APPLICATION NOTE

10 Tips to Enhance DC Power Testing and Analysis

KEYSIGHT

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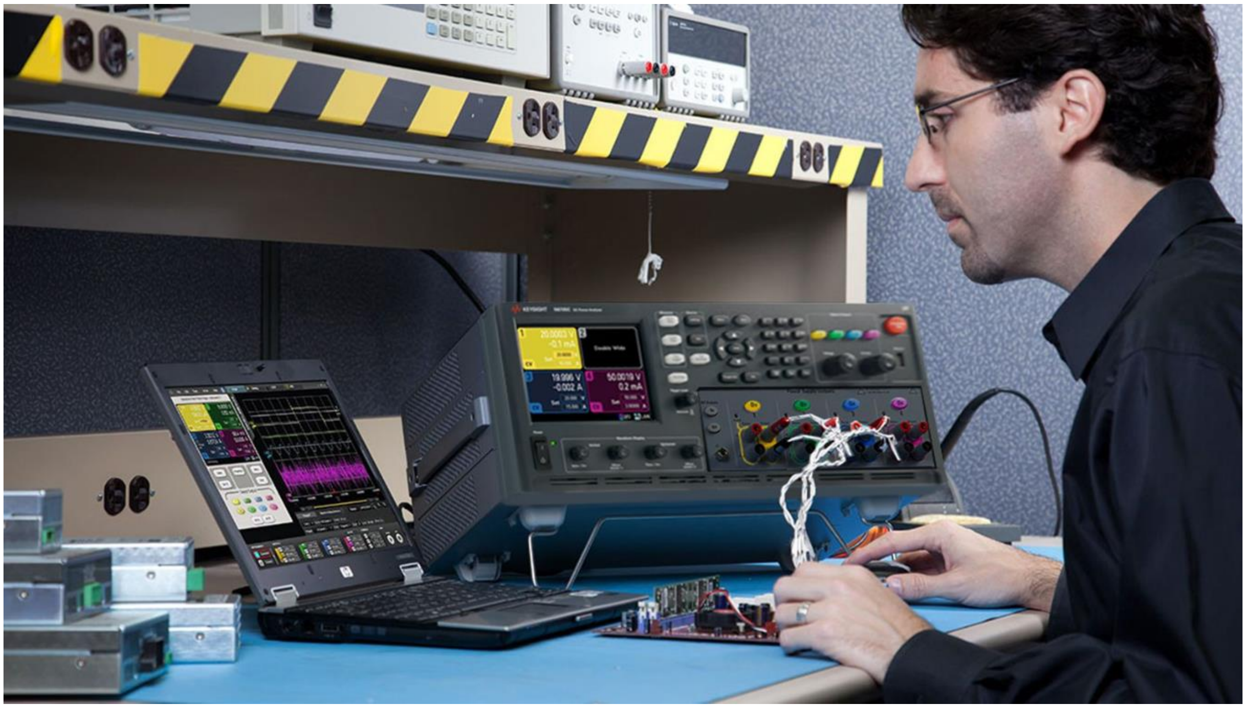
Introduction

A DC power supply is an integral part of any good test system. The capability to deliver clean and accurate power to your Device Under Test (DUT) removes doubts and ensures you get the right results. Our practical tips will enable this and let you get more out of your power supply. If you ever need to get a new power supply, you can count on these tips to help you choose the right one. Remember, more power and features do not mean a better power supply. It is about how you use your power supply.

Don't worry about your power supply. Let us do that for you. We want you to focus on what's important to you. We hope you enjoy our tips.



1. Program Your Power Supply Correctly to Operate in Constant Voltage or Constant Current Mode

In most circumstances, the output of a power supply operates in either constant voltage (CV) or constant current (CC) mode, depending on the voltage setting, current limit setting, and load resistance. However, some unusual circumstances will cause the power supply to enter unregulated (UNR) mode. Understanding these three modes will make it easier to program your power supply correctly.

Constant voltage

A power supply will operate in CV mode, provided the load does not require more current than the current limit setting. Based on Ohm's law, V = I x R, maintaining a constant voltage while changing the load resistance requires the current to increase or decrease. As long as the current draw $I_{out} = V_s / R_L$ is less than the current limit setting, the power supply regulates the output at the voltage setting. In Figure 1, the power supply will operate on the horizontal line V_s with $I_{out} = V_s / R_L$.

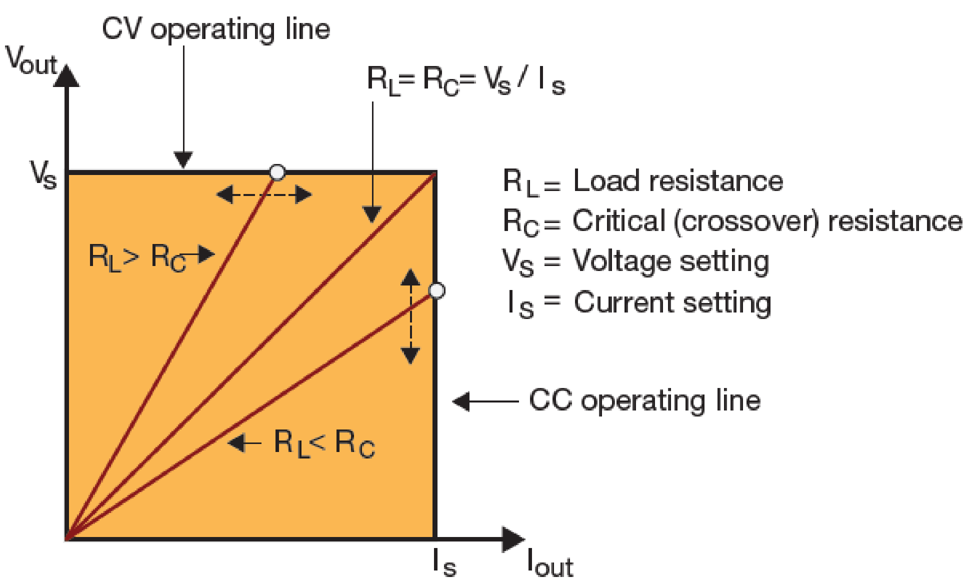


Figure 1. Power supply output characteristic

Constant current

If the load resistance decreases, such as when a device under test (DUT) component fails, and the load resistance, R_L, is less than R_C, where R_C is the ratio of the power supply voltage setting to the current limit setting, the power supply will regulate the current instead. Again, Ohm's law dictates a change in voltage if the current stays constant at the current limit setting. This is the CC mode. In Figure 1, the power supply will operate on the vertical line I_S with $V_{out} = I_S \times R_L$.

Unregulated state

If a power supply cannot regulate its output voltage or output current, the output will become unregulated and indicate UNR mode. Neither the voltage nor the current will be at the corresponding set point, and the values at which they settle are unpredictable. While UNR mode can occur for various reasons, it is uncommon.

- Possible causes of UNR include the following:
- The power supply has an internal fault.
- The AC input line voltage is below the specified range.
- The load resistance is R_C, the value at which the output will cross over from CV to CC or CC to CV (see Figure 1).
- Another power source is connected across your power supply output, such as when you set up outputs in parallel.
- The output is transitioning from CV to CC or CC to CV. This transition can cause a momentary UNR.

2. Use Remote Sense to Regulate Voltage at Your Load

Ideally, lead connections from your power supply to your load have no resistance. In reality, lead resistance increases with lead length and wire gauge. As a result, the voltage at the load may decrease when a supply delivers current through the wire. To compensate, use remote sensing to correct for these voltage drops.

Typically, a power supply ships from the factory with the sense leads connected locally at the output terminals. However, for setups with long load leads or complex setups with relays and connectors, the voltage at the output terminals will not accurately represent the voltage at the load (Figure 2).

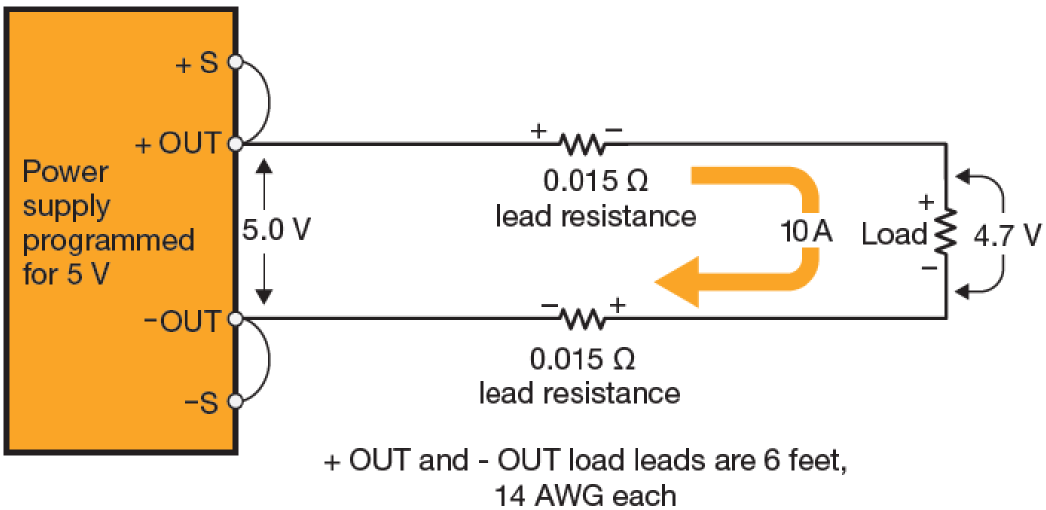


Figure 2. The effects of 6 feet of 14 AWG leads with sense leads connected to the output terminals. A 0.3 V drop develops over the leads (0.15 V per lead).

Depending on the gauge and length of the wire, the resistivity of your load connections could cause a much lower voltage at your load than you want. High-current situations, for example, will invariably lead to significant voltage drops even with short load leads. Consider the resistances of different gauges of copper wire in Table 1.

Table 1. Resistance in mΩ per foot for different wire gauges

Wire gauge (AWG)	Resistance (mΩ / ft)
22	16.1
20	10.2
18	6.39
16	4.02
14	2.53
12	1.59
10	0.999

Generally, for every three-gauge increase in your copper wire, the resistance doubles. Since you must select the gauge wire to satisfy the current requirements of the load, remote sense at the load will improve voltage regulation without shortening lead length or decreasing wire gauge.

When you connect the remote sense terminals to the load, the internal feedback amplifier sees the voltage directly at the load rather than at the output terminals. Since the control loop senses the voltage directly at the load, the supply will keep the load voltage constant, regardless of voltage drops caused by load lead gauge, load lead length, output relays, or connectors.

Remember the following when you use remote sense:

- Use a two-wire shielded twisted-pair cable for your sense leads.
- Connect the sense lead cable's shield to the ground on only one end of the cable.
- Do not twist or bundle sense leads together with load leads.
- Prevent an open circuit at the sense terminals, which are part of the output's feedback path.
- Keysight uses internal sense protect resistors. These resistors prevent the output voltage from rising more than a few percentage points if the sense leads inadvertently open.
- Most supplies can compensate only for a maximum load lead drop of a few volts.

To implement remote sensing (Figure 3), disconnect the sense terminal connections from the main outputs. Then connect each sense terminal to the proper polarity load contact. Finally, set the power supply to remote sense mode or four-wire mode, if necessary.

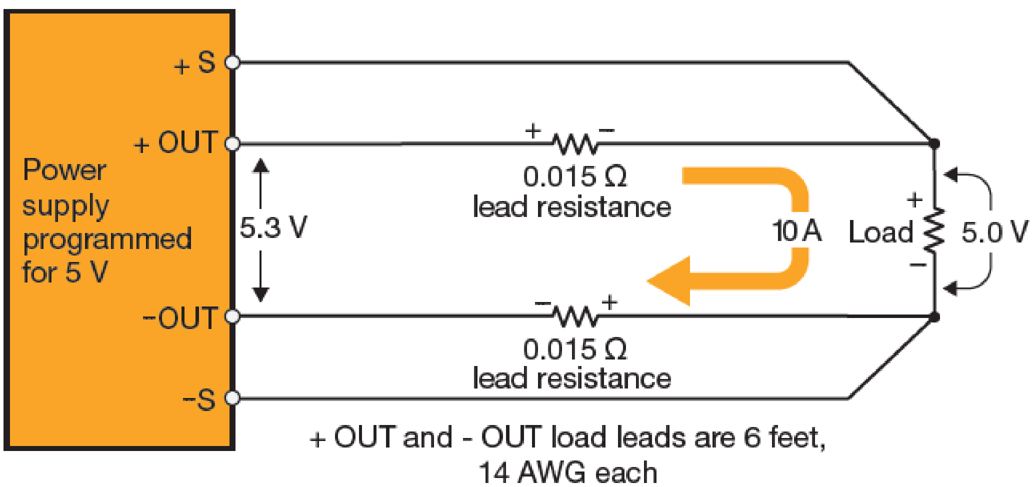


Figure 3. Using remote sense to compensate for load lead voltage drop

3. Use Your Power Supply to Measure DUT Current

You can obtain an accurate DUT current measurement with an ammeter, a current shunt, or the built-in readback on your power supply. Ultimately, you should select a method after considering the advantages and disadvantages of each. Often, the current readback on your power supply can provide the measurement accuracy you need.

Ammeter

A common way to measure DUT current is to use a bench digital multimeter (DMM) set in ammeter mode. While an ammeter has the benefit of a specified accuracy, you must break the circuit to insert the ammeter. A DMM also limits the maximum current you can measure, typically several amps.

External current shunt / DMM

You can also make current measurements with shunts. With a current shunt, you can conveniently select the most appropriate shunt resistor to match your current range. Your accuracy is based on the DMM's voltage measurement accuracy and the precision of the shunt.

While this method can produce highly accurate results, certain errors can adversely affect your measurements. Commonly overlooked complications include thermal electromotive force, which occurs when dissimilar metals cause thermocouple voltages to develop; shunt miscalibration; and self-heating effects, which occur when higher temperature from current flow causes shunt resistance to change.

In addition to these concerns, installing a current shunt requires breaking your circuit to connect the shunt in series. A current shunt installed in a rack-mount system may require complex connections involving relays and switches.

Built-in current readback

You can avoid the difficulties involved with connecting current shunts by using a power supply's built-in readback. Current readback on a power supply uses an internal shunt selected to complement the output rating of the supply. You do not need to disconnect the DUT or connect a DMM.

Consider the level of measurement accuracy you can expect with a high-quality power supply (Table 2).

Table 2. Relative accuracy of power supply current readback

Output current level	Typical accuracy
100% of rated output	0.1% to 0.5%
10% of rated output	0.5% to 1%
1% of rated output	Near 10%

Power supply measurement specifications account for the errors that affect an external shunt. Therefore, your power supply readback may already be accurate enough for most current measurement applications, particularly for currents between 10% and 100% of the rated output current of the supply.

Built-in current readback offers many benefits including the following:

- Reduction in connection equipment – no need for relays, switching, and wiring
- Simplicity of use
- Power supply provides readings directly in amps
- Circuit disconnects not required
- Specified accuracy – accuracy values already account for shunt errors
- Synchronized measurements – readback measurements can be triggered to start with other power-related events

4. Connect Power Supply Outputs in Series or Parallel for More Power

You can connect two or more power supply outputs in series to get more voltage or connect outputs in parallel to get more current. When you connect outputs in series for higher voltage, observe the following precautions:

- Never exceed the floating voltage rating (output terminal isolation) of any of the outputs.
- Never subject any of the power supply outputs to a reverse voltage.
- Only connect outputs that have identical voltage and current ratings in series.

Set each power supply output independently so that the voltages sum to the total desired value. To do this, first set each output to the maximum desired current limit the load can safely handle. Next, set the voltage of each output to sum to the total desired voltage. For example, if you use two outputs, set each to half the desired voltage. If you use three outputs, set each to one-third the desired voltage.

When you connect outputs in parallel for higher current, you should observe certain precautions:

- One output must operate in constant voltage (CV) mode and the other(s) in constant current (CC) mode.
- The output load must draw enough current to keep the CC output(s) in CC mode.
- Connect only outputs with identical voltage and current ratings in parallel.

Set the current limit of all outputs equally such that they sum to the total desired current limit value. Set the voltage of the CV output to a value slightly lower than the voltage value of the CC outputs. The CC outputs supply the output current to which they have been set and drop their output voltage until they match the voltage of the CV unit, which supplies only enough current to fulfill the total load demand.

Using remote sense with series connections

When using remote sense in a series configuration, wire the remote sense terminals on each output in series and connect them to the load, as shown in Figure 4.

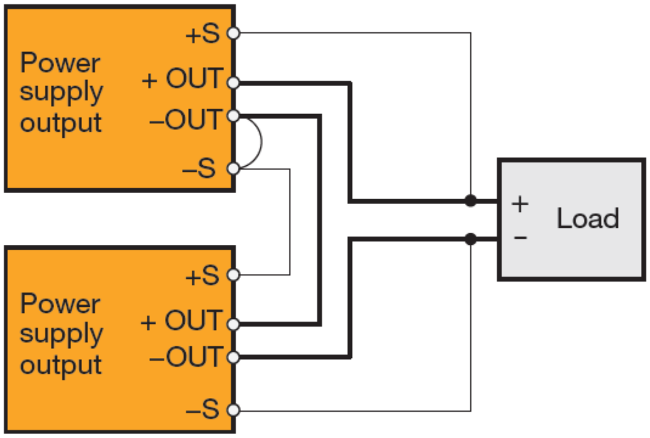


Figure 4. Series connection with remote sense

Using remote sense with parallel connections

When you use remote sense in a parallel configuration, wire the remote sense terminals on each output in parallel and connect them to the load, as shown in Figure 5.

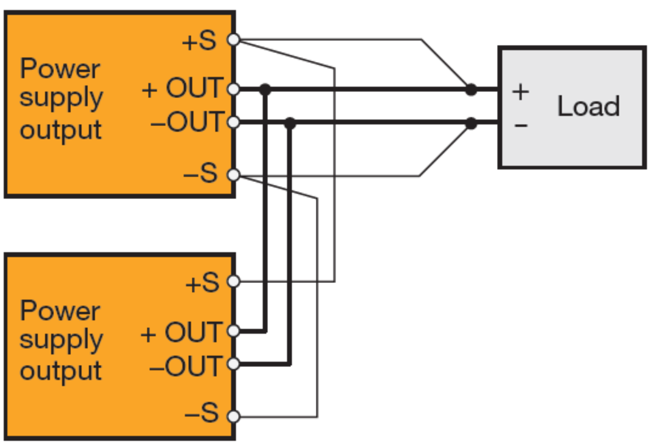


Figure 5. Parallel connection with remote sense

To simplify the settings for parallel outputs, some power supplies support an advanced feature called “output grouping.” Up to four identical outputs can be “grouped,” enabling you to control all grouped outputs as if they were a single, higher-current output.

5. Minimize Noise from Your Power Supply to Your DUT

If your DUT is sensitive to noise on its DC power input, you will want to do everything possible to minimize noise on the input. Here are three simple steps you can take.

Choose a power supply that has low noise

To minimize noise, start at your source. Since filtering noise from your power supply can be difficult, you want to select a power supply that has very low noise to begin with. Choosing a linearly regulated power supply can accomplish this; however, linear power supplies can be large and can generate large amounts of heat.

Instead, consider choosing a switching-regulated power supply. Switch-mode power supply technology has improved to the point where the noise on the output compares to that of a linear supply. Table 3 compares noise on a typical linear supply with a performance switching supply.

Table 3. Comparison of power supply noise for linearly regulated vs. switching-regulated supplies

	RMS noise	Peak-to-peak noise
Linearly regulated power supply	~ 500 μV	~ 4 mV
Switching-regulated power supply	~ 750 μV	~ 5 mV

Selecting a supply with low RMS and peak-to-peak output voltage noise specifications is an excellent start, but you can also minimize the noise with proper attention to the lead connections to your DUT.

Shield supply-to-DUT connections

The connections between your supply and DUT can be susceptible to noise pickup. Types of interference include inductive coupling, capacitive coupling, and radio-frequency interference. You can reduce noise in various ways, but the most effective is to ensure that your load and sense connections use shielded two-wire cables.

When you use a shielded cable, make sure to connect the shield to earth ground at only one end. For example, connect the shield on the power supply end to earth ground, as shown in Figure 6. Neglecting to connect the shield on either end can increase capacitive pickup.

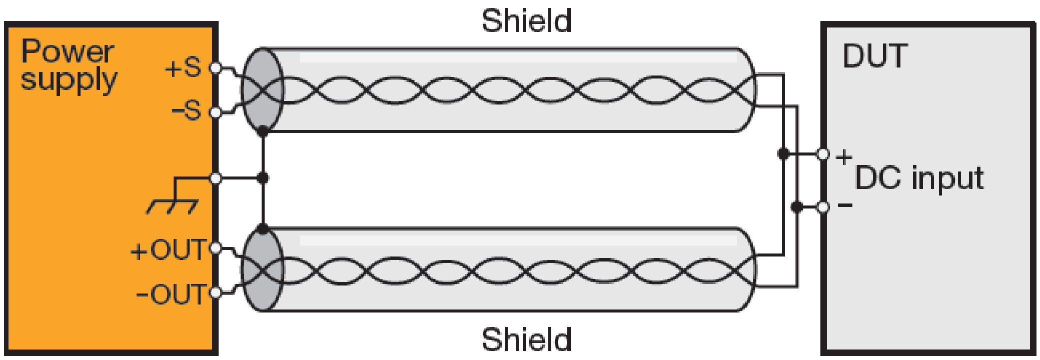


Figure 6. Shield connects to earth ground on only one end of the cable

Do not connect the shield to ground at both ends because ground loop currents may occur. Figure 7 shows a ground loop current that developed because of the difference in potential between the supply ground and the DUT ground. The ground loop current can produce voltage on the cabling that appears as noise to your DUT. In addition to proper shielding, balancing your cable impedance can preserve the power supply's low noise profile.

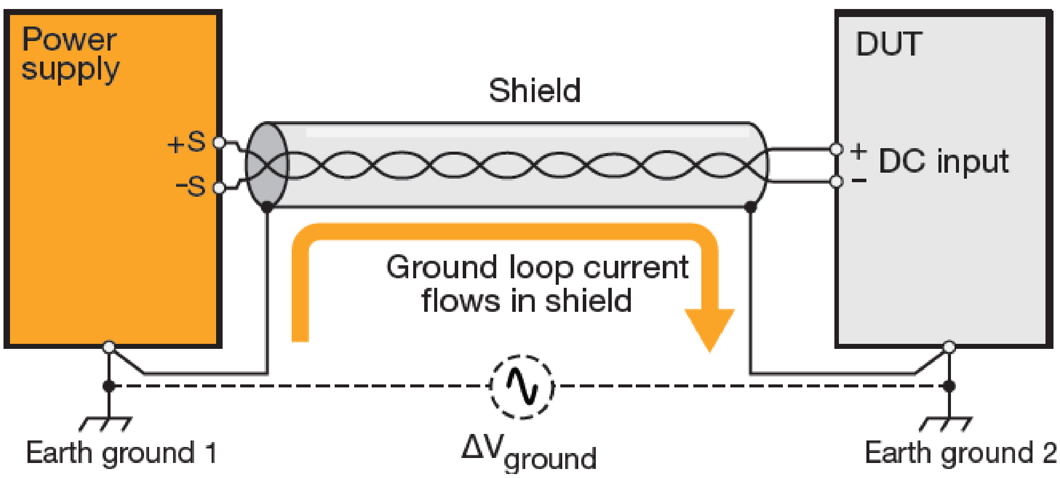


Figure 7. Shield connected improperly (at both ends) results in ground loop current

Balance output-to-ground impedance

Common-mode noise is generated when common-mode current flows from inside a power supply to earth ground and produces voltage on impedances to ground, including cable impedance. To minimize the effect of common-mode current, equalize the impedance to ground from the plus and minus output terminals on the power supply. You should also equalize the impedance from the DUT's plus and minus input terminals to ground. Use a common-mode choke in series with the output leads and a shunt capacitor from each lead to ground to accomplish this task.

6. Safeguard Your DUT Using Built-in Power Supply Protection Features

Most DC power supplies have features that protect sensitive DUTs and circuitry from exposure to potentially damaging voltage or current. When the DUT trips a protection circuit in the power supply, the protection circuit turns off the output and displays a notification. Two common protection features are overvoltage protection (OVP) and overcurrent protection (OCP).

When designing your test, it is important to understand these protection features to protect your DUT.

Overvoltage protection

OVP is a value set in volts designed to protect your DUT from excessive voltage. When the power supply output voltage exceeds your OVP setting, the protection will trip and turn off the output.

OVP is always enabled. When manufacturers ship power supplies from the factory, OVP is typically set well above the maximum rated output of the power supply. Set your OVP trip voltage low enough to protect your DUT from excessive voltage but high enough to prevent nuisance tripping from ordinary fluctuations in the output voltage. Fluctuations can occur during output transient conditions, such as load current changes.

OVP circuits can respond to an overvoltage condition in microseconds, but the output voltage itself will take longer to go down. The amount of time it takes for the output to go down depends on the down-programming capabilities of the power supply and the load connected to the output. Some power supplies have a silicon-controlled rectifier (SCR) across the output that fires when the OVP trips, which brings the voltage down much faster.

CAUTION

On most power supplies, OVP responds to the voltage at the output terminals, not the sense terminals. When using remote sense, program your OVP trip voltage high enough to account for load lead voltage drops.

Overcurrent protection

Most power supplies have an output voltage setting and a current limit setting. The current limit setting determines the value in amps at which the power supply will prevent excessive current from flowing. This constant current mode regulates the output current at the current limit but will not turn off the output. Instead, the voltage decreases below the voltage setting, and the power supply continues to produce current at the current limit setting in CC mode.

OCP shuts off the output to prevent excessive current flow to the DUT. When you enable OCP, if the supply enters CC mode, protection will trip and turn off the output. In effect, OCP turns the current limit setting into a trip value in amps. Set your current limit low enough to protect your DUT from excessive current but high enough to prevent nuisance tripping caused by regular fluctuations in the output current that can occur during output transient conditions, such as during an output voltage change. When a power supply ships from the factory, OCP is turned off.

Figure 8. Power supply front panel showing overvoltage protection, overcurrent protection, constant voltage mode, and constant current mode

7. Use Output Relays to Physically Disconnect Your DUT

Although you may expect your power supply output to be completely open when you set an "output off" state, that may not be the case. When set to "off," the output impedance will vary from model to model and may depend upon the options installed in the power supply. The output-off state will typically set the output voltage and output current to zero and disable the internal power-generating circuitry. However, these settings do not guarantee that no current will flow into or out of your DUT, as would be the case if you physically disconnected the output terminals from your DUT.

A power supply output that is off but not completely open can adversely affect your DUT test for a number of reasons:

- Your DUT contains a DC power source that connects directly across the power supply output.
- Your DUT contains a DC power source that connects across the output in a reverse-polarity configuration.
- Your DUT is sensitive to extra capacitive loading.
- Your DUT produces a changing voltage across the power supply output.

Some power supply models have an internal output relay option that can completely disconnect the power supply output from your DUT. The relay in Figure 9 opens when you use an output-off setting and stops all current flow to the DUT. But even with a relay option installed, certain models may still have output capacitors or capacitively coupled networks connected from the output terminals to the chassis ground because of the location of the relays. Therefore, your DUT will still connect to these components (see Figure 10).

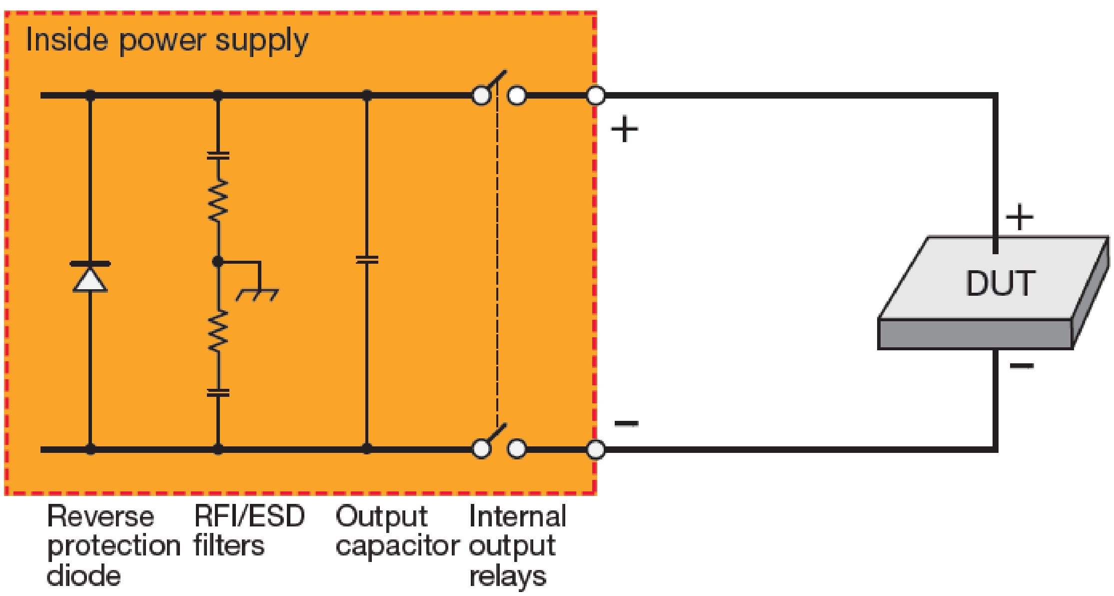


Figure 9. An example of a power supply with internal relays located right at the output terminals. With the relays open, your DUT is completely disconnected.

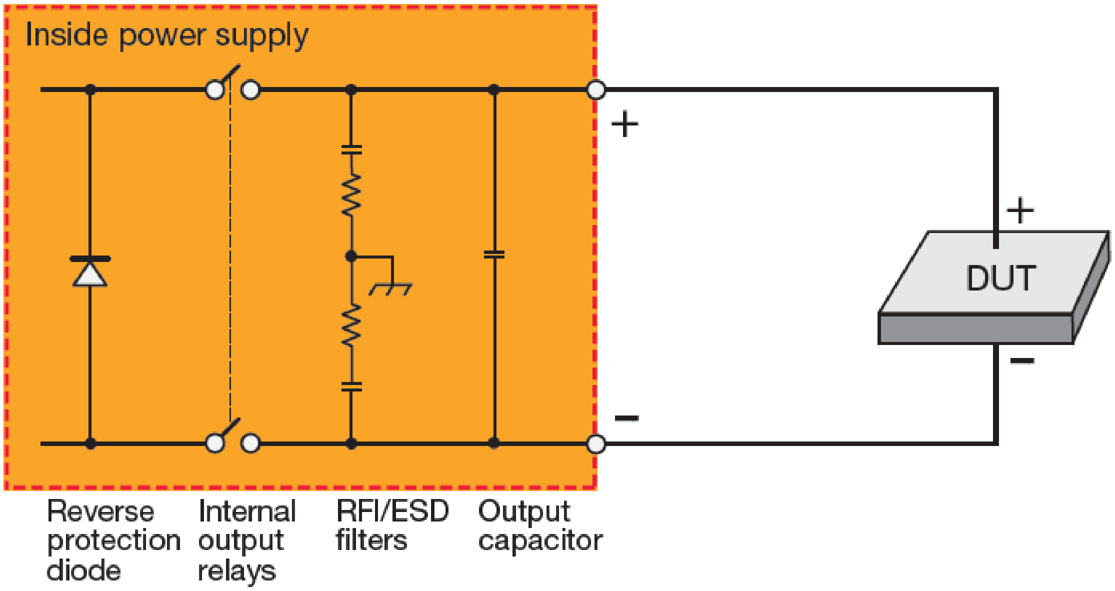


Figure 10. An example of a power supply with internal relays located inboard of some output components. With the relays open, these components remain connected to your DUT.

In critical applications that require a complete disconnect between the power supply output and DUT, check with your power supply vendor to see if an output relay option exists that will provide a complete disconnect. If this configuration is not available, you may have to provide external output disconnect relays.

The downsides of an external relay configuration are the added cost and complexity to your test setup and the extra space required. You will need to provide the relays, connect wires from the power supply output to the relays, and install a means to control the relays. You may also find it more difficult to synchronize the opening and closing of the external relays with other power-related events.

Built-in output disconnect relays provide advantages over external relays. They take up less space and are not as complex, with less wiring and no external relay control circuitry. They offer better built-in synchronization of relay open / close with other power-related events. And the relays open upon fault conditions such as overvoltage and overcurrent.

8. Capture Dynamic Waveforms Using a Power Supply's Built-in Digitizer

While most power supplies can measure DUT steady-state voltage and current, some can also measure dynamic voltage and current. These supplies feature a built-in digitizer.

Traditionally, engineers use digitizers to capture and store analog signals for data acquisition. Like an oscilloscope, which uses a digitizer to display the analog signal present on one of its inputs, a power supply's built-in digitizer captures the dynamic voltage and current waveforms produced on its output.

Basic digitizer operation

Figure 11 shows a digitizer converting an analog waveform into a set of data points. Upon a trigger, the digitizer takes measurement samples and stores them in a buffer.

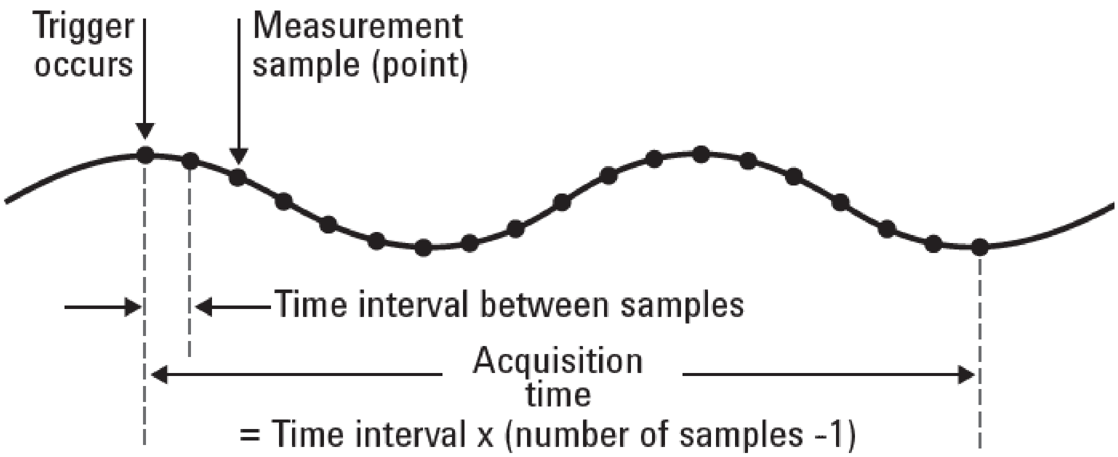


Figure 11. A digitizer converts an analog waveform into data points by sampling

When you make a digitizing measurement, you can set two of the following three parameters:

- Time interval: time between samples
- Number of samples: total number of samples you want to take
- Acquisition time: total time during which you want to take samples

When two parameters are set, the following equation will determine the remaining parameter:

Acquisition time = time interval x (number of samples - 1)

Similarly, you can configure a power supply's built-in digitizer to trigger and capture power supply output voltage or current waveforms. The supply's digitizer will store a buffer of readings with the waveform data points. You can retrieve the data and use any standard software for analysis. You also can use a customized program or available device characterization software to easily visualize the results in the time domain (oscilloscope-like view or data-logger view) or perform statistical analysis.

An example digitizer application

If you use your power supply in place of a battery, you can capture dynamic information about the current flowing into your DUT, allowing you to better understand the current drain on your DUT batteries. Consequently, you can make appropriate design adjustments to optimize power management during the DUT's modes of operation.

Figure 12 shows a sample waveform obtained on a cell phone's current draw using a power supply output digitizer and device characterization software (this is not an oscilloscope display).

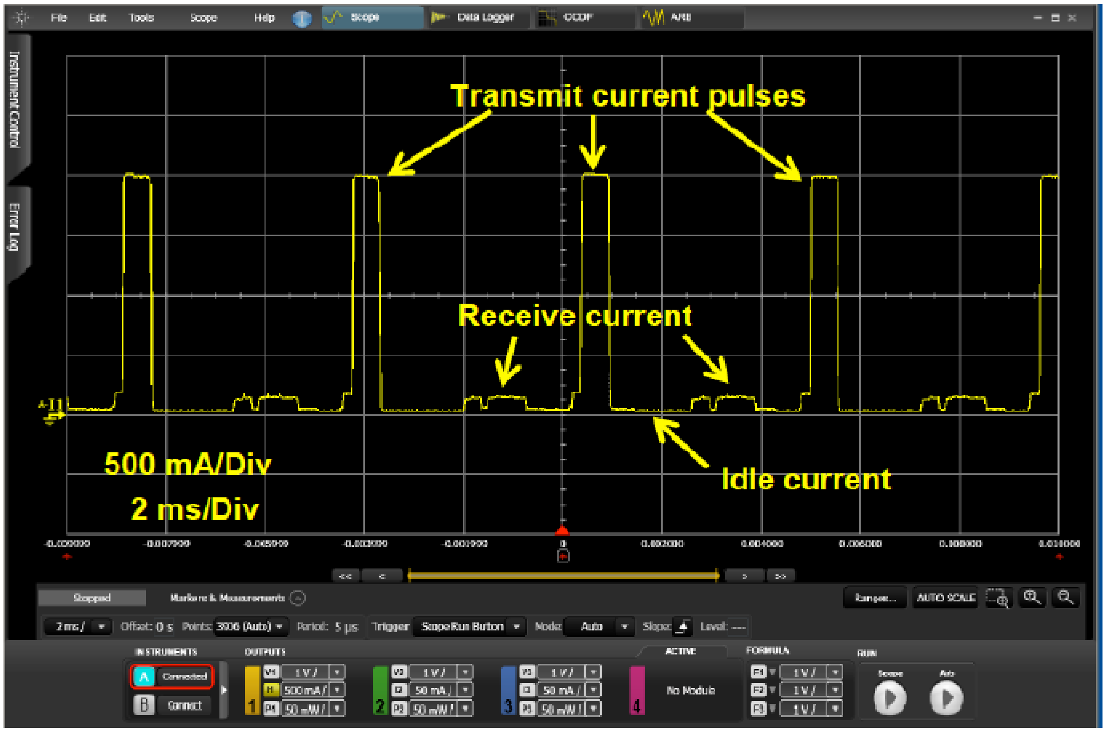


Figure 12. Device characterization software uses a power supply's built-in digitizer to capture data showing a cell phone's current draw from the power supply.

Device characterization software displays the captured data graphically in the time domain, much like an oscilloscope displays a signal. The idle, receive, and transmit current states are discernible from the waveform. Of course, you can analyze digitized data in ways other than using device characterization software.

You can use a bus interface such as USB, LAN, or GPIB to capture and retrieve digitized waveform information. Retrieved data can be returned either as a scalar value, with the power supply calculating a single number averaged from the data (as it does for the front panel display) or as an array of values. You can even acquire pre- and post-trigger data by changing the trigger offset to capture waveforms such as peak current draw during a DC inrush current test.

9. Create Time-Varying Voltages Using Power Supply List Mode

Typically, engineers use power supplies to bias circuits requiring constant voltage. However, more advanced applications may require a time-varying voltage (or current). Modern power supplies can easily manage both using list mode to address the time-varying applications.

What is list mode?

Normally, you can program a PC to change the voltages on a power supply output for discrete periods. In this way, your program controls the transitions between voltages to allow you to test your DUT at different voltages.

List mode lets you generate these voltage sequences and synchronize them to internal or external signals without tying up the computer. You set individually programmed steps of voltage (or current) and associated step duration. After setting the duration for each step, you trigger the list to execute directly on the power supply. You may set the power supply to move on to the next step based on dwell times or triggers. You can program a list to repeat once or multiple times (see Figure 13).

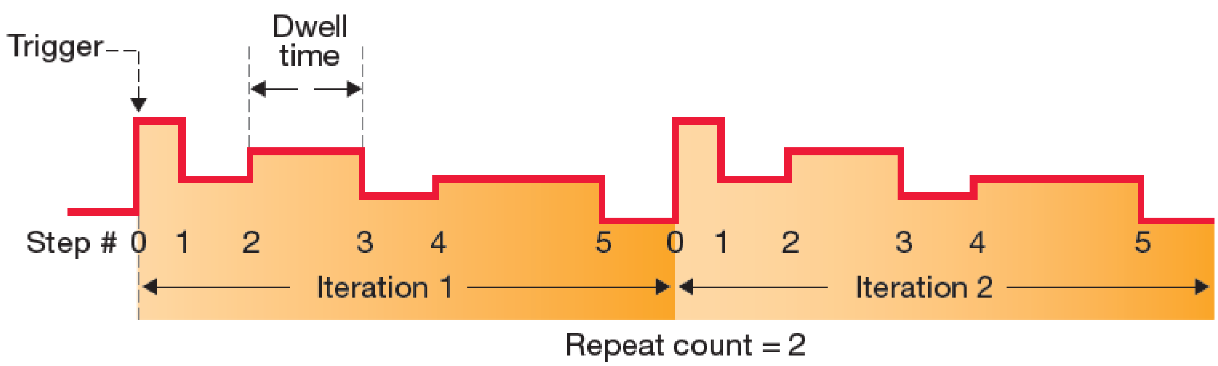


Figure 13. A list is a sequence of individually programmed voltage (or current) steps initiated with a trigger

To create a list, set the following:

- One or more voltage or current steps: defined voltage or current values
- Dwell times: duration associated with each voltage or current step
- Repeat count: the number of times you want the list to repeat

Two uses of list mode for testing

The list mode on a power supply can effectively run two types of tests, voltage sequence test and voltage waveform test.

In a voltage sequence test, you take measurements while the DUT is exposed to discrete stimulus voltage values. In a voltage waveform test, you take measurements while the DUT is exposed to a stimulus voltage waveform.

In both cases, the stimulus involves creating a sequence of voltage steps. The first has multiple levels of steady-state voltages, and the second has a continuously varying voltage profile. Engineers commonly use two tests for DUT design verification. Be aware that DC power supplies have limited bandwidth and typically generate voltage waveforms only at frequencies up to tens of kilohertz. Also, most power supplies are unipolar devices that create only positive voltages.

Using list mode

You can use list mode to perform a voltage waveform test on automotive electronic systems. During the startup of an internal combustion engine, also known as a cold crank, battery voltage levels drop considerably as the electric starter motor draws enormous amounts of current (see Figure 14). Once the engine turns, the battery voltage plateaus and hits a final level as the electric starter turns off.

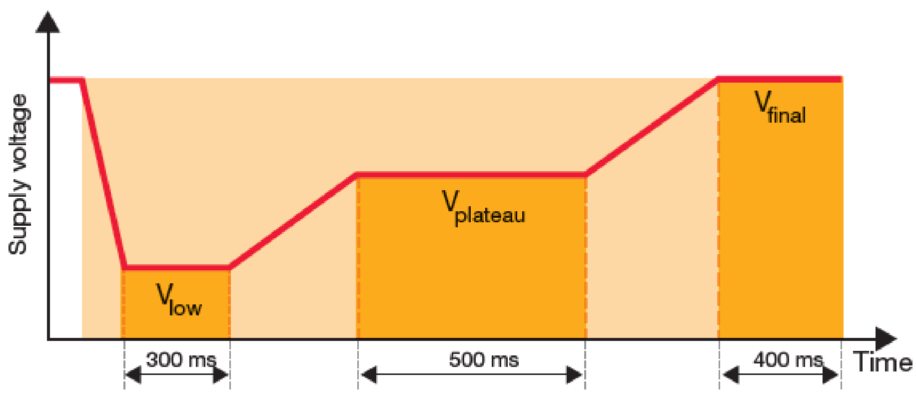


Figure 14. An automotive cold-crank profile represented with list steps

You can enter the simplified sequence in Table 4 into a list to perform electronic control unit design validation testing on an automotive electronic system. (Simulate transitions between voltage levels with additional steps.) This test ensures that the automotive electronics have adequate power transient immunity. Use list mode in this manner when you need to apply a time-varying voltage to your DUT.

Table 4. A simple list used to simulate the automotive crank voltage profile in Figure 14

Step	Voltage level	Voltage value	Dwell time
0	V_{low}	8 V	300 ms
1	$V_{plateau}$	12 V	500 ms
2	V_{final}	14 V	400 ms

10. Control Instruments, Automate Tests, and Perform Analysis with Software

Getting the most from test equipment requires that you retain valuable data and quickly analyze it to gain actionable insight into power consumption and power-related events. Software solves this challenge by enabling you to gain insight with minimum effort and maximum results. You will no longer have to deal with manual data capture and modifying your methodology from instrument to instrument.

The software allows you to control and set up your instruments centrally. It can enable you to streamline the analysis and documentation of results by capturing data, screenshots, and system states with a few clicks. Also, software platforms can work with multiple instrument types to deliver the data logging capabilities and measurement visualization your testing demands.

For example, the software can visualize measurement data from instruments such as function generators, power supplies, DMMs, oscilloscopes, data acquisition systems, source / measurement units, eLoads, and counters on a single screen to help you understand tests and derive answers. The software can also immediately analyze data captured from multiple instruments and find correlations. One example is identifying and alerting you to connections between specific device events and current consumption.

The software also enables you to quickly replicate results by recalling the past state of your bench with a single mouse click. You can easily export what you have captured to tools such as Excel and MATLAB to conduct offline analysis.

Furthermore, the software can enable you to create and automate tests rapidly with no programming needed. Combine multiple instruments to create millions of unique test sequences and quickly make sense of your test results.

An added benefit of the software is that it enables your company to have a unified test platform. This unified test platform comes from using a standardized software platform across product development lifecycles. Teams can share test methodology and have a common development and debug environment for all test requirements. In addition, team members need to learn only one test software platform, enhancing their efficiency. The benefits of standardization result in on-time product releases, reduced overall test costs, and increased return on investment.

Figure 15. Easily connect, record results, and visualize measurements across multiple instruments simultaneously, without the need for programming

Bonus Tip: Rack-Mounting Your Power Supply

When you are planning a test rack, selecting an instrument layout can be a challenging task. Safety, reliability, and performance are among the many requirements that affect your choices. Specifically, pay attention to these considerations when you put your DC power supply in a rack:

- Distribute weight properly to avoid rack instability.
- Provide adequate AC input power to avoid excessive current draw.
- Provide proper heat management to avoid excessive temperatures.
- Place instruments properly to minimize magnetic interference.
- Route wires to minimize conducted and radiated noise.

Weight distribution

Typically, a power supply is one of the heaviest instruments in your test rack. Mount the power supply near the bottom of the rack to lower the rack's center of gravity and reduce its tipping risk (Figure 16).

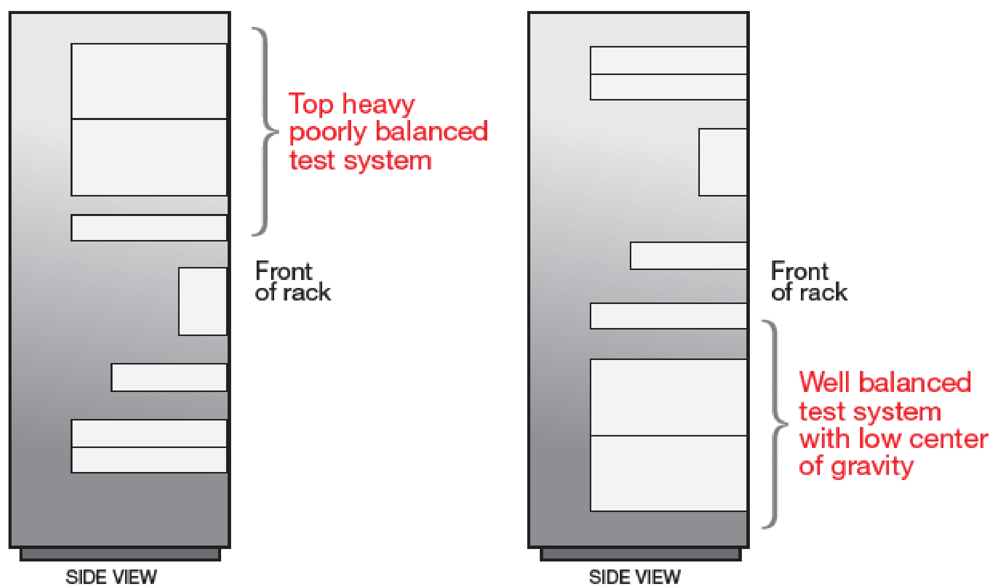


Figure 16. To properly balance your test system, place larger, heavier instruments near the bottom

AC input power

When planning the size of your AC input line, use the maximum current rating of each instrument in your rack to ensure the AC line providing power to your rack is adequate. Most instruments draw a relatively constant amount of current. However, a power supply's AC input current varies with its output loading. If you do not know the maximum load to expect on the output of the power supply, plan for the worst-case scenario by using the maximum rated input current of the supply.

Heat management

Power supplies typically have internal cooling fans. When you mount your power supply in a rack, be sure to provide adequate spacing for air intake and exhaust. Keep thermally sensitive instruments such as DMMs away from power supplies because high temperatures can have an adverse effect on their readings.

Magnetic interference

Liquid crystal displays have replaced most CRT displays; however, if you're using older computers or oscilloscopes with CRT displays, be aware that they are susceptible to magnetic fields. Magnetic fields can also affect the performance and accuracy of some instruments. For example, a voltmeter's circuitry could be susceptible to a large magnetic field produced by a transformer, such as that inside a power supply. Be sure to install your DC supplies away from your magnetically sensitive instruments, especially your DMM.

Routing wires

Since power wires can radiate electrical noise and both stimulus and measurement signal-carrying wires are susceptible to this noise, separate power wires from signal-carrying cables.

Resources

Learn more about DC power supplies