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A SIMPLE ELECTRICAL CONDUCTIVITY MEASUREMENT SYSTEM BASED ON ARDUINO

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Abstract. *The electrical conductivity measurement system of electrolyte solution with self-generated sinusoidal excitation signal based on Arduino and simple signal conditioning circuits is designed. The Arduino acts as both the sinusoidal excitation signal generator and digital signal processor. In part of signal conditioning circuits, the electrical conductivity variation of sample solution is transformed to the sinusoidal output voltage by a current-to-voltage converter. Before digital signal processing for determining the electrical conductivity, the sinusoidal output voltage is converted into the direct current (DC) voltage by an amplitude detector. The DC output is directly proportional to the electrical conductivity. A maximum error of measuring the electrical conductivity of sample solution is less than 1.40%.*
Keywords: EC measurement, Arduino, Single-supply op-amp

1. **Introduction.** Electrical conductivity (EC) measurements are used routinely in water purification system [1], food industry [2], and environmental application [3]. They are also used in hydroponic system for detecting and controlling the amount of nutrients [4]. The increasing importance of EC measurement leads to improvement of related sensors and signal conditioning circuits. Y. Wei et al. present the design of intelligent conductivity meter in which conditioning circuits for measuring EC are composed by bipolar pulse excitation circuit, range switching and amplifier circuit and waveform transformation circuit [5]. L. A. Velázquez et al. use the EC measurement circuit in development of a hydroponic system for cherry tomato culture. The circuit consists of three parts: the sine wave oscillator, the gain loop and the AC-to-DC converter [6]. Additionally, A. Kaewpoonsuk et al. design a low-ripple output interface circuit for EC measurement. The quadrature oscillator circuit is used to generate the excitation signal which is amplified by non-inverting amplifier. The peak-and-hold method is the technique used in the part of signal conditioning circuits [7]. Then, R. Katman et al. present a design technique of a readout circuit with parasitic resistance compensation of an electrode sensor for measuring EC in electrolyte solution based on commercially available current feedback operational amplifiers (CFOAs) [8]. In these previous works, the signal conditioning circuits are complicated and operated using dual supply. This may lead to high-cost system. Interestingly,

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V. R. S. T. Nagavalli et al. present a simple EC sensing circuit, using single-supply operational amplifiers (op-amps) [9]. However, the output voltage does not vary linearly with increasing of EC. This leads to the difficulty of EC measurement. In this paper, we aim to propose another simple EC measurement system which is implemented using general basic circuits and some passive components and optimized for single-supply operation based on Arduino. Linear variation of the output voltage is achieved. A maximum error of the output voltage in this study is lower than that in the previous study [8].

This paper is organized as follows. Section 2 describes analysis and designing signal conditioning circuits connected with an Arduino for measuring EC. In addition, Arduino software is designed to create logic signals for generating the sinusoidal excitation signal and convert the DC output voltage to EC. The experimental setup and results are discussed in Section 3. Finally, conclusions are given in Section 4.

2. **Design of the EC Measurement System.** The block diagram of the simple EC measurement system with a self-generated sinusoidal excitation signal using an Arduino Nano's microcontroller is shown in Figure 1. Its structure consists of an R2R ladder, a buffer, two graphite electrodes, a current-to-voltage converter, an amplitude detector, a microcontroller and a liquid crystal display (LCD). The proposed system is divided into two parts: the measurement and microcontroller parts. In part of measurement or signal conditioning circuits, the graphite electrodes, which act as an EC sensor of the system, are connected with the current-to-voltage converter. Its output voltage obtained depends on EC of the sample solution. The amplitude of the output voltage is detected by the amplitude detector. These are designed using only two single-supply op-amps and a few basic electronic components. In the second part, the Arduino Nano's microcontroller acts as the digital signal generator. The D0-D7 and Q_{RS} digital signals generated are sent to the R2R ladder connected with the buffer for providing the sinusoidal excitation signal and sent to an analog switch for resetting operation of the amplitude detector. Furthermore, it is also a digital signal processor where the output amplitude is converted to the digital output by the analog-to-digital converter on the Arduino Nano's microcontroller. Finally, the digital output is used for evaluation of EC of the sample solution before showing on the LCD.

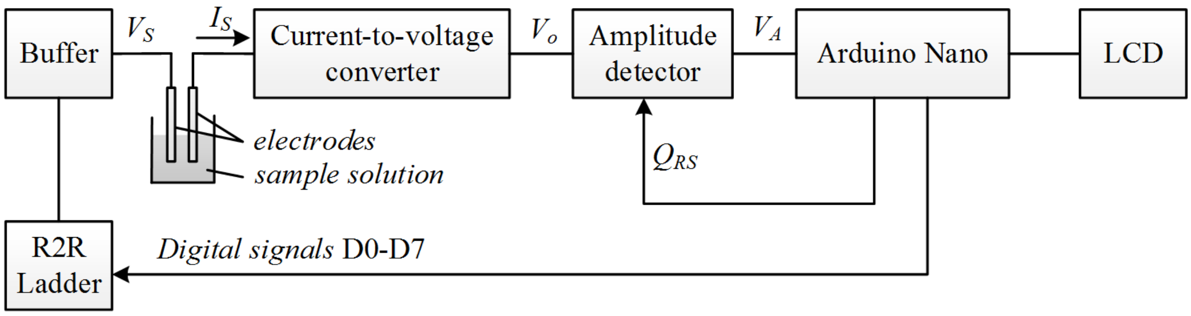

FIGURE 1. Block diagram of the EC measurement system with self-generated sinusoidal excitation signal using a microcontroller

The schematic diagram of the proposed EC measurement system in this paper is shown in Figure 2. The Arduino Nano's microcontroller provides digital signals D0-D7 for the R2R ladder to generate the sinusoidal excitation signal which is transferred from the R2R ladder to the graphite electrodes by the buffer which is represented by the op-amp OA1/1. The sinusoidal excitation signal V_S can be stated as

$$V_S = V_{DC} + A\sin(\omega t) \tag{1}$$

where V_{DC}, A and ω parameters are respectively the initial DC component, the amplitude and the angular frequency of the sinusoidal excitation signal V_S which is used to stimulate for the graphite electrodes immersed in the sample solution. The electric current that flows through the sample solution I_S can be expressed as

$$I_S = \frac{V_{DC} + A\sin(\omega t)}{R_{sol}} \tag{2}$$

The electric current I_S investigated is converted to the voltage V_o using the current-to-voltage converter constructed from the op-amp OA2/1 and the resistor R_1.

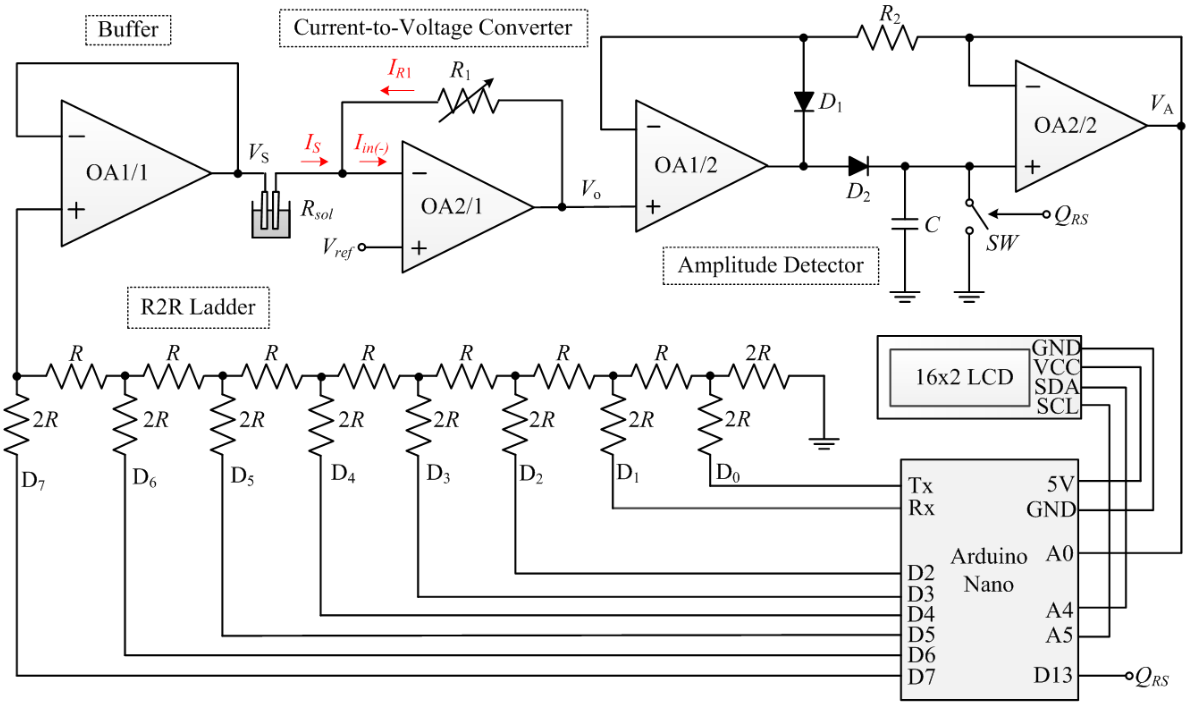

FIGURE 2. Schematic diagram of the proposed EC measurement system

After considering the sum of electric currents at the inverting node, the electric currents in each branch are expressed by the node-voltage equation, given as

$$I_S + I_{R1} = I_{in(-)} \tag{3}$$

Ideally, the input resistance of the op-amp is infinite. So, the electric current entering the op-amp $I_{in(-)}$ is zero. The non-inverting terminal of the op-amp is connected to an external reference voltage V_{ref}. Therefore,

$$I_S = \frac{V_S - V_{ref}}{R_{sol}} \tag{4}$$

and

$$I_{R1} = \frac{V_o - V_{ref}}{R_1} \tag{5}$$

Substituting (4) and (5) into (3) yields

$$\frac{V_S - V_{ref}}{R_{sol}} + \frac{V_o - V_{ref}}{R_1} = 0 \tag{6}$$

Then, the output voltage V_o will be

$$V_o = -\frac{R_1}{R_{sol}}(V_S - V_{ref}) + V_{ref} \tag{7}$$

Substituting the sinusoidal excitation signal V_S from (1) into (7) yields

$$V_o = -\frac{R_1}{R_{sol}}(A\sin(\omega t) + V_{DC} - V_{ref}) + V_{ref} \tag{8}$$

When we make $V_{ref} = V_{DC}$, the output voltage V_o in (8) reduces to

$$V_o = -\frac{R_1}{R_{sol}}(A\sin(\omega t)) + V_{ref} \tag{9}$$

From the theory of EC, it is well known that EC σ of solution can be evaluated by $\sigma = GK$, where the conductance G is the reciprocal of the solution resistance R_{sol} and K is a cell constant value. Therefore, the output voltage V_o in (9) can be rewritten as

$$V_o = -\frac{R_1}{(1/\sigma)K}(A\sin(\omega t)) + V_{ref} \tag{10}$$

or

$$V_o = -\frac{R_1}{K}(A\sin(\omega t))\sigma + V_{ref} \tag{11}$$

in which the amplitude A_{out} of the output voltage V_o is

$$A_{out} = \frac{R_1}{K}A\sigma + V_{ref} \tag{12}$$

It is detected by the amplitude detector which is simply constructed from two op-amps OA1/2-OA2/2, two diodes D_1-D_2, a resistor R_1, a capacitor C and an analog switch SW. Finally, the DC output voltage V_A achieved from the amplitude detector is

$$V_A = A_{out} = \frac{R_1}{K}A\sigma + V_{ref} \tag{13}$$

We will notice that the DC output voltage V_A is directly proportional to EC σ. The DC component V_{ref} existing in the DC output voltage V_A is removed by software. Before processing the electrical conductivity of sample solution σ, the DC output voltage V_A is sent to the analog input pin A0 of the Arduino Nano's microcontroller which supports 10-bit analog-to-digital conversion. Then, the digital output D_{out} can be approximated as

$$D_{out} = \frac{R_1}{K}A\sigma \tag{14}$$

In the proposed EC measurement system, the Arduino Nano's microcontroller is the important device. It is used for generating the digital signals and processing the data received from the signal conditioning circuit. Firstly, the digital pins (D0-D7) as demonstrated in Figure 2 are configured as outputs to create logic signals: HIGH or LOW for the R2R ladder which acts as a digital-to-analog converter for generating the sinusoidal excitation signal. To stimulate the sample solution, the 16-cycle sinusoidal excitation signal is applied to the graphite electrodes that dip into the sample solution. After measuring EC by the proposed conditioning circuit, the Arduino Nano's microcontroller receives and converts the DC output voltage V_A to EC, achieved from the amplitude detector, into the digital value through the analog input pin A0. Next, EC of the sample solution is evaluated using relationship between the digital output D_{out} and the EC σ as indicated in (14). Finally, the obtained EC is sent to display on the LCD. To prepare for a new cycle of the signal, the digital pin D13 is defined as an output to create a logic signal Q_{RS} for resetting the analog switch of the amplitude detector.

3. **Experimental Setup and Results.** The circuit diagram of the proposed EC measurement system, shown in Figure 2, was implemented on the breadboard using basic electronic devices and an Arduino Nano's microcontroller. The 8-bit R2R ladder digital-to-analog converter was constructed using a set of resistors of two values: 10 kΩ and 20 kΩ. Two single-supply op-amps LM358, two diodes D1N4148 and an analog switch

CD4066BC were used for the op-amps OA1-OA2, diodes D_1-D_2 and analog switch SW, respectively. The variable resistor 50 kΩ and fixed resistor 1 kΩ were selected for resistors R_1 and R_2. The capacitor was chosen as $C = 0.1$ μF. For displaying the measured results, 16×2 LCD with I2C interface was used. The supply voltage of the conditioning circuit designed was set to be 9 V. The known EC of NaCl solution in the range of 0.25-4.00 mS/cm was prepared. Two electrodes made up of two graphite rods were stimulated by a generated sinusoidal excitation signal V_S of 3 Vpp with frequency 1 kHz. To verify the operation of the proposed EC measurement system, the NaCl solution with the EC of 2 mS/cm is prepared. Figure 3 shows the output voltage signals for each signal conditioning circuit part: the current-to-voltage converter V_o and the amplitude detector V_A. The results of circuit operation are corresponding to the designed signal conditioning circuit.

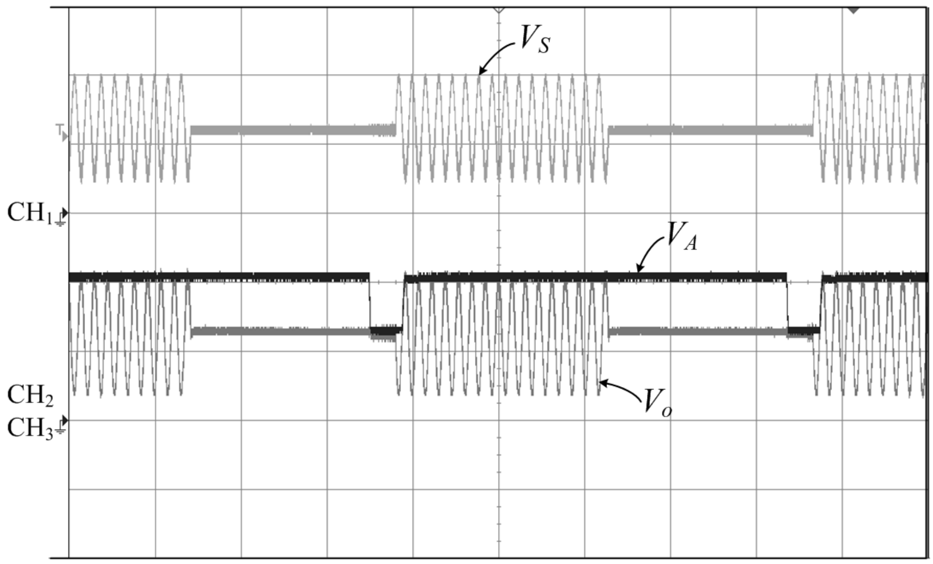

Figure 3. Measured voltage signal of the proposed EC measurement system (CH_1, CH_2 and CH_3: Vertical scale: 2 V/div., horizontal scale: 5 ms/div.)

The designed EC measurement system based on the Arduino Nano's microcontroller is used to measure EC of sample solution. EC of NaCl solution in the range of 0.25-4.00 mS/cm, increased by 0.25 mS/cm, measured by the standard EC meter (COM-100 HM Digital) which is called "known EC σ_{in}" was prepared and the digital output D_{out} of the system is measured. Figure 4 shows the plot of digital outputs D_{out} for various known EC σ_{in}. It is observed that the trend line of our results is approximately the straight line as expected in (14). The empirical relationship between the known EC σ_{in} and the digital output D_{out} is used to convert back to EC. In this paper, we defined it as "measured EC σ_{out}".

Figure 5 demonstrates comparing the measured EC σ_{out} and known EC σ_{in}. It is found that σ_{out} varies linearly with σ_{in}. That is, the results from the proposed system are in good agreement with the standard EC meter. A maximum error of measuring the EC of 0.25-4.00 mS/cm of the NaCl solution using the proposed system is 1.40% of full scale as shown in Figure 6, which is better than previous study [8].

4. **Conclusions.** The EC measurement system with self-generated sinusoidal excitation signal based on the Arduino Nano's microcontroller has been designed to measure EC of the sample solution. This whole system consists of the simple signal conditioning circuit which is interfaced with the Arduino Nano's microcontroller and has been optimized for single-supply operation. The experiment results show the feasibility of using the Arduino

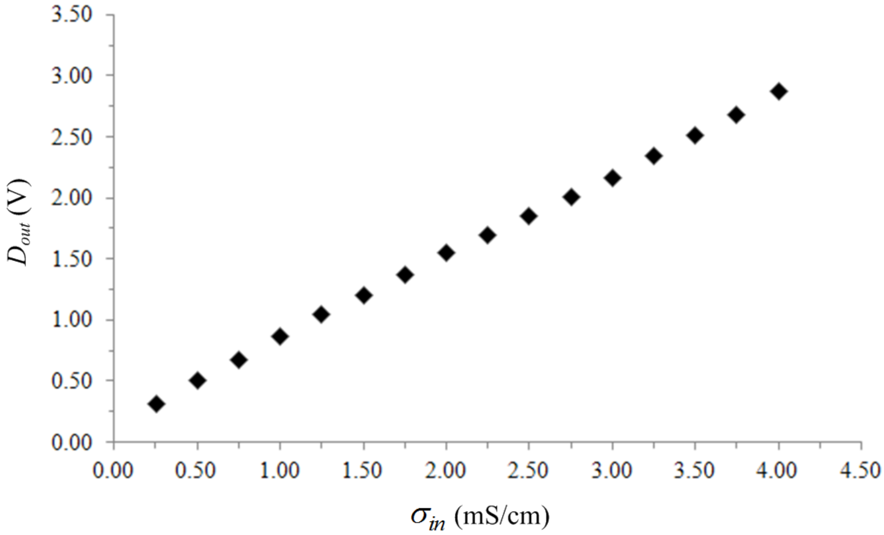

FIGURE 4. Plot of the digital output D_{out} for various the known EC σ_{in}

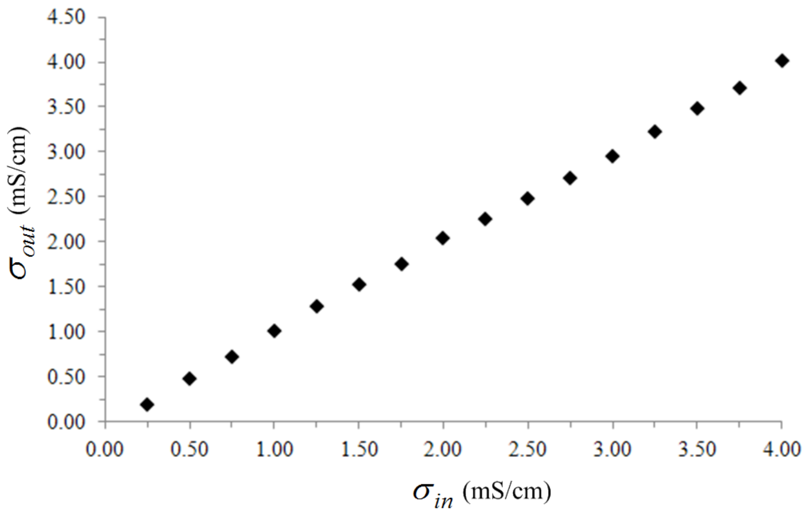

FIGURE 5. Comparison of the known EC σ_{in} and the measured EC σ_{out}

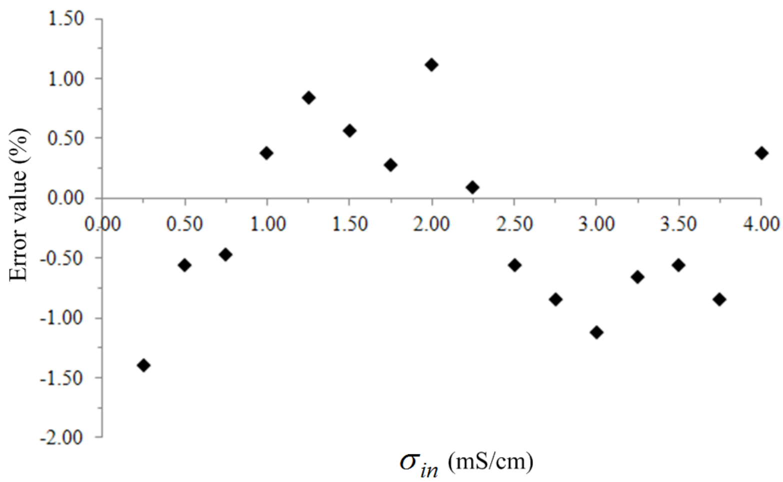

FIGURE 6. Error values of the EC measurement

Nano's microcontroller for generating the sinusoidal excitation signal and processing EC of the sample solution. The EC measured by the proposed system is calibrated using the standard EC meter (COM-100 HM Digital). A maximum error of measuring the electrical conductivity over the investigated range is 1.40% of full scale. This proposed system could be combined with Internet of Things (IoT) system to provide the advancement of EC measurement technology for hydroponic farms, food industries, and detecting water quality.

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