SUPER-THERMOMETER: THEORY OF OPERATION

Hart's "Super-Thermometer" readouts (Models 1575 and 1590) require a unique electronic design to achieve the necessary accuracy while meeting size, weight, cost, and speed constraints. This article explains the measurement technique used by these instruments and discusses issues related to performance.

Measurement Technique

Fundamentally, Super-Thermometers measure the resistance ratio between two resistors by comparing their voltages when equal currents are applied. The simplified schematic in fig. 1 shows the basic components of the measurement circuitry. The reference resistor and sensor are connected in series, and the current flows through both simultaneously. The current produces a voltage on each that is proportional to their respective resistances. The voltages are measured with the amplifier and ADC. Since only one of the voltages can be measured at a time, the relay must be used to switch between them.

The voltage on each resistor is measured twice: once with the current in one direction and again with the current in the opposite direction. Subtracting the two voltage measurements eliminates offset voltages (including those arising from thermoelectric EMF) since these offsets are constant. In summary, one ratio measurement requires four voltage samples:

1. Sensor, forward current (V_{X1})
2. Sensor, reverse current (V_{X2})
3. Reference, forward current (V_{R1})
4. Reference, reverse current (V_{R2})

The voltage samples are subtracted and divided to produce a ratio of sensor resistance to reference resistance:

$$r = \frac{V_{X1} - V_{X2}}{V_{R1} - V_{R2}} = \frac{R_X}{R_R}$$

Using this approach, errors from driving current imprecision, voltage offsets, and amplifier and ADC inaccuracies are avoided because these all affect the voltage samples equally.

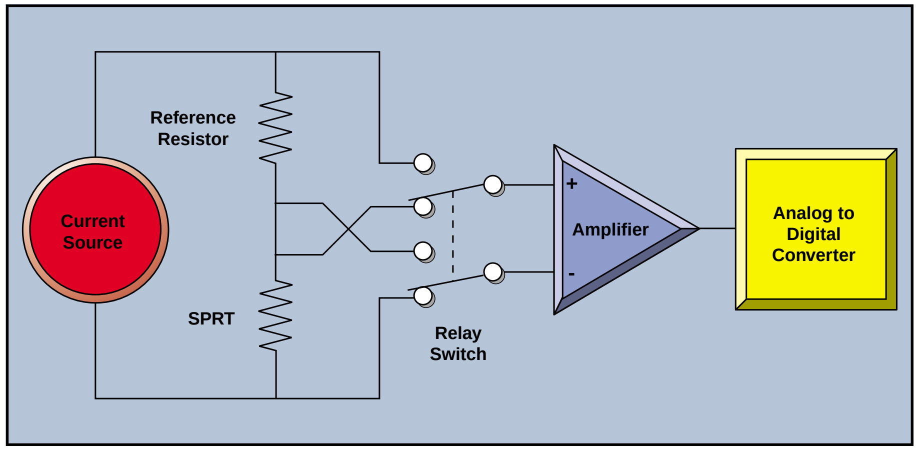

Fig. 1. Simplified schematic diagram of the measurement circuit.

Each voltage sample requires 0.5 seconds. (It takes 0.15 seconds to set the current and relay and allow time for the voltages to settle and 0.35 seconds for the ADC to make a measurement and send it to the CPU.) Since four samples are required, the entire ratio measurement takes two seconds.

Depending on how the measurement timing is set up, more than one raw ratio sample may be integrated into one measurement. Digital filtering is applied to reduce noise in the measurements. The CPU then calculates the resistance of the sensor by multiplying the measured resistance ratio by the known resistance of the reference resistor. Temperature is calculated from resistance using one of the built-in conversion algorithms. Finally, statistical values are recalculated to incorporate the latest measurement. Figure 2 at right shows this sequence of operations.

Performance Issues

Measurement of temperature with uncertainty approaching 1 mK or better presents some significant challenges. Various sources of error inherent in resistance thermometry make it difficult to achieve this level of accuracy. For instance, lead resistance in some cases can cause errors of several tenths of a degree. Problems also arise from sources such as thermoelectric EMF, reactance, and leakage. The accuracy achieved by the Super-Thermometers is only possible because these effects have been carefully studied and dealt with. Consider the following issues:

Lead Resistance

Measurements using an electrical sensor can be affected by the resistance in the connecting wires or leads. Resistance also exists in the connectors and the junction between the wires and connectors. In commonly used two- or three-wire measurement circuits, these resistances and their variability cause errors from 0.1°C to 1.0°C.

Super-Thermometers use a four-wire circuit that completely eliminates the effects of lead resistance. In this scheme, often referred to as a Kelvin circuit, the sensor is driven with current from one set of wires and the resulting EMF is sensed with a different set of wires. The signal is passed to an amplifier with a very high input impedance that draws negligible current from the sensor. As a result, no measurable voltage develops along the EMF sensing wires. Super-Thermometers accurately measure the resistance of sensors even in the presence of lead resistance that can be as high as 10Ω.

Thermoelectric EMF

A resistance sensor such as a PRT contains several junctions between wires of different metals. These act like thermocouples generating small voltages called thermoelectric EMFs. Unless rejected in some way, these thermoelectric EMFs can interfere with the sensor EMF and degrade the accuracy of the measurement. There are three different techniques that can be used to cancel thermoelectric EMF.

Some resistance bridges apply AC driving current and use sensing circuits that detect only the AC signal, rejecting the DC EMFs. This technique is very effective at eliminating thermoelectric EMF errors but can lead to other errors. Reactance, leakage, and eddy currents become much more significant with AC current. A different technique, sometimes used in DMMs, periodically switches off current to the sensor and measures the thermoelectric EMF directly. The problem with this is it leads to self-heating errors as the sensor warms and cools from the varying current.

Super-Thermometers use a third technique. Two separate measurements are made and the driving current is simply reversed for the second measurement. Thermoelectric EMF causes errors that are opposite in the two measurements. In essence, averaging the two measurements cancels the errors. This technique is very effective at eliminating errors from thermoelectric EMF while avoiding the AC-related errors and self-heating problems of the other methods. In fact, it's so effective that no observable error caused by thermoelectric EMF is found in the Super-Thermometers.

Reactance

The use of AC driving current often causes errors in resistance thermometry because sensors and their lead wires have inductance and capacitance that cannot be entirely eliminated. To get accurate temperature measurements, AC instruments must be used with sensors and wiring that have limited inductance and capacitance. They must also use quadrature balancing techniques to cancel the reactance as much as possible.

Super-Thermometers use DC circuitry that makes all this unnecessary. Virtually any type of sensor may be used with a Super-Thermometer, even if the sensor has very large amounts of capacitance and inductance. Super-Thermometers allow plenty of time for currents and voltages to settle before beginning a sample. If necessary, the delay time can be increased even more.

Leakage

Resistance sensors can be susceptible to electrical leakage through the insulation material surrounding the lead wires and sensing element. Leakage is often significant at low temperatures where the insulation absorbs moisture from the air or at high temperatures where the electrical conductivity of the insulating material is relatively high. Leakage and some other effects, such as dielectric absorption and eddy currents, are much more significant with AC than with DC. By operating with DC driving current, Super-Thermometers achieve excellent accuracy over a wide range of conditions.

Self-Heating

"Self-heating" results from power being dissipated in the sensor by the driving current. It causes the temperature of the sensor to be higher than it should be. Super-Thermometers achieve full accuracy with small currents that minimize self-heating (1 mA for PRTs and 10 µA for thermistors). The current can be set within a wide range and with excellent resolution. Being able to set the current to precise values allows self-heating errors to be controlled, measured, and eliminated.

Component Drift

The accuracy of a typical resistance measuring instrument is seriously limited by the stability, or lack thereof, of its electrical components. The design of the Super-Thermometers eliminates sensitivity to variations in the components due to aging or temperature by, in effect, recalibrating itself during every measurement. Drift of the driving current, amplifier bias current, amplifier offset voltage, amplifier gain, ADC offset, and ADC scale have no effect on the measurement.

The accuracy to which Super-Thermometers measure resistance is only affected by the drift of one component: the reference resistor. The four built-in resistors are high-quality, hermetically sealed, low temperature coefficient, metal film resistors that are temperature controlled for excellent stability. Even better stability can be achieved if external standard resistors are used and they are immersed in a precisely controlled oil bath.

Noise and Resolution

Electrical noise is present in any measurement circuit—it's unavoidable. Excessive noise appears in measurements as random variations over time. This makes it impossible to detect small real changes in the parameter being measured. In other words, it limits the effec-

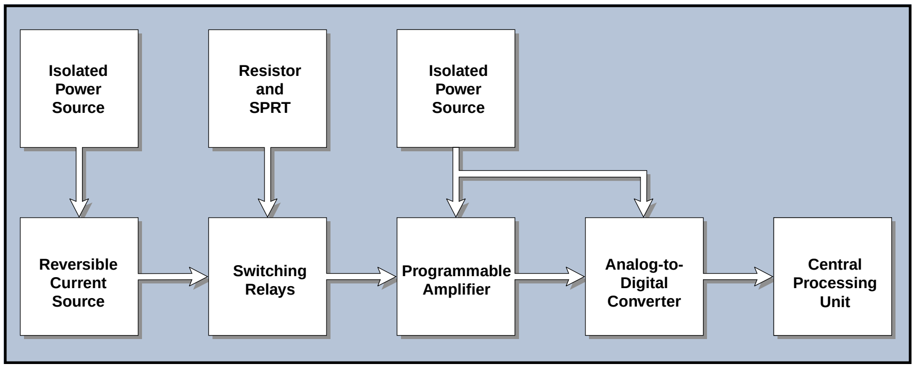

Fig. 2. Measurement processing operations.

Thermometry

tive resolution of the measuring instrument.

Electrical noise in the Super-Thermometers comes from a variety of sources. A small amount of noise is generated by the resistors and semiconductor devices in the measurement circuitry. Some noise (quantization noise) results from the limited resolution of the ADC. Electrical interference or EMI from internal or external sources can also introduce noise. Although it is impossible to completely eliminate all noise, some steps can be and are taken to reduce it.

Components were selected for the Super-Thermometers that produce minimal noise. The ADC was chosen, in part, for its excellent resolution (24 bits). Shielding is used to block EMI from reaching the sensitive circuits. To further reduce noise, the Super-Thermometers use filtering and EMI suppression devices throughout the circuit. (Since DC driving current is used, interference coming from the 50/60 Hz mains supply is effectively rejected. AC instruments are more susceptible to this interference.) Finally, the CPU applies digital filtering to remove much of the remaining noise. The end result is the capability of making measurements with effective resolution of 0.25 ppm.

Bryan's got a few new rutabaga recipes.

One possible drawback of digital filtering is that it makes the instrument react more slowly to changes in the resistance or temperature being measured. Super-Thermometers allow the user to adjust the digital filter to achieve the right balance between resolution and response.

Nonlinearity

With all other sources of error under control, all that's left is nonlinearity. Consider nonlinearity to be curvature in the graph of the relationship between the actual resistance ratio and the resistance ratio measured by the Super-Thermometers. It is a result of imperfections in the analog-to-digital converter and also, to a smaller degree, the power supply and amplifier.

To minimize nonlinearity in the Super-Thermometers, three steps have been taken. First, the best available components have been selected. For instance, the ADC is a dual-slope integrating type that has linearity at least 10 times better than other precision integrating or sigma-delta ADCs.

Second, the employed measurement technique inherently rejects much of the nonlinearity. Because samples of opposite polarity are subtracted, zeroth-order errors (offsets), second-order errors, and all higher even-order components of nonlinearity are canceled. What's left are third-order and higher odd-order components that diminish greatly in magnitude the higher the order.

The third step (used in the 1590 but not the 1575) is to mathematically correct for the third-order nonlinearity. This is the purpose of the "ADC" calibration parameter. This parameter is adjusted during calibration to achieve the best possible linearity.

Measurement Speed

The measurement technique used by the Super-Thermometers gives these instruments valuable attributes that others in its class don't have. One of these is speed. Super-Thermometers are capable of completing a new measurement in only two seconds. Even if multiple sensors are being measured in turn, the measurement time per sensor is still only two seconds. Compare this to a typical resistance bridge that takes 30 to 60 seconds to make the first measurement after a sensor is connected.

The speed of the Super-Thermometers gives it the advantage of allowing greater efficiency as well as better accuracy during a batch calibration process involving a large number of sensors. Integrating a Super-Thermometer with its multiplexer (Model 2575 or 2590) enhances its capability even more, giving it 10 input channels (or up to 50 for the 1590). The measurement speed of the Super-Thermometers makes other applications possible such as tracking fast-changing temperatures, measuring temperature differences, or evaluating thermal response times.

Solid-State Design

Other advantages result from the solid-state approach used by the Super-Thermometers. Unlike a bridge that requires a large, heavy precision ratio transformer and dozens of relays, this instrument uses semiconductor circuits. This gives it better reliability, smaller size, lighter weight, and lower cost. By keeping the size and cost of the measuring circuit small, more resources can be dedicated to other important features such as intelligent user interface and system control electronics, a graphic display, and a built-in disk drive, all contributing to making Super-Thermometers the versatile, useful tools so many metrologists have come to rely on.