

Linear vs Switching Regulators: Taking Accurate Efficiency Measurements

This application note explains the similarities and differences between linear and switching regulators, how switching regulators are more energy efficient, and how to measure the efficiency of a switching regulator.

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1. Introduction

DC/DC Regulators convert an input voltage into a reliable and steady output voltage while supplying current to a load. Two common DC/DC regulators are linear and switching regulators. The primary goal of a linear regulator and switching regulator is to maintain the output voltage constant through changes in the input voltage and/or load current. Linear regulators achieve this by dropping the difference of V_{IN} and V_{OUT} across its pass transistor. The undesirable consequence of this is dissipating excess power as heat. As a result, switching regulators are used instead. However, due to practical limitations, a considerable amount of energy is dissipated as heat in a switching regulator.

Designers should measure the efficiency to assess and optimize the performance of DC/DC regulators. Efficiency (η) reveals the proportion of input power (P_{IN}) that is delivered to the output (P_{OUT}) in relation to the power that is wasted as heat. [Equation 1](#) is the equation for efficiency.

$$\text{(EQ. 1)} \quad \text{Efficiency or } \eta(\%) = \frac{P_{OUT}}{P_{IN}} \times 100$$

The complement of efficiency ($1-\eta$) represents how much power is lost when converting input power to output power, as shown in [Equation 2](#).

$$\text{(EQ. 2)} \quad \text{Loss}(\%) = 100\% - \eta(\%)$$

1.1 Linear Regulator Efficiency

Linear regulators dissipate excess power as heat to maintain a stable output voltage. When calculating the efficiency of a linear regulator, it is sufficient to consider the power lost due to the internal circuitry of the regulator itself, as shown in [Equation 3](#).

$$\text{(EQ. 3)} \quad \text{Efficiency or } \eta(\%) = \frac{P_{OUT}}{P_{IN}} \times 100 = \frac{V_{OUT} \times I_{LOAD}}{V_{IN} \times (I_Q + I_{LOAD})} \times 100$$

You can see that the larger the input voltage, the lower the output voltage, the larger the load current, and the higher the quiescent current, the less efficient the linear regulator is. This is why linear regulators are generally favored in applications where the input voltage is only slightly above the output voltage, hence the popularity of low-dropout linear regulators or LDOs.

While linear regulators are straightforward, cost-effective, generate minimal output noise, and respond quickly to load changes, they still produce a lot of heat. Therefore, switching regulators are a better choice in applications where high efficiency is a primary concern.

1.2 Switching Regulator Efficiency

Switching regulators use high-frequency switching to temporarily store input energy and release that energy to the output. Remember that, unlike the linear regulator, the average input current of the switching regulator is not the same as the load current. The reason is that a switching regulator stores energy during one part of its cycle and delivers energy during another part of the cycle, resulting in a non-continuous current flow. The efficiency of a switching regulator is given in [Equation 4](#).

$$\text{(EQ. 4)} \quad \text{Efficiency or } \eta(\%) = \frac{P_{OUT}}{P_{IN}} \times 100 = \frac{V_{OUT} \times I_{LOAD}}{V_{IN} \times (I_{IN} + I_Q)} \times 100$$

Linear vs Switching Regulators: Taking Accurate Efficiency Measurements Application Note

An ideal switching regulator would convert all its input power to the output, resulting in 100% efficiency (we assume I_Q is 0A for now). For example, suppose a designer had a 12V input power supply and wanted to convert it to 1V while delivering to a 50A load. The 12V supply would need to supply 4.17A of input current.

$$(EQ. 5) \quad I_{IN} = \frac{100}{100\%} \times \frac{V_{OUT} \times I_{LOAD}}{V_{IN}} = 1 \times \frac{1V \times 50A}{12V} = 4.17A$$

In real life, the efficiency of a switching regulator is less than 100% due to power losses in various areas of the circuit which include:

- Switching losses – Real switches cannot instantaneously switch on to off (or off to on), so during the finite time in which the switch is not fully conducting or blocking, power is dissipated across the switch.
- Conduction losses – When the switches fully conduct, power is lost across the switch's finite ON resistance.
- Inductor losses – Parasitic resistance (DCR) in the inductor wire and core losses.
- Capacitor losses – The output capacitor's parasitic resistance (ESR) causes power loss during switching.
- Diode losses – When the diode is forward-biased, the conducting current causes power loss across the diode.
- Control circuit losses – Power consumed by the control circuitry, including the PWM controller, oscillator, gate driver ($V_{IN} \times I_Q$ expression in [Equation 4](#)).

Assuming 75% efficiency, the input current in the example above would be 5.6A.

Furthermore, the efficiency of switching regulators is affected by a range of parameters, including switching frequency, input and output voltage levels, load currents, and temperature. Consequently, it's important to measure the switching regulator efficiency for the specific operating conditions of an application. Because the efficiency of a linear regulator is straightforward, more time is spent on the switching regulator from here on out.

[Figure 1](#) shows an example of a typical regulator efficiency plot.

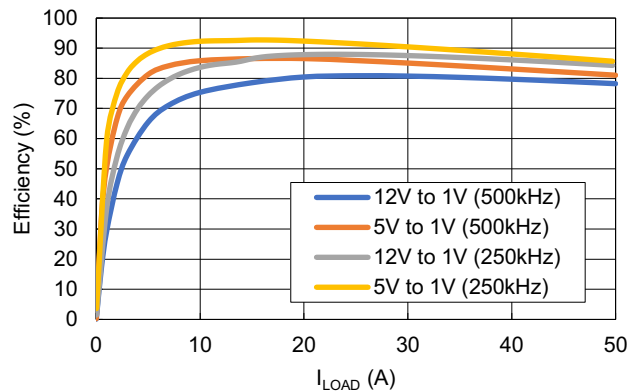


Figure 1. ISL73847SEH Efficiency

2. Measurement Test-Setup

2.1 Simplified Test-Setup

The setup needs to supply and measure the input and output power to measure the efficiency of a switching regulator. Because power is the product of voltage and current, the setup must supply and measure the input and output voltages and currents.

- The setup needs a bench power supply to supply various input voltages. Modern bench supplies have internal voltmeters to measure back the input voltage and an internal ammeter to measure the supplied input current to the Device Under Test (DUT), in our case, the switching regulator.
- The setup needs a way to measure the efficiency at various load currents. A resistor load would work; however, you would need to have a variety of load resistors for different load currents and output voltages ($R_{LOAD} = V_{OUT}/I_{LOAD}$) while ensuring that the resistors can handle the power dissipation. To avoid these limitations, an electronic load is a helpful piece of lab equipment that can be quickly programmed to simulate a resistive load or constant current source. If you prefer resistor loads, the rated power should be twice what you expect to dissipate ($P = 2 \times V_{OUT} \times I_{LOAD}$).
- Ensure the wires connecting the instruments to the switching regulator can handle the large currents flowing through them.

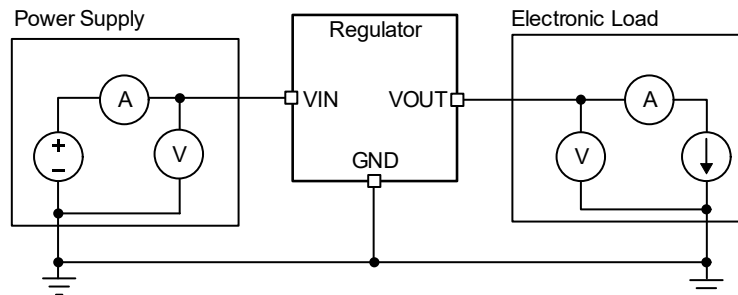


Figure 2. Simple Efficiency Test Setup

2.2 Better Test-Setup

2.2.1 Input Voltage Error

There is an issue that arises when using the [Simplified Test-Setup](#). The wire and connector resistance between the power supply output and regulator input causes a voltage drop ($V_{WIRE1} = I \times R_{WIRE1}$). As a result, the voltage at the regulator's input is lower than the target input voltage as the load current increases. There is an additional voltage drop across the wire between the regulator ground and the power supply negative output ($V_{WIRE2} = I \times R_{WIRE2}$). When measuring the voltage from the regulator input to the regulator ground, the voltage would be $V_{WIRE1} + V_{WIRE2}$ lower than the target voltage across the power supply outputs. [Figure 3](#) shows this input voltage error.

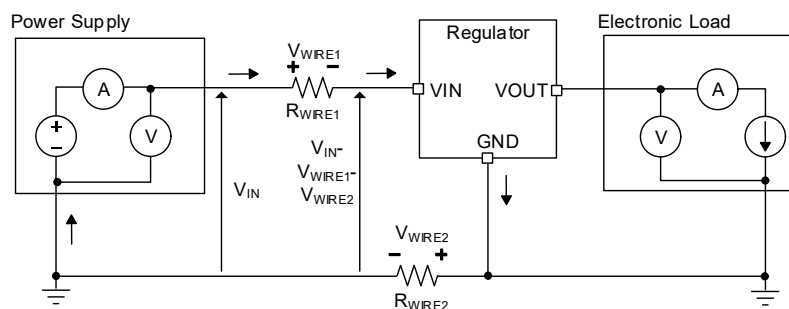


Figure 3. Input Voltage Error due to Wire and Connection Resistance

To fix this issue, use specialized power supplies with a Kelvin sense feature that compensates for voltage drop caused by wire/connector resistance by sensing the voltage across the regulator and increasing the voltage at the power supply's output until the sensed voltage is equal to the target voltage. Figure 4 shows the power supply Kelvin connection function.

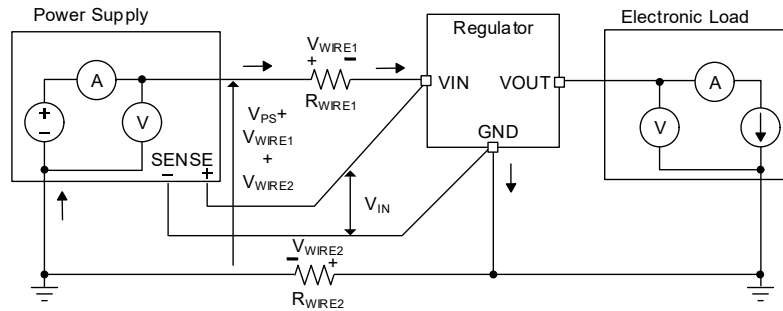


Figure 4. Power Supply Kelvin Connection Function

To use the Kelvin feature correctly, connect the sense wires as close to the input and input ground of the regulator as you can. Suppose your power supply does not have this feature. In that case, the next best thing is to use a dedicated external voltmeter and manually adjust the power supply's programmed voltage until the voltmeter reads the target input voltage. Voltmeters have additional features that enhance measurements, such as averaging and power line cycles.

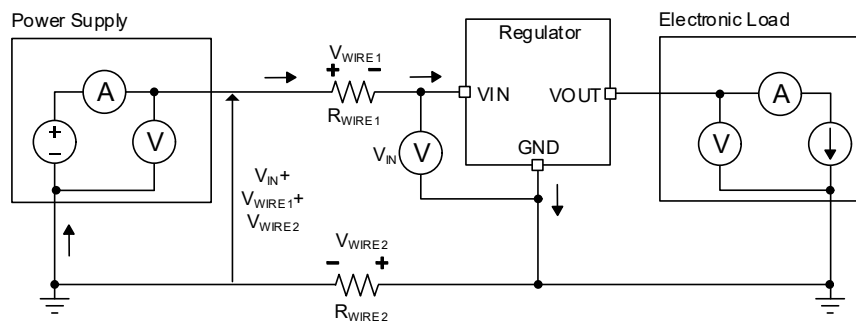


Figure 5. Input Voltage Correction using an External Voltmeter

2.2.2 Output Voltage Error

Like the input voltage, there is a voltage drop between the switching regulator output and the electronic load input at increasing loads because of the wire and connector resistance. As a result, measuring the voltage from the internal voltmeter does not equal the regulator output at high loads. Therefore, if you use this voltage to calculate efficiency, your result is incorrect. Figure 6 illustrates this error.

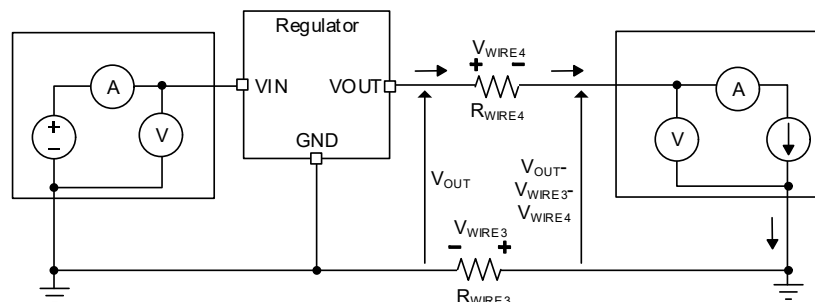


Figure 6. Output Voltage Error due to Wire and Connection Resistance

To fix this, most electronic loads also have a Kelvin sense feature that measures the output separately instead of through the load current wires, eliminating the voltage drop in the measurement (not in the actual circuit). Connect the sense wires as close to the output of the regulator as you can, as shown in Figure 7.

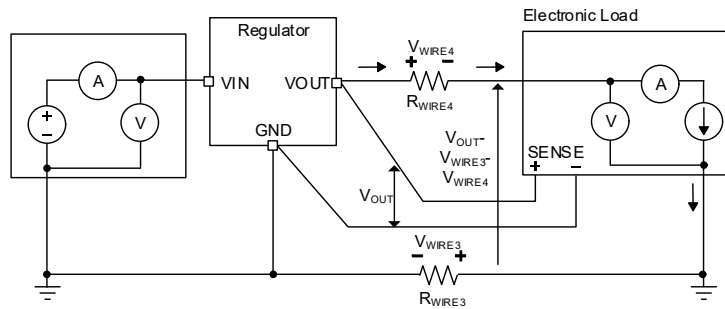


Figure 7. Electronic Load Kelvin Connection Function

If your electronic load does not have this feature, the next best thing is to use a dedicated external voltmeter to measure the output voltage correctly. Figure 8 illustrates the output voltage correction using an external voltmeter. Voltmeters have additional features that enhance measurements, such as averaging and power line cycles.

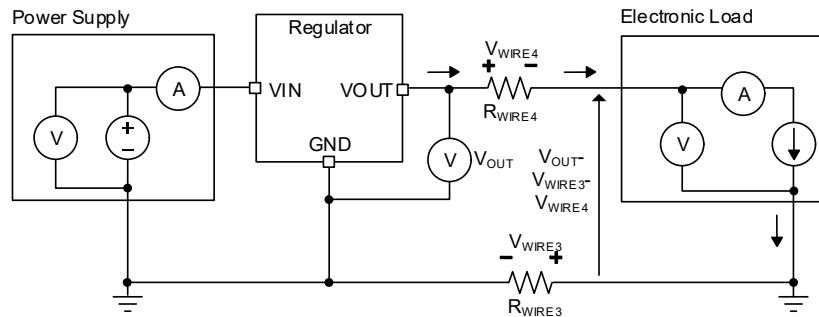


Figure 8. Output Voltage Correction using an External Voltmeter

2.2.3 Measuring Input and Load Current Accurately using a Sense Resistor

To ensure accurate and reliable input current and output current measurements, Renesas recommends using current-sense resistors (R_{SENSE}). The current-sense resistor is placed in series with the power supply or electronic load, and the voltage across it is measured using an external voltmeter (V_{SENSE}). By knowing the resistance of the sense resistor and the voltage across it, you can calculate the current flowing into or out of the switching regulator.

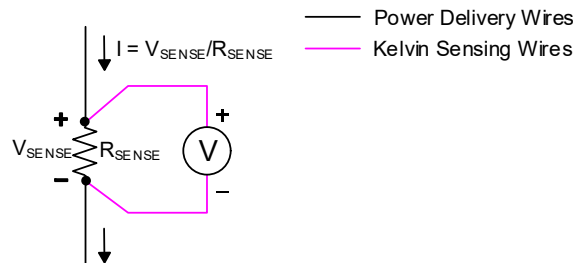


Figure 9. Current-Sense Resistor

The resistor value used for the current-sense resistor should be small enough to minimize the voltage drop across it and avoid excessive power dissipation. A rule of thumb is to use a resistor that gives a 100mV voltage drop at

twice the maximum current to be tested, which you can calculate using [Equation 6](#), where R_{SENSE} is the resistance of the current-sense resistor and I_{MAX} is the maximum current that is tested.

$$\text{(EQ. 6)} \quad R_{\text{SENSE}} = \frac{100\text{mV}}{2 \times I_{\text{MAX}}}$$

Next, the resistor value should be large enough to ensure accurate voltage measurements at low currents. This value ensures that the voltage developed across the resistor is large enough at low currents to be measured on the voltmeter. When selecting a resistor, consider the voltage range, resolution, and noise floor of the voltmeter. Most voltmeter datasheets specify the range and resolution of the voltmeter, but not all specify the noise. For practical reasons, the quickest way to measure the resolution and noise of a multimeter is shown.

For the resolution, go to the lowest possible range for the measured voltage. Most voltmeters have a minimum range of 100mV, which is how the 100mV rule of thumb was established in [Equation 6](#). In addition, most voltmeters have a resolution of 6-1/2 digits, which means that at 100mV, the theoretical lowest voltage that can be measured is 100nV. If the multimeter is 6-1/2 digits, it should display four significant figures after the decimal point in units of mV (nnn.nnnnmV).

As already mentioned, this is a theoretical minimum resolution. In practice, the noise of the multimeter limits the smallest voltage the multimeter can measure accurately. Renesas recommends having a 20dB signal-to-noise ratio (SNR) or higher for reliable analog measurements, which means the measured voltage should be ten times or greater than the noise floor of the voltmeter. To determine the noise floor, connect the voltmeter's positive (+) and negative (-) terminals to each other.

Before taking noise measurements, it is crucial to set the number of power line cycles (NPLC) to determine the integration time of the instrument's ADC. The integration time is important because DC signals often have 60Hz power line noise from the environment. Integrating over at least one period ($1/60\text{Hz} = 16.67\text{ms}$ in America) or 1 PLC helps reject this noise. However, 60Hz noise is not uniform, so integrating over a number of power line cycles provides better noise rejection and resolution. Renesas recommends setting the multimeter's integration to 10 PLCs.

After setting the NPLCs, take a single measurement and record the voltage value as $V_{\text{NOISE(RMS)}}$. Use [Equation 7](#) to determine if there is enough SNR for the given measurement. If the SNR is not good, R_{SENSE} needs to be increased, the minimum current (I_{MIN}) needs to be increased, or a multimeter with a lower noise floor needs to be used.

$$\text{(EQ. 7)} \quad R_{\text{SENSE}} \times I_{\text{MIN}} \geq 10 \times V_{\text{NOISE(RMS)}}$$

When looking at the current-sense resistor datasheets, choose a resistor whose current rating is two times or greater than the max current to be tested to avoid self-heating, as shown in [Equation 8](#).

$$\text{(EQ. 8)} \quad I_{\text{RATING}} \geq 2 \times I_{\text{MAX}}$$

Lastly, the resistor should have a 0.25% tolerance or lower to ensure precision. Renesas recommends Rideon's RS Series Precision Current Resistor/Shunts. When a resistor is chosen, the next thing is to measure its actual value.

Figure 10 and Figure 11 are the improved setups using the Kelvin sense features in the power supplies, electronic loads, and external voltmeters. However, the user is free to mix and match depending on what they have available in the lab.

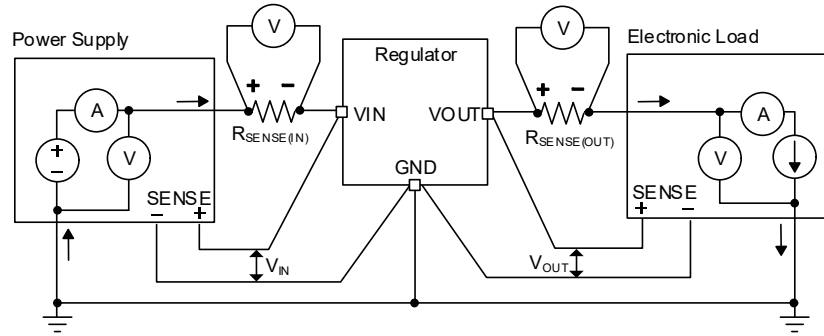


Figure 10. Efficiency Test Setup using Kelvin Connections

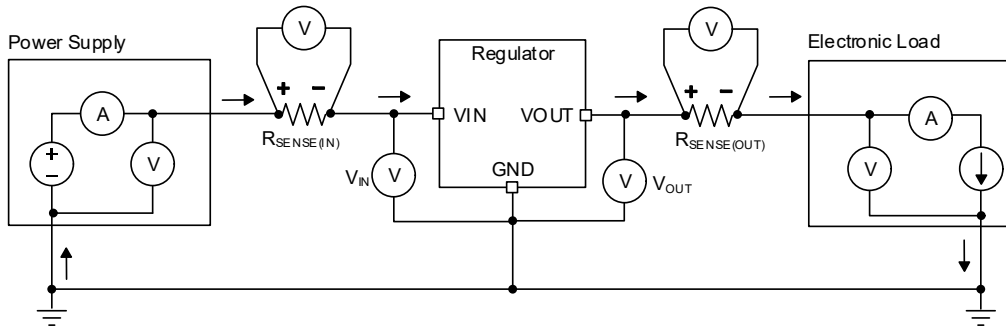


Figure 11. Efficiency Test Setup using External Voltmeters

3. Procedure

3.1 Measuring the Sense Resistor Value

Accurately measuring the input and output current is critical to getting accurate efficiency. Therefore, measuring the sense resistor value is essential. After getting the actual value of the sense resistor, Renesas recommends using one of two verification methods before using the resistor value to measure efficiency.

3.1.1 Finding the Actual Sense Resistor Value

1. Take a power supply and set the voltage to 1V and the current limit to the max current to be tested.
2. The current-sense resistor should have four connector points: two should be for the power delivery wires, which handle the large input or load currents, and two additional points are for Kelvin sensing. Kelvin sensing measures the voltage directly at the sense resistor, compensating for the voltage drop in the power delivery wires.
3. Connect the power delivery wires to the power supply and the resistor.
4. Connect a voltmeter to the Kelvin sense points on the resistor.
5. Set the voltmeter integration to 10 PLCs.
6. Turn on the power supply. You should see the power supply go into current control (CC) or current limit mode.
7. Record the power supply current and record the voltage on the voltmeter.
8. Turn off the power supply.
9. Calculate the current-sense resistor value ($R_{SENSE} = V_{SENSE} / I_{CC}$).

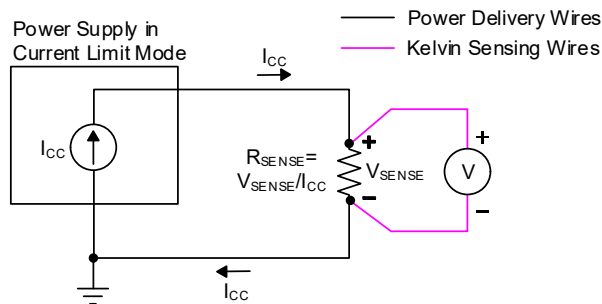


Figure 12. Current-Sense Resistor Value Measurement Setup

3.1.2 Verification #1, Ammeter

One method to verify the measured value is correct before using it for efficiency measurements is to use a calibrated ammeter. Most ammeters can't measure currents greater than a few amps, but we know the current sense resistance is linear up to the full-load current, so the current is lowered for this method.

1. Turn off the power supply.
2. Set a power supply to 1V and set the current limit to something a little lower than the rated current of your ammeter to avoid breaking the fuse but large enough to develop a voltage that can be measured on the voltmeter. For example, if the ammeter is rated for 3A and the lowest measured current is 1A, set the current limit to 1.5A.
3. Connect the ammeter in series with the power supply and the current-sense resistor using power delivery wires.
4. Connect a voltmeter to the Kelvin sense points on the resistor.
5. Set the voltmeter integration to 10 PLCs.
6. Turn on the power supply. You should see the power supply go into current control (CC) or current limit mode.
7. Record the current reading from the ammeter.
8. Record the voltage on the voltmeter.
9. Turn off the power supply.
10. Using the calculated sense resistor value from Section 3.1.1, calculate the current through the resistor ($I_{CC} = V_{SENSE} / R_{SENSE}$).
11. Verify the calculated current is within $\pm 0.1\%$ of the current on the ammeter.

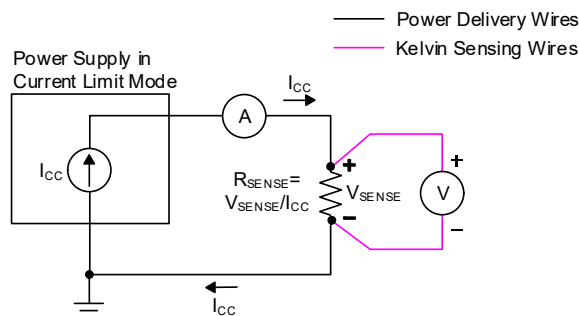


Figure 13. Verification #1, Ammeter Setup

3.1.3 Verification #2, Oscilloscope Current Probe

Another method to verify the measured resistor value is correct before using it for efficiency measurements is to use a calibrated oscilloscope current probe. The current probe should be rated higher than the max current to be tested. If it is not higher, you need to lower the current limit for this test to avoid over-saturating the probe.

1. Turn off the power supply.
2. Set a power supply to 1V and the current limit to the max current to be tested. The current probe you use should be rated higher than this max current. If not, you need to lower the current limit for this test to avoid over-saturating the probe.
3. Connect the power delivery wires to the power supply and the resistor.
4. Connect the current probe to the high-side power delivery wire.
5. Connect a voltmeter to the Kelvin sense points on the resistor.
6. Set the voltmeter integration to 10 PLCs.
7. Turn on the power supply. You should see the power supply go into current control (CC) or current limit mode.
8. Record the current reading on the oscilloscope.
9. Record the voltage on the voltmeter.
10. Turn off the power supply.
11. Using the calculated sense resistor value from [Finding the Actual Sense Resistor Value](#), calculate the current through the resistor ($I_{CC} = V_{SENSE} / R_{SENSE}$).
12. Verify the calculated current is within $\pm 0.1\%$ of the current on the current probe oscilloscope measurement.

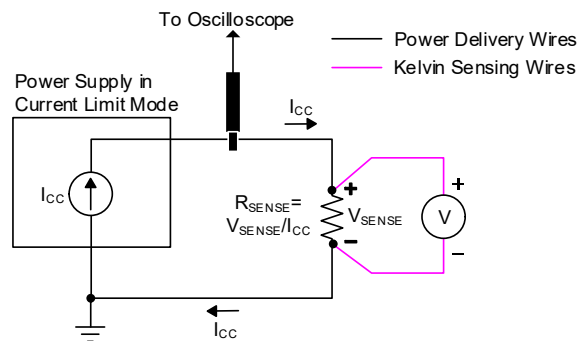


Figure 14. Verification #1, Oscilloscope Current Probe Setup

3.2 Measuring Efficiency Manually

3.2.1 Putting Together the Test Setup

1. Ensure the power supply is off.
2. Connect the positive (+) output of the power supply to one end of the input current-sense resistor (referred to as the positive (+) side of the input current-sense resistor).
3. Connect the other end of the input current-sense resistor (referred to as the negative (-) side of the input current-sense resistor) to the input of the switching regulator.
4. Connect the negative (-) output of the power supply to the GND on the input side the switching regulator.
5. Connect the positive (+) lead of the voltmeter to the Kelvin connection on the positive (+) side of the input current-sense resistor.
6. Connect the negative (-) lead of the same voltmeter to the Kelvin connection on the negative (-) side of the input current-sense resistor.
7. Connect the positive (+) output of the electronic load to one end of the output current-sense resistor (referred to as the negative (-) side of the current-sense resistor). Make sure the electronic load is disabled beforehand.
8. Connect the other end of the output current-sense resistor (referred to as the positive (+) side of the output current-sense resistor) to the output of the switching regulator.
9. Connect the negative (-) output of the electronic load to the GND at the output of the switching regulator.
10. Connect the positive (+) lead of the voltmeter to the Kelvin connection on the positive (+) of the output current-sense resistor.
11. Connect the negative (-) lead of the same voltmeter to the Kelvin connection on the negative (-) side of the output current-sense resistor.
12. Connect the positive (+) of the voltmeter to the input of the switching regulator, and its negative (-) lead to the GND on the input of the switching regulator.
13. Connect the negative (-) of the voltmeter to the output of the switching regulator, and its negative (-) lead to the GND on the output of the switching regulator.

See [Figure 15](#) for the test setup.

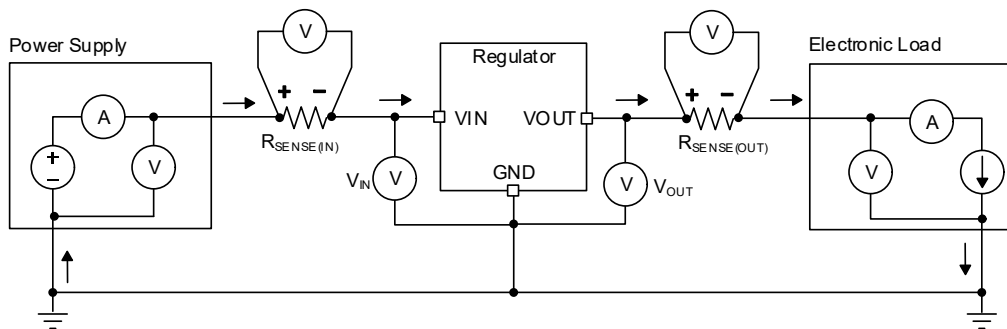


Figure 15. Test Setup

3.2.2 Efficiency Measurement Procedure

1. Program the voltage on the power supply to the first lowest input voltage.
2. Program the current limit on the power supply, so it is above the expected input current of the regulator and does not limit the supply unless there is a short in the set-up.
3. Program the electronic load as a constant current source and set it to the first lowest load current.
4. Program all the voltmeters to integration 10 PLCs.
5. Turn on the power supply output and verify everything looks ok.
6. Enable the electronic load and verify that everything looks ok.
7. This step is NOT necessary if the power supply has a Kelvin sensing correction feature that automatically adjusts for the voltage drop across power delivery wires: Adjust the programmed input voltage on the power supply to compensate for losses from the output of the power supply to the input of the DUT. This is done by measuring the input voltage on the voltmeter.
8. Record the input voltage, output voltage, input current-sense resistor voltage, and output current-sense resistor voltage.
9. Take the input current-sense resistor voltage and convert it to an input current using the resistance value calculated in [Measuring the Sense Resistor Value](#) ($I_{IN} = V_{SENSE(IN)} / R_{SENSE(IN)}$).
10. Take the output current sense resistance voltage and convert it to a load current using the resistance value calculated in [Measuring the Sense Resistor Value](#) ($I_{LOAD} = V_{SENSE(OUT)} / R_{SENSE(OUT)}$).
11. Calculate the efficiency (Efficiency (%) = $(V_{OUT} \times I_{LOAD}) / (V_{IN} \times I_{IN}) \times 100$)
12. Increase the programmed load current to the next highest value on the electronic load. Repeat the procedures starting at Step 7.
13. If you reach the highest load current, bring the load current down to the first lowest value. Then increase the programmed input voltage and repeat the procedure starting at Step 7.
14. When all input voltages and load currents are finished, disable the electronic load, followed by the power supply. Repeat the procedures for a different output voltage starting at Step 1.

3.3 Measuring Efficiency through Python Automation

This code is a Python script that communicates with multiple instruments using GPIB to test the efficiency of a regulator under various input voltage and load current conditions.

The code imports the PyVISA and time libraries, which are used to communicate with the instruments and pause execution, respectively. The code configures the instruments' functions and settings and then enters a nested loop that iterates through various input voltages and load currents. For each set of test conditions, the code sends commands to the power supply and electronic load to set the required input voltage and load current and then reads voltage measurements from the four multimeters.

The measured values are used to calculate the efficiency of the power supply under the current test conditions, which is printed to the console along with the input and output voltage and current measurements.

After the test, the code sends commands to turn off the power supply and electronic load and closes the instrument connections.

The following commands work for most Chroma Power Supplies, Chroma Electronic loads, and Keithley/HP/Agilent/Keysight multimeters. Renesas still recommends verifying the commands before running the script.

```
#####  
# Import all the required python libraries.  
import pyvisa, time  
  
# Initialize the Resource Manager for controlling the instruments.
```

```
rm = pyvisa.ResourceManager()

# Open connections to each of the instruments. Addresses might need to be changed.
powerSupply = rm.open_resource("GPIB::01::INSTR")
electronicLoad = rm.open_resource("GPIB0::02::INSTR")
inputVoltageMultimeter = rm.open_resource("GPIB0::03::INSTR")
inputCurrentSenseMultimeter = rm.open_resource("GPIB0::04::INSTR")
outputVoltageMultimeter = rm.open_resource("GPIB0::05::INSTR")
outputCurrentSenseMultimeter = rm.open_resource("GPIB0::06::INSTR")

# Define the input voltage and load current test conditions.
inputVoltageList = [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]
loadCurrentList = [0.1, 0.5, 1, 5, 10, 20, 30, 40, 50]
currentLimit = 5.0 # Define the current limit for the power supply.

# Define the sense resistors for the input and output current measurements.
senseResistor_input = 2E-3
senseResistor_output = 1E-3

# Configure the power supply.
powerSupply.write(f"SOURce:CURRent {currentLimit}")

# Configure the Chroma electronic load.
electronicLoad.write("CHANnel:LOAD 1")
electronicLoad.write("MODE CCH")

# Configure the multimeters.
inputVoltageMultimeter.write('SENSE:FUNCTION "VOLTage:DC"')
inputCurrentSenseMultimeter.write('SENSE:FUNCTION "VOLTage:DC"')
outputVoltageMultimeter.write('SENSE:FUNCTION "VOLTage:DC"')
outputCurrentSenseMultimeter.write('SENSE:FUNCTION "VOLTage:DC"')

Define the number of power line cycles for the multimeters.
numberPowerLineCycles = 10

inputVoltageMultimeter.write(f":SENSE:VOLTage:DC:NPLCycles
{numberPowerLineCycles}")
inputCurrentSenseMultimeter.write(f":SENSE:VOLTage:DC:NPLCycles
{numberPowerLineCycles}")
outputVoltageMultimeter.write(f":SENSE:VOLTage:DC:NPLCycles
{numberPowerLineCycles}")
outputCurrentSenseMultimeter.write(f":SENSE:VOLTage:DC:NPLCycles
{numberPowerLineCycles}")

flag = True

# Loop over each input voltage test condition.
for targetInputVoltage in inputVoltageList:

# Set the power supply to the target input voltage.
powerSupply.write(f"SOURce:VOLTage {targetInputVoltage}")

# Loop over each load current test condition.
```

```
for targetLoadCurrent in loadCurrentList:

# Set the electronic load to the target load current.
electronicLoad.write(f"CURRent:STATic:L1 {targetLoadCurrent}")

# Print the target test conditions.
print(f"Target Test Conditions: VIN= {targetInputVoltage}V, ILOAD=
{targetLoadCurrent}A")

# Turn on the power supply and electronic load if this is the first iteration of the
loop.
if flag:
powerSupply.write("CONFigure:OUTPut ON")
electronicLoad.write("LOAD:STATe ON")
flag = False

# Wait for the instruments to settle before taking measurements. May need to be
adjusted.
time.sleep(1)

# Adjust the power supply voltage until the input voltage at the input of the
regulator is equal to or
# higher than the target input voltage. Can be commented out if using a power supply
with Kelvin
# sense connection feature to automatically adjust the input voltage to compensate
for wire drop.
measuredInputVoltage = inputVoltageMultimeter.query("READ?")

while measuredInputVoltage < targetInputVoltage:
setInputVoltage = float(powerSupply.query("SOURce:VOLTag?"))
newInputVoltage = setInputVoltage + 0.01
powerSupply.write(f"SOURce:VOLTag {newInputVoltage}")
measuredInputVoltage = inputVoltageMultimeter.query("READ?")

# Wait for the instruments to settle before taking measurements. May need to be
adjusted.
time.sleep(1)

# Query the input voltage meter for the measured input voltage
measuredInputVoltage = inputVoltageMultimeter.query("READ?")

# Query the input voltage meter for the measured current sense voltage
measuredCurrentSenseVoltage_input = inputVoltageMultimeter.query("READ?")

# Calculate the input current based on the measured current sense voltage and the
sense resistor value
calculatedInputCurrent = measuredCurrentSenseVoltage_input / senseResistor_input

# Query the output voltage meter for the measured output voltage
measuredOutputVoltage = outputVoltageMultimeter.query("READ?")

# Query the output current sense meter for the measured current sense voltage
measuredCurrentSenseVoltage_output = outputCurrentSenseMultimter.read()
```

```
# Calculate the load current based on the measured current sense voltage and the
sense resistor value
calculatedLoadCurrent = measuredCurrentSenseVoltage_output / senseResistor_output

# Calculate the efficiency based on the input and output measurements
calculatedEfficiency =
((calculatedLoadCurrent*measuredOutputVoltage)/(calculatedInputCurrent*measuredInputVoltage)) * 100

# Print the measured test conditions and calculated efficiency
print(f"Measured Test Conditions: VIN= {measuredInputVoltage}V, IIN=
{calculatedInputCurrent}A")
print(f"VOU= {measuredOutputVoltage}V, ILOAD= {calculatedLoadCurrent}A")
print(f"Efficiency= {calculatedEfficiency}%")

# Turn off the power supply output and electronic load.
powerSupply.write("CONFigure:OUTPut OFF")
electronicLoad.write("LOAD:STATE OFF")

# Close all instrument connections.
powerSupply.close()
electronicLoad.close()
inputVoltageMultimeter.close()
inputCurrentSenseMultimeter.close()
outputVoltageMultimeter.close()
outputCurrentSenseMultimeter.close()

rm.close() # Close the resource manager connection
#####
```


3.4 Possible Issues

3.4.1 Insufficient Headroom Voltage at the Electronic Load

For test cases where the output voltage of the regulator is very low, the load current is very high, and/or there is too much voltage drop between the regulator output and the electronic load terminals, the electronic load may struggle to sink the programmed load current because of insufficient headroom voltage at its input.

There are several solutions:

- Ensure all cables and wires are correctly connected and tightened to minimize resistance and voltage drop to the electronic load.
- Use an electronic load with a lower headroom voltage requirement.
- Reduce the wire losses between the regulator output and the electronic load by shortening the wires, paralleling more wires, or using thicker connections and wires.
- Use two or more sense resistors to minimize the voltage drop across the resistor. For example, if you use two 100mΩ resistors instead of one 100mΩ resistor, at 100A, the voltage drop across both is reduced by 50mV, improving the voltage to the electronic load terminals 50mV. [Figure 16](#) illustrates this setup.

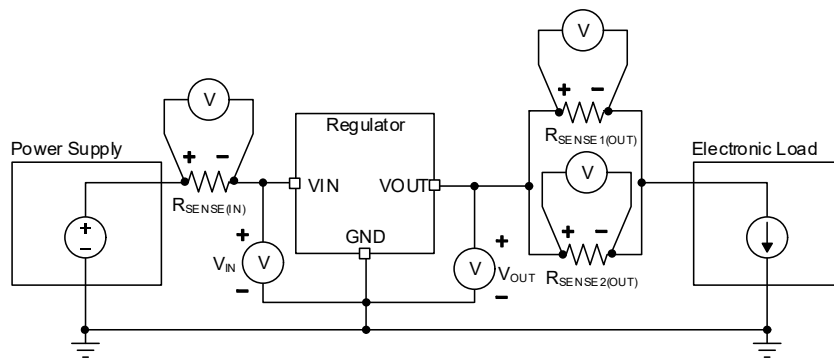


Figure 16. Setup for Reducing Voltage Drop at the Electronic Load

3.4.2 Self-Heating at Increasingly Higher Loads

The efficiency might drop more than expected during testing as the load increases. This drop can sometimes be tied to the self-heating of the PCB/components on the regulator board. There are a couple of solutions to overcome self-heating issues:

- Shorten the overall time between measurements.
- Turn off the part or set the load current to 0A for a set time between measurements to cool the board.
- The number of PLCs proportionally increases the integration time of the multimeter, which is how long the multimeter takes for a single measurement. Ten PLCs make the multimeter integrate for 166.67ms, increasing the time that the PCB/components heat up if you do that for many measurements. Shortening the number of PLCs helps but might affect the noise rejection of the measurement, so it is important if using sense resistors to ensure 20dB or better SNR at the chosen PLC (See [Measuring Input and Load Current Accurately using a Sense Resistor](#) for more information).
- Cooling the board with a fan. Keep in mind cooling the board becomes a test condition, and you would need to quantify the airflow in Linear Feet per Minute (LFM).

4. Revision History

Revision	Date	Description
1.00	Mar 23, 2023	Initial release

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