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Other Parts Discussed in Post: LM7301

Protecting expensive, critical or hard-to-repair equipment against overcurrent and power-supply fault conditions can be achieved with universally available operational amplifiers (op amps) and a few external components.

In this post, I will present one example of a versatile variable load-current detection/protection scheme that you can easily alter for a large range of load currents, as it has ubiquitous op amps at its core.

"Variable" refers to the benefit of having a nominal "operating" power-supply load-current limit (I_load) that drops on demand. An example would be if you needed to throttle the main system's power-supply current limit in a transient power-up condition before one or more other supplies have reached their nominal voltage. In Figure 1, if Vref (which represents another monitored power supply) is below nominal (Vnom), the load current drops for safety or reliability reasons. With Vref less than Vmin, the load current pinches off (I_pinch).

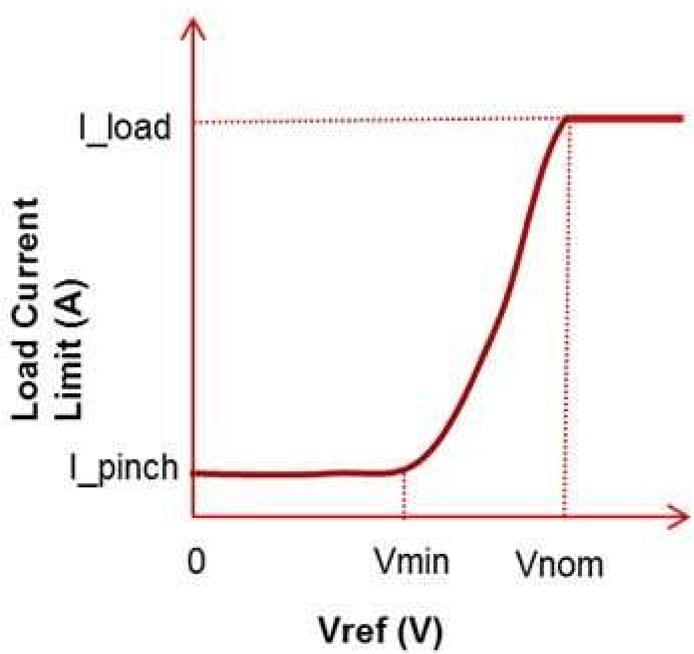

Figure 1: Load current is a variable function of another supply voltage (Vref)

Once Vref is at Vnom or higher, normal I_load limit is permitted to flow.

Figure 2 uses the versatile LM7301 rail-to-rail input and output op amp to implement the load current limit profile shown in Figure 1. The circuit monitors the Vsupply current to the load. When the current exceeds the limit determined by the Vref voltage, it produces an output that turns Q1 on and can trigger a protection mechanism. The op amp's large operating supply voltage (1.8V to 32V) simplifies the design task by extending the range of usable supply voltages (Vsupply) monitorable for load current. In addition, a full-range output swing eases the output drive (on/off) to the gate of a protection transistor or MOSFET (Q1 in Figure 2). Since the input common-mode voltage range extends from below ground to above V+, you can tie the high-side sense resistor (Rsense) directly to the op amp inputs.

U1A, which monitors Vref, must have an output swing close to Vsupply in order to allow the kind of behavior depicted in Figure 1, where a reduced Vref pinches off the allowable load current. Furthermore, you could use the same op amp as an amplifier (U1A) or comparator (U1B) to reduce the bill of materials (BOM).

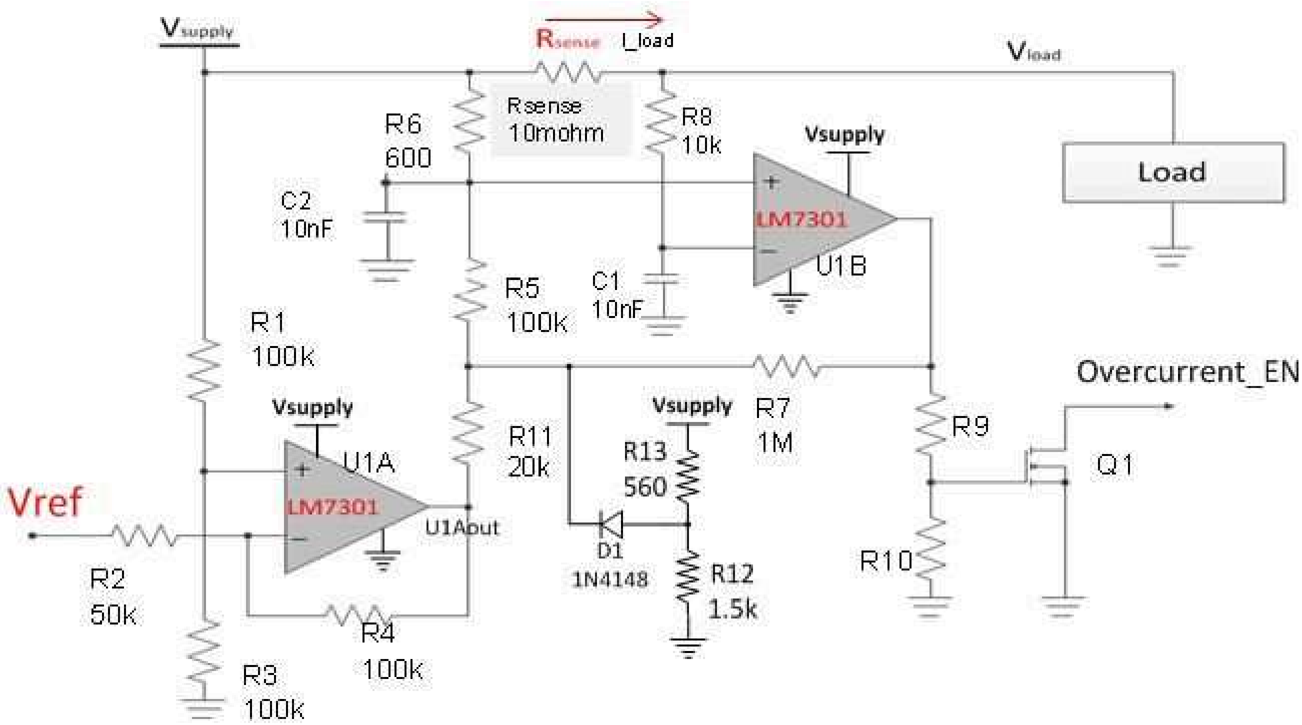

Figure 2: Variable current-limit detector

The circuit operates by passing all of the load current through a single sense resistor (Rsense), with U1B monitoring both terminals. Enough load-current flow will cause the U1B output to switch high toward the Vsupply rail, which then could turn on a protection device such as Q1. U1A monitors Vref; its output changes the voltage that appears on the non-inverting input of U1B. A low Vref voltage raises U1A output and reduces the I_load value that triggers the U1B output high (fault condition), and vice versa. Diode D1 turns on when U1A detects Vref approaching Vnom and prevents any further increase in I_load with increasing Vref voltage (see Figure 1, where I_load is maintained for Vref ≥ Vnom). The hysteresis resistor R7 works with other external resistors to set the amplitude of the hysteresis, which introduces a difference between the load current that initiates overcurrent and the load current that resets overcurrent. This difference in currents ensures that the circuit does not enter an unstable condition where the U1B output chatters back and forth.

- At a 4MHz gain-bandwidth product, the op amp can respond to fast current transients if necessary. However, capacitors C1 and C2 can slow down the circuit response time so that transient current spikes do not trigger the overcurrent limit detection – such as those encountered at startup when the supply decoupling capacitors draw excess current to reach their operating voltage.

Here are some of the governing equations that make it easier to modify the circuit for different operating conditions. I've also included an example operating condition to allow numerical results using the component values shown in Figure 2.

Vsupply = 12V

Vref = 5V (Vnom condition)

$$U1A_{out} = Vsupply\frac{R3}{R1+R3}\left(1+\frac{R4}{R2}\right) - Vref\frac{R4}{R2} = 12V\frac{100k}{200k}\left(1+\frac{100k}{50k}\right) - Vref\frac{100k}{50k} = 8V \qquad (1)$$

To find the current limit as a function of Vref (or $U1A_{out}$):

$$I_{load} = \frac{(Vsupply - U1A_{out})\times R6}{Rsense\times(R5+R11+R6)} = \frac{(12V-8V)\times 600\Omega}{10m\Omega\times(100k+20k+600\Omega)} = 2\ Amps \qquad (2)$$

When Vref drops, U1A output moves high until U1A output saturates with the values shown. Vmin corresponds to the Vref voltage where the U1A output has saturated high. For a rail-to-rail output device, that means:

$$U1A_{out}\ (saturated) = \sim V_{supply} \qquad (3)$$

To find the Vmin in Figure 1:

Calculate Vmin with Equation 3 and rearrange Equation 1 to solve for Vref as Vmin:

$$Vmin = \frac{R2.Vsupply}{R4}\left(\frac{R3}{R1+R3}\left(1+\frac{R4}{R2}\right)-1\right) = \frac{50k\times 12V}{100k}\left(\frac{100k}{200k}\left(1+\frac{100k}{50k}\right)-1\right) = 3V \qquad (4)$$

Any lowering of Vref below Vmin has no effect on the load-current limit, which is already pinched off (I_pinch). For the LM7301, the saturated $U1A_{out}$ voltage is about 100mV lower than Vsupply, or:

$$Vsupply - U1Aout = 100mV\ (in\ saturation) \qquad (5)$$

To find I_pinch in Figure 1, plug the information from Equation 5 into Equation 2:

$$I_{pinch} = \frac{100mV \times R6}{Rsense.(R5+R11+R6)} = \frac{100mV \times 600\Omega}{10m\Omega.(100k+20k+600\Omega)} = 50mA \quad (6)$$

To find the amount of hysteresis in the load current detection point:

$$I_{hysteresis} \cong \frac{Vsupply}{Rsense} \times \frac{R11}{R7} \times \frac{R6}{R5} = \frac{12V}{10m\Omega} \times \frac{20k}{1M} \times \frac{600}{100k} = 144mA \quad (7)$$

So lowering the value of R7 increases hysteresis proportionally.

Increasing Vref beyond Vnom is clamped by D1 such that the load-current limit remains constant. The value of Vref when this occurs has to do with the voltage divider set by R12 and R13. With the values shown in Figure 2, the D1 anode is set to 8.7V and starts conducting when Vref ≥ 5V, thus establishing Vnom=5V. The voltage divider resistor values should be low enough to supply the current to keep D1 forward-biased with $U1A_{out}$ saturated to ground.

Once you have all of the governing expressions for the most important operating points of the circuit, you can easily modify it to fit your intended application. Having a versatile op amp as the main active element in a system can offer added flexibility in setting the operating conditions and load current profile. As an added benefit, it is possible to have more than one supply voltage throttle the load current; just add a series resistor from these other supply voltages to the U1A inverting node, similar to Vref.

What considerations do you face when protecting equipment against overcurrent and power-supply fault conditions? Log in to post a comment or visit the TI E2E™ Community Precision Amplifiers forum.

Additional resources

- For more information on dedicated current sense amplifiers, read Dan Harmon's blog, "How to get started with current sense amplifiers – part 1."
- Read the Precision Hub blog post, "Circuit-protection basics."
- Start designing with these evaluation modules:
  - Evaluation board for high-speed single op amp in the 5- to 6-pin SOT-23 package.
  - Evaluation board for high-speed single op amp in the 8-pin SOIC package.
  - Universal operational amplifier evaluation module.
- Download the LM7301 PSPICE model to simulate your designs.
- Watch the video, "When to choose a current sense amp."
- Search TI high-speed op amps and find technical resources.