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An analog electronic interface to measure electrical conductivity in liquids

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Abstract

Measuring conductivity in aqueous solutions is a problem which is not easy to solve due to the differences in mass and mobility that exist between ions conduction and electrons. Additionally, it is necessary to keep in mind the interaction processes electrode-solution. As a consequence, the electrolytic conductivity cell has to be polarized with alternating voltage of adequate amplitude and frequency in order to extract the correct information. In this paper an electronic conditioning circuit is presented which converts electric conductivity into a value of continuous voltage. A hardware solution is proposed to do the conductivity temperature compensation. Experimental results obtained in KCl solutions are also offered by following a close discussion of them.
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1. Introduction

Electrolytic conductivity is the capacity of ion solution to conduct electricity. The process of conducting electricity in a chemical solution has differences regarding the usual electronic conductivity.

The electrolytic current involves a transport process of ions which mass ranges 10^4 times the electron mass. As a consequence, ions mobility is highly reduced so that it differs from the electron mobility in a range of 10^{-5}. On the other hand, electrolytic conduction is associated with complex processes of electrolyte–electrode interaction, which requires that measurements of electrolytic conductivity be carried out under alternate polarization conditions. All these aspects make it difficult to extract electrolytic conductivity (ohmic conductance) in an ionic solution [1].

From an applied point of view, recently different solutions have been presented to measure conductivity. In [2] a circuit model is presented which responds to the electric behaviour in conductivity frequency. In [3] an analog interface is presented which provides good accurate results but with a four-electrode cell. In [4] an electronic conditioning circuit, based on a variant of Wheatstone bridge is presented with the help of a digital processing stage based on a microcontroller. The temperature compensation in this case is performed by the software developed. However, conductivity readings are affected by an offset term which depends on the bridge impedance. In this paper an electronic conditioning circuit is presented to measure electrolytic conductivity using a two-electrode cell. Firstly, the most important features and the limitations which have to be kept in mind when using a cell of this type are presented. Then, an electronic circuit to measure conductivity is designed. The readings are free of offset terms. A hardware temperature compensation solution is also proposed and finally the experimental results obtained by critical interpretation are showed.

2. Electrical behaviour of an electrochemical conductivity cell

For a two-electrode electrochemical cell, electrolytical conductivity κ is given by the expression (1)

$$\kappa = \frac{d}{A} \cdot G \qquad (1)$$

where G is the ohmic conductance of solution ($=1/R_{sol}$, $[G]$ = siemens = $1/\Omega$), d is the distance between electrodes (cm) and A is the electrode surface (cm^2).

Usual dimensions of conductivity κ are siemens/cm. The quotient d/A is called the cell constant. This value must not be determined by geometric calculations due to the leakage of the electric field at the ends of the electrode plates. Its determination is much more convenient by calibration with pattern solutions [5].

Polarizing the conductance cell by an external DC potential V_{DC} (Fig. 1a) produces some unde-
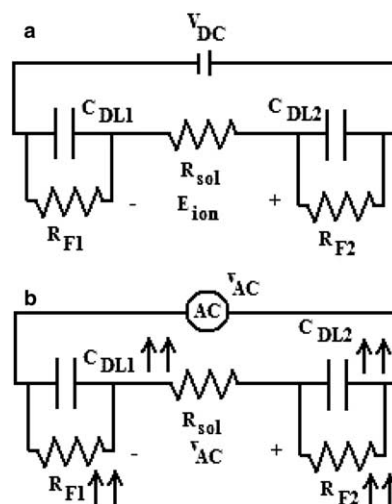

Fig. 1. Behaviour of an electrochemical conductivity cell.

sirable effects (double-layer capacitance, electrolysis, ohmic resistance and electrolytic saturation) [1]. However, determination of electrolytic conductivity R_{SOL} is not computed by the quotient between the external polarization voltage V_{DC} and the detected current (easily measurable), that is to say $R_{SOL} \neq V_{DC}/I$. Determination of R_{SOL} needs to know the electric potential E_{ion} which moves ions in the solution regardless the double-layer capacitance, electrolysis and polarization effects ($R_{SOL} = E_{ion}/I$). It is possible to minimize the DC effects, if the electrodes are submitted to an alternate polarization (Fig. 1b) [6]. For example, if the electrodes are designed in order for the capacitances C_{DL1} and C_{DL2} increase their value, then its AC impedance offered can be small enough compared to the faradaic resistances R_{F1} and R_{F2} ($|Z_{CDL1}|, |Z_{CDL2}| \ll R_{F1}, R_{F2}$). In this way, resistances R_{F1} and R_{F2} can be bypassed in their contribution to the electrolytic current. In practice, C_{DL1} and C_{DL2} can be increased many times by coating the electrodes with black spongy platinum which increases the effective surface area.

Another additional effect which contributes to increase the value of R_{F1} and R_{F2} with respect to $|Z_{CDL1}|$ and $|Z_{CDL2}|$ is to polarize the cell with AC voltage of low amplitude. This fact makes the values of faradaic resistances higher in relation to the double-layer capacitance [1].

On the other hand, it was proved that the electrolytic saturation is reduced considerably if the AC polarization frequency is high enough. Practical values are (1–5 kHz) although those values must not be high in excess because it would appear the effect of the capacitance in parallel with the electrolytic solution itself [1].

In the above conditions, electrolytic resistance is determined by expression (2)

$$R_{SOL} \cong \frac{v_{AC}}{i_{AC}} \qquad (2)$$

Fig. 1b shows the electric behaviour of the conductivity cell under AC polarization conditions of appropriate amplitude and frequency.

3. Description of the conditioning electronic circuit

The proposed electronic circuit is shown in Fig. 2. It was thought that the electric conductivity to be measured by the circuit would sweep a wide range of values. In this application the design interval corresponded to an electrical conductivity between $G_x \sim [0.1\text{–}13.0 \text{ mS}]$ with a total sensitivity of the conditioning circuit of 1.0 V/mS.

The main objective in designing the conditioning circuit was to find an electronic circuit capable to provide a voltage proportional to the electric conductivity. In this way, a configuration was chosen, in which the sensor resistance was in the denominator of its transfer function.

For this reason, a resistive pseudobridge structure was proposed in the first stage [7] with operational amplifier (in Fig. 2, stage formed by U2, R2, R3, R4 and R_x—the sensor). The inverse of R_x value is a direct reading of the electric conductivity measured by the sensor and can be expressed keeping in mind its dependency with temperature in (3)

$$G_x(G_0, T) = G_0 \cdot [1 + \alpha \cdot (T - T_0)] \qquad (3)$$

where α is the temperature coefficient of the solution to be measured and G_0 is the solution conductivity at a T_0 reference temperature, in this case 25 °C. With this equation, considered as

input for the first stage, it is obtained, according to its transfer function, the following output voltage (4)

$$V_1 = V \cdot \frac{R3}{R3 + R4} - V \cdot \frac{R2 \cdot R4}{R3 + R4} \cdot G_x \qquad (4)$$

being V the AC alternate voltage provided by the oscillator circuit (pin number 19). In this expression the first term is independent from conductance G_x, and it is not desirable because if it is not suppressed during the analog process it could contribute to the saturation of the subsequent conditioning stages. The second term is the one that contains the G_x information of interest and must be conveniently treated by the subsequent conditioning blocks.

The second stage is formed by U3 and U4 components. The U3 component is an operational amplifier shaped as a follower. Its function is to produce an impedance level high enough so that the level present in the non-inverting input of U2 is not loaded by the U4 component. This U4 component is formed by an integrated differential amplifier using the model INA105, which provides, at its output, a voltage equals to the difference of voltages at its inputs with a unity gain. The function of the differential amplifier is to eliminate the constant term in expression (4) and thus, to obtain a reading which is directly proportional to the conductivity and without offset voltages [4]. Voltage present at the output of U4 is

$$V_3 = V \cdot \frac{R2 \cdot R4}{R3 + R4} \cdot G_x \qquad (5)$$

At this point of the conditioning circuit the need for proportionality between conductivity and voltage has been met.

To solve the problem of the dependency of conductivity from temperature it is necessary to introduce a temperature sensor and a circuit which will process voltage V_3 in order to provide the conductivity reading at a given temperature (25 °C). In this case an inverting amplifier circuit has been proposed. The voltage level at its output (V_4), with the conductivity reading already compensated, has the expression

Fig. 2. Analog electronic interface.

$$V_4 = -\frac{R_{th}(t^a)}{2 \cdot R_{tho}} \cdot V_3 = -V \cdot \frac{R_{th}(t^a)}{2 \cdot R_{tho}} \cdot \frac{R2 \cdot R4}{R3 + R4} \cdot G_x \tag{6}$$

All the voltages presented so far are of the sine-type of a fixed frequency, and the conductivity information is stored in their amplitude. In order to provide a DC voltage at the output of the conditioning circuit, it is necessary a filtering and a rectifying stage. This is the function of the last block, which is formed by components U6, U7, R4–R9, P3, C3–C6, D1 and D2. With these components a full wave rectifier has been configured. This rectifier has a low-pass function directly implemented by capacitor C5 [8]. It also provides a direct reading of the conductivity according to total sensitivity thanks to the DC level adjustment made by P3 trimmer which selects the peak level instead of the average level. The reading offered by this stage is

$$V_0 = S \cdot G(25\,°C) \tag{7}$$

where S is the sensitivity required by the conditioning circuit 1 V/mS and G is the conductivity temperature compensated.

The oscillator stage must provide a sine-type electric voltage to the first analog processing stage (pseudobridge). This stage is formed by components U1, C1, C2, R1 and P1. Component U1 is a sine-type function generator. Model MAX038 with its special features, provides a precise sine-type wave of high stability. The frequency of such a wave is selected by the P1 potentiometer.

4. Thermal compensation

The effect of temperature is also important when an electric conductivity of a liquid or solution must be done. A solution at a higher temperature will present higher quantity of ions dissociated, therefore the concentration of electric charges will raise and as a consequence, conductivity will be higher. On the contrary, the same solution at low temperature will have a low conductivity due to the low quantity of ions present which results in lower electric conductivity.

From an application point of view, conductivity is given at a certain temperature, which has been stated as a reference to better compare the measurements at different times and locations. This temperature is usually 25 °C. For this reason, the modern meters, along with the conductivity sensor, present a temperature meter, which allows measurements correction when temperature is different from 25 °C and at the same time, gives the reading for this or another specific value. A thermistor was used as a temperature sensor and placed at the inverting stage U5. Optimum thermal compensation was obtained by a numeric calculation programme which provided the appropriate characteristic parameters of the thermistor, resistance at 25 °C, $R_{tho} = 1\,k\Omega$ and its characteristic temperature, $B = 2075\,K$. These specifications were matched by a Philips thermistor model 2322-63313102, which has a relative thermal sensitivity of $-1.9\%/°C$.

5. Experimental results

Once the circuit was designed using the appropriate thermistor for a correct thermal compensation, it was implemented in a printed circuit board. The experimental results, after the necessary adjustments, are shown below. The conductivity sensor was used to measure such parameters in different solutions of KCl, which presented a certain molarity. At the same time, temperature was measured in order to determine the theoretical conductivity to be measured. In this way, a relative error in reference to the reading provided by the conditioning circuit was obtained. Theoretical conductivity was calculated at 25 °C, and the sine wave excitation AC voltage was selected with a frequency of 4 kHz and a peak amplitude of 1 V. Graphics in Fig. 3 show the amplitude of the signal compensated at the output of the inverting amplifier ($V_4(G_x, T)$ voltage) and the signal provided by the output of differential amplifier U4 (uncompensated signal, $V_3(G_x, 25\,°C)$ and $V_3(G_x, T)$). For the cases studied here, the maximum relative error in the 0–30 °C interval was 1.5% for conductivity values between 0.1 mS and 10 mS.
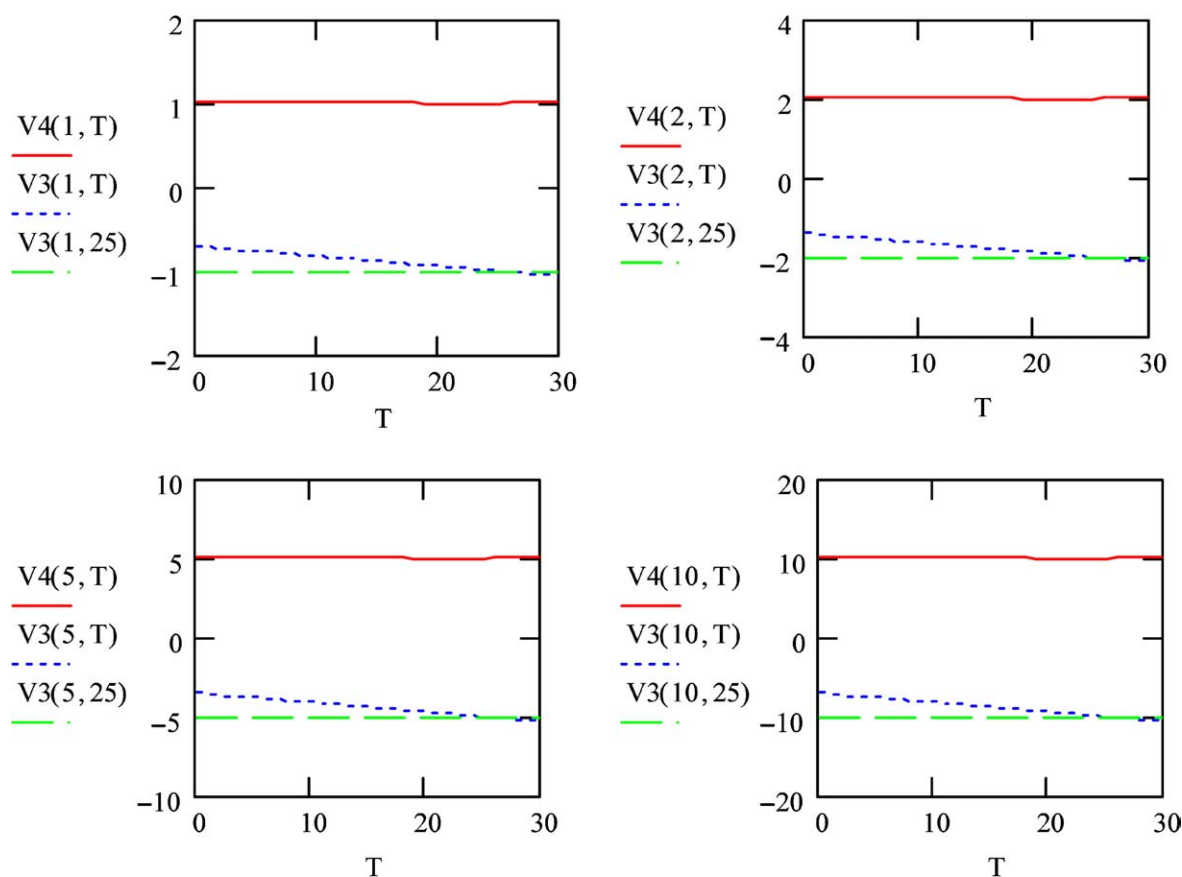
Fig. 3. Experimental results. $V_4(G_x, T)$ compensated voltage, $V_3(G_x, T)$ non-compensated voltage. G_x in mS and T in °C.

6. Discussion and conclusions

The above mentioned experimental results show that the circuit designed provides conductivity readings which accurately approach their theoretical values. Experimentally, relative errors in KCl solutions are maintained in acceptable levels for low molarities. It was observed that in the case of high concentrations of KCl solutions (especially for 0.05 M and 0.1 M) the errors obtained are already appreciable. This fact is due to the behaviour of the sensor itself, which has an accuracy limited to the low concentration areas. At the time to read high conductivities it will be necessary to use another sensor with a higher constant cell. An error curve for the sensor was

provided by the manufacturer, and it was proved that such a sensor is apt for measuring low conductivities. For molarity values around 0.1 M, deviation of sensor behaviour is already appreciable.

These experimental results show that the conditioning circuit designed for measuring electric conductivity in water is appropriate within the limitations set by the sensor (high concentrations). In conductivity measurements not higher than 10 mS the accuracy of the conditioning circuit is appropriate for use in field measurements. On the other hand, the design method obtained by computer software allows an efficient and easy solution to the thermal compensation needed in this type of measurements. The design proposed

here uses a series of components which are available in the electronic market. In addition, it has a great capacity of adaptation to new situations in which a new thermal compensation different from 25 °C would be desired. In this specific case, it would only be necessary to replace the thermistor for another one with new characteristics. If a digital processing stage is incorporated to the electronic circuit then the inverting amplifier can be omitted. Temperature could be measured with another conditioning circuit, and compensation of readings could be performed by the processing software of the digital unit if the temperature coefficient of the solution is known.

Acknowledgement

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