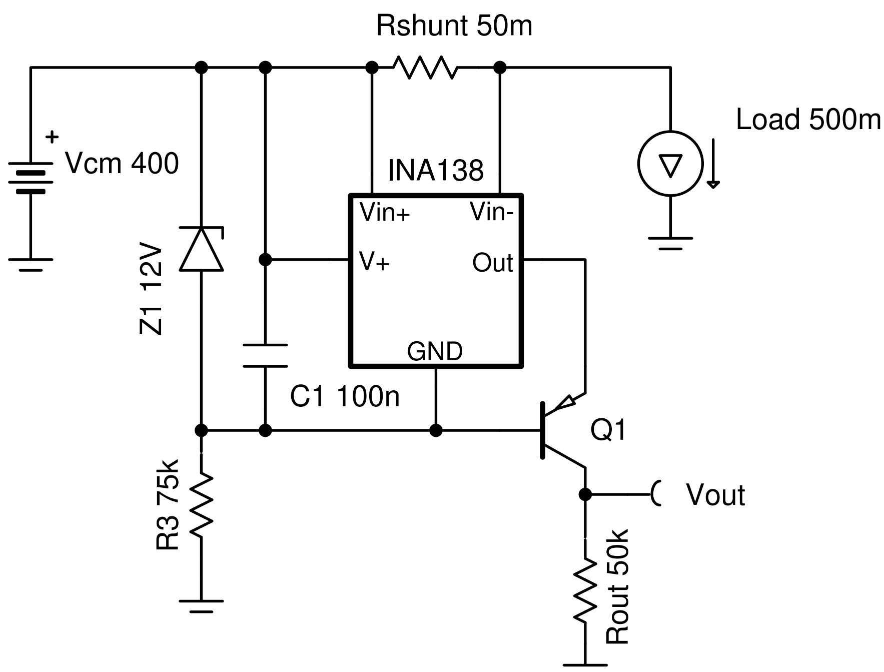
Analog Engineer's Circuit

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 option 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 12V – 400V 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).
   - Verify that 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.
2. Choose a Zener diode to create an appropriate voltage drop for the INA138 supply:
   - The Zener voltage of the diode falls 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 12V V_{in+} to the GND pin so a 12V 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 dissipates more power, but if it is too high R3 does not allow the Zener diode to avalanche properly. Since the data sheet specifies I_Q for V_S = 5V, estimate the maximum 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 10 V/V gain where V_{out} = 1V if V_{sense} = 100mV:

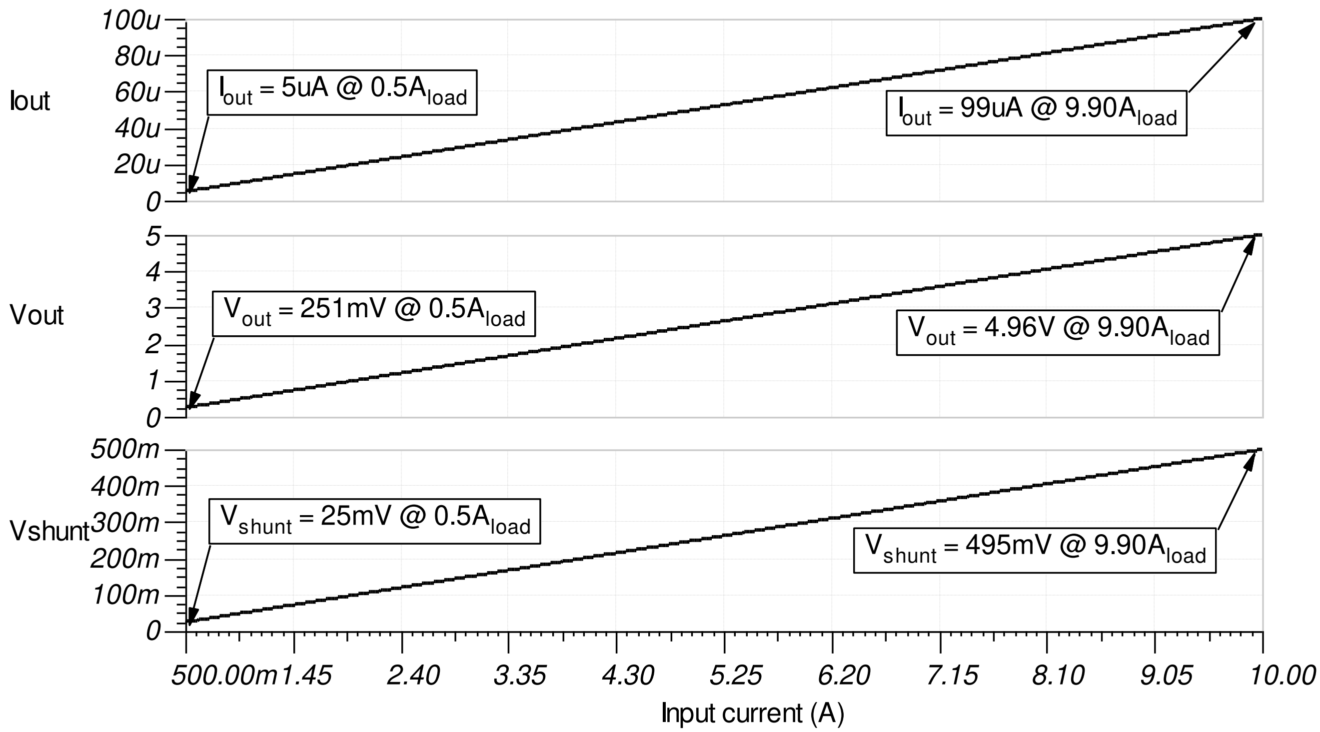
$$I_{out\ INA138} = 200\frac{\mu A}{V} \times (V_{sense\ max}) \rightarrow 200\frac{\mu A}{V} \times (0.5V) = 100\mu A$$

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

Design Simulations

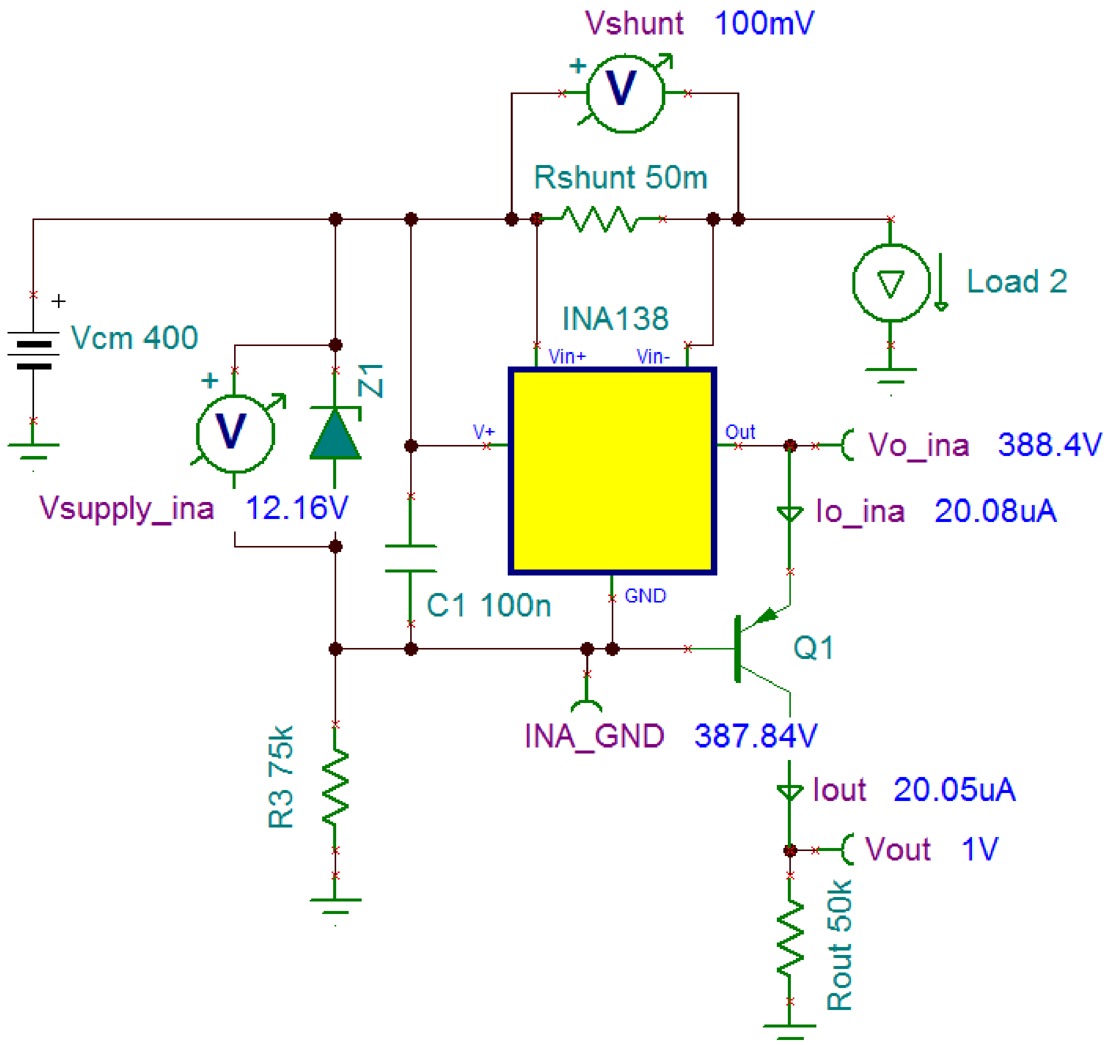
DC Simulation Results

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 2A load current. The output voltage is 10× greater than the measured voltage across R_{shunt}.



Design References

Texas Instruments,SPICE SGLC001 simulation files, SBOA295 software support

Texas Instruments, Current sense amplifiers, Precision lab video series

Texas Instruments, Extending the Common-Mode Voltage Range of Current-Output Current Shunt Monitors, application brief

Texas Instruments, High Voltage 12V – 400V DC Current Sense Reference Design, TIDA-00332 tool

Texas Instruments, Source files for SBOA295, design tool

Texas Instruments, Current-sense amplifiers, product page

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 45µA
I_b	2µA
UGBW	800kHz
# of Channels	1
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 45µA
I_b	2µA
UGBW	800kHz
# of Channels	1
INA168	

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