Precision Temperature Calibration On Platinum Resistance Thermometers Using AC Thermometry Bridges

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Since developing the world's first automatic resistance bridge in 1966, Automatic Systems Laboratories (ASL), has spent over 25 years developing AC thermometry bridges for use in conjunction with platinum resistance thermometers. Automated AC bridges provide equivalent temperature measurement uncertainties in the range ±0.01 °C to ±0.0001 °C to cater to industrial applications and national standards applications. This paper describes the various sources of error associated with precision resistance thermometer measurement and provides a comparison to automated DC bridges and DC voltmeter techniques.

Temperature Scales

The International Temperature Scale of 1990 (ITS-90),[1] represents the current basis for all temperature measurements and provides a method of making sure that temperatures measured in one country agree with temperatures measured in another. The ITS-90 scale is based on a series of intrinsic reference points that naturally occur when high purity material changes phase. The tether point for the scale is the triple point of water, which has been assigned the value 0.01°C and exists when the solid, liquid and gaseous states of water all coexist.

There are some twelve reference points that span the temperature range -189°C to 962°C, and for practical thermometry it is necessary to use some type of interpolation device to transfer the ITS-90 scale to everyday work. The standard platinum resistance thermometer (SPRT) has become the recognized transducer for this scale interpolation.

Platinum Resistance Thermometers

A variety of platinum resistance thermometers are available for both measurement and calibration applications. Possibly, the most common thermometer in metrology circles is the SPRT, which covers the range -189°C to 660°C and offers reproducibilities of 0.001°C. The SPRT has an $R_{0.01}$ of 25.5Ω and at maximum temperature the SPRT resistance is approximately 80Ω.

With the advent of ITS-90, the high temperature platinum resistance thermometer or HTSPRT has been used for scale interpolation in the region 660°C to 962°C, replacing the type S thermocouple standard. The $R_{0.01}$ for a high temperature SPRT is usually 0.25Ω or 2.5Ω.

For lower performance applications, the industrial platinum resistance thermometer or IPRT offers considerable cost savings over the SPRT. However, the trade off is reproducibility and range. The IPRT offers 0.1°C to 0.01°C reproducibility, and in most cases covers a range of -100°C to 450°C. The IPRT has an $R_{0.01}$ of 100Ω, and at maximum temperature the IPRT resistance is approximately 300Ω.

New industrial, high temperature platinum resistance thermometers are also becoming available for measurements in the range 0°C to 962°C. Research work is still being performed to establish reproducibility. However, initial tests indicate that it is possible to achieve 0.1°C at 962°C. These new thermometers have an $R_{0.01}$ of 5Ω and 10Ω.

The platinum resistance thermometer offers a highly repeatable resistance versus temperature characteristic. However, due to the low resistivity of pure platinum, the change in resistance for a given temperature is small. This means that a high resolution, stable and low noise measurement system is essential.

Sources of Measurement Error

The measurement of standard platinum resistance thermometers to an accuracy level of 1ppm (0.001°C) or better presents a number of interesting challenges to all instrument designers, with many sources of error being unavoidable. However, through careful circuit design, these sources of error can be reduced to negligible proportions. There are four main categories of error:

1. Sources of error associated with the standard resistor and thermometer being measured,
2. Sources of error associated with the interconnections between the resistors and the measurement instrument,
3. Sources of error associated with the measurement instrument,
4. Sources of error which can appear anywhere in the system.

(Note: These errors occur in different frequency regions; some more significant at high frequencies, some more significant at low frequencies and DC, some are independent of frequency and some occur at quite specific frequencies.)

Sources of Error Associated With the Resistor Being Measured

The errors which are significant at high frequencies fall into two groups; those that produce a *quadrature component* and those that produce an *in-phase component*. For high value resistors (>500Ω), parallel capacitance produces a phase lag in the impedance being measured, which is:

$R \times (w \times C \times R)$ ohms

where: w = radian frequency ($2 \times \pi \times F$)
R = standard resistor or thermometer resistance
C = standard resistor or thermometer self capacitance and/or cable capacitance

There is also a much smaller phase term:

$-R \times (w^2 \times C^2 \times R^2)$ ohms

which varies at the square of the frequency and reduces the apparent value of resistance slightly. If the parallel capacitance is lossy and has a given Tanδ, then the equivalent in-phase component is:

$R \times (w \times C \times R) \times \mathrm{Tan}\delta$ ohms.

To put the magnitude of this component into perspective, a typical application with $R=100\Omega$ and $w=565$ rads/sec @ 90Hz AC:

$(w \times C \times R) = 1$ part in 1000, (for capacitance values of up to 18nF)

which equates to connecting two coaxial cables of 90 meters length between the thermometer and AC bridge before overloading the measurement circuit. Two techniques are used to eliminate the quadrature component:

1. Use of a sufficiently accurate phase sensitive detector to ignore the 1 part in 1000 quadrature component,
2. Use of a detection and compensation circuit to automatically balance out the measured quadrature component.

Due to dielectric absorption in a relatively large parallel capacitance, certain older types of standard resistors intended for DC use can generate in-phase components even when measured at low frequency. However, for all modern AC/DC standard resistors, the effects of parallel capacitance are negligible. Wilkins reported components of 0.1ppm.[2]

A further source of high frequency error in low value resistors is series inductance. Since most standard resistors are wound for reasons of compactness, this problem is associated with the resistor itself rather than with the leads. Unlike the case of parallel capacitance, series inductance is loss free and introduces a pure quadrature component of magnitude:

$w \times L$

where: w = radian frequency ($2 \times \pi \times F$)
L = standard resistor or thermometer self inductance

Again, to put this component into perspective, with $R=100\Omega$ and $w=565$ rads/sec @ 90Hz AC, the AC bridge design can accommodate $L=176\mu H$ before the quadrature component overloads the measurement circuit. This represents more than 1 part in 1000 of the resistance being measured. Wilkins reported series inductance of 0.1ppm for an AC/DC standard resistor.[2]

There is no additional $(w^2 \times L^2 / R^2)$ term to produce an in-phase component. However, errors can be generated if the inductance is lossy. This results in an in-phase error of magnitude, $(w \times L) \times \mathrm{Tan}\delta$ ohms, which is independent of the actual value of resistance being measured.

Another inductive effect is eddy current loss, which is due to the magnetic field set up by the measurement current inducing currents to flow in nearby metalwork through transformer action. Since the resistance of the metalwork is reflected across the transformer primary and appears in series with the resistance being measured, this results in a higher ohmic resistance at high frequencies.

Errors that are significant at low frequency are caused mainly by thermal effects, which have long time constants – unlike the high frequency errors, which have short time constants.

The main thermal error is the thermocouple or Seebeck effect, which occurs when a junction between dissimilar metals varies in temperature. This generates a voltage which can then drive a current around a circuit. The thermal voltage is proportional to the temperature difference of the junction relative to the rest of the circuit and depends on the Seebeck coefficient for the two metals involved. It is typically in the order of several tens of microvolts per °C, so that even when low thermal emf materials are chosen, very small temperature changes can create substantial measurement errors for DC systems.

The opposite of the Seebeck effect is the Peltier effect, which occurs when a current is passed through a metallic junction. Heat is either emitted or absorbed, depending on the direction of current flow and magnitude of the Peltier coefficient for the materials involved. Taken together, these two thermal effects introduce significant errors for DC measurement systems, even when there are no external temperature variations. Essentially, the measurement current itself sets up a Peltier heating and cooling of the intermetallic junctions where the resistance element joins the copper leads, which results in a Seebeck voltage opposing the original current flow. This makes the resistance value artificially high at low frequencies and DC, where there is significant time for heating and cooling to take place.

At higher frequencies, there is insufficient time for this heating and cooling to produce significant temperature variation, hence the correct ohmic value of the resistor is obtained. At low frequencies and DC, some heating and cooling takes place, but not in phase with the driving current waveform. The resulting Seebeck error voltage is out of phase with the main (I x R) drop across the resistor, resulting in a quadrature component in addition to the original in-phase component. Even DC systems that employ a polarity reversal circuit for the carrier current develop a quadrature component that is neither measured nor corrected for.

Another thermal effect, which is less significant but needs to be addressed, is the Thomson effect. This occurs when a wire of uniform composition has a temperature gradient along its length, which results in an emf being generated. When a high current is passed through a conducting wire connected to a relatively large thermal mass at each of the ends, the middle of the wire becomes hotter than the two ends. The Thomson effect sets up a voltage of one polarity along one half of the wire and an equal and opposite voltage along the other half. If DC current is being used, one of these voltages assists the current while the voltage in the other half of the wire opposes it. This results in power being dissipated in one half of the wire, so that one end is hotter than the other. This generates a Seebeck voltage across the resistor as a whole, opposing the current flow and increasing the apparent DC resistance value.

All of these thermally induced effects reverse their direction when the DC is reversed. The combined Peltier-Seebeck effect is proportional to the current, so that the error is constant irrespective of the carrier current level, whereas the Thomson-Seebeck effect is larger at high currents compared with lower currents. These thermally induced effects result in measured DC resistances that are in error, giving values greater than the correct ohmic values, irrespective of whether DC reversals are made or not. The only way to avoid these effects is to make DC reversals fast enough to eliminate time for any Peltier heating to occur, i.e. much faster then the relatively slow thermal time constants involved.

There are other sources of error with less significant effect that need to be noted: Johnson noise and 1/F or flicker noise. The Johnson noise contributes a small ran-

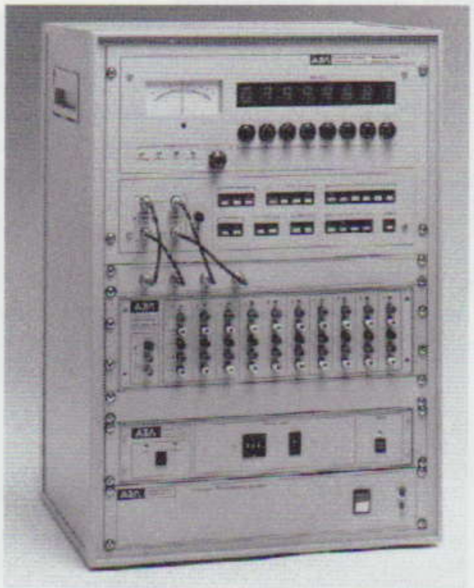

Figure 1. Automatic Systems Laboratories Model F18 AC Resistance Bridge

dom noise voltage across the resistor, or equivalently, a small random noise current through it.

The power in any 1 Hz bandwidth system is constant, no matter where in the frequency range the frequency band is centered. However, if the frequency band is widened, the total noise voltage varies with the square root of the bandwidth. This noise can be reduced relative to the desired carrier signal by narrowing the bandwidth of output filters. The result is a better signal to noise ratio, but an increased time period for a given result.

Flicker or 1/F noise behaves in a different manner, getting larger at lower frequencies, so that lowering the carrier frequency toward DC gives more result uncertainty. This is one of the main reasons, apart from thermal induced errors, that DC measurement systems are inherently noisy. Essentially, the longer the wait time, the more likely something will change and contribute an error signal.

Sources of Error Associated With Interconnectors

The four-terminal impedance standard is defined as the ratio of the voltage developed between its potential terminals divided by the current flowing between its current terminals. This assumes two things, that no stray voltages are present in the resistance itself or its potential leads, and that no stray leakage currents are allowed to flow from the resistor or its current leads.

When comparing the ratio of two, four-terminal resistances connected in series, the ratio is defined as the voltage developed between the first resistors' potential terminals divided by the voltage developed between the second potential terminals. This assumes that no stray voltages are present in either the resistances themselves or their potential leads and that no stray leakage currents flow into or out of the connection between the resistors or the resistors themselves, so that an identical current flows through each resistor.

It is possible, however, to have leakage current from points in the measurement circuit before the current goes through both resistors, or after the current has been through both resistors. It is also possible to have a leakage path from the junction between the two resistors, provided there is no voltage available to drive current down it. It is assumed that the lead resistances are small, i.e. less than 1ppm of the leakage paths on them, so that the resulting errors are not greater than 1ppm.

If the leakage paths on the measurement circuit can be arranged so that they all go to ground and do not shunt the resistors being measured, an accurate measurement can still be achieved despite leakages on the interconnecting cables. This type of measuring system is referred to as a *guarded system* and can provide accurate measurements when unguarded systems or isolated systems would produce errors.

All of Automatic Systems Laboratories' AC bridges use a guarded system and the basic principles are covered in a technical paper developed by ASL.[7] This design feature is not always used on DC systems, but has proven extremely useful in improving the accuracy of HTSPRT (0.25Ω and 2.5Ω $R_{0.01}$) measurements at high temperatures, especially near the silver and gold fixed points where the thermometer element silica supports become significantly conductive.

An additional feature of the AC bridge is coaxial cabling, so the out and return currents are coaxial and do not radiate a magnetic field. Likewise the potential leads are coaxial, so stray magnetic fields cannot influence the measured voltages between the inner and outer conductors.

This configuration is preferred for low to medium value resistors where the magnetic effects are significant, but the effects of parallel cable capacitance are not. For higher value resistances where the magnetic effects are smaller and the shunting effects of cable capacitance are significant, one of the current carrying conductors is paired with a potential lead.

Another useful feature of the AC bridge is that the connections from the junction between the resistances can be screened by the outer conductors of the coaxial leads, which are themselves driven from low impedance sources. This makes the resulting circuit relatively immune from interference due to stray signals.

The effects of series lead resistance are negligible, since with four-terminal impedance, the voltage drop on leads carrying the measurement current are irrelevant and no current flows in the leads measuring the voltage. However, when taken in conjunction with leaky cables, small errors can occur if both effects are large. This effect, being purely resistive, is the same for both AC and DC systems. The effect of small series lead resistances and parallel capacitance acting together is also very small and generates a quadrature component, which the AC bridge phase-sensitive detector ignores. The effects of series lead inductance is normally negligible in AC bridge designs.

Sources of Error In Measurement Equipment

The basic measurement principle in the AC bridge is a comparison of the ratio of the voltages developed by the standard resistor (Rs) and the unknown resistance thermometer (Rt). The ratio of voltages is defined by an inductive ratio transformer using a highly sensitive low noise null detector amplifier. The use of inductive ratio transformers or dividers for precise measurements of impedance ratios is very well established. An inductive divider has the property of dividing AC potentials applied to it in very precise ratios. The accuracy of division does not vary with time or changes in ambient operating temperature, which is an essential feature for any standard or reference device.

Inductive voltage divider designs are in routine production that offer resistance ratio accuracies of 0.1ppm to 10ppm, with fullscale linearities of 1 part in 10^9. Instrument linearity is most important when making temperature measurements over a wide range, since the thermometer resistance changes from a few ohms to many tens of ohms and it is essential to maintain the same measurement accuracy.

The AC bridge is a simple, fundamental measurement that is not dependent on using accurately calibrated linear amplifiers with no DC offsets. Calibration of DC amplifiers each measurement cycle adds significant time and uncertainty to the measurement. When the ratio transformer is adjusted to the same ratio as the resistors being measured, the out-of-balance voltage is zero, which is indicated on the bridge front panel with the matching transformer ratio. This leaves the transformer and connections to the standard resistor. The transformer primary cannot be connected across the standard resistor directly, as it would shunt the resistor, consequently some means has to be found to supply the transformer current while copying the voltage accurately from the standard resistor. It is fairly simple to build an amplifier to meet the required specifications and interface it to the transformer in a suitable fashion. The transformer itself can be designed and constructed by well established methods, as described by Hill and Miller.[3]

The precision amplifiers and transformer used in the AC bridge are taken as a complete unit and designed to meet their specification "as is", without any adjustments, nonstandard or selected components. The input impedance of the combination can be designed to be high enough ($>> 10^9\Omega$) and the noise level sufficiently low that measurement specifications can easily be met. The instrument ratio accuracy can be proven using a set of stable resistors supplied with each instrument and performing a series of compliment checks. Ratio linearity can be verified using a reference voltage divider.

Additional Sources of Error

Additional sources of error can exist within the system itself. One source of error is Johnson noise, caused by high resistance cables or connectors. The effects occur with use of faulty, dirty or oxidized connectors.

Another error source is electromagnetic interference, which can enter the system by a variety of routes. Essentially it interferes with the active devices in the system (i.e. transistors and operational amplifiers), by causing cross-modulation and inter-modulation. Both of these can cause previously unrelated signals to become mixed with the bridge carrier frequency. However, the wiring techniques used on AC bridges to prevent stray low frequency signals from causing problems also assist in providing considerable immunity from higher RF frequencies.

Since electromagnetic interference is coupled into the system by a nonlinear mechanism, it becomes much worse if the interfering signal is increased slightly. However, the converse is also true if the interfering signal is reduced slightly, the effect on the system as a whole may disappear completely.

Finally, the last source of error is the mains frequency, which can get into the system anywhere. This does, however, occur at quite well-defined frequency bands together with all its harmonics, which facilitates substantial filtering. A useful technique used by AC bridges is to have the carrier frequency one-half or one and one-half times the line frequency, i.e. 30Hz or 90Hz for a 60Hz supply. The carrier phase-sensitive detector is then designed to be insensitive to the even carrier harmonics. When detected by the system, all the remaining line related frequencies (half line frequency) fall away from the carrier frequency and its odd harmonics, separated out with a simple low pass filter after detection. This technique is very powerful as it provides additional line frequency filtering, enabling complete rejection of line frequencies for all practical purposes, while at the same time enabling the carrier frequency amplitude to be measured accurately in only two cycles of the line frequency. In addition, the wiring techniques that use twisted pairs, coaxial leads, screened wiring and a fully guarded measurement circuit all help to reduce line frequency interference.

Differences In AC and DC Measurement

During the late 1980's extensive comparison tests were performed around the world by national laboratories and commercial calibration laboratories to quantify what differences existed between AC and DC measurements on standard platinum resistance thermometers over the range -183°C to +630°C. Most reported minimal differences in the order of 1ppm, often hidden by the platinum resistance thermometer reproducibility. Brown[4] reported <1ppm with measurements at water triple point and Odom[5] also reported <1ppm with measurements at water triple point, tin and zinc freeze points. Cutkosky[6] performed a series of tests on an AC/DC standard resistor to verify if any AC/DC difference existed. The tests reported <0.1ppm AC/DC difference up to 100Hz AC.

Conclusion

The AC bridge offers the preferred measurement to the DC bridge or super voltmeter for platinum resistance thermometry. Temperature is a dynamic property and the AC bridge provides fast, continuous balance, the lowest noise measurement, complete freedom from significant DC thermal effects, automatic compensation of thermometer and standard resistor reactive components and finally the use of a guard circuit to eliminate leakage currents.

In addition, since the AC bridge measures only resistance ratio and the inductive divider has such stability, the instrument is an intrinsic standard that requires no calibration, which saves both time and money. The simple compliment checks described provide all the required information to verify the instrument performance.

AC bridges have been adopted by most of the world national standards laboratories, as well as many corporate and commercial calibration laboratories for precision measurements on platinum resistance thermometers.

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