ICIC Express Letters
Volume **13**, Number **4**, April **2019**

ICIC International ©2019 ISSN 1881-803X
pp. 311–316

OP-AMP BASED INTERFACE CIRCUIT FOR RESISTIVE SENSOR WITH LEAD-WIRE-RESISTANCE COMPENSATION

Anucha Kaewpoonsuk[1,2], Ratchanoo Katman[1,2] and Apinai Rerkratn[3]

[1]Department of Physics
Faculty of Science
[2]Research Center for Academic Excellence in Applied Physics
Naresuan University
Phitsanulok 65000, Thailand
anuchak@nu.ac.th; ratchanook@psru.ac.th

[3]Faculty of Engineering
King Mongkut's Institute of Technology Ladkrabang
Chalongkrung Rd., Ladkrabang, Bangkok 10520, Thailand
apinai@gmail.com

Received September 2018; accepted December 2018

Abstract. *This paper presents a simple technique to implement the resistive sensor interface for remote measuring. The circuit is designed using a relaxation oscillator to generate a square wave signal. The time difference during charging and discharging a capacitor is directly proportional to the sensor's resistance. The structure of the circuit is composed of two op-amps, three bipolar junction transistors, a capacitor, four fixed resistors and a variable resistor. Features of the proposed circuit are single-supply operation and direct interface with a microcontroller without an analog-to-digital converter. In addition, the lead-wire resistance is automatically compensated. When the resistance values of the sensor are varied in the range of 500-1500 Ω with lead-wire resistance values of 0-100 Ω, the result of the circuit testing is found that the maximum error is approximately equal to 1.15% of full scale. The performance of the circuit is in accordance with principles proposed.*

Keywords: Interface circuit, Resistive sensors, Remote measurement, Op-amp

1. **Introduction.** Resistive sensors are widely used in measurement and control systems. Sometimes the measuring (including the sensor) and the processing units are separated to the convenience and safety for measurement. In case of a long lead-wire, the resistance of the lead-wire affects the accuracy of the system. There are different design techniques for realization of the interface circuit with lead-wire-resistance compensation. The first interesting circuit is the use of two operational amplifiers (op-amps) connected to two diodes as the main device in the design [1]. After that, the square-wave input voltage is entered to this circuit. The measured square-wave output with a mean value corresponds to the resistance of the sensor. The second circuit is designed using a 555 timer IC in a stable mode with two diodes [2]. It does not require the excitation voltage signal. This circuit provides a square-wave signal which the time difference between the charging and discharging time depends on the resistance of the sensor. The third circuit uses a second generation current conveyor (CCII) connected to two diodes, four analog-switches and four op-amps [3]. Similarly, after a square-wave input voltage is entered to the circuit reported in [1]. The circuit provides the direct current-type (DC) output voltage. The fourth circuit uses three analog switches coupled with two diodes. The time constant of the RC-circuit is measured by microcontroller. Its value is directly proportional to the resistance of the sensor [4]. It is well known that op-amp is a low-cost commercial device

---

DOI: 10.24507/icicel.13.04.311

that is familiar to circuit designers. This paper aims to propose the simple and accurate interface circuit for resistive sensor-based remote measurement. The realization method bases on two diodes as well as the technique reported in [1-4]. However, the superior design is the use of two op-amps that does not require an analog switch.

This paper is divided into 5 sections. The design and analysis of the proposed interface circuit for resistive sensor with lead-wire-resistance compensation are described in Section 2. After that, Section 3 shows effect of non-ideal characteristics of transistors used in this paper. The experimental setup and results are discussed in Section 4. Finally, the conclusions are stated in Section 5.

2. Circuit Description.

The relaxation oscillator-based interface circuit proposed by employing two op-amps and three bipolar junction transistors is shown in Figure 1. The V_{cc} and V_{os} denote a supply voltage of the circuit and an output voltage of the op-amp A$_1$, respectively. The resistances R_{sens}, r_{w1} and r_{w2} represent the resistances of the sensor, the first lead-wire and the second lead-wire, respectively. The op-amp A$_2$ connected with the variable resistor R_v acts as the voltage generator to provide the voltage V_b for the relaxation oscillator. When the R_{v1} and R_{v2} are first and second resistances of the variable resistor R_v, the voltage V_b is as follows:

$$V_b = \frac{R_{v2}}{R_{v1} + R_{v2}} V_{cc} \tag{1}$$

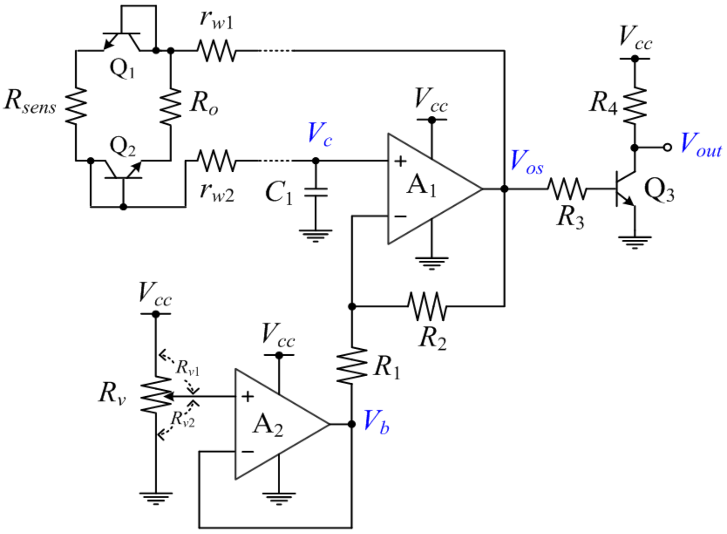


FIGURE 1. Proposed interface circuit

After considering the oscillator designed using the op-amp A$_1$, capacitor C_1 and bipolar junction transistors Q$_1$ and Q$_2$, the function of the Q$_1$ and Q$_2$ is similar to a diode. Define that $V_{sat(H)}$ and $V_{sat(L)}$ are the upper-saturation and the lower-saturation values of the output voltage V_{os}. The resistors R_1 and R_2 are used to provide the upper-threshold voltage V_H and the lower-threshold voltage V_L, which can be expressed as

$$V_H = \frac{R_1}{R_1 + R_2} V_{sat(H)} + \frac{R_2}{R_1 + R_2} V_b \tag{2}$$

$$V_L = \frac{R_1}{R_1 + R_2} V_{sat(L)} + \frac{R_2}{R_1 + R_2} V_b \tag{3}$$

For the case of $V_{os} = V_{sat(H)}$: the capacitor (C_1) is charged via the transistor Q$_1$. Thus, the charging time T_1 can be written as

$$T_1 = k_1 C_1 \left[R_{sens} + r_{w1} + r_{w2} \right] \tag{4}$$

$$k_1 = \ln\left[\frac{V_{sat(H)} - V_{be1} - V_L}{V_{sat(H)} - V_{be1} - V_H}\right] \tag{5}$$

where V_{be1} is the voltage across the transistor Q_1 while receiving forward bias. For the case of $V_{os} = V_{sat(L)}$: the capacitor is discharged via the transistor Q_2. Thus, the discharging time T_2 can be written as

$$T_2 = k_2 C_1 \left[R_o + r_{w1} + r_{w2}\right] \tag{6}$$

$$k_2 = \ln\left[\frac{V_H - V_{sat(L)} - V_{be2}}{V_L - V_{sat(L)} - V_{be2}}\right] \tag{7}$$

where V_{be2} is the voltage across the transistor Q_2 while receiving forward bias. The $V_b = (V_{sat(H)} + V_{sat(L)})/2$ is assigned. Assume that parameters $V_{be2} = V_{be1} = V_{be}$. Therefore, the time difference ΔT between T_1 and T_2 can be expressed as

$$\Delta T = T_1 - T_2 = kC_1 \left[R_{sens} - R_o\right] \tag{8}$$

where

$$k = k_1 = k_2 = \ln\left[\frac{V_{sat(H)} - V_L - V_{be}}{V_{sat(H)} - V_H - V_{be}}\right] = \ln\left[\frac{V_H - V_{sat(L)} - V_{be}}{V_L - V_{sat(L)} - V_{be}}\right] \tag{9}$$

From Equation (8), it is evident that time difference ΔT is directly proportional to the sensor resistance. In addition, the ΔT also contains only R_{sens} and R_o without r_{w1} and r_{w2}. The transistor Q_3 connected with the resistors R_3 and R_4 is used to adjust the level of the obtained square wave signal V_{os} until it is suitable for interfacing with a microcontroller. In the logical "1" state, the input voltage level must be higher than 2.4 V and lower than 0.8 V in the logical "0" state. Then, the output voltage V_{out} and the voltage V_{os} are out of phase. The predicted signals V_c, V_{os} and V_{out} can be demonstrated as Figure 2.

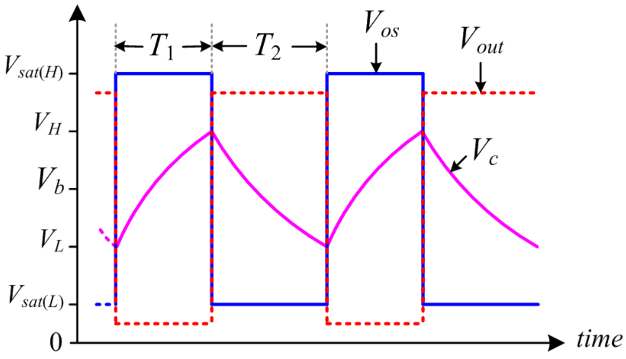


FIGURE 2. The V_{os} signal

3. **Effect of Non-Ideal Characteristics of Transistors Q_1 and Q_2.** In conductive state of transistors Q_1 and Q_2, the voltage drop across each transistor will be equal to each other. After that Equation (9) is achieved. Practically, the voltages V_{be1} and V_{be2} may be slightly different which result in changing Equation (9). We assume

$$V_{be2} = V_{be1} + \Delta V_{be} \tag{10}$$

where ΔV_{be} is the value of the difference between the voltages V_{be1} and V_{be2}. We define

$$V_{sat(H)} - V_{be1} - V_L = V_H - V_{sat(H)} - V_{be1} = X_o \tag{11}$$

$$V_{sat(H)} - V_{be1} - V_H = V_L - V_{sat(L)} - V_{be1} = Y_o \tag{12}$$

When Equations (10) to (12) are substituted into Equations (5) and (7), the ΔT can be evaluated by

$$\Delta T = T_1 - T_2 = kC_1 \left[R_{sens} - R_o\right] \ln\left(\frac{X_o}{Y_o}\right) - \varepsilon_{off} \tag{13}$$

where

$$\varepsilon_{off} = C_1 \left[R_o + r_{w1} + r_{w2}\right] \ln\left(\frac{Y_o\left(X_o - \Delta V_{be}\right)}{X_o\left(Y_o - \Delta V_{be}\right)}\right) \tag{14}$$

In Equation (14), the value of the ε_{off} is zero, when $X_o = Y_o$ or $\Delta V_{be} = 0$. In the first case, it is impossible because the gain or the transfer function between the ΔT and R_{sens} will be zero. Then, the array transistor is used in this paper to provide two transistors Q_1 and Q_2 that have the best match.

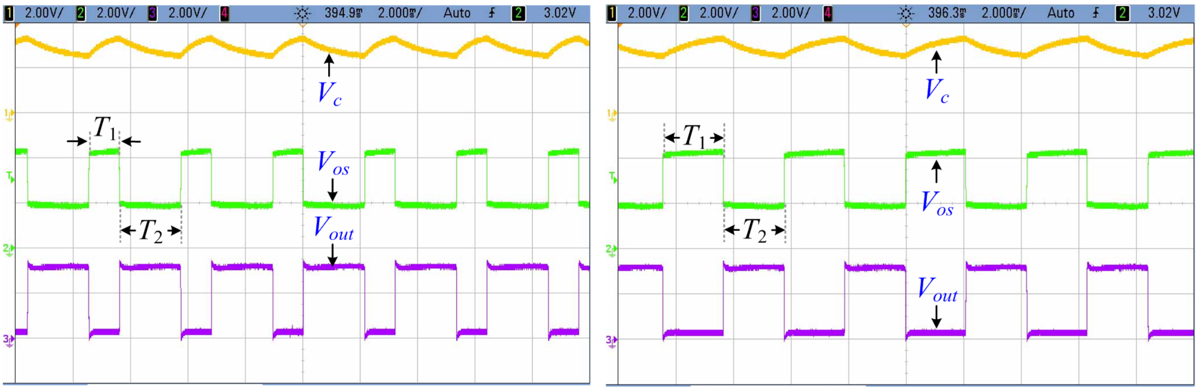
4. **Experimental Results.** The proposed circuit, shown in Figure 1, was constructed using commercially available op-amps LM741 (A_1 and A_2), array transistors CA3046 (Q_1 and Q_2), a bipolar junction transistor Q2N3904 (Q_3) and a variable resistor (R_v) of 1 kΩ. The fixed capacitor $C_1 = 1$ μF and resistors $R_1 = 5$ kΩ, $R_2 = 10$ kΩ, $R_3 = 50$ kΩ and R_4 = 1 kΩ used in the circuit were selected. The supply voltage V_{cc} was set to 5 V. Values of the voltages: $V_{be1} \cong V_{be2} \cong 0.625$ V, $V_{sat(H)} = 4.282$ V and $V_{sat(L)} = 1.900$ V were measured. Thus, the voltage $V_b = 3.091$ V was assigned. After considering Equations (2) and (3), we get values of the voltages $V_H = 3.488$ V and $V_L = 2.694$ V. It results in the k in Equation (9) is 1.74. Then, the value of gain (kC_1) in Equation (8) is equal to 1.74 ms/Ω.

In order to simulate resistive sensor-base remote measuring, the sensor resistance R_{sens} and the lead-wire resistance r_{w1} and r_{w2} were set with different values as shown in Table 1. Hence, the resistance $R_o = 1$ kΩ was selected. From Table 1, it can be observed that the measured ΔT agrees well with the calculated values. The worst-case error is 1.15% of full scale. In case $r_{w1} = r_{w2} = 0$ Ω, the R_{sens} is varied as 0.5 kΩ, 1 kΩ and 1.5 kΩ. The measured signals V_c, V_{os} and V_{out} are demonstrated in Figures 3(a) to 3(c). Notice that when the R_{sens} is less than 1 kΩ, equal to 1 kΩ and more than 1 kΩ, the T_1 will be less than T_2, equal to T_2 and more than T_2 respectively.

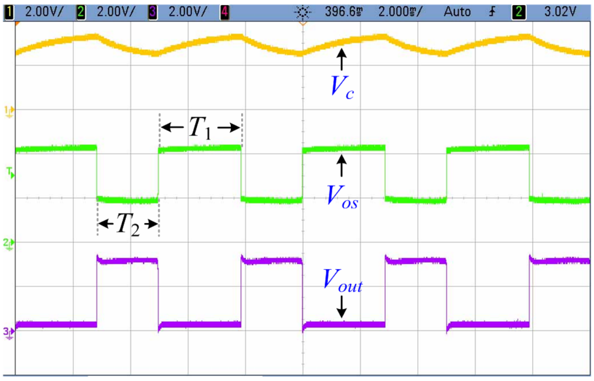
Table 1. Experimental results

R_{sens} (kΩ)	Calculated ΔT (ms)	Measured ΔT (ms)					Worst-Case *Errors* (%FS)
		$r_{w1} = r_{w2} = 0$ Ω	$r_{w1} = r_{w2} = 25$ Ω	$r_{w1} = r_{w2} = 50$ Ω	$r_{w1} = r_{w2} = 75$ Ω	$r_{w1} = r_{w2} = 100$ Ω	
0.5	−0.870	−0.88	−0.88	−0.88	−0.88	−0.87	1.15
0.6	−0.696	−0.69	−0.69	−0.69	−0.69	−0.69	−0.69
0.7	−0.522	−0.53	−0.52	−0.52	−0.52	−0.52	0.92
0.8	−0.348	−0.35	−0.34	−0.34	−0.34	−0.34	−0.92
0.9	−0.174	−0.17	−0.17	−0.18	−0.17	−0.17	0.69
1.0	0.000	0.00	0.00	0.00	0.00	0.00	0.00
1.1	0.174	0.17	0.17	0.17	0.18	0.17	−0.69
1.2	0.348	0.35	0.34	0.35	0.34	0.34	0.92
1.3	0.522	0.53	0.52	0.52	0.52	0.52	−0.92
1.4	0.696	0.70	0.69	0.69	0.69	0.69	−0.69
1.5	0.870	0.86	0.86	0.86	0.87	0.87	1.15

Plots of the measured ΔT and the calculated ΔT versus the sensing resistance R_{sens} are displayed in Figure 4. It is apparent that all graphs are similar and linear with R_{sens} values. In addition, slopes of all graphs are according to the calculated value. Figure 5 shows the plots of the error values between the measured ΔT and the calculated ΔT versus the sensor's resistance R_{sens}. Although the value of the lead-wire resistance is changed, it slightly affects the circuit performance.



(a) $R_{sens} = 0.5$ kΩ (b) $R_{sens} = 1$ kΩ



(c) $R_{sens} = 1.5$ kΩ

Figure 3. The voltage signals V_c, V_{os} and V_{out} (Vertical scale: 2 V/div., horizontal scale: 2 ms/div.)

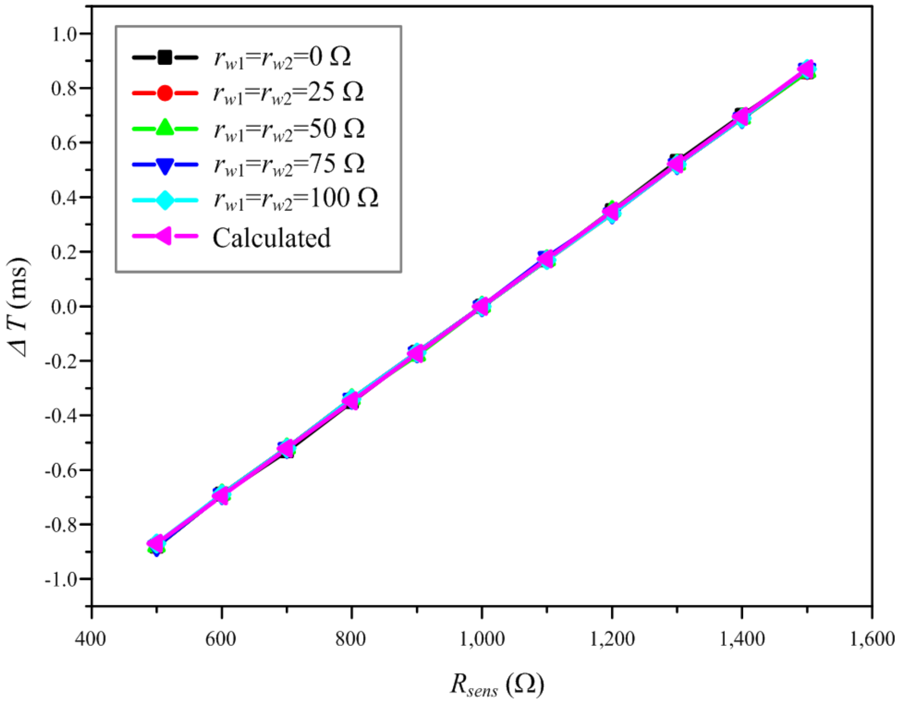


Figure 4. Plots of ΔT versus R_{sens}

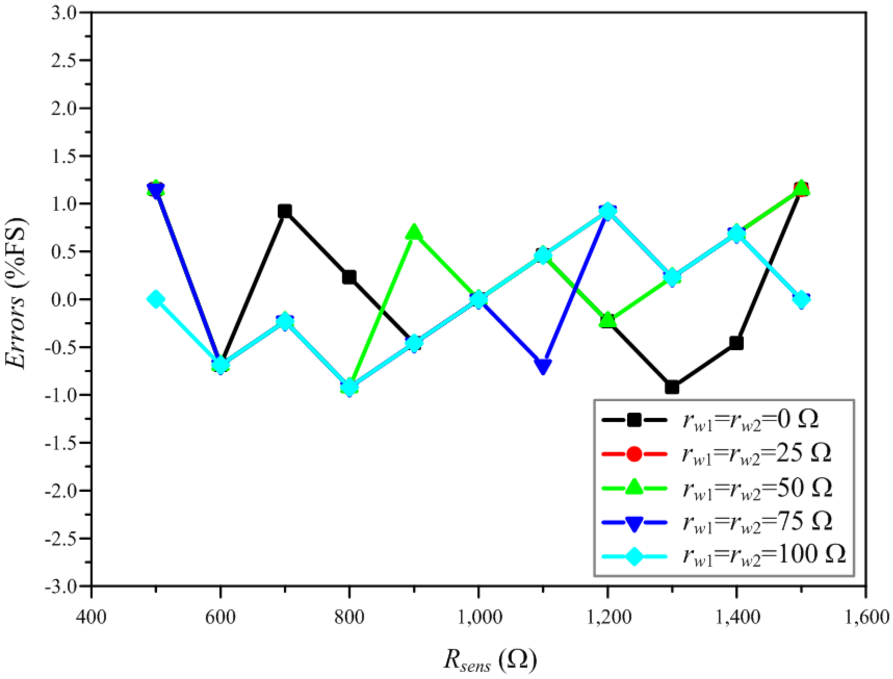


Figure 5. Plots of *Errors* versus R_{sens}

5. **Conclusions.** We have demonstrated that the simple and accurate interface circuit for resistive sensor-base remote measuring can be implemented by using two op-amps and three bipolar junction transistors. Based on the relaxation oscillation technique, the proposed circuit was used to provide the square-wave signal which the difference between charging and discharging time is directly proportional to the sensor resistance. The lead-wire resistance was also compensated. Experimental results have been shown to agree very well with the expected values. Finally, we expect that our proposed circuit can be applied to a resistive sensor in remote measurement systems.

REFERENCES

[1] T. K. Maiti and A. Kar, Novel remote measurement technique using resistive sensor as grounded load in an opamp based V-to-I converter, *IEEE Sensor*, vol.9, no.3, pp.244-245, 2009.
[2] T. K. Maiti and A. Kar, A new and low cost lead resistance compensation technique for resistive sensors, *Measurement*, vol.43, pp.735-738, 2010.
[3] W. Petchmaneelumka, P. Julsereewong, A. Julsereewong and J. Tongpakpanang, Simple interface circuit with lead-wire-resistance compensation for single resistive sensor, *ICCAS Conf.*, Jeju Island, Korea, 2012.
[4] P. R. Nagarajan, B. George and V. J. Kumar, Improved single-element resistive sensor-to-microcontroller interface, *IEEE Trans. Instrum. Meas.*, vol.66, no.10, pp.2736-2744, 2017.