Considerations regarding Temperature Measurement using RTDs for Industrial Process Plants

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1. Introduction

Temperature is the most important parameter to be measured in industrial process plants such as power and chemical plants. Four types of temperature sensors are generally used in the industrial instrumentation and control systems for such plants. Because each type of sensors has its own unique features, careful considerations should be reviewed to avoid undesirable effects when we select the sensor types and design an instrumentation system.

This paper presents a review of the key factors to be considered when a temperature instrumentation system is designed for high-temperature processing plants such as nuclear power and petrochemical industry plants. In particular, three main error factors influencing the accuracy of the RTDs (Resistance Temperature Detectors) are reviewed and addressed in this paper.

2. Selection of Temperature Sensor Types

In this section, the general selection criteria of sensor types for industrial temperature measurements for an I&C (Instrumentation and Control) system are described.

2.1 Features of Sensor Types

In General, four sensing devices are considered when process instrumentation engineers design a fluid monitoring and control system on temperature measurement if a direct contact measurement is allowed, namely, thermocouples, RTDs, thermistors, and IC (Integrated Circuit) sensors.

Each sensor type has its pros and cons [1, 2]. The best points of each type are as follows:

- Thermocouple: highest temperature range,
- RTD: highest accuracy,
- Thermistor: highest sensitivity (resolution),
- IC sensor: lowest cost.

2.2 Selection Criteria

Basically, the selection of sensors is a compromise between the requirements of the users or systems and the limitations of the sensor types which are possible to be used under the measurement conditions. Based on the typical characteristics and evaluations of each temperature sensor type [1-4], the followings will be the rules of thumb for selection.

- If the maximum temperature to be measured is above 500 ℃, thermocouples will only be the first choice.
- If accuracy and stability are concerns for a process temperature control system within the range of 100-500 ℃, then RTDs are the best choice.
- If high resolution or sensitivity is required for a fine control of the temperature below 200 ℃, then the thermistor sensors will be the answer.
- If the lowest cost is essential by scarifying other features, then IC sensors should be considered for the first priority
- If the temperature sensor is installed in a nuclear reactor in which the neutron flux is dominant, then thermocouples will be the only choice [5].

3. Key Factors Affecting to Accuracy of RTD based Temperature Measurement

RTDs are one the most common industrial temperature sensors, owing to their excellent stability and accuracy. For example, they are used for measuring the temperatures of the RCS (Reactor Coolant System) in the primary side and also the feed water temperatures in the secondary side in NPPs (Nuclear Power Plants). Because these parameters are very important in calculating the reactor power and thermal efficiency, they need to be measured accurately to the greatest extent possible.

However, there are many factors affecting the accuracy of the measurement value such as the wire resistance, self-heating, EMF errors, non-linearity, corrosion and contamination, radiation, and insulation loss [3, 5]

In the following subsections, three main factors related to the potential errors in an RTD measurement circuit have been reviewed and analyzed

3.1 EMF Errors

The RTD element, generally made of platinum, is connected to a measuring circuit via the lead wires, which are copper or other alloy wires. Fig. 1 illustrates a typical RTD connection circuit.

In Fig. 1, the materials of the RTD element wires, internal lead wires, and connection lead wires are usually different from each other. In general, an RTD element is made of pure platinum. However, internal wires are made of a platinum alloy or a gold alloy, and the copper wires are used for external connection from the internal wires to the measuring device [6].

If the temperature of each end of an electric conductor is not the same, for example, T_1 is not the same as T_2, then an EMF (Electromagnetic Force), E1, arises in proportion to the temperature difference (T_1-T_2) because of the Seebeck effect.

Eq. (1) shows the total EMF in the 4-wired configuration method and Eq. (2) applies to 2-wired RTD instrumentation circuits.

$$EMF_4 = E1 + E2 + E3 \quad (1)$$

$$EMF_2 = E1 + E2 + E3 + E4 + E5 \quad (2)$$

In the case of a 4-wired system, the total thermoelectric EMF_4 is not zero when there is a temperature deviation between T1 and T2, or between T3 and T4, or if there is a deviation in homogeneity between the materials of the two internal wires. This unnecessary EMF voltage yields a small error in the RTD resistance reading of the voltmeter in this circuit.

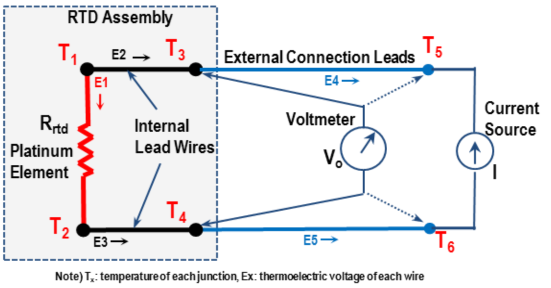

Fig. 1. RTD connection wires

Research has shown the EMF values within the range of 0.1~17.9 μV for 25 nuclear grade RTDs at 300 ℃ [7]. The max value, 17.9 μV, corresponds to an error of 0.09 ℃ when I = 0.5 mA in the case of a Pt-100 RTD, and becomes 0.0046 ℃ when I = 10 mA. Therefore, the higher excitation current has less effect of EMF.

3.2 Self-heating Errors

A self-heating error occurs because the RTD element is heated up to beyond the process temperature additionally by the excitation current injected from the instrument used to measure the resistance.

The temperature increment due to self-heating can be calculated through Eq. (3) [3, 8].

$$\Delta T = (I^2 \times R_{rtd}) \times h \quad (3)$$

Here, ΔT is the change in temperature owing to the power dissipation, I is the excitation current to the RTD, R_{rtd} is the resistance of the RTD in Ω, and h is the self-heating coefficient in ℃/mW.

On the contrary to the EMF effect presented in Section 3.1, the self-heating effect is alleviated as less excitation current is injected to the RTD sensor.

If the self-heating coefficient is 0.05 ℃/mW (a typical value for flowing water [8]), then the temperature deviation, ΔT in Eq. (3), will be +1.05 ℃ when the excitation current is 10 mA and the process temperature is 300 ℃.

However, if we take 0.5mA for the excitation current, it decreases to 0.00265 ℃. This figure indicates a significant improvement compared to the case of a 10 mA current.

The above examples tell us why it is recommended that the excitation current be less than 1mA for Pt-100 RTDs in IEC 60751 [9].

However, there are also limitations in using a low excitation current because a noise issue (signal-to-noise) and a low-resolution (accuracy) issue in the resistance measurement circuit should also be considered.

3.3 Lead Wire Resistance Effects

Because of the fabrication ability and self-heating issues, the 100Ω-RTDs, called pt-100 are generally used in most industrial plants. If so, the sensitivity(temperature coefficient) becomes 0.385 Ω/℃. This low sensitivity means that a 1-Ω deviation corresponds to a 2.6 ℃ error in the temperature measurement value.

Therefore, the resistance of the lead wires is not negligible when their length is more than even a couple of meters. For example, the resistance of a 20AWG wire is 0.33 Ω/m, and thus it will contribute to an error of 0.84℃ per meter when the wires are used for the connection leads of pt-100 RTDs.

To compensate or cancel the effects of the resistance of the lead wires in an RTD measurement circuit, one of the techniques for eliminating or reducing the influence of an RTD signal line wire resistance should be selected and used in the temperature instrumentation design of an industrial process plant.

One of simple ways is to compensate the reading error by a proper *in-situ* calibration method.

However, the resistance change in lead wires due to the ambient temperature change between the RTD element and the instrument circuit is another factor affecting the accuracy of the measurement values.

For example, a 300 m 20AWG wire with 10Ω resistance at 10℃ will become 11Ω when the ambient temperature changes to 35 ℃ [9]. Then, the total increase of 2Ω in two wires for a circuit brings about a 5.2℃ deviation in the measurement reading. This error is too large to accept in most industrial applications.

Thus, one of the techniques for eliminating or cancelling the resistance effect of the connection wires is selected and adopted in the RTD measurement circuits of an I&C system.

3.4 Comparison of Different Connection Methods

This section introduces and compares some typical connection methods compensating the lead wire resistance effect in the RTD measurement circuits. A more detailed explanation and accuracy calculation analyses of each connection method are presented in [10].

Fig. 2 illustrates a three-wired bridge connection. In this method, the resistance effect is negligible only when the bridge circuit is balanced, i.e., $V_o = 0$.

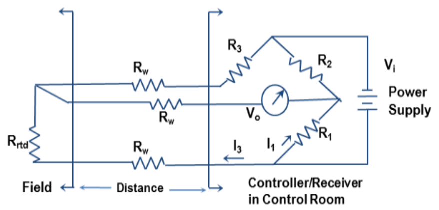

Fig. 2. Three-wired RTD bridge connection circuit [10]

Fig. 3 illustrates a three-wired RTD measurement system with one current-source and one voltmeter. In this method, only one of two wires is compensated, thus the deviation still becomes half that of two-wired measurement circuits

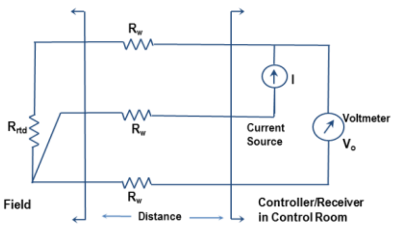

Fig. 3. Three-wired connection with one current-source and one voltmeter [10]

Fig. 4 illustrates a three-wired RTD measurement system with two current-sources and one voltmeter. This connection strategy is one of the best three-wired circuits used to cancel the lead-wire resistance effect without any *in-situ* calibration [10].

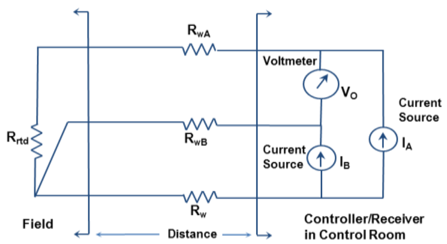

Fig. 4. Three-wired connection with two current sources and one voltmeter [10]

The four-wired configuration is illustrated in Fig. 5. It is regarded as the best solution for compensating the resistance effect of the lead wires, although it needs an additional lead wire.

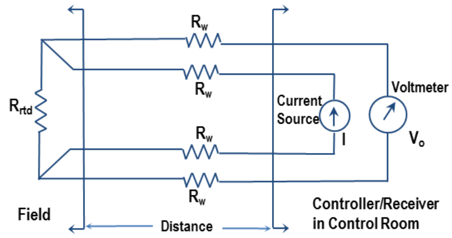

Fig. 5. Four-wired connection with one current source and one voltmeter [10]

Another way to account for the lead wire resistance effect is to install an RTD transmitter near to the RTD sensor, and then receive a 4-20 mA current signal related with the sensor resistance, as illustrated in Fig. 6.

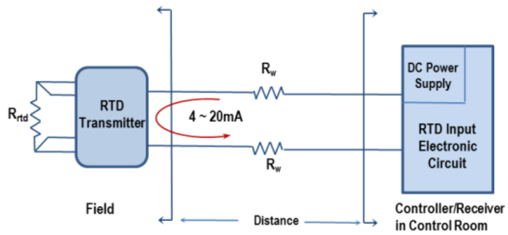

Fig. 6. RTD measurement circuit using a transmitter

Table 1 summarizes the general features of the RTD temperature configurations described above.

Table I: Features of Different RTD Connection Methods

Connection Methods (Note)	1)	2)	3)	4)	5)
Lead Wire Resistance Effect	Yes	Yes	No	No	No
Necessity of In-Situ Calibration	Yes	Yes	No	No	Yes
Number of Wires	3	3	3	4	2
Recommended for Industrial Application	No	Limited	Yes	Yes	By Case

Note: 1) 3-wired bridge circuit (Fig.2)
2) 3-wired 1-current source with 1-voltmeter (Fig.3)
3) 3-wired 2-current source (Fig. 4)
4) 4-wired circuit (Fig. 5)
5) Transmitter method (Fig. 6)

4. Conclusions

Among the various temperature sensors, RTDs are used the most commonly for high-temperature control and monitoring systems in industrial plants thanks to their excellent accuracy and stability compared to other sensors.

However, several factors should be considered for using them properly with regard to their advantages.

This paper addressed three key factors affecting the accuracy performance of RTDs.

Although the EMF effect may become slightly bigger, it is recommended to design an RTD instrumentation circuit with a low excitation current or voltage to reduce the self-heating effect unless the usage of a low current ruins the noise immunity feature of the circuit.

In addition, because the compensation of lead wire resistance in RTD circuits is an essential factor to be addressed, it is desirable to carefully review the installation circumstances and connection configuration of a temperature sensor.

ACKNOWLEDGEMENT

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