Accuracy Review on Long Wired RTD Instrumentation Circuits

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Abstract: This paper presents a review on the several measurement circuits alleviating the influence of signal line wire resistance in the RTD applications in a plant instrumentation and control system. A 3-wired bridge circuit, a 3- or 4-wired current source circuit, or a usage of a transmitter is the typical solution which is widely adopted in instrumentation and control industries. The amounts of accuracy errors in different measuring techniques were calculated and compared each other in a practical installed situation. Other pros and cons of each circuit to be considered for I&C designers were also reviewed.

Keyword: RTD

1 Introduction

RTD (Resistance Temperature Detector) is one of the very common industrial temperature sensors with which the temperature is measured from the change of electrical resistance of the metal wire integrated to the sensing element when temperature changes. Since proposed by William Siemens in 1870, platinum RTDs have been widely used for industrial high temperature measurement as well as thermocouples because of their excellent stability and accuracy[1]-[3].

Although other metals have the characteristic of resistance increase vs. temperature increase, platinum shows the best linearity and highest temperature range applicability as illustrated in Fig. 1.

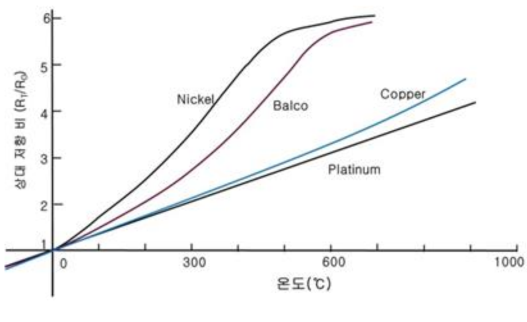

Fig. 1 Temperature coefficient of RTD materials

Since the RTD temperature sensing element in industrial plants is usually contacted to the fluid or gas in the target process to be measured, the distance from the sensor to its measuring circuit is not negligible. Furthermore, the resistance of a RTD, which is 100 ohms or 200 ohms at 0℃, is very small when compared with the other resistance-based temperature sensor called thermistor of which the resistance is over 50 kilo-ohms[4]. This implies that measurement errors or inaccuracy due to the resistance of long wires between the sensor and its instrument circuit may be significant when a RTD is used in a process plant such as power or chemical plants.

Therefore, one of the techniques for eliminating or reducing the influence of RTD signal line wire resistance should be selected and used in the temperature instrumentation design of an industrial process plant.

This paper presents a review result on several measurement circuits alleviating the above uncertainty issue of RTD application in a plant instrumentation and control system. Among three-wired bridge circuits, and three- or four-wired current source circuits adopted as the typical solutions in instrumentation and control industries, the 4-wired current source method is recommended if applicable.

2 RTD Measurement Circuit Analysis

2.1 Wheatstone Bridge

Because of errors incurred by internal resistance and input current of measurement devices, it is not adequate to measure precisely a resistance value by finding the potential difference across the resistor (with a voltmeter in parallel) then dividing by the current through the resistor (as read from an ammeter in series). A Wheatstone bridge circuit, invented by Samuel Hunter Christie in 1833, is one of the most accurate resistance measurement methods[5]. It consists of 4 resistors and is used for finding the value of unknown resistance by comparing it with the known ones as shown in Fig. 2.

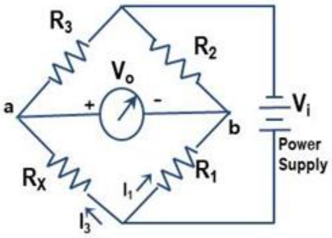

Fig. 2 Wheatstone bridge Circuit

In Fig.2, the unknown resistance, Rx, is determined as Eq. (1).

$$R_X = R_3\left(\frac{V_i-2V_o}{V_i+2V_o}\right) \quad (1)$$

By placing a RTD for R_x in Fig. 2, we can measure the temperature at the location of the RTD installed. Although a Wheatstone bridge circuit in Fig. 2 provides a perfect method for measuring resistance accurately, errors will occur if there is a distance between the RTD and the bridge circuit because the long lead wires connecting the RTD installed in the field location in a plant to the bridge circuit will have non-negligible resistance as well.

The following sections describe how significantly the lead wire resistance results in the temperature measurement error in two- and three-wired bridge configurations for RTD applications.

2.1.1 Two-wired bridge configuration

If a remote RTD is connected to a Wheatstone bridge circuit for measuring temperature without any consideration of wire resistance as illustrated in Fig. 3, it means that the total resistance (R_{rtd}+$2R_w$) is measured accurately rather than the true RTD resistance value (R_{rtd}).

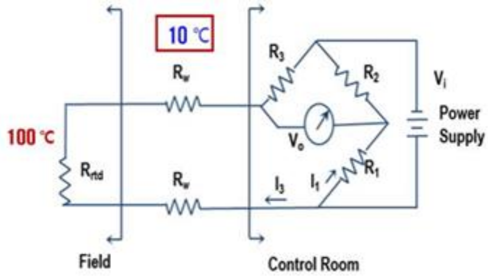

Fig. 3 Two-wire RTD connection bridge circuit

In a practical situation where V_i=10V, R_1=R_2 =R_3 =100Ω, R_w=10Ω (corresponding to the length of 300m of 20AWG wire), R_{rtd}=140Ω (calibrated for 100℃), then measured resistance (R_x) will be 160Ω in accordance with Eq. (1). This resistance value corresponds to 150℃ in terms of RTD value. It is too erroneous to use it. It should be calibrated as 160Ω=100℃ as it is installed (in-situ calibration). However, when the ambient temperature of the signal wires around R_w in Fig. 3 increases to 35℃ from 10℃, the R_w will become 11Ω for each wire. Then the measured resistance becomes 162Ω which is equivalent to 105.1℃, even if 160Ω is regarded 100℃. This quite a big error (+5.1℃) is presented because the change of total resistance of two RTD extension wires is not negligible (=2Ω) compared to the temperature-resistance coefficient value of RTD (2.55℃/Ω for 100Ω-RTD at 0℃). If the resistance of RTD were 10kΩ at 0℃, the amount of error would significantly decrease (5.1℃→0.05℃) because the temperature-resistance coefficient of the RTD will be decreasing as 0.025℃/Ω. However, 10kΩ-RTD sensors would not be practicable to manufacture for using in industrial process plants.

2.1.2 Three-wired bridge configuration

To avoid the extension wire resistance problem illustrated in section 2.1.1, a three-wired bridge method can be a solution. In this circuit, three wires are needed to connect a remote RTD to the Wheatstone bridge as illustrated in Fig. 4.

In this configuration with the same condition given in section 2.1.1, the voltage across R_3 and R_w becomes 4.2306V. Thus -0.7694V is presented as Vo which corresponds 136.37Ω calculated from Eq. (1).

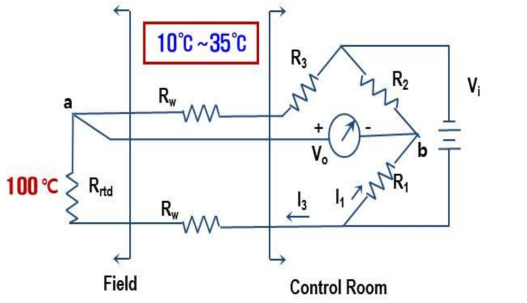

Fig. 4 Three-wired RTD bridge connection method

This deviation from the true value, -3.63Ω (140Ω -136.37Ω), comes up because the bridge circuit is unbalanced (V_o is not zero). Although it is much closer to the true value than in section 2.1.1, it will indicate 92℃(=136.37Ω) rather than 100℃ (=140Ω) in temperature unit unless it is calibrated in-situ.

Now, assuming this 136.37Ω is calibrated for 100℃, what if the ambient temperature of the extension wires changes to 35℃ from 10℃ (i.e. R_w becomes 11Ω from 10Ω)?

The resulting resistance will be presented as 136.04Ω which is corresponding to 99.16℃. Still a deviation of 0.84℃ occurs even it is much better than in two-wire bridge circuits. The measurement error of ~1℃ due to only the change of 20 degree in ambient temperature would not be acceptable in most of process plants.

2.2 Current source methods

As a constant current source is easily composed with solid state devices, injecting a current through a resistor and measuring the voltage drop across the resistor is practical approach in measuring resistance for industrial purpose. This section introduces several current-source-based methods for measuring a remote RTD resistance.

2.2.1 Two-wired current-source configuration

Fig. 5 illustrates a two-wired RTD measurement circuit using a constant current-source and a voltage meter.

In this circuit, assuming I=10mA, R_w=10Ω, R_{rtd}=140Ω, R_o (input resistance of voltmeter) = 1MΩ, then the current through the voltmeter, I_o, becomes 1.599744μA which makes V_o=1.59974V. Thus RTD resistance ($R_{rtd}=V_o/I$) is presented as 159.9744Ω.

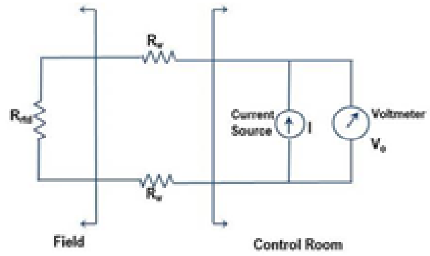

Fig. 5 Two-wire current-source configuration and its equivalent circuit

When R_w=11Ω, R_{rtd} will be measured as 161.9737Ω which is 2Ω higher, corresponding 5℃ deviation.

This result is almost same as section 2.1.1. Therefore, any two-wired configurations, either of a Wheatstone bridge or a current-source method, are not an appropriate method to measure temperature with RTDs particularly connected by a couple of long extension wires.

2.2.2 Three-wired system with one current-source and one voltmeter

Fig. 6 illustrates a three-wired RTD measurement system with one current source and voltmeter.

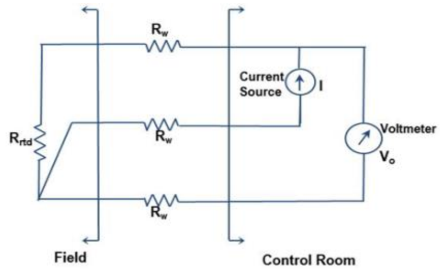

Fig. 6 Three-wired connection with one current source and voltmeter

In this configuration, with the same condition of section 2.2.1, RTD resistance(R_{rtd}) is measured as 149.9760Ω when R_w=10Ω, and 150.976Ω when R_w=11Ω respectively. Thus, it is identified that the deviation (1Ω=2.55℃) comes down to an half of it in section 2.2.1 because the voltage drop across one leg(wire) of the two legs does not affect to the reading of V_o.

2.2.3 Three-wired system with one current-source and two voltmeter configuration

To cancel the voltage drop across one of RTD extension wires in Fig. 6, another voltmeter can be added to measure the voltage of the wire as illustrated in Fig. 7. Because the voltmeter B reads the voltage drop across an extension wire (R_w), the voltage across the RTD is precisely obtained with Eq. (2) and it makes it possible to estimate RTD resistance accurately.

$$V_{rtd} = V_{oA} - V_{oB}\ ,\ R_{rtd} = {V_{rtd}}/{I} \qquad (2)$$

With the same condition of the example in section 2.2.1, the RTD resistance is presented as 139.9761Ω when R_w=10Ω, and 139.9756Ω when R_w=11Ω respectively. There is almost nothing in deviation as well as it provides very accurate measurement of RTD resistance compared the previous methods. Therefore, it can be concluded that this connection circuit is not affected from wire resistance change, thus any in-situ calibration is not necessary. Total accuracy will be only affected from uncertainties of two voltmeters and one current source.

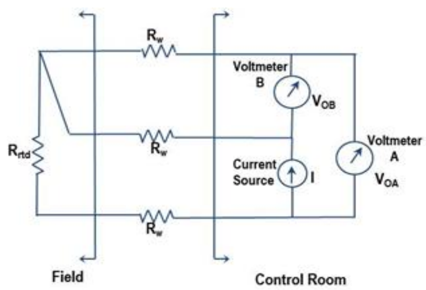

Fig. 7 Three-wired connection with one current source and two voltmeters

2.2.4 Three-wired system with two current-sources and one voltmeter configuration

Another strategy to remove the influence of the extension wire resistance in the three-wired RTD measurement configuration is to use two identical current sources and a voltmeter as illustrated in Fig.8.

The voltage output, V_o, is determined as Eq. (3) assuming the input resistance of voltmeter, R_o, is infinite.

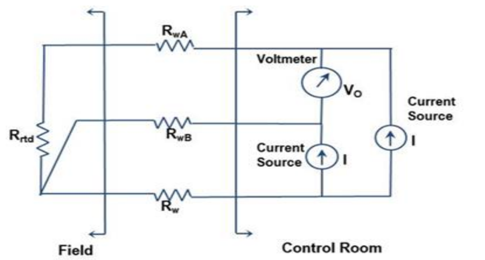

Fig. 8 Three-wired connection with two current sources and one voltmeter

The voltages across R_{wA} and R_{wB} are identical if two current sources are equal to each other. When looked from the voltmeter, those two voltages are canceled because their directions are opposite. Therefore, RTD resistance can be obtained by Eq. (4) regardless of wire resistance.

$$V_o = IR_{wA} + IR_{rtd} - IR_{wB} = IR_{rtd} \qquad (3)$$

$$R_{rtd} = V_o/I$$

In Fig 8, with the same conditions of the example in section 2.2.1, even considering the input resistance of the voltmeter (R_o=1MΩ), the RTD resistance, R_{rtd}, is presented as 139.9776Ω when R_w=10Ω, and 139.9773Ω when R_w=11Ω, respectively. This result is almost same as the one in section 2.2.3. In this method, only one voltmeter is needed. Instead, a duplicate current-source is used.

2.2.5 Four-wired system with one current-source and one voltmeter configuration

Four wire RTD measurement configuration is illustrated in Fig. 9. It only needs one current source and one voltmeter although it requires four wires.

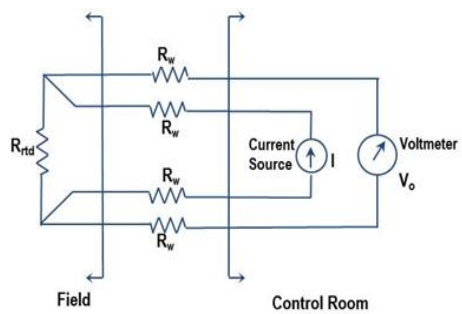

Fig. 9 Four-wired connection with one current source and one voltmeter

In Fig. 9, with the same conditions of the example in the previous sections, even considering the input resistance of the voltmeter (R_o=1MΩ), the RTD resistance, R_{rtd}, is presented as 139.9776Ω when R_w=10Ω, and 139.9711Ω when R_w=11Ω, respectively. This result is also almost same as the ones in section 2.2.3 and 2.2.4. However, in this configuration, there are only two devices affecting to the total accuracy, i.e. one current source and one voltmeter.

3 Conclusions

With a practical example condition, comparison reviews have been performed to identify how significantly the change of resistance of long extension wires brings up the errors affecting to the accuracy in various measurement configurations for RTDs. Although some of three-wired systems have been analyzed that the wire resistance is perfectly compensated, the four-wired system with one current source and one voltmeter is proposed as the best solution. Two-wired systems using either a Wheatstone bridge or a current source method should not be selected unless the distance of connection wires are very short. When a three-wired Wheatstone bridge circuit is selected, careful design should be conducted because as the bridge is unbalanced then the error may increase.

Acknowledgement

This research supported by the nuclear research and development projects funded by the Ministry of Science and ICT (Grant. 2017M2A8A4017932) and Korea Atomic Energy Research Institute.

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