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Precision Temperature Measurement Using Resistance Temperature Detector

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Abstract – **Temperature is a very important parameter and its measurement is a routine process in industries and laboratories. Many industries and processes, from steel manufacturing to semiconductor fabrication, depend on temperature. Accuracy of the temperature measurement will depend on the sensor selected, signal cables used, and the instruments. Selecting the right temperature sensor usually depends on the temperature range of the process being measured, accuracy desired, and the operating environment encountered. A data acquisition system conditions the analog signal from the RTD sensor, making the analog translation of the temperature usable in the digital domain.**

Keywords: **Sensor, Acquisition System, Digital Domain**

I. Introduction

A Various types of sensors are available to measure temperature. All of them infer temperature by sensing some changes in a physical characteristic. The two prime sensors used to measure the temperature are resistance temperature detectors (RTD) and the thermocouples (TCs). A variety of other temperature sensors such as semiconductor, diodes, and thermistors can be employed to measure relatively narrow temperature ranges. [1]

Design methods have evolved over time, from purely intuitive (as in art) to formal (managerial). The process of sensor selection is somewhere in between: it is an act of engineering, in which the design is supported by advanced tools for simulating system behavior based on scientific knowledge. The basic attitude is (still) the use of know-how contained in the minds of people and acquired through experience.

The acronym "RTD" is derived from the term "Resistance Temperature Detector". The most stable, linear and repeatable RTD is made of platinum metal. The temperature coefficient of the RTD element is positive. An approximation of the platinum RTD resistance change over temperature can be calculated by using the constant 0.00385Ω/Ω/^{0}C. This constant is easily used to calculate the absolute resistance of the RTD at temperature. [2]

EQUATION

$$RTD(T) = RTD_0 + T \times RTD_0 \times 0.00385\Omega/\Omega/^0C$$

Where:

RTD (T) is the resistance value of the RTD element at temperature T^{0}C.

RTD_0 is the specified resistance of the RTD element at 0^{0}C and, T^{0}C is the temperature environment that the RTD is placed.

The RTD element resistance is extremely low when compared to the resistance of a NTC thermistor element, which ranges up to 1 MΩ at 25^{0}C. Typical specified 0^{0}C values for RTDs are 50, 100, 200, 500, 1000 or 2000Ω. Of these options, the 100W platinum RTD is the most stable over time and linear over temperature. If the RTD element is excited with a current reference at a level that does not create an error due to self-heating, the accuracy can be ±4.3^{0}C over its entire temperature range of -200^{0}C to 800^{0}C. If a higher accuracy temperature measurement is required, the linearity formula below (Calendar-Van Dusen Equation) can be used in a calculation in the controller engine or be used to generate a look-up table.

$RTD\,(T) = RTD_0\,[1 + AT + BT^2 - (100CT^3 + CT^4)$

where:

RTD(T) is the resistance of the RTD element at temperature, RTD_0 is the specified resistance of the RTD element at 0°C, T is the temperature that is applied to the RTD element and, A, B, and C are constants derived from resistance measurements at 0°C, 100°C and 260°C.

Table I Tolerances Set by IEC Publication 751 For Platinum Rtds[1]

Temperature	Resistance	Tolerance				Industrial tolerance	
		Class A		Class B		Class C	
^{0}C	Ω	^{0}C	Ω	^{0}C	Ω	^{0}C	Ω
-200	18.49	±0.55	±0.24	±1.3	±0.56	±2.27	±1.15
-100	60.25	±0.35	±0.14	±0.8	±0.32	±1.77	±0.71
0	100.00	±0.15	±0.06	±0.3	±0.12	±1.27	±0.50
100	138.50	±0.35	±0.13	±0.8	±0.30	±1.77	±0.67
200	175.85	±0.55	±0.20	±1.3	±0.48	±2.27	±0.83
300	212.02	±0.75	±0.27	±1.8	±0.64	±2.77	±0.98
400	274.04	±0.95	±0.33	±2.3	±0.79	±3.27	±1.10
500	280.90	±1.15	±0.38	±2.8	±0.93	±3.77	±1.22
600	313.59	±1.35	±0.43	±3.3	±1.06	±4.27	±1.32
650	329.51	±1.54	±0.46	±3.6	±1.13	±4.52	±1.36

II. Sensor Fabrication Technology

Realization of a thin film sensor involves the deposition of a sensing film on a suitable substrate. There could be many combination of metals and insulating materials needs to be deposited on one another depending upon the application or sensing requirements. [3]

A. Film Deposition Methods for Sensor Fabrication

Based on the thickness of the deposited film and the technology used to deposit these films, fabrication technology is broadly divided into two categories like i) thick film technology and ii) thin film technology, details of which are given below.

1.Thick Film Technology

Thick film technology uses pastes or "inks" with fine particles (5μ average diameter) of common or noble metals dispersed in an organic vehicle, along with a glass frit that binds them. Depending on the dispersed particles, the paste can be conductive, resistive or dielectric. Those pastes are screen printed on a substrate according to pattern involving width lines from 10 μ to 200μ. The printed film is dried by heating at about 150 ^{o}C to remove the organic solvent that provided the low viscosity needed for the paste to squeeze through the open areas in the screen. The substrate with the deposited film is then fired on a conveyor belt furnace, usually in the atmosphere air, so that the metal powder sinters and glass frit melts, thereby bonding the film to the substrate. The result is 10μ to 25μ thick film, impermeable to many substances but relatively porous for specific chemical or biological agents. Thick film components have a printed tolerance of about ±10% to ± 20%, but they can be later trimmed to within ±0.2% to ±0.5% through selective abrasion or laser evaporation.

Thick film technology finds at least three different uses in sensors. It has been used for years to fabricate hybrid circuits offering improved performance compared to monolithic integrated circuits for signal conditioning and processing. Thick film circuits and some sensors can be integrated in the same package, which improves the reliability (strong connections), permit functional trimming and reduces cost. It is also used to create support structures or substrates onto which a sensing material is deposited.

Some thick film pastes directly responds to physical and chemical quantities. There are pastes – some developed for sensing applications- with high temperature coefficients of resistance useful for temperature sensing, piezo-resistive pastes, magneto-resistive pastes, pastes with high Seeback coefficient among others. Pastes based on organic polymers and metal oxides such as SnO_2 can detect humidity and gases because of adsorption and absorption. Using thick film technology, it is straightforward to define the inter-digitated structures required for those sensors. Thick film sensors with ceramic substrate withstand high temperatures, can be driven with relatively large voltages and currents, can integrate heaters and can resist corrosion. Because the paste is fired into the ceramic, thick film sensors are compact and sturdy. The printing process is quite inexpensive, which permits competitive low volume fabrication. [4-6]

2. Thin Film Technology

Thin films (generally less than 1 micron thick) are obtained, in general by vacuum deposition on a substrate. Sensor and circuit patterns are defined by masks and transferred by photolithography, similar to monolithic IC fabrication. Even though their names may suggest that the only difference between thick film and thin film technology is in film thickness, they are quite different technologies. In fact, metalized thin films may become thicker than some thick films. The properties of thin film differ from the bulk material.

Common materials in thin film circuits are nichrome for resistors, gold for conductors, silicon dioxide for dielectrics. Many thin film sensors are resistive. Piezo-resistors use nichrome and poly crystalline silicon, conductivity sensors use platinum, strain gauge based sensors use platinum – tungsten alloys, and gas sensors use zinc oxide.

III. NI MULTISIM

The National Instruments Electronics Workbench Group (formerly Electronics Workbench) equips the professional printed circuit board (PCB) designer with world-class tools for schematic capture, interactive simulation, board layout, and integrated test. [7]

A. Sources of Errors and Correction

RTDs are externally powered sensors and based on the variation of resistance with temperature. The accuracy of platinum Resistance Thermometer (PRT) temperature measurement is largely determined by the number of leads used between the probe and the instrument. Two leads are often acceptable in the case of short cable runs; three leads compensating for lead resistance variations give improved accuracy; and four leads provide the greatest precision.

Self-heating of RTD also causes measurement inaccuracy. The maximum excitation current is determined by the self-heating within the RTD and this limits the maximum signal for a required measurement temperature range. To produce a higher-level signal for indication and recording, a separate signal conditioner is needed.

Noise interference can have a significant effect on accuracy. Shielded twisted pair signal cable minimizes noise interference on measuring circuit. For long cable runs, a 4-20mA current transmitter may be used.

RTD elements are, in fact very vulnerable to contamination of all kinds, and must be used only in hermetically sealed probes for any industry application. Moisture, dirt or any seriously affect the accuracy of RTD. [1]

TABLE II RTD ADVANTAGES AND DISADVANTAGES

Advantages	Disadvantages
Very Accurate and Stable	Expensive Solution
Fairly Linear to ±4%C	Requires Current Excitation
Good Repeatability	Danger of Self-Heating
	Low Resistive Element

B. Selection of Temperature Sensors

TABLE III THERMOCOUPLES, RTDS, THERMISTORS AND SILICON IC SENSORS [8]

ATTRIBUTE	THERMOCOUPLE	RTD	THERMISTOR	SILICON IC
Range	-184°C to 1260 °C	-200°C to 850 °C	-55°C to 150 °C	-55°C to 125 °C
Temperature (t) Accuracy	Greater of ± 2.2 °C or ± 0.75	Class B = ±[0.012 + 0.0019t – 6 x $10^{-7}\ t^2$]	Varies ± 0.5°C to 5°C	Varies ± 0.5°C to 4 °C
Output Signal	40 µV°C	≈ 0.00385 Ω/Ω/°C	≈ 4 % ΔR°C	Analog, Serial, Logic, Duty Cycle
Linearity	Fair	Excellent	Poor	Good
Precision	Fair	Excellent	Poor	Fair
Durability	Good at lower temp., Poor at high temp, Open-circuit vibration failures	Good, Wire wound prone to open-circuit vibration failures	Good, Power derated with temperature	Excellent
Thermal Response Time	Fast (function of probe material)	Fast (function of probe material)	Moderate	Slow
Cost	Low	Wire wound – High, Thin-film – Moderate	Low	Moderate
Interface Issues	Cold junction compensation, Small ΔV	Small ΔR/°C	Non-linear resistance	Sensor located on PCB

Common elements, such as Resistance Temperature Detectors (RTDs), thermistors, thermocouples or diodes are used to sense absolute temperatures, as well as changes in temperature. Of these technologies, the platinum RTD temperature sensing element is the most accurate and stable over time and temperature.

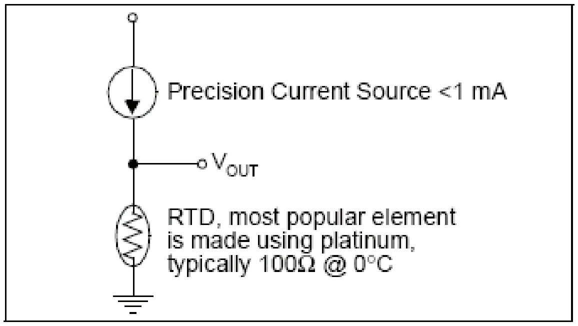

Fig.1. Current Excitation.

C. RTD Current Excitation Circuit

For best linearity, the RTD sensing element requires a stable current reference for excitation. In this circuit, a voltage reference, along with two operational amplifiers, are used to generate a floating 1 mA current source.

This is accomplished by applying a 2.5V precision voltage reference to R_4 of the circuit. Since R_4 is equal to R_3, and the non-inverting input to U1 is high impedance, the voltage drop across these two resistors is equal. The voltage between R_3 and R_4 is applied to the non-inverting input of U1. That voltage is gained by $(1 + R_2/R_1)$ to the output of the amplifier and the top of the reference resistor, R_{REF}. If $R_1 = R_2$, the voltage at the output of U1 is equal to:

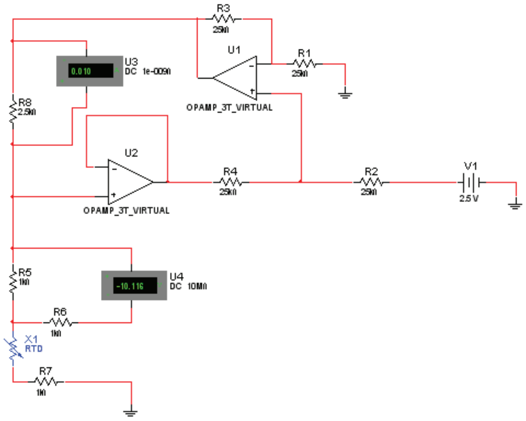

Fig.2 A Current Source for the RTD element can be constructed in a single-supply environment from two operational amplifiers and a precision voltage reference.

Equation

$$V_{OUTU1} = \left(1 + {}^{R_2}\!/_{R_1}\right) \times \left(V_{REF} - V_{R4}\right)$$

$$V_{OUTU1} = 2 \times V_{REF} - V_{R4}$$

Where:

V_{OUTU1} is the voltage at the output of U1 and

V_{R4} is the voltage drop across R_4.

The voltage at the output of U1 is equal to:

Equation

$$V_{OUTU1} = V_{REF} - V_{R4} - V_{R3}$$

This same voltage appears at the inverting input of U2 and across to the non-inverting input of U2.

Solving these equations, the voltage drop across the reference resistor, R_{REF}, is equal to:

$$V_{RREF} = V_{OUTA1} - V_{OUTA2}$$

$$V_{RREF} = 2 \times \left(V_{REF} - V_{R4}\right) - \left(V_{REF} - V_{R4} - V_{R3}\right)$$

$$V_{RREF} = V_{REF}$$

Where:

V_{RREF} is the voltage across the reference resistor, R_{REF} and, V_{R3} is the voltage drop across R_3

The current through R_{REF} is equal to:

Equation

$I_{RTD} = V_{REF} / R_{REF}$ This circuit generates a current source that is ratio metric to the voltage reference. The same voltage reference can be used in other portions of the circuit, such as the analog-to-digital (A/D) converter reference. Absolute errors in the circuit will occur as a consequence of the absolute voltage of the reference, the initial offset voltages of the operational amplifiers, the output swing of U1, mismatches between the resistors, the absolute resistance value of R_{REF} and the RTD element. Errors due to temperature changes in the circuit will occur as a consequence of the temperature drift of the same elements listed above. The primary error sources over temperature are the voltage reference, offset drift of the operational amplifiers and the RTD element.

D. RTD Signal-Conditioning Path

Changes in resistance of the RTD element over temperature are usually digitized through an A/D conversion. The current excitation circuit is used to excite the RTD element. With this style of excitation, the magnitude of the current source can be tuned to 1 mA or less by adjusting R_{REF}. The voltage drop across the RTD element is sensed by U3, then gained and filtered by U4. With this circuit, a 3-wire RTD element is selected. This configuration minimizes errors due wire resistance and wire resistance drift over temperature.

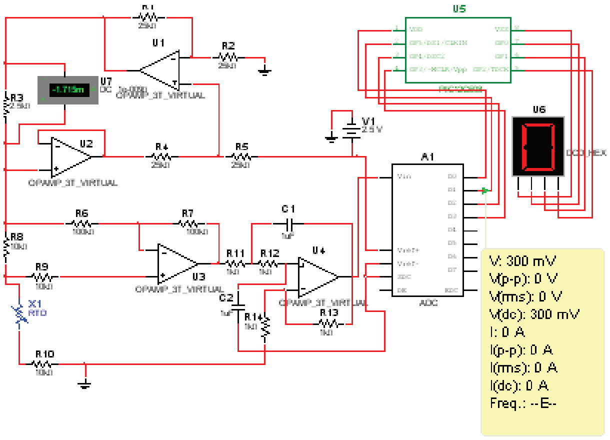

Fig.3 Simulated Circuit

Figure-3 Simulated Circuit uses a RTD temperature-sensitive element to measure temperatures from -200^{0}C to 800^{0}C. The current generator circuit excites the sensor. An operational amplifier (U3) is used to zero wire resistance error. A fourth amplifier (U4) is used to gain the signal and filter possible alias interference. A 12-bit converter (MCP3201) converts the voltage across the RTD to digital code for the 8-pin controller (PIC12C508).

In this circuit, the RTD element equals 100Ω at 0^{0}C. If the RTD is used to sense temperature over its entire range of -200^{0}C to 600^{0}C, the range of resistance produced by the RTD would be nominally 23Ω to 331Ω. Since the resistance range is relatively low, wire resistance and wire resistance change over temperature can skew the measurement of the RTD element. Consequently, a 3-wire RTD device is used to reduce these errors. The errors contributed by the wire resistances, R_{W1} and R_{W3}, are subtracted from the circuit with U3, the operational amplifier circuit. In this configuration, R_1 and R_2 are equal and are relatively high. The value of R_3 is selected to ensure that the leakage currents through the resistor do not introduce errors to the current in the RTD element. The transfer function of this portion of the circuit is:

Equation

$$V_{OUTU3} = \left(V_{IN} - V_{W1}\right)\left(1 + {R_2}/{R_1}\right) - V_{IN}\left({R_2}/{R_1}\right)$$

where:

$$V_{IN} = V_{W1} + V_{RTD} + V_{W3}$$

V_{Wx} is the voltage drop across the wires to and from the RTD and

V_{OUTU3} is the voltage at the output of U3.

If it is assumed that

$R_1 = R_2$ and $R_{W1} = R_{W3}$ the transfer function above reduces to:

$V_{OUTU3} = V_{RTD}$

The voltage signal at the output of U3 is filtered with a 2nd order, low pass filter created with U4, R12, C1, R13 and C2. This same signal is also gained by the resistors R_5 and R_6.

IV. Conclusions

The following conclusion have been made in this study.

1. Although the RTD requires more circuitry in the signal conditioning path than the thermistor or the silicon temperature sensor, it ultimately provides a high-precision, relatively linear result over a wider temperature range [-200^{0}C to 800^{0}C].
2. Stable, repeatable and reliable within the temperature range.
3. RTDs exhibit faster responses and cost is also reasonable for the thin film RTD.
4. The change of resistance is converted into mill volts [10mv/^{0}C].
5. If further linearization is performed in the controller, the RTD circuit can achieve ±0.01°C accuracy.

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