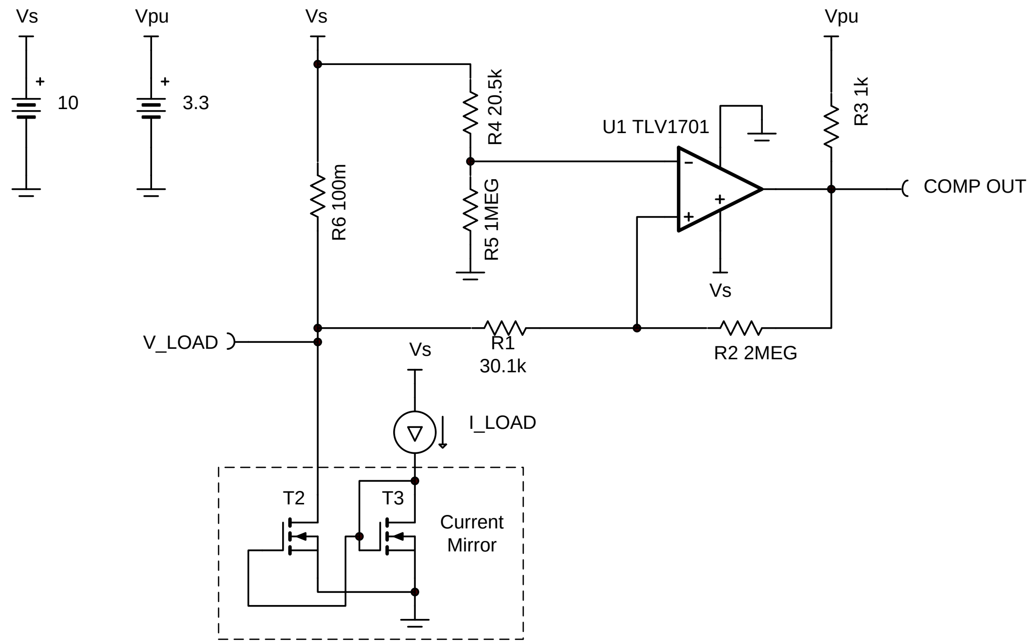
High-side current sensing with comparator circuit

Design Goals

Load Current (I_L)		System Supply (V_S)	Comparator Output Status	
Over Current (I_{OC})	Recovery Current (I_{RC})	Typical	Over Current	Normal Operation
1 A	0.5 A	10 V	V_{OL} < 0.4 V	$V_{OH} = V_{PU}$ = 3.3 V

Design Description

This high-side, current sensing solution uses one comparator with a rail-to-rail input common mode range to create an over-current alert (OC-Alert) signal at the comparator output (COMP OUT) if the load current rises above 1A. The OC-Alert signal in this implementation is active low. So when the 1A threshold is exceeded, the comparator output goes low. Hysteresis is implemented such that OC-Alert will return to a logic high state when the load current reduces to 0.5A (a 50% reduction). This circuit utlizes an open-drain output comparator in order to level shift the output high logic level for controlling a digital logic input pin. For applications needing to drive the gate of a MOSFET switch, a comparator with a push-pull output is preferred.



Design Notes

1. Select a comparator with rail-to-rail input common mode range to enable high-side current sensing.
2. Select a comparator with an open-drain output stage for level-shifting.
3. Select a comparator with low input offset voltage to optimize accuracy.
4. Calculate the value for the shunt resistor (R_6) so the shunt voltage (V_{SHUNT}) is at least ten times larger than the comparator offset voltage (V_{IO}).

Design Steps

1. Select value of R_6 so V_{SHUNT} is at least 10x greater than the comparator input offset voltage (V_{IO}). Note that making R_6 very large will improve OC detection accuracy but will reduce supply headroom.

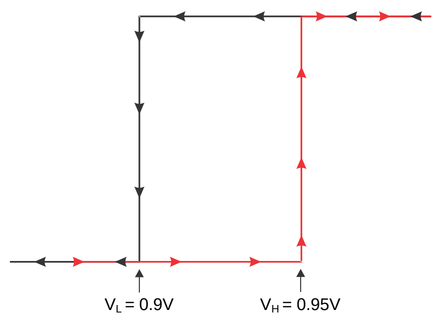
$$V_{SHUNT} = (I_{OC} \times R_6) \geq 10 \times V_{IO} = 55mV$$

$$\text{set } R_6 = 100m\Omega \text{ for } I_{OC} = 1A \;\;\&\;\; V_{IO} = 5.5mV$$

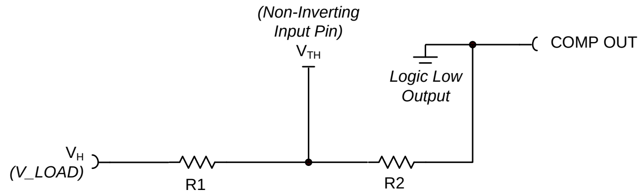
2. Determine the desired switching thresholds for when the comparator output will transition from high-to-low (V_L) and low-to-high (V_H). V_L represents the threshold when the load current crosses the OC level, while V_H represents the threshold when the load current recovers to a normal operating level.

$$V_L = V_S - (I_{OC} \times R_6) = 10 - (1 \times 0.1) = 0.9V$$

$$V_H = V_S - (I_{RC} \times R_6) = 10 - (0.5 \times 0.1) = 0.95V$$

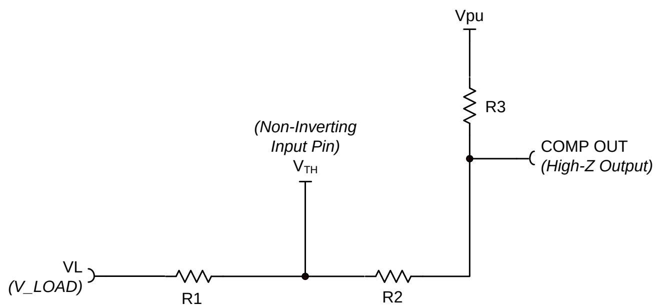


3. With the non-inverting input pin of the comparator labeled as V_{TH} and the comparator output in a logic low state (ground), derive an equation for V_{TH} where V_H represents the load voltage (V_{LOAD}) when the comparator output transitions from low to high. Note that the simplified diagram for deriving the equation shows the comparator output as ground (logic low).



$$V_{TH} = V_H \times \left(\frac{R_2}{R_1 + R_2}\right)$$

4. With the non-inverting input pin of the comparator labeled as V_{TH} and the comparator output in a high-impedance state, derive an equation for V_{TH} where V_L represents the load voltage (V_{LOAD}) when the comparator output transitions from high to low. Applying "superposition" theory to solve for V_{TH} is recommended.



$$V_{TH} = V_L \times \left(\frac{R_2 + R_3}{R_1 + R_2 + R_3}\right) + V_{PU} \times \left(\frac{R_1}{R_1 + R_2 + R_3}\right)$$

5. Eliminate variable V_{TH} by setting the two equations equal to each other and solve for R_1. The result is the following quadratic equation. Solving for R_2 is less desirable since there are more standard values for small resistor values than the larger ones.

$$0 = (V_{PU}) \times R_1^2 + (V_{PU} \times R_2 + V_L \times (R_3 + R_2) - V_H \times R_2) \times R_1 + (V_L - V_H) \times (R_2^2 + R_2 \times R_3)$$

6. Calculate R_1 after substituting in numeric values for V_{PU}, R_2, V_L, V_H, and R_3. For this design, set V_{PU}=3.3, R_2=2M, V_L=9.9, V_H=9.95, and R_3=1k. Please note that R_3 is significantly smaller than R_2 (R_3<<R_2). Increasing R_3 will cause the comparator logic high output level to increase beyond V_{PU} and should be avoided. For example, increasing R_3 to a value of 100k can cause the logic high output to be 3.6V.

   $$0 = (3.3) \times R_1^2 + (6.591M) \times R_1 - (200.1G)$$

   $$\text{the positive root for } R_1 = 29.9k\Omega$$

   $$\text{using standard 1\% resistor values, } R_1 = 30.1k\Omega$$

7. Calculate V_{TH} using the equation derived in Design Step 3; use the calculated value for R_1. Note that V_{TH} is less than V_L since V_{PU} is less that V_L.

   $$V_{TH} = V_H \times \left(\frac{R_2}{R_1 + R_2}\right) = 9.802V$$

8. With the inverting terminal labeled as V_{TH}, derive an equation for V_{TH} in terms of R_4, R_5, and V_S.

   $$V_{TH} = V_S \times \left(\frac{R_5}{R_4 + R_5}\right)$$

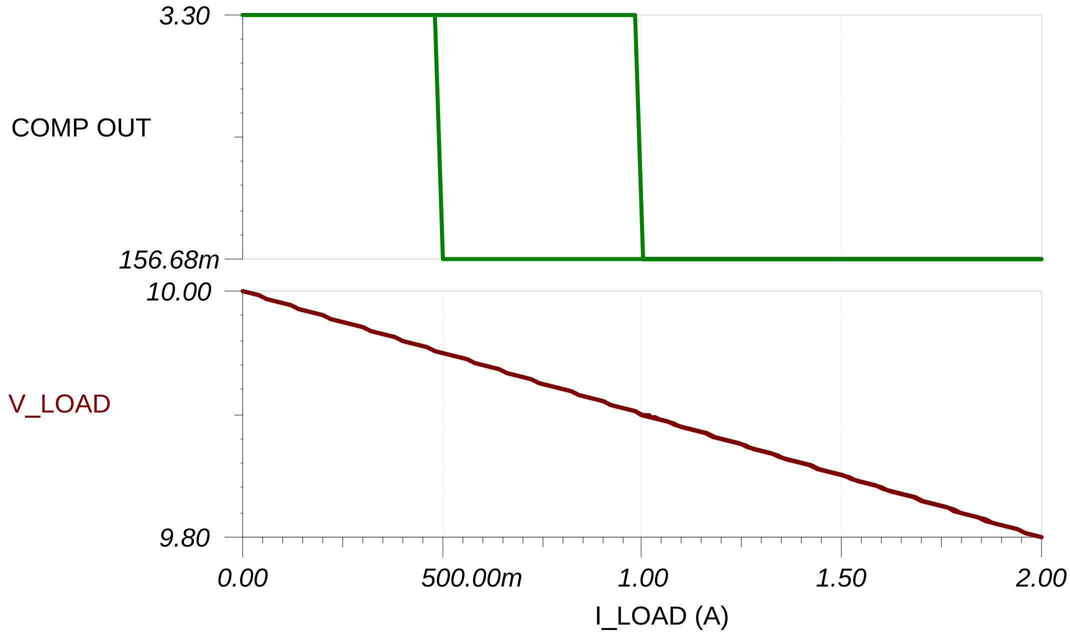
9. Calculate R_4 after substituting in numeric values R_5=1M, V_S=10, and the calculated value for V_{TH}.

   $$R_4 = \left(\frac{R_5 \times (V_S - V_{TH})}{V_{TH}}\right) = 20.15k\Omega$$

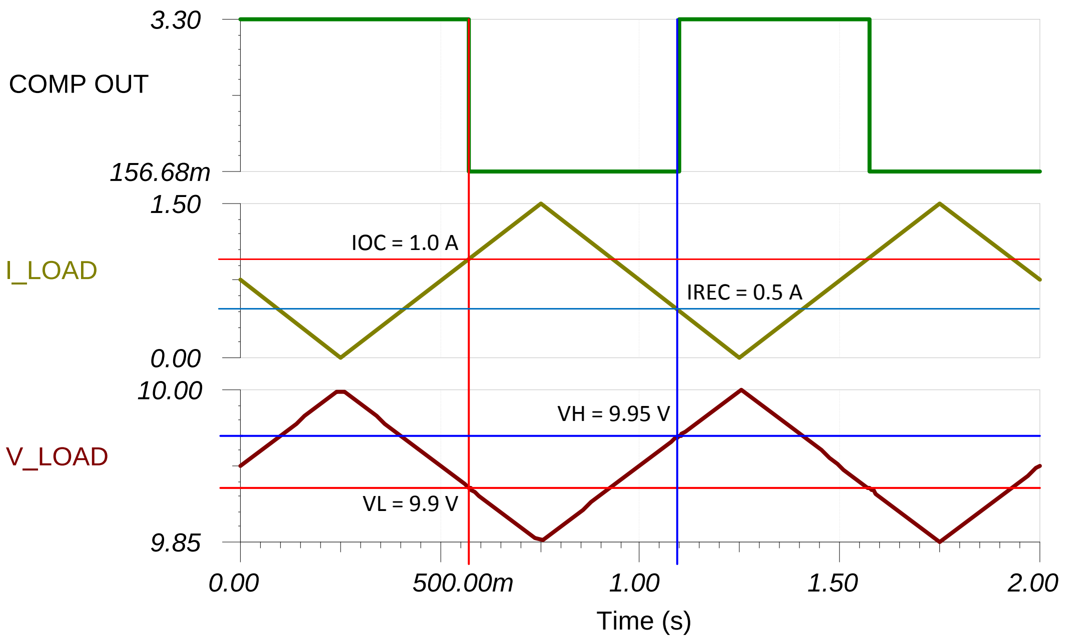
   $$\text{using standard 1\% resistor values, } R_4 = 20.5k\Omega$$

Design Simulations

DC Simulation Results



Transient Simulation Results



Design References

See Analog Engineer's Circuit Cookbooks for TI's comprehensive circuit library.

See Circuit SPICE Simulation File SLOM456, http://www.ti.com/lit/zip/slom456.

Design Featured Comparator

TLV170x-Q1, TLV170x	
V_S	2.2 V to 36 V
V_{inCM}	Rail-to-rail
V_{OUT}	Open-Drain, Rail-to-rail
V_{OS}	500µV
I_Q	55 µA/channel
$t_{PD(HL)}$	460 ns
#Channels	1, 2, 4
www.ti.com/product/tlv1701-q1	

Design Alternate Comparator

	TLV7021	TLV370x-Q1, TLV340x
V_S	1.6 V to 5.5 V	2.7 V to 16 V
V_{inCM}	Rail-to-rail	Rail-to-rail
V_{OUT}	Open-Drain, Rail-to-rail	Push-Pull, Rail-to-rail
V_{OS}	500 µV	250 µV
I_Q	5 µA	560 µA/Ch
$t_{PD(HL)}$	260 ns	36 µs
#Channels	1	1, 2, 4
	www.ti.com/product/tlv7021	www.ti.com/product/tlv3701-q1