Platinum RTD sensor based multi-channel high-precision temperature measurement system for temperature range −100°C to +100°C using single quartic function

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Abstract: A method and system for measuring multiple temperature points using two wire configuration Resistance Temperature Detectors (RTD) for temperature range −100°C to +100°C is mainly composed of the Micro Controller Unit (MCU), analog–digital converter (ADC), reference Voltage source, Multiplexers (MUX) and resistance network including the RTD temperature sensors. The RTDs are sequentially scanned using a reference/constant voltage source, and resistance values of the RTDs are calculated based on the voltage measured across the RTDs and the current sensing resistor. Improving the precision of temperature measurement is based on a line fitting algorithm—Newton’s divided differences interpolation polynomial based on three reference resistor values representing two extreme end points and the center point of the temperature range for which the system is made. The test results show that the device temperature measurement precision can reach ±0.02°C, has the advantage of using a single quartic function for the entire temperature range −100°C to +100°C with dynamic calibration to address errors related to in-circuit resistance, tolerance, temperature coefficient, linearity and offset error in the circuit, and it also supports the detection of degradation of linearity and offset in the circuit because of aging factors.
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Subjects: Algorithms & Complexity; Electrical & Electronic Engineering; Instrumentation, Measurement & Testing

Keywords: RTD; PT100; PT1000; nonlinearity correction; nonlinear circuits; signal processing; Callendar-Van Dusen method; high precision temperature measurement; Newton’s divided differences interpolation polynomial; curve fitting algorithm

1. Introduction

FOR Data Acquisition and Control Systems, temperature monitoring using Platinum RTD sensors is very common for a wide temperature range of −100°C to +100°C (Acromag Inc, n.d.; Tse & Morse, 1989; Wang, Tang, & Younce, 2003). The RTDs available for commercial or industrial use have the limitation of the measuring current to avoid self-heating; e.g., for PT1000, the recommended current is 0.1 mA–0.3 mA (Heraeus Sensor Technology, 2016), and for PT100, it is near 1 mA (Heraeus Sensor Technology, 2016).

In the case of PT1000, at a temperature of −100°C, the sensor resistance is equal to 602.5 Ohms (Heraeus Sensor Technology, 2016; Kongsberg Maritime, n.d.), and at a temperature of +100°C, the sensor resistance is equal to 1385.1 Ohms (Heraeus Sensor Technology, 2016; Kongsberg Maritime, n.d.). Considering the excitation current of 0.15 mA, for the temperature range −100°C to +100°C, the calculated minimum and maximum voltage difference across the sensor are 90.38 mV and 207.75 mV, respectively. Any offset or gain error in the circuit in terms of millivolts will impact the measured value (Acromag Inc, n.d.; Tse & Morse, 1989; Yi & Liu, 2009). Also, in-circuit resistance like trace impedances and the tolerance of the components will also influence the temperature measurement (Tse & Morse, 1989; Acromag Inc, n.d.).

The correlation between the resistance and temperature of the RTD is described by the Callendar-Van Dusen equation—where we need to use two different equations for negative and positive temperatures (Hocenski et al., 2008). Calculation of Temperature using the Callendar-Van Dusen equation for positive temperatures requires one conditional branching and square root computation, which calls for iterative loop function (Kaw & Kalu, 2008); and for negative temperatures, the program counter needs to go through the conditional branching instructions a minimum of 3 times to obtain sufficient accuracy. Hence, in low-end microcontrollers, the computation of temperature from the resistance value of the RTD using the Callendar-Van Dusen equation requires a decent number of machine cycles, which may not be desirable in real-time applications or where the CPU already has high-priority overheads.

Some researchers have suggested using a higher-order polynomial function or a temperature correction term of a factorial form in order to determine a better interpolating function for temperature measurement using RTD. A higher-order polynomial describes the behavior of R(t) better than the Callendar-Van Dusen equation because of the additional terms it has (Yang, Suherlan, Sool Gam, & Kim, 2015).

This paper suggests a single quartic function for the entire temperature range −100°C to +100°C with dynamic calibration to address errors related to in-circuit resistance, tolerance, temperature coefficient, linearity and offset error in the circuit, and it also supports the detection of degradation of linearity and offset in the circuit because of aging factors.

2. Callendar-Van Dusen equation

For Temperature \( T < 0°C \) (Kongsberg Maritime, n.d.):

\[
R_T = R_0 \times \left[ 1 + A \cdot T + B \cdot T^2 + (T - 100) \cdot C \cdot T^3 \right] \tag{1}
\]

For Temperature \( T \geq 0°C \) (Kongsberg Maritime, n.d.):
\[ R_T = R_0 \times \left[ 1 + A \cdot T + B \cdot T^2 \right] \]  \hspace{1cm} (2)

Equations (1) & (2) are the complete version of the Callendar-Van Dusen equation. A, B and C are known as the Callendar-Van Dusen constants, defined by the following equations (Acromag Inc, n.d.; Honeywell, n.d.; Kongsberg Maritime, n.d.):

\[
A = \alpha + \frac{\alpha \cdot \delta}{100} \hspace{1cm} (3)
\]

\[
B = -\frac{\alpha \cdot \delta}{100^2} \hspace{1cm} (4)
\]

\[
C = \begin{cases} 
\frac{-\alpha \cdot \delta}{100} & \text{For } T < 0°C \\
0 & \text{For } T \geq 0°C 
\end{cases} \hspace{1cm} (5)
\]

Alpha (\(\alpha\)) is the temperature coefficient of resistance obtained by measuring the detector resistance at both 0°C (\(R_0\)) and 100°C (\(R_{100}\)) and is defined as (Acromag Inc, n.d.):

\[
\alpha = \frac{(R_{100} - R_0)}{(100 \cdot R_0)} \hspace{1cm} (6)
\]

The second order term \(\delta\) comes from Callendar and is based on the disparity that exists between the actual temperature \(T_h\) and the temperature that is calculated above using only the linear coefficient term \(\alpha\). This coefficient \(\delta\) is calculated as (Acromag Inc, n.d.):

\[
\delta = \frac{T_h - R_h}{R_h} \hspace{1cm} (7)
\]

The third order coefficient \(\beta\) comes from Van Dusen and is only required for converting negative temperatures with \(T < 0°C\). It is based on the disparity between the actual temperature \(T_l\) and the temperature calculated using only \(\alpha\) and \(\delta\). We can calculate \(\beta\) as follows (Acromag Inc, n.d.):

\[
\beta = \frac{T_l - \left( \frac{1}{\frac{R_l - R_0}{100 \cdot R_0}} + \frac{T_h - R_h}{R_h} \right)}{\left( \frac{1}{\frac{T_l}{100 \cdot R_0}} - 1 \right)} \hspace{1cm} (8)
\]

IEC 751, the most commonly used standard for Platinum RTDs, defines Class A and B performance for 100 Ω 0.00385 alpha Pt RTDs. IEC751 defines the coefficients of a standard PT100 sensor as follows listed in Table 1 (Acromag Inc, n.d.; Honeywell, n.d.; Kongsberg Maritime, n.d.):

For \(T \geq 0°C\), quadratic Equation (2) (Honeywell, n.d.) can be used to solve for temperature as a function of measured resistance with the result:

\[
T = -\frac{A + \sqrt{A^2 - 4B \cdot \left( \frac{1}{R} - \frac{R_l}{100 \cdot R_0} \right)}}{2B} \hspace{1cm} (9)
\]

| Table 1. Coefficients of a standard PT RTD |
|--------------------------------------------|
| \(A\) (°C\(^{-1}\)) | \(3.9083 \times 10^{-3}\) |
| \(B\) (°C\(^{-2}\)) | \(-5.775 \times 10^{-7}\) |
| \(C\) (°C\(^{-4}\)) | \(-4.1830 \times 10^{-12}\) For \(T < 0°C\)  
\hspace{1cm} 0 For \(T \geq 0°C\) |
| Alpha, \(\alpha\) (°C\(^{-1}\)) | \(3.850 \times 10^{-3}\) |
| Beta, \(\beta\) (°C) | \(0.10863\) For \(T < 0°C\)  
\hspace{1cm} 0 For \(T \geq 0°C\) |
| Delta, \(\delta\) (°C) | 1.49990 |
For temperatures below 0°C, the Equation (1) is too complex to solve, so successive approximation is employed (Hocenski et al., 2008):

\[
T_1 = \frac{R_T - 1}{A + 100 - B}
\]

Equation (10) is the initial approximation.

\[
T_{n+1} = T_n + \frac{1 + AT_n + BT_n^2 + CT_n^3 \cdot (T_n - 100) - \frac{R_T}{R_0}}{A + 2BT_n - 300CT_n^2 + 4CT_n^3}
\]

With two iterations, Equation (11) gives the temperature value with sufficient accuracy.

As per the flow chart in Figure 1, the implementation of the Callendar-Van Dusen equation for temperature calculation for a temperature range including both positive and negative temperature is somewhat complicated as it requires two different computation equations and also the computational algorithm requires iterative loops in both cases. For low-end processors, the number of iterative loops significantly increases the overhead on the processor. Also, there is a trade-off
between the number of conditional branching instructions in the code and CPU throughput. In a nutshell, in low-end microcontroller computation of temperature using the Callendar-Van Dusen equation, it is not an effective approach considering the computational complexity and time.

3. The measurement principle and system
The challenge with the RTD measurement circuit as shown in Figure 2 is the limitation of the measuring current because of self-heating effect, in-circuit resistance, like lead-wire resistance and the errors in individual components related to tolerance, temperature coefficient, linearity, offset, etc. adding up to give the total error in the calculated temperature (Acromag Inc, n.d., Tse & Morse, 1989; Yi & Liu, 2009).

This paper suggests adding three reference resistors through MUX, values of which should represent two extreme end points and the center point of the temperature range for which the system is made, as shown in Figure 3 and use of line fitting algorithm—Newton’s divided differences interpolation polynomial (Kaw & Kalu, 2008).

The temperature measurement system includes a microcontroller with internal/external ADC coupled to a 2X 1:(3 + n) Mux, where n ≥ 1 and n is equal to the number of RTD that need to be measured via linear gain amplifiers.

Equations (12), (13) and (14) are the formulas for resistance calculation of the RTD (PT1000) connected to a channel.

Measuring current passing via the equivalent resistance of RTD (i.e., RTD || R2) is given by Equation (12)—

\[ I_{R3} = \frac{V_B}{G_2 R_3} \]  

(12)
The equivalent resistance of RTD (i.e., RTD || R2) is given by Equation (13)—

\[ R_{\text{EQU}} = \frac{V_B/G1 - V_A/G2}{I_{R3}} \]  

(13)

The resistance value of RTD (PT1000) calculated along with the effects of circuit errors is given by Equation (14)—

\[ R_{\text{RTD}} = \frac{R_2 \times R_{\text{EQU}}}{R_2 - R_{\text{EQU}}} \]  

(14)

The general form of the Newton’s divide difference polynomial for \( n + 1 \) data points \((x_0, y_0), (x_1, y_1), \ldots, (x_{n-1}, y_{n-1}), (x_n, y_n)\) is defined by Equation (15) (Kaw & Kalu, 2008)—

\[ f_n(x) = b_0 + (x - x_0)b_1 + (x - x_0)(x - x_1)b_2 + \cdots + (x - x_0)(x - x_1)(x - x_2) \cdots (x - x_{n-1})b_n \]  

(15)

Where—

\[ b_0 = f(x_0) \]  

(16)

\[ b_1 = f(x_1, x_0) \]  

(17)

\[ b_2 = f(x_2, x_1, x_0) \]  

(18)

\[ b_{n-1} = f(x_{n-1}, x_{n-2}, \ldots, x_0) \]  

(19)

\[ b_n = f(x_n, x_{n-1}, \ldots, x_0) \]  

(20)

where the definition of the \( m^{\text{th}} \) divided difference is
\[ b_n = f[x_m, ..., x_0] = f[x_m, ..., x_1] - f[x_{m-1}, ..., x_0] \quad (x_m - x_0) \quad (21) \]

Equation (22) is the formula for final resistance calculation of the RTD (PT1000) using Newton’s divided differences interpolation (Kaw & Kalu, 2008) for three data points, which will help in eliminating the effects of errors in the circuit.

\[ RTD_{CAL} = A_0 + \{(R_{RTD} - R_{S1}) \cdot A_1\} + \{(R_{RTD} - R_{S2}) \cdot (R_{RTD} - R_{S1}) \cdot A_2\} \quad (22) \]

Where—

\[ A_0 = R_{S60} = 560 \quad (23) \]

\[ A_1 = \frac{(R_{1000} - R_{S60})}{(R_{S2} - R_{S1})} = \frac{440}{(R_{S2} - R_{S1})} \quad (24) \]

\[ A_2 = \frac{\{(R_{1000} - R_{S60}) / (R_{S2} - R_{S1})\} - A_1}{(R_{S3} - R_{S1})} = \frac{(R_{S3} - R_{S1})}{(R_{S3} - R_{S1})} \quad (25) \]

\[ R_{1000} = 1000 \quad (26) \]

\[ R_{1500} = 1500 \quad (27) \]

\[ R_{S1} = \text{Value of RCAL}_1 (560 \Omega) \text{ using Equation (14)} \quad (28) \]

\[ R_{S2} = \text{Value of RCAL}_2 (1000 \Omega) \text{ using Equation (14)} \quad (29) \]

\[ R_{S3} = \text{Value of RCAL}_3 (1500 \Omega) \text{ using Equation (14)} \quad (30) \]

The three on-board reference resistors are selected such that:

- \( R_{S60} \) \text{ (RCAL}_1): One should be the resistance of the RTD near the least temperature of the range \((-100^\circ C \text{ to } +100^\circ C)\) for which the system is meant. For PT1000, resistance value 560 \( \Omega \) indicates a temperature near \(-110^\circ C\).

- \( R_{1000} \) \text{ (RCAL}_2): The second on-board reference resistor should be the resistance of the RTD near the mid-value for the temperature range \((-100^\circ C \text{ to } +100^\circ C)\) for which the system is meant. For PT1000, resistance value 1000 \( \Omega \) indicates the temperature 0°C.

- \( R_{1500} \) \text{ (RCAL}_3): The third on-board reference resistor should be the resistance of the RTD near the maximum value of the temperature range \((-100^\circ C \text{ to } +100^\circ C)\). For PT1000, a resistance value of 1500 \( \Omega \) indicates a temperature near 130°C.

These three calibration resistors should be thin film resistors with a tolerance of less than or equal to 0.1% and a temperature coefficient less than or equal to \( \pm 25 \text{ ppm/}^\circ C\).

Equation (12), (13) and (14) are used to measure the on-board reference resistors—\( R_{S60} \) \text{ (RCAL}_1), \( R_{1000} \) \text{ (RCAL}_2) and \( R_{1500} \) \text{ (RCAL}_3), and the respective measured values \( R_{S1}, R_{S2} \) and \( R_{S3} \) will be stored in memory as per the array structure shown in Table 2. With the power on, it is required to read the values of on-board reference resistors—\( R_{S60} \) \text{ (RCAL}_1), \( R_{1000} \) \text{ (RCAL}_2) and \( R_{1500} \) \text{ (RCAL}_3); then, depending on the application, the values of on-board reference resistors can be measured after a fixed interval of time based on application requirements like duration of operations, thermal management of the product—how the temperature variation within the product affects the circuit performance.
Figure 4 is a flow chart diagram for calculation of the coefficients after reading the on-board reference resistors $R_{560}$ (RCAL$_1$), $R_{1000}$ (RCAL$_2$) and $R_{1500}$ (RCAL$_3$). The detection of aging error can also be performed using the algorithm of the flow chart diagram in Figure 4.

Equation (31) is the formula for temperature calculation from measured RTD (PT1000) resistance value using Newton’s divided differences interpolation (Kaw & Kalu, 2008) for five data points defined in Equation (15):

$$
T_{RTD} = B_0 + (RTD_{CAL} - 560) \times B_1 + (RTD_{CAL} - 560) \\
\times (RTD_{CAL} - 750) \times B_2 + (RTD_{CAL} - 560) \\
\times (RTD_{CAL} - 750) \times (RTD_{CAL} - 1000) \times B_3 \\
+ (RTD_{CAL} - 560) \times (RTD_{CAL} - 750) \\
\times (RTD_{CAL} - 1000) \times (RTD_{CAL} - 1200) \times B_4
$$

(31)

Where—

$$B_0 = T_{560} = -1.1047 E + 02$$

(32)

$$B_1 = \frac{(T_{750} - T_{560})}{(750 - 560)} = 2.4813 E - 01$$

(33)

$$B_2 = \frac{(C_1 - B_1)}{(1000 - 560)} = 1.1793 E - 05$$

(34)

$$B_3 = \frac{(C_2 - B_2)}{(1200 - 560)} = -2.7585 E - 09$$

(35)

$$B_4 = \frac{(C_3 - B_3)}{(1500 - 560)} = 3.1986 E - 12$$

(36)

$$C_1 = \frac{(T_{1000} - T_{750})}{(1000 - 750)} = 2.5332 E - 01$$

(37)

$$C_2 = \frac{(D_1 - C_1)}{(1200 - 750)} = 1.0028 E - 05$$

(38)

$$C_3 = \frac{(D_2 - C_2)}{(1500 - 750)} = 2.4818 E - 10$$

(39)

$$D_1 = \frac{(T_{1200} - T_{1000})}{(1200 - 1000)} = 2.5783 E - 01$$

(40)

$$D_2 = \frac{(E_1 - D_1)}{(1500 - 1000)} = 1.0214 E - 05$$

(41)

Table 2. Array structure to store data

| RTD Ideal Res. Value (Ω) | On Board Reference Resistor Values (Ω) Measured Using Equation (14) | Aging Error (Ω) | RTD Ideal Temperature Values (°C) |
|--------------------------|-------------------------------------------------|-----------------|---------------------------------|
| 560                      | $R_S1$ (RCAL$_1$)                                | $\Delta R_{560} = 560 - R_S1$ | $T_{560} = -110.47$            |
| 750                      |                                                  |                  | $T_{750} = -63.33$             |
| 1000                     | $R_S2$ (RCAL$_2$)                                | $\Delta R_{1000} = 1000 - R_S2$ | $T_{1000} = 0.00$              |
| 1200                     |                                                  |                  | $T_{1200} = 51.57$             |
| 1500                     | $R_S3$ (RCAL$_3$)                                | $\Delta R_{1500} = 1500 - R_S3$ | $T_{1500} = 130.45$            |

Equation (31) is the formula for temperature calculation from measured RTD (PT1000) resistance value using Newton’s divided differences interpolation (Kaw & Kalu, 2008) for five data points defined in Equation (15):
Figure 4. Flow chart diagram for reading on-board reference resistance value and detection of aging error.
\[ E_1 = \frac{(T_{1500} - T_{1200})}{(1500 - 1200)} = 2.6294 \times 10^{-1} \] (42)

\( T_{560}, T_{750}, T_{1000}, T_{1200} \) and \( T_{1500} \) are temperature values in °C for the RTD (PT1000) resistance values equal to 560 Ω, 750 Ω, 1000 Ω, 1200 Ω and 1500 Ω, respectively. These temperature values can be taken from the RTD manufacturer datasheet and will be used as constant values.

Figure 5 is a flowchart diagram for the method for detection of RTD sensor resistance out of range and for calculation of temperature from RTD resistance using Equation (12–14, 22, 31).

The detection of degradation of the linearity and offset in the circuit because of the aging factor is explained in more detail below:

Whenever the system reads the on-board Calibration Resistors \( R_{560} \), \( R_{1000} \) and \( R_{1500} \), either at power on or after a pre-defined time interval, it also calculates the aging error as explained in Equations (43–45):

\[ R_{560} = 560 - R_{S1} \] (43)

\[ R_{1000} = 1000 - R_{S2} \] (44)
\[ R_{1500} = 1500 - R3 \]  

(45)

If the calculated aging errors \( \Delta R_{560} \), \( \Delta R_{1000} \) and \( \Delta R_{1500} \) are more than the threshold value which is defined by application requirement, it will generate an alarm, so that the user can look into the hardware.

4. Test results and analysis

To evaluate the concept, a model of the hardware was simulated using LTSpice with the tolerance factor shown in Figure 6 (Schematic Diagram). Monte Carlo Analysis was executed for 100 steps with step size of 1 for values of RTD (PT1000) starting from 600 \( \Omega \) to 1400 \( \Omega \) incremented by 100 \( \Omega \). Consider summation of On-State Resistance of the Mux and lead resistance as 5 \( \Omega \pm 1\% \), and the interconnecting trace resistance as 0.5 \( \Omega \pm 1\% \).

Based on Monte-Carlo Analysis, the minimum and maximum calculated value of the RTD resistances were considered. And then the temperature was calculated based on the RTD resistance value using the conventional method of the Callendar-Van Dusen equation using Equations (9) or (10) and (11) as well as the proposed method with Equations (22,31)

As per the conventional method using the Callendar-Van Dusen equation, considering that the RTD is PT1000, the absolute error in temperature reading is more than 10\(^\circ\)C in most of the cases for the range \(-100\,^\circ\text{C} \text{ to } +100\,^\circ\text{C}\)—i.e., for RTD Resistance from 600 \( \Omega \) to 1400 \( \Omega \). When the temperature is calculated using the proposed method with Equations (22,31), the absolute error in temperature reading is less than 0.02\(^\circ\)C for the range \(-100\,^\circ\text{C} \text{ to } +100\,^\circ\text{C}\)—i.e., for RTD Resistance from 600 \( \Omega \) to 1400 \( \Omega \).

For the minimum value calculated by Monte-Carlo Analysis—the results of the calculated temperature and error values using the conventional method as well as the proposed method for RTD Resistance from 600 \( \Omega \) to 1400 \( \Omega \) with a step size of 100 \( \Omega \) are shown in Tables 3 and 4, respectively.

For the maximum calculated value by Monte-Carlo Analysis—the results of the calculated temperature and error values using the conventional method as well as the proposed method for RTD Resistance from 600 \( \Omega \) to 1400 \( \Omega \) with a step size of 100 \( \Omega \) are shown in Tables 5 and 6, respectively.

Figures 7 and 8 provide a comparison of the error in calculated temperature using the Callendar-Van Dusen equation versus the proposed equation for Monte Carlo analysis performed for the schematic diagram shown in Figure 6.
### Table 3. Calculated temperature and errors using the conventional method for minimum calculated RTD resistance values

| RTD Res. Ideal Value (Ω) $R_{RTD}$ | Temp. Theoretical Value (°C) $T_{RTD}$ | RTD Res.—MIN (Simulation) $R_{RTD}^{MIN}$ | Calculated Temperature Conventional Method Callendar Van Dusen Equation $R_{RTD}^{MIN}$ (°C) | $\Delta T$ ABS (°C) |
|-----------------------------------|----------------------------------------|------------------------------------------|------------------------------------------|-------------------|
| 600                               | -100.63                                | 570.19                                   | 570.19                                   | -107.97           | 7.34              |
| 700                               | -75.83                                 | 667.74                                   | 667.74                                   | -83.86            | 8.03              |
| 800                               | -50.77                                 | 765.29                                   | 765.29                                   | -59.50            | 8.73              |
| 900                               | -25.49                                 | 862.83                                   | 862.83                                   | -34.91            | 9.42              |
| 1000                              | 0.00                                   | 960.37                                   | 960.37                                   | -10.12            | 10.12             |
| 1100                              | 25.68                                  | 1057.91                                  | 1057.91                                  | 14.85             | 10.83             |
| 1200                              | 51.57                                  | 1155.44                                  | 1155.44                                  | 40.01             | 11.56             |
| 1300                              | 77.65                                  | 1252.98                                  | 1252.98                                  | 65.36             | 12.29             |
| 1400                              | 103.94                                 | 1350.51                                  | 1350.51                                  | 90.90             | 13.04             |

### Table 4. Calculated temperature and errors using the proposed method for minimum calculated RTD resistance values

| RTD Res. Ideal Value (Ω) $R_{RTD}$ | Temp. Theoretical Value (°C) $T_{RTD}$ | RTD Res.—MIN (Simulation) $R_{RTD}^{MIN}$ | Calculated Temperature Proposed Method $R_{RTD}^{CAL}$ (°C) | $\Delta T$ ABS (°C) |
|-----------------------------------|----------------------------------------|------------------------------------------|------------------------------------------|-------------------|
| 600                               | -100.63                                | 570.19                                   | 600.00                                   | 0.00              |
| 700                               | -75.83                                 | 667.74                                   | 700.00                                   | 0.00              |
| 800                               | -50.77                                 | 765.29                                   | 800.00                                   | 0.00              |
| 900                               | -25.49                                 | 862.83                                   | 900.00                                   | 0.00              |
| 1000                              | 0.00                                   | 960.37                                   | 1000.00                                  | 0.00              |
| 1100                              | 25.68                                  | 1057.91                                  | 1100.00                                  | 0.00              |
| 1200                              | 51.57                                  | 1155.44                                  | 1200.00                                  | 0.00              |
| 1300                              | 77.65                                  | 1252.98                                  | 1300.00                                  | 0.00              |
| 1400                              | 103.94                                 | 1350.51                                  | 1400.00                                  | 0.00              |

### Table 5. Calculated temperature and errors using the conventional method for maximum calculated RTD resistance values

| RTD Res. Ideal Value (Ω) $R_{RTD}$ | Temp. Theoretical Value (°C) $T_{RTD}$ | RTD Res.—MAX (Simulation) $R_{RTD}^{MAX}$ | Calculated Temperature Conventional Method Callendar Van Dusen Equation $R_{RTD}^{MAX}$ (°C) | $\Delta T$ ABS (°C) |
|-----------------------------------|----------------------------------------|------------------------------------------|------------------------------------------|-------------------|
| 600                               | -100.63                                | 656.56                                   | 656.56                                   | 86.63             | 14.00             |
| 700                               | -75.83                                 | 759.53                                   | 759.53                                   | 60.94             | 14.89             |
| 800                               | -50.77                                 | 862.51                                   | 862.51                                   | 34.99             | 15.78             |
| 900                               | -25.49                                 | 965.48                                   | 965.48                                   | 8.82              | 16.67             |
| 1000                              | 0.00                                   | 1068.46                                  | 1068.46                                  | 17.56             | 17.56             |
| 1100                              | 25.68                                  | 1171.44                                  | 1171.44                                  | 44.15             | 18.47             |
| 1200                              | 51.57                                  | 1274.43                                  | 1274.43                                  | 70.96             | 19.39             |
| 1300                              | 77.65                                  | 1377.41                                  | 1377.41                                  | 97.99             | 20.34             |
| 1400                              | 103.94                                 | 1480.41                                  | 1480.41                                  | 125.24            | 21.29             |
5. Conclusion

This paper describes the design of a Multi-Channel high precision temperature measuring system based on a Platinum RTD Sensor, especially where the system is required to measure temperature in both a negative and positive temperature range. Compared with traditional temperature measuring methods, the proposed method has the advantages of a simple algorithm, high accuracy, and

| RTD Res. Ideal Value (Ω) $R_{RTD}$ | Temp. Theoretical Value (°C) $T_{RTD}$ | RTD Res.-MAX (Simulation) $R_{RTD-MAX}$ | Calculated Temperature Proposed Method |
|-----------------------------------|--------------------------------------|----------------------------------------|---------------------------------------|
| 600                               | -100.63                              | 656.56                                 | 600.00                               |
| 700                               | -75.83                               | 759.53                                 | 700.00                               |
| 800                               | -50.77                               | 862.51                                 | 800.00                               |
| 900                               | -25.49                               | 965.48                                 | 900.00                               |
| 1000                              | 0.00                                 | 1068.46                                | 1000.00                              |
| 1100                              | 25.68                                | 1171.44                                | 1100.00                              |
| 1200                              | 51.57                                | 1274.43                                | 1200.00                              |
| 1300                              | 77.65                                | 1377.41                                | 1300.00                              |
| 1400                              | 103.94                               | 1480.41                                | 1400.00                              |

$\Delta T AB S (°C)$ for RTD Res. Min
$\Delta T AB S (°C)$ for RTD Res. Max

Figure 7. Monte Carlo Simulation—Errors in calculated temperature using Callendar-Van Dusen equation.

Figure 8. Monte Carlo simulation—Errors in calculated temperature using proposed Equations (22) and (31).
good stability and the ability to predict hardware malfunctioning. Although in this paper the temperature range of $-100^\circ\text{C}$ to $+100^\circ\text{C}$ and PT1000 as the RTD sensor was considered, the proposed method can be implemented for any temperature range as well as for any RTD sensor; the three on-board calibration resistors would need to be selected accordingly, and also the respective coefficients would need to be calculated. In this paper two-wire RTD configuration is considered, but to compensate long wire runs, four-wire RTD configurations can be considered to achieve a better accuracy.

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