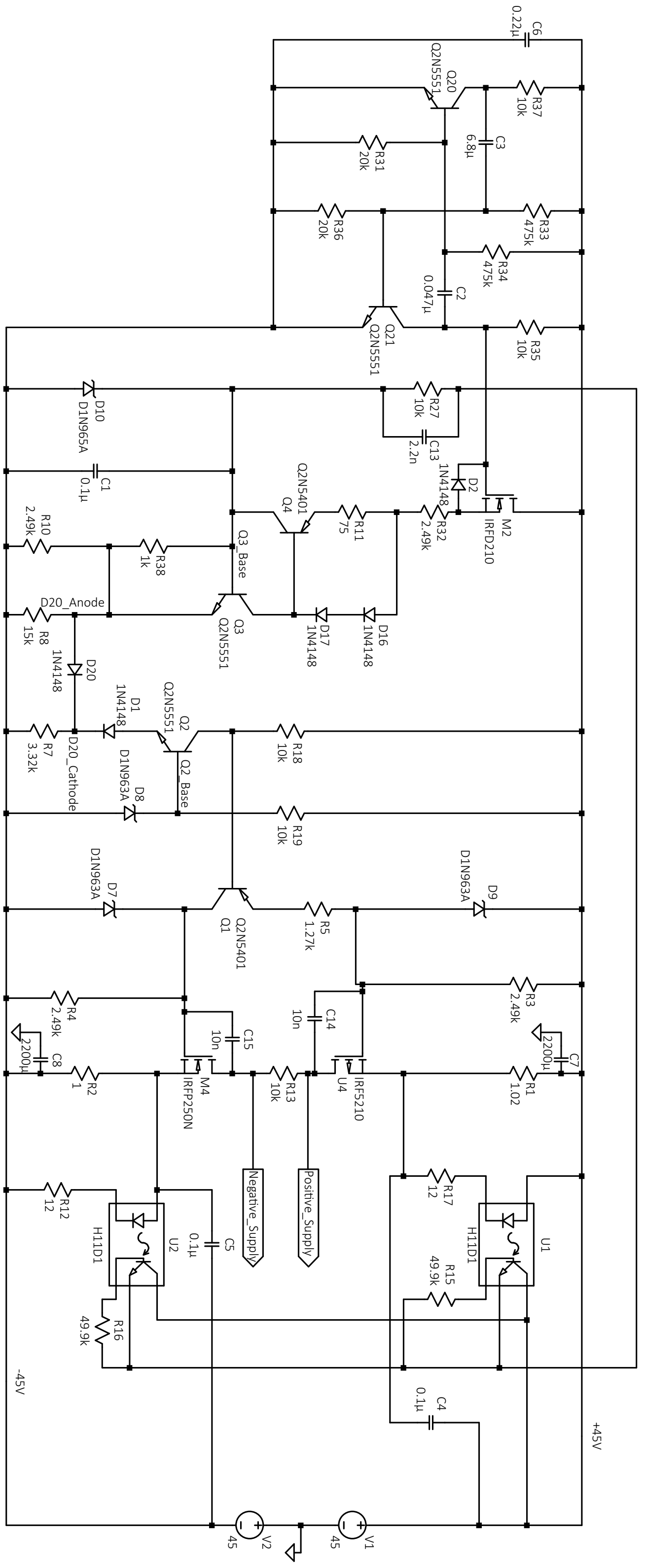
Below are the calculations for finding the detection time at 10kHz with the theoretical current limit set to 12A. Note that in table one the detection times were calculated with I_{Limit} equal to 1.08A and in table two I_{Limit} is equal to 11.4A. The expected current limits were 1.2A and 12A respectively, but due to variations in forward voltages the true current limit needed to be found on the bench. This was done using a 100hz sine wave and increasing the input signal until the current limit activated.

$$t_{detection} = 2\left(\left(\frac{T}{4}\right) - \frac{arc\sin\left(\frac{I_{Limit}}{I_{peak}}\right)}{\omega}\right) = 2\left(\left(\frac{100\mu s}{4}\right) - \frac{arc\sin\left(\frac{11.4A}{14.16A}\right)}{2\pi \times 10000}\right) = 20.21\mu s$$

APPENDIX B: BILL OF MATERIALS

Ref.	Description	Value
C1	capacitor	100nF
C2	capacitor	47nF
C3	capacitor	6.8µF
C4	capacitor	100nF
C5	capacitor	100nF
C6	capacitor	220nF
C7	capacitor	2.2mF
C8	capacitor	2.2mF
C13	capacitor	2.2nF
C14	capacitor	10nF
C15	capacitor	10nF
D1	1N4148	
D2	1N4148	
D7	D1N963A	
D8	D1N963A	
D9	D1N963A	
D10	D1N965A	
D16	1N4148	
D17	1N4148	
D20	1N4148	
M2	IRFD210	
M4	IRFP250N	
Q1	Q2N5401	
Q2	Q2N5551	
Q3	Q2N5551	
Q4	Q2N5401	
Q20	Q2N5551	
Q21	Q2N5551	
R1	resistor	
R2	resistor	
R3	resistor	2.49K
R4	resistor	2.49K
R5	resistor	1.27K
R7	resistor	3.32K
R8	resistor	15K
R10	resistor	2.49K
R11	resistor	75
R12	resistor	12
R13	resistor	10K
R15	resistor	49.9K
R16	resistor	49.9K
R17	resistor	12
R18	resistor	10K
R19	resistor	10K
R27	resistor	10K
R31	resistor	20K
R32	resistor	2.49K
R33	resistor	475K
R34	resistor	475K
R35	resistor	10K
R36	resistor	20K
R37	resistor	10K
R38	resistor	1K
U1	H11D1	
U2	H11D1	
U4	IRF5210	

APPENDIX C: SCHEMATIC



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