A Comparative Study of Accuracy Improvement of Temperature Measurement with PT100 and PT1000 for Wider Range

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Abstract

Quality assurance approaches such as Six-Sigma is increasingly adopted in process plants because of which accurate measurements and good measurement practices are becoming a necessity. This paper makes a thorough study and comparison of the accuracy of temperature measurement over a certain range that can be achieved using a PRTD100 and PRTD1000 in a measurement system. The measurement techniques that can be used to improve the accuracy over a wider range of temperature were discussed. The paper proposes hardware architecture of the measurement system that can be used with any data acquisition application system. Results indicate that, in the measurement system that uses the PRTD1000 as the sensing element, if correct linearization algorithm is used then it is possible to minimize the linearization error down to ±0.15%, over a range of -200°C till +800°C, which is better than the class F0.3 tolerance (±0.3°C).
Keywords: PRTD (Platinum Resistance Temperature Detector), ADC (Analog to Digital Converter), CJC (cold junction compensation), PRT (Platinum Resistance Thermometer),

I. INTRODUCTION

Temperature measurement and monitoring is a widespread and common engineering task. Performing high resolution accurate temperature measurement in a factory or laboratory is essential but may become difficult and expensive. Most commonly, a simple thermocouple is used along with a data acquisition device and some kind of signal conditioning hardware. Highly accurate temperature measuring equipment is now widely available at very reasonable costs but, whilst this should be making the task of making temperature measurement easy, there are errors either in using the sensor or making a correct choice of the sensor for a particular application of temperature measurement. Precision RTD (Resistive Temperature Detector) instrumentation is a key for high performance thermal management applications. Semiconductor sensors with an accuracy ±0.5°C (typical) and ±1°C (maximum) are feasible to be used with microcontrollers that doesn’t require to be linearized, but the range of temperature over which the accuracy can be achieved is limited between -40°C to +120°C. Platinum Resistance Temperature Detector offers the best accuracy and repeatability over a temperature range of -200°C to +800°C and is ideal for industrial and medical applications. With the implementation of more math intensive polynomial expression in the microcontroller firmware, ±0.1°C accuracy and ±0.01°C measurement resolution can be achieved across the RTD temperature range of -200°C to +800°C with a single point calibration.

II. LITERATURE SURVEY

In September, 2015, [1] National Instruments published an article on how to perform high accuracy temperature measurement using thermocouples and RTD. In July, 2015, [2] Garry Prentice of Moore Industries published an article in Flow Control Magazine some guidelines on making accurate temperature measurements. The issues that are required to be taken care while performing temperature measurements for specific applications were discussed.

III. TEMPERATURE MEASUREMENT WITH PT100

Figure 1 shows the scheme of using a PT100 PRTD sensing element to measure temperature.
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A. Temperature Measurement Scheme using PT100 PRTD

![Temperature measurement scheme with PT100 PRTD](image)

The MAX31865 is a sophisticated RTD-to-digital converter with a built-in 15-bit analog-to-digital converter (ADC), input protection, a digital controller, an SPI-compatible interface, and associated control logic. The signal conditioning circuitry is optimized to work with PT100 through PT1000 RTDs. A precision reference resistor of 430Ω is used with PT100. The bias voltage output from the MAX31865 is used to bias the reference resistance and the current flowing through the reference resistance excites the PRTD. The voltage across the RTD is applied to the ADC’s differential inputs (RTDIN+ and RTDIN-). The voltage across the reference resistor is the reference voltage for the ADC. Therefore the ADC produces a digital output that is equal to the ratio of the RTD resistance to the reference resistance. The ADC can measure the temperature accurately and ratio-metrically.

The bias voltage applied to the reference resistor is 1.93V and the excitation current flowing through the PRTD element is measured to be 1.5mA.

\[ R_t = \left( \frac{A_{adc}}{32768} \right) \times 430 \]

Where \( A_{adc} \) is the ADC output code of MAX31865

B. Error due to lead wires

The resistance of a 22-Gauge copper wire is 0.0161Ω per foot. The lead wire resistance for a 10 ft. long lead wire is given by

\[ R_W = 2 \times 10 \times 0.0161 = 0.322Ω \]

The error in temperature due to the lead wire resistance \( T_{WER} \) is \( R_W / S \), where \( S \) is the average PRTD sensitivity. For a PT100 device \( S = 0.385Ω/°C \) at 0°C. Therefore

\[ T_{WER} = 0.322Ω / 0.385Ω/°C = 0.836°C \]

According to IEC60751 standard it is higher than the class F0.3 tolerance of ±0.30°C. This means that 10-feet long lead wires require some kind of wire compensation method if PRTD100 is used as the temperature sensing element. Therefore 4-wire configuration as shown in figure 1 is used to remove the error due to lead wires resistances.
C. Error due to PRTD self heating

The thermal error $T_{err}$ is given by

$$T_{err} = I_{ext}^2 \times R_t \times K_{tpack}$$

where $I_{ext}$ is the excitation current, $K_{tpack}$ is the PRTD self-heating error coefficient (0.7°C/mW) of the PRTD in free air.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>$I_{ext}$ (mA)</th>
<th>$R_t$ (Ω)</th>
<th>$T_{err}$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20</td>
<td>1.5</td>
<td>92.16</td>
<td>0.145</td>
</tr>
<tr>
<td>0</td>
<td>1.5</td>
<td>100</td>
<td>0.1575</td>
</tr>
<tr>
<td>50</td>
<td>1.5</td>
<td>119.4</td>
<td>0.188</td>
</tr>
<tr>
<td>120</td>
<td>1.5</td>
<td>146.07</td>
<td>0.23</td>
</tr>
</tbody>
</table>

So, between temperature of -20°C and +120°C maximum value of $T_{err} = 0.23°C$ which is below the class F0.3 tolerance of ±0.30°C. But with the increase of PRTD resistance the thermal error increases. Therefore to achieve higher accuracy over a wider range towards the higher value of temperature, we need to decrease the excitation current.

D. Linearity error

To study the linearity error of the measurement system using the PRTD100 device in figure 1, different readings were taken over a temperature range of -20°C to 120°C.

First order equation to calculate $R_t$ is given by

$$R_t = R_0 (1 + T \times a)$$

Where $R_0$ is the PRTD resistance, $T$ is the temperature to be measured, $R_0$ is the resistance at 0°C.

$$a = 0.00385 \, ^\circ C^{-1}$$

is the temperature coefficient as specified by IEC60751 standard.

Second Order equation to calculate $R_t$ is given by

$$R_t = R_0 (1 + a \times T + b \times T^2)$$

Where $R_t$ is the PRTD resistance, $T$ is the temperature to be measured, $R_0$ is the resistance at 0°C.

$$a = 0.0039083 \, ^\circ C^{-1} \ and \ b = -5.775 \times 10^{-7} \, ^\circ C^{-2}$$

is the temperature coefficient as specified by IEC60751 standard.

The microcontroller measures the ratio of $R_t / R_{ref}$

Where $R_{ref} = 430 \, \Omega$

$$R_t / R_{ref} = A_{adc} / 32768$$

where $A_{adc}$ is the analog to digital converter output code of MAX31865.
From equation (2), (3) and (4), the microcontroller firmware can calculate the temperature \( T \). Temperature measurements were taken between \(-20°C\) to \(120°C\) using 1\(^{st}\) and 2\(^{nd}\) order equation with PRTD100 using the hardware described in figure 1. Figure 2 shows the temperature measurement error\% using 1\(^{st}\) and 2\(^{nd}\) order equation.

![Figure 2: Temperature Measurement with PRTD100 between -20°C and 120°C](image)

It is seen from figure 2 that for temperature range between \(-20°C\) to \(120°C\), the error is lesser with 2\(^{nd}\) order equation.

![Figure 3: PRTD100 Linearity Error for temperature range of -20°C to +120°C](image)

The PRTD100 linearity error for temperature range between \(-20°C\) and \(+120°C\) is shown in figure 3. For temperatures up to \(120°C\), linearity error is minimum with the use of 2\(^{nd}\) order equation.

The linearity error for a wider range of temperature between \(-200°C\) and \(+200°C\) is shown in figure 4.
For negative temperatures 2\textsuperscript{nd} order equation works well with less error up to -100°C, but when temperature is decreased further up to -200°C, the linearity error can be even minimized further with the use of 3\textsuperscript{rd} order Callendar-Van Dusen equation

\[ R_t = R_0 [1 + a \times T + b \times T^2 + (T-100) \times c \times T^3] \] \hspace{1cm} (4)

having three coefficients, where

\[ a = 0.0039083 \degree C^{-1} \]
\[ b = -5.775 \times 10^{-7} \degree C^{-2} \]
\[ c = -4.183 \times 10^{-12} \degree C^{-2} \]
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IV. TEMPERATURE MEASUREMENT WITH PT1000

In figure 1, the sensor PT100 is now replaced with PT1000. The reference resistor used is 4.3KΩ.

A. Error due to lead wires

The length of the 24AWG (American Wire Gauge) copper wire that is used in figure 1 is 10 feet. Its resistance per foot at 25°C is 0.0161Ω. The lead wire resistance is given by

\[ R_W = 2 \times 10 \times 0.0161 = 0.322\Omega \]

The error in temperature due to the lead wire resistance \( T_{WER} \) is \( R_W / S \), where \( S \) is the average PRTD sensitivity. For a PT1000 device \( S = 3.85\Omega/°C \). Therefore

\[ T_{WER} = 0.322Ω / 3.85Ω/°C = 0.08°C \]

According to IEC60751 standard it is one order of magnitude below the class F0.3 tolerance of ±0.30°C. This means that 10-feet two-wire configuration of PRTD can be used directly without any method of wire compensation.

B. Error due to PRTD self heating

Excitation current that flows through the PRTD warms up the sensor that increases the sensor resistance above the level that it would otherwise assume due to the temperature being measured. This introduces the error due to self-Heating. Excitation current also produces the voltage drop across the sensor to be measured by the ADC. It must be as high as practical to ensure that it remains above the ADC’s voltage noise level. The thermal error \( T_{err} \) is given by:

\[ T_{err} = I_{ext}^2 \times R_t \times K_{tpack} \]

Where \( I_{ext} \) is the excitation current, \( K_{tpack} \) is the RTD self-heating error coefficient (0.7 °C/mW).

<table>
<thead>
<tr>
<th>Temperature</th>
<th>( I_{ext} ) (µA)</th>
<th>( R_t ) (Ω)</th>
<th>( T_{err} ) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20</td>
<td>108</td>
<td>921.6</td>
<td>0.007</td>
</tr>
<tr>
<td>0</td>
<td>108</td>
<td>1000</td>
<td>0.008</td>
</tr>
<tr>
<td>50</td>
<td>108</td>
<td>1194</td>
<td>0.0097</td>
</tr>
<tr>
<td>120</td>
<td>108</td>
<td>1460.7</td>
<td>0.011</td>
</tr>
</tbody>
</table>

So, between temperature of -20°C and +120°C maximum value of \( T_{err} = 0.011°C \) which is much below the class F0.3 tolerance of ±0.30°C. Even at the highest temperature of 800°C of PRTD range, the thermal error is 0.03°C. Since the excitation
current is low, the thermal error is brought down to a minimum value thereby increasing the accuracy of measurement.

CONCLUSION
Summarizing the points altogether for performing a high accuracy temperature measurement following need to be ensured:

a) Four-wire RTDs eliminate the errors caused by copper wire leads.
b) Use Class A RTDs that have been aged through temperature cycling.
c) The excitation current flowing through the PRTD needs to be kept as low as possible to minimize the error due to self heating.
d) The reference resistor used in the circuit for figure 1 should be of metal-film type of ±0.1% or better tolerances and ¼ power rating, and a low temperature coefficient.

Use of PRTD1000 will result in achieving higher accuracy than PRTD100, since the excitation current required in PRTD1000 is less than PRTD100. To measure temperature over increased range from 0°C to +800°C, use of 2nd order equation will result in higher accuracy as shown in figure 5. For temperatures between -20°C and +120°C, when 1st order equation is used then error lies within ±0.15% as shown in figure 3, but for more negative temperatures, error increases. Second order equation can be used for negative temperatures with minimum error up to -100°C, but for more negative temperatures beyond -100°C error increases as shown in figure 4. When 3rd order equation is used for negative temperatures beyond -100°C, it works considerably well with very less error up to -200°C, but it requires a high speed processing processor to handle the math intensive 3rd order equation.

REFERENCES
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