Department of Electrical and Computer Engineering

University of Colorado at Boulder

ECEN5730 - Practical PCB design

Lab:18, SBB version of Board 4

Report

Submitted by
Parth Thakkar

Submitted on
April 22, 2024

Contents

List of Figures

List of Tables

PDF is clickable

1 Objective / Purpose of Lab

1. One of the key parameters used to characterize VRMs is the Thevenin equivalent circuit model. The Thevenin model represents a voltage source as a combination of an ideal voltage source (Thevenin voltage, VTH) and a series resistance (Thevenin resistance, RTH). This model is particularly useful for analyzing the behavior of VRMs under varying load conditions, as the output voltage and current will depend on the values of VTH and RTH, as well as the load resistance.

2.

3. The objective of this lab is to design, build, and test a custom instrument, the "Instrument Droid," capable of measuring the Thevenin parameters (VTH and RTH) of various voltage sources and regulators as a function of the output current load. By sweeping the load current and measuring the corresponding output voltages, the Instrument Droid can determine the Thevenin voltage (the open-circuit voltage) and the Thevenin resistance (the slope of the voltage-current curve).

4. To precisely control the voltage across the sense resistor, and consequently the current through the MOSFET, an external digital-to-analog converter (DAC) is utilized. The DAC, in this case, the MCP4725, receives digital inputs from an Arduino microcontroller and generates an analog voltage output proportional to the desired current level.

5. the Instrument Droid incorporates a high-resolution analog-to-digital converter (ADC), specifically the ADS1115, to measure the voltage across the sense resistor and the loaded output voltage of the VRM. By employing differential voltage measurement techniques, the ADC can accurately capture the voltage drops across the sense resistor and the VRM, even in the presence of noise or ground offsets.

6. To account for potential power dissipation issues, especially when characterizing high-current VRMs, the Instrument Droid implements a pulsed current measurement approach. By applying short current pulses with low duty cycles, the average power dissipation in the circuit components can be maintained within safe operating limits, preventing overheating and potential damage.

2 Component listing

Table 1: Component Listing

Component	**Description**	**Quantity**
Arduino Uno	Microcontroller board	1
MCP4725	12-bit DAC	1
ADS1115	16-bit ADC	1
MOSFET (IRL520)	Electronic load	1
Op-amp (MCP601)	Operational amplifier	1
Sense resistor	Current sense resistor (10 Ω)	1
Resistors	Voltage divider resistors	2
Breadboard	Solderless breadboard	1
Jumper wires	Connection wires	As needed

3 Explanation

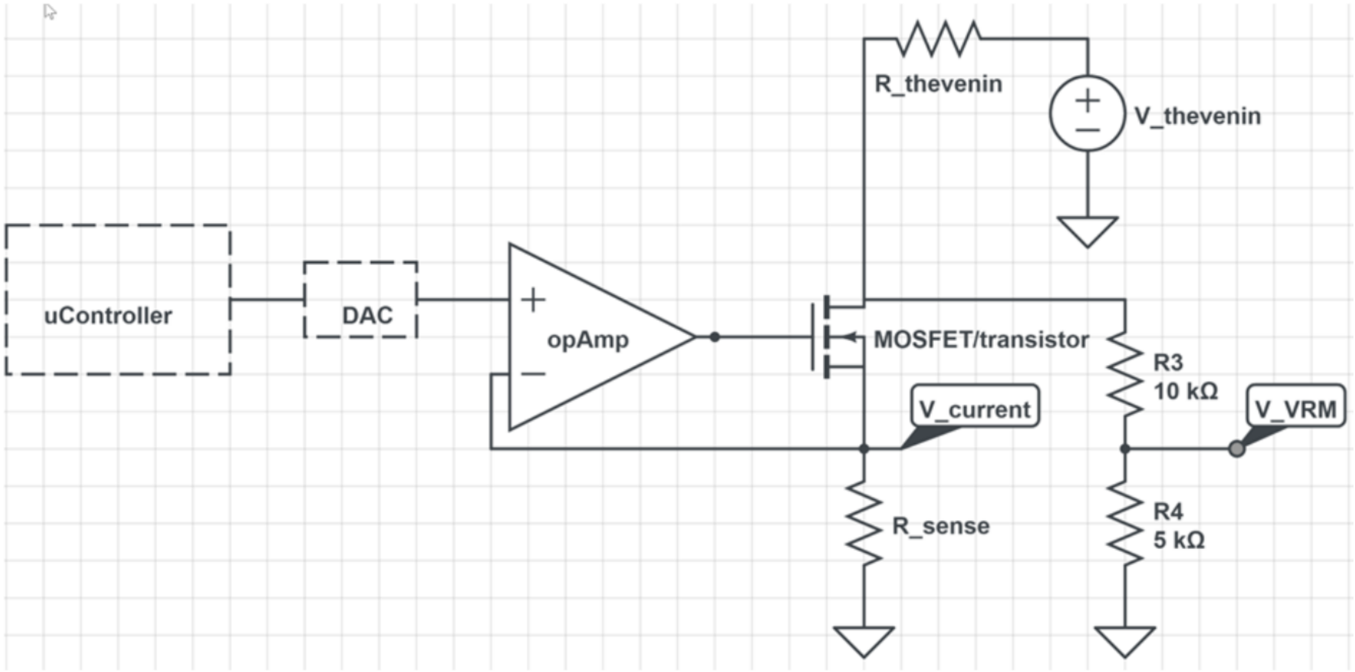


Figure 1: Block diagram

- In this circuit configuration, the operational amplifier (op-amp) is crucial for its role in controlling the MOSFET as a voltage-controlled current source. The op-amp is set up in a non-inverting configuration, where its output is fed back to its inverting input through a voltage divider formed by R3 and R4. This feedback loop allows the op-amp to adjust its output voltage to match the input voltage, effectively functioning as a voltage follower.
- The DAC, controlled by a microcontroller, generates an analog voltage proportional to the desired current level. This voltage signal is applied to the non-inverting input of the op-amp, serving as the reference voltage for the op-amp's negative feedback loop. That is why we are giving it stable output thorough DAC IC
- we are using voltage divider for measuring VRM voltage as ADS1115 is only capable of measuring 5 V , voltage sources higher than 5 v will burn the ADS11115 that is why we are using voltage divider
- In this circuit, V_current and V_VRM are used to measure the current through the VRM and the VRM's output voltage, respectively. These measurements are essential for determining the Thevenin equivalent of the VRM.
- Measuring V_current (Voltage across R_sense):
  The voltage across the sense resistor (R_sense) is directly proportional to the current flowing through it, according to Ohm's law: V = I x R. By measuring the voltage across R_sense using the microcontroller's ADC and knowing the value of R_sense, we can calculate the current through the VRM:
  - I_VRM = V_current / R_sense
  - This current measurement allows us to characterize the VRM's behavior under different load conditions.
- Measuring V_VRM:
  V_VRM represents the output voltage of the VRM. However, the VRM's output voltage may be too high for the microcontroller's ADC to measure directly. To overcome this, a voltage divider consisting

of resistors R3 and R4 is used to scale down the VRM voltage to a level suitable for the ADC. The scaled VRM voltage (V_VRM_scaled) is given by:

  - V_VRM_scaled = V_VRM · $\frac{R4}{(R3+R4)}$
  - By measuring V_VRM_scaled using the ADC and knowing the values of R3 and R4, we can calculate the actual VRM output voltage:
  - V_VRM = V_VRM_scaled · $\frac{(R3+R4)}{R4}$

- Op-amp usage:

  - The op-amp in this circuit is configured as a non-inverting amplifier, which serves as a voltage-controlled current source (VCCS) for the MOSFET. The DAC output voltage is applied to the non-inverting input of the op-amp, and the inverting input is connected to the sense resistor (R_sense).
  - The op-amp tries to maintain the same voltage at both its inputs by adjusting its output voltage. This forces the voltage across R_sense to be equal to the DAC output voltage. As a result, the current through R_sense, and consequently the current through the MOSFET and VRM, is controlled by the DAC output voltage.
  - The op-amp also provides a high input impedance, ensuring that it doesn't load the DAC output, and a low output impedance, enabling it to drive the MOSFET gate effectively.

- MOSFET usage:

  - The MOSFET acts as a voltage-controlled current source in this circuit. The op-amp output voltage, which is controlled by the DAC, is applied to the MOSFET's gate. The MOSFET's drain current (I_D) is proportional to the gate-source voltage (V_GS) when operating in the saturation region.
  - By varying the DAC output voltage, the op-amp adjusts the MOSFET's gate voltage, thus controlling the current through the MOSFET and, consequently, the current through the VRM. This allows the microcontroller to set different load currents and measure the VRM's response.
  - The MOSFET is chosen for its high input impedance, which minimizes loading on the op-amp output, and its ability to handle large currents required for characterizing the VRM.

In summary, the op-amp and MOSFET work together as a voltage-controlled current source to regulate the current through the VRM, while V_current and V_VRM measurements provide the necessary data for determining the VRM's Thevenin equivalent.

```
  // vrm characterizer board
#include <Wire.h>
#include <Adafruit_MCP4725.h>
Adafruit_MCP4725 dac;
float DAC_ADU_per_v = 4095.0 / 5.0;  //conversion from volts to ADU
int V_DAC_ADU;                       // the value in ADU to output on the DAC

void setup() {
  Serial.begin(115200);
  dac.begin(0x60);             // address is either 0x60, 0x61, 0x62,0x63, 0x64 or 0x65
  dac.setVoltage(0, false);   //sets the output current to 0 initially
}




void loop() {
  // put your main code here, to run repeatedly:
  V_DAC_ADU = 0 * DAC_ADU_per_v;
  dac.setVoltage(V_DAC_ADU, false);  //sets the output current to 0 initially
  V_DAC_ADU = 3.0 * DAC_ADU_per_v;
  dac.setVoltage(V_DAC_ADU, false);  //sets the output current to 0 initially
}
```

```
  // vrm characterizer board
#include <Wire.h>
#include <Adafruit_MCP4725.h>
#include <Adafruit_ADS1X15.h>

Adafruit_ADS1115 ads;
Adafruit_MCP4725 dac;
float R_sense = 10.0;                      //current sensor
long itime_on_msec = 100;                  //on time for taking measurements
long itime_off_msec = itime_on_msec * 10;  // time to cool off
int iCounter_off = 0;                      // counter for number of samples off
int iCounter_on = 0;                       // counter for number of samples on
float v_divider = 5000.0 / 15000.0;        // voltage divider on the VRM
float DAC_ADU_per_v = 4095.0 / 5.0;        //conversion from volts to ADU
int V_DAC_ADU;                             // the value in ADU to output on the DAC
int I_DAC_ADU;                             // the current we want to output
float I_A = 0.0;                           // the current we want to output, in amps
long itime_stop_usec;                      // this is the stop time for each loop
float ADC_V_per_ADU = 0.125 * 1e-3;        // the voltage of one bit on the gain of 1 scale
float V_VRM_on_v;                          // the value of the VRM voltage
float V_VRM_off_v;                         // the value of the VRM voltage
float I_sense_on_A;                        // the current through the sense resistor
float I_sense_off_A;                       // the current through the sense resistor
float I_max_A = 0.25;                      // max current to set for
int npts = 20;                             //number of points to measure
float I_step_A = I_max_A / npts;           //step current change


float I_load_A;  // the measured current load
float V_VRM_thevenin_v;
float V_VRM_loaded_v;
float R_thevenin;
int i;


void setup() {
  Serial.begin(115200);
  dac.begin(0x60);           // address is either 0x60, 0x61, 0x62,0x63, 0x64 or 0x65
  dac.setVoltage(0, false);  //sets the output current to 0 initially


  // ads.setGain(GAIN_TWOTHIRDS); // 2/3x gain +/- 6.144V 1 bit = 3mV     0.1875mV (default)
  ads.setGain(GAIN_ONE);  // 1x gain   +/- 4.096V 1 bit = 2mV     0.125mV
  // ads.setGain(GAIN_TWO);       // 2x gain   +/- 2.048V 1 bit = 1mV     0.0625mV
  // ads.setGain(GAIN_FOUR);      // 4x gain   +/- 1.024V 1 bit = 0.5mV   0.03125mV
  // ads.setGain(GAIN_EIGHT);     // 8x gain   +/- 0.512V 1 bit = 0.25mV  0.015625mV
  // ads.setGain(GAIN_SIXTEEN);   // 16x gain  +/- 0.256V 1 bit = 0.125mV 0.0078125mV
  ads.begin();                           // note- you can put the address of the ADS111 here if need
  ads.setDataRate(RATE_ADS1115_860SPS);  // sets the ADS1115 for higher speed
}


void loop() {
  for (i = 1; i <= npts; i++) {
    I_A = i * I_step_A;
    dac.setVoltage(0, false);  //sets the output current
    func_meas_off();
    func_meas_on();
    dac.setVoltage(0, false);  //sets the output current


    I_load_A = I_sense_on_A - I_sense_off_A;  //load current
    V_VRM_thevenin_v = V_VRM_off_v;
    V_VRM_loaded_v = V_VRM_on_v;
    R_thevenin = (V_VRM_thevenin_v - V_VRM_loaded_v) / I_load_A;
    // if (V_VRM_loaded_v < 0.75 * V_VRM_thevenin_v) i = npts;  //stops the ramping


    Serial.print(i);
    Serial.print(", ");
    Serial.print(I_load_A * 1e3, 3);
    Serial.print(", ");
    Serial.print(V_VRM_thevenin_v, 4);
    Serial.print(", ");
    Serial.print(V_VRM_loaded_v, 4);
    Serial.print(", ");
    Serial.println(R_thevenin, 4);
  }
  Serial.println("done");
  delay(30000);
}



void func_meas_off() {
  dac.setVoltage(0, false);  //sets the output current
  iCounter_off = 0;          //starting the current counter

  V_VRM_off_v = 0.0;  //initialize the VRM voltage averager

  I_sense_off_A = 0.0;  // initialize the current averager

  itime_stop_usec = micros() + itime_off_msec * 1000;  // stop time
  while (micros() <= itime_stop_usec) {
    V_VRM_off_v = ads.readADC_Differential_0_1() * ADC_V_per_ADU / v_divider + V_VRM_off_v;
    I_sense_off_A = ads.readADC_Differential_2_3() * ADC_V_per_ADU / R_sense + I_sense_off_A;
    iCounter_off++;
  }
  V_VRM_off_v = V_VRM_off_v / iCounter_off;
  I_sense_off_A = I_sense_off_A / iCounter_off;
  // Serial.print(iCounter_off);Serial.print(", ");
  // Serial.print(I_sense_off_A * 1e3, 4); Serial.print(", ");
  // Serial.println(V_VRM_off_v, 4);
}


void func_meas_on() {
  //now turn on the current
  I_DAC_ADU = I_A * R_sense * DAC_ADU_per_v;
  dac.setVoltage(I_DAC_ADU, false);  //sets the output current
  iCounter_on = 0;
  V_VRM_on_v = 0.0;                                    //initialize the VRM voltage averager
  I_sense_on_A = 0.00;                                 // initialize the current averager
  itime_stop_usec = micros() + itime_on_msec * 1000;  // stop time

  while (micros() <= itime_stop_usec) {
    V_VRM_on_v = ads.readADC_Differential_0_1() * ADC_V_per_ADU / v_divider + V_VRM_on_v;
    I_sense_on_A = ads.readADC_Differential_2_3() * ADC_V_per_ADU / R_sense + I_sense_on_A;
    iCounter_on++;
  }
  dac.setVoltage(0, false);
  //sets the output current to zero
  V_VRM_on_v = V_VRM_on_v / iCounter_on;
  I_sense_on_A = I_sense_on_A / iCounter_on;
  // Serial.print(iCounter_on);Serial.print(", ");
  // Serial.print(I_sense_on_A * 1e3, 4);Serial.print(", ");
  // Serial.println(V_VRM_on_v, 4);
```

```
}
```

Here's a breakdown of the code:

- It iterates over a specified number of points (npts) with increasing load currents (I_A). For each iteration: a. It calls func_meas_off() to measure the VRM voltage (V_VRM_off_v) and current (I_sense_off_A) when no load is applied. b. It calls func_meas_on() to apply the desired load current (I_A) and measure the corresponding VRM voltage (V_VRM_on_v) and current (I_sense_on_A). c. It calculates the load current (I_load_A), Thevenin equivalent voltage (V_VRM_thevenin_v), loaded VRM voltage (V_VRM_loaded_v), and Thevenin resistance (R_thevenin). d. It prints the measurement results (iteration, load current, Thevenin voltage, loaded voltage, Thevenin resistance). e. It checks if the loaded VRM voltage drops below 75% of the Thevenin voltage. If so, it stops the ramping process (i = npts) because the VRM is unable to supply more current without significant voltage drop.
- The func_meas_off() and func_meas_on() functions handle the actual measurement process:
  - func_meas_off() sets the DAC output to 0 (no load), then takes multiple samples of the VRM voltage and current over a specified time period (itime_off_msec). It averages the samples to obtain V_VRM_off_v and I_sense_off_A.
  - func_meas_on() sets the DAC output to apply the desired load current (I_DAC_ADU), then takes multiple samples of the VRM voltage and current over a specified time period (itime_on_msec). It averages the samples to obtain V_VRM_on_v and I_sense_on_A.
  - The reason for stopping the ramping process when the loaded VRM voltage drops below 75% of the Thevenin voltage is to prevent excessive loading of the VRM, which could potentially damage it or cause unreliable measurements. This threshold is a safety measure to ensure that the VRM is not pushed beyond its capable current delivery range.
- By measuring the Thevenin voltage and resistance at different load currents, this code can characterize the behavior of the VRM, including its output impedance, current-handling capability, and any non-linear effects that may occur at higher currents.

4 Measurement

The Instrument Droid was used to characterize various voltage sources and regulators, including known sources for verification purposes and unknown sources to demonstrate the instrument's capabilities. This section presents the measurement results and analyses for each source.

4.1 Function Generator as a Known Source

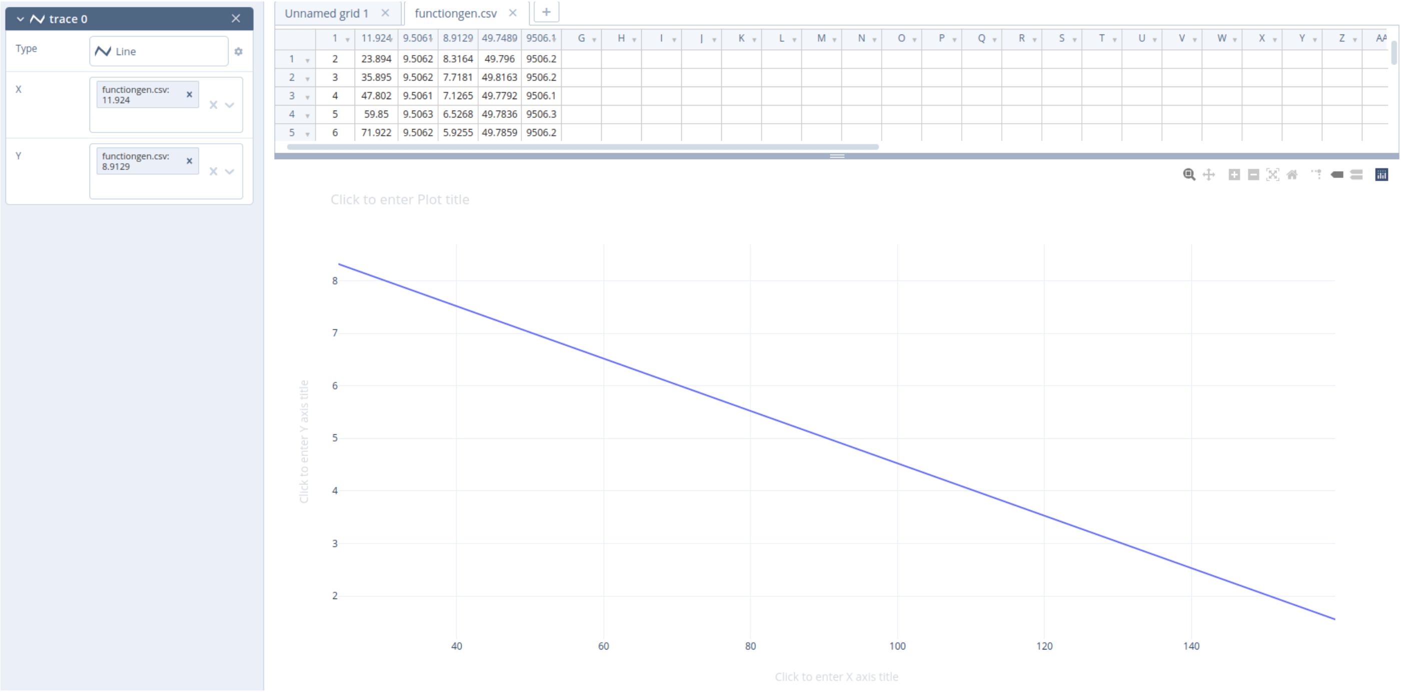
To verify the proper operation of the Instrument Droid, a function generator was initially used as a known voltage source. The function generator was set to provide a constant DC voltage output, and its Thevenin parameters were calculated based on the manufacturer's specifications & previous labs.

Expected Thevenin Resistance (RTH): 50Ω

The Instrument Droid was then used to measure the function generator's output voltage and current at various load conditions. The measured data was processed to determine the Thevenin parameters, and the results were compared to the expected values.

Measured Value
$\boxed{TheveninResistance(RTH) : 49.82\Omega}$
The measured Thevenin voltage and resistance closely matched the expected values, confirming the accurate operation of the Instrument Droid.

7 shows the plot of the measured Thevenin resistance versus the output current for the function generator.



trace 0

Type: Line

X: functiongen.csv: 11.924

Y: functiongen.csv: 8.9129

Unnamed grid 1 | functiongen.csv

	1	11.924	9.5061	8.9129	49.7489	9506.1	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
1	2	23.894	9.5062	8.3164	49.796	9506.2																					
2	3	35.895	9.5062	7.7181	49.8163	9506.2																					
3	4	47.802	9.5061	7.1265	49.7792	9506.1																					
4	5	59.85	9.5063	6.5268	49.7836	9506.3																					
5	6	71.922	9.5062	5.9255	49.7859	9506.2																					

Click to enter Plot title
8
7
6
5
4
3
2
40
60
80
100
120
140
Click to enter Y axis title
Click to enter X axis title

Figure 2: Current vs Voltage for function generator

As expected, the Thevenin resistance remained relatively constant across the measured current range, consistent with the low output impedance of the function generator, slope of this graph gives us R_th which is 50ohm in our case

```
function generator output:
1, 11.924, 9.5061, 8.9129, 49.7489
2, 23.894, 9.5062, 8.3164, 49.7960
3, 35.895, 9.5062, 7.7181, 49.8163
4, 47.802, 9.5061, 7.1265, 49.7792
5, 59.850, 9.5063, 6.5268, 49.7836
6, 71.922, 9.5062, 5.9255, 49.7859
7, 83.958, 9.5060, 5.3261, 49.7859
8, 96.045, 9.5060, 4.7236, 49.7944
9, 107.803, 9.5060, 4.1337, 49.8350
10, 119.821, 9.5059, 3.5365, 49.8195
11, 131.941, 9.5061, 2.9306, 49.8362
12, 143.925, 9.5061, 2.3353, 49.8233
13, 155.883, 9.5060, 1.7387, 49.8279
14, 159.550, 9.5062, 1.5550, 49.8350
15, 159.550, 9.5062, 1.5548, 49.8361
16, 159.560, 9.5060, 1.5548, 49.8322
17, 159.565, 9.5060, 1.5546, 49.8319
18, 159.568, 9.5062, 1.5551, 49.8290
19, 159.568, 9.5061, 1.5551, 49.8286
20, 159.570, 9.5060, 1.5554, 49.8254
done
```

4.2 Bench Power Supply

Expected Value of RTH
Thevenin Resistance (RTH) 1Ω to 5Ω

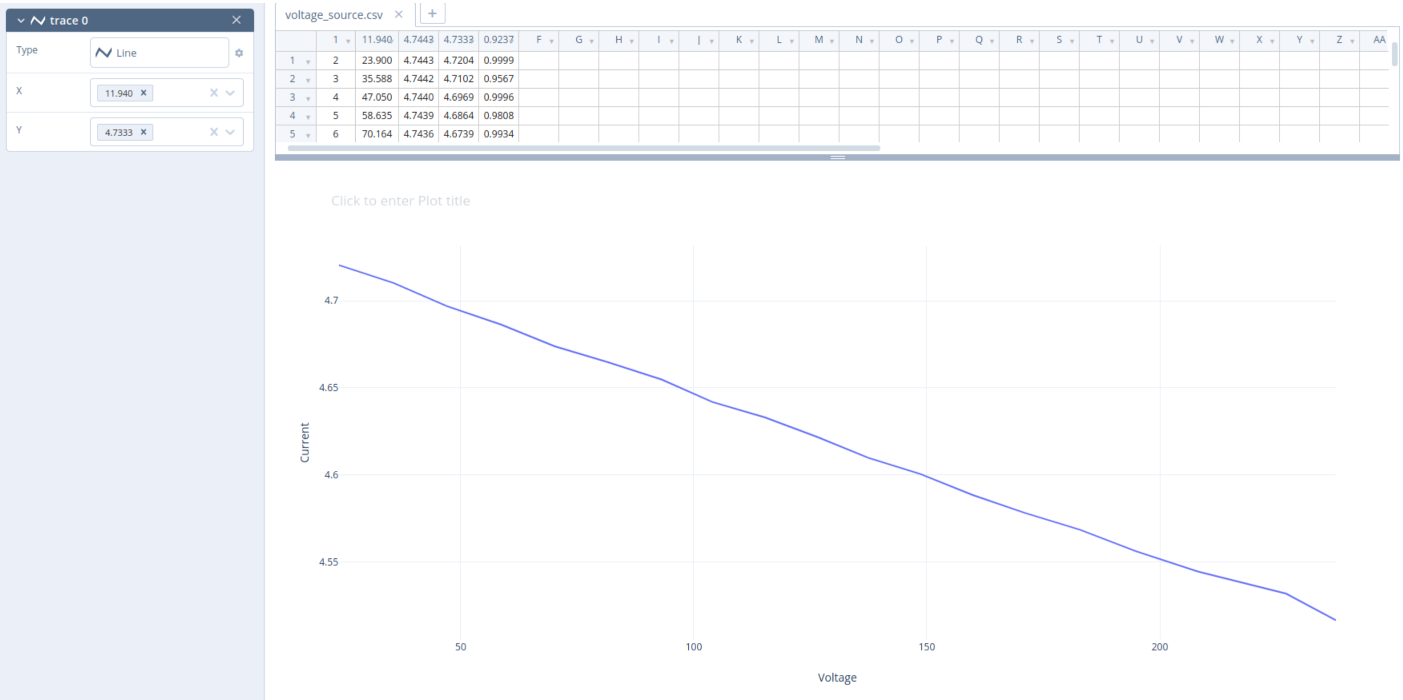
The Instrument Droid was then used to measure the Voltage Supply set at 5V voltage and current at various load conditions. The measured data was processed to determine the Thevenin parameters, and the results were compared to the expected values.

Measured Value

$\boxed{TheveninResistance(RTH) : 0.95\Omega}$

The measured Thevenin voltage and resistance closely matched the expected values, confirming the accurate operation of the Instrument Droid.

Figure 2 shows the plot of the measured Thevenin resistance versus the output current for the modified bench power supply.



	1	11.940	4.7443	4.7333	0.9237	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
1	2	23.900	4.7443	4.7204	0.9999																						
2	3	35.588	4.7442	4.7102	0.9567																						
3	4	47.050	4.7440	4.6969	0.9996																						
4	5	58.635	4.7439	4.6864	0.9808																						
5	6	70.164	4.7436	4.6739	0.9934																						

Figure 3: Current vs Voltage Source Graph for Function generator

As anticipated, the Thevenin resistance remained relatively constant across the measured current range, reflecting the combined resistance of the power supply's output impedance and the added series resistor.

```
Voltage source
1, 11.940, 4.7443, 4.7333, 0.9237
2, 23.900, 4.7443, 4.7204, 0.9999
3, 35.588, 4.7442, 4.7102, 0.9567
4, 47.050, 4.7440, 4.6969, 0.9996
5, 58.635, 4.7439, 4.6864, 0.9808
6, 70.164, 4.7436, 4.6739, 0.9934
7, 81.665, 4.7434, 4.6647, 0.9644
8, 93.135, 4.7434, 4.6548, 0.9515
9, 104.004, 4.7434, 4.6419, 0.9763
10, 115.224, 4.7435, 4.6331, 0.9585
11, 126.478, 4.7435, 4.6219, 0.9615
12, 137.464, 4.7436, 4.6099, 0.9731
13, 148.660, 4.7436, 4.6006, 0.9624
14, 159.808, 4.7435, 4.5886, 0.9689
15, 171.008, 4.7437, 4.5783, 0.9670
16, 182.815, 4.7437, 4.5687, 0.9571
17, 194.903, 4.7438, 4.5563, 0.9618
18, 208.189, 4.7437, 4.5446, 0.9560
```

```
19, 227.082, 4.7439, 4.5320, 0.9333
20, 237.792, 4.7439, 4.5167, 0.9553
done
```

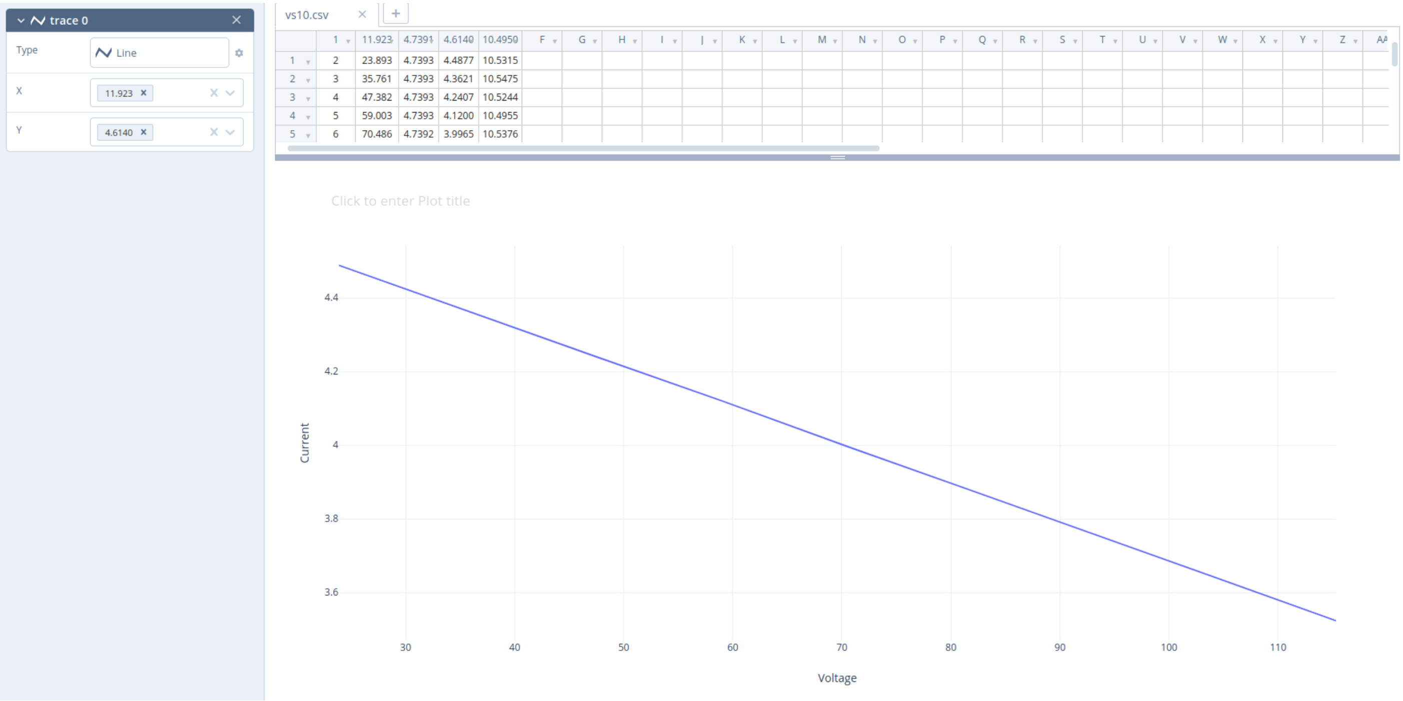
4.3 Bench Power Supply with Known Resistance

To further validate the Instrument Droid's measurements, a bench power supply was used with a known series resistor added. This configuration allowed for a predictable Thevenin resistance to be measured.

Added Series Resistor: 10Ω
Expected Thevenin Resistance (RTH): 1Ω +10Ω = 11Ω

Measured Value
$\boxed{Thevenin Resistance 11\Omega}$
The measured Thevenin voltage and resistance closely matched the expected values, further confirming the accuracy of the Instrument Droid's measurements.

Figure **??** shows the plot of the measured Thevenin resistance versus the output current for the modified bench power supply.



trace 0

Type: Line
X: 11.923
Y: 4.6140

vs10.csv

	1	11.923	4.7391	4.6140	10.4950	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
1	2	23.893	4.7393	4.4877	10.5315																						
2	3	35.761	4.7393	4.3621	10.5475																						
3	4	47.382	4.7393	4.2407	10.5244																						
4	5	59.003	4.7393	4.1200	10.4955																						
5	6	70.486	4.7392	3.9965	10.5376																						

Figure 4: current vs Voltage for Voltage Source with 10Ω added

As anticipated, the Thevenin resistance remained relatively constant across the measured current range, reflecting the combined resistance of the power supply's output impedance and the added series resistor.

```
1, 11.923, 4.7391, 4.6140, 10.4950
2, 23.893, 4.7393, 4.4877, 10.5315
3, 35.761, 4.7393, 4.3621, 10.5475
4, 47.382, 4.7393, 4.2407, 10.5244
5, 59.003, 4.7393, 4.1200, 10.4955
6, 70.486, 4.7392, 3.9965, 10.5376
7, 81.636, 4.7393, 3.8793, 10.5348
8, 92.688, 4.7395, 3.7631, 10.5339
9, 103.668, 4.7393, 3.6467, 10.5395
```

```
20, 115.301, 4.7393, 3.5235, 10.5442
done
```

4.4 Unknown Voltage Sources

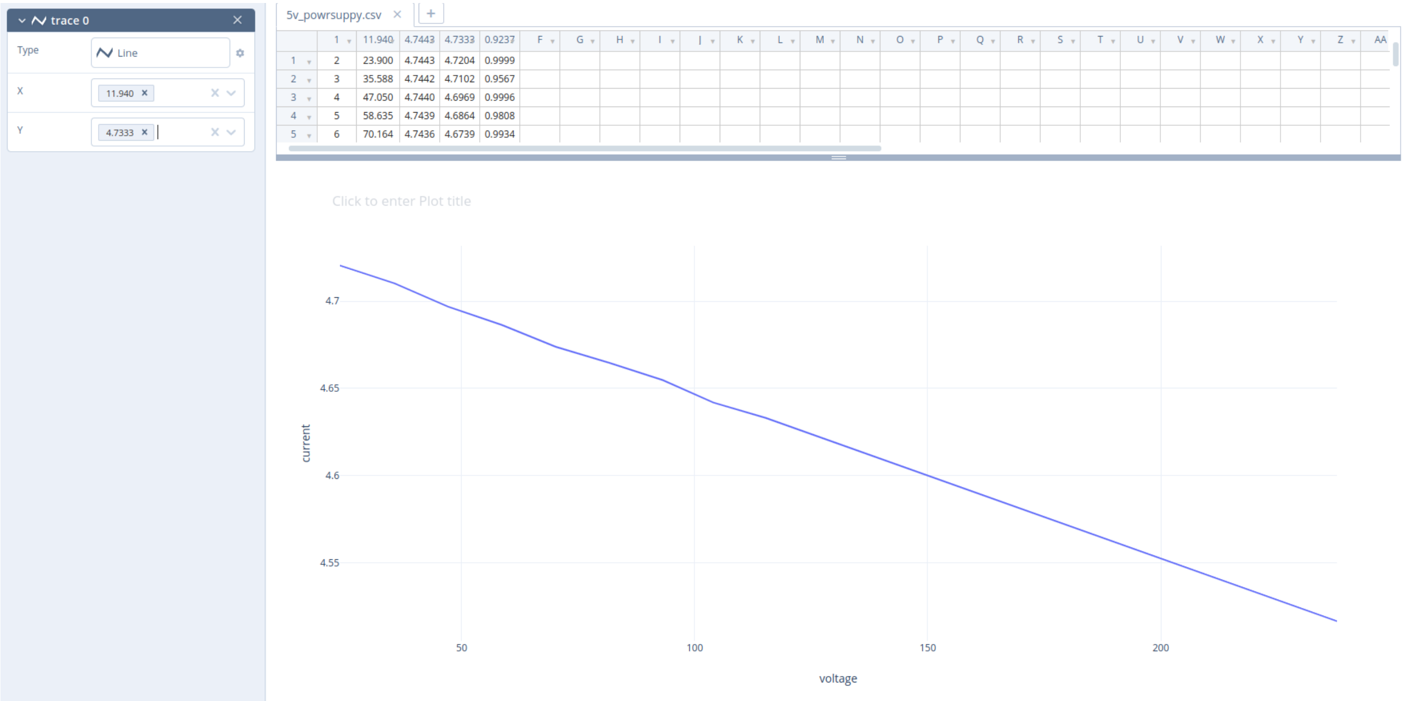
After verifying the Instrument Droid's operation with known sources, various unknown voltage sources and regulators were characterized. These sources included wall warts, batteries, Arduino outputs, op-amp outputs, and other voltage sources commonly found in electronics laboratories.

For each unknown source, the Instrument Droid measured the output voltage and current at various load conditions. The measured data was processed to determine the Thevenin parameters, and the results were analyzed to gain insights into the source's behavior.

4.4.1 5V Wall Wart

The first unknown source measured was a 5V wall wart power adapter. The Instrument Droid was used to sweep the load current and measure the corresponding output voltages.

Parameter Measured Value
Thevenin Voltage (VTH) 4.5V
$\boxed{TheveninResistance(RTH)0.9553\Omega}$
Figure **??** shows the plot of the measured Thevenin resistance versus the output current for the 5V wall wart.



trace 0
Type: Line
X: 11.940
Y: 4.7333

5v_powrsuppy.csv

	1	11.940	4.7443	4.7333	0.9237	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
1	2	23.900	4.7443	4.7204	0.9999																						
2	3	35.588	4.7442	4.7102	0.9567																						
3	4	47.050	4.7440	4.6969	0.9996																						
4	5	58.635	4.7439	4.6864	0.9808																						
5	6	70.164	4.7436	4.6739	0.9934																						

Figure 5: Voltage vs Current analysis 5V supply

Analysis and observations:
Slope of the graph gives us R_th for the 5v wall power supply, from the graph we can see that the R_th is around 1Ω which matches the output of instrument droid

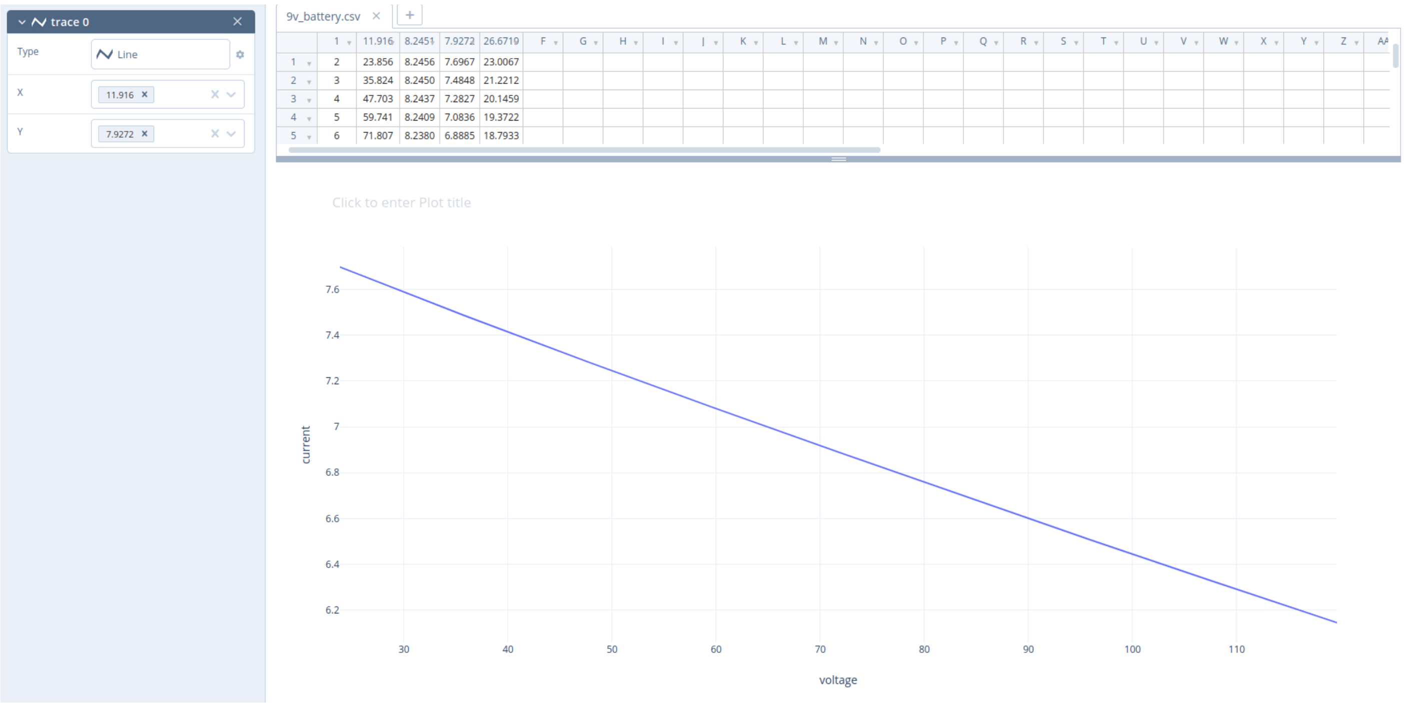
```
1, 11.940, 4.7443, 4.7333, 0.9237
2, 23.900, 4.7443, 4.7204, 0.9999
```

```
3, 35.588, 4.7442, 4.7102, 0.9567
4, 47.050, 4.7440, 4.6969, 0.9996
5, 58.635, 4.7439, 4.6864, 0.9808
6, 70.164, 4.7436, 4.6739, 0.9934
7, 81.665, 4.7434, 4.6647, 0.9644
8, 93.135, 4.7434, 4.6548, 0.9515
9, 104.004, 4.7434, 4.6419, 0.9763
10, 115.224, 4.7435, 4.6331, 0.9585
20, 237.792, 4.7439, 4.5167, 0.9553
```

4.4.2 9V battery

The second unknown source measured was a 9V wall Battery. The Instrument Droid was used to sweep the load current and measure the corresponding output voltages.

Measured Value
$\boxed{TheveninResistance(RTH)17\Omega}$
Figure **??** shows the plot of the measured Thevenin resistance versus the output current for the 5V wall wart.



9v_battery.csv

trace 0

Type: Line

X: 11.916

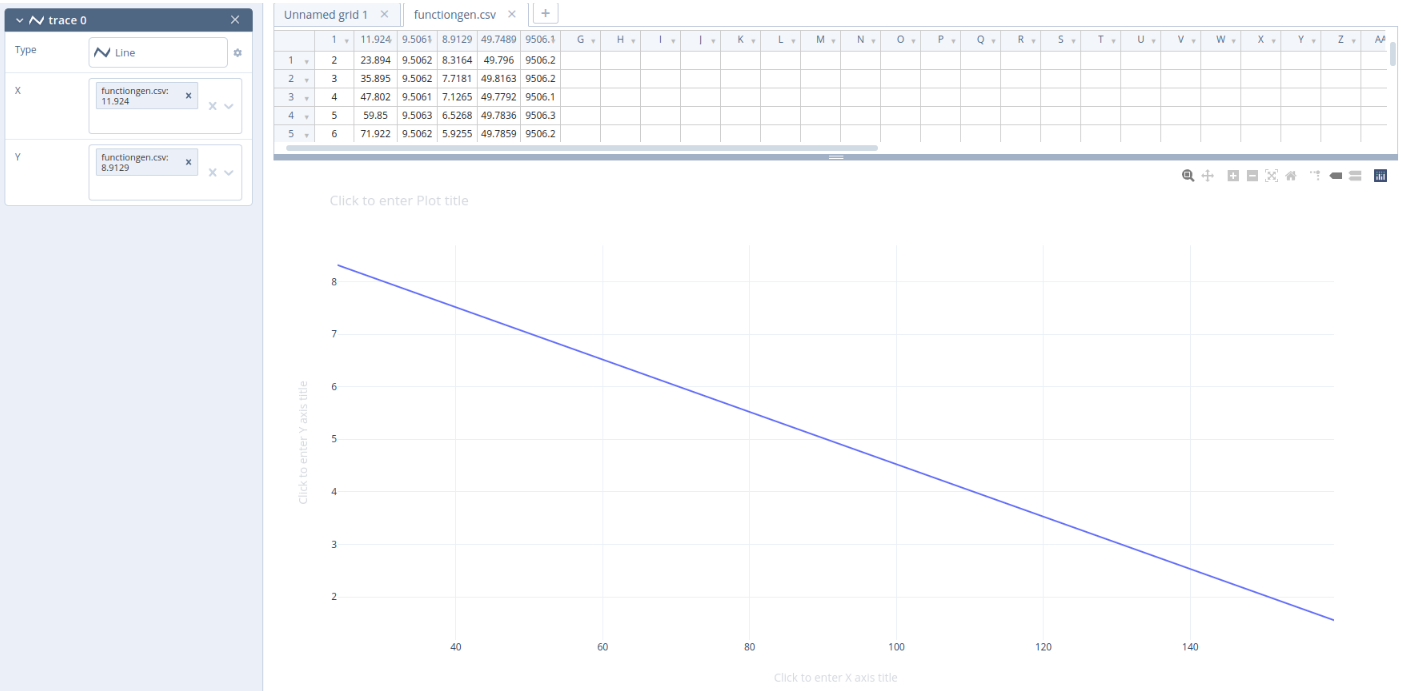
Y: 7.9272

	1	11.916	8.2451	7.9272	26.6719	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
1	2	23.856	8.2456	7.6967	23.0067																						
2	3	35.824	8.2450	7.4848	21.2212																						
3	4	47.703	8.2437	7.2827	20.1459																						
4	5	59.741	8.2409	7.0836	19.3722																						
5	6	71.807	8.2380	6.8885	18.7933																						

Figure 6: Current vs Voltage for 9V supply

Analysis and observations:
Slope of the graphs gives us 17Ω which matches our R_th output of the instrument droid

```
1, 11.916, 8.2451, 7.9272, 26.6719
2, 23.856, 8.2456, 7.6967, 23.0067
3, 35.824, 8.2450, 7.4848, 21.2212
4, 47.703, 8.2437, 7.2827, 20.1459
5, 59.741, 8.2409, 7.0836, 19.3722
6, 71.807, 8.2380, 6.8885, 18.7933
7, 83.825, 8.2347, 6.6979, 18.3336
8, 95.877, 8.2314, 6.5083, 17.9723
9, 107.644, 8.2274, 6.3271, 17.6537
20, 119.629, 8.2231, 6.1461, 17.3624
done
```



trace 0

Type: Line

X: functiongen.csv: 11.924

Y: functiongen.csv: 8.9129

Unnamed grid 1 | functiongen.csv

	1	11.924	9.5061	8.9129	49.7489	9506.1
1	2	23.894	9.5062	8.3164	49.796	9506.2
2	3	35.895	9.5062	7.7181	49.8163	9506.2
3	4	47.802	9.5061	7.1265	49.7792	9506.1
4	5	59.85	9.5063	6.5268	49.7836	9506.3
5	6	71.922	9.5062	5.9255	49.7859	9506.2

G
H
I
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z
AA
Click to enter Plot title
8
7
6
5
4
3
2
Click to enter Y axis title
40
60
80
100
120
140
Click to enter X axis title

Figure 7: Block diagram

5 Learnings and Observation

1. Practical circuit design and implementation: The lab provided hands-on experience in designing and constructing a custom instrument (Instrument Droid) for characterizing voltage sources and regulators. This involved selecting appropriate components, considering power dissipation, and implementing measurement techniques, reinforcing the importance of careful design and analysis.

2. Integration of multiple subsystems: The Instrument Droid involved the integration of various subsystems, including a microcontroller, DAC, ADC, op-amp, and MOSFET. Coordinating the operations of these subsystems and ensuring proper interfacing and communication was a valuable learning experience in system integration and design.

3. Noise management and signal conditioning: The lab highlighted the impact of noise and signal integrity on measurements. Techniques such as differential voltage measurement and proper grounding practices were essential for obtaining accurate and reliable results, reinforcing the importance of noise management and signal conditioning in electronic circuit design.

4. Data analysis and visualization: The lab involved collecting and processing measurement data, calculating parameters, and plotting the results. This reinforced the importance of data analysis, visualization, and interpretation in characterizing and understanding the behavior of electronic systems.

6 Conclusion

1. The Instrument Droid proved to be an effective tool for characterizing voltage sources and regulators by measuring their Thevenin parameters. By sweeping the load current and measuring the corresponding output voltages, the Instrument Droid could accurately determine the Thevenin voltage and Thevenin resistance.

2. Verification with known sources, such as a function generator and a bench power supply with a known series resistor, confirmed the accurate operation of the Instrument Droid. This approach allowed for

the identification and resolution of any potential issues before proceeding to characterize unknown sources.

3. The Instrument Droid successfully characterized various unknown voltage sources, including wall warts, batteries, Arduino outputs, op-amp outputs, and other voltage sources commonly found in electronics laboratories. The measured Thevenin parameters and resistance curves provided valuable insights into the behavior and characteristics of these sources under varying load conditions.

4. Comparing the measured Thevenin parameters and resistance curves with theoretical expectations or manufacturer specifications for well-understood voltage sources, such as batteries and regulated power supplies, allowed for further investigation and discussion, deepening the understanding of the underlying principles and potential sources of error.

5. The pulsed current measurement approach implemented in the Instrument Droid effectively managed power dissipation, preventing overheating and potential damage to circuit components, especially when characterizing high-current voltage sources.

6. The lab experience reinforced the importance of a systematic approach, attention to detail, and the ability to analyze and interpret data in the context of theoretical principles and practical considerations when designing and testing electronic circuits and instrumentation systems.
