Enhanced Interfacing of Single Element Resistive Sensor with Microcontroller

M. Florance Mary, D. Sathish

Abstract: ***Resistive sensors can be used in a single element, differential and bridge forms. Resistive sensors have wide applications in industries. When the resistive sensor is directly connected with the microcontroller large amount of error arises due to lead wire resistance and microcontroller port pin resistances. Here, an enhanced interfacing of single element resistive sensor with a microcontroller scheme is proposed to compensate the error due to lead wires and port pin resistances. This scheme follows three discharge cycles for the measurement of resistances of the resistive sensor. The time taken for each discharge cycle is noted. From the time taken for the three discharge cycles, the resistance R_Y of the resistive sensor is directly calculated. Since the resistances due to lead wires and internal port pin resistances are corrected, the unknown temperature measurement is done accurately.***

Keywords**:** ***RTD, Single element resistor, Microcontroller.***

I. INTRODUCTION

Resistive sensors are one of the commonly used types of an analog sensor. The resistive sensor converts the physical quantity into variable resistance for the sake of measurement. Resistive sensors are in different forms such as single element, differential, and bridge forms. Single element resistive sensor such as Resistive Temperature Detector (RTD) senses the physical quantity by using one sensing element. Resistive sensors are connected to the measuring unit through some lead wires. These lead wires have some lead wire resistances due to which large amount of error will arise. These lead wire resistances affect the accuracy of the measurement.

Many works are done for accurate measurement of temperature using temperature sensors like RTD, thermocouple, and thermistor. A two-wire method with a self- heating technique for the RTD sensors was used to provide long lead resistance compensation. It was able to compensate for large lead resistance of tens of ohms in a repetitive: time-sharing mode, avoiding its variations with the environmental temperature [1]. The temperature was measured using the RTD along with signal conditioning circuits, which includes voltage/current excitation, amplification, and linearization. From the comparison, it was found that the four-wire RTD provides good interchangeable configuration and cancels out the lead resistance effectively compared to other RTD wire configuration. This method is not suitable for two-wire and three wire RTDs [2]. A compensation technique was also proposed for three-wire and four-wire RTDs which is not a suitable technique for the single element resistive sensors. Here it was found that the output would be affected by the non-ideal characteristics of the op-amps [3], [4]. A lead wire compensation for two-wire Resistance Temperature Detectors (RTD) having signal conditioning circuits using sample and hold, current source and diodes was also proposed and found to be complex [5].

When considering the interfacing of RTD to the microcontroller, many schemes are proposed. In the multi-point temperature measurement scheme stated for three-wire RTD having lead wire compensation for measurement of temperature, it was found to have complex analog signal conditioning circuits [6]. Op-amp based V-to-I converter was used along with the resistive sensor as a novel remote measurement technique. Here, V-to-I converter needs to be excited by a square wave of 50 % duty cycle [7]. Direct interface circuits can measure different categories of resistive sensors using an 8-bit microcontroller along with internal timer. This technique was found to be feasible for low-value resistive sensors and not for the high-value resistive sensors [8]. A realization technique using an interface circuit for single resistive sensors, that provides an output signal linearly related to resistive sensor was implemented. This scheme needs a separate circuitry for current source [9]. There are few works carried based on discharge cycles. Discharging performed through three different micro-controller port pins was used for measurement and it was found that the accuracy was affected by the mismatch between the port pin resistances as detailed in [10].

The sensor to microcontroller interface with long lead wires to connect and measure using a resistive element was also implemented. Using four diodes with four discharge cycles with proper switch arrangement the resistive sensor was directly connected to the port lines of microcontroller to reject lead resistance [11]. An improved single-element resistive sensor-to-microcontroller interface was presented in [12]. With the help of single microcontroller pin, this circuit compensates the lead wire resistance using information available from three discharge cycle for computation. Here, an analog comparator through interrupt was used to limit the time of count during the discharge cycles.

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In this proposed work, the hardware comparator is replaced by the software comparator to limit the time of count of discharge cycles and more study is made on the lead wire and port pin resistances compensation, when the resistive sensor is used as a single element. Here, the circuit complexity is also reduced by proposing a compensation technique that eliminates the error due to lead wire resistances.

II. DESIGN OF SENSOR INTERFACING WITH MICROCONTROLLER

The circuit diagram of the proposed resistive sensor for microcontroller interfacing scheme is shown in Fig.1. The resistive sensor R_Y is connected to the measurement section using two diodes D1 and D2 and connecting wires, such as R_{WR1} and R_{WR2}. The measurement section consists of a microcontroller, transistor, four relay switches namely, RELAY1 (S_1), RELAY2 (S_2), RELAY3 (S_3) and RELAY4 (S_4) and three resistances R_G, R_H and R_I and a capacitor C. In the measurement process, microcontroller port pins P1-P6 (digital pins) and P7 (analog pin) are used. The port pin P1 acts as the charging pin and port pin P2 acts as the discharging pin. Port pin P7 act as internal analog comparator pin in between resistance R_H and capacitor C. Port pins P3, P4, P5, P6 are used to provide control signals for the relay and relay acts as switching device. Here, between microcontroller port pin P1 and the capacitor C, a resistor R_G is included to enhance the removal of power supply interference. Here, resistor R_H is used to make the discharge current drawn by the capacitor C to be lower than the maximum output current, when R_Y is zero.

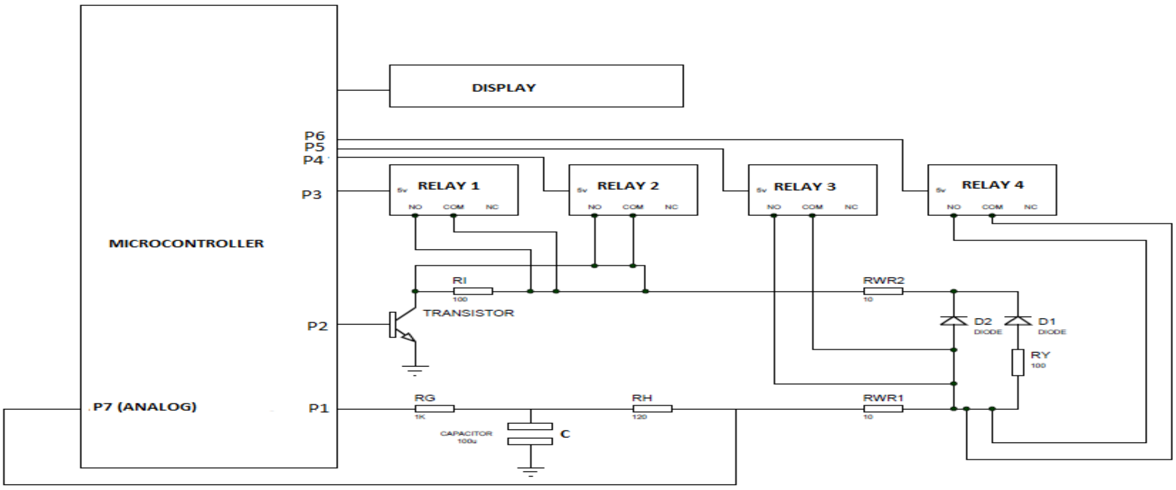

Fig. 1. Circuit diagram of the enhanced resistive sensor interface with microcontroller

The nominal resistance of the sensing element is taken to be equal to the resistor, R_I connected between the two terminals of the switch. To charge the capacitor C during the charge cycle (charging pin set as HIGH) the port pin P1 is used. The port pin P2 serves as the discharging pin during the discharge cycle (discharging pin set as HIGH). In the discharging period, the discharging current of capacitor C flows through the emitter of the transistor, where the emitter is connected to the ground. Here, the measurement will be done on the basis of the three charging cycles and the three discharging cycles of the capacitor C. The charging pin P1 will be set to digitally high to charge the capacitor C till it reaches the operating voltage of the capacitor (5V) at the time of charging period of the charging cycle. The time period of the capacitor needs to be greater than $5R_GC$ to get the capacitor C charged fully. The discharging pin P2 will be set to digitally high to discharge the capacitor operating voltage (5V) till it equals to the threshold voltage of the capacitor C (1.1V) at the discharging period of the discharging cycle. A discharge cycle follows every charge cycle.

In the first discharge cycle A, the port pin P1 acting as the charging pin is set as digitally high, the port pin P2 acting as the discharging pin is set as digitally low. Port pin P3, P5 used as relay pins are set as digitally high and port pin P4, P6 used as relay pins are set as digitally low. The relay switches S_1 and S_3 are at the position of normally open and the relay switches S_2 and S_4 are at the position of normally closed. In the discharge cycle A, diode D1 is ON and diode D2 remains OFF. Capacitor C now discharges through resistance R_{Q1}, where

$$R_{Q1} = R_Y + R_{CP} \qquad - (1)$$

$$R_{CP} = R_G + R_{WR1} + R_{WR2} + R_{PIN} + R_{SR1} + R_{SR2} + R_{SR3} + R_{SR4} \qquad - (2)$$

Here, R_{SR1}, R_{SR2}, R_{SR3}, and R_{SR4} are the resistances of the relay switches S_1, S_2, S_3 and S_4 and R_{PIN} is the internal resistance of the microcontroller port pin P2. R_{WR1} and R_{WR2} are the lead wire resistances of the resistive sensor. The internal timer of the microcontroller gets activated at the start of the discharging cycle. When the capacitor voltage gets equal to the threshold voltage V_{TL}, the counter gets stopped. The count value N_A is the count when counter is stopped, for the time T_A for first discharge cycle. Here $T_A = N_AT_C$ where T_C is the clock period of the microcontroller. During this period, discharge current $i_1(t)$ is

$$i_1(t) = \frac{(V_{DD} - V_{D1})}{R_{Q1}} e^{-t/R_{Q1}C} \qquad - (3)$$

Here, V_{D1} is the ON-state forward voltage drop of diode D1. The voltage, $V_{R_{Q1}}(t)$ across R_{Q1}, can be expressed as

$$V_{R_{Q1}}(t) = i_1(t)R_{Q1} = (V_{DD} - V_{D1})e^{-t/R_{Q1}C} \qquad \text{- (4)}$$

and the capacitor voltage can be stated as

$$V_C(t) = V_{DD} + V_{RQ1}(t) \qquad \text{- (5)}$$

By substituting $V_{RQ1}(t)$ from (4) into (5), $V_C(t)$ becomes,

$$V_C(t) = V_{D1} + (V_{DD} - V_{D1})e^{-t/R_{Q1}C} \qquad \text{- (6)}$$

The capacitor voltage, $V_C(t)$ at (t = 0) will be

$$V_C(t) = V_{DD} \qquad \text{- (7)}$$

The discharging takes place till the capacitor voltage moves down to a threshold voltage, V_{TL} hence

$$V_{TL} = V_{D1} + (V_{DD} - V_{D1})e^{-T_A/R_{Q1}C} \qquad \text{- (8)}$$

Applying the natural logarithm to (8), T_A becomes

$$T_A = N_A T_c = R_{Q1} \ln\left[\frac{V_{DD} - V_{D1}}{V_{TL} - V_{D1}}\right] \qquad \text{- (9)}$$

For the considered system, if the values of C, V_{DD}, V_{TL}, and V_{D1} are considered to be constants, then T_A will be proportional to the total resistance R_{Q1}. Once T_A has been measured, the capacitor C is once again charged and the discharge cycle B will start.

Similarly, the time taken for discharging T_B in the second discharge cycle B is calculated as

$$T_B = N_B T_c = R_{Q2} \ln\left[\frac{V_{DD} - V_{D2}}{V_{TL} - V_{D2}}\right] \qquad \text{- (10)}$$

Here V_{D2} is the cut-in voltage of diode D2. Once T_B has been measured, the capacitor C is once again charged and the discharge cycle C will start.

Similarly, the time taken for discharging T_D in the third discharge cycle C is calculated as

$$T_D = N_D T_c = R_{Q3} \ln\left[\frac{V_{DD} - V_{D2}}{V_{TL} - V_{D2}}\right] \qquad \text{- (11)}$$

After the discharge cycle C gets completed, the capacitor C is charged again and the discharge cycle A gets started.

From the above discharge cycles, the value of T_A - T_D is calculated from (9) and (11) as

$$T_A - T_D = (N_A - N_D)T_C \qquad \text{- (12)}$$

$$T_A - T_D = R_{Q1} \ln\left[\frac{V_{DD} - V_{D1}}{V_{TL} - V_{D1}}\right] - R_{Q3} \ln\left[\frac{V_{DD} - V_{D2}}{V_{TL} - V_{D2}}\right]$$

- (13)

Substituting the values of R_{Q1} and R_{Q3} in (13) and assuming that $V_{D1} = V_{D2}$ since the diodes D1 and D2 are identical, it is found that

$$(N_A - N_D)T_C = C \ln\left[\frac{V_{DD} - V_{D1}}{V_{TL} - V_{D1}}\right][R_Y + R_{CP} - R_{CP}]$$

- (14)

Similarly, the value of $T_B - T_D$ is calculated from (10) and (11) as

$$T_B - T_D = (N_B - N_D)T_C \qquad \text{- (15)}$$

$$T_B - T_D = R_{Q2} \ln\left[\frac{V_{DD} - V_{D2}}{V_{TL} - V_{D2}}\right] - R_{Q3} \ln\left[\frac{V_{DD} - V_{D2}}{V_{TL} - V_{D2}}\right]$$

- (16)

Substituting the values of R_{Q2} and R_{Q3} in (13) and assuming that $V_{D1} = V_{D2}$ since the diodes D1 and D2 are identical, it is found that

$$(N_B - N_D)T_C = C \ln\left[\frac{V_{DD} - V_{D1}}{V_{TL} - V_{D1}}\right][R_Y + R_{CP} - R_{CP}]$$

- (17)

Dividing (14) by (17) and rearranging, R_Y becomes,

$$R_Y = R_I \left[\frac{N_A - N_D}{N_B - N_D}\right] \qquad \text{- (18)}$$

From the equation (18), it is understood that the value of sensor is calculated from the three count values N_A, N_B and N_D obtained during the three discharge cycles. Table 1 shows the measurement path of the three discharge cycles.

Table 1 Measurement path of the Discharge Cycles

Measurement Path	**Microcontroller Port pin conditions**						**Relay switch positions**				**Diode Conditions**		**Equivalent resistance of the discharge path**
	P_1	**P_2**	**P_3**	**P_4**	**P_5**	**P_6**	**S_1**	**S_2**	**S_3**	**S_4**	**D_1**	**D_2**	
Discharge cycle A(R_{Q1})	H	L	H	L	H	L	NO	NC	NO	NC	ON	OFF	$R_{Q1} = R_Y + R_{CP}$
Discharge cycle B (R_{Q2})	H	L	L	H	L	H	NC	NO	NC	NO	OFF	ON	$R_{Q2} = R_I + R_{CP}$
Discharge cycle C (R_{Q3})	H	L	L	H	H	L	NC	NO	NO	NC	OFF	ON	$R_{Q3} = R_{CP}$

NC – Normally Closed, NO – Normally Open, H – High, L – Low

For example, if RTD is used as the resistive sensor, then $R_Y = R_o(1 + K\theta)$ where θ is the value of temperature being sensed and K is the sensitivity of the RTD. Hence, by choosing R_I to be equal to nominal value R_o in (18)

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$$R_o(1+K\theta) = R_I\left[\frac{N_A - N_D}{N_B - N_D}\right] \qquad \text{- (19)}$$

Rearranging (19)

$$\theta = \frac{1}{K}\left[\frac{N_A - N_B}{N_B - N_D}\right] \qquad \text{- (20)}$$

From (20) it is found that the count values N_A, N_B, N_D are sufficient to find the value of temperature.

III. SIMULATION STUDY

The simulation of the circuit was done using the simulation tool, Proteus. The circuit was simulated using microcontroller, diodes, transistor and relay switches. The lead wire resistances such as R_{WR1} and R_{WR2} were set as 10Ω and the nominal resistance R_I was set as 100Ω. The sensor resistance was incremented from the temperature value of 0°C to 100°C, by increasing the temperature value in the step of 10°C. Here, the resistance value of 100Ω to 139.16Ω is equal to the temperature value of 0°C to 100°C for the resistive sensor RTD. The sensor resistance R_Y is calculated from the acquired three count values N_A, N_B and N_D. It was found from simulation that the maximum error was 0.17 %. Table 2 shows the comparison of the standard resistance vs measured resistance and its percentage error when proposed enhanced direct resistive sensor was interfaced with a microcontroller interface for the developed simulation study.

Table 2 Simulation results for different temperature ranges

Temperature (°C)	Standard Resistance (Ω)	Measured Resistance (Ω)	% Error
0	100	100.04	0.04
10	103.97	104.01	0.04
20	107.93	107.99	0.05
30	111.88	111.96	0.07
40	115.81	115.88	0.06
50	119.73	119.75	0.07
60	123.64	123.70	0.04
70	127.54	127.60	0.04
80	131.11	131.21	0.07
90	135.30	135.44	0.10
100	139.16	139.40	0.17

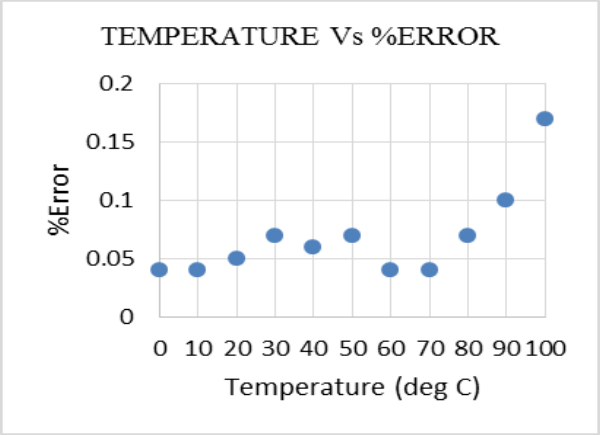

Fig.2. Temperature vs % Error for Simulation Results

From the graph shown in Fig. 2, it is observed that the enhanced direct resistive sensor with microcontroller interface shows a minimum error. The simulation study for the enhanced direct resistive sensor with microcontroller interface circuit was carried out using the Proteus software is shown in Fig. 3.

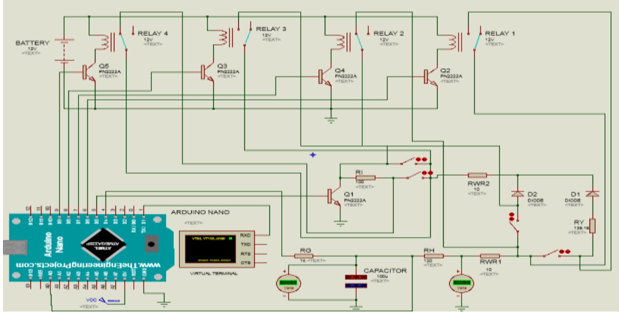

Fig.3. Circuit connection taken for simulation studies

IV. PROTOTYPE DETAILS

While constructing the prototype, RTD (Pt100) was used as the resistive sensor and the four-channel relay RELAY1 (S_1), RELAY2 (S_2), RELAY3 (S_3) and RELAY4 (S_4) are used for the switching purpose of the three discharge cycles. The resistance values of R_G, R_H, and R_I were selected as 1KΩ, 120Ω, 100Ω and the capacitance value of 100 µF was selected respectively. Two diodes (1N4007) such as D1 and D2 were selected having the same diode voltage. The switches, diodes, and resistors were connected to the microcontroller (Arduino Nano) as shown in Fig. 4. The experimental results were taken from the value of 0°C to 100°C by changing the temperature value in steps of 10°C. The internal comparator in the software was used to compare the threshold voltage and capacitor voltage. When the capacitor operating voltage drops from 5V and equals to the threshold voltage of the capacitor C (1.1V) at the discharging period of the discharging cycle, the counter gets stopped. For all the three discharge cycles, the time taken for the capacitor voltage to reach the threshold voltage was observed and the sensor resistance R_Y was calculated. The microcontroller was connected to the computer through the USB port to read the value of count and display the results. The experimental results are also displayed through the LCD display as shown in Fig 4.

Fig.4. Prototype Image

Table 3 shows the comparison of the standard resistance vs measured resistance and it's percentage error when proposed enhanced direct resistive sensor was interfaced with microcontroller interface for the developed prototype.

Table 3 Prototype results

Temperature (°C)	Standard Resistance (Ω)	Measured Resistance (Ω)	% Error
0	100	100.82	0.82
10	103.97	104.05	0.07
20	107.93	108.35	0.38
30	111.88	112.65	0.68
40	115.81	115.88	0.06
50	119.73	120.18	0.37
60	123.64	123.41	0.18
70	127.54	127.71	0.13
80	131.11	131.69	0.44
90	135.30	135.24	0.04
100	139.16	139.54	0.27

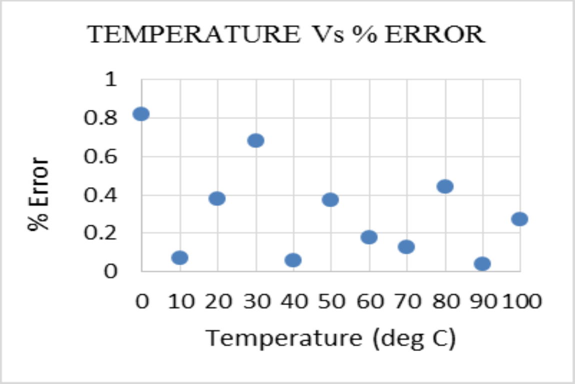

Fig.5. Temperature vs % Error for Experimental Results

From the graph shown in Fig 5, it is observed that the enhanced resistive sensor with a microcontroller interface scheme shows a maximum error of 0.8 % for the prototype model.

V. CONCLUSION

An enhanced scheme of interfacing single element resistive sensor with a microcontroller is proposed. This scheme is simple, uses low-cost components, and offers excellent accuracy during measurement. This improvement is achieved by the compensation of the lead wire resistances and the port pin resistances. The simulation studies were developed and tested using the simulation tool, Proteus. The maximum error obtained from the simulation studies is 0.17 %. A prototype circuit was developed and tested for the temperature value of 0°C to 100°C. The maximum error obtained from the prototype circuit was 0.8% and hence long lead wires can also be used for the sake of measurement, since its effect is compensated accurately.

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