Calibrating DC Shunts:

Techniques and Uncertainties

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***Abstract* — Accurate electrical current measurement is critical to the power and electrical test industries. A recent North American 100 Ampere Inter-Laboratory Comparison (ILC) revealed errors in current shunt measurement and uncertainty budgeting. Based on the ILC results, suggestions for improved measurement and uncertainty budgeting are presented.**

***Index Terms* — Current Shunt, Shunt Calibration, Current Measurement**

I. INTRODUCTION

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, similar 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).

Until a new definition of the ampere is accepted, the ampere is in practice derived 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 measurements.

Practical current measurement uses Ohm's law: I=E/R. If resistance and voltage are known, current can be calculated. A multimeter has an internal shunt and measures voltage to display current. Higher current measurements use external shunts, such as those used in the ILC. These shunts are common in labs, and are often treated as resistance standards, subject to the same measurement methods, uncertainty budgets and calibration controls. However, unlike most resistance standards, shunts are often not properly measured, so a lab's data and history may be suspect.

These shunts were manufactured when 400 μΩ/Ω was near state of the art. A 20 μΩ/Ω error would have been considered negligible at that time, and the original OEM manuals make no mention of error sources which easily overwhelm uncertainty budgets based on mofsdern equipment.

Figure 1. Typical 100 amp lab shunt

II. Measurement Techniques

Shunts are measured by comparison, either with a resistance standard using a current comparator bridge, or with a calibrated standard shunt.

A current comparator bridge compares current passed through a shunt with current passed through a resistance standard. This system can achieve measurement uncertainties down to the μΩ/Ω (ppm) level. The high system (type B) accuracy of modern measurement systems can sometimes cause users to underestimate error sources (type A uncertainty) in the shunt under test.

A shunt comparison system connects a calibrated standard shunt in series with a shunt under test. Current is passed through both shunts simultaneously. The voltage output of the standard shunt is compared with the voltage output of the shunt under test. The uncertainty is higher due to the calibration uncertainty of the standard shunt. Figure 2 illustrates a well designed dc shunt comparison system. Such a system has a significantly lower cost than a current comparator bridge system.

Shunt calibration uncertainty budgets consist of type B components, which are under the lab's control, combined with type A components unique to the unit under test at the time of test.

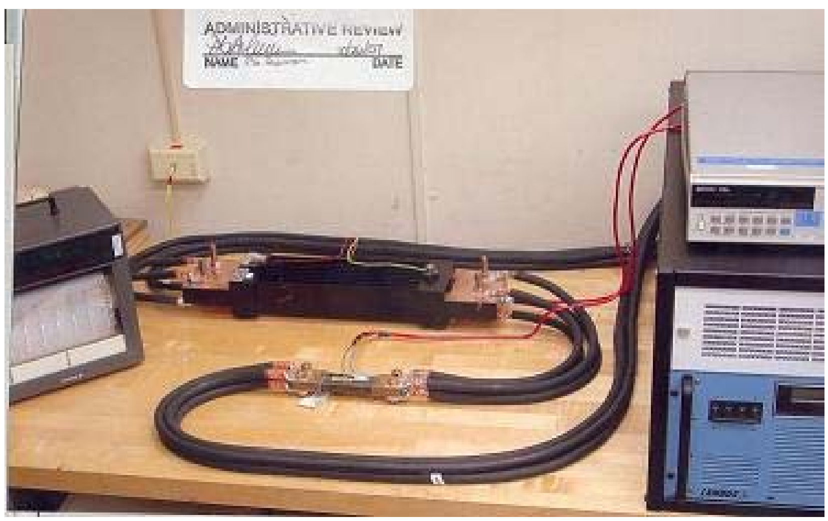

Figure 2. Shunt comparison system – note proper lead wire connection and orientation

III. Error Sources

The five error sources inherent to current shunts are:

1) Connection
2) Temperature
3) Frequency
4) Drift
5) Thermal emf

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 lab shunts in use, or more widely used metering type shunts, suggests that these five error sources need to be understood and addressed by the calibration lab.

Connection errors are due to shunts being four wire resistors. Current is passed through the resistor via the current connection points; voltage is measured at the potential points. As illustrated in figure 3, moving the potential points towards the center of the shunt lowers the measured resistance; moving them towards the ends increases the measured resistance.

Changing the position or torque of the current connections changes the distribution of current through the shunt element, changing the measured resistance.

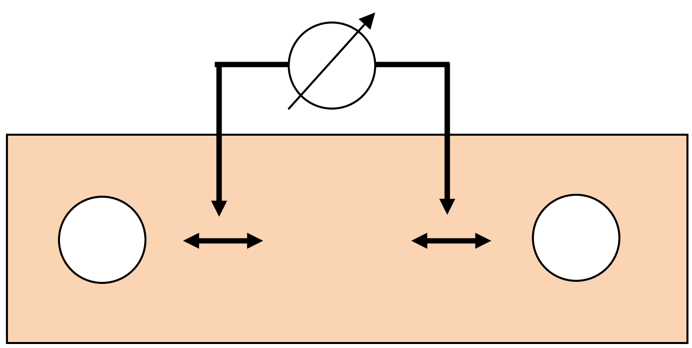

Figure 3. Four wire connection errors

Figure 4 shows a shunt susceptible to large connection errors. Significantly different measurements will be obtained by connecting current cable lugs to surface points A or C, or to both; through holes B or D or both; and both the diameter of the current cable and the torque of the current cable clamping screws will affect the measured value.

The connection error alone on this shunt is approximately 0.117 %, or 1170 μΩ/Ω. If this shunt were sent to a commercial lab for calibration, it might be returned reporting a claimed uncertainty of 10 or 20 μΩ/Ω. The calibration would have been done 'properly,' but the results would be valid only if the user carefully duplicated the lab's connection and torque scheme.

The L&N shunt in figure 1 is susceptible to errors caused by the diameter of the current cable, the torque of the clamping screw, and whether current cables are connected to the tops of the posts or through the holes.

Dirt, oxidation or surface unevenness will also cause connection errors by affecting the distribution of current through the shunt. It is helpful to clean the current connection surfaces with an abrasive pad prior to measurement.

Figure 4. A shunt with connection errors of 0.117 % (1170 ppm)

Temperature errors are caused by the heating of a shunt under power and by ambient temperature variations. All metals change resistance with temperature. Most old (and many new) shunts use a copper-manganese alloy called Manganin, which typically has a temperature coefficient of resistance (TCR) of about 20 μΩ/Ω/°C, or about 0.002 % per degree. For a typical lab shunt of the type illustrated in figure 1, a 5 °C difference between the lab and the location in use will cause an error of approximately 100 μΩ/Ω, or 0.01 %.

A shunt's TCR is not linear. Measurements at low currents will not predict the resistance at higher currents. Failing to calibrate a shunt through its full useable current range is failing to calibrate it.

The shunt will continue to change resistance until it reaches thermal equilibrium at the applied current. For large, high current shunts, this can take over an hour. Only at this point should measurements begin.

Heat distribution in a shunt also affects its resistance. Smaller gage cables and lugs can add heat to the current measurement connection points. Larger gage cables and lugs can act as heat sinks, lowering the temperature at the current connection points. Thermal uniformity errors are difficult to evaluate without thermal imaging equipment or a series of temperature sensors along the shunt element. These errors are also impractical to duplicate from one lab to another.

Heat from power or heat from an oven produce similar resistance changes. Bonding a temperature sensor to the shunt element and performing a current / temperature characterization can generate a table of corrections. This correction may be applied at a given temperature, reducing uncertainty.

Some shunts under full power reach a temperature above 120 °C. Excess current can overheat a shunt, causing an unpredictable and permanent shift in its resistance. For this reason, metering type shunts are recommended for use below 2/3 rated current. Most metrology type shunts are rated for full current.

Frequency errors are caused by inductive components of the shunt. At line frequencies of 50 or 60 Hz, these errors can be minimized by arranging the current cables in line with the shunt, and by arranging the potential wires into a twisted pair extending at right angles from the shunt (as shown in figure 3). The ac/dc resistance difference of a properly connected shunt at line frequency is less than the measurement uncertainty of ac/dc difference measuring systems, so the dc resistance may be used with reasonable assurance.

Higher frequency current measurement requires specially designed ac shunts, which are beyond the scope of this article.

Drift errors are caused by the long term drift of the resistance of a shunt, or by shifts caused by damage due to handling, shipping or application of excess current. Because of the often elevated temperature of shunts, drift over time can be accelerated. As with all standards, periodic recalibration can establish long term drift.

As with all standards, measuring before and after recalibration can reveal shifts caused by transport, mishandling or other damage.

Thermal emf errors are caused by thermocouple effects in the potential junctions of shunts. At higher temperatures, this effect becomes stronger. Thermal emf errors may be canceled by reversing the current flow and averaging the forward and reverse measurements.

IV. Shunt Calibration Uncertainty Budgets

Uncertainty budgets for shunt calibration can be developed by combining the root sum square (or more conservatively by addition) of the type B components built in to the system, and the type A components unique to the test.

For a current comparator system, the main type B components are:

1) Uncertainty of the resistance standard (including temperature, drift, etc.)
2) Uncertainty of the current comparator bridge
3) Uncertainty of the bridge range extender

For a shunt comparison system, the main type B components are:

1) Uncertainty of the standard shunt (including temperature, drift, etc.)
2) Uncertainty of the standard shunt voltmeter
3) Uncertainty of the shunt under test voltmeter

Type A uncertainties are variable and largely dependent on the design and type of shunt. Common sources of error can be stated on the report and estimated in the budget, including:

1) Position, orientation, torque and type of current connections
2) Location and type of potential connections
3) Temperature of shunt element (for Manganin shunts, a 20 μΩ/Ω estimate may be added for every 1 °C of claimed lab stability and uniformity)
4) The standard deviation of the repeatability of separate tests on separate days, with deliberate connection variations

V. Conclusion

In 2000, Dr. D. W. Braudaway published a paper tilted 'The Problem With Shunts.' The problem with shunts often resides in the shunts themselves. Connection, temperature, frequency, drift and thermal emf errors in shunts are common, particularly in older lab and metering type shunts. Understanding and accounting for these errors can improve the accuracy of shunt measurement and can assist in developing realistic uncertainty budgets.

References

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VI. Addendum

The following checklist may be helpful to labs calibrating shunts:

1) Current connections
   a. Location
   b. Orientation
   c. Lug or connector size
   d. Torque
   e. Cleanliness / surface condition
2) Potential connection points
   a. Location
   b. Orientation
   c. Connector or wire type
3) Temperature
   a. Lab temperature stability & uniformity
   b. Full stabilization at applied current
   c. Temperature of shunt element (if supplied with sensor)
4) Frequency (or electromagnetic coupling in dc shunts)
   a. Current lead wire layout
   b. Potential lead wire layout
5) Thermal emf
   a. Reversals performed
   b. Forward and reverse measurements averaged
6) Repeatability
   a. Separate tests on separate days
   b. Deliberate current and potential connection changes