DC/DC Power Supply
Module 2

2 Channel
Dual Voltage-Current Meter

Application Report

Marcos Buydid

2024

Contents

Abstract

On November 2021 I finish the design of the module. As you may know, on a DC-DC power supply having control of the voltage and current is as important as visualizing the values on a calibrated device. Applying them in a wrong way on electronic devices can lead to irreversible damage.
Along this document you will find important information and details taken into account to build a device capable of measure voltage and current simultaneously up to 2 channels independently.

What is a Dual Voltage-Current Meter?

This type of devices can measure simultaneously the voltage that's been applied to a load and the current is flowing through it from up to two different DC voltage sources.

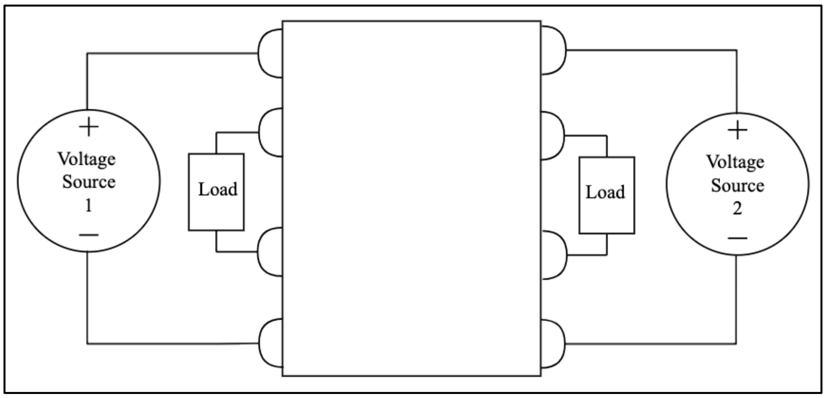


Figure 1 Simplified Model

Voltage sources are placed in parallel with the module and loads needs to be connected in series between the source and the module so current can be measured. Figure 1 shows a simplified representation of the module.

Module Characteristics

The design contemplates voltages readings from 0V to 20V and current readings from 0A to 5A.

VIN is 12V. F1 [1] is a fast-acting fuse to protect the circuit from overcurrent. I choose one with 1A of current rating. In series connected to it, there's a p-channel mosfet (IC7) [2] used to protect the module from reverse polarity. According to datasheet maximum gate-source voltage (V_{GSS}) is ±25V. If this value is exceeded and mosfet eventually gets damaged, D2 [3] an unidirectional TVS diode protects U2 [4], a voltage regulator that provides +10V in the circuit. I choose a unidirectional TVS because voltage in the circuit is always positive.
In order to power-up a 16x2 LCD used to display the voltage and current values, a +5V voltage regulator is used U2 [5].

Voltages References

An Arduino Nano [6] fitted on a DIL socket (J8) is used as a microcontroller board to process all the analog voltages. The board uses the ATmega328 microcontroller containing 8 analog inputs with 10 bits of resolution. A range of 0 to 1023 values can be represented (2^{10}) that translated into a 0-5V scale gives a minimum voltage of 0.00488V ≈ 0.005V (5V / 1023). To achieve that, a voltage reference (IC2) [7] with ±0.02% of accuracy is used with OUT pin connected to AREF pin of the microcontroller board.
An additional voltage reference (IC6) [8] with ±0.05% of accuracy is used to power up the operational and current sense amplifiers (discussed on the next section).
A trimmer (VR2) [9] connected to TRIM pin of IC6 is used to calibrate the output to 5V as this IC does not have same accuracy as IC2.
IC6 TEMP pin output specific voltage values (around 0.630V at 25°C according to datasheet) depending on his working temperature. By connecting to A6 pin of the microcontroller board, voltages can be monitored to ensure the temperature does not reach the maximum specified.

Voltage Measurement

Each channel uses a precision RRIO operational amplifier (IC3, IC5) [10] configured as a differential amplifier. A model with this configuration is shown on figure 2.
Resistors [11] used with IC3 and IC5 (R4, R5, R6, R7, R8, R9, R10, R12, R15, R16) have 0.1% of tolerance and (R11, R14) 0.5%.
According to schematic, OUT pin of IC3 and IC5 connects to an analog input of the microcontroller board. This inputs accept a maximum voltage of 5V.

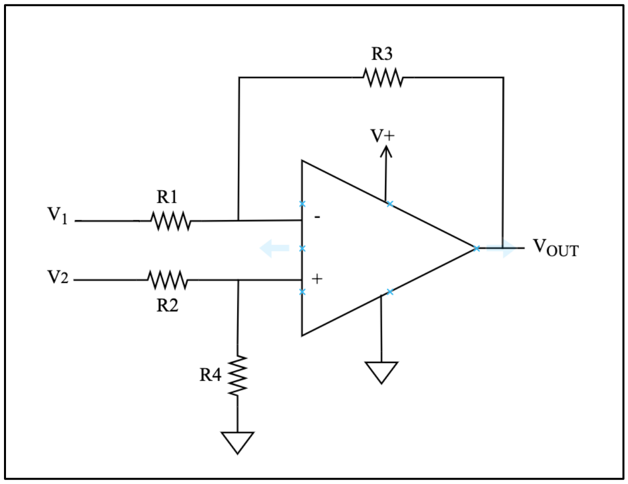


Figure 2 Differential Amplifier Model

Using figure 2 model, the transfer function [12] for this amplifier is given by:
V_{OUT} = $-V_1$ x (R3 / R1) + (R4 / R2 + R4) x (R1 + R3 / R1) x V_2

Selecting this resistor values: R1 = 51.02KΩ, R2 = 31KΩ, R3 = 1KΩ, R4 = 10KΩ and powering the amplifier with +5V, if we apply the maximum voltage we will measure (+20V) on V_2 and connect V_1 to ground, using the transfer function we can calculate the voltage output:
V_{OUT} = (10KΩ / 31KΩ + 10KΩ) x (51.02KΩ + 1KΩ / 51.02KΩ) x 20V
V_{OUT} = 0.243 x 1.019 x 20V
V_{OUT} = 4.952V

As you can see, the ratio between V_2 / V_{OUT} ≈ 4.04. This allows to measure all voltages from 0V to 20V without exceeding maximum voltage on the analog inputs where OUT pin of the amplifiers are connected. See (VIN vs VOUT Using Transfer Function).

According to IC3-IC5 datasheet, if voltage at any of the inputs exceeds the voltage supply of the amplifier by more than 0.5V, is necessary that input resistors limit the current to 5mA or less.

Additionally, you may notice on the schematic there are two small-signal diodes (D1-D3) [13] connected between +IN pin resistors and GND on both amplifiers. They are used to protect the inputs from reverse polarity. See (Reverse Polarity Protection on Inputs).

Current Measurement

Each channel uses a precision rail to rail current amplifier (IC1, IC4) [14] with a fixed gain of 90V/V and configured to work unidirectionally. They operate with a full-scale sense voltage of 50mV, but what this mean? According to datasheet they are rated to measure a maximum voltage of 50mV between RS+ and RS- pins.

Considering the range of currents to measure (0-5A) along with the maximum sense voltage and fixed gain of the amplifiers, let's calculate current resistor value. Working on full scale, at 5A sense voltage must be 50mV, so resistor value is 0.01Ω. Each channel uses a precision current resistor (R13, R19) [15] connected across RS+ and RS- pins of the amplifiers using Kelvin connection [16].

Now, to get the voltage at OUT pin we use this formula:
$V_{OUT} = A_G \times R_{SNS} \times I_{RSNS}$ with A_G the fixed gain of the amplifier, R_{SNS} the value of the sense resistor and I_{RSNS} the current through R_{SNS}.
Selecting a 10mA step as the minimum current to read along the full scale, voltage will be:
90 x 0.01Ω x 0.01A = 0.009V. At 5A however we get: 90 x 0.01Ω x 5A = 4.50V.

As a result, even when the current reaches its maximum value, voltage on the analog input (where OUT pin is connected) never exceed its maximum (+5V). See (Current vs Voltage Output).

Circuit Simulation

This section talks about the simulations made on some parts of the design before making the final version. This allowed to study some scenarios and identify some improvements that in other way would had to be studied after the final build.

VIN vs VOUT Using Transfer Function

I make a DC Sweep from 0V to 20V as the module is able to measure only positive voltages contained on this range.
Green line of the graphic showed on Figure 3 displays the relation between voltage applied at the input of +IN pin (labeled V_2 on Figure 2) and OUT pin voltage of IC3. As you can see, this relation is pretty similar as the one calculated before (≈ 4.04).
IC3 is used for simulation analysis but the results are similar for IC5.

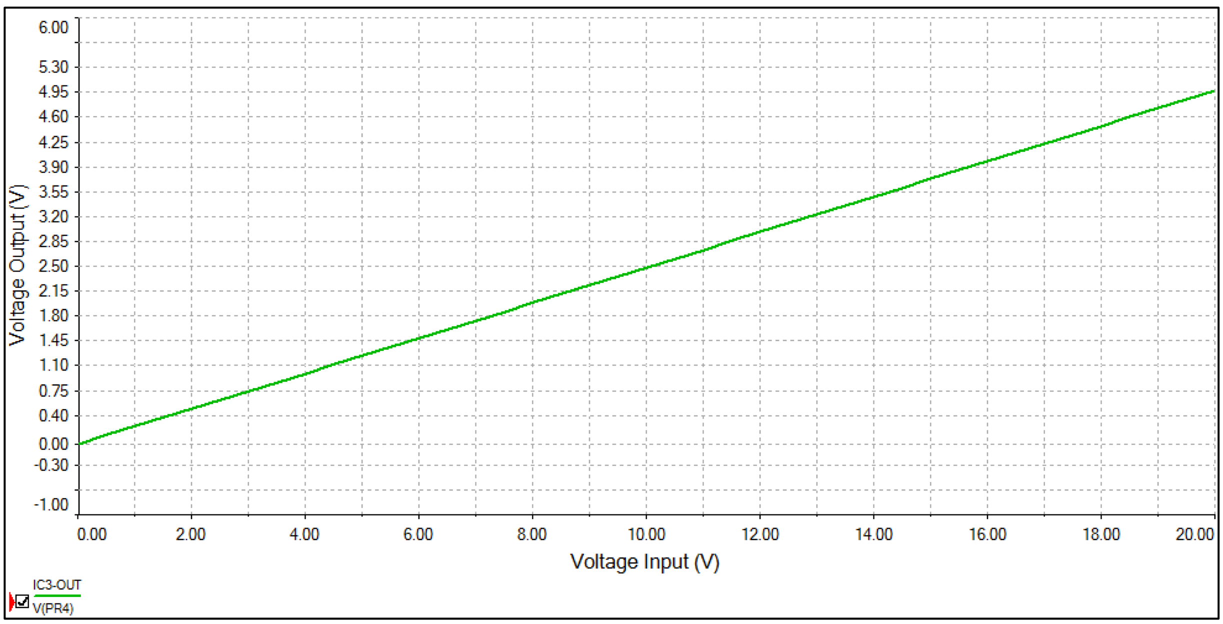


Figure 3 Voltage Input vs Voltage Output

Reverse Polarity Protection on Inputs

To avoid reverse polarity on the inputs a small signal diode serves it purpose. This types of diodes are selected due to their low forward voltage drop and low leakage current.
The light blue trace in the graphic of Figure 4 shows OUT pin voltage of IC3 when inputs are reversed on polarity.

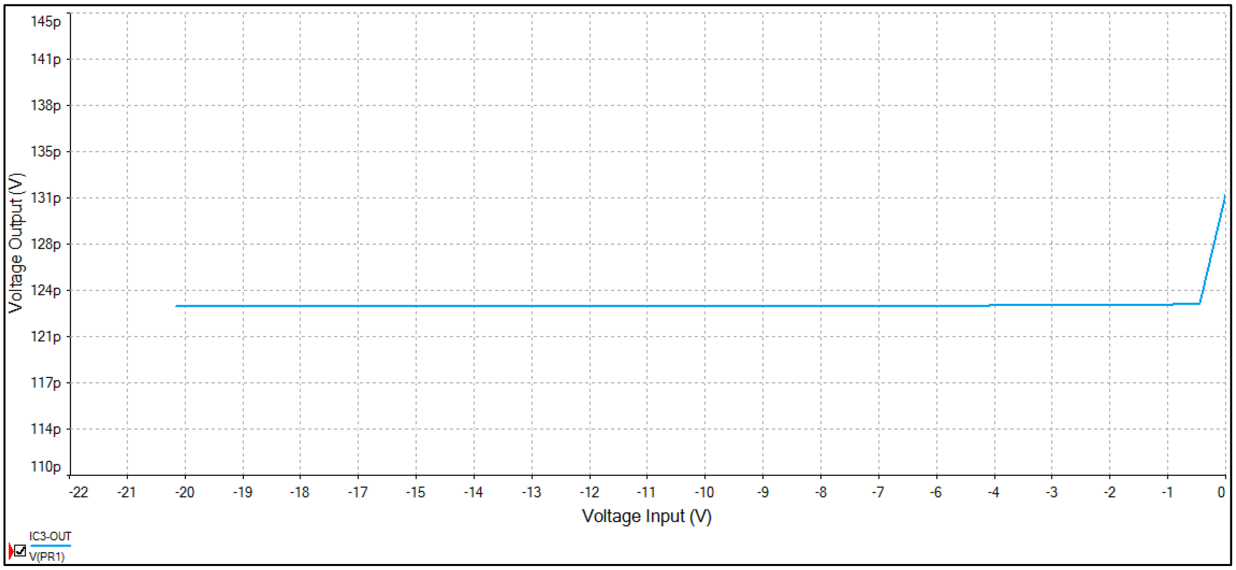


Figure 4 Voltage Output with Reverse Polarity on Inputs

Current vs Voltage Output

For this simulation, I studied the behavior of OUT pin depending on the current across RS+ and RS- pins of IC1. The results are similar for IC4.

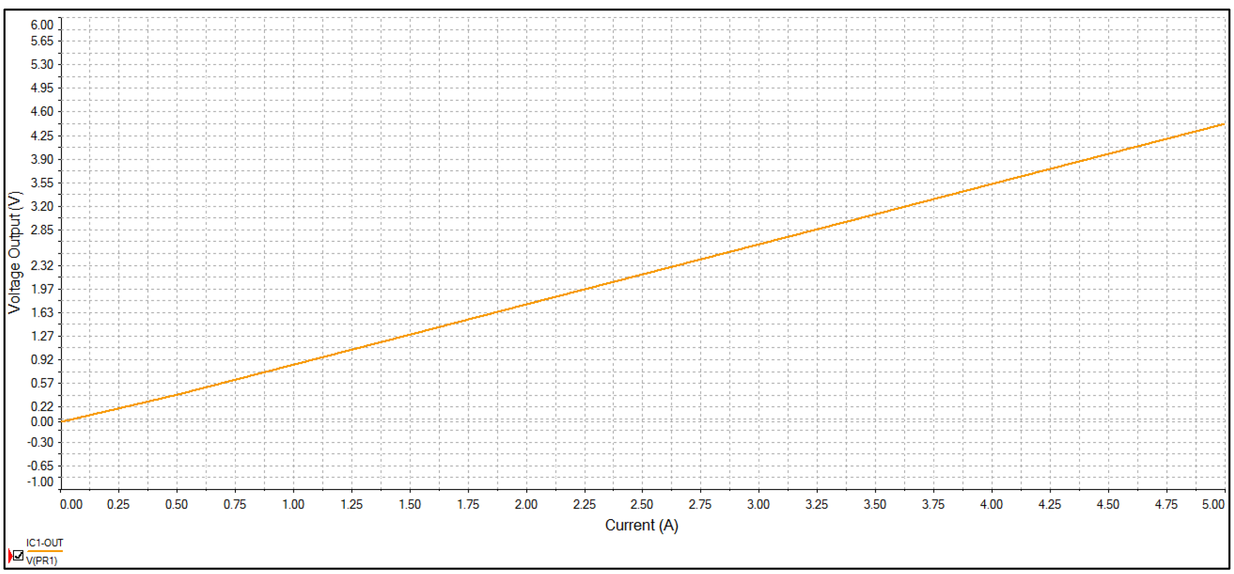


Figure 5 Current vs Voltage Output

Orange line of the graphic displayed on Figure 5 shows the relation of this two magnitudes. For any given current we can see that, if we multiply it by 0.01 (sense resistor value) and the result by 90 (gain of the current amplifier) we get voltages pretty similar to the ones calculated previously considering that, according to datasheet this amplifiers have a 0.6% (max) gain accuracy error.

Additional Characteristics

I’ve included two headers (J6-J7) [17] that provide additional capabilities to the module. Leave J6 without a shunt if you want to power up the microcontroller board using USB port only. It’s useful when debugging code. With a shunt, board is powered by the voltage output of U2 (check that USB port is not connected to a power source).
J7 instead, with a shunt lets the microcontroller board use the external reference voltage provided by IC2. Without it, the default or an internal reference voltage of the board can be used.

Conclusions

After testing the module, I consider it offers all the capabilities needed to measure voltage and current in a power supply.

The calibration process took some time due to the analysis on the module behavior across voltage and current ranges.

References

[1] “251/253 Series” [Online]. Available: https://www.littelfuse.com/media?resourcetype=datasheets&itemid=f47a0bb7-8ede-4679-9646-7114c3787688&filename=littelfuse_fuse_251_253_datasheet.pdf (Accessed Sep. 14, 2024).

[2] “Fairchild Semiconductor” [Online]. Available: https://www.onsemi.com/pdf/datasheet/fds6679-d.pdf (Accessed Sep. 14, 2024).

[3] “SA Series” [Online]. Available: https://m.littelfuse.com/~/media/electronics/datasheets/tvs_diodes/littelfuse_tvs_diode_sa_datasheet.pdf.pdf (Accessed Sep. 14, 2024).

[4] “LM2940x 1-A Low Dropout Regulator datasheet (Rev. J)” [Online]. Available: https://www.ti.com/lit/ds/symlink/lm2940c.pdf (Accessed Sep. 18, 2024).

[5] “250mA Low Dropout Regulator” [Online]. Available: https://www.mouser.com/datasheet/2/268/MIC2954_250mA_Low_Dropout_Regulator_DS20006563A-3442137.pdf (Accessed Sep. 18, 2024).

[6] “A000005 Datasheet - Arduino® Nano” [Online]. Available: https://docs.arduino.cc/resources/datasheets/A000005-datasheet.pdf (Accessed Sep. 18, 2024).

[7] “MAX6225/MAX6241/MAX6250-Low-Noise, Precision, +2.5V/+4.096V/+5V Voltage References” [Online]. Available: https://www.analog.com/media/en/technical-documentation/data-sheets/max6225-max6250.pdf (Accessed Sep. 19, 2024).

[8] “REF02: +5V Precision Voltage Reference datasheet (Rev. B)” [Online]. Available: https://www.ti.com/lit/ds/symlink/ref02.pdf (Accessed Sep. 19, 2024).

[9] “3339 – 5/16″ Round Trimpot® Trimming Potentiometer” [Online]. Available: https://www.bourns.com/docs/Product-Datasheets/3339.pdf (Accessed Sep. 19, 2024).

[10] “AD8605/AD8606/AD8608 (Rev. O)” [Online]. Available: https://www.analog.com/media/en/technical-documentation/data-sheets/AD8605_8606_8608.pdf (Accessed Sep. 22, 2024).

[11] “CMF Industrial Metal Film Resistors, Axial, Industrial, Precision” [Online]. Available: https://www.vishay.com/docs/31018/cmfind.pdf (Accessed Sep. 22, 2024).

[12] Harry Holt, “deeper-look-into-difference-amplifiers.pdf,” Feb 2014. [Online]. Available: https://www.analog.com/media/en/analog-dialogue/volume-48/number-1/articles/deeper-look-into-difference-amplifiers.pdf (Accessed Sep. 22, 2024).

[13] “BAT54W Small Signal Schottky Diode” [Online]. Available: https://www.vishay.com/docs/86408/bat54w.pdf (Accessed Sep. 28, 2024).

[14] “MAX9918/MAX9919/MAX9920 - -20V to +75V Input Range, Precision Uni-/Bidirectional, Current-Sense Amplifiers” [Online]. Available: https://www.analog.com/media/en/technical-documentation/data-sheets/max9918-max9920.pdf (Accessed Sep. 28, 2024).

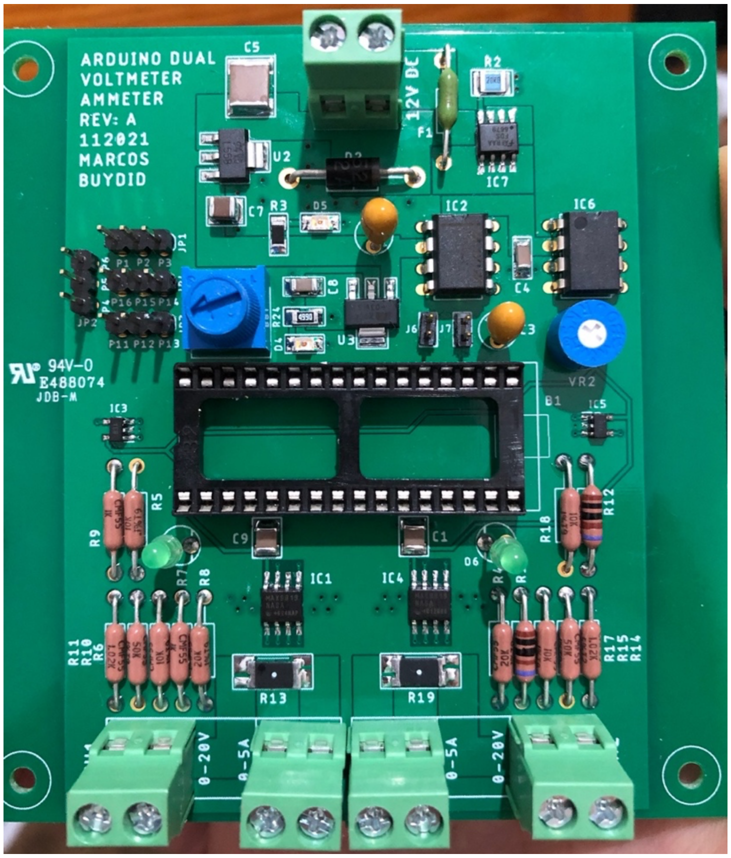
[15] “CSM Series Bulk Metal® Technology High Precision, Current Sensing, Power Surface Mount, Metal Strip Resistor Bulk Metal® Technology High Precision, Current Sensing, Power Surface Mount, Metal Strip Resistor with Resistance Value from 2 mΩ, Rated Power up to 3 W and TCR to 0±15 ppm/°C Maximum” [Online]. Available: https://www.foilresistors.com/docs/63089/csm.pdf (Accessed Sep. 28, 2024).

[16] “lord kelvin's sensing method lives on in the measurement accuracy of ultra-precision current-shunt monitors/current-sense amplifiers” [Online]. Available: https://pdfserv.maximintegrated.com/en/an/AN5761.pdf (Accessed Sep. 29, 2024).

[17] “THROUGH-HOLE LOW PROFILE HEADER” [Online]. Available: https://www.mouser.com/datasheet/2/527/tmm_th-2583629.pdf (Accessed Sep. 29, 2024).

Annexes

Finish Assembly Photos



Module Upper View

Revision History

Date	Version	Changes
Oct-2024	1	First version