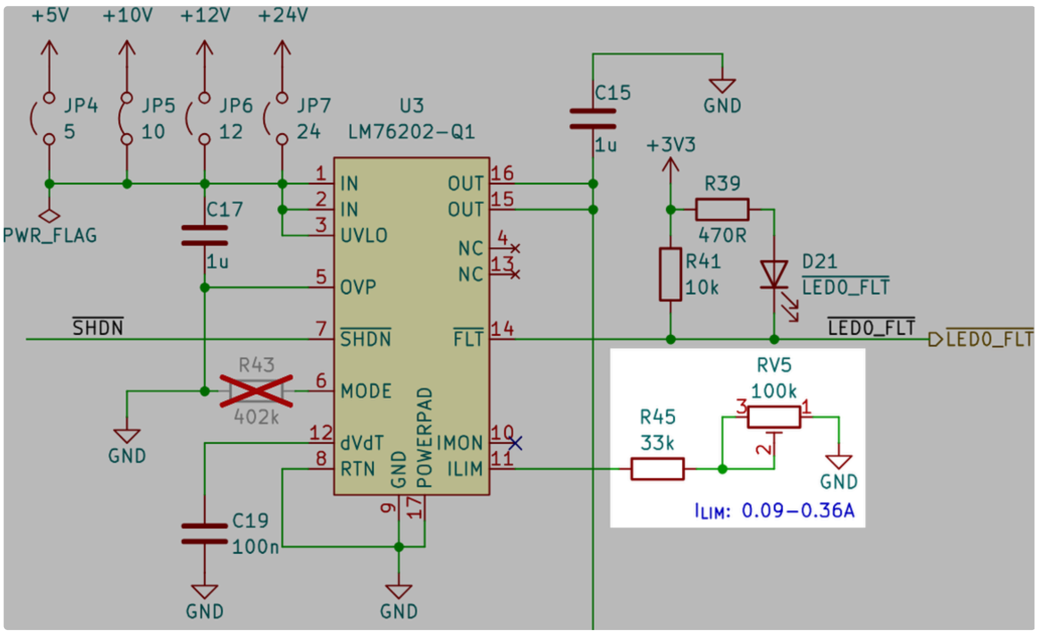
LED Current-Limiting Fuse Problem

The LED Driver in the Functional Controller has a redundancy in which an increase the LED current above a safe limit is stopped by an electronic circuit breaker. The chip LM76202-Q1 is used for this purpose and the circuit is described in Functional Controller v2giga | Schematics: LED Driver. The problem is that during the verification tests we always find that the resistor setting the threshold current is far smaller than what the datasheet says.

Description of the Problem

The schematic diagram below shows the circuit-breaker schematics. The important parts for setting the maximum current are the resistor R45 (33 kΩ) and trimmer RV5 (100 kΩ) highlighted in the schematics.



Schematic diagram of the circuit-breaker with the highlighted current-setting resistors.

The LM76202-Q1 datasheet gives the calculation for the circuit-breaker threshold $I_{(CB)}$ in equation 5. The equation assumes current $I_{(CB)}$ in Amperes and current-limiting resistor $R_{(ILIM)}$ in kilo-Ohms:

$$I_{(CB)} = \frac{12}{R_{(ILIM)}} + 0.03A$$

Equation 5 from LM76202-Q1 datasheet.

We are setting the current threshold just above 0.110 A as described in FLIO Controller v2 Pre-Assembly Test Protocol | Set Maximum LED Current to 110 mA. In four tested devices we found that the trip current was achieved with a resistance of RV5 between 49 kΩ and 50 kΩ for all the devices. This value if far off (0.11 A) from what it should be according to Equation 5 in the LM76202-Q1 datasheet (0.27 A).

$$I_{(CB)} = 12 / 50 + 0.03 \text{ A} = 0.27 \text{ A}$$

It is a problem that we do not understand why we are repeatedly finding the current-limiting trimmer value being widely different from the predictions of the datasheet. Therefore, a series of verifications were done to ensure the circuit-breaker works as designed.

Verification of Circuit Breaker Function

The basic function of the circuit breaker is to cut supply to the load circuit if the total current exceeds the limit.

Testing Step Increase in Current

The test protocol is described in FLIO Controller v2 Pre-Assembly Test Protocol | Test Maximum Current Limit Fuses. In brief, the powered circuit is programmed for LED current of 0.115 A (or 5 mA above the threshold). The LED is rapidly turned on and the circuit breaker trips as designed. In each of the tested boards, the circuit breaker indeed tripped, so it works as designed, despite the resistance of the current threshold-setting resistor not being in accordance with the datasheet.

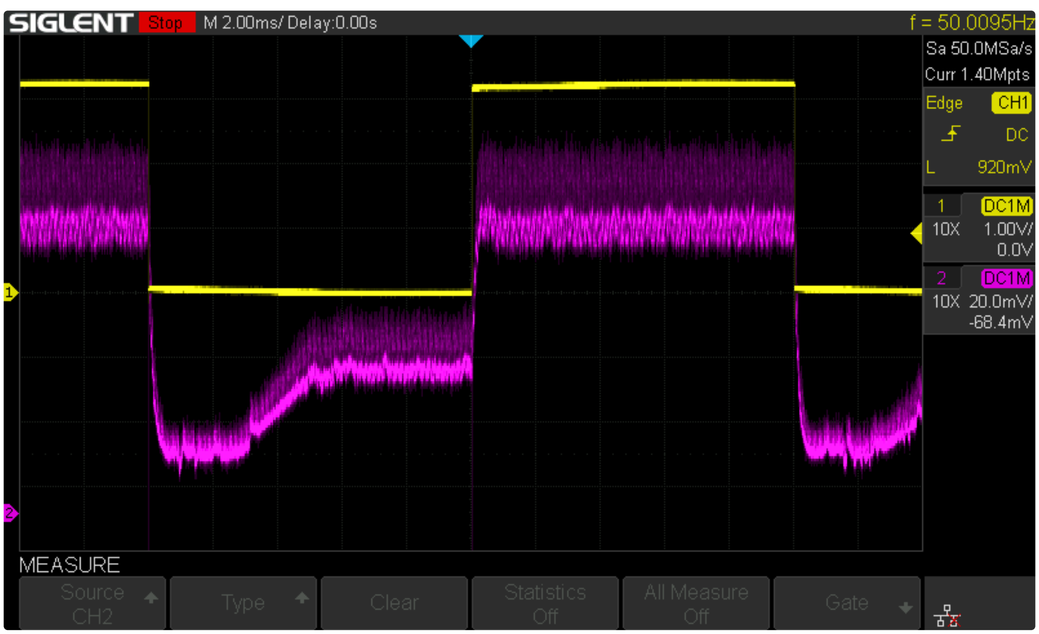
Further Investigation

The output of the circuit breaker is bypassed by large capacitors (110 µF), which draw current on power up. It could be that the turn on of the LEDs leads to Voltage droop and the subsequent recharge of the bypass capacitors transiently increases the current draw. It could be that there is a large overshoot that trips the circuit breaker. To verify whether any of these effects could be causing increased current draw a series of tests were designed and are outlined below.

Checking for Sudden Current Increase

Current Monitoring with the TPS259474

The Safety Controller supplying power to the Functional Controller board has power monitoring circuits TPS259474, which allow the measurement of current each power supply branch. Oscilloscope was connected with channel 1 (yellow) to the LED0_ENABLE signal and with channel 2 (purple) to the I_{10V} current monitoring test point TP12.



Active high LED enable signal (yellow). I_{10V} current monitor signal (purple).

The current through the TPS259474 chip is calculated from the equation 9 below. In our case, R_{ILM} is 4220 Ω. G_{IMON} is specified by the datasheet to be 180 µA/A (limits 160 µA/A to 200 µA/A), suggestion a ~20 % error in the measurement.

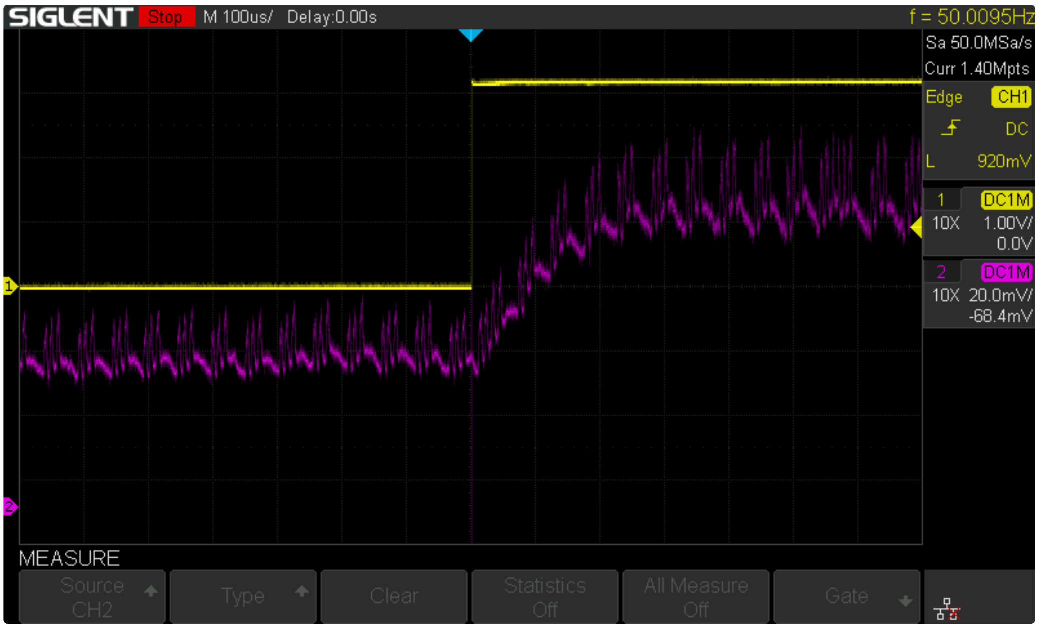
$$I_{OUT}\,(A) = \frac{V_{ILM}\,(\mu V)}{R_{ILM}\,(\Omega) \times G_{IMON}\,(\mu A/A)}$$

Equation 9 in TPS259474 datasheet

The oscilloscope curve shows the current monitor output being noisy. Even with nearly zero current draw, when the LED enable signal is LOW, the circuit gives ~20 mV output Voltage. Using the above equation, it suggests a current of 27 mA. This is probably the base consumption of the microcontroller board, which is not controlled by the circuit breaker, but shares the same power supply. It forms an offset that should be subtracted from the result. When the LED is enabled, the Voltage is ~90 mV, which is equivalent to 119 mA, by subtracting the 27 mA offset, we get ~95 mA. This is within the accuracy TPS259474 with the programmed LED current of ~90 mA.

There is no obvious current spike measured on the I_{10V} current monitoring test point TP12 when the LED is turned on. This could be because the current monitor is too slow to capture it or because there is no current surge when the LED is turned on or both.

Zooming on the rising-edge transition reveals that the current monitor in the TPS259474 is slow to capture a fast current transient if it was present. The current certainly rises much quicker than the ~200 µs it takes the TPS259474 chip to report it.

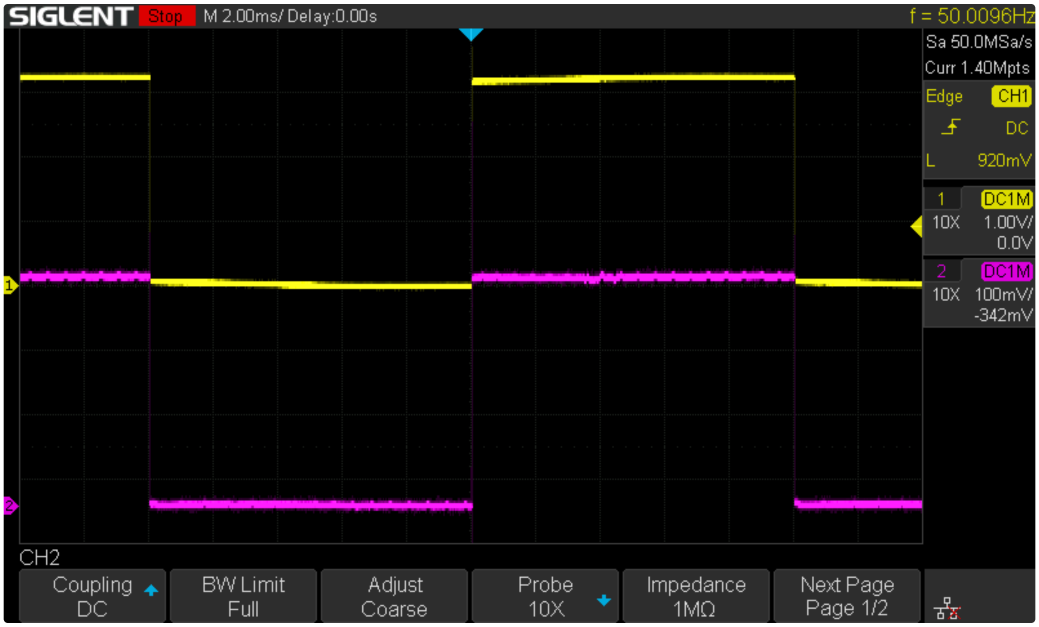


LED on transition (yellow) and gradual rise of Voltage on the I_{10V} current monitor test point.

In conclusion, the TPS259474 chip is too slow in its response to verify whether there is an inrush current on the LED driver that could trip the circuit breaker.

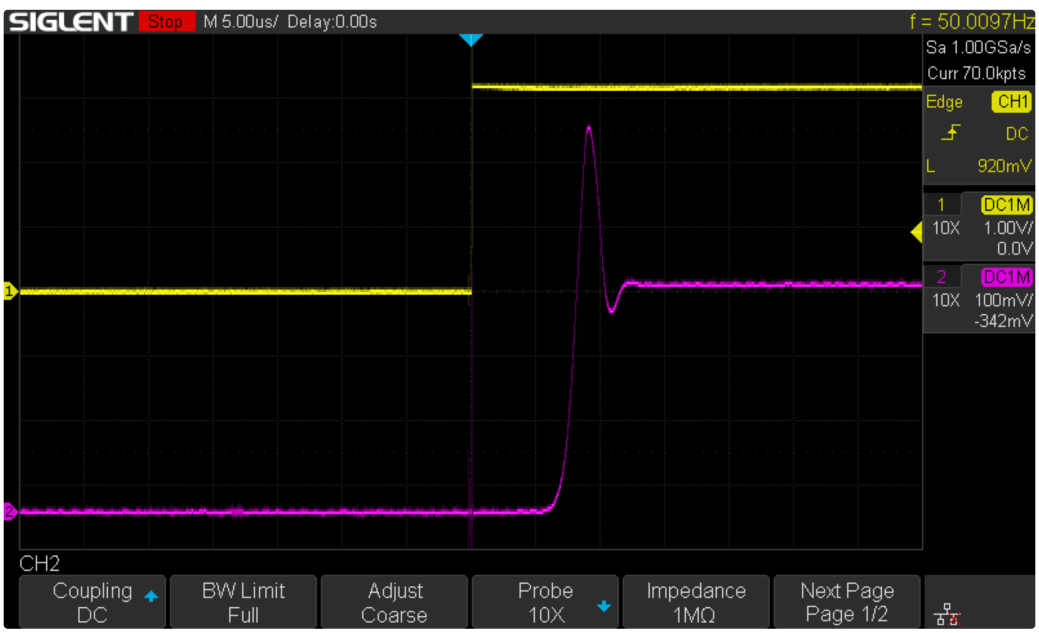
Current Monitoring with the Current Sense Resistor

The current sense resistors in the LED driver can be used to monitor the current through the LED, but it cannot measure any extra current flow to parts like the bypass capacitors. The oscilloscope was connected to the LED enable signal with channel 1 (yellow) and to the 3.9 Ω current sense resistor R61 with channel 2 (purple).



LED enable signal (yellow). LED current (purple)

The above oscilloscope measurement shows that the LED current is nice and square at ~ 96 mA, consistent with the measurement using the [TPS259474] chip current monitor capability discussed above. Zooming in on the rising edge reveals a short (~5 µs) spike in the current consumption. The spike peaks at ~150 mA. However the circuit breaker should not trip on this spike. It has a 4 ms FLT assertion delay $t_{CB(dly)}$ in circuit breaker mode. Furthermore, the bypass capacitors are going to take most of the current spike away from the circuit breaker and the chip will not experience such high current increase as seen on the oscilloscope. It will be a small-hardly measurable wobble. The capacitor current draw cannot be measured on the PCB, but the Voltage on the capacitor can and is done in the next step.

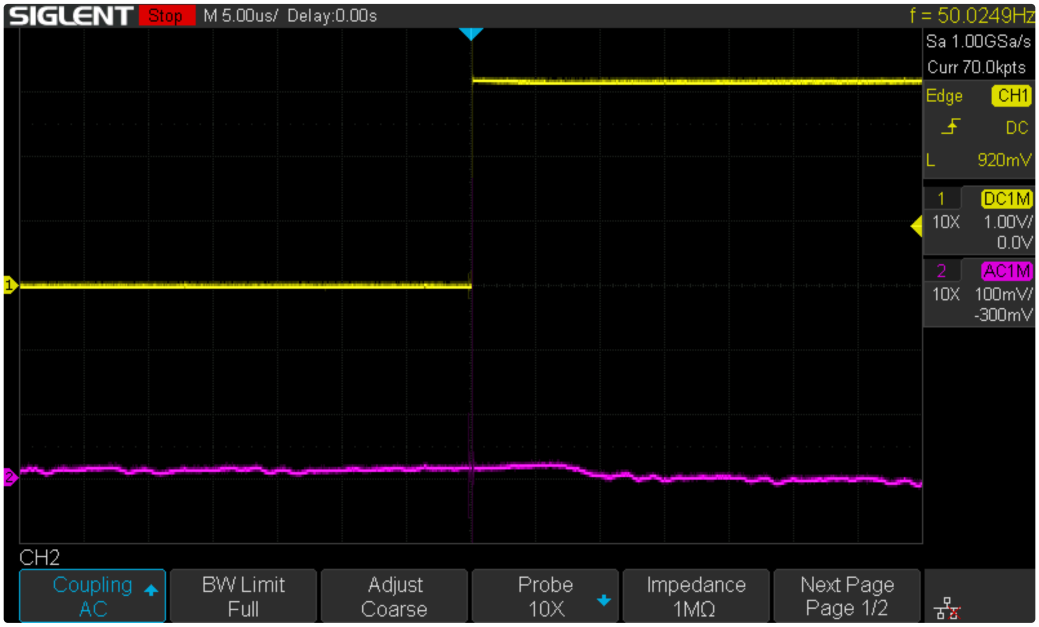


LED enable signal (yellow). LED current (purple)

In conclusion, there appears to be indication of substantial in-rush current into the LED that should cause the circuit breaker to trip.

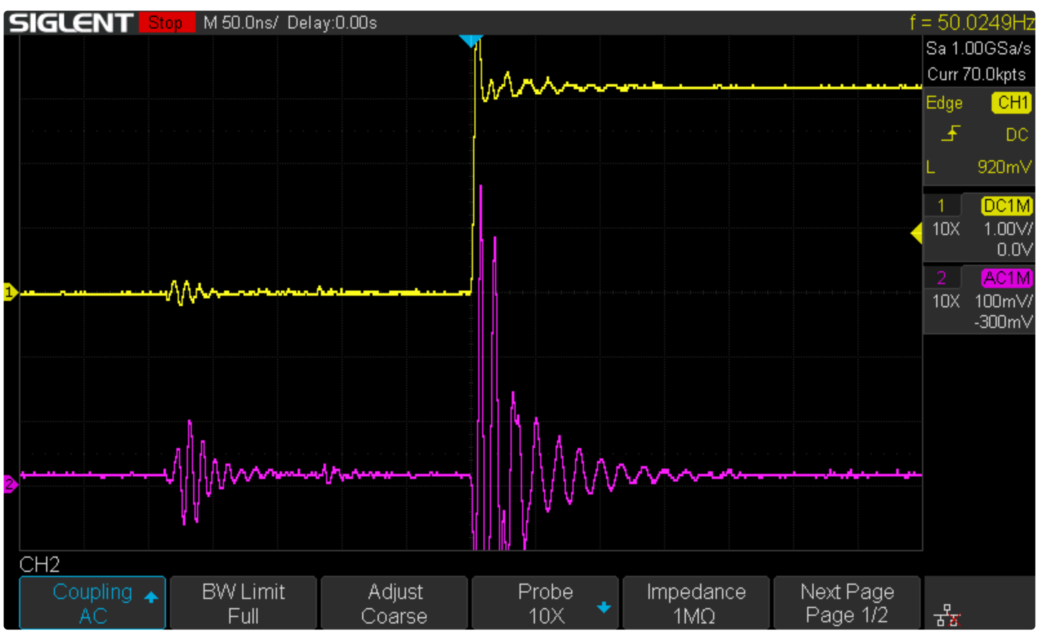
Checking the Bypass Capacitor Voltage

If the power supply droops when the LED is turned on, it would lead to in-rush current recharging the bypass capacitors. The capacitor Voltage was measured with AC coupling on the oscilloscope channel 2 (purple) to see if the Voltage drops and rises when the LED is turned on. This could be indicative of capacitors drawing current through the circuit breaker. There is a small (~10 mV) drop of the supply Voltage once the LED is on, but that is constant and does not return to the value before the LED has been turned on. This means there is no droop that would suggest the bypass capacitors will be drawing current to recharge once the LED was turned on.



LED enable signal (yellow). 10 V power supply on AC coupling (purple)

We measure substantial ringing on the rising edge for the LED control signal and the +10 V power supply. This ringing is very fast and dissipates within 150 ns. I expect some ringing, but I also think it is likely an artefact of poor connection of the oscilloscope, cross-talk, and ground loops. Given the fact that the LED current start rising ~ 8 µs after the LED control signal rising edge, but the ringing appears within a fraction of a microsecond, I think it is more an artefact than a real thing. In any event, the circuit breaker has the 4 ms FLT assertion delay $t_{CB(dly)}$ that should filter all these fast transients out.



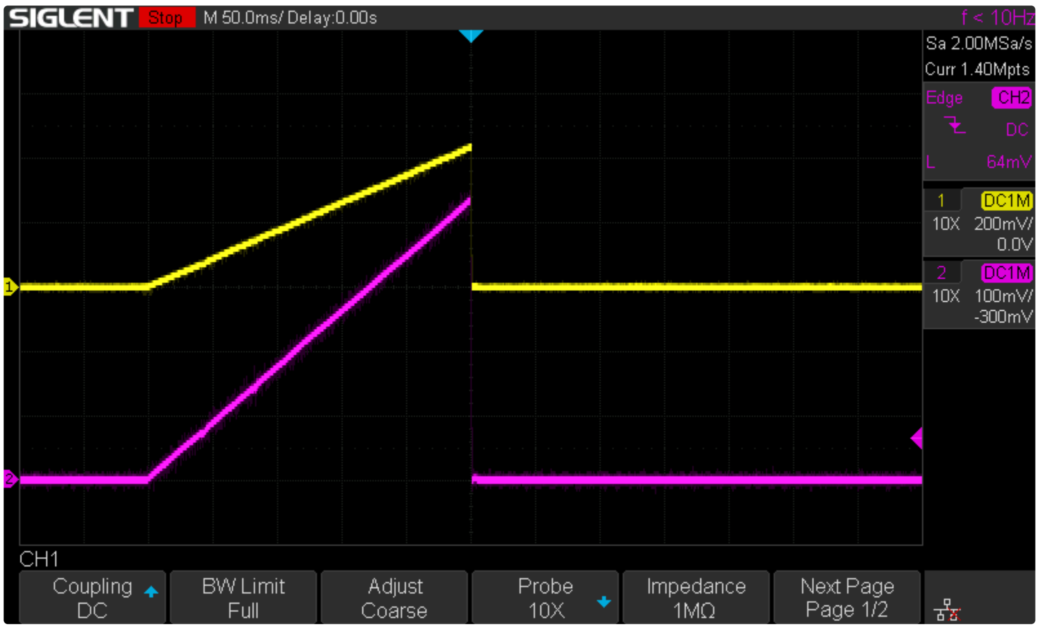
LED enable signal (yellow). 10 V power supply on AC coupling (purple)

In conclusion, it does not appear that extra current required to recharge the bypass capacitors is causing the trip of the circuit breaker at lower LED current than set by the threshold current-setting resistors.

Gradual Current Increase

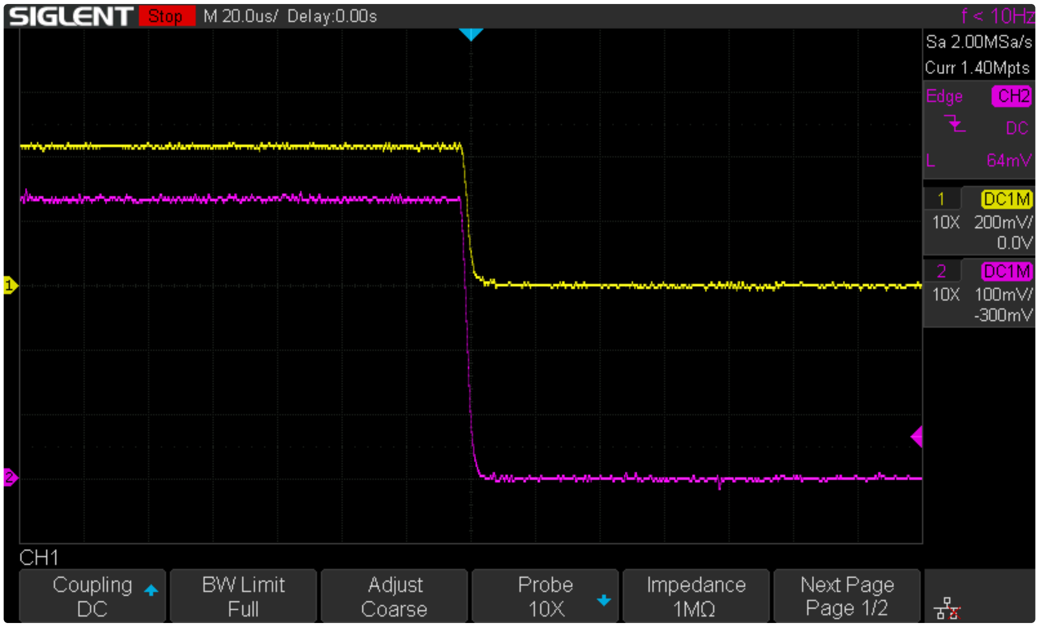
None of the above investigations 100 % ruled out that there is some effect that transiently increases the current through the circuit breaker to a higher value than we think. Therefore a measurement was derived where the current was slowly increased up to a point and decreased again. The LED current was increased linearly up to a maximum value, then the LED was turned off for 2 seconds and it was linearly increased again. The maximum value was varied by changing the MCU firmware and the highest value was found that did not trip the circuit breaker. Below are the oscilloscope traces showing the buildup of the Voltage on the 3.9 Ω current sensing resistor R61 on channel 1 (yellow) and the driving Voltage on the output of the control DAC on channel 2 (purple). Both traces show gradual linear increase until a sudden drop programmed into the firmware. The maximum code of the DAC at the peak was 372. Increasing the DAC code to 373 resulted in the circuit breaker tripping.

This measurement demonstrated that with a gradual increase of current over 250 ms, where any transient effects can be ruled out, the circuit breaker trips with DAC code 373 and the current-sense resistor Voltage of ~ 430 mV.



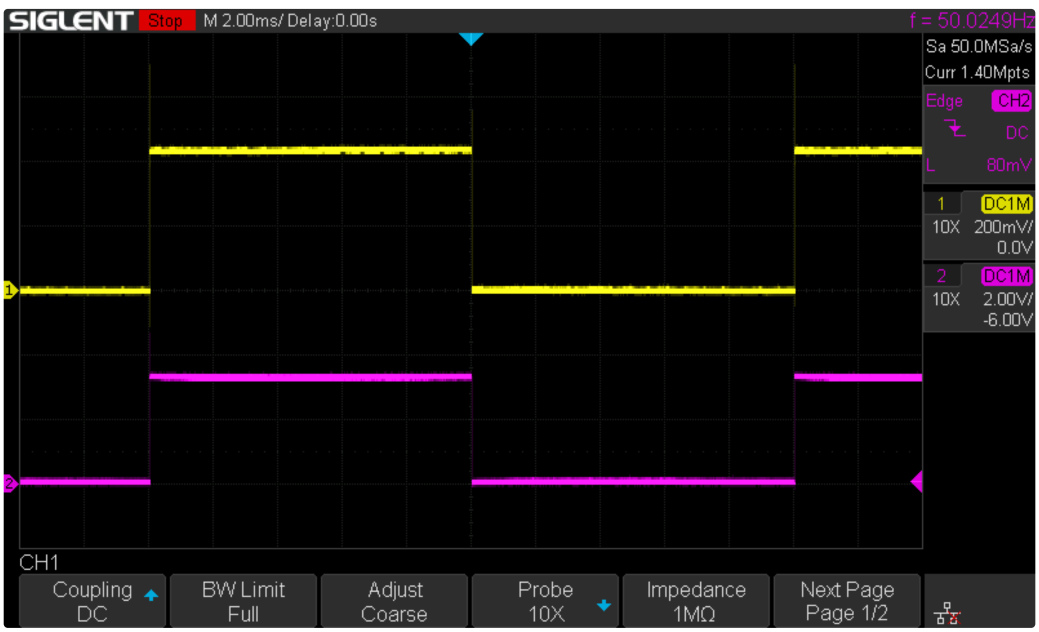
Gradual current increase: Current sense resistor Voltage (yellow). DAC driving Voltage (purple).

Just to make sure there is no strange effect going on when the DAC code drops from 372 to 0, a zoomed oscilloscope traces are shown in the image below. There is no surprise, the Voltage over the current-sensing resistor closely follows the DAC driving Voltage without any ringing or other problems.



Falling edge: Current sense resistor Voltage (yellow). DAC driving Voltage (purple).

The measurement was compared to the step measurement, where the current was abruptly turned on by the analog switch. The DAC code was programmed to a constant value, but the LED control switch was toggled. The DAC code was varied until the highest value was found that did not trip the circuit breaker. It was 372, exactly the same as with the gradual increase of the current.



Step current increase: Current sense resistor Voltage (yellow). DAC driving Voltage (purple).

These measurements conclude that any potential transitionary spikes in current associated with the switching on of the LED driver were **not** the cause of the tripping. The circuit breaker works exactly the same way whether the LED is suddenly turned on, of the current is gradually ramped up.

Verification of Using a Benchtop Power Supply

All the above tests could not rule out there is some current flow around the LED driver current-sense resistor. The solder jumper JP5, connecting the internal 10 V power supply was disconnected. Instead a cable was soldered in and connected to the RS-2005P power supply. The supply was set to 10.00 V and 0.200 A maximum current. The current was double checked using the

Victor 86E multimeter. The DAC code of 372 was programmed to create a Voltage drop on the current-sensing resistor of 0.4426 V. With the 3.9 Ω resistance, it give a current of 113.5 mA. The power supply shows a current of 113 mA, the multimeter shows 114.3 mA. Either way, the values are very similar and show that there is no additional current sink that could explain why the circuit breaker trips. To double check the function, the DAC code was increased by 2 codes to 374 and the circuit breaker tripped. This experiment verifies that the circuit breaker threshold is indeed between 110 mA and 115 mA as all the above tests indicated. It does not explain, why the current-set resistor is far smaller than the datasheet specifies.

Question to Texas Instruments

On 12. June 2025 I posted a question on the TI forum: (2) LM76202-Q1: Actual required R_ILIM resistor value does not match the datasheet - Power management forum - Power management - TI E2E support forums to try and figure out why the circuit behaves differently than the datasheet specifies.

Conclusions

A series of independent tests were performed to check various hypotheses why the LM76202-Q1 circuit breaker trips at a current that is not the same as the current predicted by the datasheet. None of the tests provided any evidence any of stray current consumption, but none of them could conclusively rule it out. The important finding is that the circuit breaker works exactly as designed, albeit with current-limiting resistors adjusted to different values than the datasheet suggests. The most conclusive measurement was the last one, that compared a gradual increase in LED current to step increase in current and in both scenarios the circuit breakers tripped with exactly the same maximum DAC code 373. This means the circuit does not suffer from any non-linearity that would lead to transient current increases associated with fast turn-on of the LED and thus different tripping point for slow and fast turn-ons.