



Calibrating DC Current Shunts: Techniques and Uncertainties

Author: Jay Klevens
Ohm-Labs, Inc.
611 E. Carson St., Pittsburgh, PA 15203
(412)431-0640 jklevens@ohm-labs.com

Abstract:

The base SI unit for electricity is the Ampere. There is no intrinsic standard for the Ampere, so in practice the Ampere is realized by measuring voltage across a current shunt, using Ohm's Law ($I=E/R$). Accurate electrical current measurement is critical to the power and electrical test industries.

In cooperation with the NCSLI Utilities Committee, Ohm-Labs performed a North American 100 Ampere inter-laboratory comparison (ILC). The results revealed common errors in current measurement and uncertainty budgeting. Based on these results, suggestions for improved measurement and uncertainty budgeting are presented.

The author wishes to thank NIST for performing the opening and closing measurements, NCSLI for support of this ILC, and all the participants for their time and contributions.

In a recent inter-laboratory comparison (North American 100 Ampere ILC), many participants did not meet their claimed accuracy when measuring common metrology-type current shunts at the 100 ampere level. This indicates that despite a century of practice, numerous publications, and state-of-the-art equipment, 'best practice' methods for accurate current measurement and uncertainty estimation appear to be lacking.

The base Standard International (SI) unit for electricity is the Ampere, which is defined as the attractive force between two parallel conductors of negligible cross section. In 1820, Andre-Marie Ampère presented a paper and a demonstration of this electrodynamic phenomenon, and to date, the best representation of the Ampere is with a Watt Balance, identical in principal to M. Ampère's 1820 demonstration model. Work is underway to redefine the Ampere by relating it to fundamental physical constants (as has been done with several other SI units), by counting electrons through a conductor. A report is due in 2015.

Until a new definition of the Ampere is accepted, the Ampere is in the awkward position of being derived, in practice, from its own derived units, the Ohm and the Volt. There are intrinsic standards for the Ohm (the Quantum Hall resistor) and the Volt (the Josephson Junction array), which have led to wide dissemination of highly accurate resistance and voltage measurement. Practical current measurement is derived from resistance and voltage measurements, using Ohm's law: $I=E/R$. If the resistance and voltage are known, the current can be calculated. This method is the same whether using a shunt resistor internal to a meter, comparing two shunts with two meters, or comparing the voltage drop across a shunt and a resistance standard with a current comparator bridge system.

A current comparator bridge with a range extender may give uncertainty as low as a few parts per million. A lab using such a system can pass a rigorous audit claiming (to use one commercial lab's example) 1.1 ppm uncertainty at the ILC artifact's nominal values of 0.01 and 0.001 ohm.

The comparison calibration method uses a calibrated standard shunt in series with a shunt under test. The calibrated standard shunt may have an uncertainty of 0.05 % (500 ppm) or less if properly characterized. If used to calibrate metering shunts, with accuracies to 0.1 %, this is a good method, and does not require a costly, specialized system. Two calibrated voltmeters simultaneously monitor both shunt outputs; the ratio is used to assign a value to the shunt under test.

Both methods require appropriate care to avoid errors described below. For reference, figure 1 shows a properly assembled shunt comparison system.

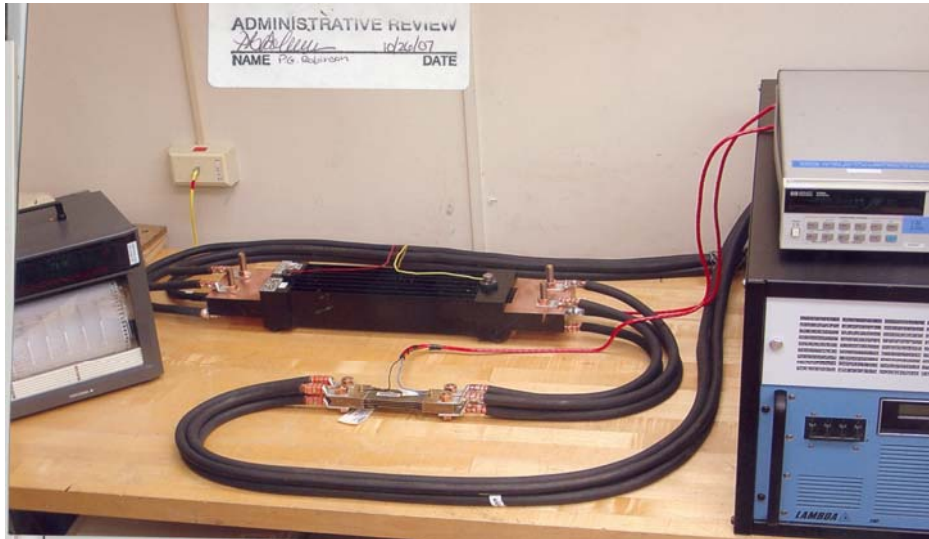


Figure 1

In 2000, Dr. D. W. Braudaway published a paper titled 'The Problem With Shunts.' The problem with accurate shunt measurement lies in the shunts themselves. Using a measurement system with very low systematic (type B) uncertainty, it is possible, perhaps tempting, to underestimate the type A uncertainty contribution of the shunt under test. A lab's motivation is often to perform and report its best measurements.

The problem with shunts is fivefold:

- 1) Connection errors
- 2) Temperature errors
- 3) Frequency errors
- 4) Drift over time
- 5) Thermal emf errors

Most modern metrology-grade shunt manufacturers are aware of these problems and have attempted to design them out of their products. The prevalence of older shunts in use, such as the artifacts in the ILC, or, more widely, in common low cost metering shunts, suggests that these five problems need to be better understood and addressed.

Connection errors are due to shunts being four-wire resistors. Figure 2 shows a current circuit which includes the resistance of the cables, the resistance of the connections, and the resistance of the shunt. The potential (voltage or sense) measurement points are somewhere along this current path.

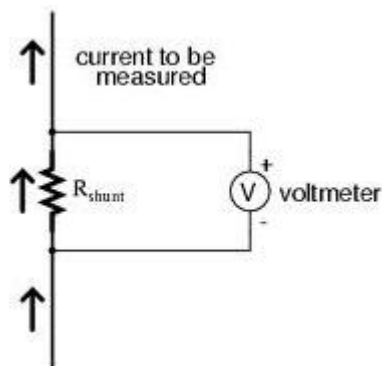


Figure 2

Figure 3 shows that if the potential connections are moved outwards towards the current cables, the system will measure a higher resistance. If moved inwards towards the center of the shunt, it will measure lower resistance.

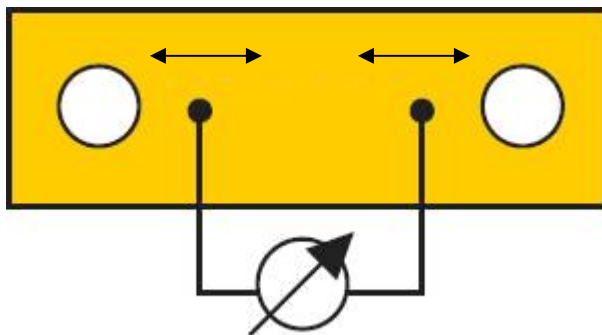


Figure 3

To account for this error, any shunt with potential connections on the current blocks (such as metering shunts) should be measured several times with potential wires connected at different spots under the screws, for example, under the inner edges, under the outer edges and wrapped around the screw. The standard deviation of these three measurements should be included in the type A uncertainty. If the lab does not know or reproduce the potential connection of a metering type shunt in service, an estimation of 100 ppm (0.01 %) may be added to the Type A uncertainty.

Permanently affixing potential lead wires to a metering type shunt, and connecting only to these lead wires during use and calibration, will reduce potential connection errors.

Figure 4 shows the current connection point on a common older shunt. Many modern metrology-grade shunts have current equalizing bus bars built into them, but as with metering shunts, this older type of shunt is subject to current connection errors. Different current connections affect the distribution of current flow through the shunt. Cleanliness of the connection, torque on the bolt, position of the cable, and cable diameter all cause errors.



Figure 4

A large error will result from connecting to the top of the posts, instead of through the holes. A pair of precision machined copper posts which closely fill the connection holes in this type of shunt can minimize current connection errors. The posts should be threaded for bolt connection of cables terminated in lugs.

Changing the orientation (in-line or at right angles) of current connections affects the current distribution through the shunt, and thus the resistance. The cleanliness and integrity (the surface resistivity) of the connection also affects the resistance. The balance of multiple hole shunt connections affects the resistance. Figure 5 shows a metering type shunt highly susceptible to current and potential connection errors.



Figure 5

In general, always clean the current connection surfaces. Connect cables in line with the shunt. For multiple hole shunts, always connect lugs to both sides and use all holes. Evenly and securely torque the bolts. Silicon bronze bolts are better for shunts with copper bus bar connections, as silicon bronze has closer electrical and thermal expansion properties to copper than stainless or mild steel. For L&N type shunts with a hole in the current post, use a copper bar which snugly fills the hole, extend the bar an inch from the post. Thread the end to affix cable lugs using silicon bronze bolts. Insure that the bolts and the shunt's wing nuts are tightened to a torque of 20-30 NM (15-20 foot-pounds).

As with potential connections, current connection errors can be reduced in metering type and horseshoe shaped shunts by permanently affixing current leads. These leads should be used both in calibration and in service.

If the current connection method of a shunt is not known by a calibration lab, a further estimation of 100 ppm (0.01 %) may be added to the Type A uncertainty.

The second source of error is temperature. Manganin, a copper-manganese alloy developed in 1889 in Germany, has a relatively high temperature dependence among modern resistance alloys. Virtually all shunts with exposed blades are made with Manganin; shunts with exposed parallel wires are made with Zeranin, a relative of Manganin with a lower temperature coefficient; shunts enclosed in heat sinks are generally made with Evanohm, which has a near-zero temperature coefficient but high sensitivity to strain (hence the rigid housing).

The resistance of shunt Manganin rises about 20 ppm (0.002 %) per degree C around lab ambient. Applying current causes self-heating, which changes resistance. This change is not linear. Some shunts rise to a maximum resistance at a certain current / temperature level, then fall as temperature continues to rise.

Figure 6 shows the change in temperature (X axis) and resistance (Y axis) of a shunt measured at 10 amp increments up to 100 Amps. This is a 'near ideal' shunt of its era, exhibiting a peak at about the one-half power level of 67 Amps.

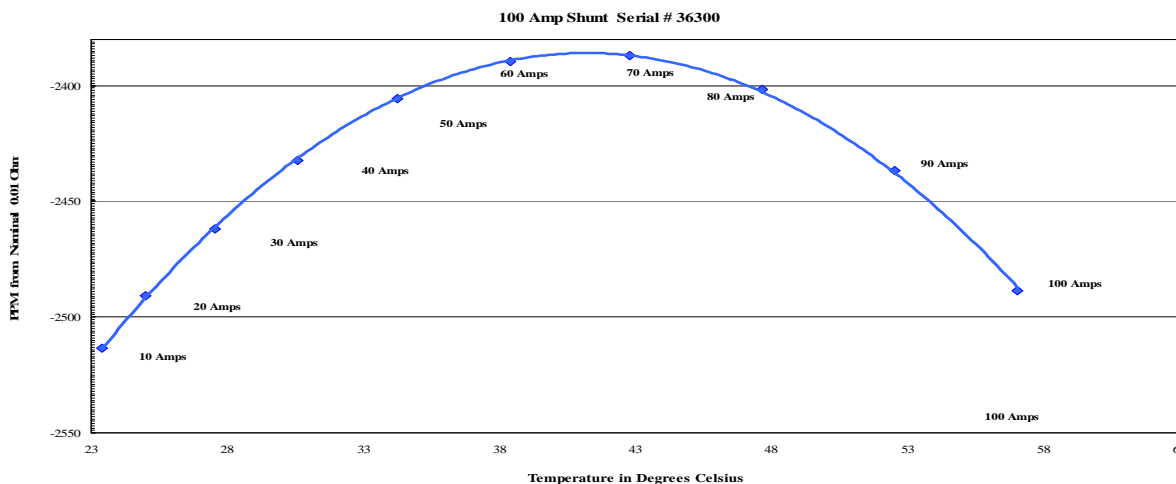


Figure 6

Because of changes caused by self-heating, failing to calibrate a shunt through its full current is failing to calibrate it.

Unless a complete temperature and current characterization has been performed on a shunt, a low current measurement of the shunt is practically useless if the shunt is used at any other current.

Like snowflakes, no two shunts are identical; each has a unique temperature curve. Although the base resistance may drift over time, the temperature curve generally will not change. Temperature characterization of a shunt is similar to current characterization, as both relate to heat. A temperature sensor (thermocouple, RTD or thermistor) at the center of the shunt will show where the shunt is on its temperature curve. Both artifacts provided by NIST included type T thermocouples. Most ILC participants did not use them, but without access to the prior temperature characterization of the shunts, the data would have been of little use.

If the temperature characterization of a shunt is known, its resistance can be closely approximated on a temperature / resistance chart. Some metrology shunts are supplied with a temperature sensor and include this characterization. NIST and qualified commercial labs can provide this calibration service on request. However, this testing is time consuming, and due to the expense is not generally performed.

A shunt must stabilize at each temperature / current level. The thermal mass of a shunt includes its resistance element, its end blocks, the current cable lugs and connection hardware, and the cables themselves. At higher current levels, a shunt may require more than an hour to reach thermal equilibrium. This is when measurement should begin.

Figure 7 shows a typical stabilization curve for a 100 Amp shunt – after 45 minutes, the shunt is fairly stable.

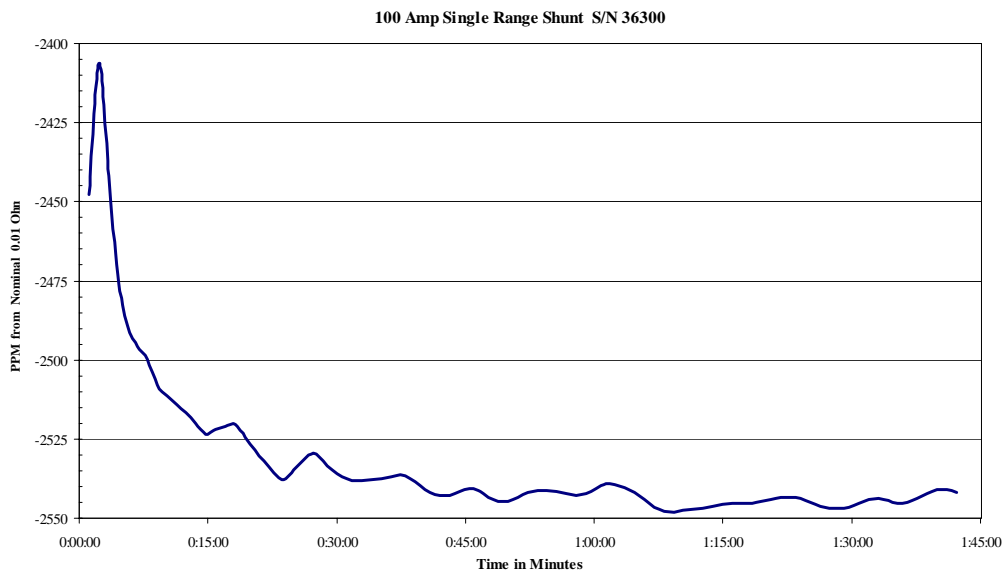


Figure 7

One cautionary note: many metering type shunts should not be used above 2/3 rated current. Their design dates to the era of moving coil meters with best accuracy at mid scale. Most metrology shunts are designed for use up to continuous full current, but excessive current on any shunt can overheat and permanently shift its value.

To estimate type A uncertainty for temperature, a minimum of 20 ppm (0.002 %) per degree Centigrade should be added. For example, if a lab claims +/- 2 °C temperature stability, an estimation of 80 ppm (0.008 %) may be added to the Type A uncertainty.

A third source of error is from frequency. All shunts have inductive and capacitive components which causes them not to be 'pure' resistors at higher frequencies. For this ILC, only dc measurements were made, but for dc / low frequency, a few notes can be offered.

Figure 8 shows ac coupling between current and potential circuits. Coupling can be reduced by connecting current leads in line with the shunt and routing potential leads together into a shielded, twisted pair extending at right angles from the shunt (green, not red).

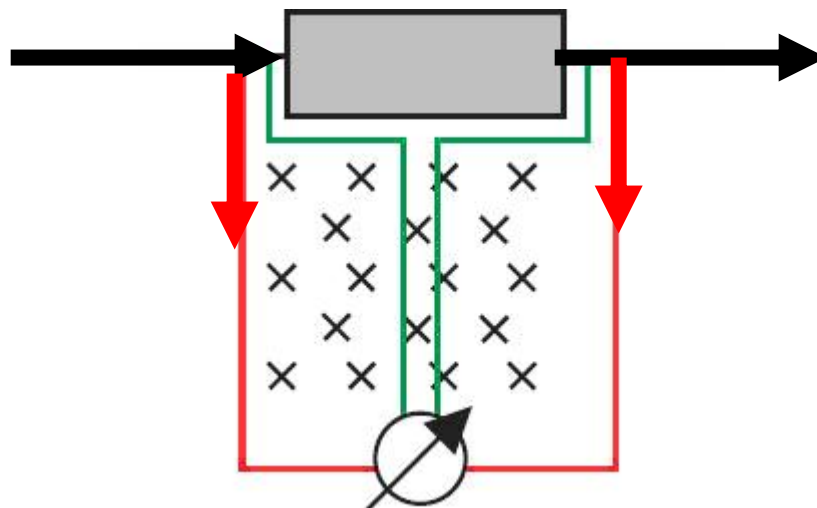


Figure 8

Generally, at low frequency (50/60 Hz), the ac/dc difference of any shunt is below the uncertainty of state-of-the-art ac/dc difference measurements, so if correct lead wire routing is observed, accurate mains frequency measurements may be performed using dc calibrated values.

A fourth source of error is drift over time. All resistors change over time. Shunts, due to elevated operating temperatures, can be especially subject to drift. Beyond normal drift over time, larger shunts may suffer transport damage due to mechanical degradation of the joint between the blades and the current blocks. As with other standards, it is important to check a shunt's value before and after transport.

The fifth source of error is caused by parasitic thermal emf in the circuit. Joining two dissimilar metals creates a thermocouple. A thermocouple generates an electromotive force (emf) proportional to the heat difference between the junction and the measuring terminals. A copper potential wire connected to a brass shunt block with a steel screw is a complex thermocouple. The thermocouple voltage adds to the voltage measured across the shunt. Reversing the current flow reverses this effect, so it may be measured and arithmetically cancelled. A current comparator bridge uses a switch to periodically reverse the current flow, allowing this effect to be cancelled during measurement.

In the direct shunt comparison method, one or both shunts may give readings offset by a thermal emf. Repeating the test with current reversed, given identical temperature and connection conditions, will show an equal and opposite offset, which can be used to cancel the error. However, if the shunt under test is placed into service measuring dc current, the error should be accounted for and reported.

Accurate current measurement requires properly characterized precision current shunts. Characterizing shunts with low uncertainty requires that the shunt owner understand the chief sources of error and how to assign uncertainty components to those errors. Accounting for connection, temperature, frequency, drift and thermal emf effects is crucial to obtaining valid measurement results, both in the use and the calibration of shunts.

Citations

- 1) D. W. Braudaway, 'The Problem With Shunts,' (publication history unclear).
- 2) M. Kraft, 'Measurement Techniques of Low-Value High-Current Single-Range Current Shunts from 15 Amps to 3000 Amps,' Measure Magazine, V. 2, No. 1, March 2007.
- 3) R. E. Elmquist, D. G. Jarrett, G. R. Jones, M. E. Kraft, S. H. Shields, and R. F. Dziuba, 'NIST Measurement Service for DC Standard Resistors,' NIST Technical Note 1458, January 2004.
- 4) R. E. Elmquist et. al. 'The Ampere and Electrical Standards,' Journal of Research of the National Institute of Standards and Technology, V. 106, No. 1, February 2001