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Self-heating and Wire Resistance Effects in Temperature Measurement using RTD Sensors

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1. Introduction

Since their introduction in 1870 by William Siemens, RTDs (Resistance Temperature Detectors) are regarded as one of the most widely used temperature sensors for industrial purposes, owing to their excellent linearity, stability and accuracy [1-3].

However, several factors should be carefully considered to avoid undesirable accuracy issues when an RTD is selected for temperature instrumentation in a process plant.

This paper presents a review of two main issues, self-heating and lead wire resistance, which will significantly ruin the accuracy benefit of RTDs unless properly addressed in the instrumentation circuits.

2. Self-heating Effects

2.1 Principles

Because the RTD is a resistance-based sensor, its resistance must be measured by the current-voltage relationship stated in Ohm's law. When a current passes through a resistor, power consumption occurs in the resistor. This power consumption also heats up the resistor to increase its resistance. If a constant current is injected into an RTD to measure the resistance, the increment in resistance will be balanced when generated heat is equal to the heat dissipated to the surrounding media. Therefore, the equilibrium temperature of the RTD sensor becomes higher than the actual temperature of the medium to be measured. This self-heating phenomenon causes a positive error in temperature measurement when RTDs are used.

2.2 Calculation of Temperature Error caused by Self-heating Effect

In a certain surrounding condition of a RTD sensor, its temperature increment due to self-heating can be calculated by Eq. (1) [4, 5].

$$\Delta T = (I^2 \times R_{rtd}) \times h \quad (1)$$

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

If a conventional RTD instrument circuit requires a 6V input at 558℃ with a Pt-100 RTD, the excitation current should be 20mA because the resistance of an RTD at 558℃ is 300 Ohms.

The self-heating coefficient of an RTD submerged in the water flowing at 1 m/s is within the range of 0.1 to 0.01℃/mW [4-7]. Therefore, if we take 0.05 as the self-heating coefficient, then the error in temperature reading, ΔT, will be 6℃ at 558℃. This is a big error corresponding to a reading of 1%.

The self-heating effect is very dependent on the medium in which the RTD is immersed. It becomes more significant in still air because an RTD in air can heat up 100 times higher than in flowing water, which means the coefficient in air will be 100 times higher than the above range [4, 8].

Therefore, it is recommended to reduce the excitation current of RTDs in order to minimize the self-heating error. However, there is limitation 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. In general, it is recommended that the excitation current should be less than 1mA for Pt-100 RTDs [6, 9].

3. Lead Wire Resistance Effects

3.1 Principles

An RTD is generally connected to a resistance measurement circuit with copper lead wires. The resistance of lead wires is not negligible when it is compared to the resistance sensitivity of the RTD elements.

For example, the resistance of a 20AWG wire is 0.33Ω/m, and thus it will contribute to an error of 0.84℃ per meter when the leads are used for 100Ω platinum RTDs.

Therefore, it is usually necessary to compensate or cancel the effects of the resistance of the lead wires when an RTD is used for a temperature measurement with the wires longer than a few meters.

Even though the resistance of long lead wires connecting to an RTD could be compensated using a proper calibration method at a certain time, the resistance change in lead wires due to the ambient temperature change between the RTD element and the instrument circuit cannot be compensated all of the time.

The effects of a long lead wire resistance are widely addressed and reviewed with various practical wiring methods in [3].

4. Potential Measurement Errors from Lead Wire Resistance and Self-heating Effects

In this section, we summarize the potential error ranges of each RTD connection methods in practical conditions presented in [3] and also discuss the estimated errors from self-heating under the same conditions.

4.1 Potential Errors in Different RTD Connection Methods

4.1.1 Two-wired Wheatstone Bridge Configuration

A two-wired bridge circuit for an RTD measurement is shown in Fig. 1.

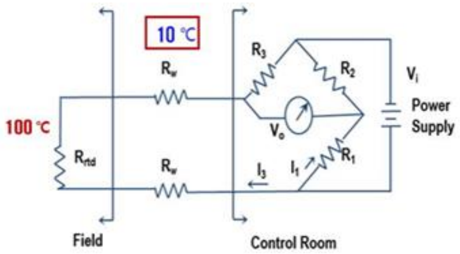

Fig. 1 Two-wired RTD connection bridge circuit [3]

In Fig. 1, assuming a circuit condition in which V_i =10V, R_1=R_2=R_3=100Ω, R_w=10Ω (corresponding to a length of 300m of a 20AWG wire), and R_{rtd} = 140Ω (assuming it is adjusted for 100 ℃), the reading of the measurement (Rx) is 160 Ω because 2 x R_w is added in the measurement scheme [3].

However, under this condition, if the self-heating coefficient is 0.05, then the temperature deviation, ΔT in Eq. (1), will be +10.35℃ making the measurement reading 164Ω.

If it is calibrated to 100℃ under this condition, an error of +5.1℃ is presented when the ambient temperature of the signal wires around R_w in Fig. 1 increases to 35℃ from 10℃ [3]. The error is caused from the wire resistance change.

In this in-situ calibrated condition at 10℃ in ambient temperature, if the process temperature moves to 200℃, thus it makes R_{rtd} =180Ω, then the temperature deviation, ΔT in Eq. (1), will be +9.87℃ making the measurement error of -0.48℃. This error is contributed by the self-heating effect.

4.1.2 Three-wired Wheatstone Bridge Configuration

In the three-wired bridge circuit illustrated in Fig. 2, if we take the same conditions discussed in Section 4.1.1, the error from the wire resistance will be -8℃ [3], and the error from the self-heating will be +10.35℃ making the total error +2.35 ℃.

If it is calibrated to 100℃ under this condition, an error of -0.84℃ is presented when the ambient temperature of the signal wires around R_w in Fig. 2 increases to 35℃ from 10℃ [3].

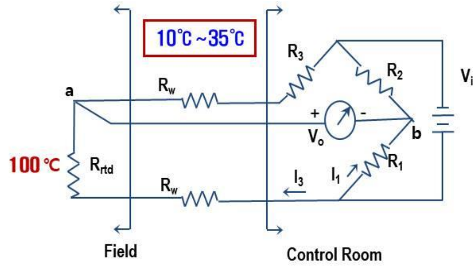

Fig. 2 Three-wired RTD bridge connection circuit [3]

Without ambient temperature change in this calibrated condition, if the process temperature moves to 200℃, thus it makes R_{rtd}=180Ω, then the temperature deviation, ΔT in Eq. (1), will be the same in Section 4.1.1 which is an error of -0.48℃.

However, if we take V_i=1V regardless of noise immunity issues, ΔT will be 1/100 less than in the case of V_i=10V, which is a significant improvement in self-heating errors.

4.1.3 Three-wired Circuit with One Current-source and One Voltmeter

Fig. 3 illustrates a three-wired RTD measurement system with one current-source and one voltmeter.

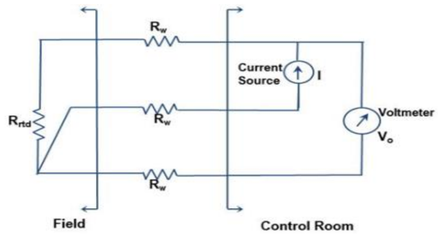

Fig. 3 Three-wired connection with one current-source and one voltmeter [3]

In this configuration with the same conditions as Section 4.1.1, the RTD resistance (R_{rtd}) is measured as 150Ω when R_w=10Ω, and 151Ω when R_w=11Ω. Thus, it creates an error of 25.5℃ and 28.05℃ for each case (1Ω = 2.55℃) [3].

The self-heating effect in this circuit creates an error of +0.7℃, when the excitation current-source is 10 mA.

If it is calibrated in-situ to 100℃ under this condition, an error of +2.55℃ is presented when the ambient temperature of the signal wires around R_w increases to 35℃ from 10℃ [3].

With this calibrated status, if the process temperature moves to 200℃, thus it makes R_{rtd}=180Ω, then the temperature deviation, ΔT in Eq. (1), will be +0.9℃ making an additional error of +0.2℃.

4.1.4 Three-wired Circuit with Two Current-sources and One Voltmeter

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 to cancel the lead-wire resistance effect without any in-situ calibration [3].

With this method, even when the ambient temperature of the signal wires around R_w increases to 35℃ from 10℃, the temperature reading is almost the same as 140Ω corresponding to 100℃ [3].

However, when the excitation current source is 10mA, the self-heating effect will contribute to an error of +0.7℃ in the process condition of 100℃ and +0.9℃ in the condition of 200℃.

Therefore, in this three-wired configuration, the self-heating effect will be a dominant error factor.

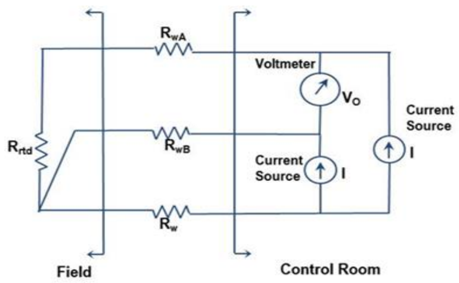

Fig. 4 Three-wired connection with two current sources and one voltmeter [3]

4.1.5 Four wired Circuit with One current-sources and One Voltmeter

The four-wired RTD measurement configuration illustrated in Fig. 5 is regarded as the best solution for compensating the resistance effect of lead wires.

The error analysis results regarding the lead wire resistance and self-heating effect in this circuit are the same as described in Section 4.1.4.

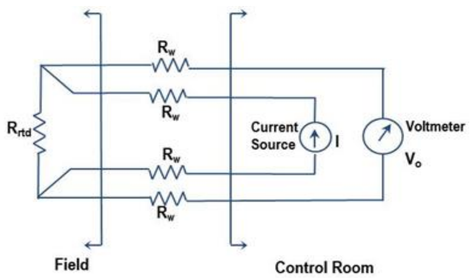

Fig. 5 Four-wired connection with one current source and one voltmeter [3]

5. Conclusions

Among the issues to be considered when an RTD is used to measure the temperature in industrial process plants, the effects of lead wire resistance and self-heating are the most significant considerations to avoid the misreading of temperature.

Some three-wired connection methods and a four-wired method have been analyzed to reveal that the lead-wire resistance is compensated almost perfectly [3].

However, the self-heating effect in the RTD sensor cannot be resolved perfectly. The error caused by the self-heating phenomenon will further increase in a high temperature range when a current-source method is adopted for an RTD measurement.

Therefore, it is recommended to choose an RTD measurement circuit using a low excitation current or voltage to reduce the self-heating effect as long as the low current does not ruin the noise immunity feature of the circuit. The selection of a lower resistance RTD, for example, Pt-100 rather than Pt-1000, will also decrease the self-heating error in proportion to the resistance of the RTD element.

In particular, when a RTD sensor is used to measure the temperature of gas or air, the potential error induced from self-heating should be more carefully considered because its effect in gas or air is much larger than in water or liquid.

ACKNOWLEDGEMENT

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