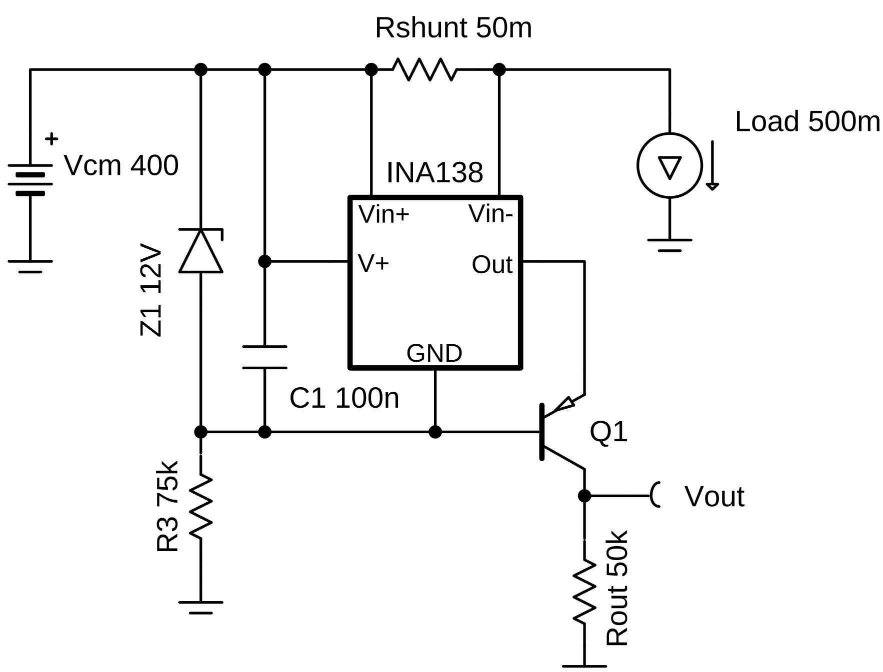
High-voltage, high-side floating current sensing circuit using current output, current sense amplifier

Input		Output		Supply		
$I_{load\ Min}$	$I_{load\ Max}$	$V_{out\ Min}$	$V_{out\ Max}$	$V_{cm\ Min}$	$V_{cm\ Max}$	V_{ee}
0.5A	9.9A	250mV	4.95V	12V	400V	GND (0V)

Design Description

This cookbook is intended to demonstrate a method of designing an accurate current sensing solution for systems with high common mode voltages. The principle aspect of this design uses a unidirectional circuit to monitor a system with V_{cm} = 400V by floating the supplies of the device across a Zener diode from the supply bus (V_{cm}). This cookbook is based on the High Voltage 12 V – 400 V DC Current Sense Reference Design.



Design Notes

1. The Getting Started with Current Sense Amplifiers video series introduces implementation, error sources, and advanced topics for using current sense amplifiers.
2. This example is for high V_{CM}, high-side, unidirectional, DC sensing.
3. To minimize error, make the shunt voltage as large as the design will allow. For the INA138 device, keep V_{sense} >> 15mV.
4. The relative error due to input offset increases as shunt voltage decreases, so use a current sense amplifier with low offset voltage. A precision resistor for R_{shunt} is necessary because R_{shunt} is a major source of error.
5. The INA138 is a current-output device, so voltages referenced to ground are achieved with a high voltage bipolar junction transistor (BJT).
   - Ensure the transistor chosen for Q1 can withstand the maximum voltage across the collector and emitter (for example, need 400V, but select > 450V for margin).
   - Multiple BJTs can be stacked and biased in series to achieve higher voltages
   - High beta of this transistor reduces gain error from current that leaks out of the base

Design Steps

1. Determine the operating load current and calculate R_{shunt}:
   - Recommended V_{sense} is 100mV and maximum recommended is 500mV, so the following equation can be used to calculate R_{shunt} where $V_{sense} \leq$ 500mV:

$$R_{shunt} = \frac{V_{sense\ max}}{I_{load\ max}} \rightarrow \frac{0.5V}{10A} = 50m\Omega$$

   - For more accurate and precise measurements over the operating temperature range, a current monitor with integrated shunt resistor can be used in some systems. The benefits of using these devices are explained in Getting Started with Current Sense Amplifiers, Session 16: Benefits of Integrated Precision Shunt Resistor.
2. Choose a Zener diode to create an appropriate voltage drop for the INA138 supply:
   - The Zener voltage of the diode should fall in the INA138 supply voltage range of 2.7V to 36V and needs to be larger than the maximum output voltage required.
   - The Zener diode voltage regulates the INA138 supply and protects from transients.
   - Data sheet parameters are defined for 12-V V_{in+} to the GND pin so a 12-V Zener is chosen.
3. Determine the series resistance with the Zener diode:
   - This resistor (R3) is the main power consumer due to its voltage drop (up to 388V in this case). If R3 is too low, it will dissipate more power, but if it is too high R3 will not allow the Zener diode to avalanche properly. Since the data sheet specifies I_Q for V_S = 5V, estimate the max quiescent current of the INA138 device at V_S = 12V to be 108µA and calculate R3 using the bias current of the Zener diode, 5mA, as shown:

$$R_3 = \frac{V_{CM} - V_{zener}}{I_{zener} + I_{INA138}} = \frac{400V - 12V}{5mA + 108\mu A} \approx 75.96k\Omega$$

$$\text{standard value} \rightarrow 75k\Omega$$

   - The power consumption of this resistor is calculated using the following equation:

$$Power_{R3} = \frac{(V_{cm} - V_{Zener})^2}{R3} \rightarrow \frac{(400V - 12V)^2}{75k\Omega} \approx 2.007W$$

4. Calculate R_{out} using the equation for output current in the INA138 data sheet.
   - This system is designed for 10V/V gain where V_{out} = 1V if V_{sense} = 100mV:

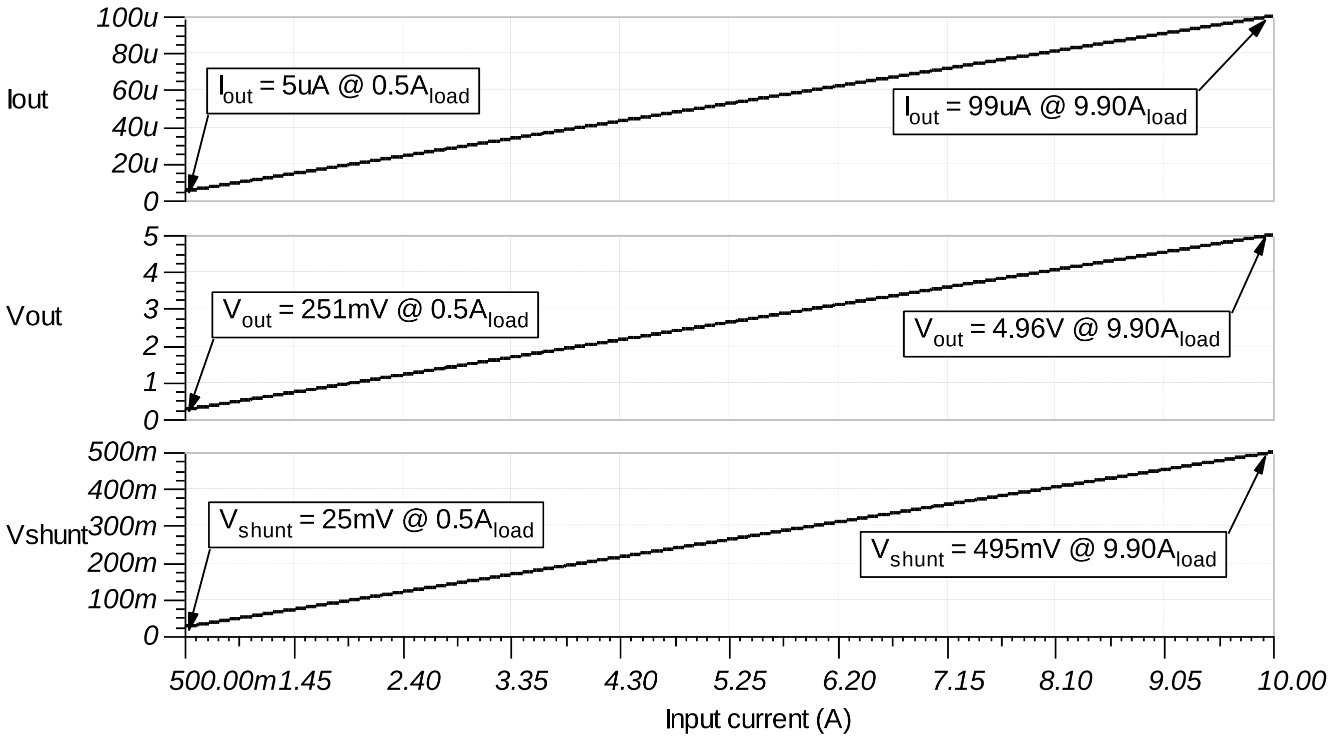
$$I_{out\ INA138} = 200\frac{\mu A}{V} \times (V_{sense\ max}) \rightarrow 200\frac{\mu A}{V} \times (0.5V) = 100\mu A$$

$$R_{out} = \frac{V_{out\ max}}{I_{out\ INA138}} \rightarrow \frac{5V}{100\mu A} = 50k\Omega$$

Design Simulations

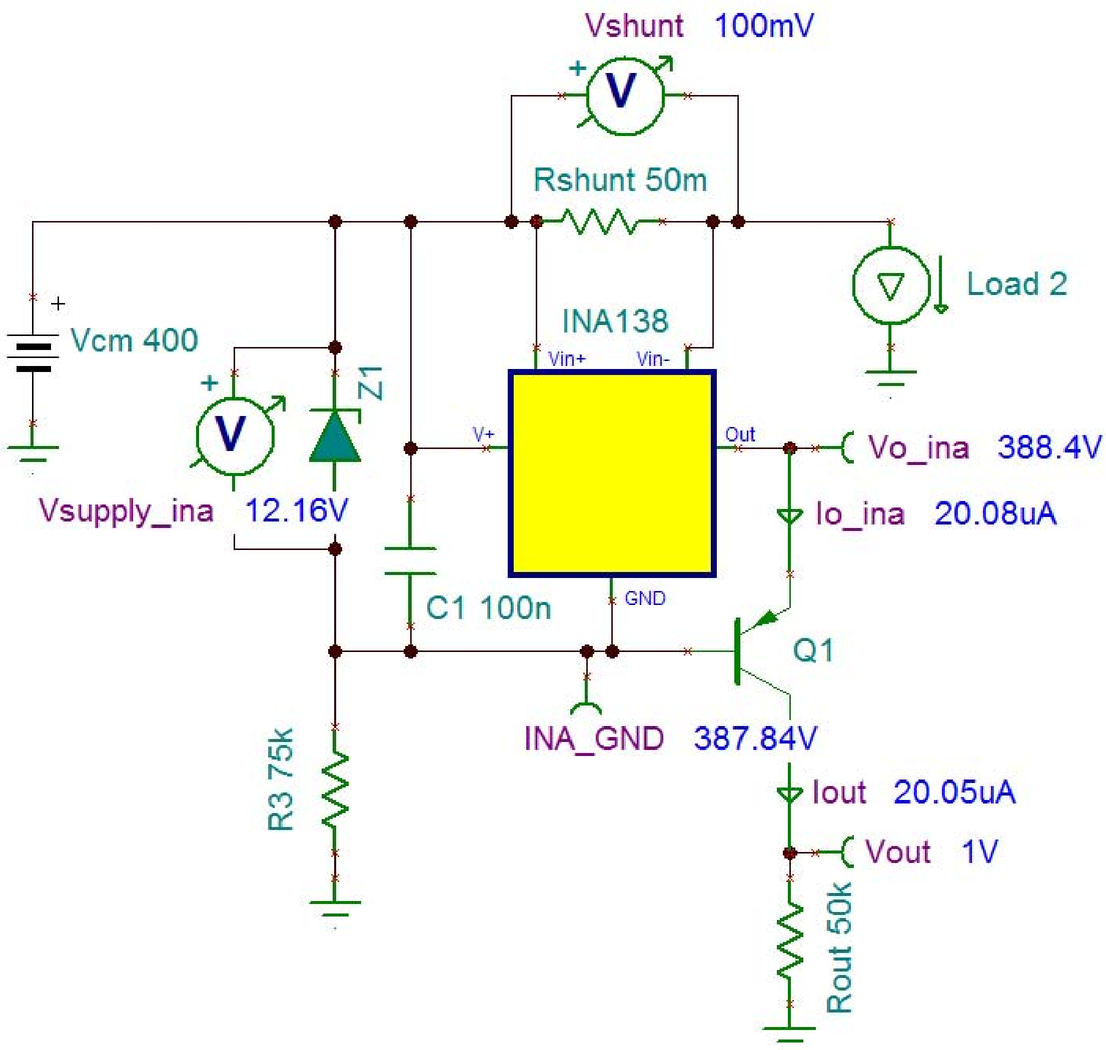
DC Simulation Results

The following graph shows a linear output response for load currents from 0.5A to 10A and 12V ≤ V_{cm} ≤ 400V. I_{out} and V_{out} remain constant over a varying V_{cm} once the Zener diode is reverse biased.



Steady State Simulation Results

The following image shows this system in DC steady state with a 2-A load current. The output voltage is 10× greater than the measured voltage across R_{shunt}.



Design References

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

See circuit SPICE simulation file SGLC001.

Getting Started with Current Sense Amplifiers video series:

https://training.ti.com/getting-started-current-sense-amplifiers

Abstract on Extending Voltage Range of Current Shunt Monitor:

http://www.ti.com/lit/an/slla190/slla190.pdf

High Voltage 12V – 400V DC Current Sense Reference Design:

http://www.ti.com/tool/TIDA-00332

Cookbook Design Files:

http://proddms.itg.ti.com/stage/lit/sw/sglc001a/sglc001a.zip

Current Sense Amplifiers on TI.com:

http://www.ti.com/amplifier-circuit/current-sense/products.html

For direct support from TI Engineers use the E2E community:

http://e2e.ti.com

Design Featured Current Shunt Monitor

INA138	
V_{ss}	2.7V to 36V
$V_{in\ cm}$	2.7V to 36V
V_{out}	Up to (V+) - 0.8V
V_{os}	±0.2mV to ±1mV
I_q	25µA to 45 µA
I_b	2 µA
UGBW	800kHz
# of Channels	1
http://www.ti.com/product/ina138	

Design Alternate Current Shunt Monitor

INA168	
V_{ss}	2.7V to 60V
$V_{in\ cm}$	2.7V to 60V
V_{out}	Up to (V+) - 0.8V
V_{os}	±0.2mV to ±1mV
I_q	25µA to 45 µA
I_b	2 µA
UGBW	800kHz
# of Channels	1
http://www.ti.com/product/ina168	