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READOUT CIRCUIT FOR CONDUCTIVITY MEASUREMENT WITH PARASITIC RESISTANCE COMPENSATION

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Abstract. *This paper presents a simple method based on commercially available current feedback operational amplifiers (CFOAs) to realize the readout circuit for measuring the solution conductivity including the parasitic resistance in the electrode sensor. The enhanced readout circuit for conductivity measurement in electrolyte solution, compared with the conventional readout circuit using the op-amp inverting amplifier, offers a technique for the parasitic resistance compensation to improve the linearity of the measurement results. The proposed readout circuit provides the digital output which is directly proportional to the conductivity of electrolyte solution. The experimental verification and the measured results of the method are included in this paper.*
Keywords: Readout circuit, Conductivity measurement, Parasitic resistance compensation

1. **Introduction.** The conductivity measurement is a widespread method for testing the material property and determining the ability of electrical conductivity in liquid. It is an indirect measurement and a reliable method, compared with chemical analysis methods. The application of the conductivity measurement in agricultural purposes is reviewed by Corwin and Lesch [1]. The conductivity can be used to determine the soil water content, organic matter, depth to clay-rich layers, and soil salinity [2]. The conductivity is also useful for monitoring quality of drinking water. It is a basis parameter which relates to the total dissolve solid (TDS) in water. In the proposed TDS measurement system [3], two electrodes were used as part of a non-inverting amplifier for measuring the conductivity. The DC output voltage achieved using a full wave rectifier was calibrated against a commercial TDS measurement instrument. Furthermore, the conductivity is a factor for estimating nutrient solution in hydroponic systems [4,5].

Readout circuit designs for measuring the conductivity have been evolved and adapted in particular purposes. A non-inverting amplifier with electrode sensing element is used as a current-to-voltage converter. It is designed for conductivity measurement in seawater desalination. Results of the different conductivity ranges are measured by the variable frequency excitation [6]. The current-to-voltage converter is a simple and popular readout circuit for resistive and electrode sensors. In dairy industries, the conductivity measurement system is used to detect the bovine mastitis of cows. The system consists of

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current-to-voltage converter and AC-to-DC converter parts. The used platinum electrode sensor is excited with a 2.4 kHz square wave signal to avoid a polarization effect [7]. In addition, the intelligent conductivity meter is proposed by Wei et al. [8]. It has been shown that the design of a bipolar pulse voltage source can be easily adjusted to generate the excitation signal for electrodes. Recently, the conductivity measurement is applied to the apparatus for determining salinity in the Kimchi fermentation. Pair of electrodes and a capacitor are used as a salinity sensing unit. The switching technique of a voltage to charge and discharge to the capacitor of the salinity sensing unit is used in the proposed apparatus. The duty ratio of a pulse signal which is applied to controlling the voltage switching depends on the salinity measured [9].

In the literature mentioned above, the electrodes are used for measuring the conductivity. The measurement results are inevitable affected by the polarization resistance which mainly causes the parasitic resistance. The alternating current (AC) voltages are used as the excitation signal to solve this problem by reducing the accumulation of ions in the electrodes. However, the parasitic resistance still exists in measuring the conductivity with the AC excitation signals as reported by Kaewpoonsuk et al. [10]. They verify the existence of the parasitic resistance by the nonlinear relationship between the voltage output and the conductivity of solution. In order to improve the linearity of measurement results, the aim of this paper is to present an analog-technique-based circuit design for the parasitic resistance compensation of conductivity measurement in electrolyte solution.

The rest of the paper is organized as follows. In Section 2, we show how to find the parasitic resistance of electrodes. After obtaining a value of the parasitic resistance, we propose a circuit to compensate for the resistance value as demonstrated in Section 3. Details of experimental setup and results are shown and discussed in Section 4. The conductivity measured by our circuit is compared with that measured by the standard electrical conductivity (EC) meter. Finally, conclusions are given in Section 5.

2. **Determining Parasitic Resistance of Electrodes.** In this proposed design technique, we have to know the parasitic resistance of the electrodes before designing the compensation circuit. Therefore, the parasitic resistance can be determined by measuring the conductivity in electrolyte solution with the simple readout circuit as shown in Figure 1.

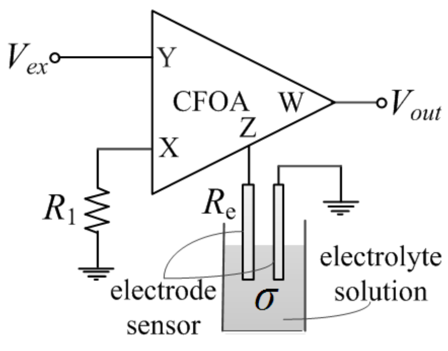

Figure 1. CFOA-based current-to-voltage converter

For experiment setup, the presented circuit has been designed using the commercial AD844 CFOA powered with ±9 V and the 5 kΩ resister R_1 with ±1% tolerance. We prepare the NaCl solution with conductivity in the range of 0.5-5.0 mS/cm. The sinusoidal voltage V_s with the frequency of 1 kHz and amplitude of 6 $V_{p\text{-}p}$ is fed to input of the designed CFOA-based current-to-voltage converter. Then, the output voltage V_{out} is indicated in (1). It can be considered that the resistance R_{sens} of the electrode sensor immersed in the solution is the solution resistance R_{sol} which includes the parasitic resistance R_e as depicted in (2)

$$V_{out} = \left(\frac{R_{sens}}{R_1}\right) V_{ex} \tag{1}$$

$$R_{sens} = R_{sol} + R_e \tag{2}$$

From definition, the conductivity σ is the ability of ions in solution to conducting electrical current which can be calculated by the formula $\sigma = GK$, where the conductance G is the inverse of the solution resistance R_{sol} and K is a cell constant value. The output voltage V_{out} can be revised as

$$V_{out} = \left(\left(\frac{1}{\sigma}\right) K + R_e\right) \frac{V_{ex}}{R_1} \tag{3}$$

When we rewrite (3) in a linear equation form of $y = mx+c$, according to (4), R_1/KV_{ex} is a slop and R_e/K is a y-axis intersection point of the linear equation. If the parasitic resistance R_e disappears, Equation (3) suggests that the inverse of output voltage $1/V_{out}$ will be directly proportional to the conductivity σ.

$$\frac{1}{\sigma} = \left(\frac{R_1}{KV_{ex}}\right) V_{out} - \frac{R_e}{K} \tag{4}$$

However, Figure 2 shows the relationship between them is nonlinear. This is because of the existence of the parasitic resistance R_e. As expected, when we plot the results of the measured output voltage V_{out} against the inverse of the conductivity input $1/\sigma$, the trend line of our results is the straight line shown in Figure 3. Thus, the cell constant K and the parasitic resistance R_e, indicated in (3), can be determined by the straight line equation. Its slope and y-axis intersection point are 229.92 and -271.05, respectively. These values correspond to the cell constant $K = 2.044$ cm^{-1} and parasitic resistance $R_e \cong 554\ \Omega$ of the electrode sensor used.

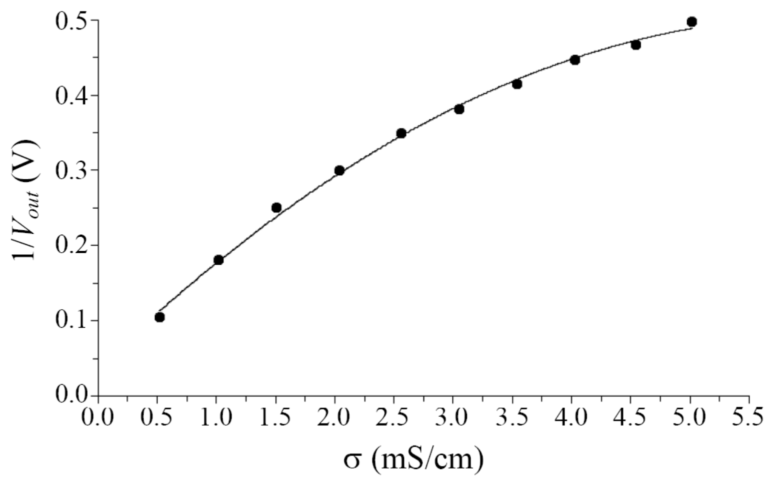

FIGURE 2. Conductivity of solution against the inverse of the measured output voltage

In short, we present the approach to find the parasitic resistance by the solution whose conductivity values are known. The important evidence of existence of the parasitic resistance is the linearity and y-axis intersection point of the plot in Figure 3. After that the obtained value of the parasitic resistance is used to design compensation circuit so as to achieve the linear relationship between the voltage output from our proposed circuit and the conductivity measured by the standard EC meter.

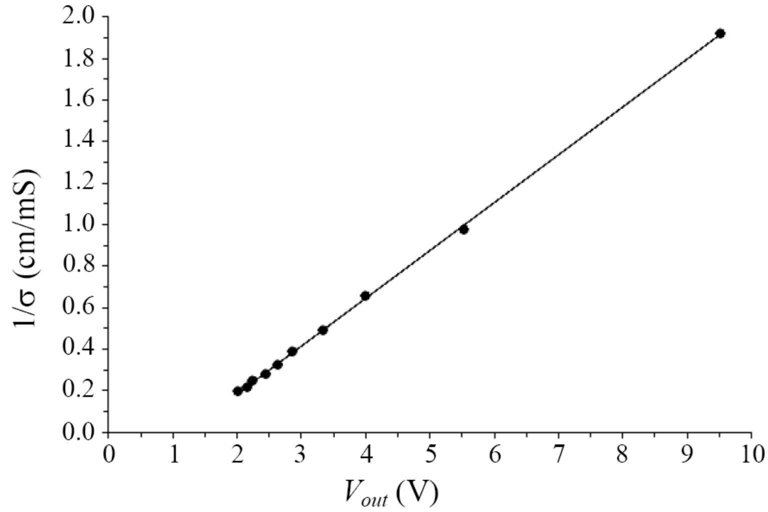

FIGURE 3. Plot of the measured output voltage against the inverse of the conductivity

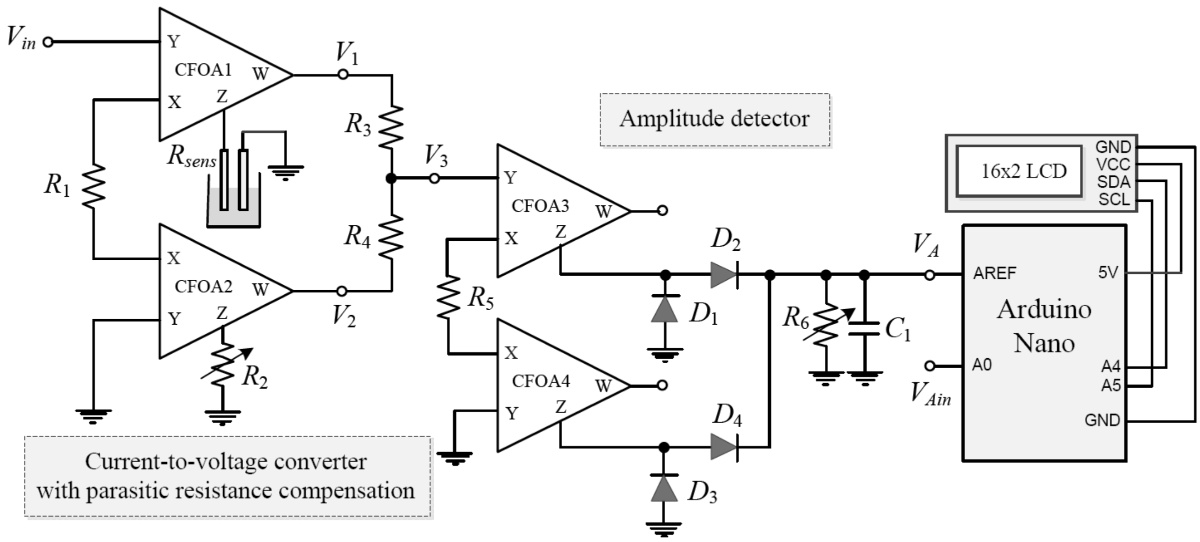

FIGURE 4. Proposed readout circuit for measuring the conductivity of solution

3. **Compensation Circuit Design.** In order to compensate for the known parasitic resistance, we design the current-to-voltage converter as shown in Figure 4. The value of the resistance R_2 has to be adjusted properly, which will be discussed below.

For the operation analysis of the proposed interface, it is assumed that all CFOAs are well matched. The sinusoidal input voltage V_{in} can be stated as

$$V_{in} = A\sin(\omega t + \phi) = A\sin(2\pi ft + \phi) \tag{5}$$

where A, f and ϕ parameters are the amplitude, the frequency, and the initial angle of the sinusoidal input voltage V_{in}, respectively.

The voltages V_1, V_2, and V_3, indicated in Figure 4, can be expressed as

$$V_1 = \left(\frac{R_{sens}}{R_1}\right) V_{in} \tag{6}$$

$$V_2 = \left(-\frac{R_2}{R_1}\right) V_{in} \tag{7}$$

When the resistance $R_3 = R_4$, the voltage V_3 can be given by

$$V_3 = \frac{V_{in}}{2R_1}\left(R_{sens} - R_2\right) \tag{8}$$

Previously, we know that the resistance $R_{sens} = R_{sol} + R_e$ in which $R_{sol} = 1/\sigma$. Then the voltage V_3 can be rewritten as

$$V_3 = \frac{V_{in}}{2R_1}\left(\left(\frac{1}{\sigma}\right)K + R_e - R_2\right) \tag{9}$$

To compensate the parasitic resistance R_e of the conductivity sensor, the condition of the resistance $R_2 = R_e$ is allocated. The voltage V_3 can be extracted as

$$V_3 = \frac{K}{2R_1}\left(\frac{1}{\sigma}\right)V_{in} = \frac{K}{2R_1}\left(\frac{1}{\sigma}\right)A\sin(\omega t + \phi) \tag{10}$$

We will see that the achieved voltage V_3 varies with the conductivity σ of solution without the parasitic resistance R_e. Its amplitude A is detected by the amplitude detector which is constructed from the group of electronic components: two op-amps $CFOA_3$ and $CFOA_4$, four diodes D_1 and D_4, two resistors R_5 and R_6, and a capacitor C_1. The output voltage V_A can approximately be written as

$$V_A \cong \frac{R_6}{R_5}\left(\frac{AK}{2R_1}\right)\frac{1}{\sigma} \tag{11}$$

The output voltage V_A is used for the external reference voltage V_{ref} at the AREF pin on the microcontroller board which has 10-bit ADC on board. We apply an analog input voltage V_{Ain}, which is much less than V_A, to an analog pin A0 in order that the conductivity σ is direct proportional to the digital output D_{out}. This technique leads to the digital output D_{out}:

$$D_{out} \cong \frac{V_{Ain}}{V_A} \cong \frac{R_5}{R_6}\left(\frac{2R_1V_{Ain}}{AK}\right)\sigma \tag{12}$$

4. **Experimental Setup and Results.** To verify the performances of the proposed readout circuit, the circuit in Figure 4 was experimentally implemented using commercial AD844 CFOAs, 1N4148 diodes, a 16 × 2 LCD with I2C interface, and an Arduino Nano microcontroller board. The values of the electronic components used were set as $R_1 = R_5 = 5$ kΩ, $R_2 \cong R_e \cong 554$ Ω, $R_3 = R_4 = 1$ kΩ, $R_6 = 50$ kΩ, and $C_1 = 1$ μF while all CFOAs are powered by ±9 V power sources. The electrode sensor used is made from two carbon rods which have the distance of 1 cm. The resin is used for handling construction to keep the distance between two carbon rods stable. In this experiment, the NaCl solution with conductivity of 0.5-3.5 mS/cm was prepared. We fixed 1 kHz frequency and 6 $V_{p\text{-}p}$ amplitude for the sinusoidal input voltage V_{in}.

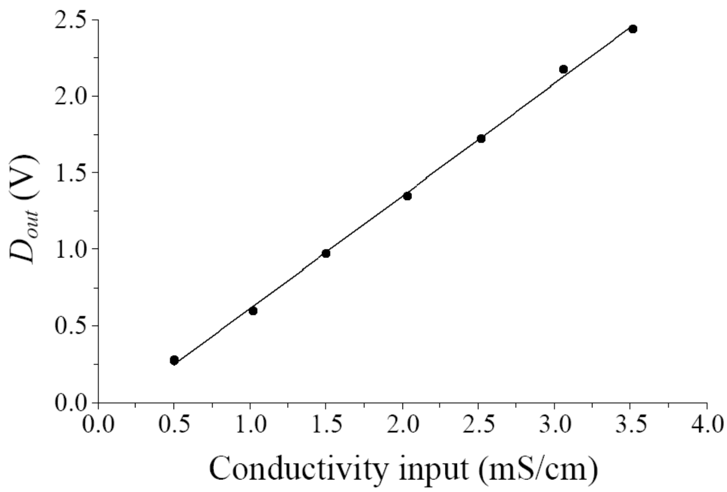

FIGURE 5. Relation between the conductivity input and measured digital output

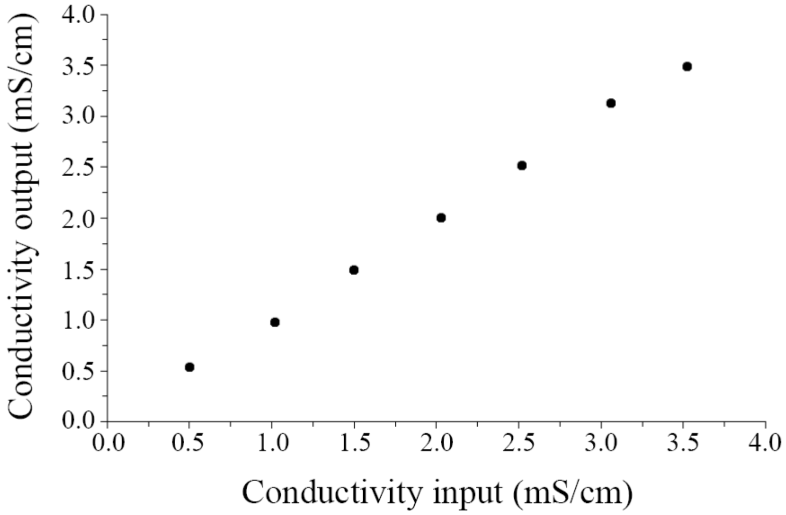

FIGURE 6. Results from measuring the input and output of conductivity values

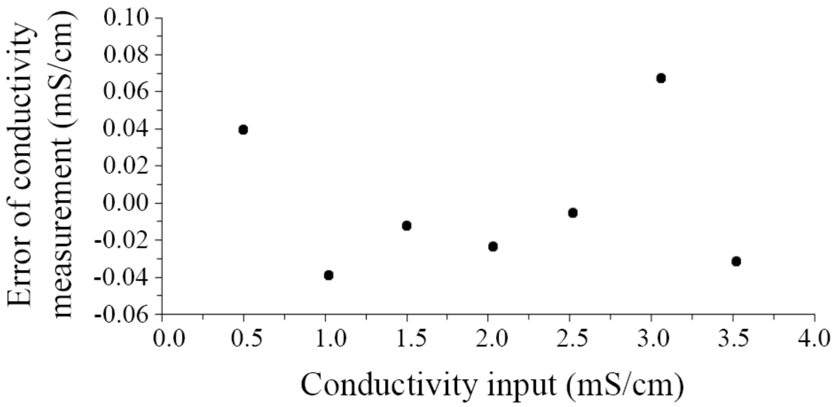

FIGURE 7. Error between the input and output of conductivity values

The plot of the measured digital output D_{out} against the conductivity input measured by standard EC meter is shown in Figure 5. It should be noticed that the proposed readout circuit can produce the digital output D_{out} which is linearly related to the conductivity input without the parasitic resistance of the electrode sensor. Figure 6 demonstrates the conductivity input of electrolyte solution against the conductivity output measured by the proposed circuit. The error from comparison between the input and output of conductivity values, plotted in Figure 7, is in the range of -0.04 to 0.07 mS/cm over the entire range being investigated.

5. **Conclusions.** A simple technique for circuit design to compensate the existence of the parasitic resistance in the electrode sensor has been described in this paper. The proposed readout circuit for conductivity measurement of electrolyte solution is mainly composed of a current-to-voltage converter with parasitic resistance compensation, an amplitude detector, and an Arduino Nano microcontroller board. The circuit can produce the digital output which is directly proportional to the conductivity input. Finally, the conductivity measured by the proposed circuit is in good agreement with that due to the standard EC meter. A maximum error of measuring the conductivity over the investigated range is 2.23% of full scale. Moreover, we expect that our circuit analysis would be adapted to other different electrode designs.

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REFERENCES

[1] D. L. Corwin and S. M. Lesch, Apparent soil electrical conductivity measurements in agriculture, *Computers and Electronics in Agriculture*, vol.46, pp.11-43, 2005.

[2] P. Neelamegama and R. Vasumathi, ATMEGA32 microcontroller based conductivity measurement system for chloride estimation of soil samples, *Instruments and Experimental Techniques*, vol.53, no.4, pp.591-595, 2010.

[3] S. P. Sakti, L. S. Huda, V. R. Wijayanto and M. A. Syahbana, Sensor interface design for monitoring drinking water quality in water treatment plant, *Proc. of the 5th Annual Basic Science International Conference*, Indonesia, pp.234-237, 2015.

[4] A. F. A. Hadid, E. M. Abd-Elmoniem, M. El-shinawy and M. Abou-Elsoud, Electrical conductivity effect on growth and mineral composition of lettuce plants in hydroponic system, *Acta Horticulturae*, vol.434, pp.59-66, 1996.

[5] U. C. Samarakoon, P. A. Weerasinghe and W. A. P. Weerakkody, Effect of electrical conductivity [EC] of the nutrient solution on nutrient uptake, growth and yield of leaf lettuce (Lactuca sativa L.) in stationary culture, *Tropical Agricultural Research*, vol.18, pp.13-21, 2006.

[6] S. Hu, K. Wu, H. Wang and J. Chen, Electrical conductivity measurement method in seawater desalination based on variable frequency excitation, *Proc. of the 9th International Conference on Electronic Measurement & Instruments*, China, pp.810-813, 2009.

[7] K. Shahane, V. D. Bachuwar and P. P. Gundewar, Online detection of subclinical mastitis using electrical conductivity, *Proc. of the 5th International Conference on Innovations in Electronics and Communication Engineering*, India, 2016.

[8] Y. Wei, J. Wang, D. Li and Q. Ding, Design of intelligent conductivity meter based on MSP430F149, *Proc. of International Conference on Computer and Computing Technologies in Agriculture III*, Beijing, China, pp.240-247, 2009.

[9] N. J. Park, J. S. Han and H. S. Lee, Salinity measuring apparatus, *U.S. Patent, US8 963 564 B2*, 2015.

[10] A. Kaewpoonsuk, S. Suphramit and A. Rerkratn, Low-ripple output interface circuit for electrical conductivity measurement, *Proc. of the International Multi Conference of Engineers and Computer Scientists*, Hong Kong, vol.2, pp.581-584, 2016.