# How to Select Shunt Resistors for High Bandwidth Oscilloscope Current Measurements

APPLICATION NOTE

Shunt resistors are necessary for many applications requiring higher bandwidth and lower inductance current measurements than can be achieved with a Rogowski or clamp-style current probe. In addition to the inductance associated with the probe itself, the inductance associated with wire loop test points and leads can add significant inductance, as shown in **Table 1**. In systems with extremely fast changing currents (high di/dt), even a small inductance can produce large voltage transients.

| Device | Insertion Inductance |
|---|---|
| 6″ twisted pair wire | 123 nH |
| Clamp Probe wire loop | >80 nH |
| Tektronix Wideband Shunts | 7 to 8 nH |
| Surface Mount Shunt | <1 nH |

**Table 1. Insertion inductance of clamp-based current measurements versus shunt-based current measurements**

The need to accurately measure the voltage across precision, high bandwidth shunts inspired the development of the IsoVu Isolated Current Probe. This probe provides galvanically isolated, 50 Ω differential inputs to provide high bandwidth, high signal fidelity, and exceptionally high common mode signal rejection.

Selecting the right shunt is critical to achieving optimal results when making shunt-based current measurements. Understanding shunt properties and careful selection from the wide variety of available shunts will ensure accurate, wide-bandwidth current measurements that minimize parasitic inductance and maximize signal-to-noise ratio.

The selection process can be iterative and involves several interconnected considerations:

- Target current range and dynamic range requirements
- Resistance value optimization for signal amplitude and burden voltage
- Power dissipation limits and thermal management
- Bandwidth limitations due to parasitic inductance
- Test point implementation strategies
- Form factor selection based on space, power, and bandwidth requirements

## This Application Note

- Offers a systematic approach to selecting shunt resistors for high bandwidth current measurements, covering current range identification, power limits, resistor value selection, form factor considerations, bandwidth optimization, and test point implementation.
- Explains the trade-offs between signal-to-noise ratio, power dissipation, and measurement bandwidth while providing practical selection criteria for various applications.
- Gives an overview of different shunt resistor technologies and gives examples of several wideband resistors that may be used with current shunt probes, including Tektronix wideband shunts.
- Gives examples of how to select an appropriate resistor value for Tektronix Wideband Shunts for IsoVu Isolated Current Probes.

This application note talks about several types of shunt resistors, any of which can be used with IsoVu Isolated Current Probes. This document explains how to choose and apply Tektronix Wideband Shunts. The oscilloscope used in this application note is a 6 Series B MSO, however the isolated current probe and wideband shunts are also compatible with 4 and 5 Series B MSOs.

## Establishing Characteristics of the Current to be Measured

The target current RMS value, peak current, and ideal bandwidth are the first places to start exploring shunt options. These factors will all affect downstream variables like burden voltage, resistor value, power dissipation, insertion inductance, and compensation strategy.

If the maximum current is dominated by a steady state DC value with small transients or excursions, the DC current can be used to establish the maximum RMS current, while allowing headroom for anticipated transients. However, in many cases transients and excursions may be large and may dominate range and dissipation considerations. In the case of dissipation, pulsing the current can usually extend the power handling capability of a shunt.

### Pulsed vs. Continuous Current

If a signal is periodic or pulsed, shunt resistors can handle significantly higher peak currents compared to continuous current.

For very short on-times (narrow pulse widths), the average power dissipated by the shunt is much smaller than the power dissipated for a continuous current. This is illustrated in **Figure 1**, which shows the relationship between maximum current and pulse width for Tektronix wideband shunts.

For example, **Figure 1** shows how a 5 mΩ wideband shunt can handle a 200 A square or triangle pulse of 10 µs pulse width but would be limited to 12 A RMS for a continuous signal. Note that specific shunts may have duty cycle limitations to allow energy to dissipate between pulses. Maintaining a low duty cycle is good practice whenever possible.

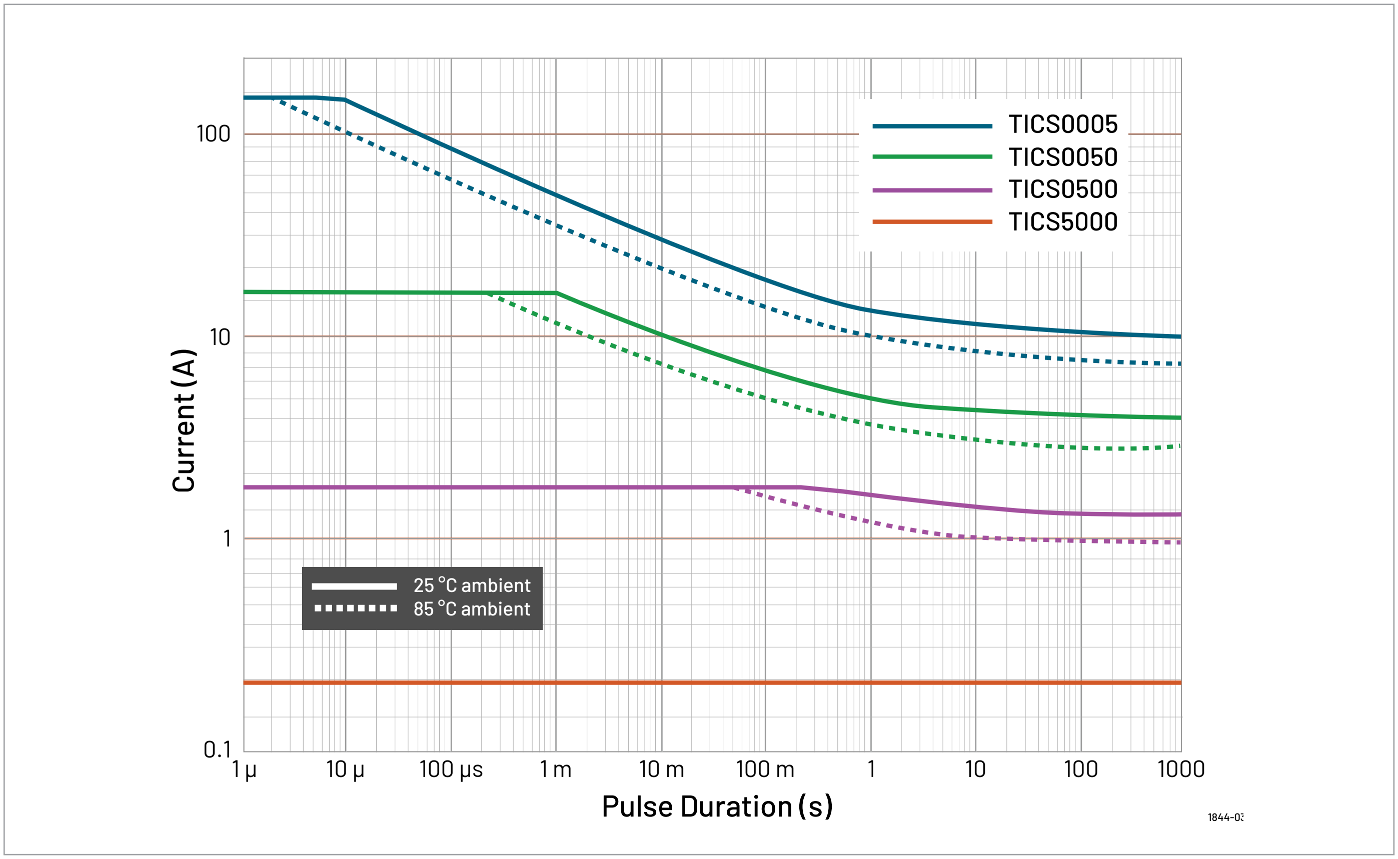


**Figure 1.** Maximum current by pulse duration for Tektronix Wideband Current Shunts.

## Bandwidth of the Current Signal

Traditionally, bandwidth has been of secondary concern for current measurements. However, with the advent of fast switching technologies such as GaN and SiC, and dynamic loads such as GPUs and FPGAs, rise-times have decreased dramatically. By approximating the measurement system as a first order system, one can estimate the bandwidth of required to measure a desired rise-time.

$$Bandwidth = \frac{0.35}{t_r} \tag{1}$$

Where $t_r$ is the 10% to 90% rise time of the signal.

For example, a load device that draws current with a rise time of 1 ns implies an estimated bandwidth of 350 MHz.

# Resistor Value Selection

To select the right shunt resistor, one must choose the highest value resistor that will survive the RMS current while not violating the DUT’s load impedance or burden voltage limits. In high-bandwidth applications, low insertion inductance is also an important criterion. Thus, the process involves several trade-offs.

## Anticipating Design Trade-offs

If an ideal resistor was available with zero inductance and unlimited power dissipation, then one could choose the value based solely on noise and acceptable voltage drop. In reality, it is important to understand that the specifications must balance several competing factors.

1. **Burden Voltage**: Lower resistance decreases voltage drop across the shunt, reducing the impact on the device being powered (i.e. lowering the final rail voltage experienced by the DUT).
2. **Power Dissipation:** Lower resistance decreases power dissipation in the shunt.
3. **Signal Amplitude:** Higher resistance provides larger signal amplitude, raising signal-to-noise ratio
4. **Measurement Bandwidth:** Both higher resistance and lower insertion inductance increase the corner frequency of the shunt.

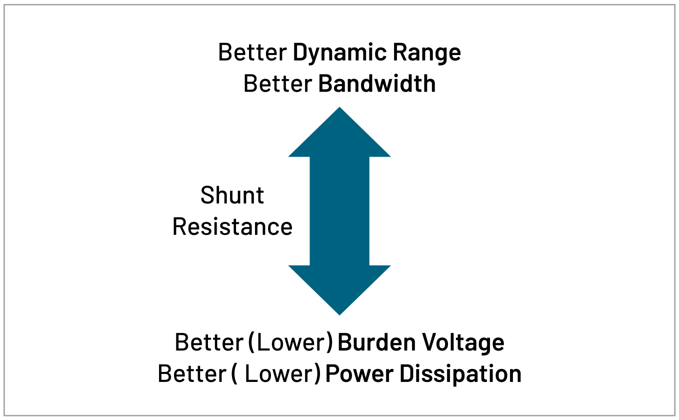


**Figure 2.** Choosing a shunt resistor value requires balancing range, bandwidth, voltage drop and power dissipation.

With the expectations that trade-offs are inevitable, one can calculate an ideal resistance and then check the other parameters to determine what, if any, trade-offs are needed.

## Acceptable Burden Voltage

Higher resistance increases voltage drop across the shunt, lowering the final rail voltage experienced by the load. This factor can matter for any load but is especially critical for low-voltage processors that have a 5% power rail tolerance. (e.g. ±40 mV tolerance on a 0.8 V core voltage power rail).

### Calculate First-pass Resistance Based on Current and Burden Voltage

Assuming decoupling capacitors are in place to support voltage levels, the burden voltage imposed by the shunt will be determined by the RMS input current. This information can be used to estimate the resistance of the shunt.

$$R_{shunt} = \frac{V_{burden(max)}}{I_{RMS}} \tag{2}$$

For example: a 40 mV voltage budget with 8 $A_{RMS}$ current allows a 5 mΩ resistor.

Of course, calculations may produce non-standard values. If the burden voltage is a rigid constraint, it will be necessary to drop down to the next lower standard resistance value. Resistor tolerance will translate into current uncertainty, so this should also be considered.

### Calculate Power Dissipation

The next limiting factor is power dissipation in the shunt.

$$P_{avg} = I^2 \cdot R \tag{3}$$

With a known RMS target current and resistance, one can calculate average power dissipated. Although the maximum power dissipation for specific shunts will vary by device and thermal conditions, good rules of thumb are to shoot below 3 W for larger CVRs and 1 W for SMD devices.

Example: By applying Equation 3, a 5 mΩ resistor experiencing 8 $A_{RMS}$ current needs to dissipate 1/3 W of heat continuously. That power value is easily achievable with SMD devices and trivial for bus bars, wideband shunts, and other dedicated current viewing resistors.

After determining the likelihood that a shunt will survive the current measurement, the next task is to optimize the measurement for dynamic range, bandwidth, and insertion inductance.

## Verify Signal Amplitude and Check Noise Floor

The measurement system being used to measure the voltage drop across the shunt will determine the lowest measurable current. This may be specified as a resolution, or as the noise floor of the system. Ohm's law relates voltage noise floor to current noise floor.

$$I_{noisefloor} = I_{min} = \left(\frac{V_{noisefloor}}{R_{shunt}}\right) \tag{4}$$

Where I and V are in amps (RMS) and voltage (RMS) respectively.

From this inverse relationship it is clear that a larger shunt resistance decreases the minimum measurable current.

The voltage noise of the system increases with the bandwidth of the measurement. Noise Spectral Density (NSD), is measured in $V/\sqrt{Hz}$ and relates the total bandwidth of the system to noise, as shown in Equation 6.

$$V_{noisefloor} = NSD \cdot \sqrt{Bandwidth} \tag{5}$$

$$I_{noisefloor} = \frac{NSD \cdot \sqrt{Bandwidth}}{R_{shunt}} \tag{6}$$

Example: The 8 $A_{RMS}$ current from the previous example has occasional impulses up to 12 A which need to be measured. In other words, the system must be able to handle 8 $A_{RMS}$ continuous, but be able to measure up to 12 A. On a 5 mΩ shunt, 12 A implies a 60 mV measurement. Probe and scope ranges and offsets may also come into play. For example, a TICP isolated current probe in its ±45 mV range enables a 60 mV measurement with 15 mV of offset. The ±45 mV input range on a TICP probe has an NSD of 4.7 $nV/\sqrt{Hz}$. Assuming a bandwidth of 200 MHz and using a 5 mΩ shunt results in a 13.3 $mA_{RMS}$ noise floor according to Equation 6.

Since lowering the shunt resistance increases the noise floor for current measurements, if this same measurement were performed on a 3.3 mΩ shunt, the noise floor would increase to 20 $mA_{RMS}$. **Table 2** shows how different shunt values (Column A) can make the same 12 A measurement, where noise floor (Column B) drops with higher resistance, but at the cost of more power dissipation in the shunt (Column C).

| Shunt Value to Measure *Imax* Amps (Ω) | Noise Floor at BW (A RMS) | Power Dissipation at 100% Duty Cycle (W) |
|---|---|---|
| 54.2E-3 | 4.5E-3 | 7.8 |
| 41.7E-3 | 5.1E-3 | 6.0 |
| 29.2E-3 | 4.6E-3 | 4.2 |
| 20.8E-3 | 5.9E-3 | 3.0 |
| 15.0E-3 | 5.9E-3 | 2.2 |
| 10.8E-3 | 7.2E-3 | 1.6 |
| 7.5E-3 | 8.9E-3 | 1.1 |
| 5.0E-3 | 13.3E-3 | 0.7 |
| 3.3E-3 | 19.9E-3 | 0.5 |

**Table 2. Spreadsheet calculations using Equations 3 and 5. NSD values are for Tektronix Isolated Current Probe. Maximum current is 12 A and target bandwidth is 200 MHz. Note the interaction between shunt value, measurement system noise floor and power dissipation for the specified maximum current and bandwidth.**

To ease some of these calculations with the Tektronix Isolated Current Probe, several calculators are posted on the Tektronix website. If the shunt value is known, use TICP Current Calculator to see the noise floor and dynamic range for different TICP settings. If the target current is known and the shunt is still undecided, use TICP Shunt Calculator to see how different shunt values impact the noise floor and dynamic range; just don't forget to factor in power dissipation and burden voltage!

## Shunt Inductance and Bandwidth

As explained in the previous section, resistor value selection affects dynamic range, but it also interacts with a shunt's parasitic inductance to limit the effective bandwidth of the measurement system. At a first order level, a shunt resistor can be modeled as a single pole RL circuit: a resistor and inductor in series. This basic model ignores transimpedance and coupling effects which can be significant but are very difficult to characterize and model correctly [4]. In this application note the simplified model will be used.

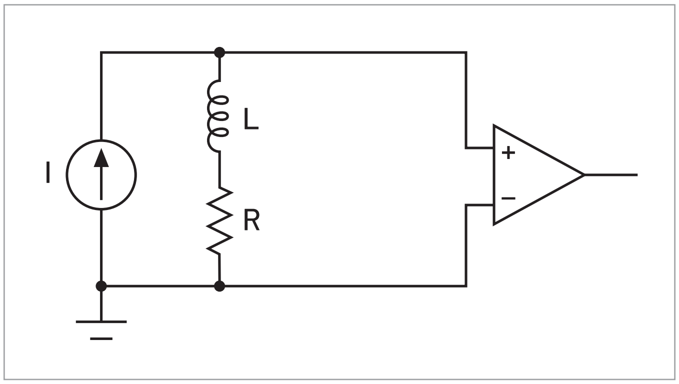


**Figure 3.** A practical shunt resistor can be modeled as a series RL circuit.

In systems with highly dynamic currents, that is, high di/dt, even small inductances can generate disruptive voltage transients. Even if the circuit is designed to tolerate transients from added inductance, voltage spikes and ringing can show up in oscilloscope measurements due to probing parasitics. Because of this potential impact to both system performance and measurement quality, designers and test engineers avoid adding inductance.

For our simplified model, Equation 7 gives the relationship between shunt resistance, series inductance, and the corner frequency at which the impedance of the shunt results in a 3 dB increase in voltage drop across the physical shunt.

$$f_c = \frac{R_{shunt}}{2 \cdot \pi \cdot L_{shunt}} \tag{7}$$

This relationship makes it clear that maximizing the resistance of the shunt has a positive effect on bandwidth. **Figure 4** demonstrates this by showing curves for increasing resistance values. Above the corner frequency ($f_c$) the inductive reactance increases the impedance of the shunt, so its response is no longer flat.

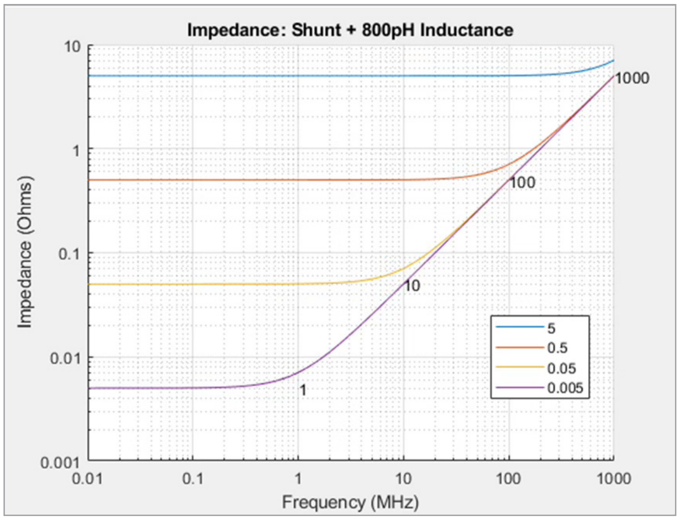


**Figure 4.** Simulated uncompensated frequency response of different shunt resistor values. Higher shunt resistance increases bandwidth.

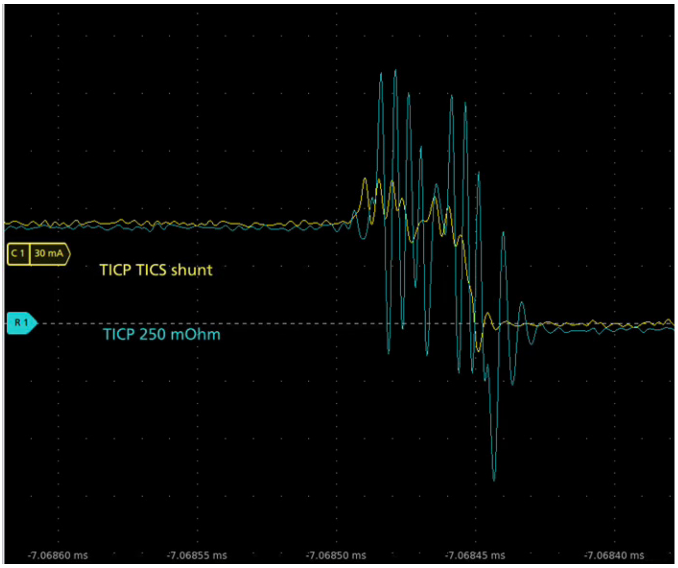


**Figure 5.** The yellow trace is from a compensated wideband shunt. The cyan trace is from an uncompensated resistor. Both traces are captured using the same probe to measure voltage drop.

Individual SMD resistors can have several nanohenries of inductance. Designers sometimes place four to eight higher value resistors in parallel rather than using a single component to implement a shunt. **Figure 6** shows an example of this approach. This reduces both the resistance and inductance of the shunt. However, this approach has practical limits as current stops being distributed evenly at wider form factors.

Capacitors may also be used to compensate for the series inductance and flatten frequency response for an order of magnitude or more. Additional detail on this technique may be found in the Tektronix white paper [Compensating for Series Inductance in Shunt Resistors for High Frequency Measurements](). Newer shunts, optimized for lower insertion inductance and higher bandwidth, may include compensation networks to tune the measurement frequency response. Tektronix Wideband Shunts integrate a compensation network and this is described in a subsequent section.

One important note is that although the measurement quality may be improved through probe compensation, the DUT still experiences the insertion inductance of the shunt. It is only in the measurement that the effects of the inductance are compensated.

## Examples of Test Point Implementation

Ideally the shunt resistor, compensation network, and test points are all built into the board design. In the second best case, a shunt resistor already exists on the board. And finally, there are cases where no measurement point exists and the entire chain needs to be added.

### Implementation Strategies

1. **Integrated PCB Design:** Best performance, requires early planning.

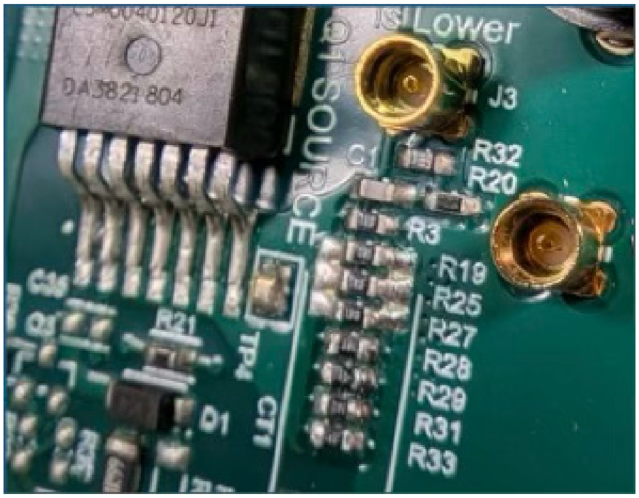


**Figure 6.** An integrated current test point using a high bandwidth MMCX connector with compensation.

On this board, the $I_{S\_LOWER}$ test point at MMCX connector J3 is designed into the board, complete with compensating pole at C1, R32, and R20.

2. **Existing Shunt Modification:** Quick implementation, may degrade signal integrity.

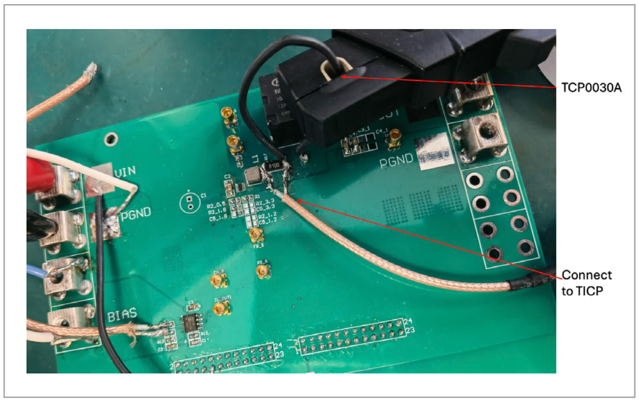


**Figure 7.** A 50 Ω coaxial cable, terminating in an MMCX connector, soldered across a surface mount shunt. In this example, the clamp-on current probe is used to compare results.

In this case, the DUT includes a built-in shunt. **Figure 7** shows how an existing 0.1 Ω SMD shunt has an MMCX cable soldered across it, allowing a TICP current measurement. This implementation does not include a compensation circuit for the parasitic inductance which amplifies high frequency ringing.

3. **Complete Addition:** Maximum flexibility, highest complexity.

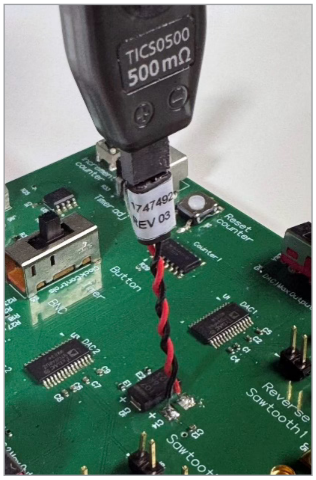


**Figure 8.** Using a probe-based wideband shunt connected via twisted pair.

If no provisions have been made for a shunt, the DUT must be carefully modified. This can involve cutting power traces or lifting legs of components to place a resistor in-line. **Figure 8** shows an example in which, after cutting a current carrying trace, a twisted pair wire was added in series with the current flowing through a newly added shunt. This design is convenient but adds the most insertion inductance into the current measurement path, impacting the device behavior. Replacing the Y-lead with square pins or putting the SMD directly across the cut trace can reduce insertion inductance.

## Connector Choices

In addition to the shunt location and compensation, the physical connection to the device will also impact measurements based on their sensitivity to radiated emissions. In the examples above, MMCX, square pins, a coaxial cable with MMCX connector, and twisted pair with square pins were shown. These different methods have different levels of sensitivity to radiated emissions and care should be taken to choose the best connection.

Shielded test points using MMCX, SMA, and coaxial cables will perform the best, as the outer braid provides effective shielding to the center conductor. Even better than coaxial is a twinax cable such as those used with the Tektronix Wideband Shunts. Twinax cables put both conductors inside a third, braided shield—protecting both positive and negative conductors from EMI with the added benefit of true differential signaling.

# Shunt Resistor Technologies and Form Factors

For high-bandwidth measurements, the IsoVu Isolated Current Probe can be used with any resistor form factor. Nevertheless, there are tradeoffs in the different designs.

In-circuit shunts are often incorporated into a standard bill of materials and used for current monitoring during regular circuit operation. They can also function as oscilloscope shunts for validation and debug. The inductance and bandwidth of these devices may or may not be specified. **Table 3** gives some ballpark figures for generic components.

## SMD Resistors

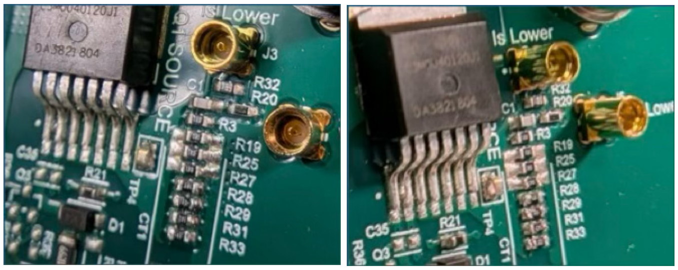


**Figure 9.** Built-in SMD shunt resistors. In this application 8 devices are wired in parallel to reduce the shunt resistance and parasitic inductance, as well as distribute current and control dissipation.

SMD Resistors come in a wide variety of form factors and ohmic values, making them a flexible and affordable option for many applications. The tradeoffs of SMD devices are their limited power dissipation capabilities and uncompensated frequency response.

Inductance for SMD resistors can be low to medium, often landing in the few nanohenries range. The form factor has flexible options with the caveat that as the width of the device increases relative to the length, the resistor starts to look more like a distributed transmission line and less like a lumped element. Impedances vary based on the probing position and therefore currents start being distributed unevenly across the SMD resistor. This effect is called transimpedance[4] and will impact both the effective inductance and any measurements attempted on the SMD device. It's also likely that this transimpedance is non-linear, meaning the effect changes with different current amplitudes or different step speeds.

## Bus Bar Shunts

Bus bars are larger than SMD devices and therefore can dissipate much more heat. Although they take up significant space, they are good solutions for high-current measurements. For example, for a high-RMS current measurement such as a 100 A continuous DC current with a smaller 1 A transient of interest riding on top, the resistor

## In-circuit Components (typical measured values)

| Shunt Type | Resistance Range | Power Rating | Inductance (typical, measured) | Package Type | Key Applications |
|---|---|---|---|---|---|
| SMD Thick/Thin Film | 50 μΩ–10 Ω | 0.25 W–2 W | <1 nH | Solder-on surface mount | Compact designs, pulsed current |
| Bus Bar/Metal Strip | 50 μΩ–10 mΩ | 10–100 W | 10 nH–50 nH | Solder-on/bolt-on | High RMS current, thermal stability |

**Table 3.** Rough figures for generic shunt components.

must dissipate the power created by the full RMS current, not just the smaller signal of interest. A busbar shunt may be a good choice. These devices are typically made of materials that have stable resistance over temperature and can have inductance values in the 10s of nH range, but can be subject to the same transimpedance issues as larger SMD resistors.

Their larger size means the designer often needs to think ahead and design these resistors into the schematic. If your traction inverter or motor drive application already uses current sense devices for over-current protection or short-circuit detection, bus bar shunts may already be incorporated in the design and it may be possible to measure across the existing shunt.

Keep in mind that the vendors of these resistors do not always think of them as high bandwidth devices. Mostly, they are used for DC and very low frequency current monitoring by onboard integrated circuits. This may mean information about the resistors' inductance, frequency response, or bandwidth information is not available.

## Special-purpose Wideband Shunt Devices

Specialty shunts, optimized for testing, are also available. These shunts are often connected temporarily or connected as part of an evaluation or test system. Tektronix Wideband Shunts fall into this category. In addition to the Tektronix shunts, other types of shunts known to work well with the IsoVu current probe are listed in **Table 4**.

## Tektronix Wideband Shunts

One family of shunts designed to work with the Tektronix Isolated Current Probe and MSO oscilloscopes is Tektronix Wideband Shunts. These plug-and-play smart shunts integrate with Tektronix oscilloscopes — auto-configuring the units and vertical scale, and ensuring measurements are performed at minimal noise levels. This design interfaces with square pins (**Figure 10**) and connects to the IsoVu current probe using a flexible, low-noise twinax tip. It features frequency compensation, temperature compensation, and high-performance fuses to protect the test equipment (**Figure 11**). Values range from 5 mΩ to 5 Ω, providing 250 MHz of bandwidth and reliable connection to boards.

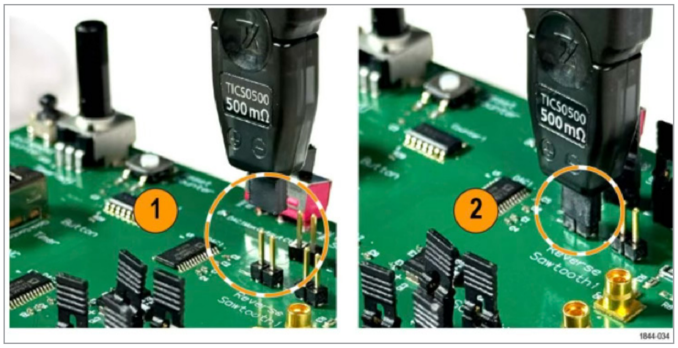


**Figure 10.** Tektronix wideband shunts can connect directly to 0.025 in. square pins on 0.1 in. centers, shown in Reference 1. The probe tip and shunt are shown attached to the pins in Reference 2.

| Shunt Type | Resistance Range | Power Rating | Inductance | Package Type | Key Applications |
|---|---|---|---|---|---|
| Tektronix Wideband Shunts [1] | 5 mΩ to 5 Ω | 1 W | 7 to 8 nH | Square pin, re-usable | High bandwidth, precision compensation |
| Picotest | 1 mΩ to 50 mΩ | Not broadly published | ~2 pH reported in-system; tens of pH plausible by implementation | PCB-integrated thin-film / surface-mount style | PDN, VRM, load-step, and WBG switching measurements with minimal circuit disturbance |
| PMK Ultra Fast Current Shunts [2] | 1 mΩ to 52 mΩ | 3 W | < 150 pH | Solder-in with low L pads | WBG testing on devices sensitive to insertion inductance |
| T&M Research Current Viewing Resistors [3] | 1 mΩ to 50 mΩ | 3 W and up | Not published | Through-hole solder mount, panel mount | WBG testing on devices sensitive to insertion inductance |

**Table 4.** Wideband shunts designed for testing applications

Combined with a Tektronix oscilloscope, software, and isolated current probes, these wideband shunts enable precise characterization of standby and operating currents in embedded designs, high-performance computing systems, or other applications that require precision high-bandwidth current measurements with continuous shunt dissipation of 1 W or lower.

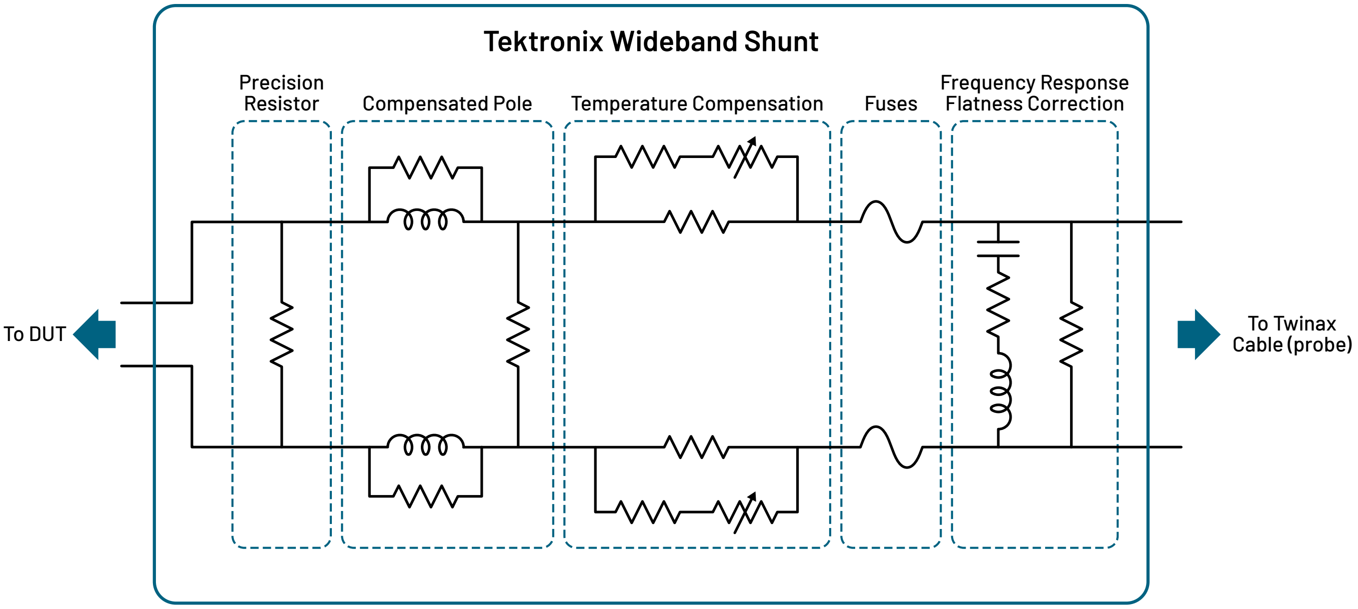


**Figure 11.** Tektronix wideband shunts include bandwidth compensation, temperature compensation, overvoltage and overcurrent protection.

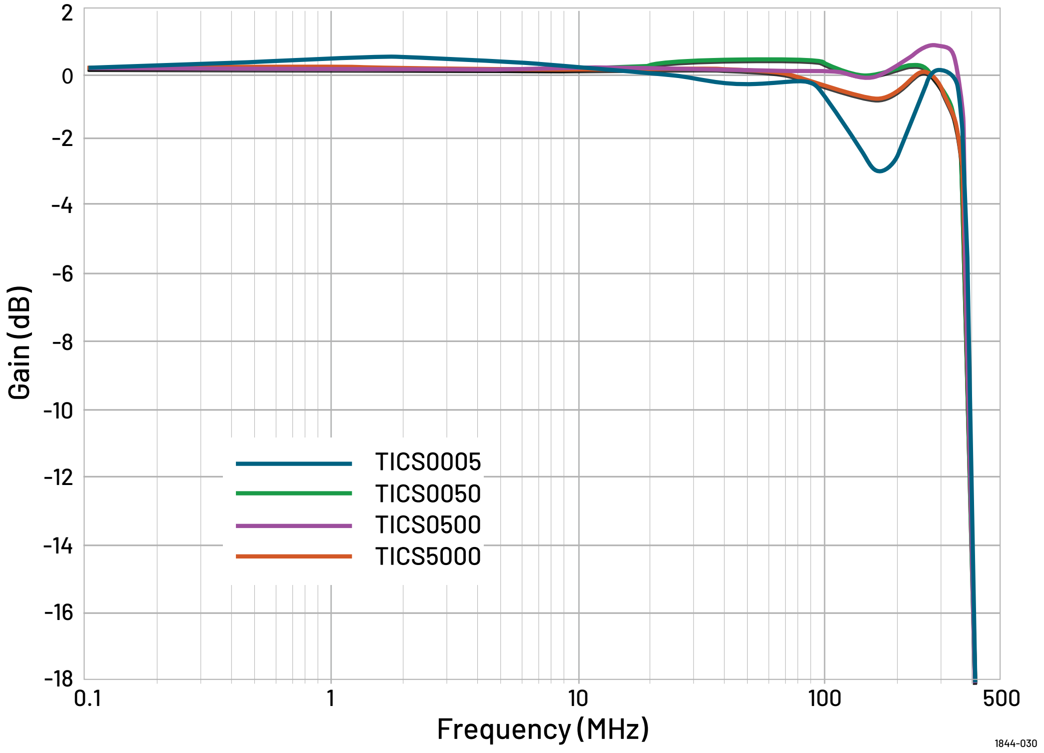


**Figure 12.** A precision compensation network in the Tektronix wideband shunts flattens the frequency response out to 250 MHz.

## Current Viewing Resistors from T&M Research

T&M Research Current Viewing Resistors (CVRs) are a popular option for current sensing and their orange labels are a familiar sight in many power electronics labs. With a coaxial body and a BNC connector, these CVRs have advantages in shielding over an SMD or bus bar shunt. They also offer large, high power dissipation form factors, useful for continuous power testing. However, similar to other shunts, parasitic inductance can impact measurement quality and steps should be taken to control it and understand the frequency response of the shunt.

While BNC connectors are convenient, one should use caution when connecting the CVR directly to an oscilloscope with a cable. This grounds the low measurement terminal and creates a ground loop, leading to ground current injection and ground bounce. Ground bounce directly impacts the measurement, adding ringing that is from the test setup, not the device. Combining these devices with an IsoVu isolated current probe kills the ground loop through its RF isolation barrier, providing a galvanically isolated measurement that better reflects the DUT's performance.

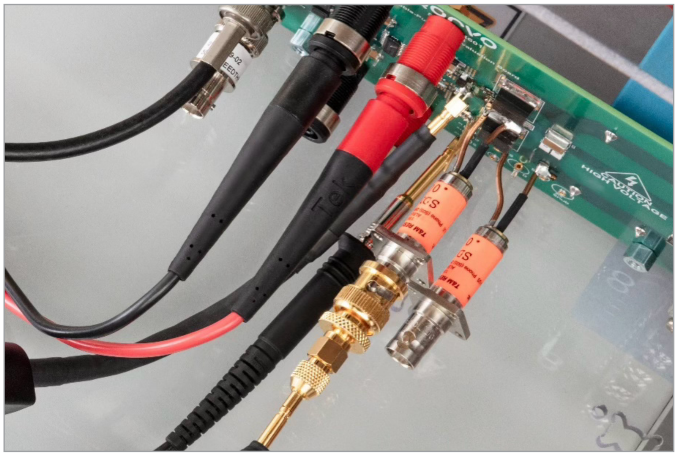


**Figure 13**. IsoVu Isolated Current Probe measuring the source current on a SiC FET with a T&M Research current viewing resistor.

## Ultrafast Current Shunt from PMK Mess- und Kommunikationstechnik GmbH

New current shunts from test and measurement companies are launching every year. One is the Ultrafast Current Shunt (UFCS) from PMK. In testing, the UFCS shows several-hundred MHz bandwidth with a desirable rolloff, indicating it is a frequency-compensated design. It performs well with low insertion inductance and 3 W power dissipation capability. The challenges with using the PMK device come from its large form factor. The low insertion inductance requires a wide space on the test board and the shunt is also tall, presenting positioning challenges in crowded enclosures.

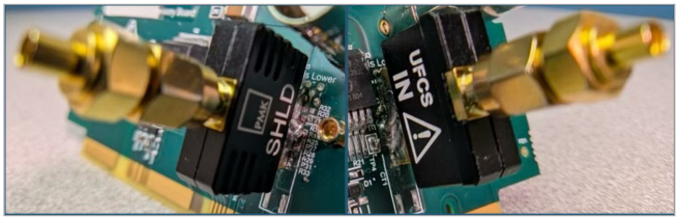


**Figure 14**. A PMK Ultrafast Current Shunt assembled on a circuit board.

This device is well-suited for current measurements on wide bandgap devices where the insertion inductance is paramount, and compromises can be made to fit the shunt onto the test board. Its cost is more in line with a measurement device than a mass-produced SMD component, so it's also more suited for R&D lab benches than production tests.

## Picotest Ultra-Low Inductance and Ultra-High-Bandwidth Current Shunts

Picotest has announced a new family of resistors called "ultra-low insertion inductance, ultra-high-bandwidth current shunts". They are targeted at high-speed PDN, VRM, load-step, and wide-bandgap switching measurements. Because of their unique footprint, the shunts are ideally integrated into the PCB layout and used for both R&D, validation, and in-system monitoring after production. Picotest describes the design as a distributed electromagnetic structure rather than a conventional lumped resistor, where the physical construction of the device is a critical component of its performance. They say the unique footprint and novel construction method enables insertion inductance in the ones or tens of picohenries, resulting in bandwidths of several hundred MHz to 1 GHz, without compensation. At the time of writing, detailed

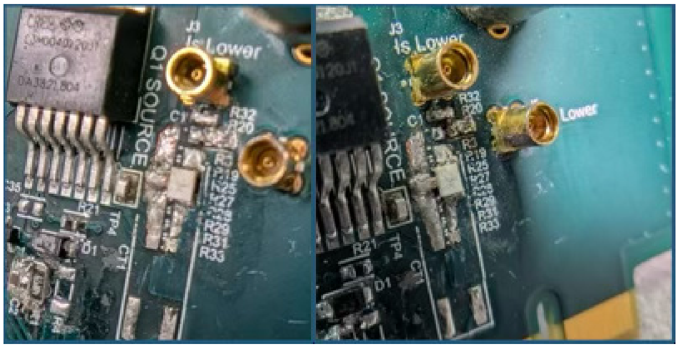


**Figure 15**. Prototypes of Picotest low-inductance shunts.

catalog information such as specific resistance values, power ratings, and production part options has not yet been broadly published, so these devices are best viewed as an emerging alternative in applications where minimizing measurement disturbance is especially important.

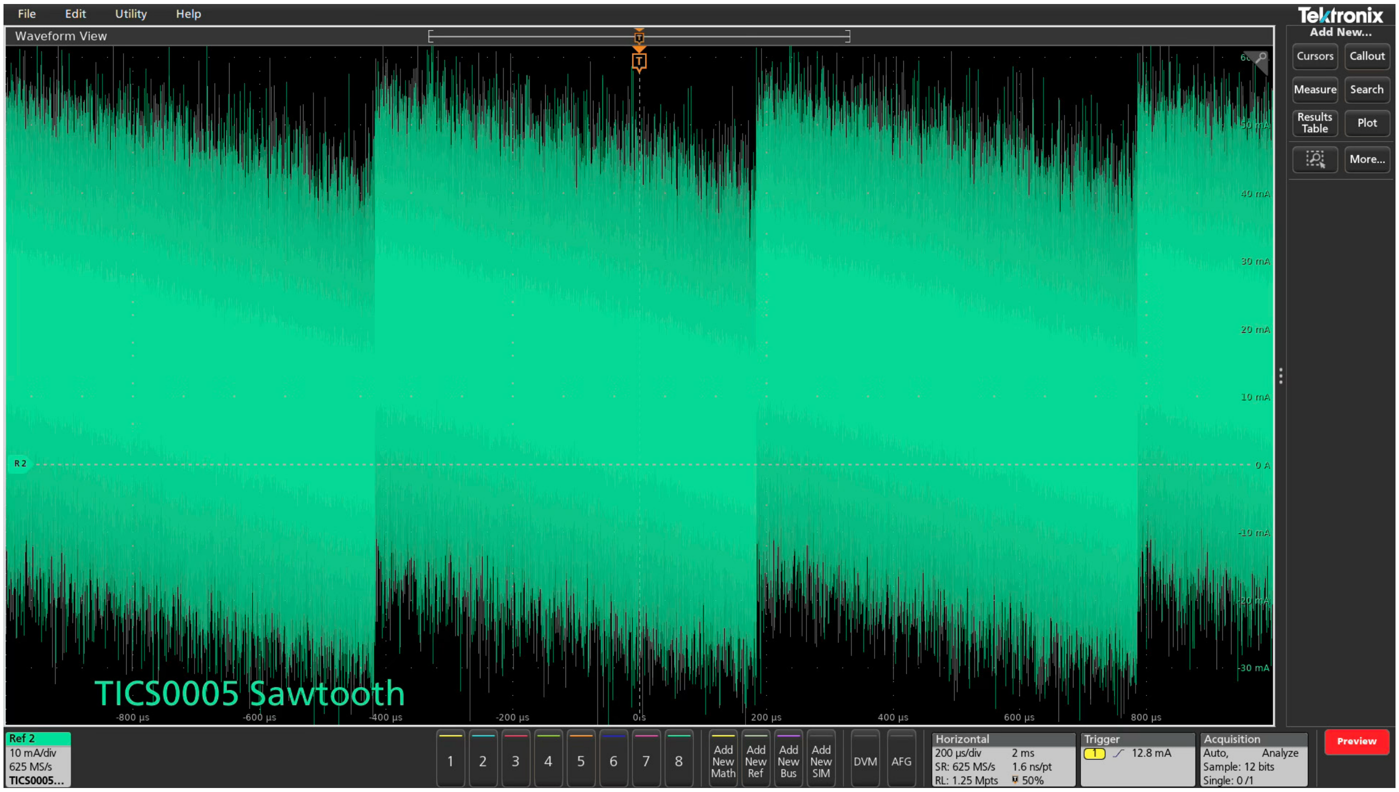
## Example application

### Measuring a current waveform from 0 to 20 mA with better than 78 µA resolution

Current is sourced from an IC generating a sawtooth output current waveform. The current steps to 20 mA and ramps back to 0 mA through 256 discrete levels: 78.1 µA per step. To monitor the transitions of this waveform, a measurement system with a noise floor below 78 µA and dynamic range of 20 mA is needed (greater than 48 dB dynamic range). Burden voltage is not a concern on this current-source IC.

A 5 mΩ shunt at 250 MHz has a noise floor of 15 mA, which is low enough to see that a 20 mA ramp *exists* but details about the curve are obscured. TICP operates in its most sensitive, ±20 mV range with 4.7 nV/√Hz NSD.

$$I_{NoiseFloor\,5\,m\Omega\,TICS} = \frac{NSD \cdot \sqrt{Bandwidth}}{R_{shunt}} = \frac{4.7\,nV/\sqrt{Hz} \cdot \sqrt{250\,MHz}}{5\,m\Omega} = 15\,mA\,RMS$$



Ref 2
10 mA/div
625 MS/s
TICS0005...

Horizontal
200 µs/div 2 ms
SR: 625 MS/s 1.6 ns/pt
RL: 1.25 Mpts 50%

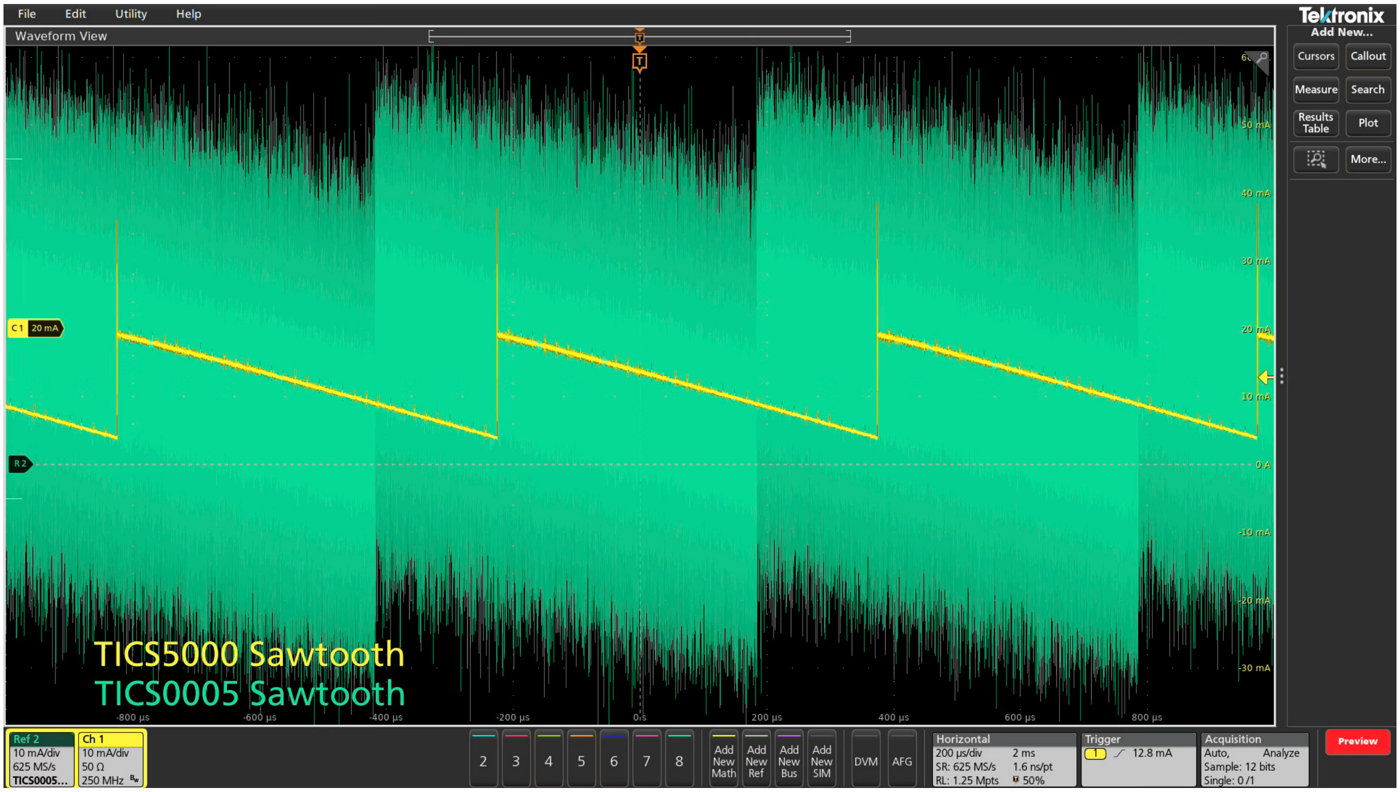
Trigger
1 12.8 mA

Acquisition
Auto, Analyze
Sample: 12 bits
Single: 0 /1

**Figure 16**. When using a 5 mΩ shunt, a 20 mA sawtooth waveform is visible through the 15 mA noise floor, but details are obscured. For this 5 mΩ shunt, the burden voltage at 20 mA would be 100 µV.

Stepping up to the 5 Ω TICS5000 with the same bandwidth lowers the noise significantly, even with the increase in NSD due to the wider ±125 mV range. The higher input range has higher noise than the more sensitive ranges but the greatly increased signal amplitude more than compensates for the slightly increased probe noise contribution.

$$I_{NoiseFloor\,5\,\Omega\,TICS} = \frac{8.7\ nV/\sqrt{Hz} \cdot \sqrt{250\ MHz}}{5\ \Omega} = 28\ \mu A\ RMS$$



Ref 2: 10 mA/div, 625 MS/s, TICS0005...

Ch 1: 10 mA/div, 50 Ω, 250 MHz

Horizontal: 200 µs/div, 2 ms, SR: 625 MS/s, 1.6 ns/pt, RL: 1.25 Mpts, 50%

Trigger: 1, 12.8 mA

Acquisition: Auto, Analyze, Sample: 12 bits, Single: 0 /1

**Figure 17**. Noise is significantly reduced with the 5 Ω Wideband Shunt on Channel 1, revealing resonances and other details about the DUT's performance. For this 5 Ω shunt, the burden voltage at 20 mA would be 100 mV.

## Conclusion

Selecting the appropriate shunt resistor for high bandwidth current measurements requires careful consideration of multiple factors including current range, power dissipation, resistance value, form factor, bandwidth limitations, and test point implementation. The selection process involves balancing competing requirements to achieve optimal performance for the specific application.

Key takeaways:

- Current range and dynamic range requirements drive initial selection criteria
- Power dissipation limits constrain resistance value selection
- Form factor selection affects bandwidth, power handling, and cost
- Parasitic inductance limits bandwidth, affects the DUT, and may require compensation
- Test point implementation strategy affects measurement accuracy and repeatability

## References

1. IsoVu Isolated Current Probes product page; https://www.tek.com/en/products/oscilloscopes/oscilloscope-probes/isovu-isolated-current-probes
2. PMK Ultra-Fast Current Shunt UFCS product page; https://www.pmk.de/en/ufcs
3. T&M Research Current Viewing Resistor product page; https://www.tandmresearch.com/index.php?page=products
4. Sandler, Steven "Making Sense of Two-Wire Current-Sense Resistors"; https://www.picotest.com/insights/july-2012-how2power-making-sense-of-two-wire-current-sense-resistors/; originally published in *How2Power Today*, July 2012

## Glossary

These terms may be encountered during shunt selection. These are general definitions and specific qualifications may be applied, depending upon the manufacturer.

**Bandwidth (or bandpass):** A range of signal frequencies. Unless otherwise indicated, oscilloscope-based system bandwidth is specified from DC to an upper frequency at which the signal amplitude changes by 3 dB. For shunt resistors the upper frequency is defined by a +3 dB increase in voltage, due to inductive reactance.

**Burden voltage:** The voltage drop across a shunt resistor, proportional to current. Usually determined as a worst-case value at maximum current.

**Continuous power rating:** The maximum steadystate power a shunt resistor can dissipate without damage, specified as average power in watts at a specified temperature or temperature range.

**Current rating, thermal derating:** The reduction in a shunt resistor's maximum allowable continuous power dissipation as ambient temperature rises. This may be shown in shunt datasheets as a derating curve plotting maximum power versus temperature.

**Current sense resistor:** A resistor optimized for in-circuit current measurements, practically synonymous with "shunt resistor".

**Current viewing resistor (CVR):** A shunt-style resistor optimized for dynamic measurement and simulation models; often used in test and prototyping contexts.

**DC gain accuracy:** The specified maximum deviation of measured DC amplitude from the ideal value, accounting for gain (slope) error, verified using precision DC reference measurements.

**DC offset or offset current:** A DC current added to an AC signal. It shifts the waveform up or down relative to a 0 A reference.

**Insertion Inductance:** The effective inductance added to a circuit when a shunt is placed in series with the current path, measured in Henries. It represents the total inductive contribution of the resistor element and its physical current loop. It limits the risetime accuracy and high frequency performance of current measurements.

**Kelvin connection:** A 4-wire connection approach for measuring resistance or impedance in which separate conductors are used to inject current and measure voltage. This reduces the effect of lead resistance or inductance on the measurement.

**Maximum current:** Maximum continuous current in Amps RMS for shunt to maintain performance including any derating for temperature, if applicable. Exceeding this current also risks permanent damage to the shunt.

**Maximum pulse current:** Maximum current for a shunt as a function of pulse width, usually specified as a plot of peak current versus on-time. The maximum suitable current declines as pulse width increases.

**Maximum voltage:** This voltage reflects an absolute maximum voltage across a resistor, above which damage to the resistor is likely.

**MMCX Connector:** Micro-Miniature Coaxial connector (MMCX) is a small, 50 Ω, RF precision connector with snap-on coupling and 360-degree rotation.

**Noise Floor:** The minimum measurable voltage or current level set by the measurement system's intrinsic noise, specified for a frequency range (bandwidth) below which a measurement system cannot distinguish signal from noise. Typically measured in $V_{RMS}$ or $A_{RMS}$ for shunt-based measurements.

**NSD:** Noise Spectral Density, or more specifically voltage noise spectral density, captures the fact that noise increases with bandwidth and specifies the amount of RMS voltage noise in a signal per square root Hertz.

**Operating Temperature Range:** Range of temperatures over which a shunt is expected to meet its specified electrical performance.

**Power coefficient:** Change in resistance per watt of power dissipation, typically in ppm/W.

**Pulse energy capacity:** A specification that gives the maximum pulsed energy, in joules, that can be dissipated by a shunt resistor, where $E_{max} = R \cdot \int i^2(t)dt$.

**Self-heating:** The temperature increase of a resistor due to the power it dissipates internally, typically expressed in terms of thermal resistance, or temperature rise per watt (°C/W).

**Temperature Coefficient (Tcr):** The effect of temperature on resistance, in ohms or ppm per degree C. For resistors this is a positive value, that is, increasing temperature increases resistance. A low temperature coefficient is usually desirable for shunt resistors.

**Thermal Resistance:** A measure of a resistor's temperature rise per watt of power dissipation (°C/W).

**Tolerance:** Uncertainty of a shunt's resistance as a percentage of nominal, at a specified temperature.

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