PULSED VOLTAGE BASED SIGNAL CONDITIONER DESIGN FOR CONDUCTIVITY SENSOR

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ABSTRACT

Conductivity is measured by conductivity cells of specific geometries where the process medium conducts electricity and develops a potential across the cell electrodes. Due to harsh ambient conditions near conductivity sensor installation, processing electronics is required to be located at far distances of approx. 30-50m. This connecting cable introduces its capacitance in parallel to the double layer capacitance of the cell. These capacitances pose a challenge in obtaining accurate measurement of solution resistance and hence the conductivity over larger dynamic range. This paper aims to evolve a scheme for reliable and accurate measurement of solution conductivity using conductivity cell with long sensor cable.

The paper brings out the design process and performance results of signal conditioning circuit for conductivity measurement by optimizing the circuit components to achieve accurate solution resistance using extensively the PSpice circuit simulations and development of a LabVIEW algorithm in voltage pulse excitation conditions.

Keywords: Conductivity cell, Randles model, Cable capacitance, Double layer capacitance, Large dynamic measurement range, Full scale accuracy, pulse excitation, Circuit component optimization.

1.0 INTRODUCTION

The electrical conductivity of the process medium (Demineralized water) is an important parameter for maintaining healthiness of the process equipments and pipings in a coastal power plant. The conductivity of the process medium may change over prolonged operation of the plant due to generation of corrosion products, contamination of process medium and ingress of seawater into process medium. Continued plant operation with undesired chemistry of the process medium may result in the degradation(corrosion) of the process components/equipments. Inability of the purification system of the plant to maintain conductivity of the process medium may warrant for plant shutdown. Hence, it is necessary to reliably monitor conductivity of water in various process systems. The paper aims to develop a methodology for reliable measurement of conductivity of process medium and design a signal conditioner by understanding the conductivity cell characteristics.

Now, there is a need to mount electronic converter remotely (in bi-block configuration, approx.30m-50m) due to harsh ambient conditions near conductivity sensor installation. This in turn introduces a cable capacitance in parallel to the cell. Due to this cable capacitance, the present method generates non-linear output over the range of measurement. Hence, there is a need to work out measurement schemes to overcome the cable effect and to design a signal conditioner to resolve this. Target Specifications (Main):

- Measurement: Accuracy: <6% Full scale
- Dynamic measurement range: >= 1 decades
- Temperature range of operation: $-5^{\circ}C 55^{\circ}C$

2.0 CONCEPT AND LITERATURE REVIEW

A conductive solution consists of two parts: solute and a solvent. Solvent is generally a liquid medium which can dissolve other species. Solute substances are those which dissolve in the solvent. The combination of solute and solvent is known as a solution, specifically an electrolytic solution. An electrolyte is a solute which dissociates into ions and produces an electrically conductive solution. Broadly, an electrolytic solution can be classified as strong electrolytes and weak electrolytes.

Strong electrolytes are substances that are fully ionized in solution. As a result, the concentration of ions in solution is proportional to the concentration of the electrolyte added. These include ionic solids and strong acids, for example NaCl, HCl, etc.

Weak electrolytes are substances that are not fully ionized in solution. For example, acetic acid partially dissociates into acetate ions and hydrogen ions, so that an acetic acid solution contains both molecules and ions. A solution of a weak electrolyte can conduct electricity, but usually not as in case of a strong electrolyte because there are fewer ions to carry the charge from one electrode to the other.

Conductivity may be measured by passing an electrical alternating current (I) between two electrodes immersed in a solution and measuring the resulting voltage (V). During this process, the cations migrate to the negative electrode, the anions to the positive electrode and the solution acts as an electrical conductor. Both the current and the potential are used to calculate the conductance (I/V).



Based on the number of electrodes, the conductivity cells can be classified as:

- 2-pole cells
- 3-pole cells
- 4 pole cells

<u>2 pole cells</u>: It consists of two electrodes and an alternating current is passed between the 2 poles. The resulting voltage is measured to find out the solution resistance (R_{sol}). However, the resistance (R_{el}) caused by polarization of the electrodes and the fringing of the electric field near the edges of the electrode field effect interferes with the measurement as shown in the adjacent figure.



<u>3 pole cells</u>: A three-pole cell is similar in design to that of a two-pole cell with a third electrode spatially located in between the other two electrodes. The excitation is provided in the third electrode and the

current obtained is measured from the other two electrodes. The other two electrodes are shorted together. The advantage of this scheme is that it allows the field lines to be guided and confined in an optimal manner thus limiting dispersion in the measurement and minimizing environmental influences on the measurement such as pipe material and position of the cell in the process line (field effect).

<u>4 pole cells</u>: A 4-pole electrode consists of four electrodes. Two electrodes at the two extremes are used to measure the current passing through the solution and the other two electrodes in between are used to measure the voltage produced. The current is passed between the outer electrodes (1 and 4) in such a way that a constant potential difference is maintained between the



inner electrodes (2 and 3) as shown in adjacent figure. As this voltage measurement takes place with a negligible current, these two electrodes are not polarized ($R_2 = R_3 = 0$). The conductivity will be directly proportional to the applied current. The geometry of 4-pole cells with an outer tube minimizes the field effect, due to the measurement volume being well defined within the tube.

2.1 <u>Basic parameters of relevance</u>:

Resistance : The resistance of the solution (R) can be calculated using Ohm's law as

 $R = \frac{V}{I}(\Omega).$ (1)

Where:

V = voltage (volts)I = current (amperes) R = Resistance of the solution (Ω)

<u>Conductance</u>: Conductance (C) is defined as the reciprocal of the electrical resistance (R) of a solution between two electrodes. It can be calculated as

 $C = \frac{1}{R} (S)....(2)$

<u>Cell Constant</u>: This is the ratio of the distance (l) between the electrodes to the area (A) of the electrodes. It can be expressed as

$$\mathbf{K} = \frac{l}{A} \,(\mathrm{cm}^{-1}).$$

Where:

K = cell constant (cm⁻¹); A = effective area of the electrodes (cm²) & l = distance between the electrodes (cm)

<u>**Conductivity</u>** : Conductivity is the ability of a solution to pass an electric current. In solutions the current is carried by cations and anions. It depends on the following factors:</u>

- Concentration
- o Mobility of ions
- Valence of ions
- o Temperature

Based on these parameters, conductivity is generally written as:

where,

n = the number of electrons

e = the charge of an electron

 τ = the relaxation time, the time taken for the movement of the charges

m = the mass of an electron

3.0 <u>The Randles Model</u>

The Randles model is a composition of electrical circuit elements that ideally behave identically to a real electrode in solution. However, this model is limited to small-signal excitations. The model incorporates two current paths - I_c and I_f . I_c is the current that charges the double-layer



capacitance C_{dl} . The other current path I_f, represents faradaic currents - currents which correspond to the oxidation or reduction of chemical species. The flow of faradaic current is limited by the sum of two impedances, R_{ct} and Z_w . The Warburg impedance (Z_w) is also frequency dependent. R_{sol} is a general solution resistance determined by the conductivity of the electrolyte itself. Both the Faradaic and charging currents must pass through the solution resistance R_{sol} .

One of the most significant features of electrode impedance is the double-layer capacitance. If a sufficiently large DC step in potential is applied to the working electrode in an electrochemical cell, initially a large current, I_c flows to charge the double-layer capacitance. The charging time constant is the product of the double-layer capacitance C_{dl} and the series solution resistance R_{sol} . Once the capacitance charges appreciably, the Faradaic current due to redox processes, the I_f begins to take over and eventually dominates the total electrode current. After a few RC time constants, the double-layer charging current falls below detectable level. Physically, the double-layer capacitance arises due to a diffuse charge region in the electrolyte near the surface of the electrode. The geometry is similar to that of a parallel plate capacitor, where the top plate is the electrode itself and the bottom plate charges in the solution present near the electrode. The separation between the plates is of the order of molecular scales and hence the double-layer capacitance can be quite large. The parallel plate view of the double-layer capacitor is known as the Helmholtz model.

The Warburg impedance (Z_w) is one component of the impedance that sets the Faradaic current. Usually, Z_w dominates the charge transfer resistance i.e., most chemical reactions are mass transfer limited rather than charge transfer limited. At low frequencies, the Warburg impedance and the doublelayer capacitance compete to set the overall impedance of the cell. The impedance of C_{dl} rises linearly with decreasing frequency but the Warburg impedance rises only with the square root of the decreasing frequency. Therefore, at extremely low frequencies C_{dl} is effectively an open circuit, and Z_w in series with Rct and Rs determine the total electrode impedance. Eventually, Z_w will also dominate R_{ct} and R_{sol}. At high enough frequencies, the impedance due to C_{dl} falls below

the impedance of Z_W and effectively shorts out both components of the Faradaic impedance. The electrode impedance then appears as the



solution resistance R_{sol} in series with the double-layer capacitance C_{dl} as shown in the adjacent figure.

Here the purpose is to make use of the Randles model for high frequency. This essentially reduces the model to R_{sol} in series with C_{dl} . Apart from this, there exists a cable capacitance C_c in parallel to the entire model. A sense resistance R_{sense} is connected in series with the entire model to measure the total potential across the cell.

4.0 <u>Types of Possible Excitations</u>

As per the literature review, there are two broad methods of providing excitation to the cell. The first method is to provide a sinusoid excitation to the cell. This method ensures that the charge build across the double layer capacitance (C_{dl}) is very small since the direction of the supply changes rapidly. This method has a limitation that if a cable is connected in parallel to the cell, the cable might not get enough time finish charging leading to erroneous readings in the measurement of conductivity. Therefore, this method has been eliminated from further study.

The second method involves the application of pulse excitation to the conductance cell and the measurement of its response. Since the pulses can be as defined to have a very small pulse width, the effect on C_{dl} and R_{sol} is the same as using a very high frequency since C_{dl} develops very little polarization. The applied pulse can be either a voltage pulse or a current pulse. The pulse can also be a unipolar or a bipolar pulse. More detailed discussions will be carried out regarding this method in the following sections.

5.0 Theoretical Discussions

As mentioned in the previous section regarding the use of pulse excitation methods, voltage and current pulse excitation have their own merits and demerits. In case of a current pulse, it is very easy to control the amount of current that is required to flow through the circuit but at the same time it increases the complexity of the circuit since a current source can be obtained from a voltage source by creating a Howland current pump. Also, the time taken by the cable to discharge will be very large due to C_c making it very difficult to select a sampling point to measure the voltage across the cell.

In case of a voltage pulse excitation, the complexity of the circuit is minimal but at the same time it is difficult to control the voltage drop across the cell. Apart from this, the voltage pulse method does not have any specific demerits that might affect the Randles model.



In case of a pulse excitation, the duty cycle needs to be same ($T_{on} = T_{off}$) in order to maintain charge balance across C_{dl} . In case of a unipolar voltage pulse (plotted above), a fixed charge develops across

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the double layer that leads to a constant DC shift in the output as represented in the simulation plot below:

This creates the need for a bipolar excitation. Since, there are no significant demerits for the voltage pulse excitation method, we would proceed with the same. The bipolar voltage pulse excitation with 50% duty cycle (to ensure charge balance) would be represented as shown in plot below:



For the above-mentioned excitation, the response of Randles model with a cable corresponding to 6-7nf capacitance is as follows:



Since, the voltage pulse method has the potential of providing with the accurate measure of voltage across the cell, it is necessary to also measure the current across the cell which in turn can produce the conductivity. For this purpose, it is mandatory to select an optimum value of sense resistance (R_{sense}) that is in series with the cell. The procedure of selecting the sense resistance will be discussed in the next chapter. The conductivity of a solution can be measured as:

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$$C = \frac{l}{v}$$
 (5)

Where:

I = current through the cell V= Voltage across cell

6.0 <u>Mathematical derivations</u>

After a thorough analysis of the circuit, the following result was found:

Applying KVL to the circuit, $i_1=i_2+i_3$(6)

$$\frac{Va-Vb}{Rsense} = i_1 \dots (7)$$

$$\frac{1}{Cc} * \int i3 \, dt = Vb \dots (9)$$



Simplifying the differential equation, the following time constant can be observed:

$$\tau = Cc * \frac{Rsol * Rsense}{Rsol + Rsense} \dots (10)$$

7.0 <u>Procedure and Optimization of Parameters</u>

According to the discussions in the previous section, the method of bipolar voltage pulse excitation has been finalized. A very crucial part in using this method is the finalization of the sense resistance. The optimum value of sense resistance is calculated by means of plotting the conductivity curves with respect to voltage and current. The optimum results are obtained when the intersection is tending towards the lower side of conductivity. The reason for the intersection to be at the lower side is because the curve is exponential which has the best sensitivity range in the



lower side of conductivity. The intersection curves are as shown in the adjacent plot.

In the curves above, the blue curve corresponds to the change in voltage drop with a change in conductivity while the red curve depicts the amount of current flowing through the cell with a change in conductivity. As it can be observed that since the curves are exponential in nature, they are the most linear in the lower side of their region. This is because, the change in conductivity is small even if the change in voltage or the current is considerable in the lower side of its range till about 150µS whereas

after that, the change in the conductivity is very high with a small amount of change in the voltage or current. For a conductivity rage of 20-600 μ S, the optimum range of sense resistance is 7k-8k.

Now, since the optimum sense resistance has been determined, the sampling intervals need to be determined as well in order to achieve repeatable results for conductivity measurement. According to equation 10, the charging time constant for the cable is represented as

$$\tau = Cc * \frac{Rsol * Rsense}{Rsol + Rsense}$$

Hence, it would be safe to assume that the cable would be almost completely charged at 5τ . If the sample is taken at or after 5τ it would be most likely possible to achieve an accurate reading of the conductivity.



In the graph above, the arrow marking represents the 5τ value approximately. By this time the cable should be almost fully charged. Also, sampling it at this instant makes the double layer (C_{dl}) charge almost negligible.

8.0 <u>Realization Scheme</u>



In order to realize this method, a circuit is built using fixed capacitor to depict the cable capacitance. It is supplied with bipolar voltage pulse excitation using a waveform generator and the samples are captured using a data acquisition card. The algorithm for the setup is developed on LABVIEW based on principles of rising and falling edge detection followed by filtering technique. Since the waveform generator and the Data acquisition module are not synchronized, it has the potential to introduce an offset during sample and hold. This might result in the presence of a constant offset while acquiring data at mentioned sample points. In order to remove this offset, active components have been used such

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as op-amps along with capacitor to filter out the residual voltage.

9.0 Result and Discussion

According to the PSPICE simulations of the symmetric sampling method, the following are the observations.

It may be observed here that the error can be restricted to 5% of full scale reading. This is a very encouraging result since this method has the potential to measure a very large range of conductivity with a relatively high accuracy.

The measurement taken with the actual 50m cable connected to the cell produces

the reading as plotted in the error graph below: The actual results prove that the error can be restricted under 6% of FS. The excess error is proof that the actual cable does not behave similar to a lumped parameter and displays non-linear characteristics. It may sometimes even happen that a specified length of cable does not necessarily contain the designated cable capacitance but actually a little more than the prescribed value. Nevertheless, conductivity values of greater than 1 decade





can be measured accurately and repeatably within 6% of FS error for conductivity measurement over the range of 20 to 600μ S.

10.0 <u>Conclusion</u>

The results obtained from extensive simulation and experimentation establishes two broad features of the design. The first is the ability to measure the conductivity in the range of 20 to 600μ S (i.e >1 decade) within 6% FS accuracy with an actual 50m cable that presents non-linear capacitance (6-7nF) over the cable length. The second is the 30:1 rangeability i.e the design of signal conditioner evolved has the ability to accurately measure a change of 1/30 in conductivity within 6% of FS over any specified range of conductivity measurement viz. for a specified range of 10 to 40 μ S the measurement resolution will be (40-10)/30 = 1 μ S within maximum of 6% FS accuracy.

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