Method for Using 3-wire RTD for Accurate Temperature Measurement in place of 4-wire RTD, Emulating a Constant Current Source for its Excitation and Accurately Compensating for the resistances of its Lead-Wires, without a Constant Current Source and Differential Input ADCs.

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Still being worked on.

ABSTRACT

The RTD being a low-resistance sensor, coupled with the challenge that, its use in remote temperature measurement especially, the length of the lead wires is usually high enough to cause a significant measurement error and its low-resistive nature has a tendency to draw currents that is significant enough to cause self-heating. In an industrial environment, noise too, is a major concern. These constitute errors in RTD temperature measurement. Due to these errors, several wiring configurations have come up in the bid to compensate for these errors. Also, several excitation methods have been used to further reduce them. This article is introducing an entirely new method in exciting the RTD by emulating the constant current source using a variable voltage source, in order to reduce the high cost associated with high accuracy temperature measurement from that of the 4-wire RTD to that of the 3-wire RTD, to accurately compensate for the lead-wire resistances and to eliminate the necessity for a differential-input ADC in the measurement of RTD resistance in the conventional RTD excitation methods.

Keywords: RTD, temperature measurement, constant-current emulation, VDAC, excitation, lead-wire compensation,

1. INTRODUCTION

The two most common RTD excitation methods are constant current excitation and constant voltage excitation. [1] [2] [3] Most times, when a constant voltage source is used as the excitation source, the RTD is made to be a part of a bridge network [4].
Up to date, there are many factors that make a constant current source the most used excitation source for an RTD. Some of the factors that, in combination, make a constant current source the only useful excitation source for an RTD are

- *Lead Wire Resistance:*

Between the point where the RTD is inserted into the process and the transmitter/controller where the RTD resistance is measured, there are lead wires that connect the RTD to the transmitter/controller. These lead wires have resistance which varies both with length and with ambient temperature variations where the lead wires layout [5] [6]. So, other than the resistance of the RTD, the resistance measured by the transmitter has both the resistance of the RTD and those of the lead wires lumped together. Since the resistance of the lead wire would usually be unknown, the transmitter/controller reports a temperature that is usually off the actual process temperature. So there is usually need to provide compensation for the lead wire resistance. To adequately compensate for the lead-wire resistances for very sensitive measurements, the 4-wire RTD is used. The 4-wire RTD configuration naturally causes the resistances of the lead-wires to cancel out. There are methods for compensating for lead wire resistances, like the use of a single zener diode for two-wire RTDs [5]

- *Self-Heating Effect:*

When a significant amount of current flows through the RTD, it heats up the RTD and increases its resistance, adding to the resistance of the RTD that is due to the process temperature. This effect affects the accuracy of the measurement. This phenomenon is referred to as the *self-heating effect*. So, the excitation current has to be kept reasonably low because of the self-heating effect.

In the bid to compensate for these errors, up to two matched current sources are used sometimes. Dynamic Resistance are Due to low current For RTD excitation, a constant current source

MATERIALS AND METHODS

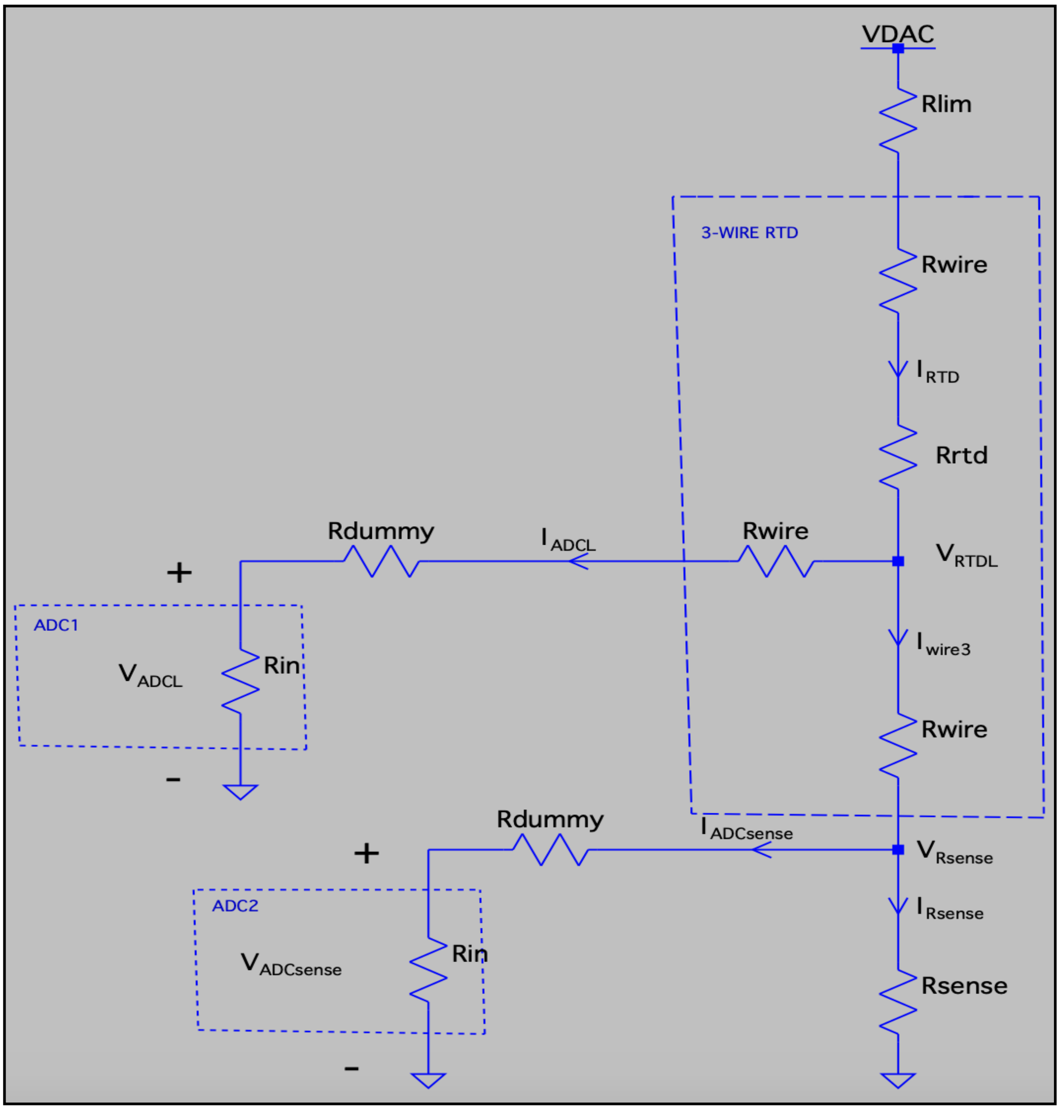
The most basic materials for the implementation of this method of excitation are

- One 3-wire RTD
- Two Single-ended input ADCs
- One VDAC
- One series resistor R_{lim}
- One sense resistor R_{sense}
- Digital logic circuit
- Two R_{dummy} resistors if necessary. R_{dummy} may (or may not be part of the circuit). If it is a part of it, then it may be the resistance of an RC filter at the input of the ADC. For it to be negligible, then the condition $R_{dummy} << (R_{wire} + R_{sense})$ must be satisfied.

Method

To achieve the aim, the circuit has to be carefully configured in a way that the resistance of the lead-wires of the RTD can be easily calculated. There is need to limit the current flowing through the RTD to a value that will not cause an intolerable self-heating of the RTD. Since the resistance of the RTD is small, additional current limiting resistance is necessary. In order to be able to measure the resistance the RTD, there has to be a way to measure the current through the RTD. Current can be inferred from voltage drop across a known resistance. So a resistor R_{sense} is necessary required for current measurement. This R_{sense} will form part of the required current-limiting resistance already discussed. The remaining part of the required series resistance will be provided by a resistor R_{lim}. The lead wires of the 3-wire RTD will have to be modelled by resistances R_{wire}. Note that the lead wires of the RTD should be approximately equal in length, so that the resistances of all the lead-wires are approximately equal.

The resulting circuit is as shown in the schematic diagram. In the diagram, R_{in} represents the input resistance of the RTD (or that of an isolating buffer if used.)



Procedure for Continuously Emulating The Constant Current Source and Taking Resistance Measurement

1. Measure the instantaneous RTD resistance (the RTD current is measured in the process).
2. Update the VDAC output voltage to achieve the desired RTD excitation current $I_{RTD(desired)}$.
3. Allow sufficient time for the VDAC output to get to steady state.
4. Repeat steps (1) to (3).

Note that the time allowed for the VDAC output to settle before performing another measurement should not be longer than necessary to avoid the RTD resistance from changing due to change in temperature from the value it was when the VDAC output was last updated, and also to avoid the consequent inaccurate measurement that would result in that event.

Effect of the spread of the ADC Input Resistance on the Accuracy of the Measurement.
If the condition that the ADC input resistance R_{in}>>$(R_{wire} + R_{sense})$ is satisfied, then $I_{ADCsense}$ and I_{ADCL} will both be relatively small compared to I_{Rsense}, and can be neglected. If the input resistance of the ADC is adequately high, then deviation of its actual value from that used in the calculation will not matter so far the value used in the analysis is within range of the deviation. For generality of the analysis, R_{in} and R_{dummy} are going to be included in the analysis and derived model.

Analysing the Circuit

The instantaneous RTD current $I_{RTD}(t)$ is given by

$$I_{RTD}(t) = \frac{V_{DAC}(t)}{R_{total}(t)}$$

The instantaneous total resistance $R_{total}(t)$ of the circuit as seen by the voltage DAC is given as:

$$R_{total}(t) = (R_{sense}//(R_{in} + R_{dummy}) + R_{wire})//(R_{wire} + R_{dummy} + R_{in}) + R_{RTD}(t) + R_{wire} + R_{lim}$$

But R_{lim} has to selected at the desired RTD excitation current. So, to select R_{lim}, the specification for the desired value of the constant current for the RTD excitation (i.e. $I_{RTD(desired)}$) is used.

$$R_{total(max)} = \frac{V_{DAC(max)}}{I_{RTD(desired)}}$$

Note that $I_{RTD(desired)}$ is the lower boundary of the RTD current as it is the minimum current that $V_{DAC(max)}$ can drive through the RTD, which happens at $R_{RTD(max)}$.

The maximum total resistance is seen by the VDAC when the resistance of the RTD is maximum.

$$R_{total(max)} = (R_{sense}//(R_{in} + R_{dummy}) + R_{wire})//(R_{wire} + R_{dummy} + R_{in}) + R_{RTD(max)} + R_{wire} + R_{lim}$$

$$R_{lim} = R_{total(max)} - (R_{sense}//(R_{in} + R_{dummy}) + R_{wire})//(R_{wire} + R_{dummy} + R_{in}) - R_{RTD(max)} - R_{wire}$$

To determine the instantaneous resistance of the RTD, $R_{RTD}(t)$, the following method is used.

$$I_{ADCsense}(t) = \frac{V_{ADCsense}(t)}{R_{in}}$$

$$V_{Rsense}(t) = I_{ADCsense}(t)(R_{in} + R_{dummy})$$

$$I_{Rsense}(t) = \frac{V_{Rsense}(t)}{R_{sense}} = \frac{I_{ADCsense}(t)(R_{in} + R_{dummy})}{R_{sense}}$$

$$I_{Rwire4}(t) = I_{ADCsense}(t) + I_{Rsense}(t)$$

$$I_{ADCL}(t) = \frac{V_{ADCL}(t)}{R_{in}}$$

$$V_{RTDL}(t) = V_{ADCL}(t) + I_{ADCL}(t)(R_{dummy} + R_{wire}) = V_{Rsense}(t) + I_{Rwire4}(t)R_{wire}$$

$$R_{wire} = \frac{V_{Rsense}(t) - V_{ADCL}(t) - I_{ADCL}(t)R_{dummy}}{I_{ADCL}(t) - I_{Rwire4}(t)}$$

$$I_{RTD}(t) = I_{ADCL}(t) + I_{Rwire4}(t)$$

$$R_{RTD}(t) + R_{wire} + R_{lim} = \frac{V_{DAC}(t) - V_{RTDL}(t)}{i_{RTD}(t)}$$

$$R_{RTD}(t) = \frac{V_{DAC}(t) - V_{RTDL}(t)}{I_{RTD}(t)} - R_{wire} - R_{lim}$$

At every measurement instance, immediately after measuring the instantaneous resistance of the RTD, the current through the RTD is updated to be equal to $I_{RTD(desired)}$ by modifying $V_{DAC}(t)$ as follows:

$$V_{DAC}(t) = I_{RTD(desired)}[(R_{sense}//(R_{in} + R_{dummy}) + R_{wire})//(R_{wire} + R_{dummy} + R_{in}) + R_{RTD}(t) + R_{wire} + R_{lim}]$$

After modifying $V_{DAC}(t)$, we wait for just enough time for the VDAC voltage to settle out before we take the next measurement.

Limitation of this Excitation Method

Degradation of ADC resolution

To have the V_{DAC} voltage at a reasonably high value and yet still have the RTD current low enough to avoid RTD self heating, this method requires that a significantly high resistances be connected in series with RTD for both current limiting and for current sensing. As these resistances, namely, R_{lim} and R_{sense} are way higher than the RTD resistance, it results in a significant trade-off of the resolutions of both the ADCs and the VDAC. For any combination of series resistances $R_{lim} + R_{sense}$ that are equal to the $R_{RTD(max)}$, one bit of the ADC is traded. Every subsequent doubling of the $R_{lim} + R_{sense}$ combination is a trade-off of one bit of the ADC resolution. This is to say that if $R_{lim} + R_{sense}$ is selected to be equal to 2*$R_{RTD(max)}$, then two bits are traded off. If $R_{lim} + R_{sense}$ = 4*$R_{RTD(max)}$, then three bits of the ADC resolution are traded off. So, generally, if n is an integer, making $R_{lim} + R_{sense} = 2^n(R_{RTD(max)})$ causes $(n + 1)$ ADC bits to be traded off.

As an illustration, let us assume that we have an application to measure a process temperature whose lower range value (LRV) results in an $R_{RTD(min)}$ of 82 ohm, and upper range value (URV) results in an $R_{RTD(max)}$ of say 160 ohm. Now, let us also assume that we have an $I_{RTD(max)}$ specified to be ≤ 500 uA and a maximum DAC voltage, $V_{DAC(max)}$ specified as 3.0 V. Then, quickly determining approximately how much series resistance (i.e. $R_{lim} + R_{sense}$) is needed by assuming that the ADC input resistance R_{in}>>($R_{wire} + R_{sense}$). Leaving say 5% tolerance (i.e. $I_{RTD(desired)}$ = 475 uA) for the excitation current, we find that $R_{lim} + R_{sense} = \frac{3.0}{0.000475} - 160$ = ~5.84 kOhm. This gives us a factor of $\frac{5840}{160} = 36.5$, approximately. So, this application results in a trade-off of six ADC resolution bits.

So, after selecting an ADC resolution for this example application based on required accuracy/precision, the additional six traded-off bits would have to be accommodated.

Initialising the Voltage DAC output, V_{DAC}

The minimum VDAC operating voltage, $V_{ADC(min)}$ is given by

$$V_{DAC(min)} = I_{RTD(desired)}[(R_{sense}//(R_{in} + R_{dummy}) + R_{wire})//(R_{wire} + R_{dummy} + R_{in}) + R_{RTD(min)} + R_{wire} + R_{lim}]$$

The upper boundary of the RTD current, $I_{RTD(max,uncontrolled)}$, can only occur if the VDAC voltage is uncontrolled and is at $V_{DAC(max)}$ while the instantaneous RTD resistance $R_{RTD}(t)$ is at the minimum RTD resistance, $R_{RTD(min)}$. So, the maximum uncontrolled RTD current, $I_{RTD(max,uncontrolled)}$ is given by

$$I_{RTD(max,uncontrolled)} = \frac{V_{DAC(max)}}{[(R_{sense}//(R_{in} + R_{dummy}) + R_{wire})//(R_{wire} + R_{dummy} + R_{in}) + R_{RTD(min)} + R_{wire} + R_{lim}]}$$

It is reasonable for the VDAC output voltage to be initialised to a value that corresponds to mid-way between the temperature URV and LRV resistance equivalent (i.e. $\frac{R_{RTD(max)}-R_{RTD(min)}}{2}$) so that at worst-case, the current deviation would be halfway from its boundaries.
The best voltage to initialise the VDAC output is a value where the current it will drive through the RTD will have a deviation that is $\pm$50% between the maximum RTD current and the minimum RTD current. This value corresponds to $(I_{RTD(desired)} \pm \frac{I_{RTD(max,uncontrolled)}-I_{RTD(desired)}}{2})$. This corresponds to a VDAC voltage that is halfway between the minimum operating VDAC voltage and the maximum operating VDAC voltage, which is $(V_{DAC(min)} + \frac{V_{DAC(max)}-V_{DAC(min)}}{2})$. This initial value of VDAC output $V_{DAC(initial)}$ value is thus given by:

$$V_{DAC(initial)} = I_{RTD(desired)}[(R_{sense}//(R_{in} + R_{dummy}) + R_{wire})//(R_{wire} + R_{dummy} + R_{in}) + (R_{RTD(min)} + \frac{R_{RTD(max)} - R_{RTD(min)}}{2}) + R_{wire} + R_{lim}]$$

This will result in an initial RTD current with a maximum deviation of $\pm \frac{I_{RTD(max,uncontrolled)}-I_{RTD(desired)}}{2}$ from $I_{RTD(desired)}$. If this margin was provided during the overall transmitter design, then this initial deviation will not cause the transmitter current loop to saturate, and the transmitter will immediately correct its instantaneous current from $(I_{RTD(desired)} \pm \frac{I_{RTD(max,uncontrolled)}-I_{RTD(desired)}}{2})$ to $I_{RTD(desired)}$ in the following $V_{DAC}(t)$ update.

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