SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Precision Temperature Measurement and Error Analysis for Three-Wire PT100 Resistance Temperature Detector (RTD) using LTSpice

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ARTICLE INFO

Article history:
Received 5 March 2024
Received in revised form 28 May 2024
Accepted 13 June 2024
Available online 30 June 2024

Keywords:
Precision temperature; three-wire Pt100; resistance temperature detector; error analysis; LTSpice

ABSTRACT

This work focuses on temperature measurement and error extraction for Resistance Temperature Dependence (RTD). RTD is notable for its high accuracy, linearity, and stability. However, obtaining a system error of less than unity in RTD is critical. A platinum RTD is an ideal option if the system requires an accuracy level over a wide temperature range (-200°C to +800°C). Therefore, this work investigated the temperature measurement and extraction of error in RTD by simulating a three-wired PT100 RTD using LTSpice. The analytical calculations were also developed to demonstrate the RTD's error and were compared with the simulation results for verification purposes. It was discovered that the optimized temperature measurement and percentage errors are 0.01°C and 0.004% respectively. The values of Vc, Sense Resistor (RSENSE), and Reference Resistor (RREF) for the excitation current were found to be significant to maximize the output voltage and mean absolute error (MAE) on the test set, offering insights into the model's overall fit, average deviation, and sensitivity to outliers. Results reveal strong correlations between PV module temperature, irradiance, and AC power generated.

1. Introduction

A Resistance Temperature Detector (RTD) contains a sensing element whose electrical resistance change with temperature. There are three kinds of wiring configurations for the RTDs that are frequently used in industries these days which are the two- wire, three-wire, and four-wire RTDs. Each arrangement considers its unique excitation and circuit blueprint, so the measurement reduces as much error as possible [1].

In the two-wire configuration, the RTD is connected by two wires to its two ends. This configuration plays a hand in the accuracy of the RTD measurement that cannot be separated [2].

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https://doi.org/10.37934/arfmts.118.2.148159

Even though the two-wire configuration is the most cost- effective, it gives the least accurate measurements and is often used when the accuracy of the measurement is not the focal point of the application [3]. Another frequently seen setup for the RTD is the three-wire configuration where it is connected to one lead wire at one end and two lead wires at the other end of the configuration. Lead resistance effects can be successfully terminated using alternate circuit topologies and tests, reducing measurement error for three-wire RTDs [2]. Compensating for lead wire resistance implies that the resistances of the leads are the same. Finally, each end of the RTD is connected to two lead wires in the four-wire configuration. Four-wire resistance measurement provides the highest degree of precision [4]. In industrial plants where a significant number of processes are to be monitored from a control room, however, the cost of the additional compensating leads is prohibitively expensive [2]. Despite providing the most exact measurement, this configuration is the most expensive of all three designs [5].

In addition to the wire configurations of the RTD, the wire-wound and thin-film RTD sensors are the two most common types of RTD sensors that are made nowadays [6]. After considering all criteria, the three-wire configuration RTD is selected for this work as a trade-off for both accuracy and cost. Alas, their outcome will always consist of a certain amount of inaccuracy since the resistance calculated for the circuit takes into account both the resistance in the lead wires and connections and the resistance in the RTD element. Figure 1 portrays the three-wire RTD configuration used in this work [7].

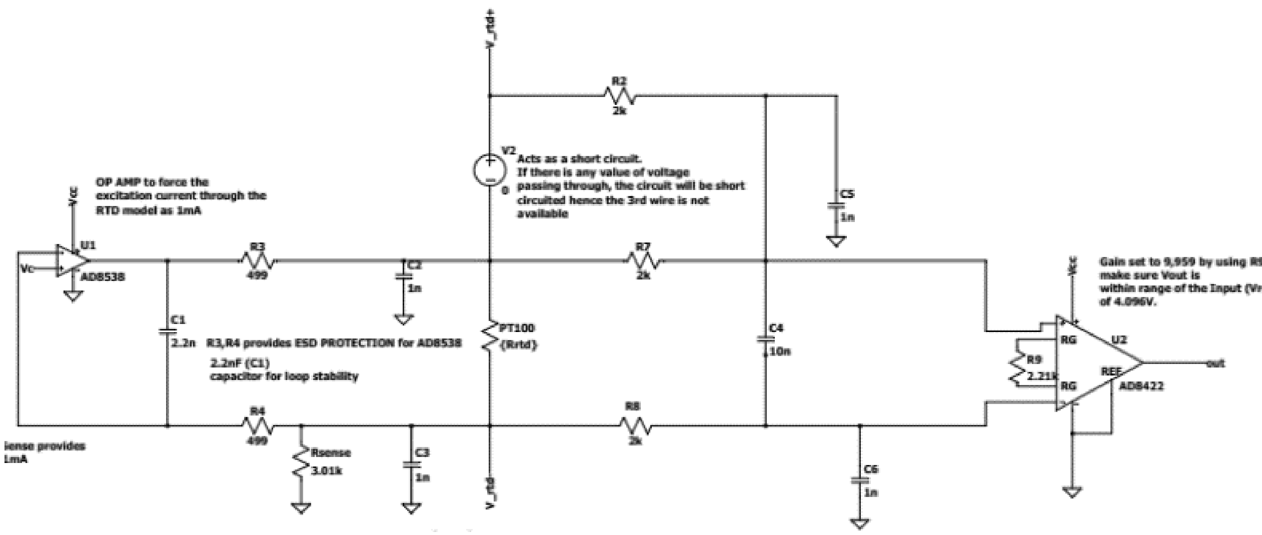

Fig. 1. Three-wire RTD configuration measurement circuit employed

The entire operation of a system will certainly be compromised by any error, and temperature measurement is no exception. Despite being challenging to observe, temperature sensor malfunctions happen quite regularly [1]. To preserve the sensor's performance in any temperature-sensing system, it is crucial to identify and correct these errors and faults. For a RTD, common sensor defects include fixed bias, drifting bias, accuracy loss, and even outright failure of a temperature sensing element [1]. For this work, the error analysis will concentrate on the percentage error of the actual value of the ambient temperature due to self-heating, as well as the fixed bias error of an RTD [2].

The RTD releases energy in the form of heat as a result of the current flowing through it, which causes self-heating errors [2]. The excitation current that flows through the RTD and warms the sensor, increasing the sensor's resistance to exceeding what it would typically estimate based on the reported temperature, is the specific cause of the self-heating error. The RTD's power dissipation and the self-heating coefficient, which typically ranges between 2.5 and 65 mW/°C for thin-film and wire-wound elements, respectively, are additional factors that influence changes in temperature [2]. The sensor bias error can be said an occurring when the output signal of the sensing element varies by a constant value from the real value, in which case the constant value is regarded as the sensor bias error [2]. It is important to first identify the faulty resistance and the incorrect temperature of the circuit in order to determine the bias error of an RTD. Only after taking into account the self-heating error, it is possible to calculate these crucial parameters [1].

The RTD sensor can be established as a de-facto industry standard because of its resistance vs. temperature characteristic, which has a nearly linear positive temperature coefficient from -200 to 850 °C [8]. Platinum is used as the sensor element in the most reliable RTDs due to its long-term stability. Special platinum RTDs (Standard Platinum Resistance Thermometers) are able of measuring temperatures in the range of -189°C to +962°C with an accuracy of up to 0.001°C, according to the International Temperature Scale of 1990 (ITS-90) [9]. The working principle of an RTD is by sensing changes in electrical resistance with temperature which is a common occasion in most materials [10].

The RTD elements resistance and temperature relation is given by the equation [1]:

$$Rt = R0(1+\alpha\Delta t) \tag{1}$$

where,
Rt is resistance at t °C,
R0 is resistance at 0°C,
α is the temperature coefficient (Two widely recognized standards for industrial RTDs IEC 60751 and ASTM E-1137 specify an alpha of 0.00385 Ω/Ω/◦C),
Δt is the temperature difference.

The electrical resistance of certain metals rises directly in proportion to temperature increment as temperatures increase. As a result, the temperature is also measured together with the electrical resistance of the wire and calibrated material. In some materials, the variation is redundant, making accurate temperature measuring achievable.

This work presents an analytical approach to extract a fixed temperature bias error, also known as the bias error of a temperature sensor, and to quantify the measurement and percentage error of the real value of ambient temperature. The enhancement of RTD output voltage is also explored. The PT100 RTD, one of the most prominent designs, was chosen as the RTD for this work [11].

2. Principles of an RTD

2.1 Callendar-Van Dusen Equation

Hugh Longbourne Callendar (1863-1930) employed a quadratic equation in early thermometry and years later, Milton S. van Dusen observed a third order term was needed at temperatures below 0 °C. Hence, the finding led to the rise of the Callendar-van Dusen equations, which are used and considered relevant until today [12].

The Callendar-Van Dusen (CVD) equation is an equation that is used to express the relationship between a typical platinum RTD resistance and temperature [11]. The CVD equation is said to be the most common curve-fitting formula used for Industrial Platinum Resistance Thermometers (IPRTs) [12]. The Callendar-Van Dusen equation which can be expressed by Eq. (2) and Eq. (3) respectively [11].

For T<0:

$$RRTD\ (T) = R0\ [1+ \alpha T + bT^2 + cT^3\ (T-100)] \tag{2}$$

For T>0:

$$RRTD\ (T) = R0\ [1+ \alpha T + bT^2] \tag{3}$$

For a PT100 RTD, R0 is 100 Ω.

For IEC 60751 standard PT100 RTDs, the coefficients are:
A = 3.9083 x 10-3
B = –5.775 x 10-7
C = –4.183 x 10-12

2.2 Error Analysis in Resistance Temperature Detector (RTD)

Chances for a temperature sensor's fault to occur is rather often but it can hardly be discovered [11]. The fault will result in decrease in system performance and increase of energy consumption [11]. Hence, it is crucial to measure and extract these faults and errors in order to maintain and optimize the performance of the RTD. Some of the frequent sensor faults that occurs are fixed bias, drifting bias, precision degradation and even complete failure of a temperature sensing element [11]. However, in this case study, the main focus of the error analysis will be on the percentage error of actual value of ambient temperature due to self-heating and also the fixed bias error of an RTD.

The current flowing through the RTD causes the RTD itself to dispel power in the form of heat [5]. This leads to a self- heating error that will compromise the measurement of the RTD. A self-heating error is initiated by the excitation current that flows through the RTD which warms up the sensor, hence increasing the sensor's resistance beyond the extent that it would otherwise assume due to the temperature being measured [6]. The change in temperature is also dependent on factors such as power dissipation of RTD and the self-heating coefficient in mW/°C that are usually between 2.5 mW/°C for small, thin-film elements and 65mW/°C for larger, wire-wound elements [5].

For the sensor bias error, it can be defined if the sensing element's output signal varies by a constant value from the true value, in which the constant value is considered as sensor bias error [5]. In order to acquire the bias error of an RTD, the faulty resistance and the faulty temperature of the circuit must be determined and these crucial values can only be calculated once the self-heating error is considered [11].

3. Methodology

This section will go into more detail on the various approaches that were used to collect the data and conduct the analysis that was necessary for this work.

There are two kinds of methodology or approaches that were taken into consideration throughout the entire designing process of this work. The work combines both quantitative and a qualitative approach. In which certain parameters requires simulation and other parameters requires analytical approach. With that being said, one of the research methods proposed for this work is through a simulation to test the cause and effect of the characteristics and advantages of RTD. The three-wired configuration is selected for the PT100 RTD model then simulated in LTSPICE software in order to simulate the concept of RTD.

Later on, analytical calculations were done based on the voltage output obtained from the simulation to measure and extract the errors in the RTD. Additionally, the model is simulated once again to determine the significance factors in optimizing the RTD measurement.

4. Results and Discussion

4.1 RTD Characteristics

Using a 1 mA excitation current, the LTSPICE simulation sweeps the RTD temperature from -200°C to 1000°C as can be seen in Figure 2. As mentioned, the electrical resistance of certain metals increases in direct proportion to temperature increase. Hence, the electrical resistance of a known and calibrated wire can be measured while the temperature of the wire is determined. With that being said, the simulation has proven the concept of an RTD circuit. The temperature was stepped-up to 1000°C just to observe the relationship of the parameters of an RTD if it were to measure a temperature beyond 850°C. These data were shown in Table 1. As the temperature rises, the Vout is observed to increase.

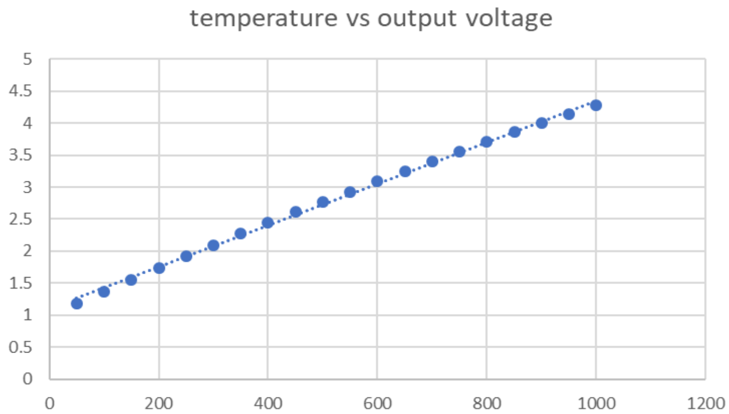

Fig. 2. Plot of simulated voltage versus temperature using PT100 SPICE RTD sensor mode and 1 mA excitation

Table 1
Temperature, Resistance of RTD and Vout obtained from the simulation

Δt (°C)	RRTD (ohm)	Vout (V)
-250	1.32	78.46m
0	100	982.39m
850	390.48	3.86

4.2 Analytical Approach on Percentage Error Extraction for Actual Value of Ambient Temperature and Fixed Bias

4.2.1 Extraction of percentage error of actual value of ambient temperature due to self-heating

The RTD's three-wire configuration is used in this paper. As a result, the configuration is said to have stopped the current mismatch error. However, there may still be system flaws brought on by factors like the sensor's self-heating [11]. Self-heating error happens when the element of the RTD gets heats up past its process temperature by the instrument's excitation current [4].

To extract the percentage error of actual value of ambient temperature due to self-heating, parameters such as excitation current, the resistance of the RTD at a temperature, and self-heating coefficient must be taken into account. The actual value of ambient temperature, Ta when self-heating coefficient, σ is considered can be calculated by using Eq. (4) [10]:

$$Ta = T(RTD) - \frac{RRTDIexcite^2}{\sigma} \quad (4)$$

Here, T(Rrtd) is the temperature during that resistance, Iexcite is the excitation current to the RTD, RRTD is the resistance of the RTD in Ω, and σ is the self-heating coefficient in ℃ /mW. In this case, the self-heating coefficient, σ is 2.5 mW/°C and the maximum excitation current is set to 1 mA. The actual value of ambient temperature, Ta when self-heating coefficient, σ is considered were calculated for the temperature of -250 to 1000°C. From Table 4, it was observed that the temperature error and percentage error for all temperatures are insignificant difference. While, Table 5 displays the data before and after self- heating for all temperatures at -250 to 1000°C. To further explain the results of the RRTD value and Ta as in Eq. (5) before and after considering the self-heating coefficient, σ, two graphs are plotted as in Figure 3 and Figure 4 respectively.

$$TTTT = (-250) - \frac{(1.32)(1mm)^2}{2.5m} \quad (5)$$

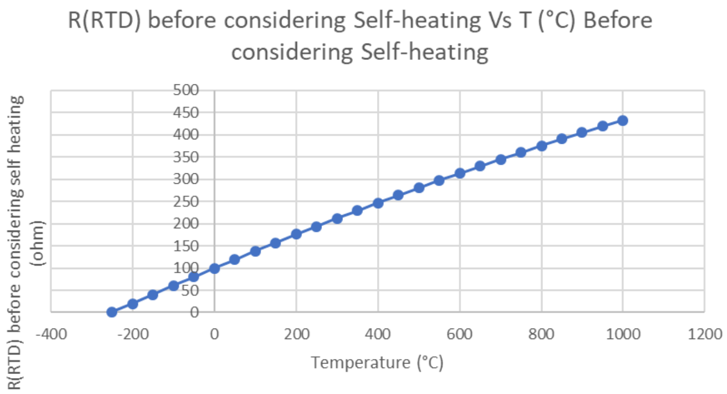

Fig. 3. Plot of RRTD Vs Temperature (°C) Before considering Self-heating

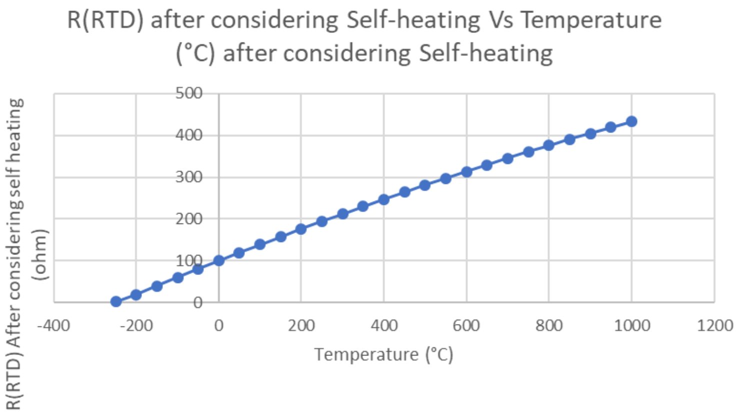

Fig. 4. Plot of RRTD Vs Temperature (°C) After considering Self-heating

From Table 2, the analytical results, it can be seen that the measurement and percentage errors for the best and worst case is 0.01°C and 0.004% and 0.05°C with 0.1% error respectively. Hence, even when the self-heating is considered, the RTD measurement still manages to maintain a reading with errors less than or equals to 0.1%. While Table 3 shows similar results for condition before and after self-heating for all temperatures for calculation and simulation.

Additionally, when comparing both plots (Figure 3 and Figure 4), it can be concluded that the RRTD value and Ta before and after considering the self-heating coefficient, σ only shows a slight difference which may also be considered as a form of stability of the temperature measurement.

From this extraction of error, it can be said that the accuracy of an RTD is better when compared to the other temperature sensor in the industry with an accuracy of up to 0.01% compared to thermistor and thermocouple whose both accuracy is only up to 1%. Even so, this error may be able to be fixed with future optimization and work.

Table 2
The actual value of ambient temperature, Ta when self-heating coefficient, σ is considered with Temperature Error and Percentage Error

Δt (°C)	R(RTD) using CVD equations	Ta (°C)	Temperature Error (°C)	Percentage Error (%)
-250	1.32	-249.99	0.01	0.004
-200	19.52	-200.01	0.01	0.005
-150	40.08	-150.02	0.02	0.013
-100	60.34	-100.02	0.02	0.020
-50	80.31	-50.03	0.03	0.060
0	100.00	-0.04	0.04	0.040
50	119.40	49.95	0.05	0.100
100	138.51	99.94	0.06	0.060
150	157.33	149.94	0.06	0.040
200	175.86	199.93	0.07	0.035
250	194.10	249.92	0.08	0.032
300	212.05	299.92	0.08	0.027
350	229.72	349.91	0.09	0.026
400	247.09	399.90	0.10	0.025
450	264.18	449.89	0.11	0.024
500	280.98	499.89	0.11	0.022
550	297.49	549.88	0.12	0.022
600	313.71	599.87	0.13	0.022
650	329.64	649.87	0.13	0.020
700	345.28	699.86	0.14	0.020
750	360.64	749.86	0.14	0.019
800	375.70	799.85	0.15	0.019
850	390.48	849.84	0.16	0.019
900	404.97	899.84	0.16	0.018
950	419.17	949.83	0.17	0.018
1000	433.08	999.83	0.17	0.017

Table 3
Temperature and Resistance of RTD before and after considering self-heating

T (°C) Before considering Self-heating	R(RTD) Before considering Self-heating	Ta(°C) After considering Self- heating	R(RTDsh) After considering Self-heating
-250	1.32	-249.99	1.31
-200	19.52	-200.01	19.52
-150	40.08	-150.02	40.07
-100	60.34	-100.02	60.33
-50	80.31	-50.03	80.30
0	100.00	-0.04	99.98
50	119.40	49.95	119.38
100	138.51	99.94	138.48
150	157.33	149.94	157.30
200	175.86	199.93	175.83
250	194.10	249.92	194.07
300	212.05	299.92	212.02
350	229.72	349.91	229.68
400	247.09	399.90	247.06
450	264.18	449.89	264.14
500	280.98	499.89	280.94
550	297.49	549.88	297.45
600	313.71	599.87	313.67
650	329.64	649.87	329.60
700	345.28	699.86	345.24
750	360.64	749.86	360.60
800	375.70	799.85	375.66
850	390.48	849.84	390.43
900	404.97	899.84	404.92
950	419.17	949.83	419.12
1000	433.08	999.83	433.03

4.2.2 Extraction of fixed bias error of RTD

Besides the error considering self-heating of the sensor, another type of error that can be extracted from an RTD measurement is fixed temperature bias error, called bias error of a temperature sensor. The parameters required to draw the bias error include the faulty resistance of the RTD, RRTDf and faulty temperature, Tf of the circuit [10]. In short, there are two values for the ambient temperature: T, which is the value without taking into account the errors in the circuit, and Tf, which is the value with the errors taken into account. The RTD's bias error, which is written as bias error, can be found in Eq. (6).

$$RRTDf = \frac{VoutxRref}{2^{22}} \tag{6}$$

where,
V_{out} = output voltage
R_{ref} = Reference Resistance

$$Tf = \frac{-a\sqrt{a^2-4b\left(1-\frac{RRTDf}{R_O}\right)}}{2b} \tag{7}$$

where,
For a PT100 RTD, R_0 is 100 Ω
For IEC 60751 standard PT100 RTDs, the coefficients are:
a = 3.9083 x 10^{-3}
b = -5.775 x 10^{-7}

$$\text{Bias Error} = T - T_f \quad (8)$$

The value of RRTDf, Tf and Bias error for temperature of -250 to 1000°C calculated are recorded in Table 4.

Table 4
The actual value of ambient temperature, Ta when self-heating coefficient, σ is considered with Temperature Error and Percentage Error

RRTDf (Ω)	Δt (°C)	T_f (°C)	bias error: $T-T_f$ (°C)
26.18	-250	- 227.77	-22.23
78.94	-200	-188.98	-11.02
130.18	-150	-151.03	1.03
197.39	-100	-100.32	0.32
264.77	-50	-48.86	-1.14
327.83	0	0	0
393.77	50	51.86	-1.86
457.17	100	102.50	-2.50
517.24	150	151.21	-1.21
580.64	200	203.43	-3.43
640.71	250	253.71	-3.71
697.44	300	301.95	-1.95
757.51	350	358.86	-8.86
814.23	400	403.71	-3.71
870.96	450	454.42	-4.42
924.36	500	502.96	-2.96
977.75	550	552.33	-2.33
1031.14	600	602.57	-2.57
1084.53	650	653.74	-3.74
1134.59	700	702.59	-2.59
1187.98	750	755.72	-5.72
1238.04	800	805.49	-5.49
1288.09	850	858.33	-8.33
1334.81	900	907.67	-7.67
1381.53	950	958.01	-8.01
1428.25	1000	1009.42	-9.42

The bias error was found between -22.2°C and 0°C, as shown in Table 4. For instance, the bias error at T=100°C is -2.50°C, which is significant for an RTD with a typical accuracy of about 0.3°C [5]. A benchmark for bias error, according to earlier studies, is between 0.945°C and 125°C; for instance, at T=27°C, bias error is 1.065°C, which is a significant value for a sensor with an accuracy of about 0.3°C [11]. Further improvement is therefore necessary to maximize the reading of the RTD measurement. The reading and measurement of the RTD will be compromised if this type of error is ignored.

4.3 Determination of Significance Factor in Optimizing RTD Output Voltage
4.3.1 V_c and R_{sense} value for excitation current, I_{excite}

One of the important considerations in maximizing RTD measurement is the Iexcite. Rref, and biassing resistors may all be driven by Iexcite in some configurations [5]. The Iexcite applied for the RTD and Rref is maximized in order to maximize the performance of the noise in RTD but is often kept lower than 1 mA because to self-heating that will cause errors in temperature measurement [2]. By adjusting Vc and Rsense, the Iexcite can be controlled [2]. However, as Rsense is a high-precision resistor in this instance with an accuracy of about 0.1%, its value is maintained at 3.01 kΩ throughout the whole simulation [12].

$$I_{excite} = \frac{V_C}{R_{sense}} \quad (9)$$

The range of output voltage recorded by manipulating the I_{excite} are as tabulated in Table 5.

Table 5
Range of Output Voltage when I_{excite} is manipulated

Vc (V)	Excitation Current (mA)	Output Voltage Range (V)
1.505	0.5	78.87m - 1.79
3.010	1.0	78.46m - 4.27
4.515	1.5	79.36m - 1.04

Initially, the value of V_c is produced by dividing down a 4.096 V, reference voltage which is chosen to be within the range of the DC common-mode of the AD8353 op-amp [1]. This is to obtain I_{excite} of approximately 1 mA when dropped across a high accuracy (0.1%) sensing resistor of 3.01kΩ.

$$I_{excite} = \frac{V_C}{R_{sense}} = \frac{3.01}{3.01k} = 1mA$$

Later on, the value of Vc is manipulated so that the Iexcite obtained are approximately around 0.5 mA and 1.5 mA. From the value of output voltage range obtained, it is observable that the Iexcite = 1 mA shows the most stable reading since the range is within the range of the VREF. Additionally, the value of Vc and Rsense are both manipulated while the Iexcite is kept constant. The range of output voltage when both Vc and Rsense are manipulated are recorded in Table 6.

From the data obtained, the output voltage range of the Vc and Rsense of 3.01 V and 3.01 kΩ respectively shows the biggest and stable range. This can conclude the fact that the value chosen to determine the excitation current is crucial in optimizing the measurement of RTD [13]. This is due to the accuracy of the Rsense which will lead to the generation of excitation current when the voltage dropped across it. In the first case, the accuracy of sensing resistor is set to be 0.1%, while on the second case the accuracy of sensing resistor is changed when the value of sensing resistor, Rsense is changed. Hence, it can be said that the excitation current is a significant factor to consider when optimizing the measurement of RTD since it will affect the measurement. The excitation current generated to drive the RTD should be chosen according to the suitability of the component inside an RTD configuration [14].

Table 6
Range of Output Voltage when V_c and R_{sense} are manipulated

Vc (V)	R_{sense} (kΩ)	Excitation Current (mA)	Output Voltage Range (V)
1.500	1.50	1.0	78.46m to 2.64
3.010	3.01	1.0	78.46m to 4.27
5.000	5.00	1.0	79.37m to 80.05m

4.3.2 Manipulation of reference resistor, R_{ref}

The value of Rref is a significant consideration in optimizing RTD measurement. In this instance, the high performance, low power, rail-to-rail precision instrumentation amplifier, AD8422, has the Rref placed between the RF terminal. To control the gain value of the instrumentation amplifier and increase the output voltage, the value of Rref in the circuit used is necessary. For AD8422, the Gain, G value can be computed using Eq. (10).

$$Gain, G = 1 + \frac{19.8k}{R_{ref}} \qquad (10)$$

The R_{ref} is modified to get various gain values and the effects on the temperature range and output voltage range are recorded in order to simulate the significance of the R_{ref} in the measurement of RTD. To change the value of R_{ref}, Eq. (10) is rewritten as Eq. (11).

$$R_{ref} = \frac{19.8k}{(G-1)} \qquad (11)$$

Initially, the value of 2.21kΩ is set so the gain of the instrumentation amplifier is set to 9.959.

$$Gain, G = 1 + \frac{19.8k}{2.21k} = 9.959$$

Then, the value of R_{ref} is manipulated to 1.05 kΩ and 4.99 kΩ to set the gain value to 19.86 and 4.968 respectively. All values of R_{ref} used in manipulating the value of gain are based on the AD8422 Datasheet. The effect of R_{ref} and Gain value toward the measurement of RTD is recorded in Table 7. According to the data obtained, it is obvious that the R_{ref} = 2.21 kΩ and G = 9.959 has the best range of temperature and output voltage range. The range of temperature range is acceptable in a de-facto industry standard while the output voltage range is almost as identical to the reference voltage of 4.096 V. Although the range of the R_{ref} = 1.05 kΩ and G = 19.86 has a good range of output voltage, the temperature range does not meet the standard industrial range while the R_{ref} = 4.99 kΩ and G = 4.968 is vice versa. It is evident from this that the value of R_{ref} has a significant impact on the measurement of RTD parameters since it affects both the temperature range and the output voltage range. Therefore, choosing the right R_{ref} for a component inside of an RTD configuration is crucial [15].

Table 7
The effect of R_{ref} and Gain value toward the measurement of RTD

Rref (kΩ)	Gain Value, G	Temperature Range (°C)	Output Voltage Range (V)
1.05	19.86	-250 to 450	77.8m - 4.78
2.21	9.959	-250 to 1000	78.46m - 4.78
4.99	4.968	-250 to 1000	92.49m - 2.13

5. Conclusion and Recommendation

This work successfully simulated the RTD characteristics using LTSpice for a three-wire PT100 RTD. In addition, it can be concluded that measurement and percentage errors for the best and worst case is 0.01°C with 0.004% and 0.05 °C with 0.1% error respectively. In terms of the bias error, the value of -22.23°C is considered as a noticeable value and cannot be ignored.

Acknowledgements

The authors would like to express deepest appreciation to College of Engineering, UiTM Shah Alam and FRGS/1/2021/TK0/ UITM/02/12 Ministry of Higher Education (MOHE); Malaysian Government for the financial support.

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