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Design of Wheatstone Bridge Based Thermistor Signal Conditioning Circuit for Temperature Measurement

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Abstract

Thermistors are widely used in temperature measurement due to their fast response, high accuracy, and low cost. However, due to the nonlinear resistance-temperature relationship, there is a need for linearisation in order to design a signal conditioning circuit for accurate temperature measurement. Thus, this paper presents the design of a thermistor signal conditioning circuit based on Wheatstone Bridge. An experiment was conducted on an NTC thermistor to acquire the resistance response to temperature change between 25 ºC to 65º C which was in turn used for the model linearization. The obtained parameters from the linearized model are used to design the Wheatstone bridge signal conditioning circuit. The designed measurement system performance evaluation demonstrated a high degree of accuracy with only 1.1 % non-linearity within the specified temperature range.

Keywords: Temperature, thermistor, Wheatstone bridge, numerical analysis, resistance, voltage.

1. Introduction

Temperature sensing is an integral part of process control in petrochemical, automotive, aerospace and consumer electronics industries. The common types of temperature sensors include the Negative Temperature Coefficient (NTC) thermistor, the Resistance Temperature Detector (RTD), thermocouple and semiconductor-based sensors [1-4]. The thermistor is a thermally sensitive resistor that exhibits high sensitivity and fast electrical resistance change when subjected to corresponding body temperature variation [5]. The two basic types of thermistor are the NTC and Positive Temperature Coefficient (PTC). The NTC is the most widely used for precision temperature measurement ranging from -80°C to +120°C. It can be operated in three different modes; the resistance-versus-temperature, the voltage-versus-current and the current-over-time characteristics. These types of thermistors are fabricated from metals of ceramic or polymer matrix that changes electrical resistance with temperature. Another notable feature of the NTC is that its resistance-to-temperature relationship is highly non-linear which requires a linearisation network in real time application [6, 7]. Thermistor generates internal heat when there is current flow during measurement resulting in power dissipation on the component. The heat energy produced whenever current passes through it, in turn, makes the resistance to reduce which indicates a temperature slightly above ambient temperature. The effect of self-heating is managed by ensuring that the operating current is relatively small so that error in measurement is minimal.

A close competitor of the NTC for temperature measurement is the RTD. In a similar way to the NTC, the resistance of the RTD increases with a decrease in temperature. The RTDs are available in the form of a coil, fine wire or a thin film deposited on a substrate. They can be fabricated from metals of different resistance mostly from platinum metal. The platinum resistance-temperature curve is relatively linear compared to other metals like copper, nickel and iron-nickel alloy. Platinum RTD is a positive temperature coefficient device in which the resistance of the metal conductor is proportional to the length (L) and inversely proportional to the cross-sectional area (A) as given in (1) [1].

$$R = \rho * (\frac{L}{A}) \quad (1)$$

where

ρ is the material resistivity (Ωm)

One of the major advantages of the RTDs in temperature measurement is that it has a wide temperature operating range. For example, the platinum sensor can be used to measure temperature ranging from -276°C to 961°C. Other merits of the RTD include higher resistance-temperature linearity and repeatability if not subjected to physical impact or heavy vibration [8]. Its major limitation is that of low sensitivity because the resistance varies only slightly over the useful range of the sensor. Unlike RTDs, NTC thermistor exhibits high sensitivity with fast response time

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when there is temperature variation. Other advantages of the sensor that makes it widely used are that it's relatively cheap and produces robust signal [9].

In this paper, thermistor linearisation and Wheatstone bridge-based signal conditioning circuit for temperature measurement is presented. A simplified linear model is used to obtain the thermistor parameters from the experimental resistor-temperature data. This permits the design of the Wheatstone bridge signal conditioning circuit that converts temperature to its voltage equivalent. The designed system is capable of realising high linearity between the signal conditioning output voltage and the temperature variation. This shows the effectiveness of the thermistor linearization and Wheatstone bridge design approach. Although the linearization model is not robust compared to some other methods, high accuracy of optimal solution is guaranteed. The results obtained compared with the complex modelling approach reported in the literature have a good similarity which confirms the effectiveness of the proposed technique. The rest of the paper is organised as follows: In Section 2 the thermistor linearisation and Wheatstone bridge design are presented. The experimental results are presented

2. Thermistor Linearization and Wheatstone Bridge Design

This section presents the NTC thermistor linearization and the design of Wheat-stone bridge signal conditioning circuit for temperature measurement. The thermistor was modelled using the experimental resistance-temperature measurement data between 25°C to 65°C range. The obtained model parameters were in turn used to calculate the exact resistance values of the Wheatstone bridge to achieve minimum possible deviation between the output voltage and the ideal output voltage.

2.1 Thermistor Linearization

Two steps are involved in the linearisation process. Firstly, the resistance-temperature data is acquired, then the data is used in the model equation to obtain the thermistor parameters. Here, the linearization process involves investigation of the input-output performance of thermistor over a temperature range between 25°C to 65°C.

2.1.1 Resistance-Temperature Measurement

A test measurement was conducted on the chosen thermistor resistance change against the temperature difference over the specified temperate range. The experimental set-up involves a direct connection of thermistor with a 5V DC power source and ohm meter for monitoring the resistance change with the temperature difference. The equivalent connection circuit is presented in Fig. 1. The NTC thermistor was placed in the glass test-tube and inserted in a beaker filled with water at room temperature. The water is heated up gradually using a hotplate and a record of temperature difference against the thermistor resistance were captured for every 2°C temperature step change.

2.1.2 Resistance-Temperature Relationship

Thermistor exhibits non-linear resistance-temperature characteristics that needed to be linearised before it can be used in constructing a temperature measurement sensor. The most popular polynomial relationship for modelling thermistor resistance against temperature is the Steinhart-Hart equation in (2). The equation has the advantage of a close approximation of actual temperature and can be used for an entire working temperature range of the sensor. [3, 10, 11].

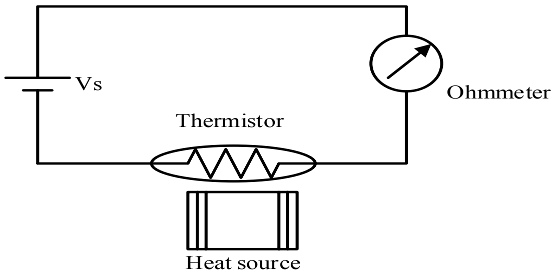

Fig. 1. Thermistor application equivalent circuit

$$\frac{1}{T} = A + B\ln R(t) + C(\ln R(t))^3 \tag{2}$$

where A, B, and C are thermistor constants which may be provided by the manufacturer

In order to obtain the relationship between the thermistor resistance and temperature under no load condition, the R-T relationship of an NTC thermistor has an inverse characteristic that can be described by the exponential relationship of (3) [10].

$$R(t) = R_n \exp\left(\frac{\beta}{T} - \frac{\beta}{T_{TO}}\right) \tag{3}$$

- $R(t)$ is the thermistor resistance (K) at absolute temperature T expressed in kelvins
- β is the thermistor material constant, and
- R_n is the resistance in K at a specified reference temperature Tn.

In order to obtain the thermistor coefficient in this application, (3) is linearised as (4) which allowed determination of the constant parameters directly from the experimental measured data R-T curve.

$$\ln R(t) = \beta \frac{1}{T} + \ln R_n \tag{4a}$$

$$T = \beta \frac{1}{\ln R(t)} + \ln R_n \tag{4b}$$

2.2 Wheatstone Bridge Design

This subsection details the Wheatstone bridge signal conditioning design. On a broader view, a Wheatstone bridge is an instrument used for measuring unknown electrical resistance values and can also be used as a voltage divider. The topology comprised of two parallel half-bridge circuits in which the current splits into two and recombined into a single conductor. It is commonly used as sensor device like in strain gauges and fault location in the electrical power distribution line when there is break down [12], [13]. The designed Wheatstone bridge signal conditioning circuit was employed to linearize the sensor output voltage as a function of the input temperature of the thermistor R(t). The equivalent circuit presented in Fig. 2 is used for converting the temperature change into a corresponding potential difference between V_1 and V_2. The output voltage of the bridge is given by:

$$V_{out} = V_1 - V_2 = \left[\left(\frac{R_a}{(R_a + R(t))} - \frac{R_c}{(R_c + R_b)} \right) \right] V_s \quad (5)$$

- V_1 and V_2 are the bridge voltages,
- R_a, R_b, and R_c are the bridge resistors
- V_s is the supply voltage

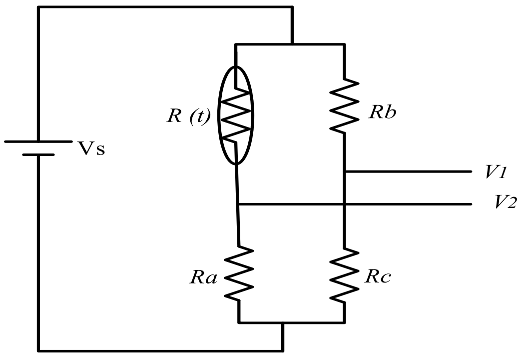

Fig. 2. Wheatstone bridge with thermistor

The corresponding R(t) values for different temperature points are calculated based on the thermistor constants determined from (4) using the experimental data (see Table 1 in section 3). To implement the Wheatstone bridge circuit for temperature measurement, suitable resistance values for R_a, R_b, and R_c were determined from a numerical model developed in an Excel Spreadsheet. This was achieved by comparing the expected output voltage range with the ideal output between 0V to 1V for the specified temperature range of 25°C to 65°C.

Thus, at room temperature i.e. when T is 25°C, R(t) is 42.7818 KΩ and V_{out} is 0V, equation (5) becomes;

$$0 = \left[\left(1/(1 + \frac{42.7818}{R_a}) \right) - \left(1/(1 + \frac{R_c}{R_b})) \right) \right] V_s \quad (6)$$

Subsequently, at T = 45°C, R(t)=17.8188 KΩ, and V_{out} is 0.5V, equation (5) becomes;

$$0.5 = \left[\left(1/(1 + \frac{17.8188}{R_a}) \right) - \left((1/(1 + \frac{R_c}{R_b}) \right) \right] V_s \quad (7)$$

Lastly, at T = 65°C, R(t)=8.2321 KΩ, and V_{out} is 1V, equation (5) becomes;

$$1 = \left[\left(1/(1 + \frac{8.2321}{R_a}) \right) - \left((1/(1 + \frac{R_c}{R_b}) \right) \right] V_s \quad (8)$$

Solving equations (7), (8) and (9) simultaneously, R_a was obtained as 13.3 KΩ, R_b / R_c as 3.2. The available suitable standard resistor for R_b, and R_c were chosen as 18 KΩ and 5.6 KΩ respectively. Although, thermistor as a resistor generates internal heat when current passed through it which brings about power dissipation on the component. The heat energy produced in turn causes the resistance of the thermistor to reduce which translate to an indication of a temperature slightly above the ambient temperature [14,15,16]. The effect of self-heating is reduced by ensuring that the current passing through the thermistor is relatively low and a 2.63V excitation voltage was used. This ensures that the possible error in measurement is very small compared to the targeted measurement accuracy.

The Wheatstone bridge circuit was built with the obtained resistance values and the thermistor as the fourth resistor based on the circuit diagram in Fig. 2. The output voltage was computed for different temperature points using the standard resistance values of R_a, R_b, and R_c from the numerical analysis and the percentage error in relation to ideal output voltage was estimated. The results show that there is an insignificant deviation between the Wheatstone bridge output and the ideal output voltage as presented in the results section. The % non-linearity between the Wheatstone bridge output voltage V_{out} and the ideal voltage V_{ideal} is obtained using the following relationship.

3. Results and Discussion

This section presents the results of the NTC thermistor linearisation and performance evaluation of the designed Wheatstone bridge signal conditioning circuit. An experiment was conducted on an NTC thermistor to determine the resistance change against temperature variation under no load condition. The thermistor was heated up and the resistance values were recorded at every two-unit step temperature change from 25°C to 65°C as presented in Table 1. The measured experimental resistance R(KΩ) and the corresponding temperature T (K) data were then used to obtain the thermistor parameters and R_T at the reference temperature based on the NTC thermistor R-T relationship presented in Section II.

Table 1. Thermistor measured resistance against temperature

Temperature (°C)	Temperature, (273 + T°C) K	Resistance (KΩ)	ln R (K)	1/T (/K)
20	293	57.5	4.05	0.003413
22	295	50.9	3.93	0.003390
24	297	46.6	3.84	0.003367
26	299	41.8	3.73	0.003344
28	301	37.2	3.62	0.003322
30	303	33.2	3.50	0.003300
32	305	29.8	3.40	0.003279
34	307	27.7	3.32	0.003257
36	309	25.2	3.23	0.003236
38	311	23.1	3.12	0.003215
40	313	21.4	3.06	0.003195
42	315	19.7	2.98	0.003175
44	317	18.2	2.90	0.003155
46	319	17.0	2.83	0.003135

48	321	15.6	2.75	0.003115
50	323	14.5	2.67	0.003096
52	325	13.3	2.59	0.003077
54	327	12.4	2.52	0.003058
56	329	11.4	2.43	0.003040
58	331	10.6	2.36	0.003021
60	333	10.0	2.30	0.003003
62	335	9.20	2.22	0.002985
64	337	8.60	2.15	0.002967
66	339	8.00	2.08	0.002950
68	341	7.50	2.02	0.002933
70	343	7.00	1.95	0.002915
72	345	6.60	1.89	0.002899

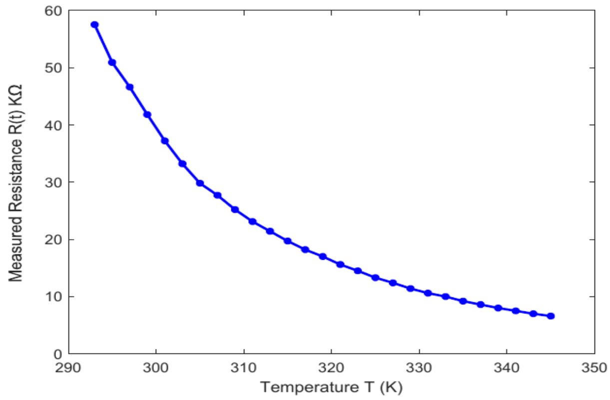

Fig. 3. Thermistor resistance versus temperature

The thermistor resistance-temperature (R-T) change plot is presented in Fig.3. The plot shows the rapid nonlinear response of the thermistor resistance to temperature change. This was further conditioned to achieve a linear relationship between the two variables. In order to establish a linear relationship between the resistance-temperature based on equation (4), ln R was plotted against 1/T as presented in Fig. 4. The thermistor parameters (β) and R_n values were then obtained from the best-fitted line as 4150 and 0.0000383 respectively.

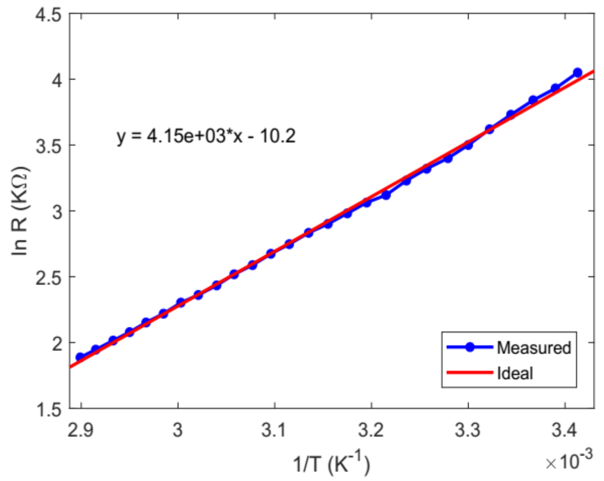

Fig. 4. Linearized thermistor resistance versus temperature

The equivalent thermistor resistance R(t) at different temperature point were computed using the obtained thermistor material constant and the reference temperature resistance R_n according to the relationship (2) and the results is presented in Table 2. The measured resistance R(KΩ) in Table 1 was compared with the computed thermistor resistance Rt(KΩ) as presented in Figure 5 graph for a temperature range of 26°C to 64°C. The graph shows good similarity between the two which is an indication that the obtained thermistor material constant and resistance at the reference temperature from the thermistor linearization is precise.

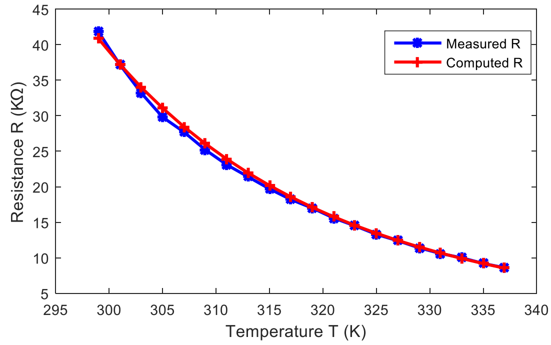

Fig. 5. Comparison of measured and computed resistance

Table 2. Wheatstone bridge V_{out} , V_{ideal} and % non-linearity

Temperature (K)	R(t) (KΩ)	V out (V)	Ideal voltage (V)	non-linearity %
298	42.7818	-0.0003544	0.000	0.0354367
299	40.8349	0.0220769	0.025	0.2923139
300	38.9887	0.0448909	0.050	0.5109134
301	37.2374	0.0680725	0.075	0.6927498
302	35.5756	0.0916057	0.100	0.8394334
303	33.9982	0.1154733	0.125	0.9526652
304	32.5005	0.1396577	0.150	1.0342322
305	31.0779	0.1641400	0.175	1.0860020
306	29.7263	0.1889008	0.200	1.1099165
307	28.4417	0.2139201	0.225	1.1079855
308	27.2204	0.2391772	0.250	1.0822803
309	26.0589	0.2646507	0.275	1.0349260
310	24.9540	0.2903191	0.300	0.9680941
311	23.9027	0.3161600	0.325	0.8839955
312	22.9019	0.3421513	0.350	0.7848716
313	21.9491	0.3682701	0.375	0.6729875
314	21.0416	0.3944938	0.400	0.5506229
315	20.1770	0.4207994	0.425	0.4200650
316	19.3531	0.4471640	0.450	0.2835998
317	18.5677	0.4735649	0.475	0.1435051
318	17.8188	0.4999796	0.500	0.0020419
319	17.1045	0.5263855	0.525	-0.1385521
320	16.4231	0.5527607	0.550	-0.2760702
321	15.7728	0.5790834	0.575	-0.4083435
322	15.1521	0.6053325	0.600	-0.5332472
323	14.5594	0.6314871	0.625	-0.6487066
324	13.9933	0.6575270	0.650	-0.7527031
325	13.4526	0.6834328	0.675	-0.8432792
326	12.9358	0.7091854	0.700	-0.9185432
327	12.4419	0.7347667	0.725	-0.9766735
328	11.9697	0.7601592	0.750	-1.0159225
329	11.5181	0.7853462	0.775	-1.0346197
330	11.0862	0.8103117	0.800	-1.0311747
331	10.6729	0.8350408	0.825	-1.0040793
332	10.2773	0.8595191	0.850	-0.9519094
333	9.89870	0.8837333	0.875	-0.8733261
334	9.53610	0.9076708	0.900	-0.7670777
335	9.18890	0.9313200	0.925	-0.6319968
336	8.85630	0.9546701	0.950	-0.4670061
337	8.53760	0.9777111	0.975	-0.2711125

Having obtained the thermistor resistance R(t) at different temperature point, a comparison was then made with the ideal output voltage readout of the Wheatstone bridge which allowed for the calculation of the other bridge circuit resistance R_a , R_b , and R_c . For the Wheatstone bridge circuit construction, the resistance R_a was obtained as 13.3 K ohms. The ratio R_b / R_c as 3.2 and the suitable standard resistor selected for R_b and R_c implementation are 18 K and 5.6 K respectively.

To evaluate the performance accuracy of the designed Wheatstone bridge-based signal conditioning circuit with the standard resistor values for temperature measurement, the output voltage of the bridge was compared with that of the ideal output voltage at different temperature points as shown in Fig. 6. It was observed that the system output voltage values (dotted) have minimal deviation from the ideal output (straight line). Even though the systematic error was avoided as much as possible during the experimental stage of the thermistor linearisation, little deviations were observed. This might be due to value approximation during the numerical analysis or in the selection of standard resistor values. The observed error could also be from environmental impact such as ambient temperature and humidity or electromagnetic interference on the thermistor and measuring instrument during the experimentation.

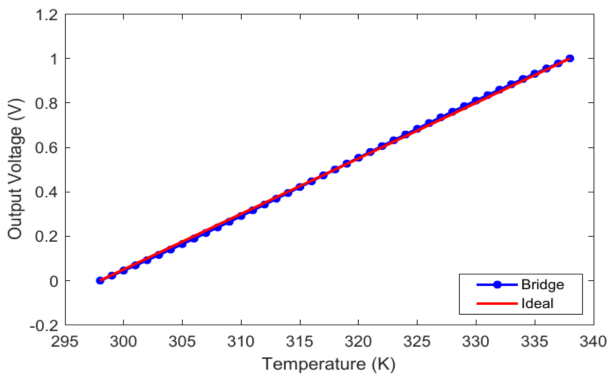

Fig. 5. Wheatstone bridge output voltage against temperature

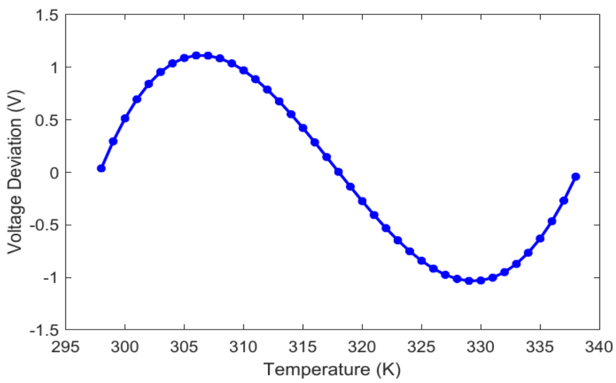

Fig. 6. Thermistor resistance versus temperature

The percentage non-linearity between the Wheatstone bridge output and the ideal output voltage were analysed to ascertain the suitability of the designed signal conditioning circuit for temperature measurement within the specified range (i.e. 25°C to 65°C). To evaluate the % nonlinearity, the output voltage deviation from the ideal is plotted against the Temperature (K) in Fig. 7. It was observed that the system has a maximum % nonlinearity of 1.1% which can be considered relatively small. The low nonlinear value in the Wheatstone bridge output voltage shows that constructing the temperature sensing circuit with the obtained standard resistor values will give an output readout closed to an ideal condition.

4. Conclusion

Thermistor resistance-temperature response had been successfully linearized and Wheatstone bridge signal conditioning circuit designed. The experimental results on NTC thermistor show that the temperature sensor exhibits a negative temperature coefficient with a decrease in resistance as the temperature increases. The measured thermistor resistance-temperature was used to model a linear relationship between the two variables which allows the design of Wheatstone bridge signal conditioning circuit for accurate temperature measurement. The performance evaluation of the designed Wheatstone bridge signal conditioning circuit was satisfactory with good accuracy of 1.1% non-linearity compared to ideal condition.

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