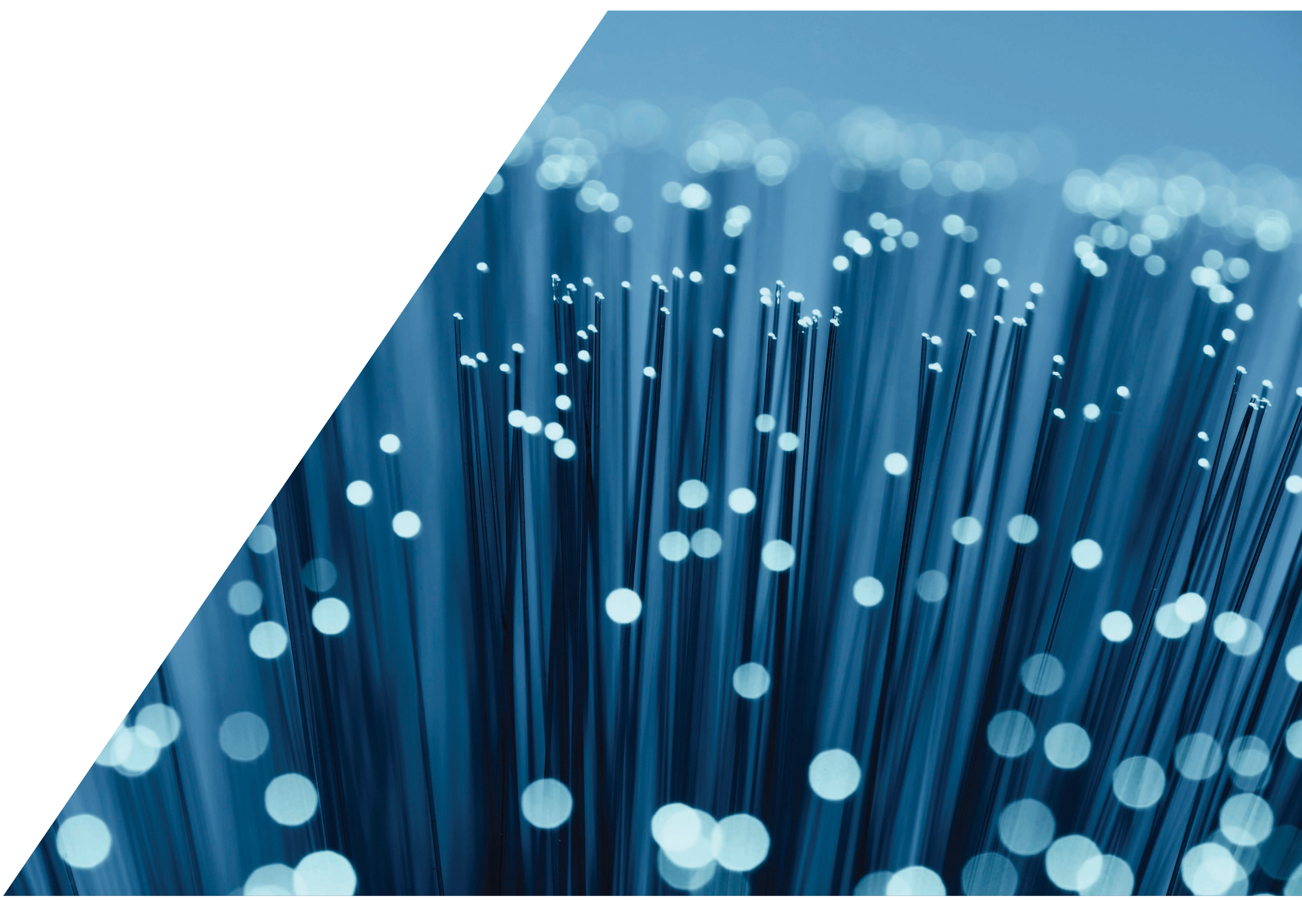
Tektronix®

MP5000 Series

Source-Measure Unit (SMU)

REFERENCE MANUAL



077-1932-01 August 2026

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USA

For product information, sales, service, and technical support:

In North America, call 1-800-833-9200.

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Contents

Safety precautions

The following safety precautions should be observed before using this product and any associated instrumentation. Although some instruments and accessories would normally be used with nonhazardous voltages, there are situations where hazardous conditions may be present.

This product is intended for use by personnel who recognize shock hazards and are familiar with the safety precautions required to avoid possible injury. Read and follow all installation, operation, and maintenance information carefully before using the product. Refer to the user documentation for complete product specifications.

If the product is used in a manner not specified, the protection provided by the product warranty may be impaired.

The types of product users are:

Responsible body is the individual or group responsible for the use and maintenance of equipment, for ensuring that the equipment is operated within its specifications and operating limits, and for ensuring that operators are adequately trained.

Operators use the product for its intended function. They must be trained in electrical safety procedures and proper use of the instrument. They must be protected from electric shock and contact with hazardous live circuits.

Maintenance personnel perform routine procedures on the product to keep it operating properly, for example, setting the line voltage or replacing consumable materials. Maintenance procedures are described in the user documentation. The procedures explicitly state if the operator may perform them. Otherwise, they should be performed only by service personnel.

Service personnel are trained to work on live circuits, perform safe installations, and repair products. Only properly trained service personnel may perform installation and service procedures.

Tektronix products are designed for use with electrical signals that are measurement, control, and data I/O connections, with low transient overvoltages, and must not be directly connected to mains voltage or to voltage sources with high transient overvoltages. Measurement Category II (as referenced in IEC 60664) connections require protection for high transient overvoltages often associated with local AC mains connections. Certain Tektronix measuring instruments may be connected to mains. These instruments will be marked as category II or higher.

Unless explicitly allowed in the specifications, operating manual, and instrument labels, do not connect any instrument to mains.

Exercise extreme caution when a shock hazard is present. Lethal voltage may be present on cable connector jacks or test fixtures. The American National Standards Institute (ANSI) states that a shock hazard exists when voltage levels greater than 30 V RMS, 42.4 V peak, or 60 VDC are present. A good safety practice is to expect that hazardous voltage is present in any unknown circuit before measuring.

Operators of this product must be protected from electric shock at all times. The responsible body must ensure that operators are prevented access and/or insulated from every connection point. In some cases, connections must be exposed to potential human contact. Product operators in these circumstances must be trained to protect themselves from the risk of electric shock. If the circuit is capable of operating at or above 1000 V, no conductive part of the circuit may be exposed.

Do not connect switching cards directly to unlimited power circuits. They are intended to be used with impedance-limited sources. NEVER connect switching cards directly to AC mains. When connecting sources to switching cards, install protective devices to limit fault current and voltage to the card.

Before operating an instrument, ensure that the line cord is connected to a properly-grounded power receptacle. Inspect the connecting cables, test leads, and jumpers for possible wear, cracks, or breaks before each use.

When installing equipment where access to the main power cord is restricted, such as rack mounting, a separate main input power disconnect device must be provided in close proximity to the equipment and within easy reach of the operator.

For maximum safety, do not touch the product, test cables, or any other instruments while power is applied to the circuit under test. ALWAYS remove power from the entire test system and discharge any capacitors before connecting or disconnecting cables or jumpers, installing or removing switching cards, or making internal changes, such as installing or removing jumpers.

Do not touch any object that could provide a current path to the common side of the circuit under test or power line (earth) ground. Always make measurements with dry hands while standing on a dry, insulated surface capable of withstanding the voltage being measured.

For safety, instruments and accessories must be used in accordance with the operating instructions. If the instruments or accessories are used in a manner not specified in the operating instructions, the protection provided by the equipment may be impaired.

Do not exceed the maximum signal levels of the instruments and accessories. Maximum signal levels are defined in the specifications and operating information and shown on the instrument panels, test fixture panels, and switching cards.

When fuses are used in a product, replace with the same type and rating for continued protection against fire hazard.

Chassis connections must only be used as shield connections for measuring circuits, NOT as protective earth (safety ground) connections.

If you are using a test fixture, keep the lid closed while power is applied to the device under test. Safe operation requires the use of a lid interlock.

If a screw is present, connect it to protective earth (safety ground) using the wire recommended in the user documentation.

The symbol on an instrument means caution, risk of hazard. The user must refer to the operating instructions located in the user documentation in all cases where the symbol is marked on the instrument.

The symbol on an instrument means warning, risk of electric shock. Use standard safety precautions to avoid personal contact with these voltages.

The symbol on an instrument shows that the surface may be hot. Avoid personal contact to prevent burns.

The symbol indicates a connection terminal to the equipment frame.

If this symbol is on a product, it indicates that mercury is present in the display lamp. Please note that the lamp must be properly disposed of according to federal, state, and local laws.

Production of this equipment required the extraction and use of natural resources. The equipment may contain substances that could be harmful to the environment or human health if improperly handled at the product's end of life. To avoid release of such substances into the environment and to reduce the use of natural resources, we encourage you to recycle this product in an appropriate system that will ensure that most of the materials are reused or recycled appropriately.

The symbol indicates that this product complies with the applicable European Union requirements according to Directives 2012/19/EU and 2006/66/EC on waste electrical and electronic equipment (WEEE) and batteries. For information about recycling options, check the Tektronix Web site (www.tek.com/productrecycling).

The **WARNING** heading in the user documentation explains hazards that might result in personal injury or death. Always read the associated information very carefully before performing the indicated procedure.

The **CAUTION** heading in the user documentation explains hazards that could damage the instrument. Such damage may invalidate the warranty.

The **CAUTION** heading with the symbol in the user documentation explains hazards that could result in moderate or minor injury or damage the instrument. Always read the associated information very carefully before performing the indicated procedure. Damage to the instrument may invalidate the warranty.

Instrumentation and accessories shall not be connected to humans.

Before performing any maintenance, disconnect the line cord and all test cables.

To maintain protection from electric shock and fire, replacement components in mains circuits — including the power transformer, test leads, and input jacks — must be purchased from Tektronix. Standard fuses with applicable national safety approvals may be used if the rating and type are the same. The detachable mains power cord provided with the instrument may only be replaced with a similarly rated power cord. Other components that are not safety-related may be purchased from other suppliers as long as they are equivalent to the original component (note that selected parts should be purchased only through Tektronix to maintain accuracy and functionality of the product). If you are unsure about the applicability of a replacement component, call a Tektronix office for information.

Unless otherwise noted in product-specific literature, Tektronix instruments are designed to operate indoors only, in a non-residential location, in the following environment: Altitude at or below 2,000 m (6,562 ft); temperature 0 °C to 50 °C (32 °F to 122 °F); and pollution degree 1 or 2.

To clean an instrument, use a cloth dampened with deionized water or mild, water-based cleaner. Clean the exterior of the instrument only. Do not apply cleaner directly to the instrument or allow liquids to enter or spill on the instrument. Products that consist of a circuit board with no case or chassis (e.g., a data acquisition board for installation into a computer) should never require cleaning if handled according to instructions. If the board becomes contaminated and operation is affected, the board should be returned to the factory for proper cleaning/servicing.

This product may contain a small installed lithium metal button cell. Please properly dispose of or recycle the cell at its end of life according to local government regulations.

This product may contain one or more type CR lithium batteries. According to the state of California, CR lithium batteries are classified as perchlorate materials and require special handling. See http://www.dtsc.ca.gov/hazardouswaste/perchlorate for additional information.

If present, the small lithium primary button cell contained in this equipment does not exceed 1 gram of lithium metal content per cell, and the cell type has been shown by the manufacturer to comply with the applicable requirements of the UN Manual of Tests and Criteria Part III, Sub-section 38.3. Consult your carrier to determine which lithium battery transportation requirements are applicable to your configuration, including to its re-packaging and re-labeling, prior to reshipment of the product by any mode of transport.

Safety precautions version April 2025

Introduction

Welcome

This manual describes the source-measure modules (SMU) for the MP5000 Series Modular Precision Test System.

It includes information for the following SMU modules:

- **MSMU60-2:** 30 W, 60 V, 1.5 A 2-channel.
- **MSMU200-2:** 30 W, 200 V, 1.5 A (with extended pulse capability) 2-channel.

Extended warranty

Additional years of warranty coverage are available on many products. These valuable contracts protect you from unbudgeted service expenses and provide additional years of protection at a fraction of the price of a repair. Extended warranties are available on new and existing products. Contact your local Tektronix office, sales partner, or distributor for details.

Contact information

If you have any questions after you review the information in this documentation, please contact your local Tektronix office, sales partner, or distributor. You can also call the Tektronix corporate headquarters (toll-free inside the U.S. and Canada only) at 1-800-833-9200. For worldwide contact numbers, visit tek.com/contact-tek.

Source and measure

Source and measurement overview

You can use the source-measure units (SMUs) for the following source and measure operations:

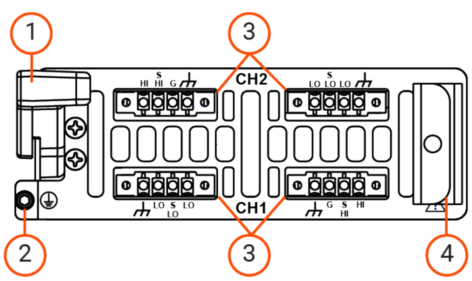
- Source voltage and measure current, voltage, resistance, or power
- Source current and measure voltage, current, resistance, or power
- Measure voltage, current, resistance, or power

The operating boundaries for the source-measure operations are provided in Operating boundaries (on page 47).

WARNING: Hazardous voltages may be present on the output and guard terminals. To prevent electrical shock that could cause injury or death, NEVER make or break connections to the MP5000 modules while the slot is powered on. Power down the slot before handling cables connected to the outputs. Verify that there is no voltage on the terminals of the module before making connections between the module and the DUT. Placing the output in standby mode does not guarantee that the outputs are not powered if a hardware or software fault occurs. For the safest operation, power down the MP5000 mainframe before you make or break connections to the MP5000 modules.

Module connections

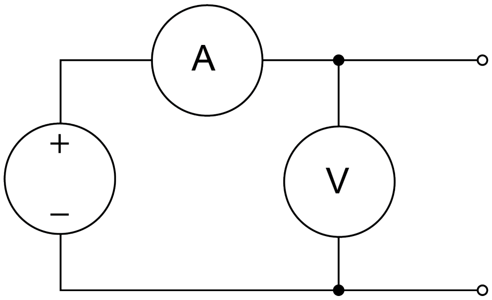
Module connections are made to the module output panel. The output panel of the MSMU60-2 and MSMU200-2 is shown in the following figure. Refer to Test connections (on page 25) for information on how to make test connections.



1	Release lever	The release lever at the top left of the output panel of the module assists with removing a module.
2	Retention screw	The module retention screw at the bottom-left of the output panel of the module must be tightened after inserting a module and loosened before removing a module.
3	Output terminals	The output terminals provide connections for SENSE HI, SENSE LO, FORCE HI, FORCE LO, GUARD, and chassis ground.
4	Spring bracket	The spring bracket ensures that the module is fully seated and locked into the mainframe. It is also used to release a module when removing it from the mainframe.

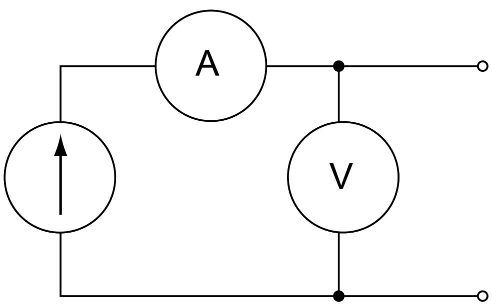
Fundamental circuit configurations

The fundamental source-measure configurations for the MP5000 Series are shown in the following figures. When sourcing voltage, you can measure current or voltage, as shown in the following figure.



A	Current meter
+ **–**	Voltage source
V	Voltage meter

When sourcing current, you can measure voltage or current, as shown in the following figure.

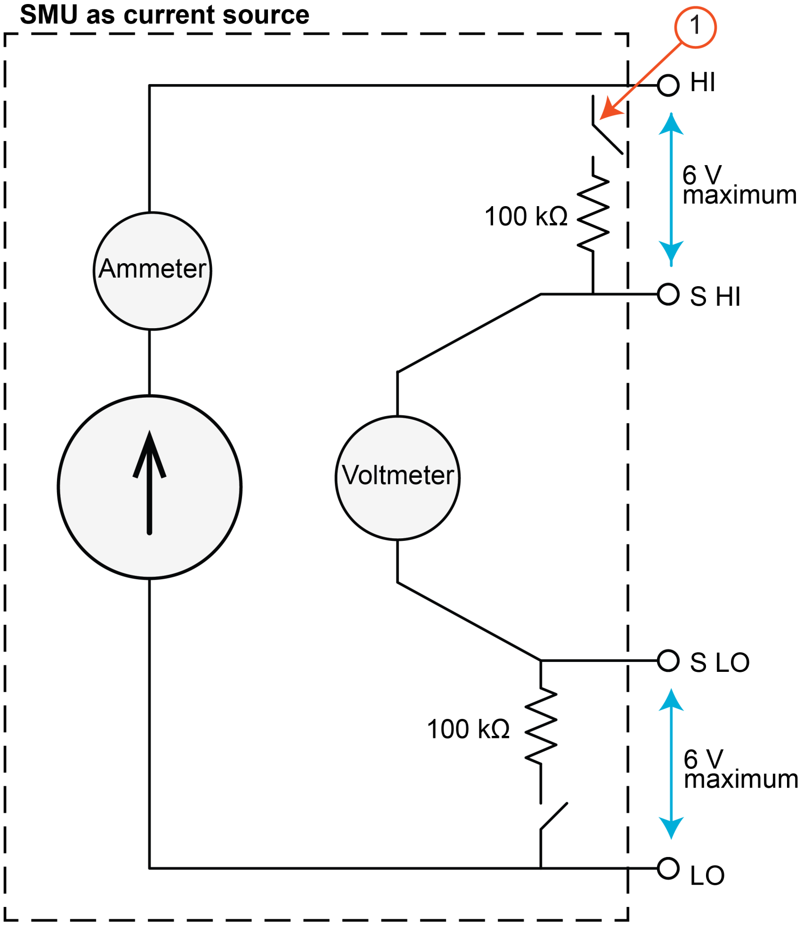


A	Current meter
↑	Current source
V	Voltage meter

Source current

When you configure a SMU to source current, the SMU functions as a high-impedance current source that can limit voltage and can measure current or voltage.

As shown in the following figure, if you set the SMU to 2-wire sense, voltage is measured at the HI and LO terminals of the SMU. If you set the SMU to 4-wire sense, voltage is measured directly at the device under test (DUT) using the sense terminals. Four-wire sense eliminates any voltage drops that may be in the test leads or in the connections between the SMU and the device under test.



1	Relay condition	Remote sense: Relay is open. Automatic sense: Relay is closed.

To enhance current source accuracy, the current source does not use the sense leads. However, if the SMU is in 4-wire sense, the SMU may reach limit levels if you disconnect the sense leads. If the sense leads are disconnected and the SMU is configured for remote sense, incorrect measurements result. If the SMU is configured for autosense, the SMU returns approximate measurement values.

It is valuable to measure the function you are sourcing if you are operating when the source limit has been exceeded. When the source limit has been exceeded, the programmed source value is not reached. Use the SMU to measure the actual output level.

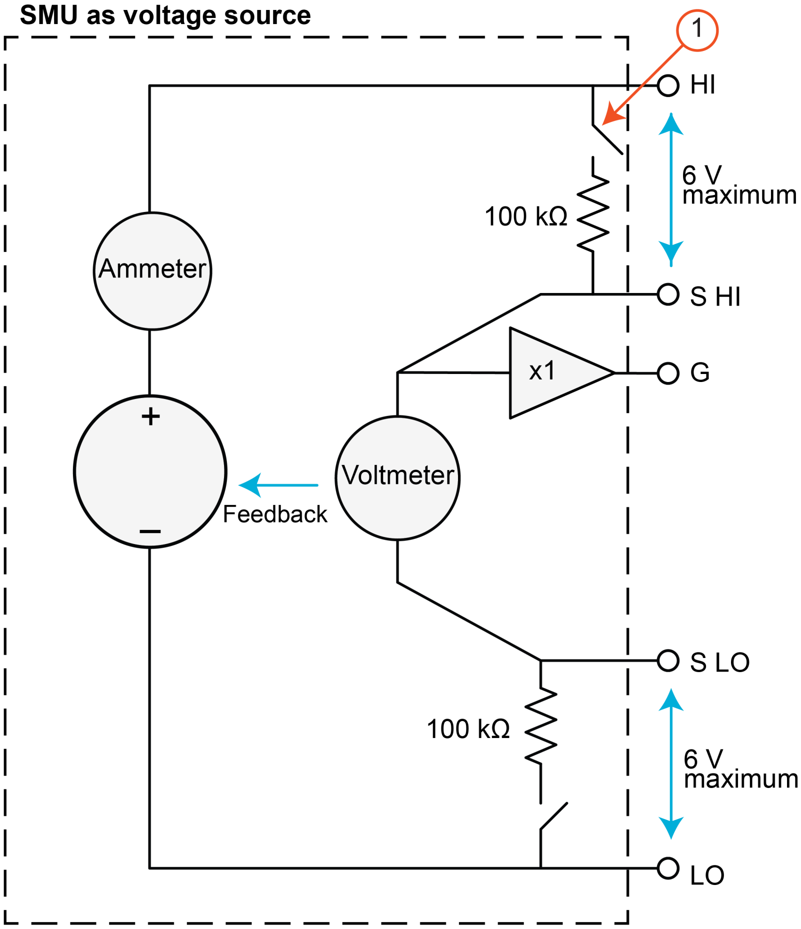
Source voltage

When a SMU is configured to source voltage, it functions as a low-impedance voltage source that can limit current. The SMU can measure current or voltage. This configuration is shown in the following figure.

Sense circuitry continuously monitors the output voltage and adjusts the voltage source as needed. The voltage meter senses the voltage and compares it to the programmed voltage level. If the sensed level and the programmed value are not the same, the source voltage is adjusted accordingly.

If the source limits have been exceeded, the programmed source value is not reached. You can measure the source to measure the actual output level.

If you set the SMU to 2-wire sense, the voltmeter senses the voltage at the HI and LO terminals. If it is set to 4-wire sense, the voltmeter senses the voltage at the device under test (DUT). Four-wire sense eliminates the effect of voltage drops in the test leads, ensuring that the exact programmed voltage is applied to the DUT. Refer to Select 2-wire or 4-wire measurements (on page 28) for more information on sense.

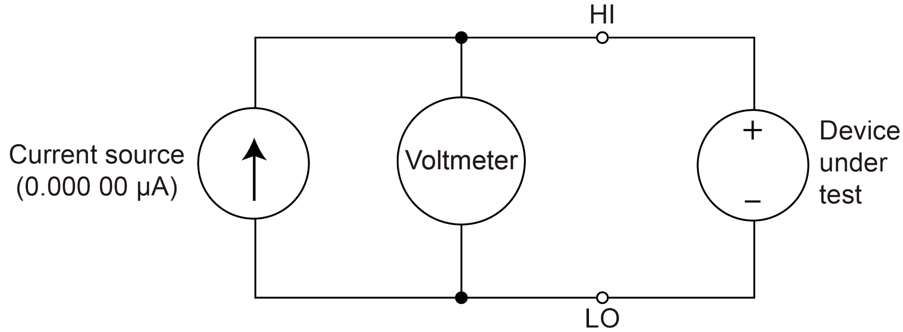


1	Relay condition	Remote sense: Relay is open. Automatic sense: Relay is closed.

Measure only (voltage or current)

The following figures show the configurations for using the SMU as a voltmeter or ammeter.

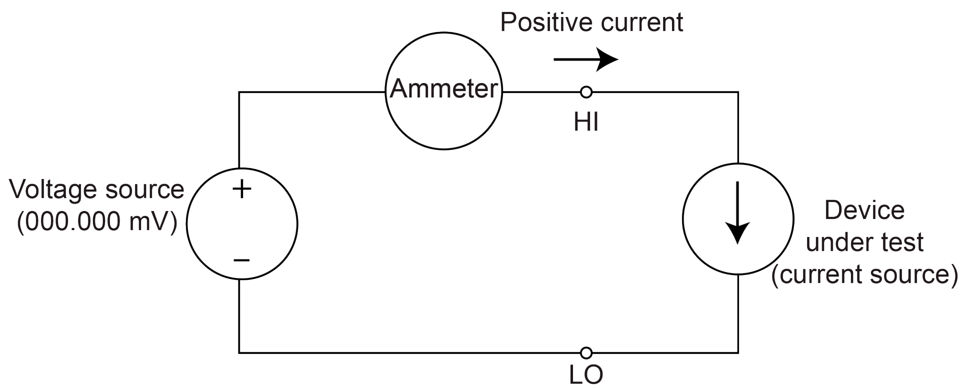
As shown in the following figure, to configure the SMU to measure voltage only, set it to source 0 A on the lowest current range and measure voltage. Using the lowest current source range ensures the highest impedance as a voltmeter.



CAUTION: Always set the voltage limit to a level that is higher than the expected measured voltage. If the voltage limit is set to a level that is lower than the measured voltage, excessive current flows into the module. This current could damage the module. For more information, see Sink operation (on page 43).

When connecting an external energy source to the module when it is configured as a current source, set the output-off state to the high-impedance mode. See Output-off state (on page 18) for more information on the output-off states.

In the following figure, the SMU uses a 2-wire local sense configuration. The module is set to measure current only by setting it to source 0 V and measure current. Note that to obtain positive (+) readings, conventional current must flow from HI to LO.



Front-panel SMU operation

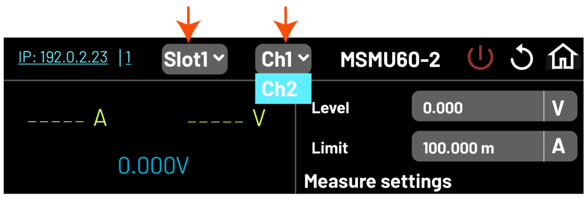
Most of the procedures in this manual assume you are using remote commands to set up and control the SMU. However, you can perform some operations using the SMU from the MP5103 front panel. You can:

- Turn the output on or off
- View the current and voltage readings
- View and set the SMU output level
- Adjust measure and source settings
- Reset the module

NOTE: The front-panel display turns off after 10 minutes of inactivity to prevent screen burn-in. Touch the display or turn the navigation wheel to return the display to normal brightness.

To access the front-panel settings:

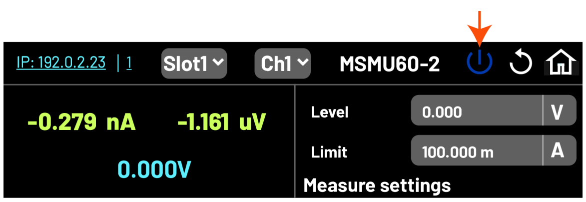
1. From the Home screen, select **Channels**. Information for channel 1 (**Ch1**) of the module installed in slot 1 (**SLOT1**) is displayed.
2. Select the slot and channel from the lists.



3. Use the touch screen and knobs to access the options on the screen.

Turn the output on or off

Select the output status indicator, shown in the following figure, to turn on the output. The indicator turns blue. The Module Status light on the front panel of the mainframe also changes from green to blue. When the output is on, the current and voltage measurements are shown on the left side of the screen. The source level is shown below the measurements.



This sets the `slot[Z].smu[Y].source.output` command.

Adjust measure and source settings

Measure and source settings are presented on the right side of the display. Use the touchscreen and the knob to make selections. Use the knob to scroll down to view additional settings. You can make the following settings.

Front-panel setting	Brief description	Equivalent command
Level	The output level of the voltage or current source	`slot[Z].smu[X].source.levelv` `slot[Z].smu[X].source.leveli`
Limit	The source limit value if the Limit Mode is set to Symmetric	`slot[Z].smu[X].source.limitv` `slot[Z].smu[X].source.limiti`
– Limit	The negative limit value if the Limit Mode is set to Asymmetric	`print(slot[Z].smu[X].source.limitnv)` `print(slot[Z].smu[X].source.limitni)`
+ Limit	The positive limit value if the Limit Mode is set to Asymmetric	`print(slot[Z].smu[X].source.limitpv)` `print(slot[Z].smu[X].source.limitpi)`
Measure settings		
Range	Voltage range	`slot[Z].smu[X].measure.rangev` `slot[Z].smu[X].measure.autorangev`
Range	Current range	`slot[Z].smu[X].measure.rangei` `slot[Z].smu[X].measure.autorangei`
Sense		`slot[Z].smu[X].sense`

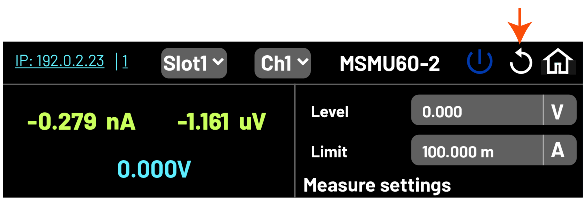
Source settings		
Source		`slot[Z].smu[X].source.func`

Range	AUTO or a specific range	`slot[Z].smu[X].source.autorangev`
		`slot[Z].smu[X].source.rangev`
		`slot[Z].smu[X].source.autorangei`
		`slot[Z].smu[X].source.rangei`

Limit Mode	Asymmetric or Symmetric	No equivalent

Reset the channel

Select reset, shown in the following figure.



Set the source function

The TSP commands that set up the source functions begin with `slot[Z].smu[X].source`. Command descriptions are provided in the TSP command reference in the *MP5000 Series Programmer Manual*.

Set the source function to source either current or voltage. For the source function, you can set the limits, delay, range, and output-off behavior. The source commands are specific to each source function (voltage or current).

Related command:

`slot[Z].smu[X].source.func`

Source level

You set the output level of the voltage or current source.

If the source is configured as a voltage source and the output is on, the new voltage level is sourced immediately. If the output is off or the source is configured as a current source, the voltage level is sourced when the source is configured as a voltage source and the output is turned on.

If the source is configured as a current source and the output is on, the current level is sourced immediately. If the output is off or the source is configured as a voltage source, the current level is sourced when the source is configured as a current source and the output is turned on.

The sign of source level dictates the polarity of the source. Positive values generate positive voltage or current from the HI terminal of the source relative to the LO terminal. Negative values generate negative voltage or current from the HI terminal of the source relative to the LO terminal.

If a manual source range is selected, the level cannot exceed the specified range. For example, if the voltage source is on the 2 V range, you cannot set the voltage source level to 3 V. When source autorange is selected, the amplitude can be set to any level supported by the module. You can configure the lowest source range to be used during autoranging with the `slot[Z].smu[X].source.lowrangeY` command. This can be especially useful if you need to avoid the longer settling times that are typically associated with lower ranges, especially when sourcing current.

Related commands:

```
slot[Z].smu[X].source.atlimit
slot[Z].smu[X].source.autorangeY
slot[Z].smu[X].source.func
slot[Z].smu[X].source.levelY
slot[Z].smu[X].source.lowrangeY
slot[Z].smu[X].source.output
slot[Z].smu[X].source.rangeY
```

Ranges

You can set ranges for the source and measurement values. You can set specific ranges or allow the source-measure unit (SMU) to choose the ranges automatically.

The source range determines how accurately the source output can be set.

The measurement range determines the full-scale input for the measurement. The measurement range also affects the accuracy of the measurements and the maximum signal that can be measured.

The highest available range is determined by the limit setting for the function that is being sourced or measured.

The range defaults to autorange for all functions. If you switch from a fixed range to autorange, autorange is set to off. The range remains at the fixed range until a measurement is made or the source level is changed, at which time the range is set to accommodate the new measurement or source level.

Source range

The source range determines how accurately the source output can be set.

You can select an automatic or fixed source range. The range defaults to automatic range (autorange) for all functions. If you select a fixed range, autorange is set to off. The range remains at the fixed range unless the source level is changed or autorange is enabled. If the level is changed, the range is set to accommodate the new source level.

When autorange is enabled, the module automatically sets the best range to source the configured signal. The full-scale output for each voltage and current source range is 101 percent of the selected range. For example, ±1.01 A is the full-scale source value for the 1 A range. The module autoranges at 100 percent of the range.

When autorange is enabled, you can define a low range limit for the source. This sets the lowest range that the module uses when autorange is enabled. Lower ranges generally require greater settling times, especially for low current ranges. By setting a low range value that is higher than the automatically selected value, the SMU may be able to source small values with less settling time.

You can also use a fixed source range. A fixed range eliminates the time that the module needs to select the range automatically. It also allows you to use the same range for all outputs. For example, you may want a sweep to use the same range to source all the sweep points.

To select a range, specify the approximate source level that will be used. The module selects the lowest range that can accommodate that level. For example, if you expect to source levels around 3 V, set the source range to 3 V. The lowest range that can accommodate 3 V is the 6 V range.

NOTE: When you change a source range, source autorange is automatically turned off and remains off until you enable it again.

The maximum output power and source/sink limit for the MSMU60-2 is 30 W per channel (maximum). With the 60 V (voltage source) range selected, the highest current limit or measurement range is 100 mA. With the 20 V source range selected, the highest current limit or measurement range is 1.5 A.

The maximum output power and source/sink limit for the MSMU200-2 is 30 W per channel (maximum). With the 200 V (voltage source) range selected, the highest current limit or measurement range is 100 mA.

The 7 A range can be used for DC output up to 1.5 A or pulsing only up to 7 A. The highest voltage limit when pulsing is 10 V (on the 20 V range).

Refer to Operating boundaries (on page 47) for power derating information and Pulse-only regions (on page 56) for extended operating area current pulse durations and duty cycle.

The source ranges are:

MSMU60-2

- **Voltage:** 200 mV, 2 V, 6 V, 20 V, 60 V
- **Current:** 100 nA, 1 µA, 10 µA, 100 µA, 1 mA, 10 mA, 100 mA, 1 A, 1.5 A

MSMU200-2

- **Voltage:** 200 mV, 2 V, 6 V, 20 V, 200 V
- **Current:** 100 nA, 1 µA, 10 µA, 100 µA, 1 mA, 10 mA, 100 mA, 1 A, 7 A

Related commands:

```
slot[Z].smu[X].source.autorangeY
slot[Z].smu[X].source.lowrangeY
slot[Z].smu[X].source.rangeY
```

Out of range entries

If you select a fixed source range, the range must be large enough to source the value. If not, an overrange condition can occur. If an overrange condition occurs, an error is displayed and the change to the setting is ignored.

If you send a source level that is out of range when output is off, the SMU does not return an error until the output is turned on.

Limits

The source limits prevent the SMU from sourcing a voltage or current over a set value.

When sourcing voltage, the SMU can be set to limit current. Conversely, when sourcing current, the SMU can be set to limit voltage. In steady-state conditions, the instrument will not exceed these limits. The maximum limit is the same as the maximum values listed in the specifications.

As the names imply, the current limit restricts the current for sourced voltage and the voltage limit restricts the voltage for a sourced current. For additional details on limits, see Operating boundaries (on page 47).

If you attempt to change the source limit to a value that is not appropriate for the selected source range, the source limit is not changed and a warning is generated. You must change the source range before you can select the new limit.

The minimum programmable limit is 10% of the smallest voltage or current range. However, when setting the limit, consider the load and the source value. For example, if you are sourcing 1 V to a 1 kΩ resistor, then the current limit should be set to at least 1 mA (1 V/1 kΩ = 1 mA) to allow for the full 1 V to be sourced into the load. If a limit lower than 1 mA is set, the source is limited.

You can set the limits to be symmetric or asymmetric.

When symmetric limits are selected, the limit circuit limits in either polarity regardless of the polarity of the source or limit value. The maximum limits are based on the source range.

As an example, assume the following:

- MSMU60-2: V_{SRC} = 10 V; I_{LIMIT} = 10 mA
- Device-under-test (DUT) resistance: 10 Ω

With a source voltage of 10 V and a DUT resistance of 10 Ω, the current through the DUT should be 10 V / 10 Ω = 1 A. However, because the limit is set to 10 mA, the current does not exceed that value, and the voltage across the resistance is limited to 100 mV. In effect, the 10 V voltage source is transformed into a 10 mA current source.

You can also set independent positive and negative limit values using `slot[Z].smu[X].source.limitnY` and `slot[Z].smu[X].source.limitpY`. Asymmetric limits allow you to set different limits when power is sourced and when power is sunk.

If you only configure the limit using the `slot[Z].smu[X].source.limitY` command, the SMU automatically sets the negative limit to the same value with opposite polarity. For example, setting `slot[1].smu[1].source.limitv` to 4 V sets `slot[1].smu[1].source.limitpv` to 4 V and `slot[1].smu[1].source.limitnv` to −4 V.

If operating in the pulse-only region, you must use the pulse limit commands to specify the current limit during pulsing. This limit does not apply in the DC operating range. The maximum voltage limit in the extended operating area is 10 V.

To check if the SMU is operating at the limit, use the `slot[Z].smu[X].source.atlimit` command.

Related commands:

```
slot[Z].smu[X].source.atlimit
slot[Z].smu[X].source.limitnY
slot[Z].smu[X].source.limitpY
slot[Z].smu[X].source.limitY
slot[Z].smu[X].source.offlimitnY
slot[Z].smu[X].source.offlimitpY
slot[Z].smu[X].source.offlimitY
slot[Z].smu[X].source.pulse.limitnY
slot[Z].smu[X].source.pulse.limitpY
slot[Z].smu[X].source.pulse.limitY
```

Active limits

When an SMU module is configured to use asymmetric voltage or current source limits, the instrument will accept values outside of the source limit range. The starting source limit range is specified by the larger absolute value of the limits set by `slot[Z].smu[X].source.limitpY` and `slot[Z].smu[X].source.limitnY`. The source limit range is adjusted by the the instrument as needed.

The lowest level that the module will limit when sourcing is 10% of the source limit range. If the smaller limit is less than that value, the module may limit the source to 10% of the source limit range.

For example, setting a positive current source limit of 1 A and a negative current source limit of -500 mA will result in the source limit range being set to 1 A and the source being limited to -500 mA, as they are on the same range. However, setting a positive current source limit of 1 A and a negative current source limit of -1 µA, may lead to the source being limited to 100 mA (10% of 1 A).

Tektronix suggests setting asymmetric limits and then using the `slot[Z].smu[X].source.activelimitpY` and `slot[Z].smu[X].source.activelimitnY` commands to monitor limit values during a test.

Related commands:

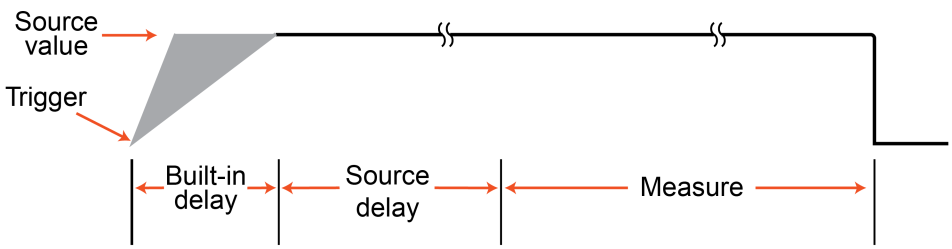
```
slot[Z].smu[X].source.activelimitnY
slot[Z].smu[X].source.activelimitpY
```

Source delay

When you use the SMU to source, there is a built-in delay between when the source is turned on or a new source level is applied. The built-in delay provides a settling time for the source. The length of the built-in delay depends on settings such as the selected range, if autorange is on, and the magnitude of a source level change.

You can also add a fixed source delay that is applied in addition to the built-in delay. You can use this if your circuit requires additional settling time after the source level changes. To specify additional delay time, use `slot[Z].smu[X].source.delay`.

The relationships between the built-in delays, fixed delays, and measurements are shown in the following figure.



Related commands:

```
slot[Z].smu[X].source.autorangeY
slot[Z].smu[X].source.delay
slot[Z].smu[X].source.lowrangeY
slot[Z].smu[X].source.rangeY
```

Output-off mode

CAUTION: Carefully consider and configure the appropriate output-off state, source, and limits before connecting the MP5000 Series to a device that can deliver energy, such as other voltage sources, batteries, capacitors, or solar cells. Only qualified personnel, as identified by the responsible body, should make these connections. Configure the settings that are recommended for the instrument before making connections to the device. Failure to consider the output-off state, source, and limits may result in damage to the instrument or to the device under test (DUT).

When the output of the SMU is turned off, it may not completely isolate the SMU from the external circuit. You can use the output-off setting to place the SMU in a known, noninteractive state during idle periods, such as when you are changing the device under test. The output-off states that can be selected for a SMU are normal or high impedance.

When you change the output-off state, the selected output-off state is set immediately. When the module is powered on, the SMU is momentarily in the high-impedance output-off state before going to the default output-off state of normal or a setting defined in a power-up script.

If an overtemperature condition occurs, the SMU goes to the off-mode setting. If the SMU continues to heat up and exceeds a higher temperature threshold, the output goes to the high-impedance output-off state and the SMU modules power down as if `slot.stop(Z)` was sent.

Related commands:

```
slot[Z].smu[X].source.offfunc
slot[Z].smu[X].source.offlimitnY
slot[Z].smu[X].source.offlimitpY
slot[Z].smu[X].source.offlimitY
slot[Z].smu[X].source.offmode
```

Normal output-off mode

When the SMU is set to the normal output-off state, you can configure the output-off function (current or voltage) and the output-off limits for either current or voltage. When the output is turned off, the output goes to either 0 V or 0 A, depending on the selected output-off function.

By default, the following settings are made when the source is turned off:

- The measurement sense is set to 2-wire
- The voltage source is selected and set to 0 V
- The current limit is set to 1 mA

Even though the voltage source is set to zero, the source value may not be exactly at zero and the SMU may source or sink a small amount of power. In most cases, this source or sink power level is insignificant. For passive devices such as resistors, normal mode should be sufficient to protect your device. However, carefully consider the output-off function and output-off limit to remove charge from large energy storage devices, such as capacitors, or to manage the charge or discharge of external sources, such as batteries. In many cases, it is recommended to use the high-impedance output-off state when external sources are connected.

High-impedance output-off state

When the high-impedance output-off state is selected and the output is turned off:

- The measurement sense is set to 2-wire
- The output relay opens, disconnecting the SMU as a load

Opening the relay disconnects external circuitry from the inputs and outputs of the instrument. To prevent excessive wear on the output relay, do not use this output-off state for tests that turn the output off and on frequently.

The high-impedance output-off state should be used when the SMU is connected to a power source or another source-measure instrument. In some cases, it may also be appropriate for devices such as capacitors.

When the output is turned on again, the relay has a settling time of approximately 5 ms.

Set the output-off state

To set the output-off state:

To set the output-off state to normal, send the command:

```
slot[Z].smu[X].source.offmode = slot[Z].smu[X].OFFMODE_NORMAL
```

To set the output-off state to high impedance, send the command:

```
slot[Z].smu[X].source.offmode = slot[Z].smu[X].OFFMODE_HIGH_Z
```

Output-off function

This setting is used only when the output is turned off and the SMU is set to the normal output-off mode (`slot[Z].smu[X].source.offmode = slot[Z].smu[X].OUTPUT_NORMAL`).

The output-off function determines the source function that is used (source 0 A or 0 V) when the output is turned off and the SMU is in normal output-off mode. The setting is made with the `slot[Z].smu[X].source.offfunc` attribute from a remote interface.

When the output is turned off and the selected output-off function is voltage (`slot[Z].smu[X].source.offfunc = slot[Z].smu[X].OUTPUT_DCVOLTS`):

- The source-measure unit (SMU) sources 0 V.
- The current limit is set by the `slot[Z].smu[X].source.offlimiti` attribute (default 1 mA).
- The measurement range is set to 1 mA.

When the output is turned off and the selected output-off function is current (`slot[Z].smu[X].source.offfunc = slot[Z].smu[X].OUTPUT_DCAMPS`):

- The SMU sources 0 A.
- The voltage limit is set by the `slot[Z].smu[X].source.offlimitv` attribute (default 60 V).

When the output-off function is set to either voltage or current, the SMU may source or sink a very small amount of power. In most cases, this source or sink power level is insignificant.

Enable the source output

To enable or disable the source output, send the `slot[Z].smu[X].source.output` command. For example, to turn on the output of slot 1, channel 2, send:

```
slot[1].smu[2].source.output = slot[1].smu[2].ON
```

You can also select slot[*Z*].smu[*X*].HIGH_Z. When the high-Z, or high impedance, output setting is selected and the output is turned off, the output relay opens, which disconnects external circuitry from the input and output of the SMU. To prevent excessive wear on the output relay, do not use the high impedance output setting for tests that turn the output off and on frequently.

Related commands:

```
slot[Z].smu[X].source.offfunc
slot[Z].smu[X].source.offmode
slot[Z].smu[X].source.output
```

Make measurements

The TSP commands that manage the measurement functions begin with slot[*Z*].smu[*X*].measure. Command descriptions are provided in the TSP command reference in the *MP5000 Series Programmer Manual*.

To make a measurement, send the slot[*Z*].smu[*X*].measure.*Y*() command. You can make voltage, current, resistance, or power measurements. Resistance and power measurements are based on calculations of the measured voltage and current. The unit of measure are volts, amperes, ohms, and watts.

You can store measurements in a reading buffer. To do so, specify the reading buffer as a parameter when calling slot[*Z*].smu[*X*].measure.*Y*().

Measurements can be made as sequential commands or overlapped commands. For sequential commands, a command is fully processed before the next one is executed. This means that all measurements are completed before the SMU begins processing the next command. Execute sequential measurement commands with the slot[*Z*].smu[*X*].measure.*Y*() command.

For overlapped measurements, the command starts the measurement and then immediately returns operation to the controller. This allows the SMU to begin processing the next command before it completes the measurement. You must specify a reading buffer to use overlapped measurements. For more detail on overlapped measurements, refer to Overlapped operations (on page 23).

Related commands:

```
slot[Z].smu[X].defbufferY
slot[Z].smu[X].makebuffer()
slot[Z].smu[X].measure.Y()
slot[Z].smu[X].measure.overlappedY()
```

Relative offset

When making measurements, you may need to subtract an offset value from a measurement.

The relative offset feature subtracts a set value or a baseline reading from measurement readings. When you enable relative offset, all measurements are recorded as the difference between the actual measured value and the relative offset value. The formula to calculate the offset value is:

Reading with offset applied = Actual measured value − Relative offset value

When a relative offset value is established for a measure function, the value is the same for all ranges for that measure function. For example, if 0.5 A is set as a relative offset value on the 1 A range, the relative offset value is also 0.5 A on the lower current ranges.

A relative offset value is saved for each function. If you change the measure function, the relative offset value is changed to the setting for that measure function.

The following example makes a current measurement, uses it as the relative offset value, and enables current relative offset:

```
-- Measure and set present current value as the relative offset.
slot[1].smu[2].measure.rel.leveli = slot[1].smu[2].measure.i()
-- Enable current relative offset.
slot[1].smu[2].measure.rel.enablei = slot[1].smu[2].ENABLE
```

Related commands:

```
slot[Z].smu[X].measure.rel.enableY
slot[Z].smu[X].measure.rel.levelY
```

Measurement speed

The analog-to-digital converters (ADCs) in the SMU make fast predictably spaced measurements. They can provide 1,000,000 readings per second. The aperture determines the reading conversion time, which is when data is gathered to create the reading.

You can set the aperture time in 1 μs intervals. If the aperture is more than 1 μs, consecutive 1 μs readings are averaged to produce the reading.

The aperture affects the amount of reading noise and the reading rate of the SMU. It can be set as a time in seconds or as the number of power line cycles (NPLC), where 1 PLC for 60 Hz is 16.67 ms (1/60) and 1 PLC for 50 Hz is 20 ms (1/50).

In general, faster aperture times result in faster reading rates, but also cause increased reading noise. Slower integration times provide better common-mode and normal-mode noise rejection, but have slower reading rates. The default power-on speed setting is 1 PLC.

Related commands:

```
slot[Z].smu[X].measure.aperture
slot[Z].smu[X].measure.count
slot[Z].smu[X].measure.interval
slot[Z].smu[X].measure.nplc
```

Measurement range

The measure range determines the full-scale measurement input for the measurement. It also affects the accuracy of the measurements and the maximum signal that can be measured.

The highest available measurement range is determined by the source limit value. The 7 A range on the MSMU200-2 is pulsing-only above 1.5 A.

You can set the measurement range to a fixed value or to automatic measure range (autorange). The range defaults to autorange for all functions. If you set a fixed range, autorange is set to off. If you set autorange on, the fixed range is in place until a measurement is made, at which time the range is set to accommodate the new measurement.

When a fixed range is selected, the range value is static. To ensure the best accuracy and resolution, use the lowest range possible that does not cause an overflow event.

When autorange is on, multiple measurements may be made to determine the best measurement range. This can result in longer measurement times. For the most consistent timing interval, use fixed measurement ranges.

The low range limit for measurements sets the lowest range that the SMU uses when autorange is on. This feature minimizes autorange settling times when measurements require numerous range changes.

NOTE: If you set the measure range to a specific value, the setting for autorange is set to OFF.

The combination of voltage and current ranges cannot exceed the maximum power of the SMU. For example, using the MSMU60-2 with the 20 V source range, the highest current measure range is 1.5 mA. Refer to Operating boundaries (on page 47) for other ranges.

Related commands:

```
slot[Z].smu[X].measure.autorangeY
slot[Z].smu[X].measure.lowrangeY
slot[Z].smu[X].measure.rangeY
slot[Z].smu[X].source.lowrangeY
slot[Z].smu[X].source.rangeY
```

Measurement delay

The measurement delay allows you to add settling time that is applied before each measurement is made. This delay is zero seconds by default (measurements begin immediately).

If the measurement count is set to more than 1, the delay is only added to the first measurement.

The settling time that is needed before a measurement can be affected by several outside factors. Effects such as dielectric absorption, cable leakages, and noise can all extend the time required to make stable measurements. Be sure to use appropriate shielding, guarding, and aperture selections when you make low current measurements. To fully characterize the settling time in your test setup, apply a voltage step and capture current measurements. Program a delay that allows for measurements to settle below an acceptable value.

Related commands:

```
slot[Z].smu[X].measure.count
slot[Z].smu[X].measure.delay
```

Count

The count is the number of measurements made when a measurement is requested. If you use a reading buffer with a measure command, the count also controls the number of readings to be stored. If a measurement count makes more new measurements than the buffer can hold, the measurement command returns an error and no measurements are made.

Related command:

```
slot[Z].smu[X].measure.count
```

Interval

If the measurement count is greater than 1, you can set the interval between the measurements. The interval controls how often the analog-to-digital converter (ADC) outputs a reading.

If no interval is set and the aperture is at the default, the SMU makes measurements on a 1 μs schedule. If the aperture is 10 μs, 10 measurements are averaged before they are returned. If the interval is 1 ms, measurements start at the next set of 10, 1 ms after the first measurement started.

If the interval is less than the aperture, the interval expires before the measurement completes, so a measurement is made immediately after the previous measurement completes. For example, if you have a 100 μs aperture with a 10 μs interval, the SMU starts a measurement that takes 100 μs immediately after the first measurement is completed.

Related commands:

```
slot[Z].smu[X].measure.aperture
slot[Z].smu[X].measure.count
slot[Z].smu[X].measure.interval
```

Manage source-measure operations

You can reset a SMU channel, set up overlapped operations, and abort overlapped operations, as described in the following topics. This section also describes overvoltage protection.

Reset a SMU channel to a default state

You can reset individual channels to the default settings. Reset also turns the output off.

Related commands:

```
*RST
reset()
slot[Z].smu[X].reset()
```

Overlapped operations

There are several types of overlapped operations, such as overlapped measurements, overlapped mode, and the trigger model. This topic describes how overlapped commands are queued up, how they interact with non-overlapped mode commands, measurements, and `waitcomplete()`.

There are several types of commands:

- **Sequential commands:** Commands whose operations must finish before the next command is executed.
- **Overlapped commands:** Commands that allow the execution of subsequent commands while device operations of overlapped commands are still in progress.
- **Wait complete:** The `waitcomplete()` function waits for all previously started overlapped commands to complete.
- **Getter commands:** Commands that return the value of an attribute.

Overlapped mode affects source commands. You can either enable or disable overlapped mode. Any getter or measure commands for both sequential and overlapped measurements implicitly call `waitcomplete()` to wait for any source commands to finish processing. When overlapped mode is disabled, both sequential and measure overlapped commands proceed as normal. When overlapped mode is enabled, commands return as soon as they are able, even if changes have not been reflected in the hardware yet.

This mode is most useful when you perform operations on multiple channels. It allows operations to perform in parallel and thus execute more quickly than sequential operation in normal mode. Overlapping only applies to commands that specify settings. If you retrieve a setting, such as when you use a print command, command execution pauses and waits for other commands to complete before the setting is retrieved. Overlapped operations are most applicable to making measurements, as measurements can continue in the background while other actions occur. Not all actions can be overlapped. In particular, overlapped measure commands cannot be used with the trigger model.

When overlapped operations are enabled, there is no synchronization between channels. Commands are executed as they come in. If synchronization is needed, you use the trigger model, which allows full synchronization between channels.

Getter and measure commands do not wait for any commands to fully complete on a different channel. For instance, changing the voltage source level of channel 1 queues up any channel 1 get or measure commands until channel 1 finishes executing, but reading information from channel 2 does not wait for channel 1 to complete execution.

The command `slot[Z].smu[X].measure.overlappedY()` makes overlapped measurements, which are overlapped commands that start asynchronous measurements. When called, the function starts measurements in the background and returns measurements immediately. The measurements are stored in a reading buffer as they are made. If the SMU is configured to make multiple readings, the readings are available as they are made. Script execution continues while the measurements are made in the background. Attempts to access readings that are not yet generated cause the script to pause and wait for the data to become available. You can also use the `waitcomplete()` function to wait for the measurements to complete before other operations continue.

Using overlapped measurements allows you to change the source level while measurements are in process. This can be useful when attempting to capture the device performance to a source step change.

One key difference between overlapped measurements and overlapped mode is that no commands are queued when overlapped measurements are in progress. Some commands are allowed to execute if there are active overlapped measurements. However, some source commands are limited during overlapped measurements, such as range changes or enabling source autorange.

Related commands:

```
slot[Z].smu[X].abort()
slot[Z].smu[X].measure.overlappedY()
slot[Z].smu[X].overlapped
waitcomplete()
```

Abort overlapped operations

To terminate all overlapped operations on a channel, send the `slot[Z].smu[X].abort()` command, where *Z* is the module slot number and *X* is the channel number. This does not turn off the output or change other settings.

Related command:

```
slot[Z].smu[X].abort()
```

Input overvoltage protection

The SMU input has overvoltage protection so that the SMU is protected in applications where device breakdown or other potential signal level failures could result in the appearance of high voltage at the SMU input terminals.

The trip voltage for the MSMU60-2 is:

- **Input (HI to LO):** 79 V minimum. Limit current to 250 mA DC when triggered.
- **LO to Chassis:** 220 V minimum. Limit current to 1 A_{RMS} when triggered.

The trip voltage for the MSMU200-2 is:

- **Input (HI to LO):** 240 V minimum. Limit current to 250 mA DC when triggered.
- **LO to Chassis:** 220 V minimum. Limit current to 1 A_{RMS} when triggered.

Test connections

NOTE: On some sensitive or easily damaged devices under test (DUTs), the instrument power-up and power-down sequence can apply transient signals to the DUT that may affect or damage it. When testing this type of DUT, it is recommended that you do not make final connections to the DUT until the instrument has completed its power-up sequence and is in a known operating state. Disconnect the DUT from the instrument before turning the instrument off. Only qualified personnel, as identified by the responsible body, should make these connections.

WARNING: To prevent any human contact with a live conductor, connections to the DUT must be fully insulated and the final connections to the DUT must only use safety-rated safety-jack-socket connectors that do not allow bodily contact.

The MP5000 Series SMU modules use screw-terminal connectors for input and output connections. They are supplied with mating screw terminal accessories. The optional Tektronix MSMU-TRX series of cable assemblies provide pre-assembled cables for 4-pin to triaxial connectors.

When making or breaking connections, follow these guidelines:

- Make sure power is removed from the modules. To remove power from the modules, you can either power off the MP5000 mainframe, which removes power from all modules, or use `slot.stop()` to power down a specific module.
- Disconnect any devices that may deliver energy.
- Make connections to the device under test through a test fixture or other safe enclosure.
- Make sure the MP5000 Series is properly connected to protective earth (safety ground).
- If the test fixture is conductive, make sure the test fixture is properly connected to protective earth (safety ground).
- Make sure the test fixture provides proper protection.
- Properly make interlock connections between the MP5000 Series, the test fixture, and any other instruments.
- Make sure to follow all warnings and cautions and to take adequate safety precautions for each set of connections.
- Properly terminate any cables. All unterminated cable ends must be in a safe enclosure.

Basic connection sequence:

1. Remove power from the mainframe or slot and wait for power to dissipate. If you are powering down a slot, use a voltmeter to verify that there is no voltage on the output terminals of the module.
2. Attach the cable, such as the MSMU-TRX-*, to the module.
3. Tighten the screws of the cable connector, such as the MSMU-TRX-*, using a flat-bladed screwdriver. Do not overtighten.
4. Make connections to the test fixture, prober, or device-under-test (DUT).
5. If using a screw-terminal connector, tighten the two captive screws.
6. Power on the mainframe or slot.

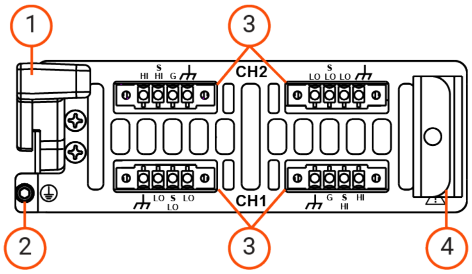
WARNING: Maximum floating (common mode) voltage for an SMU is 210 V for the MSMU60-2 and 200 V for the MSMU200-2. Exceeding this level could damage the instrument and create a shock hazard. See Float a SMU module (on page 38) for details on floating the SMUs.

The input/output connectors of the MP5000 Series SMU modules are rated for connection to circuits rated Measurement Category O only, with transients rated less than 1500 V_{PEAK}. Do not connect the MP5000 Series terminals to CAT II, CAT III, or CAT IV circuits. Connections of the input/output terminals to circuits higher than CAT O can cause damage to the equipment or expose the operator to hazardous voltages.

CAUTION: To prevent electric shock or damage to the SMU module, do not connect the input or output connectors to a source with a greater current capability than the MP5000 Series.

SMU output terminals

The output panel of the MSMU60-2 and MSMU200-2 is shown in the following figure.

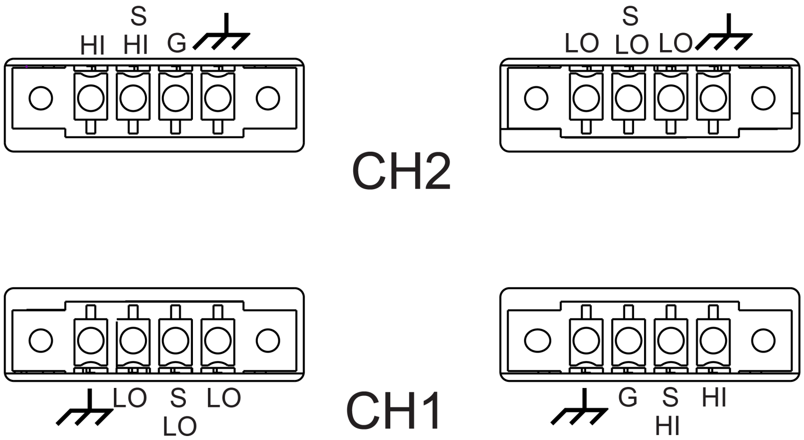


1	Release lever	The release lever at the top left of the output panel of the module assists with removing a module.
2	Retention screw	The module retention screw at the bottom-left of the output panel of the module must be tightened after inserting a module and loosened before removing a module.
3	MSMU60-2 and MSMU200-2 output terminals	The output terminals of the MSMU60-2 and MSMU200-2 provide connections for SENSE HI, SENSE LO, HI, LO, GUARD, and chassis ground.
4	Spring bracket	The spring bracket ensures that the module is fully seated and locked into the mainframe. It is also used to release a module when removing it from the mainframe.

WARNING: The module retention screw must be securely fastened to provide proper safety ground for the module. All modules must be secured in the mainframe with this screw to prevent death or serious injury due to electric shock.

Inputs and outputs

The SMU inputs and outputs are provided through screw terminals on the SMU module.



The inputs and outputs are labeled as follows:

- HI is input/output HI.
- S HI is Sense HI.
- G is Guard.
- S LO is Sense LO.
- LO is input/output LO.
-  is a chassis terminal.

The LOs are not connected between channels and are electrically isolated from chassis ground. Refer to the datasheet for additional information.

NOTE: Do not use the protective earth screw on the mainframe or the retaining screw on the module as a ground point for signal connections. High frequencies (more than 1 MHz) present at these terminals may result in higher noise at the output. The terminals labeled protective earth should only be used as a safety shield. To connect to chassis for noise, use the chassis pin on the output connector.

Interlock

The MP5103 provides an interlock circuit. You must assert this signal to turn on the output. When the signal is asserted, the front-panel INTERLOCK indicator is illuminated green.

If the interlock signal is not asserted, you cannot turn on the output and the front-panel INTERLOCK indicator is not illuminated.

To check the status of the interlock, send:

```
print(slot[X].status.measurement.INT)
```

Where *X* is the slot number of the SMU. A return of `2048` indicates that the interlock is asserted. `0` indicates that it is not asserted. If you try to turn the output on when the interlock is not engaged, message 802 “Output blocked by interlock” is generated.

If there is a fault in the interlock circuit and the interlock power supply circuit cannot provide the voltage needed to engage the interlock, the interlock LED is illuminated red. This can happen if the interlock power supply pin is shorted to ground.

For detail on setting up and using the interlock, refer to Interlock installation in the *MP5103 Reference Manual*.

WARNING: The MP5103 interlock circuit must be positively activated to enable the output of installed modules. The interlock helps facilitate safe operation of the equipment in a test system. Bypassing the interlock could expose the operator to hazardous voltages that could result in personal injury or death.

Related command:

`slot[Z].status.measurement.*`

Select 2-wire or 4-wire measurements

You can use 2-wire or 4-wire measurement techniques with the MP5000 Series SMUs. When you use 2-wire or local sense, voltage is sensed at the output connectors. You should only use 2-wire connections if the error contributed by test lead IR drop is acceptable. Use 4-wire or remote sense when you need the most accurate low-resistance measurement accuracy and voltage sourcing.

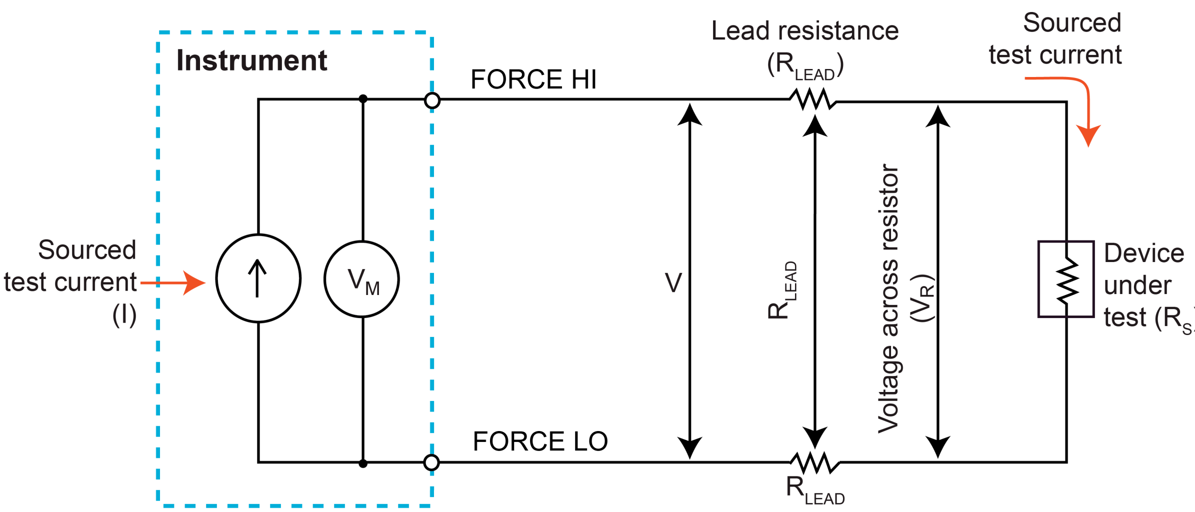
If your application results in impedances above 1 GΩ, you may also need to use guarding. This prevents leakage current from affecting measurement accuracy. For information, see Guarding (on page 33).

When to use 2-wire measurement techniques

Use 2-wire measurement techniques for the following conditions:

- Sourcing and measuring low current (less than approximately 10 mA)
- Sourcing and measuring voltage in high impedance (more than 1 kΩ) test circuits
- Measure-only operation (voltage or current)

The advantage of the 2-wire sense method is that it requires only two test leads. However, as shown in the following figure, the total lead resistance is added to the measurement. This can seriously affect the accuracy of 2-wire resistance measurements, particularly with low resistance values.



Measured resistance: $\frac{V_M}{I} = R_s + (2 \times R_{LEAD})$

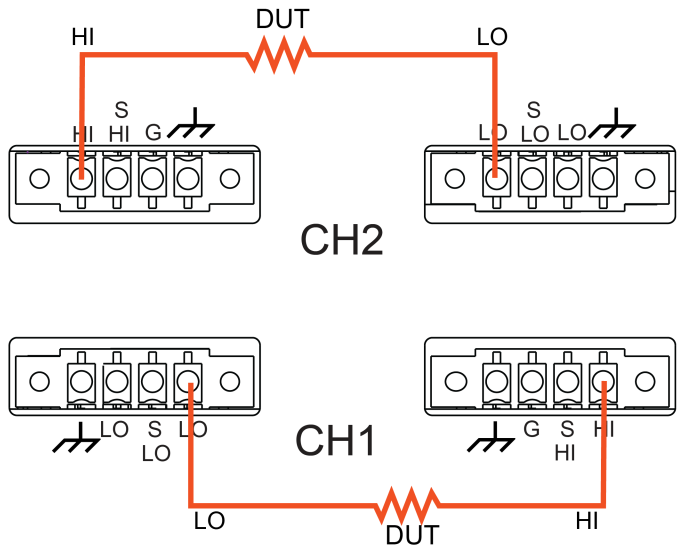
Actual resistance:

2450 actual resistance 2-wire equation.png

$$\frac{V_R}{I} = R_S$$

Make 2-wire local sense connections

Make connections to the SMU terminals as shown in the following figure.



When to use 4-wire measurement techniques

Specified accuracies for SMU source and measurement capabilities are only guaranteed when you use 4-wire remote sense.

Use 4-wire measurement techniques to prevent voltage drops because of lead or contact resistance that could affect measurement accuracy. This can occur on low impedance devices when you source or measure voltage, especially in semiconductor device testing. For example, when testing low impedance devices (less than 100 Ω), usually a higher current is sourced and small voltages are measured.

It is sometimes necessary to use 4-wire measurement techniques to source small voltages (less than 1 V) and measure current. This is true when performing I-V tests on semiconductor devices such as diodes.

When you source or measure voltage in a low-impedance test circuit, there can be errors because of lead resistance. Use 4-wire remote sense to eliminate these errors. If you use 4-wire remote sense when you source voltage, the programmed voltage is delivered to the DUT. If you use 4-wire remote sense when you measure voltage, only the voltage drop across the DUT is measured.

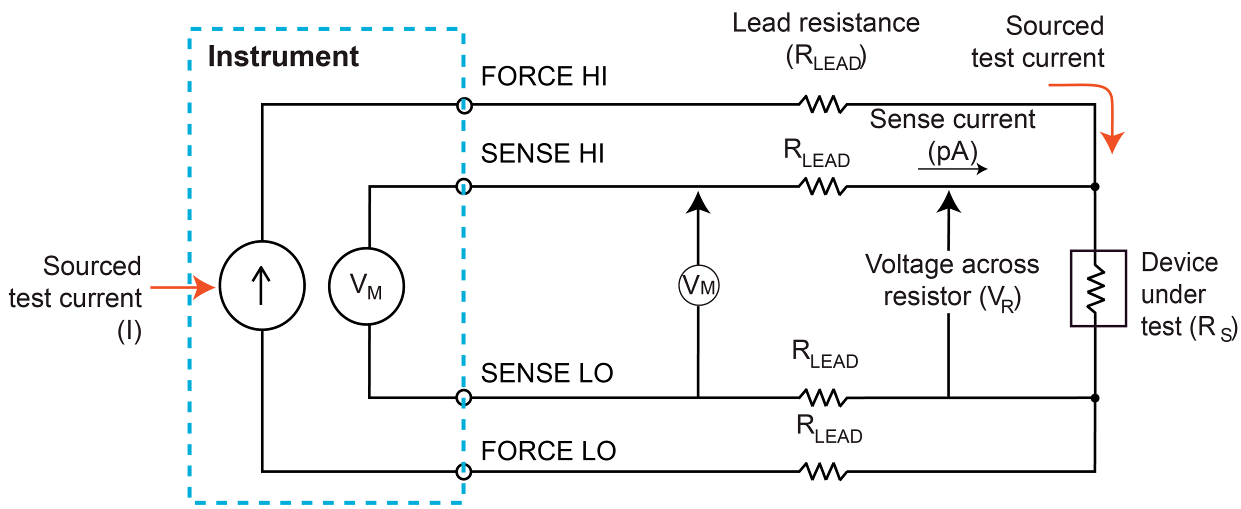
You should use 4-wire measurement techniques for the following conditions:

- Low-impedance applications
- When sourcing high current
- When sourcing low voltage
- When sourcing higher currents and measuring low voltages
- When enforcing voltage limits directly at the device under test (DUT)
- When sourcing or measuring voltage in low-impedance (less than 100 Ω) test circuits
- When optimizing the accuracy for low resistance, voltage source, or voltage measurements
- When measuring resistivity of a material using a 4-point collinear probe

The maximum voltage drop between the force and sense leads is 6 V.

Minimize the effect of lead resistance with 4-wire testing

The 4-wire sense method, shown in the following figure, minimizes or eliminates the effects of lead resistance. The effects of lead resistance are minimized by measuring the voltage across the resistor under test with a second set of test leads. The current through the sense leads is negligible, and the measured voltage is essentially the same as the voltage across the resistor under test. Connect the voltage-sense leads as close to the resistor under test as possible to avoid including the resistance of the test leads in the measurement.



Sense current is negligible, therefore $V_M = V_R$

Measure resistance is $\frac{V_M}{I} = \frac{V_R}{I} = R_s$

Make 4-wire remote sense connections

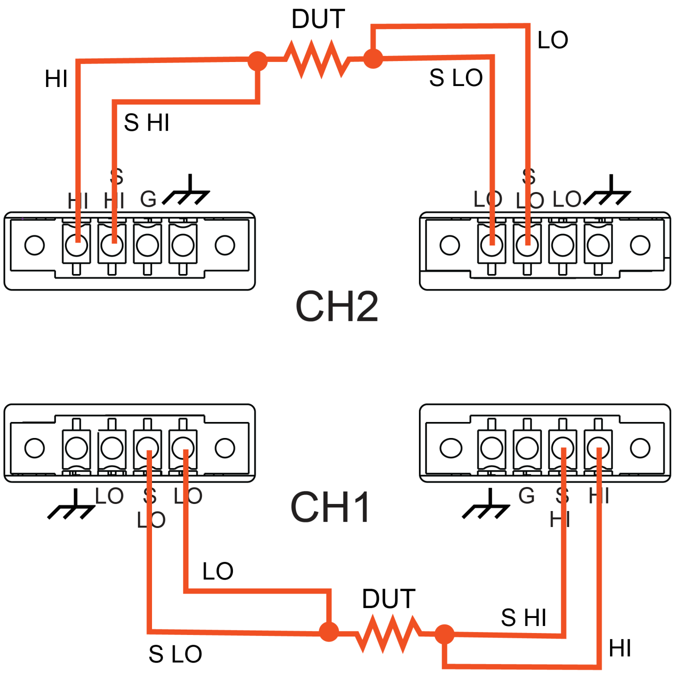
If you enable 4-wire sense connections, it is critical that you establish and maintain the proper Kelvin connections between the corresponding leads to ensure the proper operation of the SMU and to make accurate voltage measurements. Keep the HI and Sense HI together at the high impedance point of the circuit. Keep the LO and Sense LO together at the low impedance point of the circuit.

When voltage is sourced using remote sense, the SMU relies on the voltage detected with the sense lines to provide the proper closed-loop control of its output voltage and to properly limit the voltage across the device under test. If a sense line becomes disconnected from its corresponding line, an erroneous voltage is sensed. The output voltage may be adjusted to a level that is radically different than the programmed voltage level (possibly to hazardous levels). In addition, the voltage across the device may exceed the programmed source limit voltage, possibly causing damage to the device or test fixture.

In both cases, the voltage is not measured correctly if a sense lead becomes disconnected from its corresponding force lead. To prevent unexpected voltages caused by a sense lead that becomes disconnected from its corresponding force lead during remote sense operation, you can use contact check to verify connections and autosense to maintain voltage feedback. Refer to Contact check measurements (on page 40) and Configure sense connections (on page 31) for more information.

NOTE: When 4-wire sense is selected and the output is off, the remote sense lines are disconnected and 4-wire sense is disabled. The sense lines are automatically reconnected when the output is turned on. When the output is off, the SMU uses 2-wire sense, regardless of the sense setting. When the output is on, the selected sense setting is used.

4-wire remote sense connections



Configure sense connections

You need to set the sense mode of the module to use 4-wire measurements. Use the `slot[Z].smu[X].sense` command to set one of the following:

- **2-wire sense (the default):** `slot[Z].smu[X].SENSE_2WIRE` or `slot[Z].smu[X].SENSE_LOCAL`
- **4-wire sense:** `slot[Z].smu[X].SENSE_4WIRE` or `slot[Z].smu[X].SENSE_REMOTE`
- **4-wire sense with an autosense circuit:** `slot[Z].smu[X].SENSE_AUTO`

When 4-wire with automatic sense detection is selected, resistors are placed between the force and sense pairs to prevent unexpected voltages.

You can change the sense while the output is on.

Related command:

`slot[Z].smu[X].sense`

Test fixtures

You can use a test fixture to house a device or test circuit. The test fixture can be a metal or nonconductive enclosure and is typically equipped with a lid. When the test fixture is correctly connected using the interlock, the outputs of any installed modules turn off when the lid of the test fixture is opened.

WARNING: To provide protection from shock hazards, an enclosure should be provided that surrounds all live parts.

Nonconductive enclosures must be constructed of materials that are suitably rated for flammability and the voltage and temperature requirements of the test circuit. Connect the enclosure of all metal test fixtures to protective earth (safety ground). See your specific test fixture for information. Nonconductive test fixtures must be rated to double the maximum capability of the test equipment in the system.

For metallic enclosures, the test fixture chassis must be properly connected to protective earth (safety ground). A grounding wire (16 AWG or larger) must be attached securely to the test fixture at a screw terminal designed for safety grounding. The other end of the ground wire must be attached to a known protective earth (safety ground).

When hazardous voltages (>30 V_{RMS}, 42 V_{PEAK}) will be present, the test fixture must meet the following safety requirements:

- **Construction material**: A metal test fixture must be connected to a known protective earth (safety ground) as described in the above warning. A nonconductive test fixture must be constructed of materials that are suitable for flammability, voltage, and temperature conditions that may exist in the test circuit. The construction requirements for a nonconductive enclosure are also described in the warning above.
- **Test circuit isolation**: With the lid closed, the test fixture must completely surround the test circuit. A metal test fixture must be electrically isolated from the test circuit. Internally, Teflon standoffs are typically used to insulate the internal printed circuit board or guard plate of the test circuit from a metal test fixture.

The test fixture must also have a normally-open interlock switch. The interlock switch must be installed so that when the lid of the test fixture opens, the switch opens, and when the lid closes, the switch closes. The MP5000 includes an interlock connector on the rear panel of the mainframe. When properly connected to a test fixture, the outputs of the SMU module turn off when the lid of the test fixture is open.

Guarding and shielding

You can optimize source-measure performance and safety with the effective use of guards and shields (noise and safety shields).

Guarding

Use a guard to isolate impedance that you do not want to measure. Guarding is an effective way to reduce the leakage current and capacitance that can exist between HI and LO. A guard is a low impedance point in the circuit that is at nearly the same potential as the high impedance lead that is being guarded. Use guarding when you are sourcing or measuring low current (less than 1 μA) or when test circuit impedance is more than 1 GΩ. Also use guarding in noisy environments. Guard is always enabled and provides a buffered voltage.

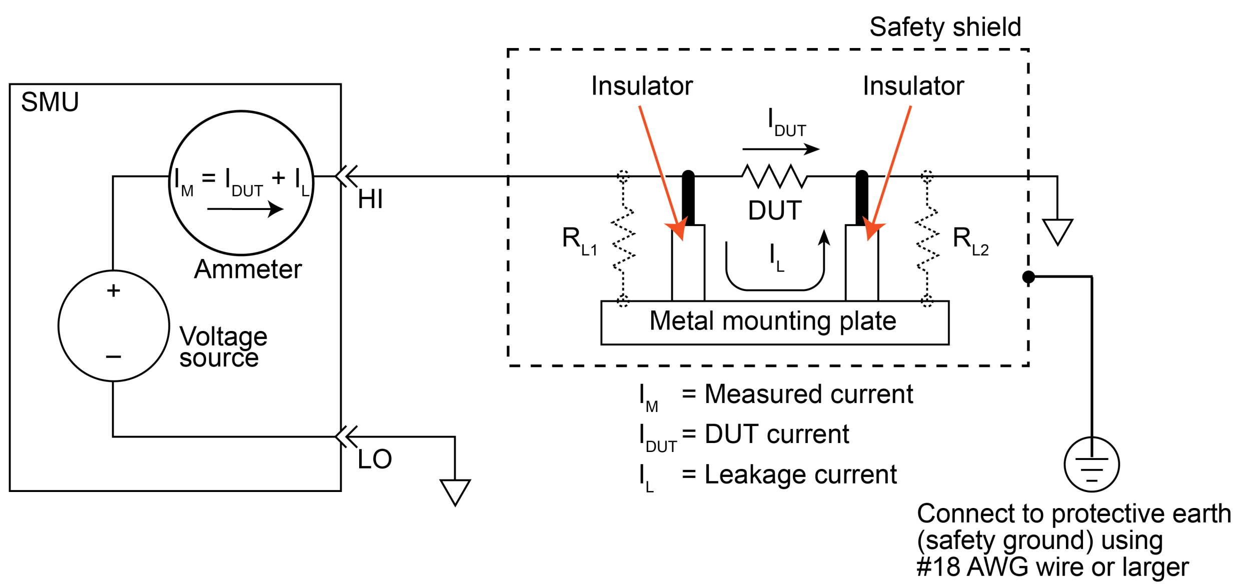
WARNING: Guard is at the same potential as HI. Therefore, if hazardous voltages are present at HI, they are also present at the GUARD terminal. Failure to heed this warning may result in personal injury or death due to electric shock.

A test fixture is typically used when testing high-impedance devices. The test fixture reduces noise and protects users from a potentially hazardous voltage on the guard shield. Connect the test fixture chassis to LO to reduce noise. The figures in this topic show the metal case of a test fixture being used as a safety shield.

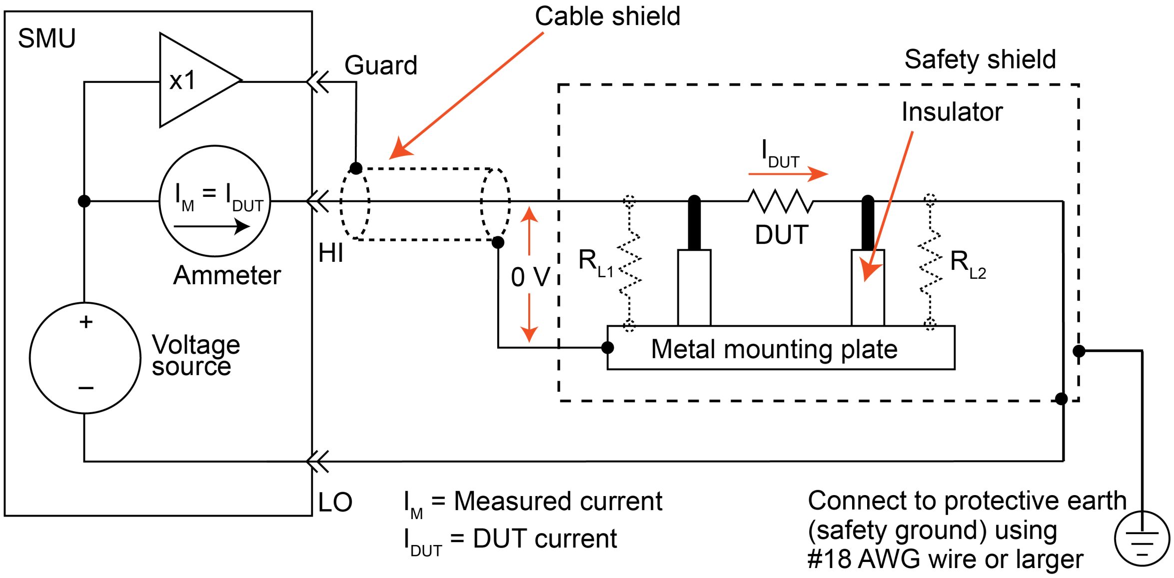
Inside the test fixture, you can use a triaxial cable to extend guard to the DUT. The Tektronix MSMU-TRX-* cables provide an easy way to convert the screw-terminal connections on the rear panel of the MSMU-60-2 to triaxial cables. Guard is extended to a test fixture from the cable guard shield. Inside the test fixture, the guard can be connected to a guard plate or shield that surrounds the DUT.

The following figures show how cable guard can eliminate leakage current through the insulators in a test fixture.

In the following figure, unguarded measurements are shown. Leakage current (I_L) flows through the insulators (R_{L1} and R_{L2}) to LO, adversely affecting the low-current (or high-resistance) measurement of the DUT.



The following figure shows guarded measurements and how guarding can eliminate leakage current through the insulators. The driven guard is connected to the cable shield and extended to the metal mounting plate for the insulators. Since the voltage on either end of R_{L1} is the same (0 V drop), no current can flow through the leakage resistance path, so the SMU only measures the current through the DUT.

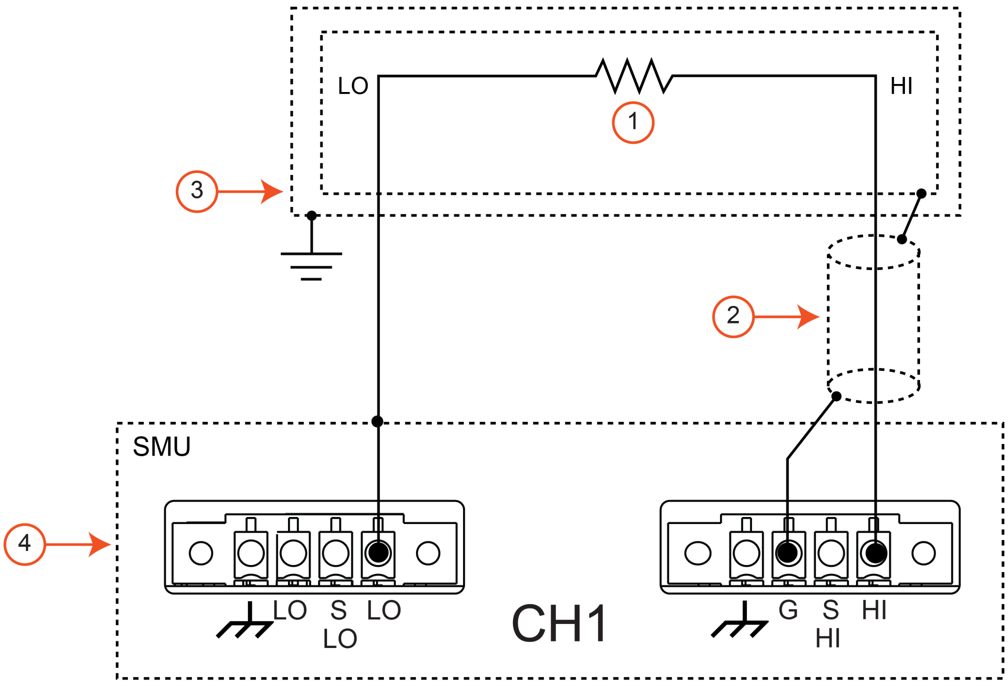


Guard connections

The following figure shows the guard connections.

If you are using MSMU-TRX-* cables, make the following connections:

1. Connect a MSMU-TRX-HI cable to the HI connector on the SMU module.
2. Connect the HI terminal to the HI side of the device.
3. Connect a MSMU-TRX-LO cable to the LO connector on the SMU module.
4. Connect the LO triaxial cable to the LO side of the device.



1 Device under test (DUT), more than 1 GΩ	
2 Guard shield	
3 Safety shield connected to earth ground	
4 Metal guard shield	

Verify guard voltage

Each channel includes a built-in diagnostic function for guard. To determine if the guard is shorted or otherwise loaded so that it is ineffective, use `slot[Z].smu[X].guard.v()` to characterize the guard voltage. Under normal conditions, when the current source or limit range is 10 µA or less, the guard voltage is 0 V. If it is much greater than 0 V, guard is shorted or has a load that makes it less effective at eliminating leakage current in the measurement. At higher current source or limit ranges, this function does not return zero; this is normal and expected behavior of the SMU.

The guard measurement is intended to be used as a diagnostic tool and does not produce a precise measurement. For example, if guard is shorted externally and is therefore ineffective, a large voltage error is observed when the SMU is on a low current range.

Related command:

```
slot[Z].smu[X].guard.v()
```

Noise shield

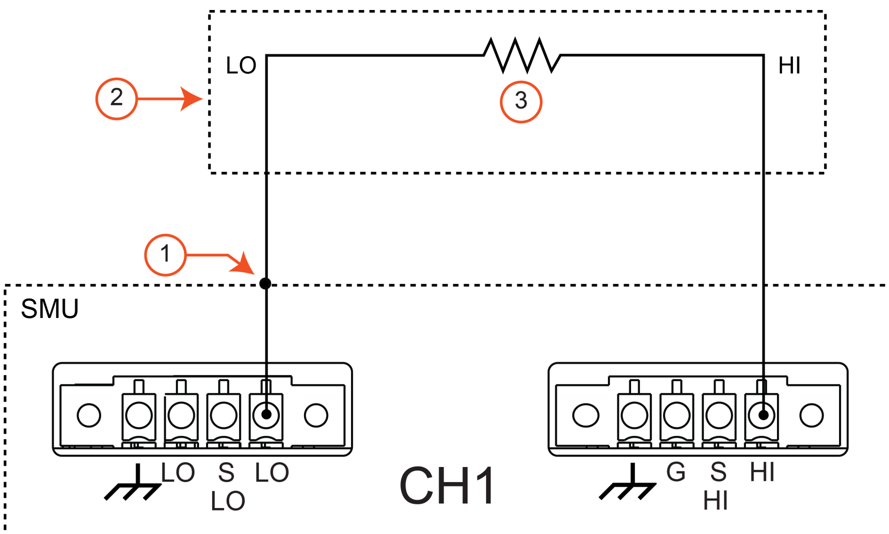
Use a noise shield, as shown in the following figure, to prevent unwanted signals from being introduced into the test circuit. Low-level signals may benefit from effective shielding. The metal noise shield surrounds the test circuit and should be connected to LO, as shown.

WARNING: Connect the enclosure of all metal test fixtures to protective earth (safety ground). See your specific test fixture for information. Nonconductive test fixtures must be rated to double the maximum capability of the test equipment in the system.

Connections to LO on the SMU are not necessarily at 0 V. Hazardous voltages could exist between LO and chassis ground. The common mode voltage specification indicates the maximum voltage allowed between LO and chassis ground. Make sure that high-voltage precautions are taken throughout the test system. Failure to make sure high-voltage precautions are used throughout the test system or a failure to limit hazardous levels could result in severe personal injury or death from electric shock.

If you are using MSMU-TRX-* cables, make the following connections:

1. Connect a MSMU-TRX-HI cable to the HI connector on the SMU module.
2. Connect the HI terminal to the HI side of the device.
3. Connect a MSMU-TRX-LO cable to the LO connector on the SMU module.
4. Connect the LO triaxial cable to the LO side of the device.



1 Noise shield connected to LO	
2 Noise shield	
3 Device under test (DUT)	

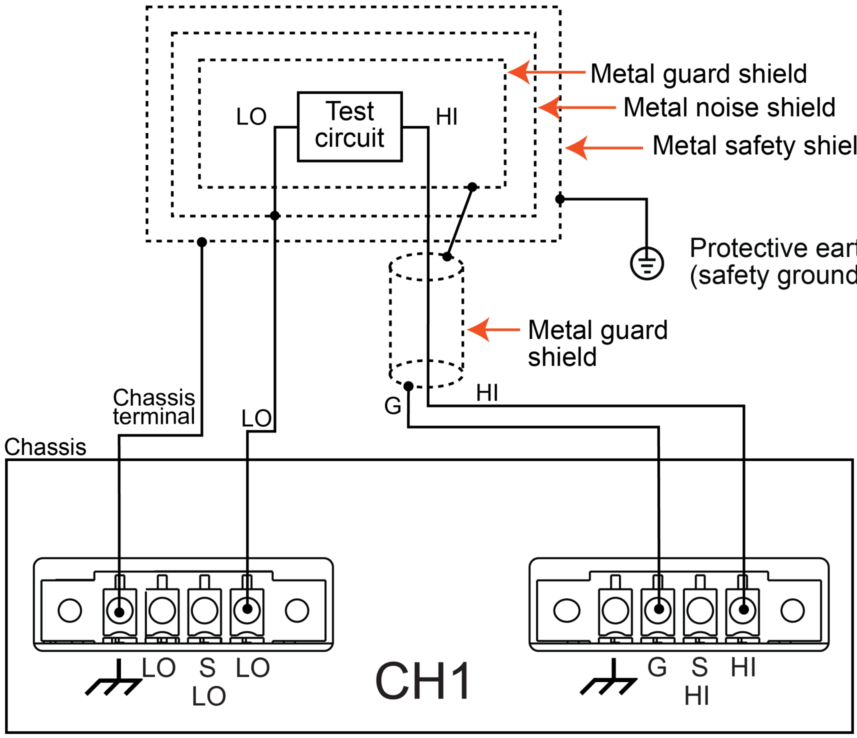
If you choose to use the SMU chassis as a ground point for signal connections, use the SMU chassis terminal on the output connector as a connection point.

For more information on preventing noise problems, refer to the Keithley *Low Level Measurements Handbook*, available on tek.com.

Use shielding and guarding together

The following figure shows connections for a test system that uses a noise shield, a safety shield, and guarding. The guard shields are connected to the driven guard (labeled G) of the module. The noise shield is connected to LO. The safety shield is connected to the chassis and to protective earth (safety ground).

WARNING: Connect the outer enclosure of all metal test fixtures to protective earth (safety ground). Refer to Safety shield (on page 37) and your test fixture documentation for more information. Nonconductive test fixtures must be rated to double the maximum capability of the test equipment in the system.



Safety shield

WARNING: A safety shield must be used whenever hazardous voltages (>30 VRMS, 42 VPEAK) will be present in the test circuit. To prevent electrical shock that could cause injury or death, never use the MP5000 Series in a test circuit that may contain hazardous voltages without a properly installed and configured safety shield.

The safety shield can be metallic or nonconductive and must completely surround the device under test (DUT) test circuit. A metal safety shield must be connected to a known protective earth (safety ground). Use #18 AWG wire or larger for connections to safety earth ground and chassis.

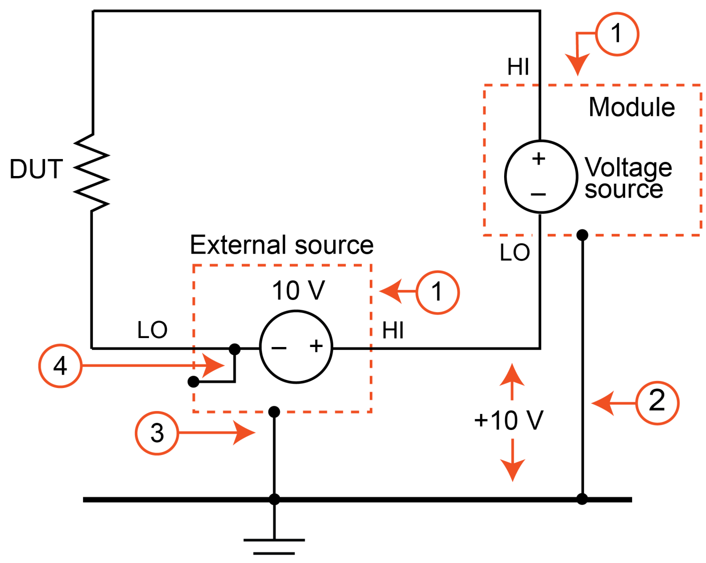
Float a SMU module

WARNING: SENSE LO and LO are not internally connected to the chassis. Do not allow them to float above chassis ground more than 210 V for the MSMU60-2 or 200 V for the MSMU200-2. Failure to adhere to these guidelines can result in personal injury or death due to electric shock.

If you use an external source in the test system, you may need the SMU to float off chassis ground. An example is shown in the following figure, which includes an external voltage source. Notice that output LO of the external voltage source is connected to chassis ground.

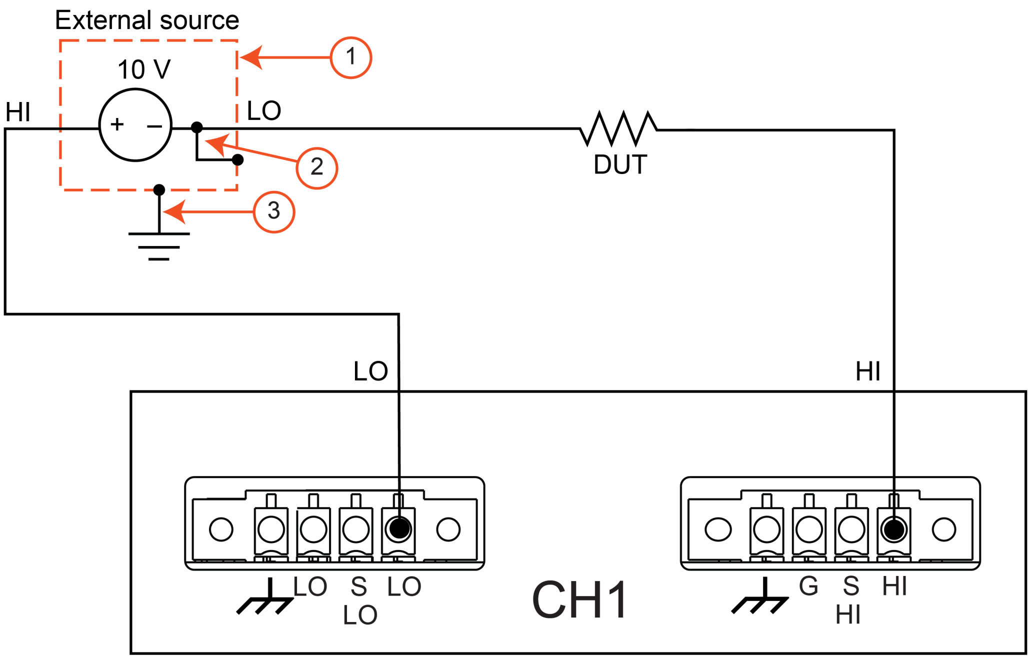
For the test circuit shown in this figure, the SMU must float off chassis ground. As shown, LO of the SMU is floating +10 V above chassis ground. If LO of the SMU was instead connected to chassis ground, the external voltage source would be shorted to the chassis ground.

The external voltage source can be another SMU or other instrument. If the combined outputs of the sources exceed ±42 V, a safety shield is required for the device under test (DUT).



1	Chassis
2	Instrument chassis connected to earth ground through the power cord
3	Source chassis connected to earth ground through the power cord
4	LO of the external source connected to chassis

The connections for the floating configuration are shown in the following figure. To float the SMU, LO and SENSE LO must be isolated from chassis ground. To do this, do not connect LO and SENSE LO to chassis ground.



1	Chassis
2	Output low connected to chassis
3	Source chassis connected to earth ground through the power cord

WARNING: All measurement connections should be considered to be hazardous.

The maximum floating (common mode) voltage for a MSMU60-2 is 210 V and for a MSMU200-2 is 200 V. Exceeding this level may cause damage to the module and create a shock hazard.

Using an external source to float a SMU could create a shock hazard in the test circuit. A shock hazard exists whenever >42 V_{PEAK} is present in the test circuit. Appropriately rated cables or insulators must be provided for all connections to prevent access to live parts.

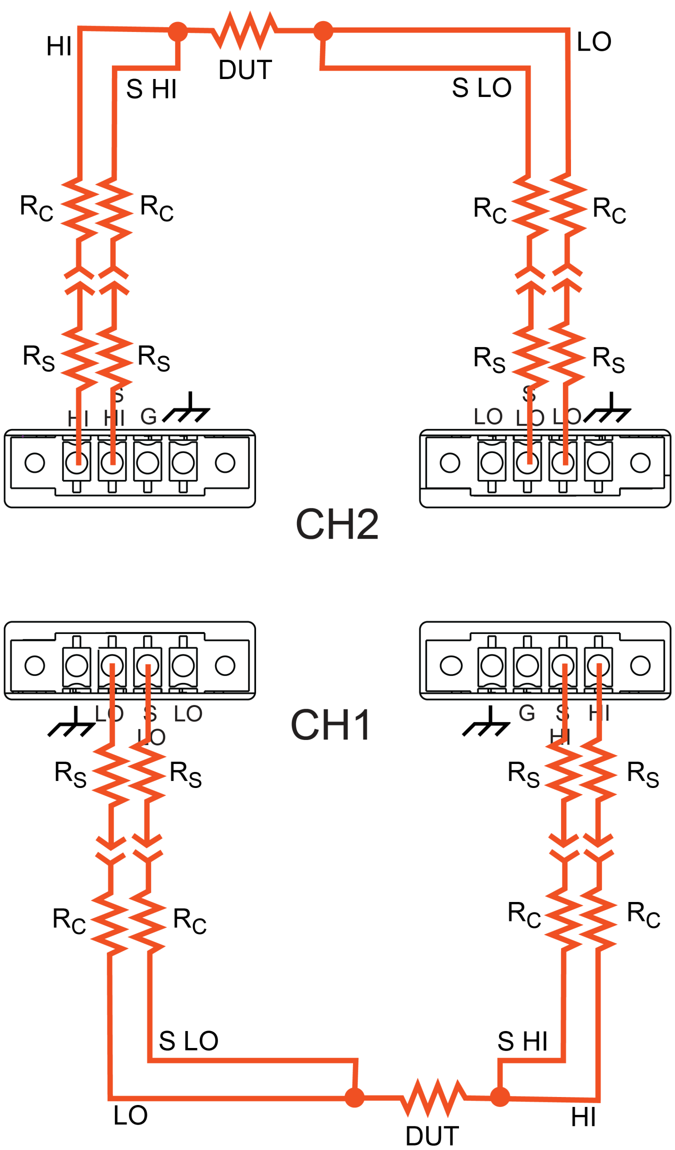
When >42 V is present, the test circuit must be insulated for the voltage used or surrounded by a metal safety shield that is connected to a known protective earth (safety ground) and chassis ground; refer to Safety shield (on page 37).

Contact check measurements

You can use the contact check function to identify excessive resistance in the force or sense leads when making 4-wire remote measurements. Potential sources for this resistance include poor contact at the device under test (DUT), failing relay contacts on a switch card, and wires that are too long or thin. To use contact check, SMU must not be in the high impedance output-off mode.

The contact check function also detects open circuits that may occur when four-point probes are misplaced or misaligned. This relationship is shown schematically in the following figure. In this figure:

- R_C is the resistance of the mechanical contact at the DUT.
- R_S is the series resistance of relays and cables.



Depending on the source function and whether the channel output is on or off, one of the following commands must be set to 1 μA for contact check to function:

- `slot[Z].smu[X].source.rangeY`
- `slot[Z].smu[X].source.limitY`
- `slot[Z].smu[X].source.offlimitY`

Use the following table as a guide, substituting `Z` and `X` with the module and channel number:

Source function	Output	Send this TSP command
Voltage	On	`slot[Z].smu[X].source.limiti = 1e-6`
Voltage	Off	`slot[Z].smu[X].source.offlimiti = 1e-6`
Current	On	`slot[Z].smu[X].source.rangei = 1e-6`
Current	Off	`slot[Z].smu[X].source.rangei = 1e-6`

Related commands:

```
slot[Z].smu[X].contact.check()
slot[Z].smu[X].contact.r()
slot[Z].smu[X].contact.speed
slot[Z].smu[X].contact.threshold
slot[Z].smu[X].source.offmode
slot[Z].smu[X].source.output
```

Autocalibration

Autocalibration removes measurement errors that are caused by performance drift on the components used in the SMU modules as a result of temperature and time. Autocalibration also improves short-term accuracy. However, to maintain overall accuracy, you must perform regular full calibration adjustment with metrology equipment.

You must run the autocalibration procedure for each channel on the SMU separately.

The autocalibration constants persist through a power cycle. You do not need to run autocalibration if the power has been cycled.

Autocalibration constants are valid for 30 days.

Check autocalibration status

The SMU regularly monitors the internal temperature. Temperature checking begins after the warmup time completes. To maintain accuracy, run autocalibration routines when the instrument temperature changes by more than ± 5 °C or when the autocalibration due date has passed.

Use the following commands to determine if you need to run autocalibration.

`slot[Z].smu[X].acal.valid(procedure)`	Returns `true` if the constants for the specified procedure are still valid. Returns `false` if the constants have expired. Expiration may be due to temperature, time, or both.
`slot[Z].smu[X].acal.temperaturedelta(procedure)`	Returns the difference between the present SMU temperature and the temperature recorded at the completion of the last specified autocalibration procedure.
`slot[Z].smu[X].acal.due(procedure)`	Returns the due date for the next autocalibration procedure.
`slot[Z].smu[X].acal.adjustdate(procedure)`	Returns the date when the specified autocalibration procedure was last run.

`slot[Z].status.questionable.ACAL`	If bit B10 is set, an automatic calibration expired summary event register bit is set.
`slot[Z].status.questionable.instrument.smu[X].*`	If bit B10 is set, an enabled bit in the questionable status automatic calibration expired summary event register is set.

Use the procedures in the following table to calibrate different functions of a SMU channel.

`slot[Z].smu[X].ACAL_I_SOURCE_OFFSET`	Learns the ADC setting that outputs nearest to 0 A for each current source range, then adjusts the source calibration constants accordingly.
`slot[Z].smu[X].ACAL_I_MEASURE_OFFSET`	Applies 0 A to the current measure circuit and learns the offset of each range, then adjusts the measure calibration constants accordingly.
`slot[Z].smu[X].ACAL_AUX_ADC`	Uses a known zero and reference voltage to characterize the auxiliary ADC, then adjusts the ADC calibration constants accordingly. This ADC is used for the guard measurement and internal measurements.
`slot[Z].smu[X].ACAL_ADJUST_ALL`	Runs all autocalibration commands sequentially.

Run autocalibration

After the module has completed its warmup period, you can run autocalibration as needed using the `slot[Z].smu[X].acal.adjust()` command. You can specify only one of the command procedures or have each procedure run sequentially. When all procedures are run, the adjusted calibration constants, time, and temperature are saved independently for each procedure.

The time to execute autocalibration depends on the procedures and may take up to 2 minutes. The module cannot be used while autocalibration is running.

If autocalibration is successful, the due date is set to the next recommended date and the calibration constants are updated. If an autocalibration procedure fails, an error message is returned and the calibration data is not changed. If a failure occurs while running all procedures (`slot[Z].smu[X].ACAL_ADJUST_ALL`), the data is not updated for any procedure.

All autocalibration procedures require the SMU to be set to a high impedance output state before they are run. This prevents the need to disconnect devices or output leads. If the SMU is not in a high impedance output state, an error message is generated when autocalibration is run.

CAUTION: To prevent instrument damage, verify that no test voltages are connected to the input terminals when performing autocalibration.

Do not cycle power during the autocalibration routine. Doing so could affect the accuracy of the instrument.

NOTE: Once autocalibration has started, you can stop it by sending `abort`. If the procedure is aborted by a command or by a critical failure, the calibration constants are not saved or changed.

To prepare for autocalibration:

1. Turn the SMU outputs off.
2. Disable any connected voltage sources.
3. Place the module and mainframe in a temperature-stable environment.
4. Ensure that SMU modules have warmed up for at least 30 minutes.

To run autocalibration:

1. Set the SMU channel to high-impedance output by sending
   `slot[Z].smu[X].source.offmode = slot[Z].smu[X].OFFMODE_HIGH_Z`
2. To start autocalibration, send the following command and specify the procedure:
   `slot[Z].smu[X].acal.adjust(procedure)`
3. Repeat the previous steps for additional SMU channels and modules, as needed.

Sink operation

When the SMU is operating as a sink, voltage and current have opposite polarities and the SMU is dissipating power rather than sourcing it. The SMU can be forced into sink operation by an external source, such as a battery, or an energy storage device, such as a capacitor. For detail on the sink region, see Operating boundaries (on page 47).

For example, if a 12 V battery is connected to the voltage source (HI to battery high) that is programmed for +10 V, sink operation occurs in the second quadrant (source +V and measure –I).

CAUTION: Carefully consider and configure the output-off mode, source, and limits before connecting the SMU to a device that can deliver energy. Devices that can deliver energy include voltage sources, batteries, capacitors, and solar cells. Configure SMU settings before making connections to the device. Only qualified personnel, as identified by the responsible body, should make these connections. Failure to consider the output-off mode, source, and limits may result in damage to the instrument or to the device under test (DUT).

When using the current source as a sink, always set the voltage limit to levels that are higher than the external voltage level. Failure to do so could result in excessive current flow into the SMU.

Battery charge and discharge

WARNING: To prevent personal injury or damage to the MP5000 Series, do not attempt to charge nonrechargeable batteries. Some of the batteries that can be charged with an MP5000 Series are nickel cadmium (Ni-Cd), nickel metal hydride (Ni-MH), lithium ion (Li-ion), rechargeable alkaline, and lead acid. If you are working with a battery type that is not listed here, please contact your local Tektronix office, sales partner, or distributor, or call one of our Applications Engineers to get technical assistance.

Always follow the requirements of the battery manufacturer for charging or discharging batteries using a MP5000 Series. Failure to properly charge or discharge batteries may cause them to leak or explode, resulting in personal injury and property damage. Overvoltage and current protection should be provided in the charge circuit, external to the instrument, when charging batteries without built-in protection.

CAUTION: Be sure to set the output-off mode of the current source for high impedance. This setting opens the output relay when the output is turned off. If the normal output-off mode is selected, some combinations of settings of the output-off function and output-off limit may cause excessive current to be drawn from the external battery or source.

A battery is usually charged using a constant current. To do this, use a SMU as a voltage source set to the voltage rating of the battery, with the target charging current set as the current limit. At the start of the test, the battery voltage is less than the voltage output setting of the SMU. As a result, this voltage difference drives a current that is immediately limited to the user-defined current limit. When in current limit, the SMU acts as a constant current source until it reaches the programmed voltage level. As the battery becomes fully charged, the current decreases until it reaches zero or near zero. To prevent safety hazards or damage to the battery, be careful not to overcharge the battery.

When discharging a battery, the SMU operates as a sink because it is dissipating power instead of sourcing it. The voltage source of the SMU is set to a lower level than the battery voltage. The current limit sets the discharge rate. When the output is enabled, the current from the battery flows into the HI terminal of the SMU. As a result, the current readings are negative. The discharge current should stay constant until the battery voltage decreases to the voltage source setting of the SMU.

Combine SMU outputs

The following information provides cautions and important considerations that must be observed when combining source-measure unit (SMU) output channels.

Use care when combining SMU channels. Whenever SMU channels are combined, it is best to use SMUs with identical current and voltage envelopes and ranges.

Combining two MSMU60-2 channels in series allows up to 120 V (60 V per channel). Combining two MSMU200-2 channels in series allows up to 400 V (200 V per channel).

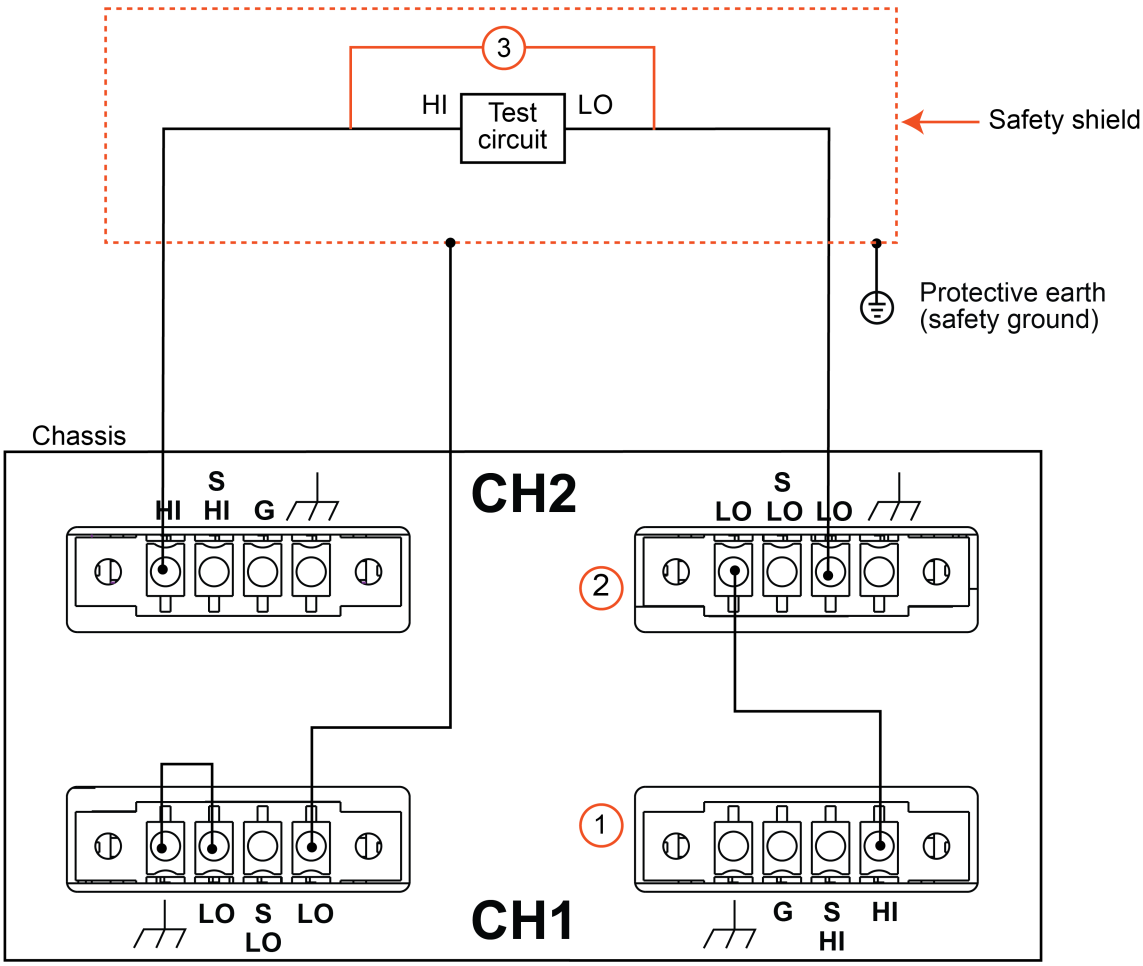
CAUTION: Carefully consider and configure the appropriate output-off state, source function, and compliance limits before connecting the MP5000 Series to a device that can deliver energy (for example, other voltage sources, batteries, capacitors, solar cells, or other MP5000 Series instruments). Configure recommended instrument settings before making connections to the device. Failure to consider the output-off state, source, and compliance limits may result in damage to the instrument or to the device under test (DUT).

Combine channels in series to output higher voltage

WARNING: Channels in series cause hazardous voltage (>30 V_{RMS}, 42 V_{PEAK}) to be present and accessible at the SMU output connector. A safety shield must be used whenever hazardous voltages will be present in the test circuit. To prevent electrical shock that could cause injury or death, never use the MP5000 Series in a test circuit that may contain hazardous voltages without a properly installed and configured safety shield.

To output a higher voltage, connect two SMU channels in series. Never connect more than two SMU channels. When combining the channels, make sure that the common mode voltage of one SMU supports the maximum output voltage of the second SMU.

The following figure illustrates the MSMU60-2 module configured with each channel connected in series to output up to 120 V (60 V per channel).

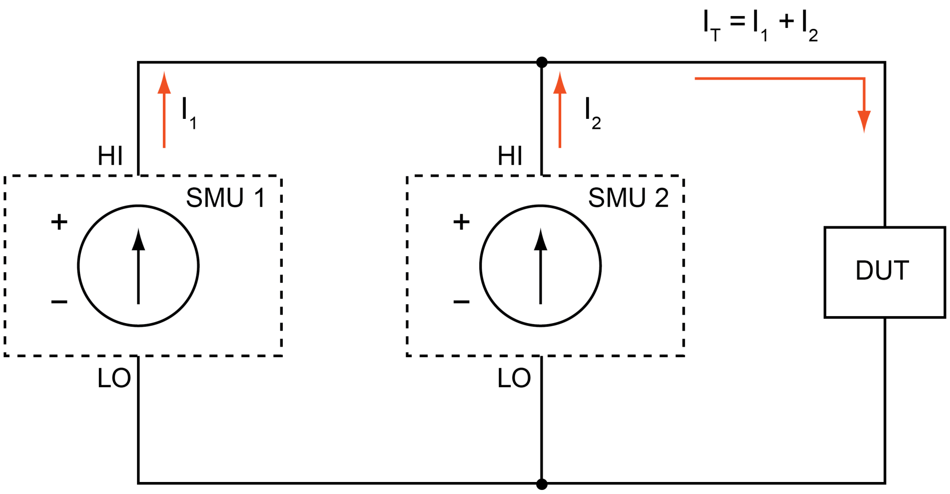


1	SMU 1: Maximum voltage: +60 V
2	SMU 2: Maximum voltage: +60 V
3	Series SMU maximum pulse voltage (as shown): 120 V

Combine channels in parallel to output higher current

To output higher current, connect two SMU channels in parallel. When you combine two source-measure unit (SMU) channels, make sure both SMUs have the same model number.

The following figure shows the connections of two MSMU60-2 channels on one module connected in parallel. Two MSMU60-2 channels in parallel can output 3 A (1.5 A × 2) at 20 V. The current delivered to the device under test (DUT) is the sum of currents output by SMU channels (I_T). When you combine two MP5000 Series SMU channels, you expand the power envelope.



I_1	Single SMU maximum DC current: 1.5 A
I_2	Single SMU maximum DC current: 1.5 A
3	Parallel SMU channels maximum DC current (as shown): 3 A

Theory of operation

Overtemperature protection

Proper ventilation is required to keep the mainframe from damage from overtemperature conditions. Even with proper ventilation, the instrument can overheat if the ambient temperature is too high or if significant power is being dissipated within the SMU for a long period. The blowers in the mainframe increase their speed as temperature increases. Additionally, the module has an overtemperature protection circuit that turns off the outputs of any channel that overheats.

When the overtemperature protection circuit turns the output off, a message that indicates this condition is displayed. You cannot turn the outputs on until the mainframe cools down. The output-off settings are applied to the channel. If the output-off state is normal mode, it may be possible for the SMU channel to sink power. If the temperature of the module continues to rise beyond a second critical temperature threshold, the mainframe shuts off power to the slot. If this occurs, user intervention is required.

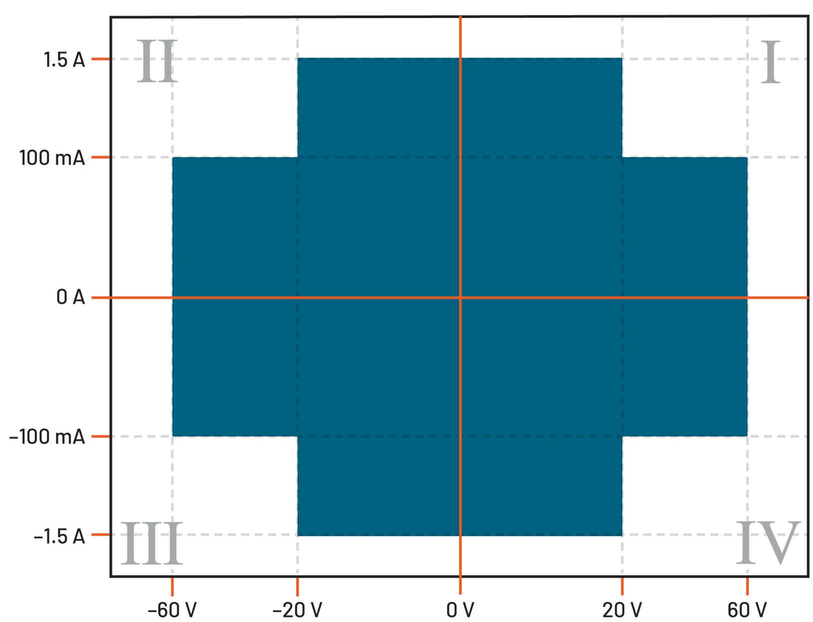
Operating boundaries

The following topics illustrate and list the operating boundaries for the SMU modules available for the MP5103 mainframe.

These operating boundaries are valid only if the instrument is being operated in an environment where the ambient temperature is 50 °C or less. High power operation could overheat the instrument, causing the output to turn off.

MSMU60-2 operating boundaries

The MSMU60-2 instrument can operate in any of the four quadrants shown in the following figure. When operating in the first (I) or third (III) quadrant, the instrument operates as a source (voltage and current have the same polarity). As a source, the instrument delivers power to a load.



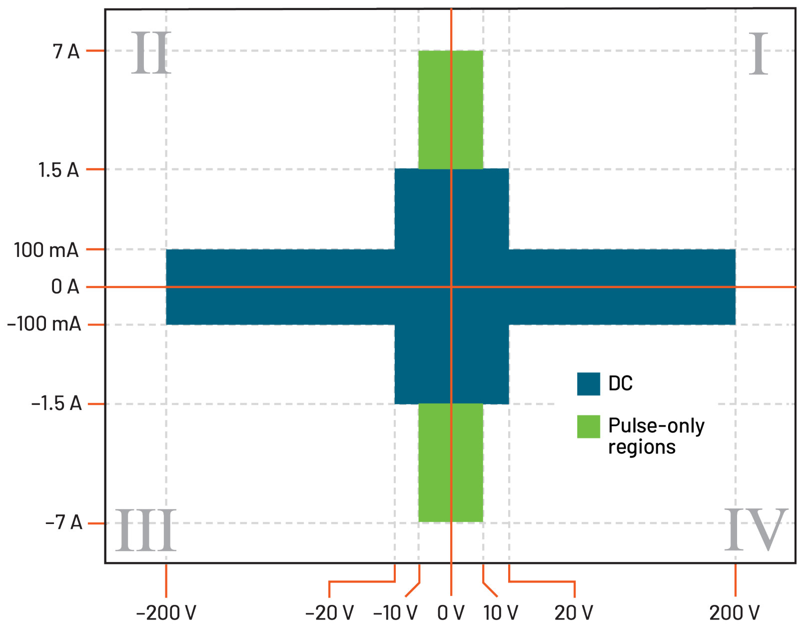
When operating in the second (II) or fourth (IV) quadrant, the instrument is operating as a sink (voltage and current have opposite polarity). As a sink, it is dissipating power rather than sourcing it. An external source or an energy storage device, such as a capacitor or battery, can force operation in the sink region.

The following table lists the source and measure limits for the voltage and current functions.

Source-measure capabilities		
Range	**Source**	**Measure**
200 mV	±202 mV	±204 mV
2 V	±2.02 V	±2.04 V
6 V	±6.06 V	±6.12 V
20 V	±20.2 V	±20.4 V
60 V	±60.6 V	±1.2 V
1 µA	±1.01 µA	±1.02 µA
10 µA	±10.1 µA	±10.2 µA
100 µA	±101 µA	±102 µA
1 mA	±1.01 mA	±1.02 mA
10 mA	±10.1 mA	±10.2 mA
100 mA	±101 mA	±102 mA
1 A	±1.01 A	±1.02 A
1.5 A	±1.51 A	±1.53 A
Maximum power = 30.5 W		

MSMU200-2 operating boundaries

The MSMU200-2 instrument can operate in any of the four quadrants shown in the following figure. When operating in the first (I) or third (III) quadrant, the instrument operates as a source (voltage and current have the same polarity). As a source, the instrument delivers power to a load.



When operating in the second (II) or fourth (IV) quadrant, the instrument is operating as a sink (voltage and current have opposite polarity). As a sink, it is dissipating power rather than sourcing it. An external source or an energy storage device, such as a capacitor or battery, can force operation in the sink region.

The MSMU200-2 can achieve higher current output in its pulse-only region. For more information on how to operate in this area, see Pulse-only regions (on page 56).

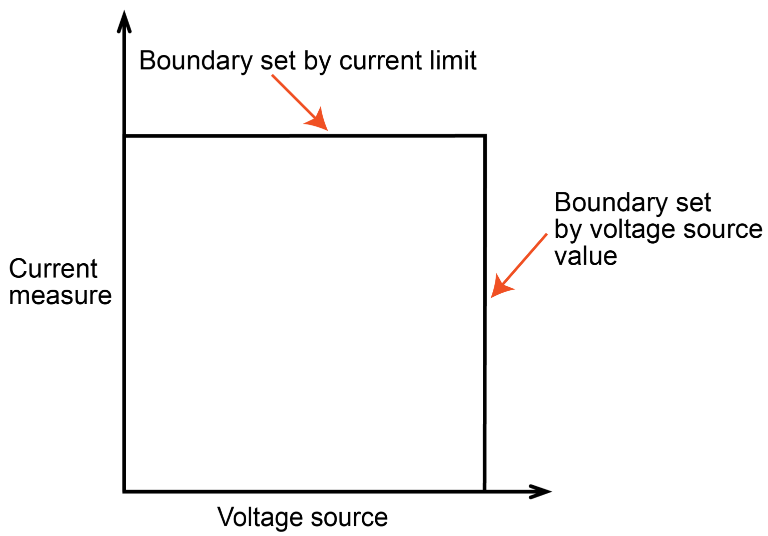
The following table lists the source and measure limits for the voltage and current functions.

Source-measure capabilities		
Range	**Source**	**Measure**
200 mV	±202 mV	±204 mV
2 V	±2.02 V	±2.04 V
6 V	±6.06 V	±6.12 V
20 V	±20.2 V	±20.4 V
200 V	±202 V	±204 V
1 µA	±1.01 µA	±1.02 µA
10 µA	±10.1 µA	±10.2 µA
100 µA	±101 µA	±102 µA

Source-measure capabilities		
Range	**Source**	**Measure**
1 mA	±1.01 mA	±1.02 mA
10 mA	±10.1 mA	±10.2 mA
100 mA	±101 mA	±102 mA
1 A	±1.01 A	±1.02 A
7 A	±7.07 A	±7.14 A
Maximum power = 30.5 W		

Voltage source operating boundaries

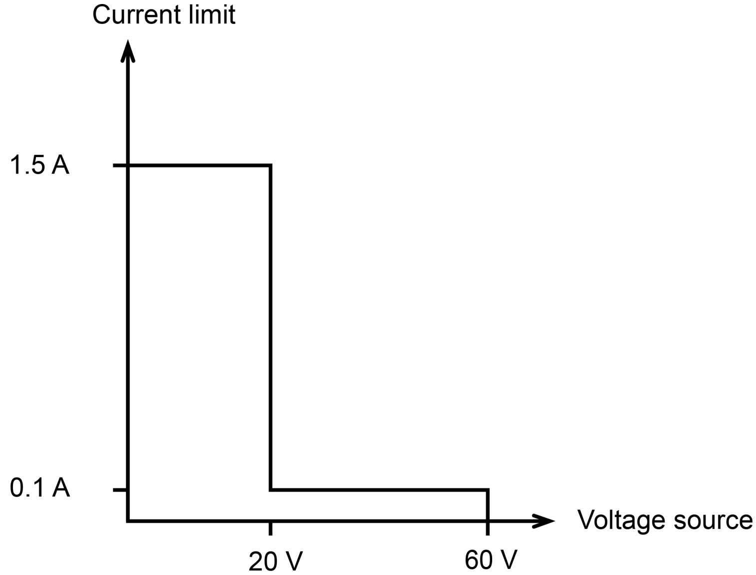
The following figure shows the boundaries for the voltage source of the SMU modules available for the MP5103 mainframe. The voltage source boundary represents the maximum source value possible for the presently selected voltage source range. For example, if you are using the 20 V source range, the voltage source boundary is at 20.2 V. The current boundary is indicated by the programmed current limit. These boundaries represent the operating limits of the SMU for this quadrant of operation. The operating point can be anywhere within these boundaries. Similar boundaries can be drawn for the other quadrants.



MSMU60-2 voltage source operating boundaries

The following figure shows the operating boundaries for the MSMU60-2 voltage source. Only the first quadrant of operation is shown; operation in the other quadrants is similar.

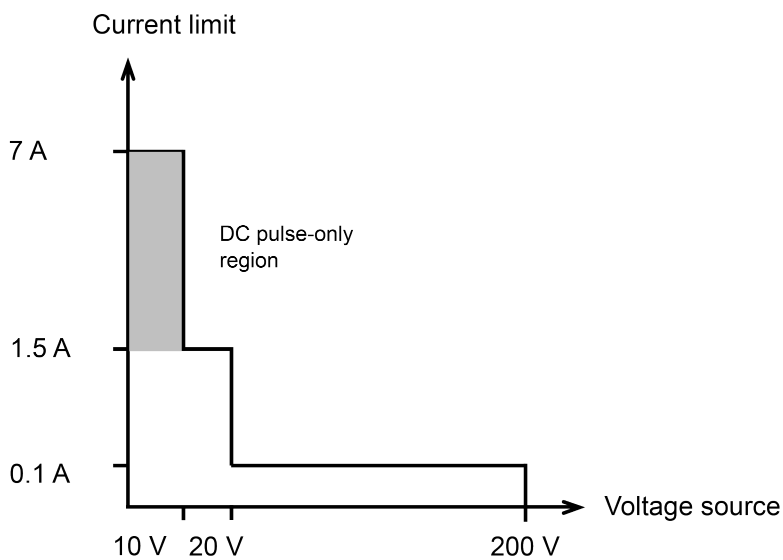
The MSMU60-2 can output up to 20 V at 1.5 A or 60 V at 100 mA.



MSMU200-2 voltage source operating boundaries

The following figure shows the operating boundaries for the MSMU200-2 voltage source. Only the first quadrant of operation is shown; operation in the other quadrants is similar.

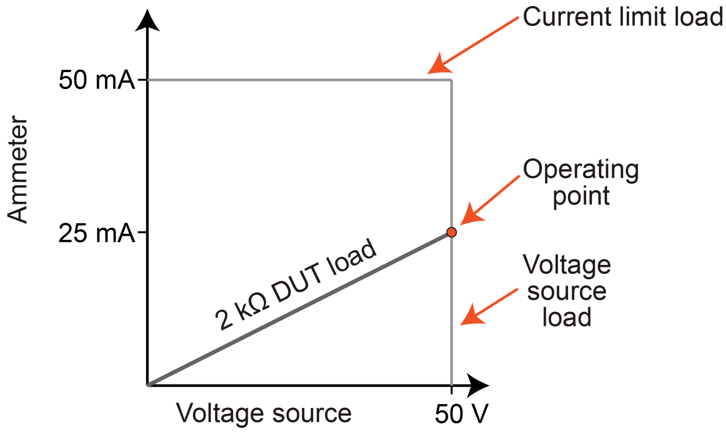
The MSMU200-2 can output up to 10 V at 7 A (pulsed) or 200 V at 100 mA.



Load considerations for voltage source

The boundaries within which the SMU operates depend on the load of the device under test (DUT) that is connected to the output of the module.

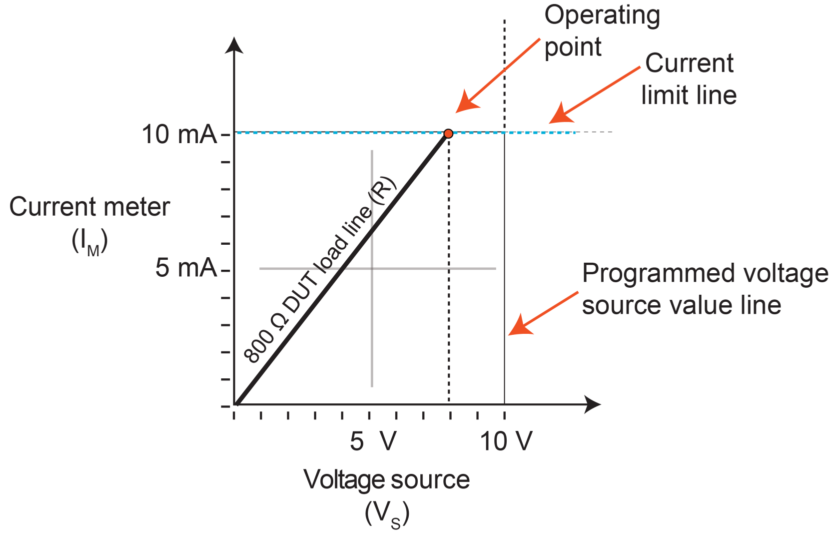
The following graphs show operation with the SMU set to source 50 V with a limit of 50 mA. In this graph, the resistive load is 2 kΩ. The SMU is sourcing 50 V to the 2 kΩ load and subsequently measures 25 mA. The load for 2 kΩ intersects the 50 V voltage source at 25 mA.



$$\text{Current meter} = \frac{\text{Voltage source}}{\text{DUT load}} = \frac{50\text{ V}}{2\text{ k}\Omega} = 25\text{ mA}$$

Voltage source operation in current limit

In the following figure, the user attempts to source 10 V with a current limit of 10 mA. The resistance of the load is 800 Ω. The DUT load line for 800 Ω intersects the current boundary, which limits the output of the SMU. When the output is limited, the SMU cannot source its programmed voltage of 10 V. For the 800 Ω DUT, the SMU only outputs 8 V (at the 10 mA limit).



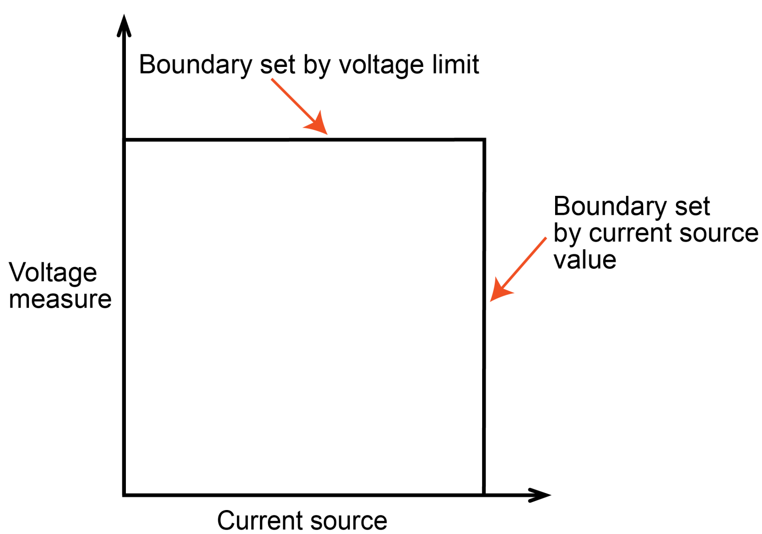
$$V_S = I_M \times R$$

$$= (10\ \text{mA})(800\ \Omega)$$

$$= 8\ \text{V}$$

Current source operating boundaries

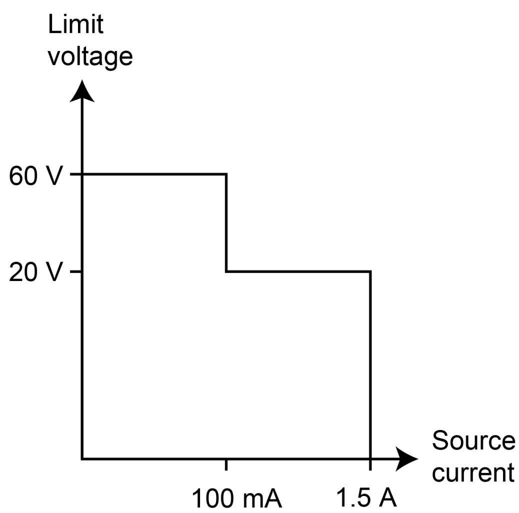
The following figure shows the boundaries for the current source of the SMU modules available for the MP5103 mainframe. The current source boundary represents the maximum source value possible for the presently selected current source range. The voltage boundary is the programmed voltage limit that is in effect (see Limits (on page 16)). These boundaries represent the operating limits of the instrument for this quadrant of operation. The operating point can be anywhere inside (or on) these limit lines. Similar boundaries can be drawn for operation in other quadrants.



MSMU60-2 current source operating boundaries

The following figure shows the operating boundaries for the MSMU60-2 current source. Only the first quadrant of operation is shown; operation in the other quadrants is similar.

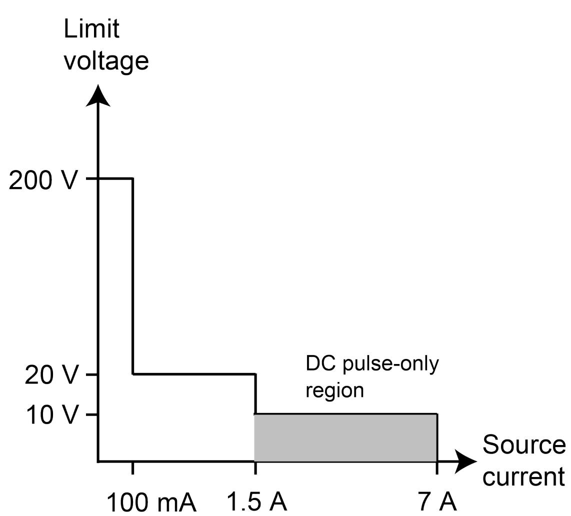
The MSMU60-2 can output up to 1.5 A at 20 V or 100 mA at 60 V. Note that when the SMU sources more than 100 mA, the voltage is limited to 20 V.



MSMU200-2 current source operating boundaries

The following figure shows the operating boundaries for the current source. Only the first quadrant of operation is shown; operation in the other quadrants is similar.

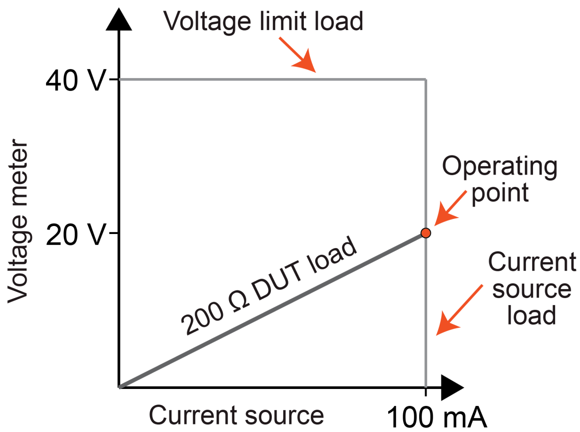
The MSMU200-2 can output up to 1.5 A at 20 V, 7 A at 10 V (pulsed), or 100 mA at 200 V. Note that when the SMU sources more than 1.5 A, the voltage is limited to 20 V.



Load considerations for current source

The actual boundaries where the instrument operates depend on the device under test (DUT) that is connected to the output of the instrument.

The following graph shows operation with a SMU set to source 100 mA with a limit of 40 V. In this graph, the resistive load is 200 Ω. The instrument is sourcing 100 mA to the 200 Ω load and subsequently measures 20 V. The load for 200 Ω intersects the 100 mA current source at 20 V.



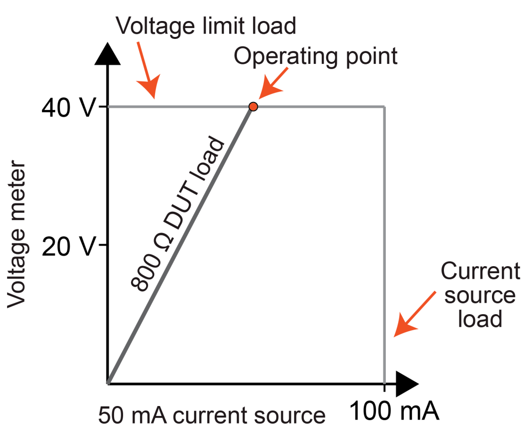
Voltage meter = Current source * DUT load

= (100 mA)(200 Ω)

= 20 V

Current source operation in voltage limit

In the following graph, the resistive load is increased to 800 Ω. The DUT load for 800 Ω intersects the voltage limit, which causes the SMU to limit the current that it is sourcing. For the 800 Ω DUT, the SMU will only output 50 mA at the 40 V limit.



$$\text{Current source} = \frac{\text{Voltage meter}}{\text{DUT load}} = \frac{40\ \text{V}}{800\ \Omega} = 50\ \text{mA}$$

Notice that as resistance increases, the slope of the DUT load increases. As resistance approaches infinity (open output), the SMU sources virtually 0 mA at 40 V. Conversely, as resistance decreases, the slope of the DUT load decreases. At zero resistance (shorted output), the SMU sources 100 mA at virtually 0 V. Regardless of the load, voltage will never exceed the limit of 40 V.

Pulse-only regions

While all modular SMUs support pulsing within their power envelope, some models (such as the MSMU200-2) feature higher watt operating capability in an Extended Operating Area (EOA). Operation in these pulse-only regions has pulse width and duty cycle limits set by the instrument firmware.

Because autoranging requires periods of adjustment, it is typically incompatible with the short durations used in pulse operation. Use fixed source and measure ranges when pulsing within an EOA. Make sure to select a range large enough for the maximum expected source or measured value.

The firmware limits the duration of the pulse and the duty cycle depending on the pulse level. Use this table as a guide for programming delays in the trigger model. If a pulse exceeds allowed delay, bit 7 in the status operation register is set. The status operation pulse limit exceeded register indicates the channel that set the bit. See "Status model" in the *MP5000 Series Modular Precision Test System Programmer Manual* for more information.

Current level	Maximum duration	Maximum duty cycle
2 A	2 s	75%
3 A	1 s	50%
4 A	0.5 s	30%
5 A	0.1 s	15%
6 A	0.001 s	10%
7 A	6.00e-04 s	5%

Within the EOA, the trigger model must be used to implement pulses. The commands used are `slot[Z].trigger.model.addblock.source.action.pulseset()` and `slot[Z].trigger.model.addblock.source.action.pulsestep()`. The compliance limit is set with the `slot[Z].smu[X].source.pulse.limitY` command. The maximum voltage limit in the EOA is 20 V.

The values sourced with the trigger model pulse commands are from a table generated by the sweep commands `slot[Z].smu[Y].trigger.source.linearY()`, `slot[Z].smu[Y].trigger.source.listY()`, and `slot[Z].smu[Y].trigger.source.logY()`.

Within the trigger model, the `slot[Z].trigger.model.addblock.source.action.bias()` command is used to set the SMU source output to the bias level.

See the *MP5000 Series Modular Precision Test System Programmer Manual* for additional TSP command details.

Calculating accuracy

Instrument accuracy specifications can be expressed in a variety of ways. To illustrate how to calculate measurement errors from instrument specifications, the following topics provide examples of calculations.

The source and measure accuracy specifications are expressed as a percentage of reading or source value and an offset. To calculate source accuracy, use the formula:

Accuracy = ± (% *of reading* + *offset)*

For example, assuming:

- Current output = 100 mA on 100 mA range
- Accuracy specification = ± (0.025% of output + 15 μA)

Calculate the current source accuracy as shown in the following equations.

Error	= {(100 mA × 0.00025) + 15 μA}
	= ± {25 μA + 15 μA}
	= ± 40 μA

Thus, the current output in this example could fall anywhere within the range of 100 mA ± 40 μA, an uncertainty of ± 0.04%.

This example shows how to use the summation method to calculate the accuracy of a resistance measurement made by sourcing current and measuring voltage. With this method, the accuracy of the source and measurements are found separately and then added together.

Device to be measured = 20 Ω resistor using 100 mA test current.

Current source accuracy

Current output = 100 mA on 100 mA range

Accuracy specification of 100 mA source range = ± (0.03% of output + 6 μA)

Error	= ± {(100 mA × 0.0003) + 6 μA}
	= ± {30 μA + 6 μA}
	= ± 36 μA
Error %	= ± 0.036%

Voltage measure accuracy

Input signal = (20 Ω × 100 mA) = 2 V

Accuracy specification of 2 V range = ± (0.014% of output + 150 μV)

	= ± {(2 V × 0.00014) + 150 μV}
	= ± {280 μV + 150 μV}
	= ± 430 μV
Error %	= ± 0.022%

For higher accuracy measurements when using SMU Instruments, measure both current and voltage. The MSMU60-2 and MSMU200-2 have independent A/D converters for current and voltage, so there is no measurement timing impact for measuring both functions.

Use the measured source value to calculate the resistance.

Current measure accuracy

Input signal = 100 mA on 100 mA range

Accuracy specification of 100 mA measurement range = ± (0.03% of reading + 6 µA)

= ± {(100 mA × 0.0003) + 6 µA}

= ± {30 µA + 6 µA}

= ± 36 µA

Error % = ± 0.036%

Maintenance and troubleshooting

Introduction

This section describes routine maintenance of the instrument that an operator can perform.

Identify the module

The module serial number is on a label on the top of the module. The serial number for a specific module can be accessed through the virtual front panel or by using the `localnode.serialno` command over a remote interface.

You can use the following commands to identify the module:

- `slot[Z].manufacturer`: Returns `TEKTRONIX`.
- `slot[Z].model`: Returns the model number of the module in the specified slot.
- `slot[Z].serialno`: Returns the serial number of the module in the specified slot.
- `slot[Z].revision`: Returns the firmware version number of the module in the specified slot.

Update the firmware

You can load a newer or older version of firmware to the mainframe or modules. The process takes about ten minutes. You can use the front panel, TSP commands, TSP Toolkit, or the web interface to update.

The mainframe and modules are updated separately, but the process is similar for both. You can update modules without upgrading the mainframe. Check the release notes for compatibility of mainframe and module firmware.

During the mainframe update, the front panel displays an update message. During a module update, the front panel is blank and the Module Status indicator for the slot blinks red and green.

Prepare to update

If you are using TSP commands or the front panel to update, you need to copy the firmware files to a USB flash drive. Verify that the flash drive is formatted with FAT32 or exFAT. In Microsoft™ Windows™, you can check the file system by checking the properties of the USB flash drive.

CAUTION: Do not remove the USB drive, turn off the instrument power, or otherwise interrupt the firmware update process. Your instrument may become unresponsive and require factory service.

To download firmware for your instrument:

1. To get the update file, go to Datasheets, Manuals, and Software Downloads.
2. Enter the model number of your instrument.
3. Select **Software** from the filter list.
4. Select **Firmware** from the filter list.
5. Download the firmware.
6. Unzip the files. The firmware file has the extension `.x`.
7. Review the release notes.

Update the firmware from the front panel

You can use a USB flash drive to update the firmware from the front panel for the mainframe and modules. The latest firmware is available from tek.com.

Make sure that the firmware is loaded onto your USB flash drive, then insert it into the USB port on the front of the mainframe.

The update process is the same for the mainframe as it is for the modules. The following example demonstrates the firmware update for a module.

CAUTION: Do not remove the USB drive, turn off the instrument power, or otherwise interrupt the firmware update process. Your instrument may become unresponsive and require factory service.

The following procedure updates a module with mainframe firmware V1.0.1 or newer installed. If you need to update using an older mainframe version, replace the first two steps in the following procedure by selecting General info from the home screen and then selecting the firmware download icon.

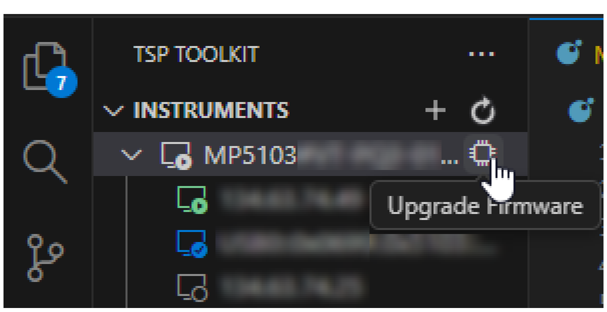
To update the module firmware (mainframe V1.0.1 and newer):

1. Select **Settings** from the mainframe home screen.
2. Select **Firmware Update**.
3. Select **Slot1**, **Slot2**, or **Slot3**.
4. Select **Browse** to locate the new firmware file on your USB flash drive, then select it.
5. Select **Update**. The firmware may take several minutes to load. The slot indicator on the front panel blinks red and green while the update is in process, and a message is displayed when the update is complete.
6. To confirm that the update was successful, select the information icon from the Home screen, then scroll to the information section for the slot to verify the module firmware version.

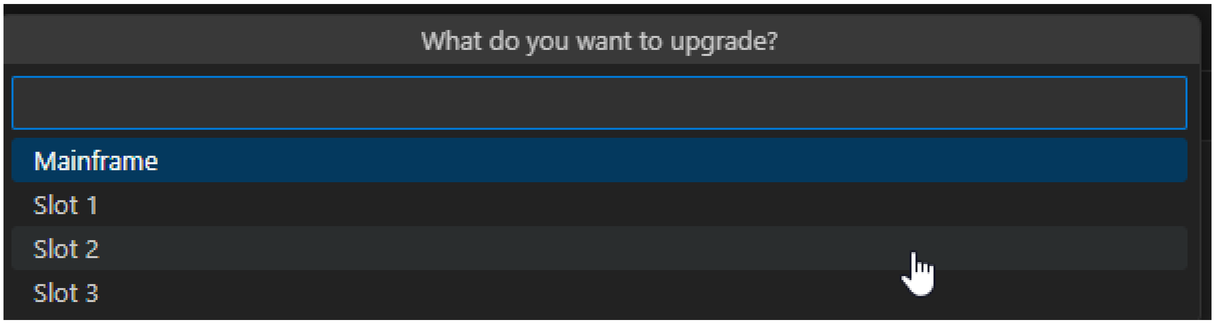
Update the firmware with TSP Toolkit

To update the firmware with TSP Toolkit:

1. Place the update file in a location that can be accessed by TSP Toolkit.
2. Open Visual Studio Code with TSP Toolkit extension installed.
3. Connect to the mainframe.
4. Select the **TSP Toolkit** icon. The mainframe is displayed in the Primary Sidebar.
5. Select the **Upgrade Firmware** icon to the right of the mainframe name.



6. Select the mainframe or slot number from the list. The Select Firmware File dialog is displayed.



7. Select the update file.
8. Select **Upgrade**.
9. Wait until the update process is complete:
   - **Mainframe:** Monitor the front panel for update status. TSP Toolkit is disconnected during the update process.
   - **Module:** The message "Module upgrade complete" is displayed in the TSP Toolkit terminal.

Update the firmware using TSP

To update firmware using TSP, you need to load the firmware file to the mainframe and then run the file.

NOTE: You can check the current firmware version of a mainframe with `print(localnode.revision)` and `print(slot[Z].revision)` for a module.

To update the firmware using TSP commands over a remote interface:

1. Copy the firmware file to a USB flash drive.
2. Insert the flash drive into the USB port on the front panel of the instrument.
3. Load the firmware. Send
   `firmware.image.load("/usb1/filename")`
   Where *`filename`* is the directory and file name for the firmware.
4. Start the firmware update.

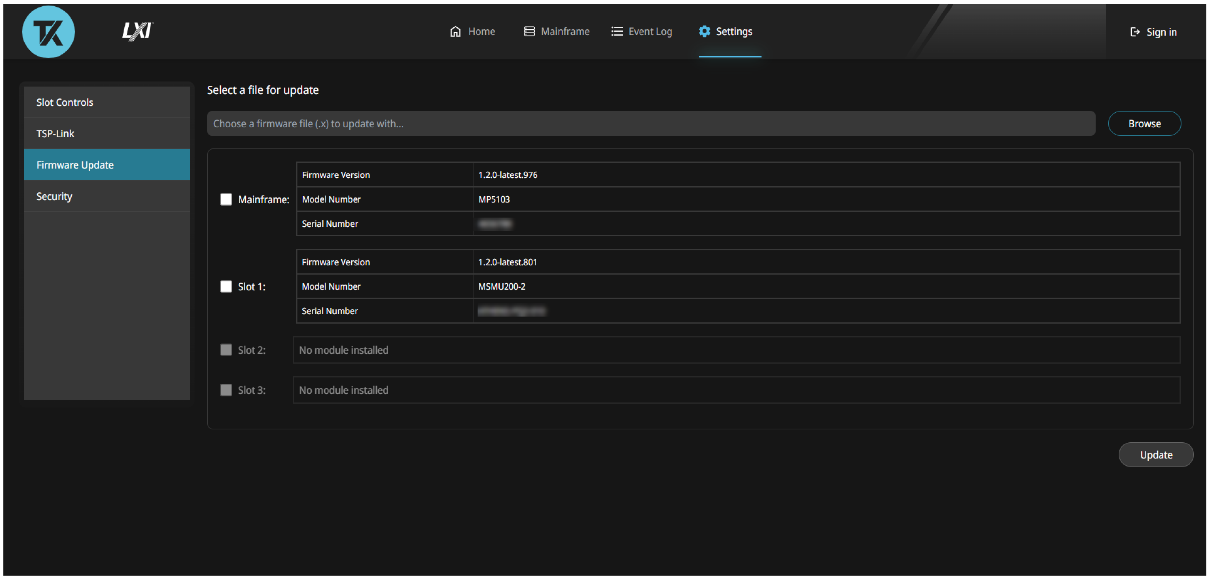
   For the mainframe, send
   `firmware.update()`

   For a module, send
   `slot[Z].firmware.update()`
   Where *`Z`* is the slot number.
5. Wait for the update to complete.

During a mainframe update, the front panel and module lights go dark for a few seconds, then the front panel displays an update message. The mainframe is restarted. During the module update, the Module Status light blinks red and green.

Update the firmware using the web interface

To update the firmware using the web interface:



1. Make sure that you are connected to the mainframe and logged in. See Log in to the MP5103.
2. Place the upgrade file in a location that can be accessed by the web browser.
3. Select **Settings**.
4. Select **Firmware Update**.
5. Select the mainframe or a module slot to be updated. You can only update one instrument at a time.
6. Select **Browse**.
7. Select the firmware update file.
8. Select **Update**.
9. Wait until the update process is complete:
   - **Mainframe:** Monitor the web page for update status. The connection will be interrupted during the update. Refresh the web page after several minutes to verify that the update has been installed. If your instrument is set to use automatic IP address assignment, check the mainframe front panel display to verify the IP address, then connect to the mainframe again.
   - **Module:** Monitor the web page for update status.

License information

To review the license information for the module, send the command:

```
slot[Z].license
```

Where *Z* is the slot number that contains the module.

Event log

The event log records errors, warnings, and information reported by the instrument. Events are logged in a first-in, first-out queue. Event messages include the event code, event message, severity, TSP-Link node, and the time of the event.

Events are assigned to one of the following levels.

Number	Event level	Description
0	NO_SEVERITY	The message is information only. This level is used when the event queue is empty.
10	INFORMATIONAL	The message is information only. This level is used to indicate status changes.
15	WARNING	This message indicates that a change occurred that could affect operation.
20	RECOVERABLE	The event was caused by improper use of the instrument or by conditions that can be corrected. This message indicates that an error occurred. The instrument is still operating normally.
30	SERIOUS	There is a condition that prevents the instrument from functioning properly. The message indicates that the instrument is presently operating in an error condition. If the condition is corrected, the instrument returns to normal operation.
40	FATAL	There is a condition that cannot be corrected that prevents the instrument from functioning properly. Disconnect the DUT and turn the power off and then on again. If the error is a hardware fault that persists after cycling the power, the instrument must be repaired.

Most events do not abort a running script. The only time a script is aborted is when a Lua runtime error (event code −286, "TSP runtime error") is detected. Runtime errors are caused by actions such as trying to index into a variable that is not a table.

Execution of scripts or commands is prevented if there is a syntax error (event code −285, "Program syntax") in the script or command.

You can retrieve events from the event log by using the commands in the following table.

Command	Description
`eventlog.clear()`	Clear event log of all errors
`print(eventlog.count)`	Number of messages in the event log
`print(eventlog.next())`	Read and return the oldest unread event message from the log and remove the event message from the log

For example, the following command requests an event log message:

```
print(eventlog.next())
```

If there are no events in the event log, the return is similar to:

```
0.00000e+00 Queue Is Empty 0.00000e+00 1.00000e+00 0.00000e+00 0.00000e+00
```