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APPLICATION NOTE

Best Practices for Ganging NI Programmable Power Supplies and Source Measure Units

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Overview

NI offers high-power and precise source measurement units (SMUs) and programmable power supplies (PPS). Notable examples include the NI PXIe-4147 (8 V, 3 A per channel) and the PXIe-4151 (20 V, 25 A). However, in certain scenarios, you may need to gang multiple channels to achieve higher current or power levels beyond what a single instrument can deliver. This document provides tips and best practices for managing the interactions between multiple ganged PPS or SMU channels to achieve the desired output power without compromising accuracy or introducing unwanted effects.

Common Ganging Schemes

Figure 1 illustrates various use cases for combining power sources, each with its own set of use cases and challanges. Understanding these configurations is crucial for effective implementation.

Some of these configurations are more prone to difficulties than others.

01

Current sources in parallel

- Commonly used for increasing the output current and power capacity
- Generally, works well and is a commonly applied configuration

02

Voltage sources in series

- Commonly used for increasing the output voltage
- This configuration is generally effective and reliable

03

Voltage sources in parallel

- Commonly used for increasing the current and power capability of the voltage source
- Poses challenges, particularly in remote sense applications

04

Current sources in series

- Commonly used for increasing the maximum compliance voltage
- Poses challenges; usability varies by module and application

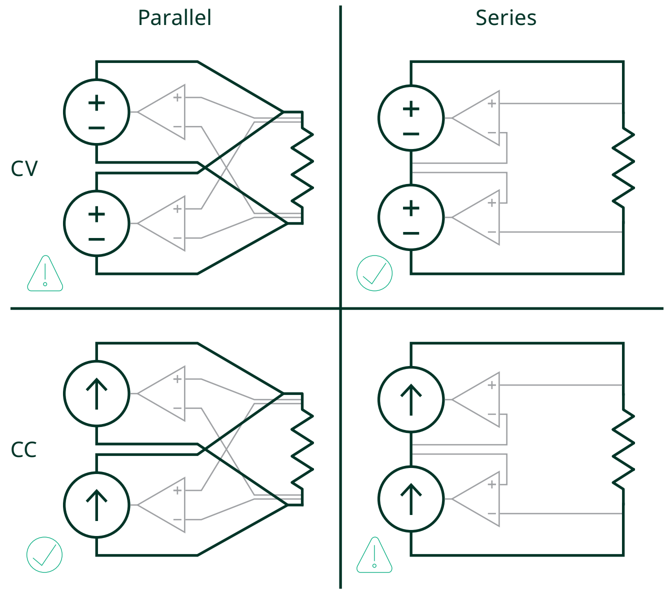

FIGURE 1
Common Series and Parallel Power Source Connection configurations

Note: These assessments assume normal operating conditions. In various compliance and fault conditions, these configurations may present different challenges, as discussed in the Details of Connection Schemes section.

General Considerations

This section outlines general considerations to ensure predictable behavior and a safe measurement system when ganging PPS/SMU channels.

1. **Identical Types:** Gang channels of the same type to ensure uniform behavior and compatibility. Connecting channels of different instrument models can be challenging and prone to instrument damage. As such, connecting one PXIe-4141 channel to a group of other PXIe-4141 channels typically is not problematic. However, connecting it to an NI PXIe-4139 channel can potentially damage the PXIe-4141 channels under various conditions.

It is not recommended to gang channels of different models. Doing so can make the behavior harder to predict and introduce various failure modes that may endanger the test system. By proceeding with this approach, you assume all risks of instrument or device under test (DUT) damage.

2. **Symmetrical configuration:** Ensure that channels are configured identically in terms of range, measurement settings, transient response, and other relevant parameters.
3. **Symmetry in wiring:** Maintain symmetry in external wiring to minimize signal imbalances and avoid introducing asymmetrical effects.
4. **Power quadrants:** Typical SMUs offer 4-quadrant operation with uniform or non-uniform VI boundaries. On the other hand, typical NI PSUs provide reversible or non-reversible polarity 1-quadrant operation. It's crucial to consider these factors when ganging instrument channels.

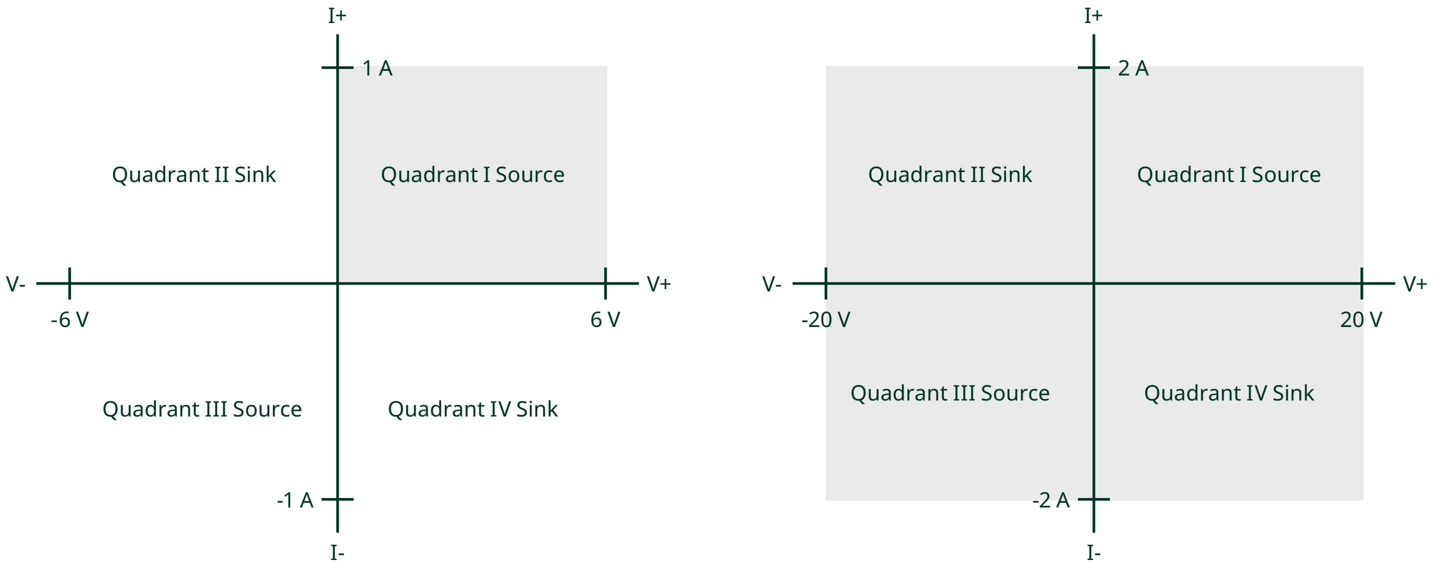

FIGURE 2

Sample Power Supply and SMU Quadrant Operation

> **Note:** The quadrant diagram of the new power subsystem, which includes ganged instruments, will depict the "superposition" of the individual instrument's quadrant diagrams. When creating the quadrant diagram for this subsystem, it's important to consider the power boundaries and adhere to the maximum ganging limitations specified for each instrument.

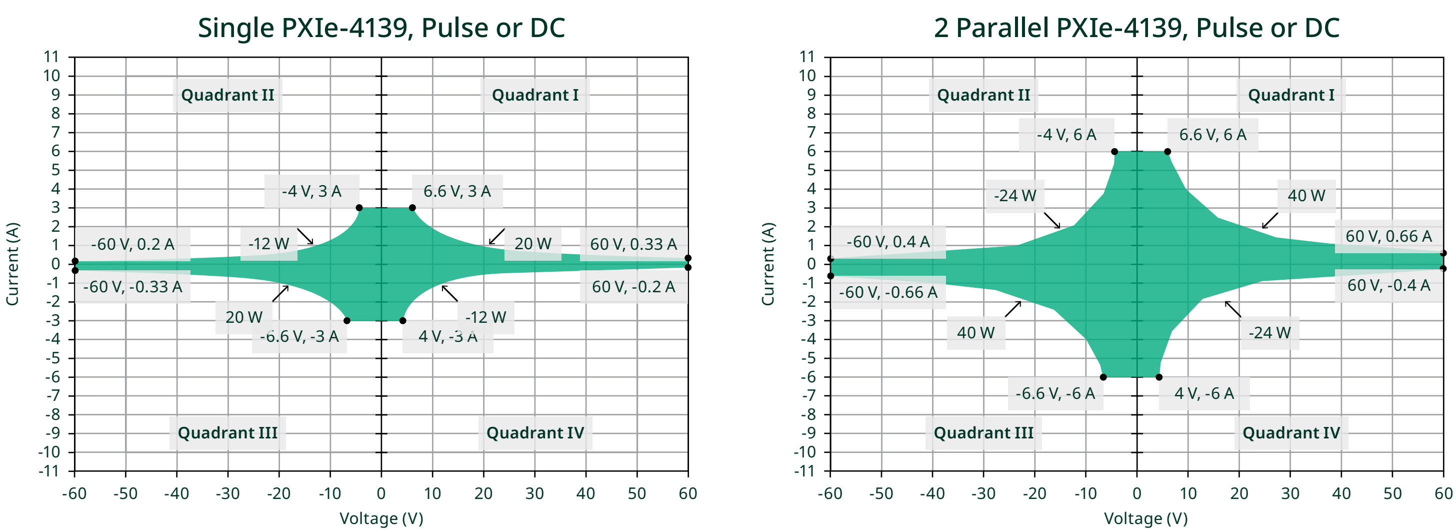

FIGURE 3

Power Envelope Superposition with Ganged Configuration | Left: PXIe-4139 20 W, Right: 2 Parallel PXIe-4139 40 W

5. **Device safety features:** Certain SMU/PPS devices include inhibit, fault, and safety interlock features. Production test systems like NI Semiconductor Test System (STS) offer the required support for utilizing these features, along with accompanying documentation. For do-it-yourself (DIY) or rack-and-stack test systems, it's crucial to correctly implement these features to ensure the safe operation of the system.
6. **Calibration:** Regularly calibrating all ganged channels is essential to maintain accuracy and prevent control loops from conflicting with each other due to artificial imbalances resulting from gain and offset errors.

7. **Autorange:** If using current level autorange, then all the devices will switch to the lowest range when they switch to force-current mode. If many devices change ranges all at once, and if everything is sequenced in software, there might be some time when some devices are forcing current in one range while others are forcing voltage in a different range. To mitigate this, consider setting all devices to fixed voltage and current ranges.

IMPORTANT NOTE: NI instruments that support the channel merging feature can effectively handle channel-to-channel cross-sourcing, control loop interaction, synchronization, and other critical aspects. This capability allows multiple channels to operate in unison. For more detailed information, please refer to the Merged Channels topic in the NI-DCPower documentation.

By adhering to these guidelines, engineers can create a parallel SMU/PPS configuration that maximizes the benefits of ganging channels while minimizing the risks and measurement errors.

Parallel Connection Scheme Details

This section explains various aspects of common parallel connection schemes for SMU/PPS channels, including the impact of remote sensing and potential issues with cross-sourcing.

Figure 4 shows possible options for parallel connection of the SMU/PPS channels.

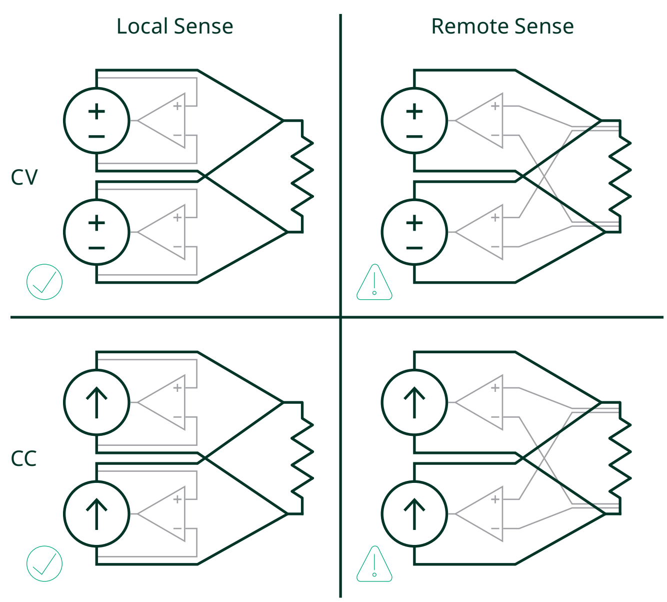

FIGURE 4
Sense Connection Options in Parallel Configuration

Parallel connection of voltage sources with remote sensing (CV, Remote Sense) is a commonly desired operation mode since most DUTs require a regulated constant voltage. This mode is usually easier to achieve in local sense mode but can be challenging in remote sense mode.

Current sources connected in parallel exhibit predictable behavior. However, if the instrument hits the voltage limit before reaching the current setpoint, it will switch to voltage control mode, and the same challenges of constant voltage (CV) mode operation with remote sense will arise.

IMPORTANT NOTES:

- Even in **voltage control mode**, the PPS/SMU device automatically switches to **current control mode** when reaching the current compliance limit to regulate the maximum output current.
- Even in **current control mode**, the PPS/SMU device automatically switches to **voltage control mode** when reaching the voltage compliance limit to regulate the maximum output voltage.

The main challenge to address when combining channels is to prevent "fighting" or cross-sourcing between interconnected channels.

The next section provides in-depth examination of cross-sourcing in CV mode.

Cross-Sourcing Detailed Analysis

Local Sense

Let's consider an example where SMU1 and SMU2 are connected in parallel while operating in constant voltage (CV) mode and utilizing local sensing. The voltage forcing setpoint is set to 400 mV (Figure 5).

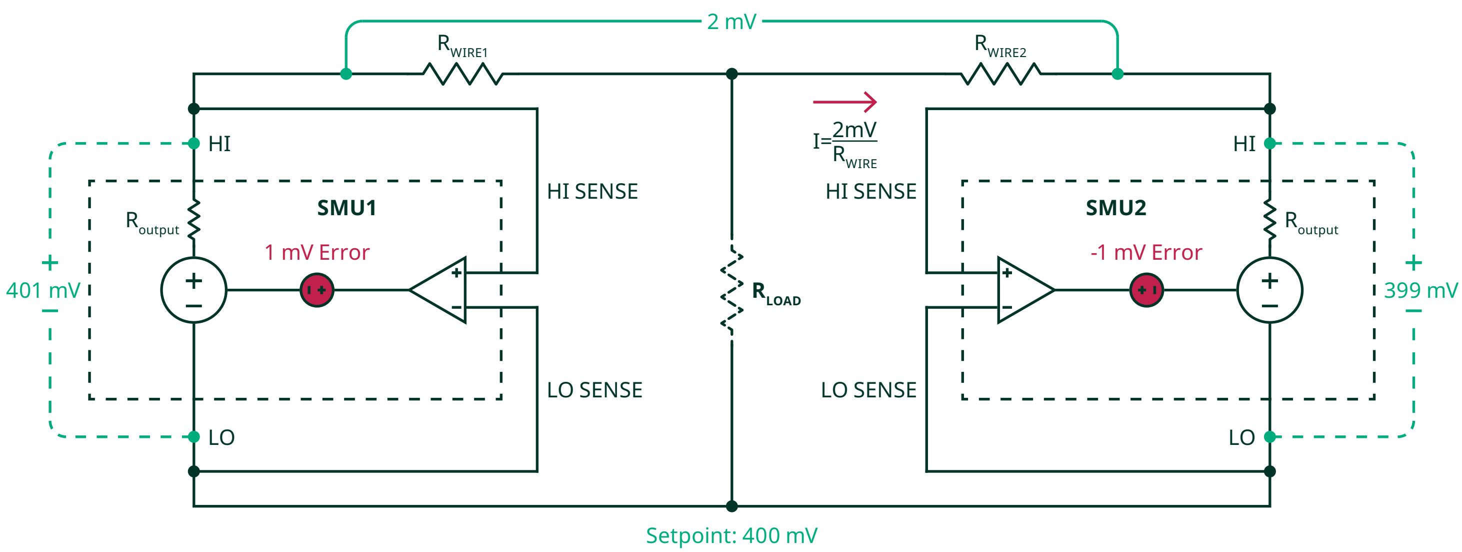

FIGURE 5

Cross-Sourcing of Ganged Channels with Local Sense

Notes:

- The same operational mode applies when the output mode is set to constant current (CC) and the output reaches the 400 mV voltage regulation (compliance) limit due to open load at the output.
- The voltage at the load in this case will be below the programmed value by an amount determined by the load current and the voltage divider formed by the wiring resistance.

If the SMU voltage programming and measurement absolute accuracy is ±500 µV for the given forcing point, in the worst case, there will be 1 mV drop on Rwire. If the SMUs are connected by a 3 m 24 AWG wire, the DCR will be around 0.25 Ω. The cross-sourcing current will be:

$$I = \frac{2\ \text{mV}}{0.25\ \Omega} = 8\ \text{mA}$$

Figure 6 shows a voltage sequence 0 V–400 mV–0 V with 2 mV offset (simulated voltage error) of two PXIe-4139 modules connected in parallel, using local sense with no load.

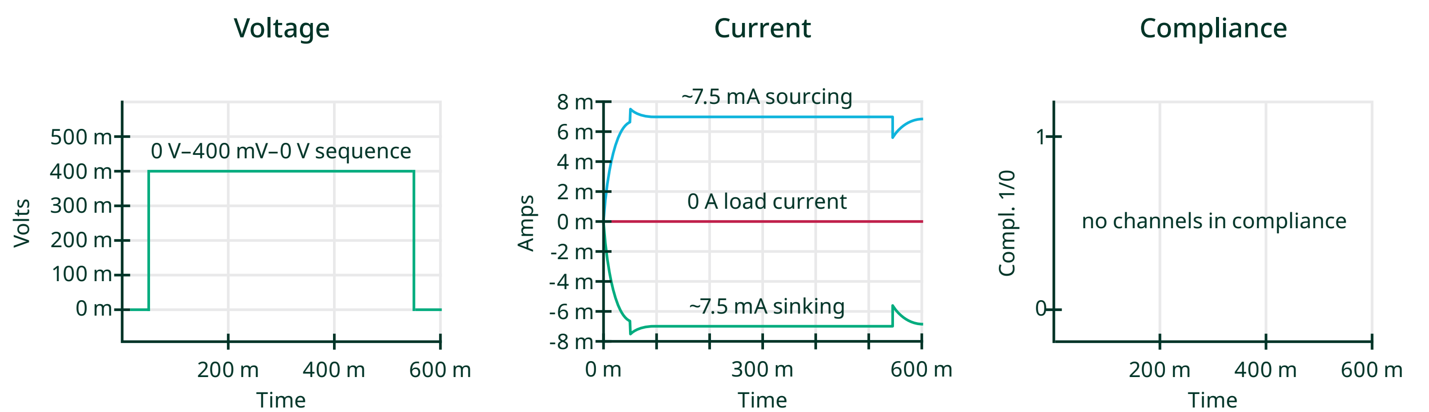

FIGURE 6

Measured Voltage, Current, and Compliance of Ganged Channels with Local Sense

As can be seen in the figure:

- The ganged current reads as 0 (indicated by the red plot).
- Approximately 7 mA of current is flowing from one instrument to another.
- None of the cards are currently operating in compliance mode.

Remote Sense

To improve voltage accuracy at the load, remote sensing should be employed, with both SMUs sensing at the load (Figure 7).

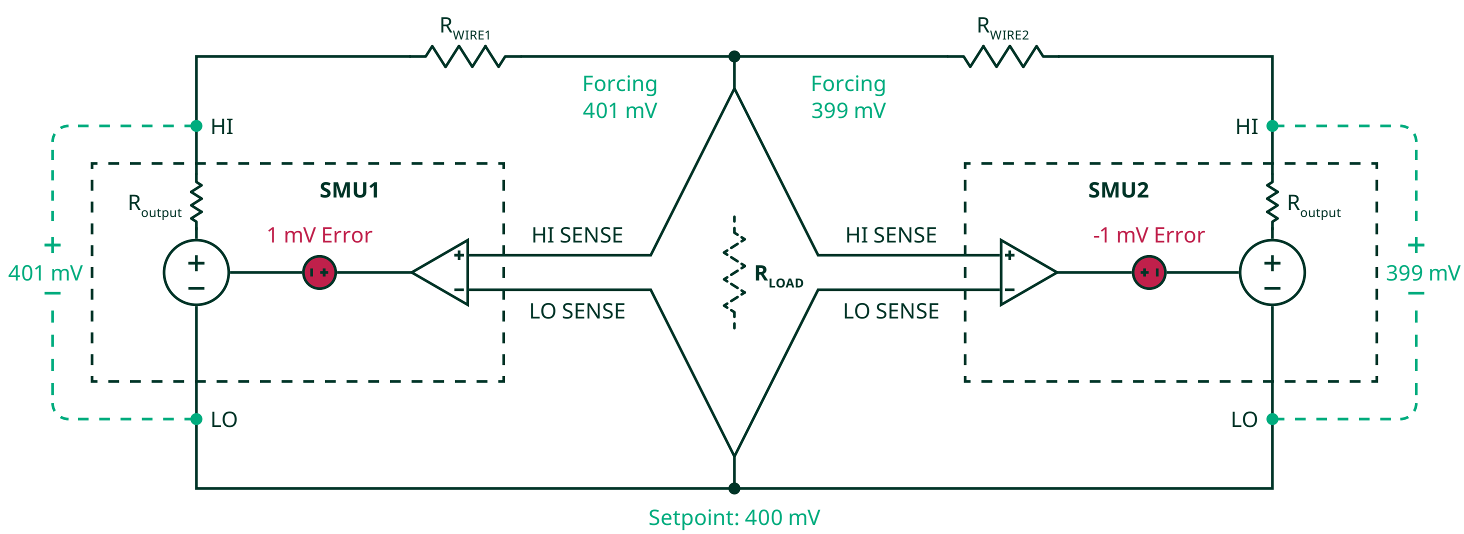

FIGURE 7

Parallel Operation Imbalance with Remote Sense

- SMU1 will apply a 401 mV force, prompting its control loop to increase the current to counteract the 399 mV force applied by SMU2.
- SMU2 will apply a 399 mV force, prompting its control loop to decrease the current to counteract the 401 mV force applied by SMU1.
- Given that SMU1 and SMU2 operate in opposite directions, this process will persist until one of them prevails. If they are configured symmetrically with the same current limits, they will reach the negative and positive current limits.

Figure 8 displays the experimental outcomes of the test.

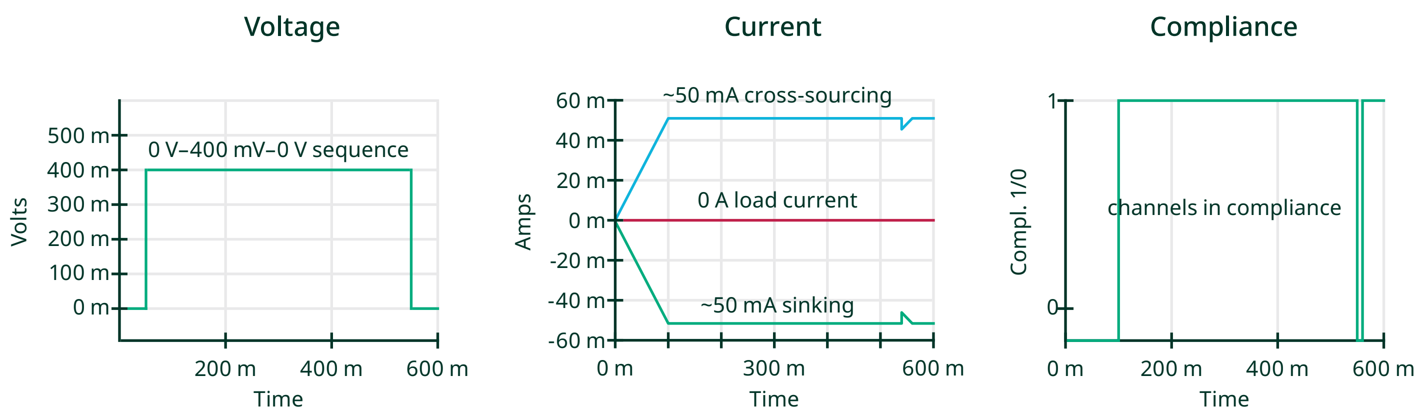

FIGURE 8
Parallel Operation with Remote Sense Behavior

As illustrated in the figure:

- Cross-sourcing reaches the current limit, leading both modules to transition into compliance mode.
- Current regulation is maintained within the 50 mA limit.
- The ganged current stays at 0 A.

This operational mode is not desired due to several considerations:

- Large amounts of current are being sourced from one instrument to another.
- Ganging programmable power supplies, especially those lacking uniform IV quadrants like the NI PXIe-4151, can pose challenges. This is because the instrument's sinking capabilities are limited, potentially resulting in overload conditions.

Notes:
- Cross-sourcing typically does not happen when the ganged SMUs are near their maximum load.
- Despite accurately regulating the 400 mV voltage setpoint, the current contribution of the two instruments is not balanced due to a simulated error of 2 mV between them (Figure 9).

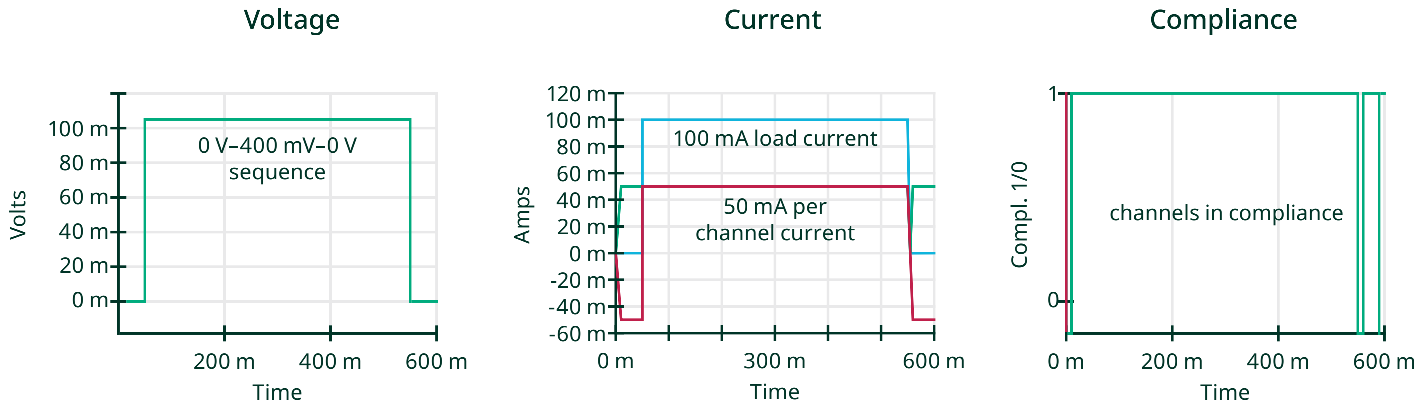

FIGURE 9

Measured Voltage, Current, and Compliance of Ganged Channels with Low Impedance Load

Fortunately, some NI programmable power supplies and source measure units support asymmetric current limits (see **Using asymmetric current limits**) that can help to limit the amount of current sourced from one channel to another in ganged operation.

Cross-Sourcing Workaround Methods

There are several ways to work around cross-sourcing in ganged configurations.

1. Remote sense for master only

This method assumes using remote sense for only one (master) channel, while other channels use local sense. This approach used for devices with channel merging support within a single device scope, where the remote sense measurement is taken from one channel and is used as a reference for others.

2. Diode-or connection

A common method to prevent cross-sourcing when linking power supplies in parallel is through the diode-OR connection, as shown in Figure 10.

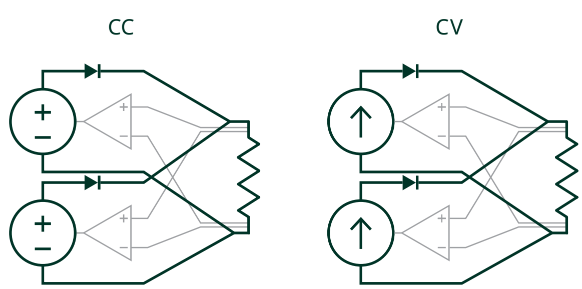

FIGURE 10

Cross-Sourcing Mitigation with Diode-OR Connection

The diodes allow current flow in only one direction at any given time. To compensate for the 0.3–0.7 V drop that occurs across the diode, remote sensing can be directly connected across the DUT terminals. This ensures that the programmed voltage accurately appears on the DUT.

Pros	Cons
In numerous applications, employing a diode-OR strategy can be acceptable and help to build a highly reliable test system.	Limitation of quadrant operation: When combining SMUs, this connection method restricts the four-quadrant operation to a single quadrant.
	Space and power constraints: In certain high-current applications, the use of bulky diodes becomes necessary, occupying additional space on the test fixture and dissipating extra power. Ideally, in such scenarios, minimizing the force path resistance (DCR) to near zero ohms is preferred.
	Reduction of voltage range: The 0.3–0.7 V voltage drop across the diodes can potentially reduce the usable voltage range of the power supply. This decrease in voltage headroom can significantly impact applications, especially when remote sensing is already pushing the limits of compensation. Moreover, in some cases, remote sensing cannot be utilized, as certain programmable power supplies (like NI PXI-4110) may lack remote sensing capability altogether.
	Noise and thermal stability issues: Diodes inherently introduce noise and may affect thermal stability within the setup.
	Reverse leakage: Diodes exhibit reverse leakage, which may impose limitations when performing low-level voltage and current (V/I) measurements.

3. Adding resistance to the force path (Figure 11).

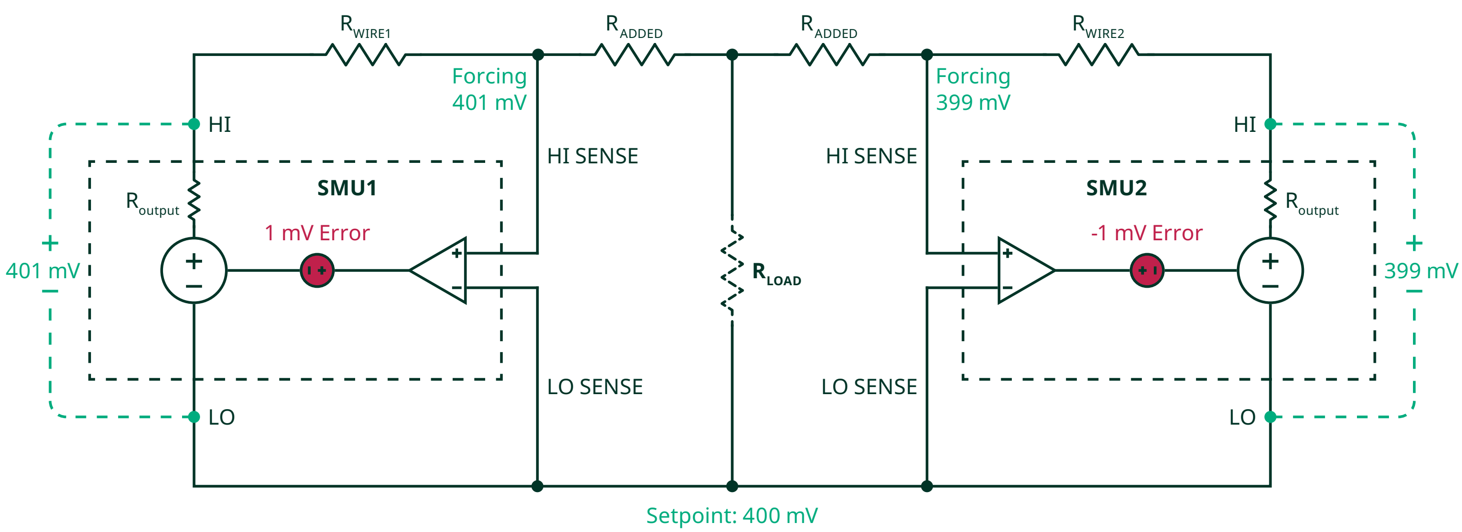

FIGURE 11

Cross-Sourcing Mitigation by Inserting Resistance

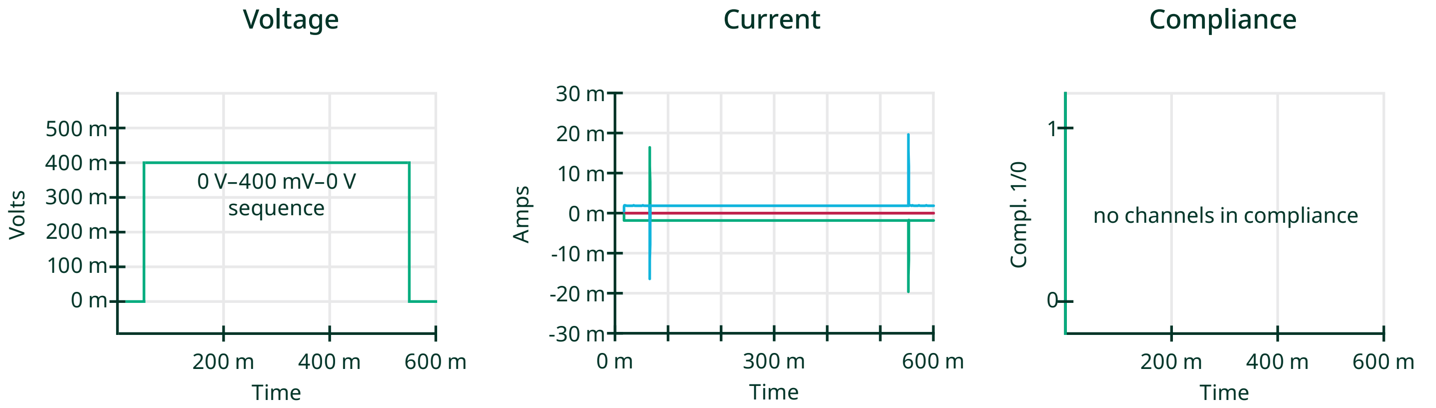

FIGURE 12

Measured Voltage, Current, and Compliance of Ganged Channels and Resistors added to the Force Path

Pros	Cons
This approach returns us to a scenario resembling local sensing, reducing performance issues while still bearing the load regulation effect.	The resistor imposes a limit on the maximum power delivered to the load, dissipates heat, and introduces its own thermal noise.
	The resistor needs to be accurate and have a known value. This ensures that any deviation from the desired setpoint can be adjusted in the software. This adjustment should be made by using the resistance value in series to calculate and program the correct voltage setpoint.

4. Programming the output resistance of the SMU

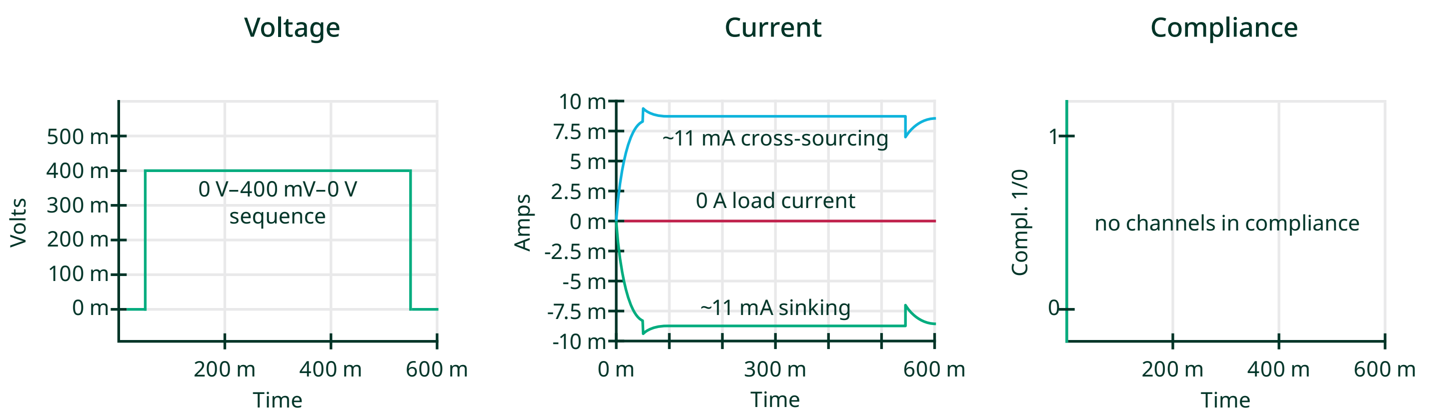

FIGURE 13

Behavior of Parallel SMUs with Programmed Output Resistance

Pros	Cons
This method has a similar effect to adding series resistors to the force path. As shown in Figure 13, the cross-sourcing between two SMUs from the previous experiment is reduced to <8 mA as in the local sense case by programming the output resistance to 0.1 Ω.	Limits the maximum power delivered to the load.
	Not all programmable power supplies and SMUs support programming the output resistance.

5. Using asymmetric current limits

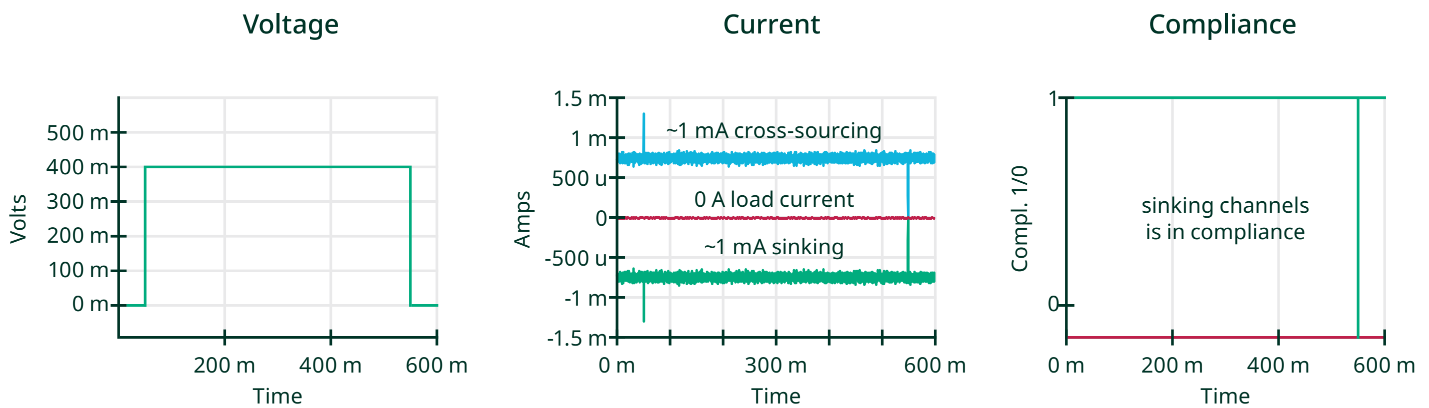

FIGURE 14

Measured Voltage, Current, and Compliance Showing the Cross-Sourcing Reduction with Asymmetric Current Limits

Pros	Cons
This method offers a reliable means to minimize current cross-sourcing between instruments. It yields a similar effect to using diodes on the force path, where backward current is significantly restricted compared to forward current. As depicted in Figure 14, setting the negative current limit to -1.5 mA on both SMUs limits cross-sourcing to several microamperes.	This method is ineffective in constant current (CC) mode. In CC mode, only voltage limits can be programmed asymmetrically, while current sinking will remain within symmetrical limits. Consequently, when the instrument operates in compliance, regulating the output voltage limit, the cross-sourcing effects will mirror those observed in CV mode, as depicted in Figure 8.
	This method effectively restricts cross-sourcing but doesn't entirely eliminate it. Generally, there's a minimum current limit that can be programmed for the chosen current range. For instance, with the PXIe-4151 set to the 25 A range, the minimum programmable negative current limit is typically -300 mA.
	Not all programmable power supplies and SMUs support asymmetric compliance limits.
	In certain applications, both sourcing and sinking are necessary, such as rapidly discharging the DUT capacitance to return the voltage to 0. In these instances, the negative current limit can be raised, approaching a symmetric limits scenario. It's crucial to establish a safe negative current limit tailored to the specific instrument type and application.

There is no universal one-size-fits-all solution to mitigate cross-sourcing in SMU/PPS ganged applications. It's essential to evaluate application specific performance before deploying the test system to the characterization lab or production floor.

Channel Ganging Potential Risks

When employing asymmetric limits with programmable power supplies (PPSs), caution is advised.

- Unlike SMUs, PPSs cannot sink as much current as they can source.
- The negative current limit in the case of a programmable power supply typically pertains to the return-to-zero circuit, which can only sink a limited amount of current to discharge the output capacitance. Exceeding this power limit may lead to overload protection errors.
- It is recommended to consult the specific instrument specifications before utilizing it in ganged configurations.

Conclusions

- Cross-sourcing is a critical limitation to consider when employing PPS and SMUs in parallel (ganged) operation.
- Both constant voltage (CV) and constant current (CC) modes operating in compliance are susceptible to cross-sourcing issues.
- Cross-sourcing can be mitigated by employing external diodes or resistors, programming the output resistance of the instrument, or utilizing asymmetric current limits.
- While asymmetrical current limits provide an effective means to mitigate cross-sourcing in CV mode, they are not effective in CC mode.

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