An Experimental Setup to Measure the Conductivity of a Solid or Liquid Sample Utilizing Multi-Frequency LCR Meter

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Abstract

A computer-controlled automated data acquisition system is designed to measure the conductivity of the liquid (saline water) or the solid sample (rock saturated with saline water) in the frequency range 10 kHz to 2 MHz. The set-up is based on LCR (Inductor, Capacitor, and Resistor) multimeter and four-terminal sample holder system that was developed to reduce the contact resistance, to minimize any stray capacitance, and residual inductance associated with the test leads or the test fixture at high frequencies. However, the instrumentation calibration scheme cannot completely eliminate the aforementioned errors. In order to accomplish this, a calibration model is designed to compensate for the inherent error of the system. In this study, the conductivity of some samples was measured. The measured data was compared with conductivity provided by Society of Core Analysis Guideline (SCA-GL). The agreement between available data and experimental data is excellent.

Introduction

The increased ability of those in the petroleum industry to analyzed the formation characteristics from electrical resistivity data, it is imperative to have more precise method to measure that parameter [1,2].

Several types of resistivity sensors are available on MWD (Measurement-While-Drilling) tools. The earlier ones were short normal sensors operating near DC (Direct Current)[3, 4, 5] and coil-type sensor operating at 2 MHz [6, 7, 8]. For instance, the coil-type MWD resistivity tool measures phase and attenuation. Then, some conversion algorithms are used to transform the measured quantities in terms of apparent resistivities. In this conversion, the formation dielectric constant is assumed to be either a constant value or a known function of the resistivity which is not a correct assumption. Therefore, it is a common practice to obtain some samples from the core selected reservoir and then an actual electric permittivity are measured in the core measurement facility.

In order to be able to utilize the measured dielectric permittivity instead of the assumed value, an automated computer controlled technique was developed for measuring the conductivity of the sample under the test at the frequency range of 10 kHz to 2 MHz. A multi-frequency LCR meter was used to measure the impedance of a four-terminal sample holder containing the core or the liquid sample. The system error of the LCR meter and sample holder is compensated by a set of compensation parameters obtained experimentally. After the system error is subtracted from the measured impedance, the conductivity of the sample is calculated.

Instrumentation

The schematic diagram of the low-frequency conductivity measurement is shown in Figure 1, it consists of an HP 4275A multi-frequency LCR meter, one sample holder, one desk-top computer, peripheral device, and four one-meter long coaxial cables with BNC (Bayonet Neill Concelman or Bayonet Nut Connector*)* connectors. The computer is used for controlling the system and data collection purposes. The communication is achieved via HP-IB cable that connects the computer to the multi-frequency LCR meter.

The HP 4275A multi-frequency LCR meter is a fully automated test instrument designed to measure the parameters of an impedance element in the 10 kHz to 10 MHz range. The test signal level can be flexibly set at the desired amplitude within the range of 1mV to 1V.

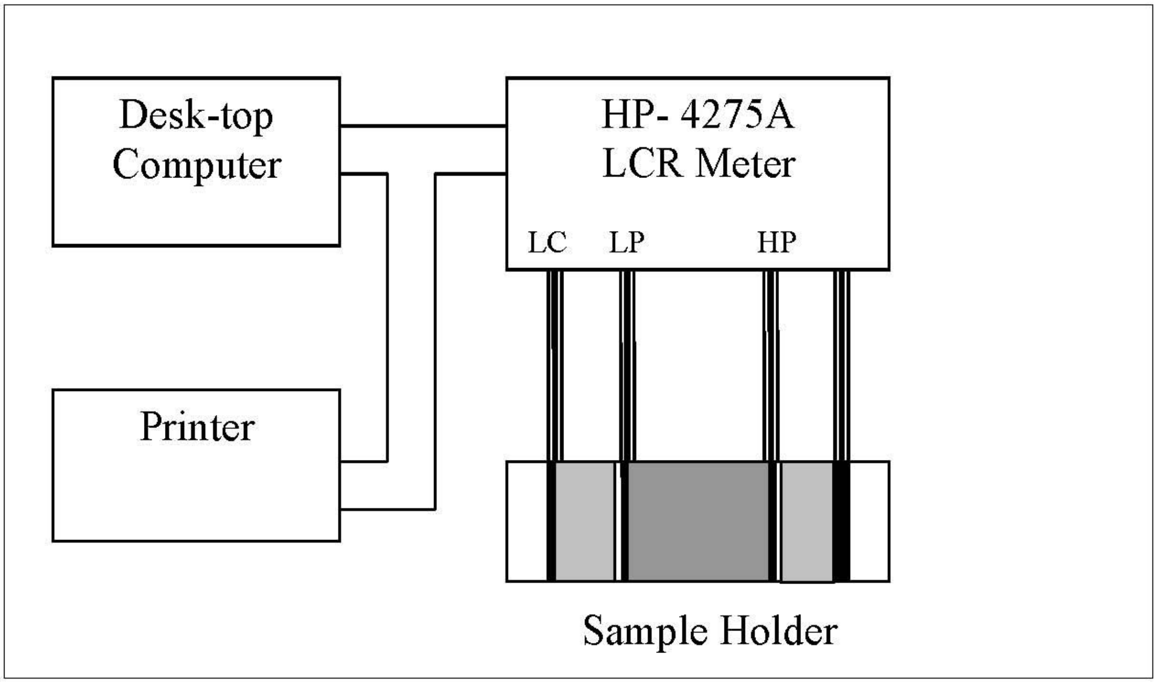

Figure 1. Block diagram of data acquisition system.

Sample holder is comprised of two Plexiglas rectangular tanks which are connected together by a circular Plexiglas tube. Two pairs of platinum mesh serve both potential electrodes, and current electrodes. The potential electrodes are placed adjacent to the end surfaces of the rock sample. The current electrodes are placed parallel to the potential electrodes. Four pieces of the platinum wire connect the platinum electrodes to the BNC connector.

Measurement Procedure

The method of four-terminal measurement is used to reduce the contact resistance and to minimize any stray capacitance and residual inductance associated with the test leads or the test fixture at high frequencies (see Figure 2).

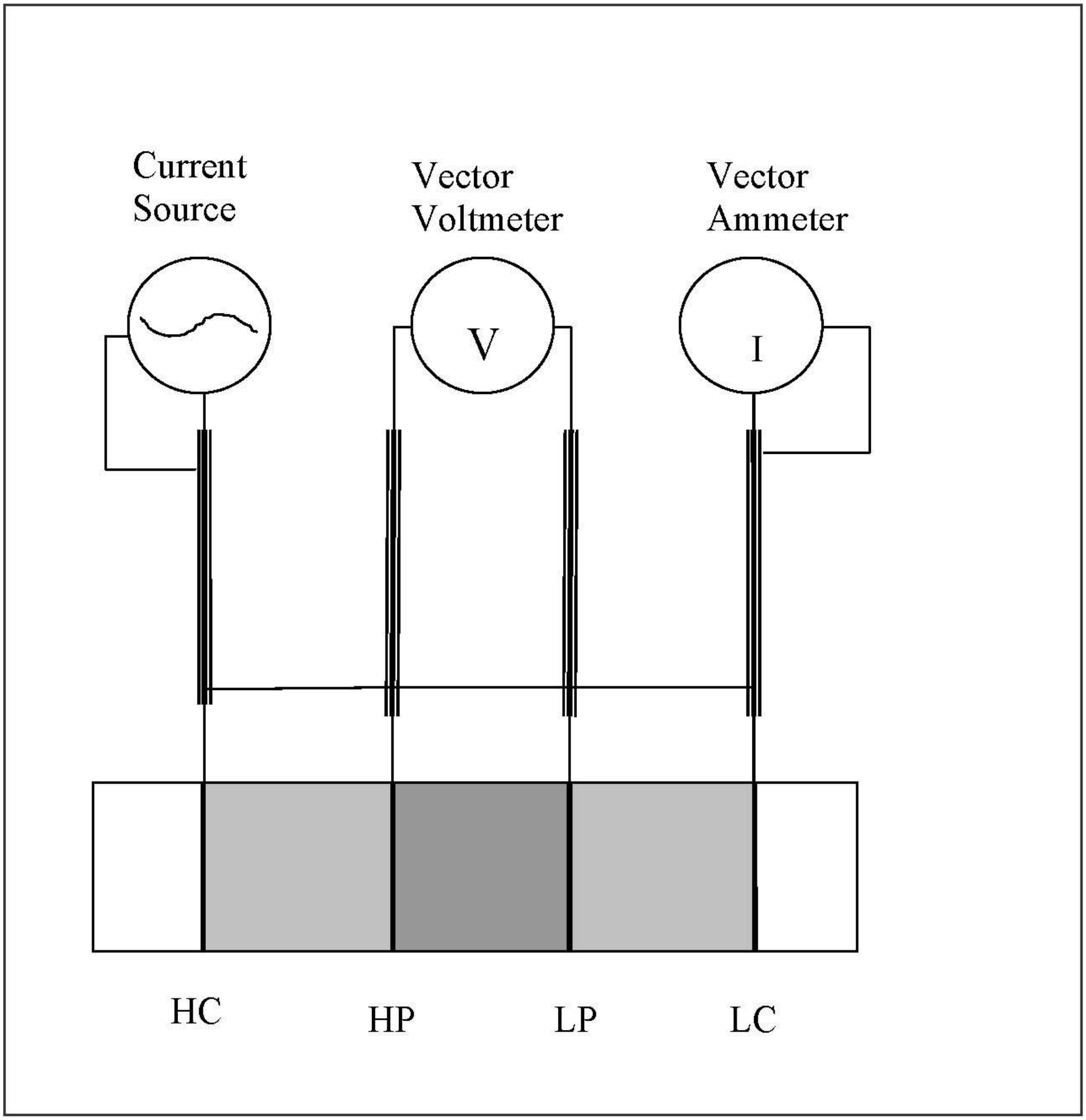

Figure 2. Four-terminal measurement method.

Four, one-meter long, coaxial cables are used as leads from the BNC connector on the LCR meter to the sample holder. These coaxial cables are connected, at one end, to the high current, the high potential, the low potential, and the low current ports of the LCR meter. The other ends of these cables (the inner conductors) are connected to four terminals on the sample holder. The four outer conductors of these cables are short-circuited at the end near the sample holder, they serve as the return path for the measurement current. The same current flows through both the center conductors and the outer shield conductors (in opposition direction) so that no external magnetic fields are generated around the conductors. Thus, the test leads do not contribute any additional measurement error due to the self or the mutual inductance between the individual leads.

Since the measurement circuit has inherent stray capacitances, residual inductances, and resistances, the measured values may be unacceptably influenced depending on the measurement range and the magnitude of the residual parameters. The ZERO offset adjustment function of the HP 4275A LCR meter automatically compensates for such residual, and minimizes the incremental error [9].

Setup Calibration

To check on the accuracy of the system several two-terminal elements, such as brass and some precision resistors, were soldered to the potential electrodes one at the time and the current electrode was shorted to the potential electrode in each side using platinum wire. The impedance of these elements were measured, and some of these results are shown in Tables 1 and 2. The error appears to be very small at low resistance values.

Table 1. A comparison between measured impedance and corrected impedance of the brass wire is shown.

Frequency (kHz)	Measured Impedance		Corrected Impedance	
	Real Part (Ω)	Img Part (Ω)	Real Part (Ω)	Img Part
10	0.01	0.01	0.00	0.00
20	0.01	0.02	0.00	0.00
40	0.01	0.03	0.00	0.00
100	0.01	0.08	0.00	0.00
200	0.01	0.17	0.00	0.00
400	0.01	0.34	0.00	0.00
1000	0.01	0.87	0.00	0.00
2000	0.06	1.76	0.00	0.00

Table 2. A comparison between measured impedance and corrected impedance of a standard resistor (15000Ω ±0.1% tolerance) is shown.

Frequency (kHz)	Measured Impedance Real Part (Ω)	Img Part (Ω)	Corrected Impedance Real Part(Ω)	Img Part(Ω)
10	14953.71	+138.65	14999.99	-0.01
20	14952.91	+35.77	14999.99	-0.02
40	14951.72	-64.85	14999.99	-0.03
100	14944.46	-230.09	14999.99	-0.08
200	14927.30	-484.04	14999.99	-0.17
400	14863.91	-960.65	14999.99	-0.34
1000	14589.32	-2347.35	14999.99	-0.87
2000	13756.40	-4429.99	14999.99	-1.76

In order to reduce the error of the system, the model shown in Figure 3 was used to correct the measured impedance.

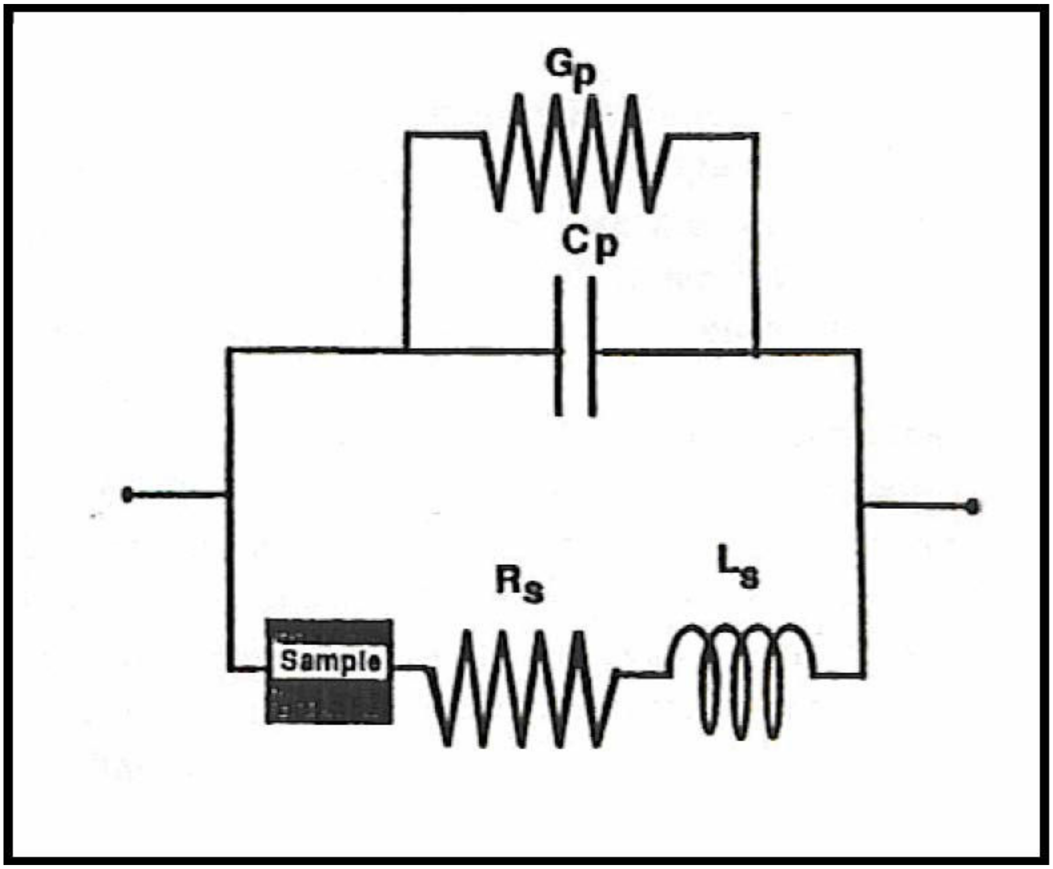

Figure 3.This model is used to eliminate the conductance, stray capacitance, residual inductance, and resistance due to the cable and sample holder

The residual inductance, stray capacitance, and resistance of this model were computed by using two-terminal elements, namely, a piece of brass (short circuit) and precision resistor (15 k-Ohm).

The total admittance of this model, in general case, can be expressed by

$$Y = G_p + j\omega C_p + \frac{1}{\left(R_s + j\omega L_s + Z_{sample}\right)} \tag{1}$$

$$Z_s = \mathrm{R}_s + j\omega L_s \tag{2}$$

$$Y_p = G_p + j\omega C_p \tag{3}$$

where

Z_{Sample} = impedance of the unknown sample,

Z_s = Series impedance,
Y_p = Parallel admittance,
R_s = Series resistance,
G_p = Parallel Conductance,
L_s = Residual inductance, and
C_p = Stray capacitance.

To compensate for the error, a short (brass wire) is used which reduces the Equation (1) to:

$$Y_o = G_p + j\omega C_p + \frac{1}{\left(R_s + j\omega L_s\right)} \tag{4}$$

When a very high-value precision resistor (15 k-Ohm) is used, the following equation is obtained

$$Y_\infty = G_p + j\omega C_p + \frac{1}{\left(R_s + j\omega L_s + R_\infty\right)} \tag{5}$$

where

Y_0 = admittance of the circuit with a short-circuited brass sample,
Y_∞ = admittance of a circuit with a 15 kΩ resistor, and
R_∞ = a 15-k-Ohm precision resistor.

Subtracting (5) from (4) yields

$$Y_0 - Y_\infty = \frac{R_\infty}{\left[\left(\mathrm{R_s} + \mathrm{j}\omega\mathrm{L_s}\right)\left(\mathrm{R_s} + \mathrm{j}\omega\mathrm{L_s} + R_\infty\right)\right]} \tag{6}$$

for simplification, it is assumed that R_∞ is much greater than $(R_s + j\omega L_s)$, so $(Y_0 - Y_\infty)$ can be reduced to

$$Y_0 - Y_\infty = \frac{1}{\left(R_s + j\omega L_s\right)} \tag{7}$$

Therefore, the series impedance and parallel admittance can be obtained as follows

$$Z_s = \frac{1}{\left(Y_o - Y_\infty\right)} \tag{8}$$

and

$$Y_p = Y_\infty - \frac{1}{R_\infty} \tag{9}$$

At this stage, all error terms can be calculated, and then the raw data of the unknown sample can be corrected. The following expression can be used to eliminate these errors from the measured data

$$Z_{Sample} = \frac{1}{\left(Y_m - Y_p\right)} - Z_s \tag{10}$$

where

Y_m = admittance of the measured sample.

The conductivity of the sample can be calculated using the following expression:

$$\sigma = \frac{d}{A}\ \mathrm{Re}\left(\frac{1}{Z_{Sample}}\right) \qquad (11)$$

where

d = the thickness of the sample,
A = cross-section area of the sample,
σ = conductivity of the sample, and
Re = indicate the real part.

Results and Discussion

Several measurements were performed on the saline water at various salinities, ranging from 0.1 kppm to 9 kppm. The measured data were corrected for the uncertainties of the system which are in terms of complex series impedance and a complex parallel admittance.

The measured conductivity and the corrected conductivity curves were plotted versus frequency. These results were compared to the Society of Core Analysis Guideline (SCA GL) data [10]. The corrected data is in good agreement with the available data (the error is less than 3%). The correction seems to be significant when the salinity is less than 0.9 Mho/m. Some of these results are presented in Figures 4 through 7.

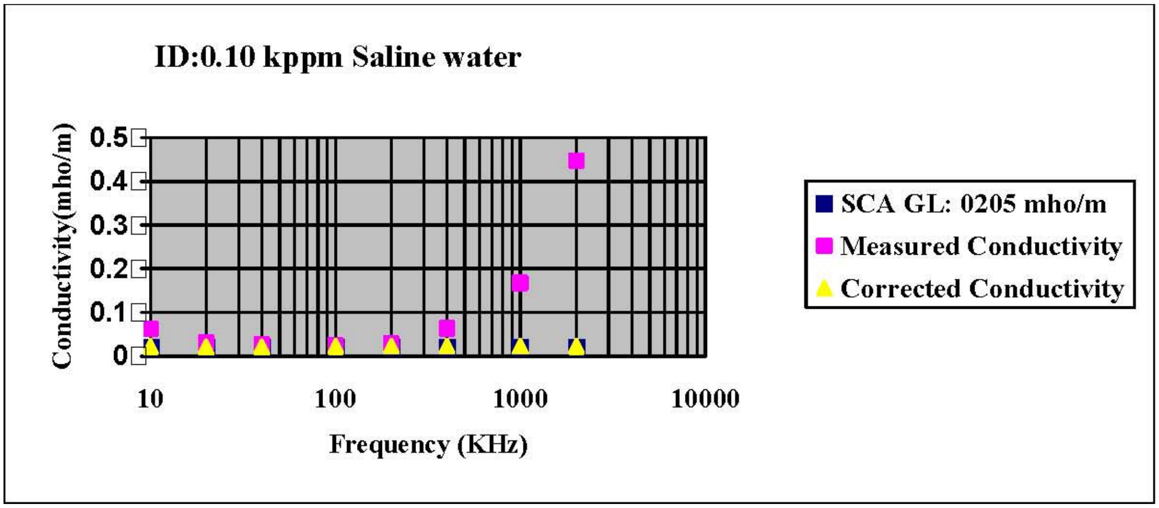

Figure 4. It shows the conductivity measurement versus frequency for the water with the salinity of 0.1 kppm and measurement temperature of 23.9^{o}C.

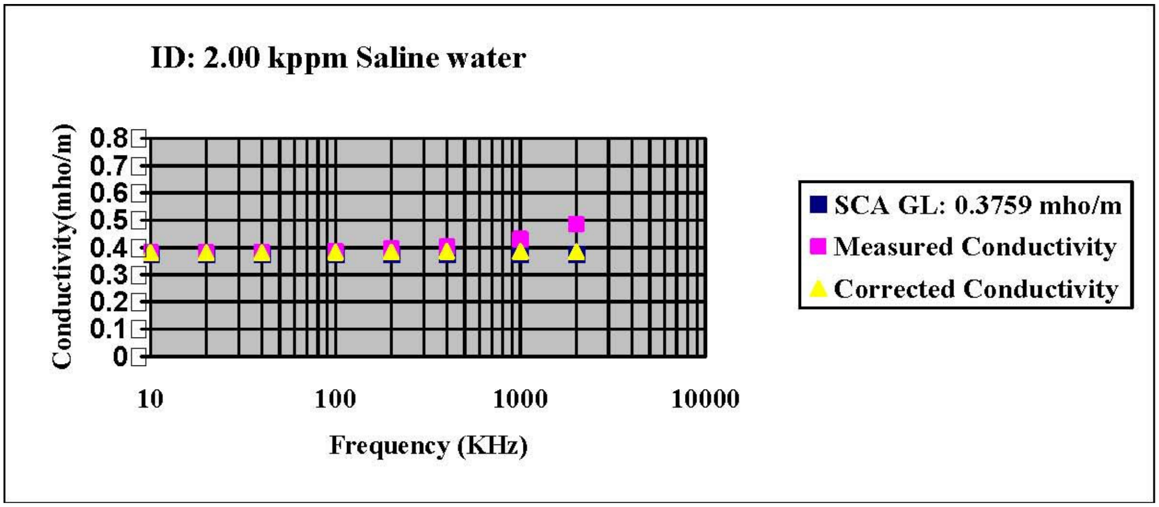

Figure 5. It shows the conductivity measurement versus frequency for the water with the salinity of 2.00 kppm and measurement temperature of 23.7 ^{o}C.

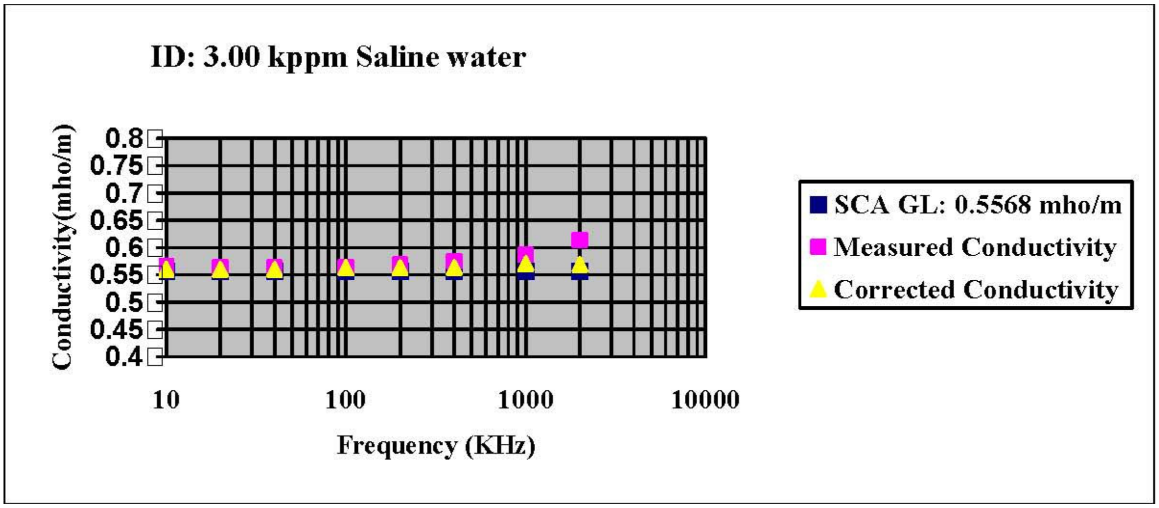

Figure 6. It shows the conductivity measurement versus frequency for the water with the salinity of 3.00 kppm and measurement temperature of 24.0 ^{o}C.

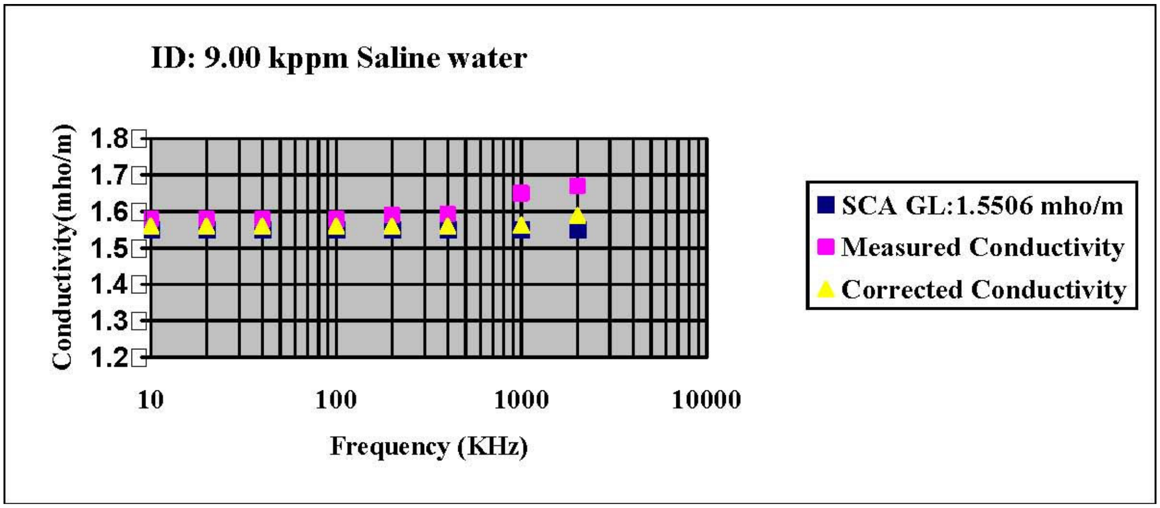

Figure 7. It shows the conductivity measurement versus frequency for the water with the salinity of 9.00 kppm and measurement temperature of 23.5 °C.

Conclusions

A fully automatic data acquisition system was designed to measure the conductivity of either a liquid or a solid sample, using multi-frequency LCR meter. A correction model was introduced to compensate the uncertainties of the system. This model is comprised of one complex series impedance and one complex parallel admittance. Samples of various salinities were measured and results were compared to the Society of Core Analysis Guideline data. From the foregoing analysis and experiments, the correction seems to be significant at the low salinities (less than 0.9 Mho/m). Furthermore, since the down-hole MWD tool is operated at 2 MHz, a set of corrected data is essential for the tool calibration and the raw data correction. Therefore, the correction at the higher frequencies, such as 2 MHz, which is essential for MWD logging, has been developed.

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Biography:

Shahryar Darayan received a Ph.D. degree in Electrical Engineering from University of Houston in 1993. At the present, he is a professor and program coordinator of Electronics Engineering Technology program at Texas Southern University. His research areas are applied electromagnetic and instrumentation, computer hardware and software design, and numerical methods.