Measurement Techniques of Low Value High Current Single Range Current Shunts from 15 Amps to 3000 Amps

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Abstract

Standard resistors that are used to measure current and are designed to dissipate relatively high levels of power are known as current shunts. This paper will discuss some of the many different types of single range current shunts in use today, and describe self-heating effects and errors associated with specific current shunt designs.

The importance of the length of time it takes for some shunts to reach both temperature equilibrium and resistance equilibrium will be discussed. Because of the effects of non-uniform temperature distribution, these are not the same length of time for some shunts and may depend on the location of the temperature sensor. Other topics include how errors in measuring current shunts can be reduced by making symmetric, low-resistance connections and considering how the current distribution and the placement of the potential terminals affect the measurement.

1. What is a Current Shunt?

In general, standard resistors are measured at 10 mW or less to reduce self-heating and for quick stabilization of the measurements. The drift characteristics of the resistor are more predictable at low power and the level of uncertainties is reduced significantly. These resistors are generally sealed and if used at 1 W or above, a change in the value and drift characteristics will occur.

Resistors used for higher currents are not sealed but expose the resistive element. This Reichsanstalt design [1,2] was commercialized by the Otto Wolff Company# in Berlin and is preferred for low value (less than 1 Ω) high power (greater than 0.1 W) resistors. It is generally

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known that these resistors should be used in stirred oil to aid in cooling and prevent a permanent change in value, which will occur if used in air at the rated current.

A current shunt is a resistor that is designed to dissipate high levels of power in air. The majority of standard precision shunts were designed to dissipate 90 W to 100 W at full current with a typical 400 μΩ/Ω total change from minimum to maximum current. Figure 1 shows the difference in size and construction of a Reichsanstalt standard resistor rated at 1 W and two ribbon current shunts rated at 100 W, all of which are a nominal value of 10 mΩ The smaller resistor at center is of the NBS-Type design [1,2] shown for size comparison only.

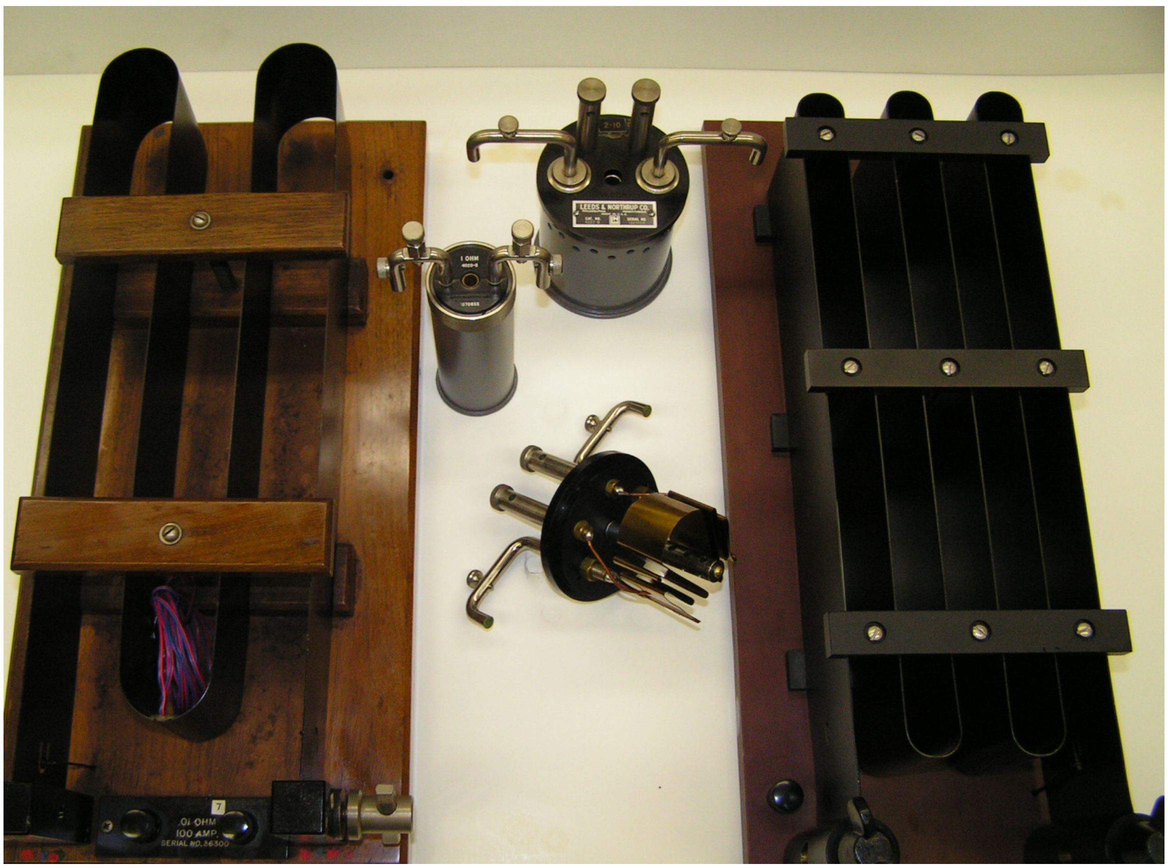

Figure 1. Example of 10 mΩ 100 amp ribbon shunts and 10 mΩ Reichsanstalt resistor element.

2. Construction of Current Shunts

There are basically two different type of construction for precision current shunts as shown in Figure 2. There is the ribbon shunt, which is constructed with a continuous strip of resistive material with one or more folds. The other type is the parallel element shunt, which has several bars of resistive material attached to large copper or brass blocks on each end with the potential terminals closest to the parallel elements. When the heavy current leads are attached to the large blocks they must be connected so that the current will flow evenly through each of the parallel elements.

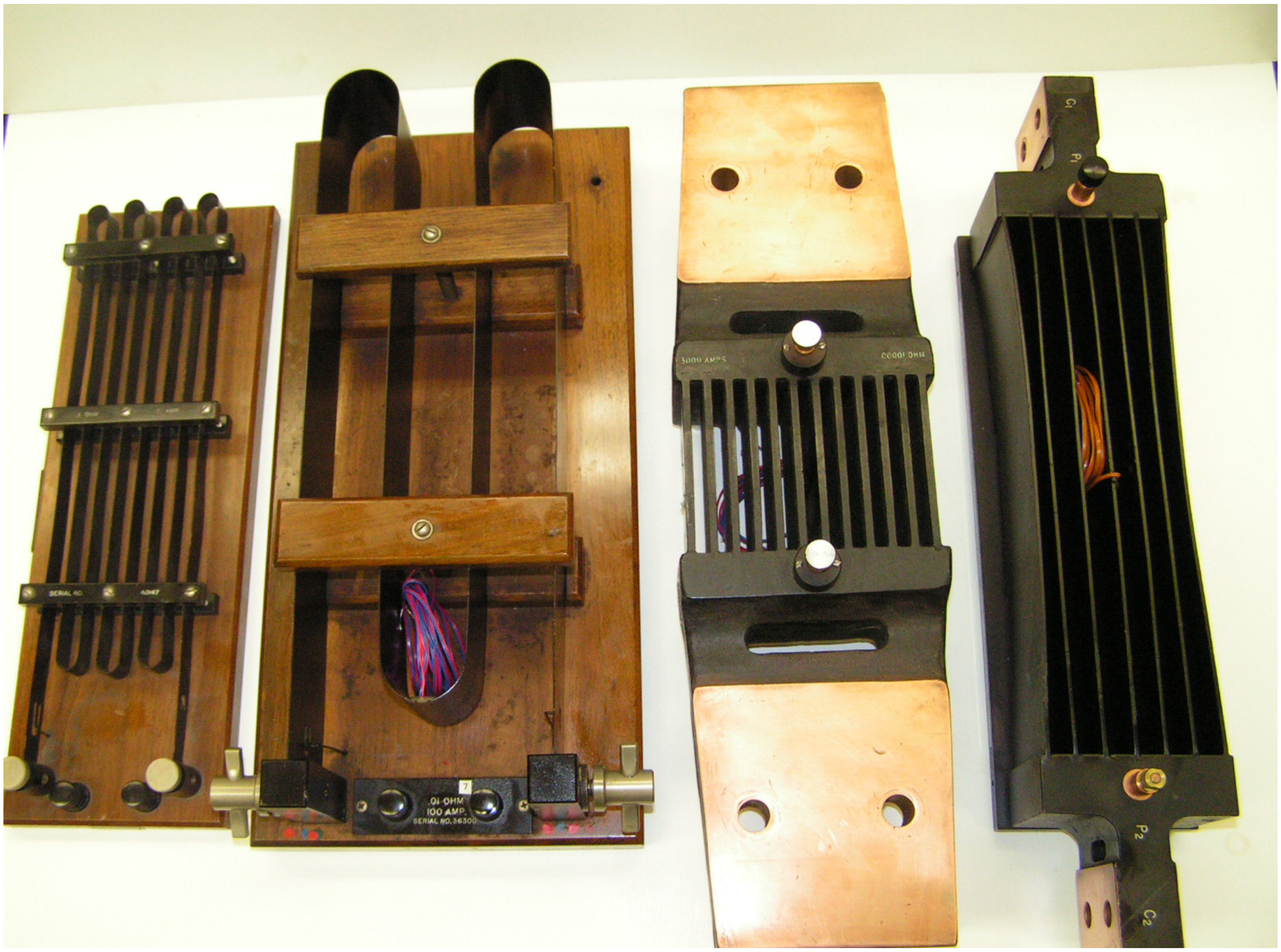

Figure 2. Shown from left to right are a 0.1 Ω / 15 A ribbon shunt, a 0.01 Ω / 100 A ribbon shunt, a 10 μΩ / 3000 A parallel element shunt, and a 100 μΩ / 1000 A parallel element shunt.

The resistance/temperature curve is found by measuring the shunt at several different current levels and plotting the equilibrium points. Equilibrium is obtained when the temperature and resistance of the shunt reach a steady state at the current level being measured. The precision resistance material Manganin [1], an alloy of Copper, Manganese, and Nickel is the material that is used in most high current shunts. Figure 3 shows the Manganin resistance/temperature curve for a 1500 A parallel element shunt. The resistance change at low temperature is about 16 (μΩ/Ω) / °C then decreases before peaking close to 55 °C. Figures 4 and Figure 5 show different behaviors of Manganin current shunts as measured at NIST. Similar behaviors were described in reference 3. Figure 6 shows the resistance/temperature curve of a parallel element shunt of an unknown type of copper alloy. Equilibrium at maximum current occurs at a higher temperature than would be expected of Manganin.

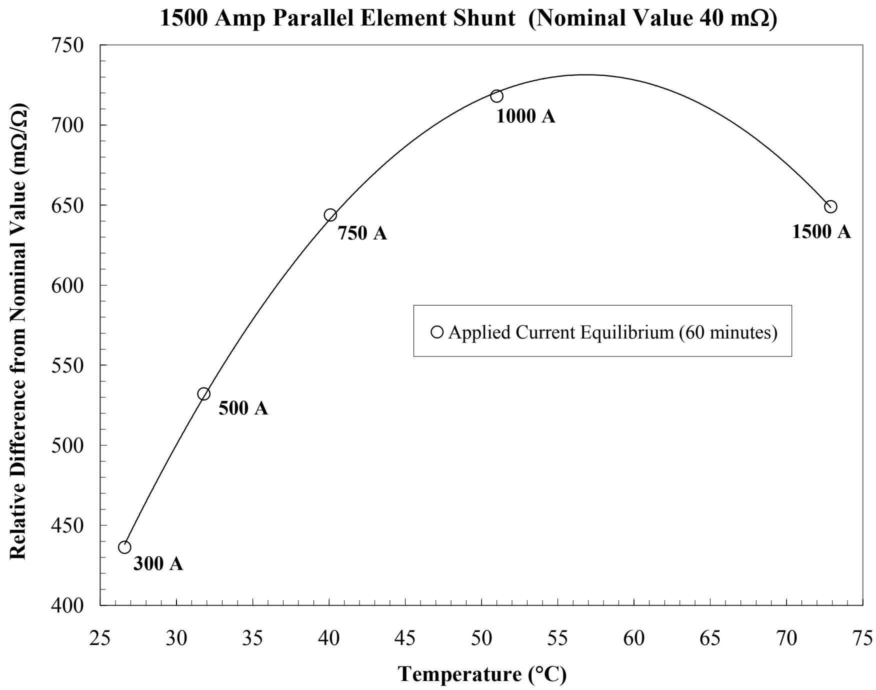

Figure 3. Equilibrium curve for the parallel element Manganin 1500 A shunt shown in Figure 2 (third from the left) shows the resistance/temperature curve peaking around 55 °C. The resistance change is about 16 (μΩ/Ω) / °C at low temperature.

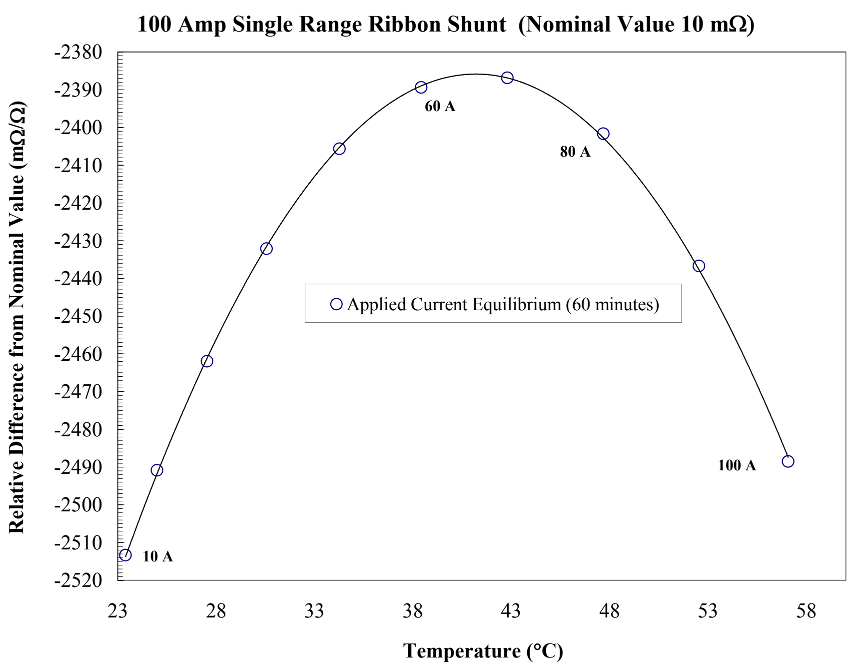

Figure 4. Equilibrium curve for the ribbon type Manganin 100 A shunt shown in Figure 2 (second from the left) shows the resistance/temperature curve peaking around 41 °C. The resistance change is about 11 (μΩ/Ω) / °C at low temperature.

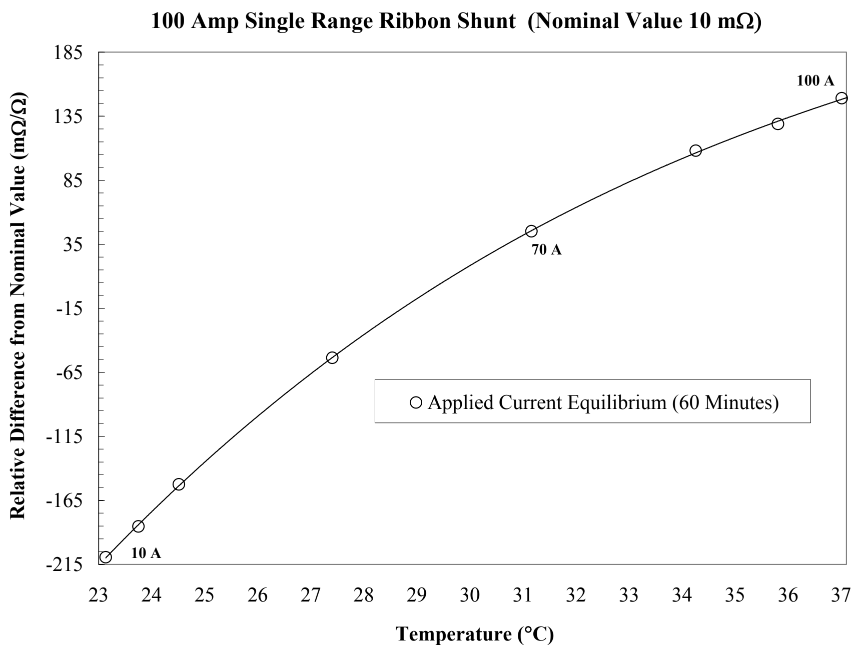

Figure 5. Equilibrium curve for the ribbon type Manganin 100 A shunt shown in Figure 1 (far right) shows the resistance/temperature curve does not reach a maximum. This shunt has about 25 (μΩ/Ω) / °C slope in first portion of the equilibrium curve.

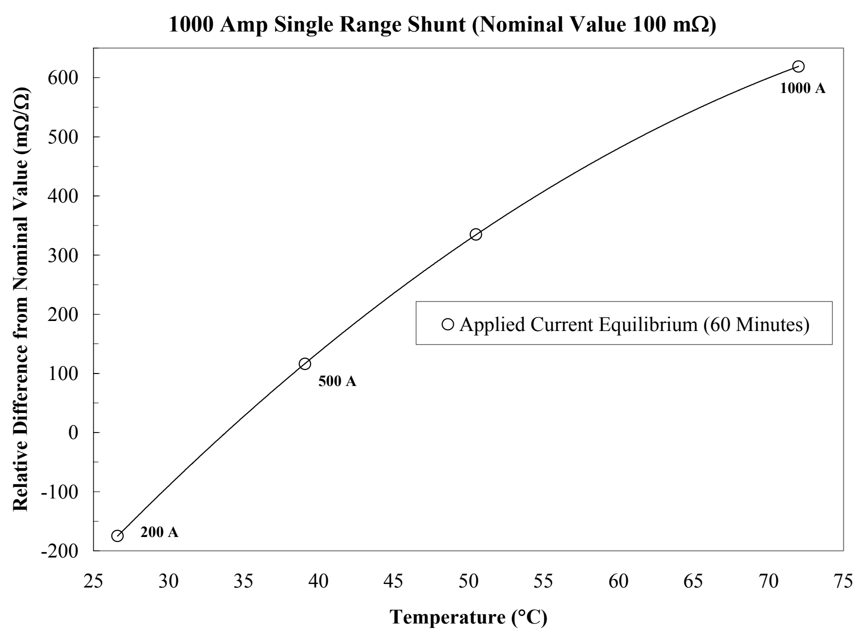

Figure 6. Equilibrium curve for the parallel element 1000 A shunt shown in Figure 2 (far right) of an unknown copper alloy. This shows the resistance/temperature curve does not reach a maximum at the rated current. This shunt has about 24 (μΩ/Ω) / °C slope in first portion of the equilibrium curve.

3. Temperature Sensors

In the past, shunts were calibrated at specific currents and temperature was not measured. Resistance equilibrium was reached at a specific current level and then the resistance reported for that current. A need for improved uncertainty for shunt calibration required measurement of the element temperature. The most cost effective way to accomplish this task is to attach a thermocouple [4] to the shunt element.

A thermocouple is a thermoelectric sensor consisting of two dissimilar metals joined together at one end, preferably welded. When the junction of the two metals is heated or cooled a thermoelectric voltage is produced that can be correlated to temperature. There are EMF-Temperature tables for the different types of thermocouples when used with a second, reference junction, or there are electronic thermocouple readouts that have internal references. NIST prefers to attach thermocouples to all high current shunts that are calibrated, so that a resistance/temperature curve can be generated. NIST will attach a Type T (Copper-Constantan) thermocouple free of charge. The thermocouple is attached with an epoxy to the center of the ribbon or the center element of the shunt.

The resistance/temperature curve that is generated when using an attached thermocouple provides more accurate temperature values and improved resistance uncertainties. This curve allows the end user to measure current more accurately before the shunt reaches equilibrium.

4. Current Cable Connections

The connection of current leads is critical for shunt accuracy [5,6]. Figure 7 shows incorrect current connections. The current is only conducting through the left side elements of the shunt.

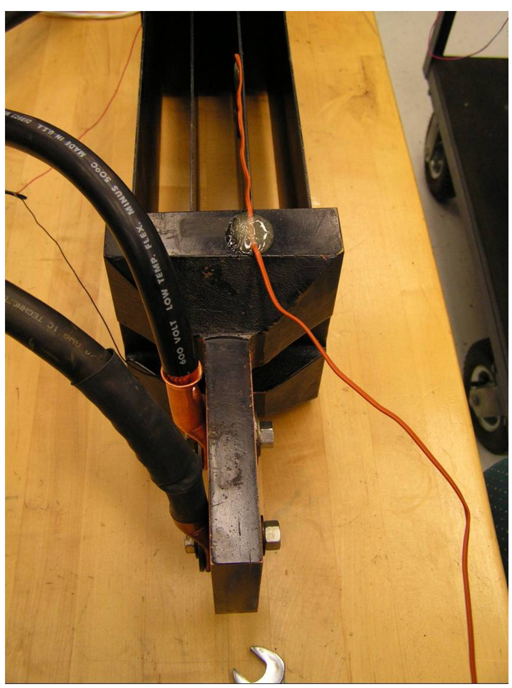

Figure 7. Incorrect current cable connections for this type of parallel element shunt.

In Figure 8, the solid circular dots illustrate the error in resistance that was measured at 350 A after reaching equilibrium for the current connections shown in Figure 7. The open triangle points with the solid regression line are the equilibrium curve using correct current cable connections shown in Figure 9. The current is flowing through all the parallel elements evenly.

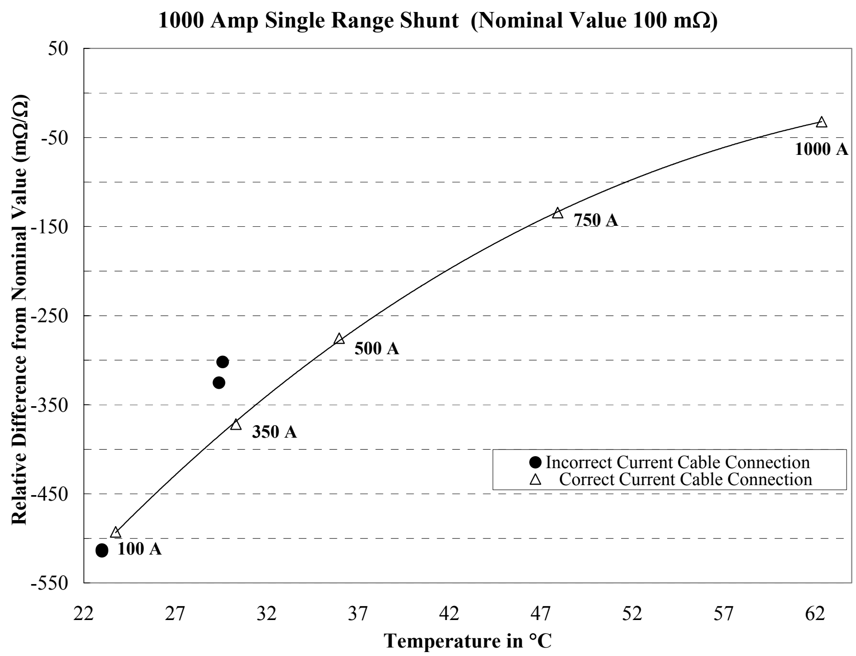

Figure 8. Correct current cable connection equilibrium curve and results with incorrect connection.

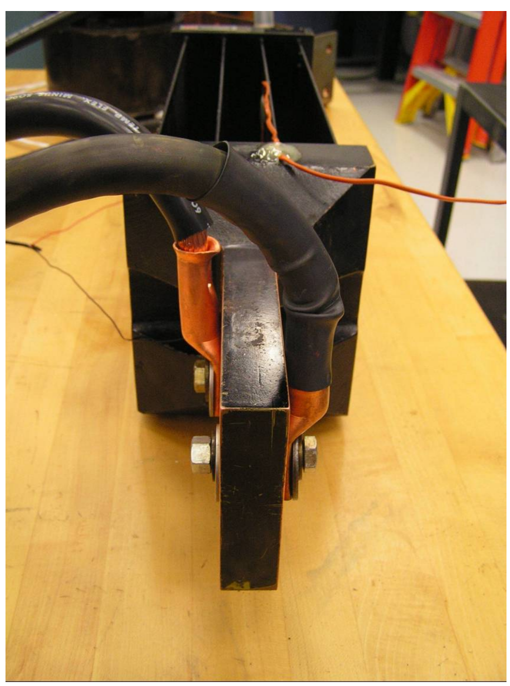

Figure 9. Correct current cable connections for this type of parallel element shunt.

5. Applied Current Self-Heating Versus External Heating

Some shunts require several thousand amperes for proper calibration. Presently there is only one commercial 2000 A system available to calibrate shunts. Some laboratories have developed an alternative method of using an external source to heat the shunt. Is it possible to retain the same uncertainties for the resistance/temperature curve with artificial heating?

In Figure 10, a 15 A ribbon shunt was measured with applied current after reaching equilibrium to obtain the solid line with open triangles equilibrium curve. The shunt was then immersed in a circulating oil bath. The current applied for the oil bath measurements was 100 mA so that no self heating was introduced, and the temperature of the oil bath was varied. The open circles with the dashed curve are the result of the heating of the shunt with circulating oil, and this tracks the self-heating curve.

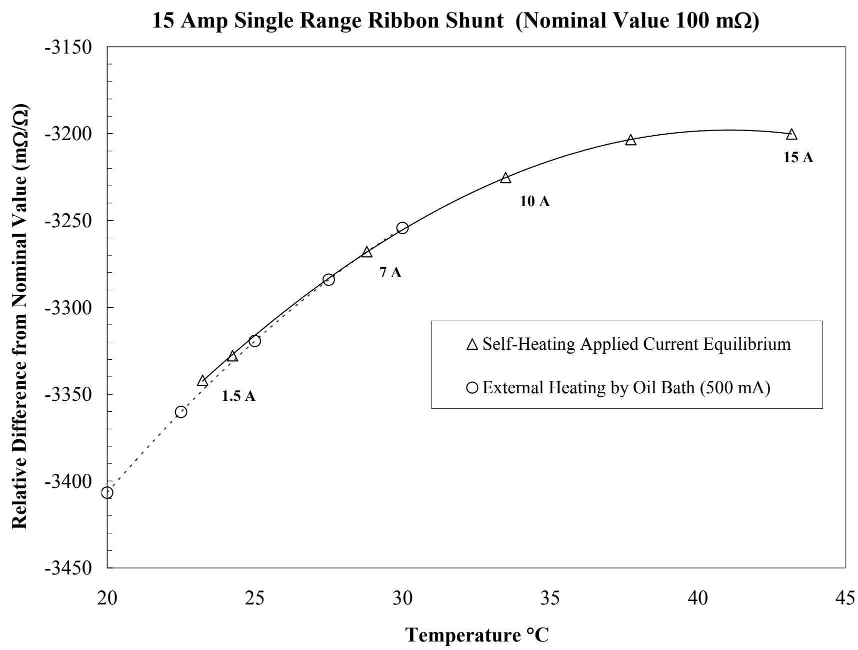

Figure 10. 15 A ribbon shunt self-heating equilibrium curve vs. external heating curve.

In Figure 11, a 100 A ribbon shunt was measured with applied current to obtain the solid black equilibrium curve with open triangles. The shunt was then immersed in a circulating oil bath. The current applied for the external heating measurements was 3.16 A (100 mW) so that no self-heating was introduced and the temperature of the oil bath was varied. The dashed curve with open circles shows the results of the heating of the shunt with circulating oil. This again tracks the self-heating curve but with the maximum difference of 8 μΩ/Ω.

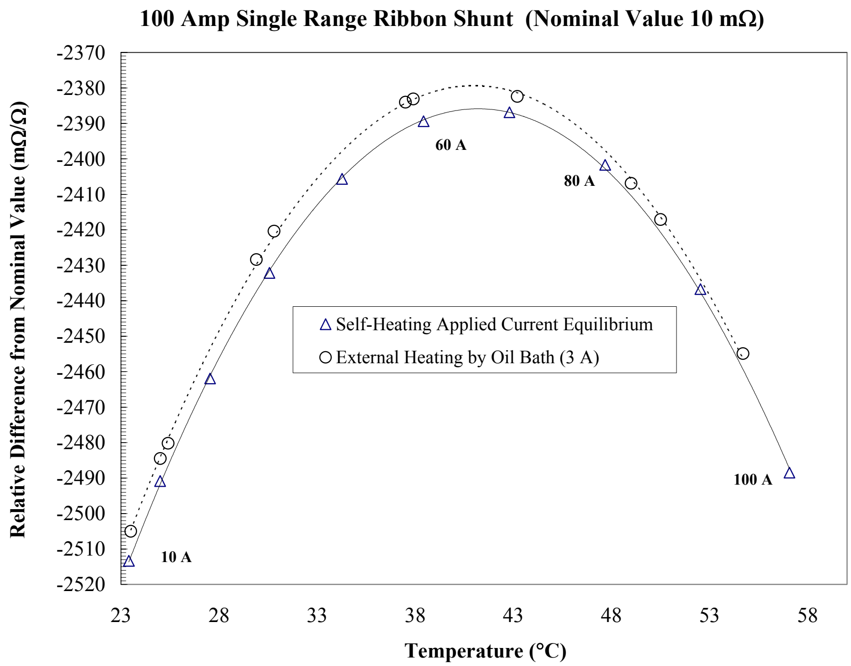

Figure 11. 100 A ribbon shunt self-heating equilibrium curve vs. external heating curve.

The tests of external heating conducted to date indicate that direct heat in a circulating oil bath can reproduce the equilibrium curve using applied current. The error seen in the 100 A shunt in Figure 11 may result from the shunt being more evenly heated with the circulating oil on the entire surface of the element. When heated only with applied current, air currents are flowing continuously over the shunt element. The different parts of the resistive element will have different temperatures in air. The temperature differences or gradient may cause a change in the measured resistance.

In future tests we will heat the air around the shunt to see if the same equilibrium curve can be obtained. It would be much more practical to use heated air rather than immersing shunts in oil. Oil cannot be removed from all surfaces of the shunt and the heated oil residue could be a hazard when full current is applied.

6. Summary

To achieve better uncertainties for high current shunts a resistance/temperature curve must be generated. Accomplishing this requires permanently attaching a thermocouple to the resistive element. Once the resistance/temperature equilibrium curve has been established the shape does not change but the resistance will drift as does a typical resistance standard. The correct connection of current cables to some high-current shunts is crucial in preventing errors in the measured resistance values. Resistance/temperature equilibrium curves can be generated by self-heating using applied current, and we will investigate how external heating may be used at or near the uncertainties of self-heating.

References

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