SMU Fundamentals

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Acquiring accurate DC measurements is a common need across many applications, but simply purchasing a highly accurate and sensitive instrument is not enough. Many different sources of error can affect the accuracy of your reading. Furthermore, minor adjustments to the settings on the instrument can yield different results. To achieve the highest level of accuracy, you need to thoroughly understand your instrument while using various methods to combat sources of error.

This guide shows you how to use a source measure unit (SMU) to perform DC measurements by reviewing instrument fundamentals, how to use SMUs, and examining the features that can help you set up your instrument.

An SMU is a precision power sourcing instrument that provides voltage sourcing and measurement as well as current sourcing and measurement capabilities. This control over voltage and current gives you the flexibility to calculate resistance and power through Ohm's law. These instruments offer four-quadrant output that incorporates both bipolar voltages and the ability to sink power. With all these capabilities, you may have trouble understanding how to use an SMU to make the measurements you need.

SMU Theory of Operation

A key feature of SMUs is flexibility in their four quadrant outputs (Figure 1). The output can provide positive voltage and positive current, negative voltage and positive current, negative voltage and negative current, or positive voltage and negative current. In quadrants one and three, the SMU is sourcing power, and in quadrants two and four, the SMU is sinking power. Sourcing power refers to the stimulus for a circuit and sinking power refers to the dissipating power applied by an external active component such as the output of a voltage regulator. The IV boundary shown in Figure 1 is a simplified version of an actual instrument's IV boundary. An actual SMU extends IV boundaries for pulsing mode (see "Pulsing" section).

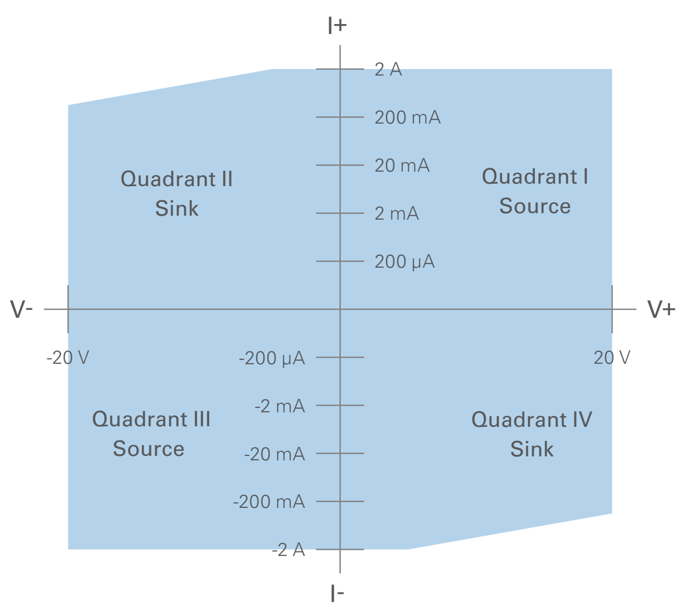

Figure 1. Simplified SMU IV Operating Boundary

Most SMUs can operate in either constant voltage mode or constant current mode. In constant voltage mode, the SMU acts as a voltage source that holds the voltage across the output terminals constant while current output varies. In this mode, you can set a current limit to ensure that the SMU is not driving too much current into your device under test (DUT). For example, if your SMU is connected to a 20 kΩ load and you set your current limit to 1.5 mA, you can sweep the voltage from 0 V to 20 V without reaching your current limit, as shown in Figure 2.

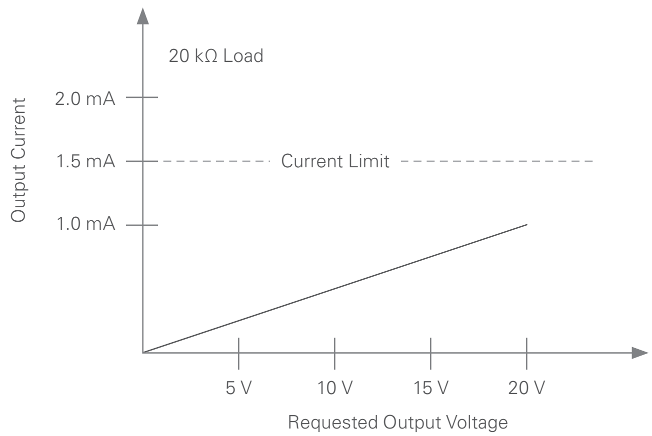

Figure 2. SMU Output While Operating in Constant Voltage Mode With a Current Limit Set to 1.5 mA for a 20 kΩ Load

However, if the load is 10 kΩ, you won't be able to sweep the voltage from 0 V to 20 V without violating the current limit. You can calculate when the SMU will reach the 1.5 mA current limit using Ohm's law.

$$V = IR$$

$$V = 1.5\ \text{mA} * 10\ \text{k}\Omega$$

$$V = 15\ \text{V}$$

According to the calculations above, the SMU will reach the 1.5 mA current limit when the voltage output reaches 15 V. When the current limit is reached, that channel is in compliance. A channel is operating in compliance when it cannot achieve the requested output level because the programmed limit has been reached. While the SMU is operating in compliance, even if the requested output voltage is greater than 15 V, the actual output voltage does not exceed 15 V. This concept is illustrated in Figure 3. Once the SMU output reaches the 1.5 mA current limit, it is in compliance, and, although the requested voltage is above 15 V, the actual voltage does not exceed 15 V. This feature is extremely useful to ensure that your SMU is not damaging your DUT by supplying too much power.

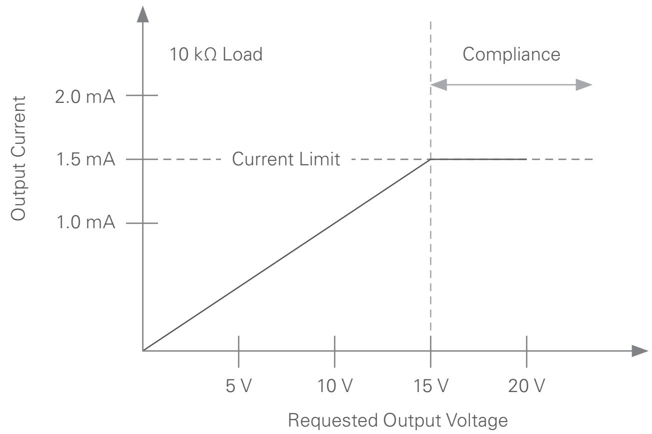

Figure 3. SMU Output While Operating in Constant Voltage Showing In-Compliance Operation for a 10 kΩ Load

When the SMU is in constant current mode, similar principles apply. Your SMU acts as a current source and holds the current across the output terminals constant while voltage varies. In this case, you can set a voltage limit and, once the channel reaches that limit, it is in compliance.

You can apply your understanding of how SMUs work in constant voltage and constant current modes to common measurement scenarios. For example, if you're trying to measure voltage with your SMU, you can put the device in current mode and set the current level to zero while using the lowest current range possible. This allows the SMU to sense the voltage on its terminals while permitting a minimal amount of current to flow through the module; the SMU effectively acts as a high-impedance load. Similarly, if you're trying to measure current with your SMU, you should put your device in voltage mode and source zero volts while using the lowest voltage range possible; your SMU effectively acts as a short. This allows you to use the SMU like a voltmeter or ammeter.

SMU as voltmeter:

- SMU in DC current mode
- Set to lowest current range
- Source 0 A

SMU as ammeter:

- SMU in DC voltage mode
- Set to lowest voltage range
- Source 0 V

Accuracy

A key difference between SMUs and power supplies is the level of accuracy that you can achieve with each. To get the most out of your SMU, you must have a good understanding of the accuracy specification and what it means. Most SMUs describe accuracy as a combination of an offset error and a gain error. Offset error refers to the difference between the actual output and the ideal output at a single point, and gain error describes the difference in slope between the actual transfer function and the ideal transfer function. These two errors are added together to determine the total accuracy specification for a given measurement. NI SMUs typically specify offset error with absolute units (mV or µA), and gain errors are specified as a percentage of the reading or requested value. This is because an offset error has the same effect no matter what value you're trying to output. But since gain error describes a difference in slope, the magnitude of the error increases as your output value increases.

Consider an example accuracy calculation using the specifications of the NI PXIe-4139 SMU to measure a 5 mA current. To make this measurement, use the 10 mA measurement range on the SMU. According to the PXIe-4139 specifications, at the 10 mA range, the SMU accuracy is 0.022 percent of reading + 200 nA. In this accuracy specification, the 0.022 percent represents the gain error and the 200 nA represents the offset error. Adding the two together gives you the complete accuracy specification.

$$\text{Accuracy} = \text{Gain Error} + \text{Offset Error}$$

$$\text{Accuracy} = (0.022\% * 5\ \text{mA}) + 200\ \text{nA} = 1.3\ \mu\text{A}$$

After plugging in the value of the current reading, you see that the accuracy is 1.3 µA meaning the reading of 5 mA should be within ±1.3 µA of the actual current.

A major factor that affects the accuracy of your instrument is the instrument temperature. The accuracy specification used in the previous sample calculation is valid only if the board temperature is within 1 °C of the board temperature at the completion of the last self-calibration. For example, if the board temperature was 25 °C when self-calibration was performed, the accuracy specification is valid only if the current board temperature is between 24 °C and 26 °C.

When the board temperature is within 5 °C of the self-calibration temperature, both gain and offset error increase; the accuracy specification becomes (0.03 percent of reading) + 600 nA. You can recalculate the accuracy of the 5 mA measurement using the new specification:

$$\text{Accuracy} = (0.03\% * 5\ \text{mA}) + 600\ \text{nA} = 2.1\ \mu\text{A}$$

This slight difference in temperature decreased the instrument accuracy by 0.8 µA. When making low-level current or voltage measurements, you should periodically perform self-calibration to correct for these temperature effects (see "Calibration" section).

Accuracy Versus Speed

You determine measurement speed for an SMU using the aperture time. Aperture time is the period during which an analog-to-digital converter (ADC) reads the voltage or current on an SMU. In Figure 4, the aperture time determines how long the measure period lasts. By varying the aperture time of the instrument, you have the flexibility to extend the acquisition window for high-precision measurements or decrease the window for high-speed acquisitions. Extending the measurement aperture gives the instrument more time to sample and average, which reduces the noise of the measurement.

Figure 4. Illustration of the Aperture Time of an SMU With Respect to a Sample Signal

SMU specifications provide quantitative data on how aperture time affects measurement noise. For reference, the PXIe-4139 SMU aperture time versus measurement noise graph is shown in Figure 5. As you can see, the noise levels decrease significantly as you increase the aperture time. In addition, the noise level is higher at higher voltage ranges. If your application requires low-voltage or low-current measurements, you should set the instrument to use the lowest measurement range possible.

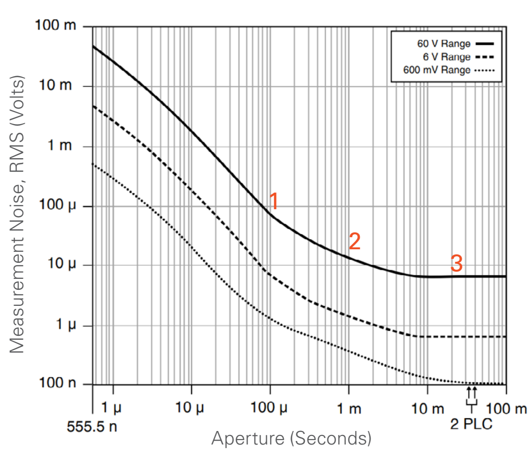

Figure 5. Voltage Measurement Noise Versus Measurement Aperture

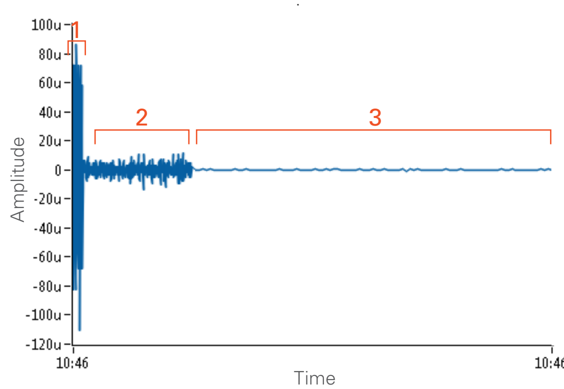

Figure 6. PXIe-4139 Noise Performance at Various Measurement Aperture Times

The actual noise performance of the PXIe-4139 SMU using 60 V range at three different aperture settings is shown in Figure 6. In the first section of the graph, the aperture time was set to 100 µs. As you can see, the noise is high when the aperture time is low. In the second section, the aperture time was set to 1 ms, which greatly reduced the noise in the reading. In the final section, the aperture time was set to 16.7 ms, which is one power line cycle. At this setting, the noise is minor and barely noticeable.

> "With our new platform based on [PXI], we've maintained both measurement and performance integrity while achieving 3X cost reduction and 10X improvement in semiconductor validation throughput."
>
> Ray Morgan, Product Line Manager, ON Semiconductor

A common best practice is to set your aperture time to whole number multiples of a power line cycle. In countries that have a grid power frequency of 60 Hz, one power line cycle equals 16.67 ms, but in countries with a 50 Hz grid, one power line cycle equals 20 ms. When you sample over multiple power line cycles, 60 Hz or 50 Hz noise is averaged out from your DC measurement.

In many applications, you need to optimize test time, which means minimizing aperture time. However, a low aperture time could introduce additional noise into the measurement and limit your reading's accuracy. On the flip side, if you are trying to examine the transient response of a load and accuracy is not your main concern, you can use short aperture times to digitize the signal with your SMU. For example, the PXIe-4139 SMU can sample up to 1.8 MS/s. This gives you the ability to observe the detailed transient characteristics of your signal. Be sure to keep in mind the trade-off between speed and accuracy when developing your application.

Pulsing

Another useful feature of many SMUs is pulsing. You can use pulsing to go beyond the maximum power level your instrument can provide for a short period of time. Because of this, the IV boundary of the SMU is different when using pulse mode versus DC mode (see the more detailed IV boundary graph shown in Figure 7).

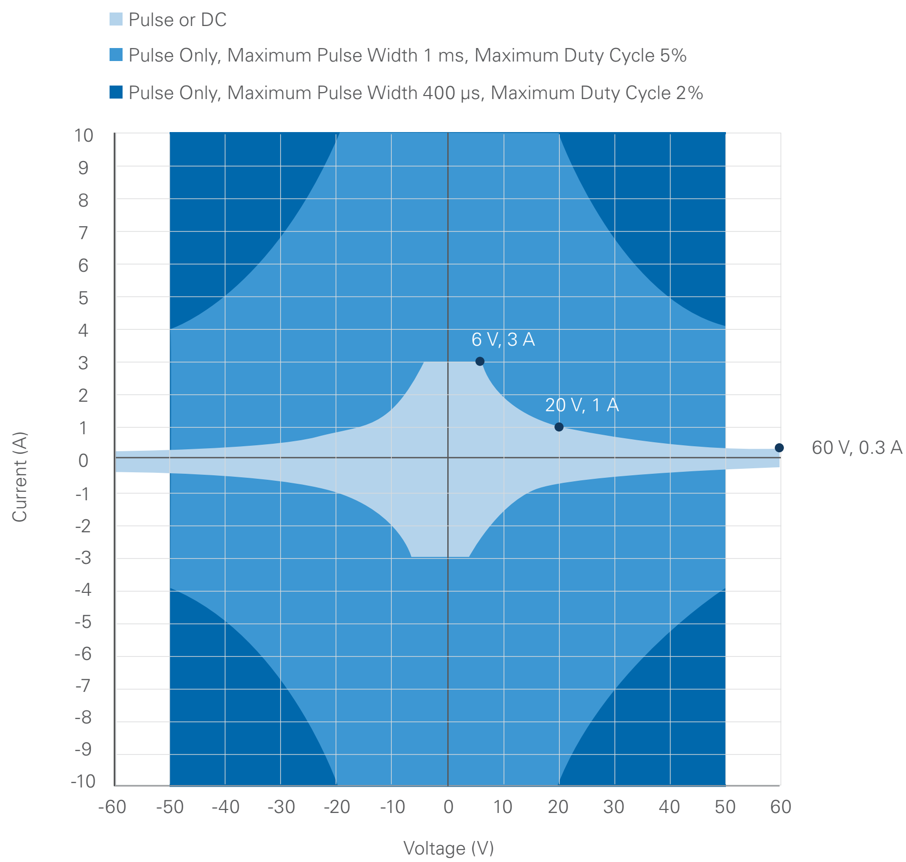

Figure 7. Sample SMU IV Boundary With Pulsing

SMUs capable of pulsing have a unique output architecture to achieve power above the rated DC boundary. They have internal capacitors that are charged when the device is not sourcing. When the device outputs a pulse, the capacitors discharge to provide power beyond the standard specifications. Because these SMUs are temporarily outputting more power than they draw from their power supply, they are limited in how fast and for how long they can output at that power. Restrictions on key pulsing specifications ensure that the SMU can consistently output the desired power without overheating from sinking too much power. These specifications include duty cycle, maximum power, maximum pulse on-time, minimum pulse on-time, and minimum pulse cycle.

$$\text{Duty Cycle} = \frac{\text{On-Time}}{\text{Pulse Cycle}}$$

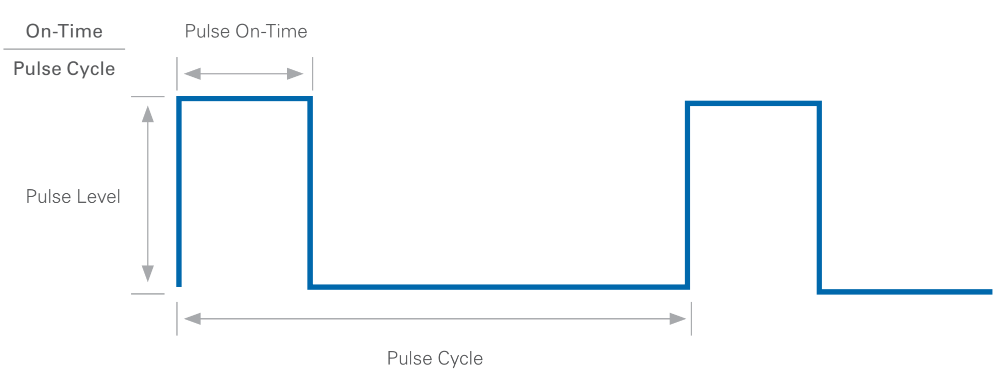

Figure 8. Key SMU Pulsing Specifications

Pulsing is commonly used to limit the heat the DUT has to dissipate during high-powered tests. If a constant high-powered DC signal is provided to the DUT, the temperature in the DUT increases, and this change in temperature can cause changes in the electrical and physical properties of the DUT. If the temperature changes are dramatic enough, they affect your measurement or even damage the DUT. But by pulsing power, you can reduce the average power dissipation through the DUT and minimize the effects of self-heating.

Another consideration when using pulse mode is the transient response of the SMU. When testing in pulse mode, the pulse width should be long enough for the instrument to take a settled measurement but short enough to minimize self-heating to the DUT. To achieve this, you need to make sure that the transient response is critically damped. When you have an under-damped response, like in Figure 9, the output overshoots or becomes unstable, which does not provide a good measurement and can even damage your DUT. If you have an over-damped response, like in Figure 10, the pulse does not reach the desired output level fast enough. When the response is critically damped, like in Figure 11, the signal settles quickly and gives you time to measure the pulse. To ensure the SMU generates a clean pulse, you need to digitize the transient response with an instrument that can sample fast enough. Some SMUs like the PXIe-4139 have this capability, but if your SMU does not, you need to use an oscilloscope.

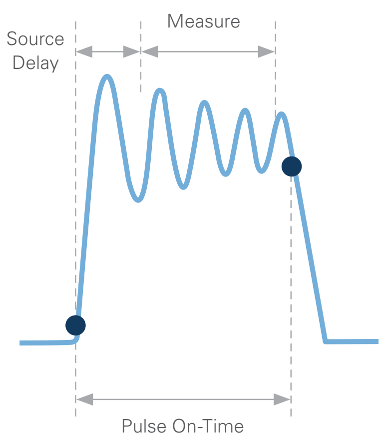

Figure 9. Under-Damped Transient Response

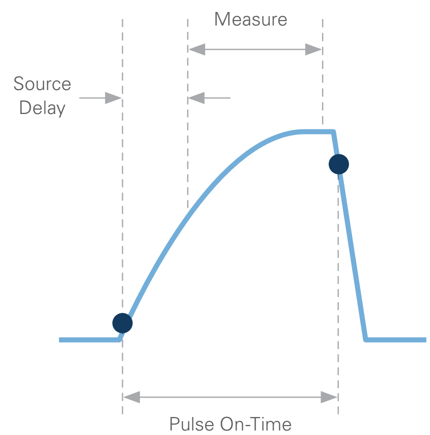

Figure 10. Over-Damped Transient Response

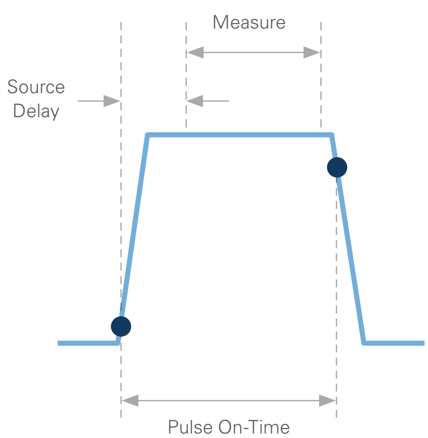

Figure 11. Critically Damped Transient Response

Conclusion

The various methods covered in this guide can help you achieve greater accuracy in your applications requiring DC measurements. When applying these methods to your own measurement setup, remember what kind of error each method is designed to address. This allows you to apply the right solution to the measurement issue you're experiencing. For example, if you're seeing slow rise times in your low-level current measurement, switching to triaxial cables and adding guarding could help. If you're seeing power line noise, you can add shielding to your setup and set the aperture time to one power line cycle. Mastering these best practices helps you get the most out of your test equipment.

To learn more about NI SMUs and their custom transient response or advanced sequencing features, visit ni.com/smu.