ELECTRICAL MEASUREMENTS: CONSIDERATIONS ON THE PERFORMANCE OF 2- AND 4-CONTACT SYSTEMS

N. Bona[1], E. Rossi[1], S. Capaccioli[2] and M. Lucchesi[2]
[1] Eni E&P, [2] INFM-CNR PolyLab & Dipartimento di Fisica Università di Pisa, Largo Bruno Pontecorvo, 3, I-56127 Pisa, Italy

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Abu Dhabi, UAE 29 October-2 November, 2008

ABSTRACT

Electrical measurements are done using either 2- or 4-contact configurations. Although an ample literature exists, advantages and disadvantages of the two methods remain relatively unexplored. Four-contact systems are believed to be less affected by electrode polarization and high contact resistances than 2-contact systems. But no direct comparison has ever been reported on a wide frequency band. We first analyse the limitations of the two techniques from a theoretical point of view. Then we discuss the results of experiments conducted using a new cell (patent pending) that enables us to investigate the performance of the two methods in great detail. Finally we give guidelines for the design of an efficient 4-contact system. The presented analysis suggests a strong complemetarity between 2- and 4-contact methods for improved assessments of the electrical response of rock over the frequency range covered by laterolog, induction and while-drilling tools. Two-contact measurements are preferable above 10-100 kHz, while 4-contact seem more reliable at lower frequencies. Standard measurements obtained at the single frequency of 1 kHz, therefore, should be made with 4 contacts.

INTRODUCTION

Electrical measurements are commonly made on rocks in the frequency domain. That means that the rock sample is excited with a harmonic signal $V(f)$ at the measurement frequency f. The impedance $Z(f)$ of the sample is determined by sensing the amplitude of the current that passes through the sample with respect to $V(f)$. Two-contact techniques use the same electrode to inject current into the sample and to measure the voltage. The most common configuration is a capacitor whose parallel plates are in contact with the faces of the sample. Four-contact techniques use separate electrodes for current and voltage. The literature reports essentially two types of systems. One is that used by Garrouch and Sharma (1992), in which current is injected using flat electrodes in contact with the faces of the sample while voltage is measured using metal rings pressed against the lateral surface of the sample. The other system is that developed by Fleury (1998), who uses current and voltage electrodes, all located on the lateral surface of the sample, like in electric tomography.

All methods, be they 2- or 4-contact, require measurements of current and voltage. Impedance analysers do these measurements in two ways: AC-impedance bridge and frequency response analysis. AC-bridge systems usually cover the frequency range from

10 to 10^7 Hz. The principle of measurement is shown in **Fig.1A**: the impedance bridge consists of the sample impedance Z_S and the adjustable compensation impedance Z_{AC}. On the left hand side of the bridge, the generator drives the sample with the voltage V_S that causes the current I_S to flow into P_1. On the right hand side of the bridge, the Variable Amplitude Phase Generator (VAPG) feeds the current I_{AC} through the Z_{AC} impedance into P_1. The bridge will be balanced if $I_{AC} = -I_S$, which corresponds to $I_0 = 0$. Any deviation is detected by the zero voltage detector which changes the amplitude and phase of the VAPG as long as $I_0 \neq 0$. In balanced state, the sample impedance is calculated from $Z_S = V_S/I_S = -V_SZ_{AC}/V_{AC}$. Frequency response analysis covers a wider frequency range (10^{-5} to 10^7 Hz) with higher precision, especially at the low frequency end. The measurement principle is shown in **Fig.1B**: the generator drives the sample with the voltage V_S that is directly measured by the Voltage Vector Analyzer (Ch1). I_S is measured with VVA's Ch2 after it has been transformed by a Current-to-Voltage Converter. Two internal harmonic reference signals are multiplied with the measured signal. After averaging over many periods, both signals correspond directly to the input signals' real and imaginary parts.

The impedance Z_S of a piece of rock is a complex quantity and in very general terms it can be expressed as:

$$Z_S = G \cdot \frac{1}{\sigma + i\omega\varepsilon_0\varepsilon} \tag{1}$$

where G [metre^{-1}] is a geometrical factor (for a cylindrical sample measured using a standard 2-contact technique, G is the ratio of the sample length to its cross sectional area), $\omega = 2\pi f$ [Hz] is the angular frequency, i is the imaginary unit, ε_0 = 8.854 pF/m is the permittivity of vacuum, σ [S/m] is the conductivity of the rock and ε [dimensionless] is its dielectric constant. The real part of Z_S is the so-called resistance, R. The R/G ratio is the rock resistivity, ρ. Thus: $\rho = \sigma/[\sigma^2+(\omega\varepsilon_0\varepsilon)^2]$. At low frequencies [$\omega << \sigma/(\varepsilon_0\varepsilon)$] resistivity is asymptotic to $1/\sigma$; but at intermediate/high frequencies it will be affected also by ε (log analysts call this ε-dependency of resistivity "the dielectric effect"). In theory, both σ and ε are dependent on frequency. However, while it is clear that ε is a decreasing function of frequency, our latest data show that σ is relatively constant in the 10^{-1} – 10^7 Hz range.

2-CONTACT SYSTEMS

The experimental setup of a 2-contact measurement is shown in **Fig.2A**. The equivalent circuit is shown in **Fig.2B**. The rock sample is represented by the impedance Z_S. In series with Z_S there are the two impedances Z_C which represent the effect of the electrode-sample interfaces. The device that measures the voltage difference across the sample is directly connected to the current electrodes and the two impedances Z_I are its input impedances. The measured impedance Z_M is given by:

$$Z_M = Z_S + 2Z_C \tag{2}$$

According to **Eq.2**, the sample impedance tends to be overestimated. High contact resistances and electrode polarisation effects may generate impedances Z_C that are of the same order of magnitude as Z_S or even greater, making a 2-contact measurement invalid. There is a high contact resistance (R_C) if the sample-electrode contact is not good. A way

to improve the contact is to use a thin metal foil**,** plastic and malleable enough to conform to the rock surface. Another way is to insert a paper or silver filter saturated with the sample brine between the sample and the electrode. We think that a paper filter is a good compromise between quality and practicality of the analysis for ambient conditions tests.
The other effect contributing to Z_C is electrode polarisation. Electrode polarisation is particularly important at low frequencies, in samples having high water saturation and good petrophysical characteristics, containing high salinity brine. This effect is caused by ionic charge accumulations at the electrodes. These form a double layer that generates an electric field opposite to the applied field. The double layer thickness can span from Angstroms up to few nanometres, depending on the ionic strength of the brine and the nature of the electrodes. The occurence of electrode polarisation depends also on the strength of the applied electric field. The effect has been extensively studied by Johnson and Cole (1951) and later by Adamec (1972). From an electric point of view, in the presence of rough interfaces such as in porous rocks, electrode polarisation can be represented as an element that is partly resistive and partly capacitive, having an impedance of the form $A_0(i\omega)^{-n}$, where A_0 is a constant characteristic of the electrode-material interface and n ($0 \leq n \leq 1$) is an exponent that describes the more resistive (n=0) or more capacitive (n=1) character of the impedance (note the identity: $i^n = \cos(\pi n/2) + i\sin(\pi n/2)$). In series with this impedance there is the previously discussed contact resistance, so $Z_C = A_0(i\omega)^{-n} + R_C$. Most of our data, however, show that $n\approx1$, and therefore we will treat Z_C as a series of a pure capacity and a resistance. Thus:

$$Z_C = R_C + \frac{1}{i\omega C_C} \tag{3}$$

The methods to discriminate between sample-electrode interface effects and the true response of the sample are very extensively discussed in the literature (MacDonald, 1987; Jonscher, 1996). Probably the best one consists of varying the applied voltage in terms of both d.c bias and a.c amplitude. The spurious impedance Z_C associated with the sample-electrode interfaces can be identified because it is much more dependent on the applied voltage than the sample impedance Z_S (Cohen et al, 1995). In addition to this method there is also the common approach of plotting the imaginary part of the measured impedance against the real part (Argand plot). Although this procedure permits the identification of the critical frequency below which electrode effects are not negligible, it does not allow the extraction of the true sample impedance below this critical frequency.

4-CONTACT SYSTEMS

Fig.3A illustrates the experimental setup of a 4-contact measurement that uses the Garrouch and Sharma configuration. The Fleury setup is not shown here, but the equivalent circuit in **Fig.3B** describes 4-contact measurements in general. The rock sample is represented by the impedance Z_S. Here, Z_S is the impedance of the part of the sample that is between the voltage electrodes. The other impedances of the circuit are Z_I, Z_C, Z_V and Z_T. Z_I is the input impedance (or impedance to the ground) of the device that measures the voltage difference across Z_S, and can be represented as a capacitance C_I and a resistance R_I in parallel. The best instruments available on the market have resistances R_I of the order of

10^{12} Ω and capacities C_I around 10^{-11} F. However, if we consider also the unavoidable capacity associated with the cables connecting the voltage electrodes to the voltmeter, then C_I becomes on the order of 10^{-10} F. In fact, typical capacities of coaxial cables are about 120 pF per meter of cable length. The poorer the quality of the instrumentation, the lower R_I and the higher C_I. An additional contribution, $i\omega L_I$, could come from the cables inductance L_I, but this is relevant only at very high frequencies. Neglecting this inductive contribution, the mathematical form of Z_I is:

$$Z_I = \frac{R_I}{1 + i\omega R_I C_I} \tag{4}$$

Z_C is the impedance associated with the current electrode-sample interface and has been already discussed in the previous section of the paper (**Eq.3**). Additionally, Z_C should include also the series inductance effect ($i\omega L_C$) of the cable connections, but usually this contribution is relevant only at high frequency (> MHz). The R_C and C_C values of the resistance and the capacity that form Z_C can vary a lot depending on the design of the system, but in general $R_C << R_I$ and $C_C >> C_I$. If the system is designed properly, the contact resistance R_C is below, say, 100 Ω. However, if insufficient precautions are taken to minimize R_C and, for example, an oil or air film is let to form between the rock and the electrode, then R_C can reach values up to 10^4 Ω. The capacitance C_C is more difficult to estimate, but it should reasonably be between 10^{-8} and 10^{-4} F.

Z_V is the impedance associated with the voltage electrode-sample interface. It is essentially a contact resistance, given that in a 4-contact system the voltage electrode is not a working electrode and therefore it is free from polarisation effects. Analogously to R_C, also R_V can reach values of the order of 10^4 Ω if the system is not designed properly. Thus:

$$Z_V = R_V \tag{5}$$

The last impedance we define is Z_T. This is the impedance of the part of the sample that is between the current and voltage electrodes. In a 4-contact measurement, some current passes through Z_T and the amount of it depends on the geometry of the system. If the sample is not very heterogeneous, Z_T will be proportional to Z_S and the proportionality constant (A) will depend only on geometrical parameters such as the area of the current electrodes, the distance between current and voltage electrodes, the distance between the voltage electrodes, the diameter of the sample, etc. Thus:

$$Z_T = AZ_S \tag{6}$$

WHAT IS MEASURED USING 4 CONTACTS

The objective of a 4-contact analysis is to obtain Z_S. From the circuit of **Fig.3B,** it can be seen that the measured impedance Z_M, defined as the ratio of the voltage difference ΔV to the current passing through the sample, is given by:

$$Z_M = Z_S\left(1 + \frac{Z_C + Z_V + Z_T}{Z_I}\right) \tag{7}$$

The three additional impedances on each side of Z_S enter the evaluation process because a non zero current passes through Z_I. Only if $(Z_C + Z_V + Z_T) << Z_I$, will the measured impedance be equal to the sample impedance Z_S. And since all these impedances are a function of frequency, in general the condition $(Z_C + Z_V + Z_T) << Z_I$ will be met only for certain frequency intervals. We now discuss the effect of Z_C, Z_V and Z_T separately.

Effect of Current Electrode-Sample Interface. The Z_C/Z_I term can be estimated from **Eq.3** and **Eq.4**. Then, substituting into **Eq.7** we obtain the $Z_M - Z_S$ relationship. Since we want to evaluate only the effect of Z_C/Z_I, in doing these calculations we will assume that Z_V and Z_T are zero. Considering only the real part of the measured impedance Z_M, which is the quantity of biggest practical interest, the result is:

$$Z_M' \approx Z_S' - \omega R_C C_I Z_S'' \tag{8}$$

This relation, which represents the high frequency limit ($\omega^2 >> (R_I R_C C_I C_C)^{-1}$) of the general solution, is valid in the whole frequency range covered by laboratory measurements (that is from a few Hz to 10 MHz). Z_S' and Z_S" are the real (i.e. the resistance) and the imaginary parts of the impedance of the sample. Dividing by Z_S' after noting from **Eq.1** that:

$$\frac{Z_S''}{Z_S'} = -\frac{\omega \varepsilon_0 \varepsilon}{\sigma} \tag{9}$$

gives:

$$\frac{Z_M'}{Z_S'} \approx 1 + \frac{\omega^2 R_C C_I \varepsilon_0 \varepsilon}{\sigma} \tag{10}$$

Eq.10 gives the error in Z_S'. The fact that it does not contain the C_C parameter indicates that electrode polarisation should not be a problem. Contact resistance, on the other hand, may be a problem. Resistive samples (low σ) measured at high frequency ($f > 10$ kHz) using a bad contact (high R_C) represent the most critical case. Assuming $C_I \sim 10^{-10}$ F and $\varepsilon \sim 10^2$, the following percentage errors are calculated for various values of σ and R_C:

	Frequency = 1 kHz					Frequency = 10 kHz					Frequency = 100 kHz				
***Rc*, Ω**															
10 k	3	0	0	0	0	>100	35	3	0	0	>100	>100	>100	35	3
1 k	0	0	0	0	0	35	3	0	0	0	>100	>100	35	3	0
100	0	0	0	0	0	3	0	0	0	0	>100	35	3	0	0
10	0	0	0	0	0	0	0	0	0	0	35	3	0	0	0
	0.1	**1**	**10**	**100**	**1000**	**0.1**	**1**	**10**	**100**	**1000**	**0.1**	**1**	**10**	**100**	**1000**
	σ, mS/m					**σ, mS/m**					**σ, mS/m**				

Tab.1: Percentage errors in the measurement of sample resistance Z_S' due to the effect of current electrodes in a 4-contact system. For example, at 100 kHz, a sample that has a true conductivity of 10 mS/m and is measured using a contact resistance of 1 kΩ will exhibit a resistance that is 35% higher than the true one.

Effect of Voltage Electrode-Sample Interface. The effect of the Z_V/Z_I term is perfectly analogous to that of Z_C/Z_I. At low frequency, contact resistances at the voltage electrodes do not generate errors, while at high frequencies ($f > 10$ kHz) they may lead to significant errors in low conductivity samples. In these cases, 2-contact measurements can be more accurate.

Effect of the Part of the Sample Outside the Voltage Electrodes. The Z_T/Z_I term can be calculated from **Eq.4** and **Eq.6**. We then substitute into **Eq.7** assuming $Z_C = Z_V = 0$, and finally we express the sample impedance in terms of rock conductivity and dielectric constant, according to **Eq.1**. The result is:

$$\frac{Z_M{}'}{Z_S{}'} \approx 1 + 2C_I AG \frac{\omega^2 \varepsilon_0 \varepsilon}{\sigma^2 + (\omega \varepsilon_0 \varepsilon)^2} \tag{11}$$

A and *G* are geometrical parameters. In the Garrouch and Sharma system *A*~1, given that the volume of sample between the current and voltage electrodes has more or less the same impedance as the part of sample between the voltage electrodes. *G* is equal to the distance between the current and voltage electrodes (~ 10^{-2} m) divided by the cross sectional area of the sample (~ 10^{-3} m^2), so $G \sim 10$ m^{-1}. In the Fleury system, the *A* and *G* factors are difficult to evaluate, because of the non-linear geometry of the configuration, but their product should be <<1. According to **Eq.11**, the following percentage errors in the measured sample resistance are obtained for various values of the *AG* product and σ (we assume $C_I \sim 10^{-10}$ F and $\varepsilon \sim 10^2$ as before).

	Frequency = 1 kHz					Frequency = 10 kHz					Frequency = 100 kHz				
AG															
10	1	0	0	0	0	53	1	0	0	0	>100	53	1	0	0
1	0	0	0	0	0	5	0	0	0	0	22	5	0	0	0
0.1	0	0	0	0	0	1	0	0	0	0	2	1	0	0	0
	0.1	**1**	**10**	**100**	**1000**	**0.1**	**1**	**10**	**100**	**1000**	**0.1**	**1**	**10**	**100**	**1000**
	σ, mS/m					**σ, mS/m**					**σ, mS/m**				

Tab.2: Percentage errors in the measurement of sample resistance Z_S' due to impedance Z_T for various values of the *AG* product and rock conductivity. For example, at 100 kHz, a sample that has a true conductivity of 1 mS/m and is measured using a system with *AG*=10 will exhibit a resistance that is 53% higher than the true one.

In conclusion, the Z_T/Z_I term may produce a big error on the measured resistances, but only at high frequencies, at low rock conductivities and using the Garrouch and Sharma configuration ($AG \sim 10$ m^{-1}).

EXPERIMENTAL RESULTS

In this section of the paper, we present and discuss measurements performed on a standard load, on three water samples and one rock sample. These measurements were carried out with both 2 and 4 contacts. The measurement cell design is patent pending. It is different from other cells as both current and voltage electrodes are in contact with the sample faces. We believe that this configuration allows us to minimize all contact resistances as well as the impedance Z_T. Furthermore, it simplifies the sample loading and dismounting operations, making the system suitable for frequent electrical measurements. The instrument used for these measurements is the impedance analyser Novocontrol Alpha.

The confidential characteristics of the design of the cell are not disclosed here, but this will not undermine the intelligibility of the presented analysis.

Standard Load. The load consists of three elements in series: $Z_C + Z_S + Z_C$. Two of them (Z_C) are equal and consist of a capacity C_C = 10 μF and a resistance R_C = 10 kΩ in series. The impedance of these two elements is $Z_C = R_C + 1/(i\omega C_C)$ and simulates the impedance that forms at a current electrode-rock interface due to the polarisation of the electrode (C_C) and the presence of a contact resistance (R_C). The mid element, Z_S, consists of a capacitance C_S = 180 pF and a resistance R_S = 10 kΩ in parallel: its impedance is $Z_S = R_S/(1+i\omega R_S C_S)$ and simulates the response of rock. Such an element exhibits Z_S' values that are relatively constant up to a frequency f on the order of $(2\pi R_S C_S)^{-1}$ ~100 kHz, and then decrease as frequency increases with a trend that appears linear on a bi-log scale. The three elements are arranged in such a way that when the load is inserted in the measurement cell, current flows through the series of the three elements. In the 4-contact setup, the voltage electrodes detect the voltage difference across Z_S; in the 2-contact configuration they detect the voltage difference across the three elements. The resistances measured at both 2- and 4-contacts are shown in **Fig.4**, along with their expected values and the true value of Z_S'.

As can be noted, there is a good match between predicted and measured Z_S' values. Let us first consider the 2-contact measurement. As expected, the true Z_S' (thick solid line) is overestimated when measuring at 2-contacts, because what is measured in this case is (Z_S'+2Z_C'). Since Z_C' = R_C = 10 kΩ, the measured resistance has a +20 kΩ bias. The deviation at low frequencies is due to the non-ideal behaviour of the capacitance C_C, which has a small but not negligible resistive component below 10 Hz. At around 20 kHz, Z_S' starts decreasing and so does the measured resistance. At around 400 kHz, Z_S'<<2R_C and the 2-contact measurement becomes insensitive to Z_S'. Above this frequency, the measurement is dominated by contact resistance and, therefore, the expected resistance is 2R_C = 20 kΩ. This is the value that is measured up to around 3 MHz. Above 3 MHz the measured resistance drops, due to the inductance effect of the cable connections.

The 4-contact measurement, on the other hand, provides a resistance that is equal to Z_S'(1+ Z_C/Z_I), according to **Eq.7** (Z_V and Z_T are not present here). As can be seen, up to 100 kHz the measured resistance is equal to the true Z_S', consistent with the fact that the Z_C/Z_I ratio is negligible in this frequency region. Above 100 kHz, Z_S' starts to be overestimated because Z_C/Z_I is no longer negligible. According to **Eq.8**, the difference between measured and true Z_S' is on the order of $\omega C_I R_C \cdot Z_S$'' and increases as frequency increases.

Water. The measurements carried out on water are shown in **Fig.5** for three KCl brines with a concentration of $0.17 \cdot 10^{-3}$, $9.39 \cdot 10^{-3}$ and 0.89 Moles/litre respectively. At 4-contacts, the measured resistance (Z') is independent of frequency up to 1 MHz for the two more conductive brines. The other brine, on the other hand, shows constant values of Z' only up to 100 kHz. Then Z' starts decreasing because ω becomes comparable with $\sigma_{dc}/(\varepsilon\varepsilon_0)$ and the dielectric effect becomes important. Z' decreases at a faster rate in the 4-contact measurement because of the additional effect of the inductance of cable connections coupled to the input capacity of the voltmeter, resulting in:

$$Z_M{}' \approx Z_S{}'(1-\omega^2 L_C C_I) - \omega R_C C_I Z_S{}'' \tag{12}$$

There is a relatively good match between the *Z*' values obtained with 4- and 2- contacts at intermediate frequencies. Actually, a constant proportionality factor (of the order of unity) between the two impedances is present: this difference is generated by the slightly different G factors that exist in our cell when measuring at 2- and 4- contacts. At low frequencies, the 2-contact *Z*' is higher because of the polarization of the electrodes. Electrode polarisation effects become progressively smaller as the conductivity of the tested brine gets lower. Note that contact resistances are very low because water conforms perfectly to the electrodes.

Rock. The measurements presented on **Fig.6A** were performed on a carbonate sample (diameter = 1.5 inches; length = 5 cm) with a porosity of 6% and a water saturation of 100%. Basically, here we see the same differences between 2- and 4-contact results that we have seen in the standard load and pure brine. Apparently, at low frequency the 4-contact measurement is not affected by the polarisation of the current electrodes while the 2-contact measurement shows an effect. In the 100 kHz region, both 2- and 4-contact resistances start decreasing (although the 2-contact resistance decreases at a lower rate) due to the effect of contact resistance.

Solving the equivalent circuit and evaluating the electical properties of the sample give the conductivity σ and dielectric constant ε that are presented in **Fig.6B** and **6C**. We show also the σ and ε values obtained at higher frequencies from Frequency Domain Reflectometry (FDR) measurements (see Bona *et al* (2001) for details). FDR is a completely different technique and the fact that the σ and ε spectra join the lower frequency ones in a rather consistent way is an indication of the good quality of the data. As can be seen, in the 4-contact measurement σ is constant up to 10 MHz, while ε decreases with increasing frequency: this decrease in ε occurs at a relatively low rate at intermediate/high frequencies, while at low frequencies (f < 1 Hz) it takes place at a higher rate. This indicates that also in the 4-contact data there is an electrode polarization effect (which cannot be detected in the resistance-frequency plot but is not entirely eliminated). It is interesting to note that not even the Argand diagram, which graphically displays the imaginary part of the measured impedance versus the real part, can detect this weak polarization: as can be seen in **Fig.6D**, the 4-contact curve consists of a single circle arc. Plots with a single circle arc are normally taken as an indication of the absence of interface effects, but this is not the case as we have seen. The 2-contact data, on the contrary, show a circle arc that degenerates to a straight line at low frequencies. These data are affected by a larger electrode polarisation effect and the Argand diagram can reveal it.

Besides the sample discussed in this paper, we have analysed many others, covering different lithologies, petrophysical characteristics and water saturation levels. Most of them exhibited conductivities that are independent of frequency at least up to 100 kHz. This result represents good news for log-analysts, who tend to use the same *m* and *n* exponents to calibrate measurements performed by laterolog and induction tools, without correcting the latter for the dielectric effect. But to us, who observed significant dispersion in the past (Bona et al, 1999; Capaccioli et al, 2000; Bona et al, 2001), the results are quite unexpected. In fact, there is a large body of literature reporting dispersion in rock (Garrouch and Sharma, 1997, Fleury and Liu, 2000; Anderson et al, 2007) in the 1-100 kHz region. How can this discrepancy be resolved? The fact that certain authors present their results in terms of resistivity instead of conductivity may be a factor: according to **Eq.1**, resistivity tends to decrease as frequency increases even though conductivity remains constant. Another factor might be the possibility that certain old experimental data showing dispersion are somehow affected by electrode polarisation, high contact resistances, too large Z_T values or too small Z_I values. Even four-contact data may not be free of errors as we have discussed. All this introduces a fictitious dispersion in the data. This point deserves a lot of attention and needs further work to be fully understood.

GUIDELINES FOR DESIGNING EFFICIENT 4-CONTACT SYSTEMS

A critical aspect of 4-contact measurements is contact resistance. Contrary to what we might believe, contact resistances must be minimized also in 4-contact systems and not only in 2-contact. Since current and voltage electrodes generate the same type of error, all contact resistances should be minimized. High contact resistances translate into errors at high frequencies, and above 10 kHz these errors may be significant. The ratio between the volume of sample that is investigated by the voltage measurements and the volume of sample that is not investigated but conducts current, is another important aspect. It introduces an error at high frequencies too, particularly if the sample has a low conductivity. In order to increase the maximum measurable frequency, three things might be implemented:

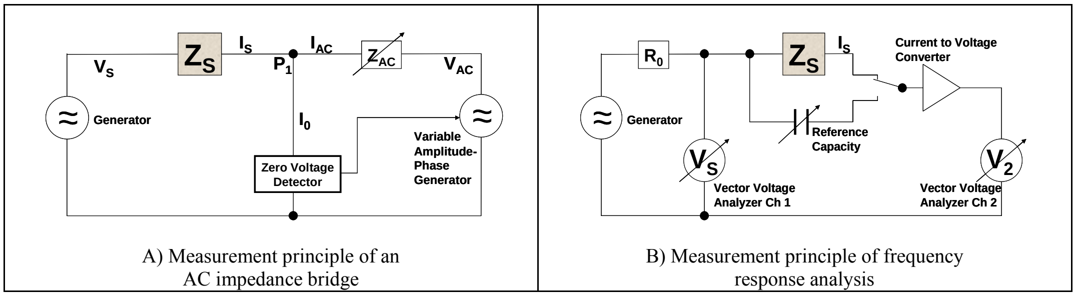
1) *Increasing the voltmeter input impedance* Z_I. The resistance ($R_I = 10^{12}\ \Omega$) of the best instruments found on the market is already very high, but their capacitance C_I can be reduced. Moreover, long cables can add inductance effects to Z_I, which are a possible source of perturbation at high frequency. A system using pre-amplifiers having an input capacity around 2-3 pF and very short coaxial cables with very low values of capacitance per unit length, might have a C_I around 10^{-11} F. That would increase the frequency range by approximately a factor of 10.
2) *Minimizing contact resistances*. In addition to using a brine saturated filter paper between electrode and sample (only for ambient conditions tests), the simplest way to reduce contact resistance is to increase the area of the electrodes. However, while increasing the current electrodes' area does not impose constraints, voltage electrodes that are too large can perturb the electric field configuration and have an effect on the measured ΔV. This is the reason why in the Garrouch and Sharma system the voltage rings are thin.
3) *Reducing the volume of sample that conducts current, but does not contribute to the measured* ΔV. This helps reducing Z_T. However, it should be noted that the voltage electrodes cannot be too close to the current electrodes, because in this case current electrode polarisation might disturb the measurement. Moreover, if the capacitive coupling of voltage and current electrodes is too large, the two electrodes might be at the same potential, making the measurement invalid.

CONCLUSIONS

This study reveals aspects that we believe heretofore were relatively unknown. Contact resistance is a key issue. Four-contact configurations stop giving an accurate response when the impedance between voltage and current electrodes is comparable with the input impedance of the impedance analyzer. That can happen with resistive rocks, in the presence of high contact resistances (> 1 kΩ), but only at high frequencies (> 10 kHz). The distance between current and voltage electrodes is another critical factor. Two-contact measurements are unreliable if the resistance of the sample is comparable with the resistance of the sample/electrode interface. With 2 contacts, contact resistances generate an error that is independent of frequency. Our conclusion is that 4-contact measurements are preferable below 10 kHz, but 2-contact tend to perform better at higher frequencies, especially with resistive samples. Electrode polarisation is another source of errors but it plays a minor role. Even though 2-contact systems are more affected by electrode polarization than 4-contact, if the measurement cell is designed properly the error due to electrode polarization becomes quite small above 100 Hz. Finally, in our experiments we see little dispersion up to 100 kHz. This result would support current log-analysis practices of using fixed *m* and *n* values to interpret logs operating at different frequencies.

REFERENCES

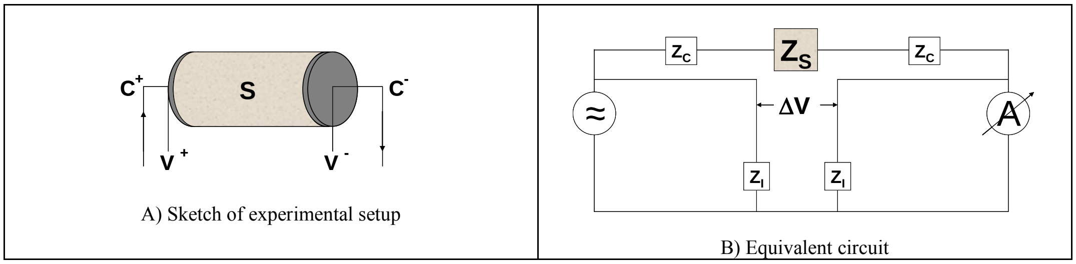
1. Adamec, V., *J. Polym. Sci.*, (1972) **10**, 1277
2. Anderson, B.I., Barber, T.D., Luling, M.G., Rasmus, J., Sen, P.N., Tabanou, J.R. and Haugland, M., ”Observations of large dielectric effects on LWD propagation-resistivity logs”, (2007) paper BB, SWPLA 48th Annual Logging Symposium.
3. Bona, N., Rossi, E., and Capaccioli, S., “Wettability and dielectric constant” (1999) SCA paper 9925.
4. Bona, N., Rossi, E. and Capaccioli, S., “Electrical measurements in the 100 Hz - 10 GHz frequency range for efficient rock wettability determination”, *SPE Journal*, (2001) **6**, 80-88.
5. Capaccioli, S., Lucchesi, M., Casalini, R., Rolla, P.A. and Bona, N., “Influence of wettability on the electrical response of microporous systems”, *Journal of Physics D: Applied Physic*s, (2000) **33**, 1036-1047.
6. Cohen, Y., Davidovich, A. and Riess, I., "Use of high direct current bias to separate electrode from bulk impedance", *Appl. Phys. Lett.*, (1995) **66**, 706.
7. Fleury, M., "Frim: a fast resistivity index measurement method”, (1998) SCA paper 9829.
8. Fleury, M. and Liu, F., "Frequency effect on resistivity index curves using a new method", (2000) SWPLA 41st Annual Logging Symposium.
9. Garrouch, A.A. and Sharma M.M., "Techniques for the measurements of electrical properties of cores in the frequency range 10 Hz to 10 MHz”, (1992) SCA paper 9211.
10. Garrouch, A.A. and Sharma, M.M., "A novel study of the dielectric dispersion in porous media in the frequency range 10 Hz to 10 MHz", (1997) SCA paper 9725.
11. Jonscher, A.K., *Universal Relaxation Law*, Chelsea Dielectric Press, London, (1996)
12. Johnson, J.F. and Cole, R.H., *J. Am. Chem. Soc.*, (1951) **73**, 4536.
13. MacDonald, J.R., *Impedance Spectroscopy*, John Wiley & Sons, Inc., New York (1987).



A) Measurement principle of an AC impedance bridge

B) Measurement principle of frequency response analysis

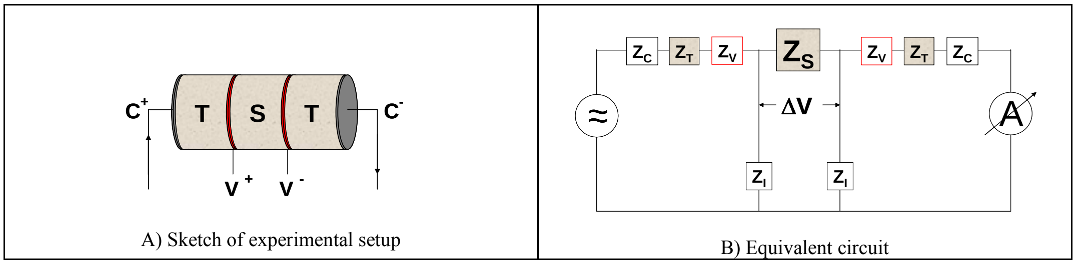
Fig.1: Techniques for measuring the impedance Z_S



A) Sketch of experimental setup

B) Equivalent circuit

Fig.2: Two-Contact systems



A) Sketch of experimental setup

B) Equivalent circuit

Fig.3: Four-Contact systems

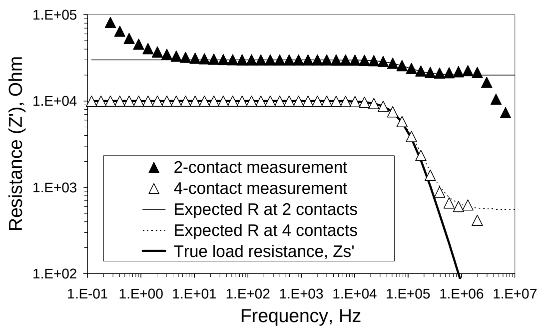


Fig.4: Two- and four-contact resistance measured on a standard load

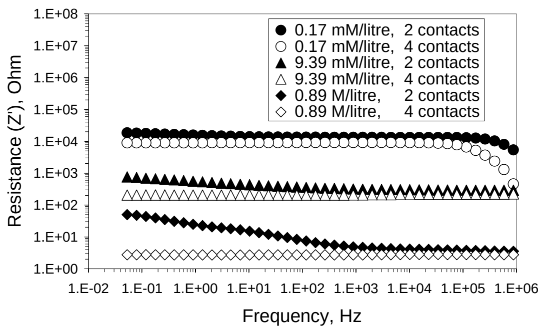


Fig.5: Two- and four-contact resistance measured on two KCl brines

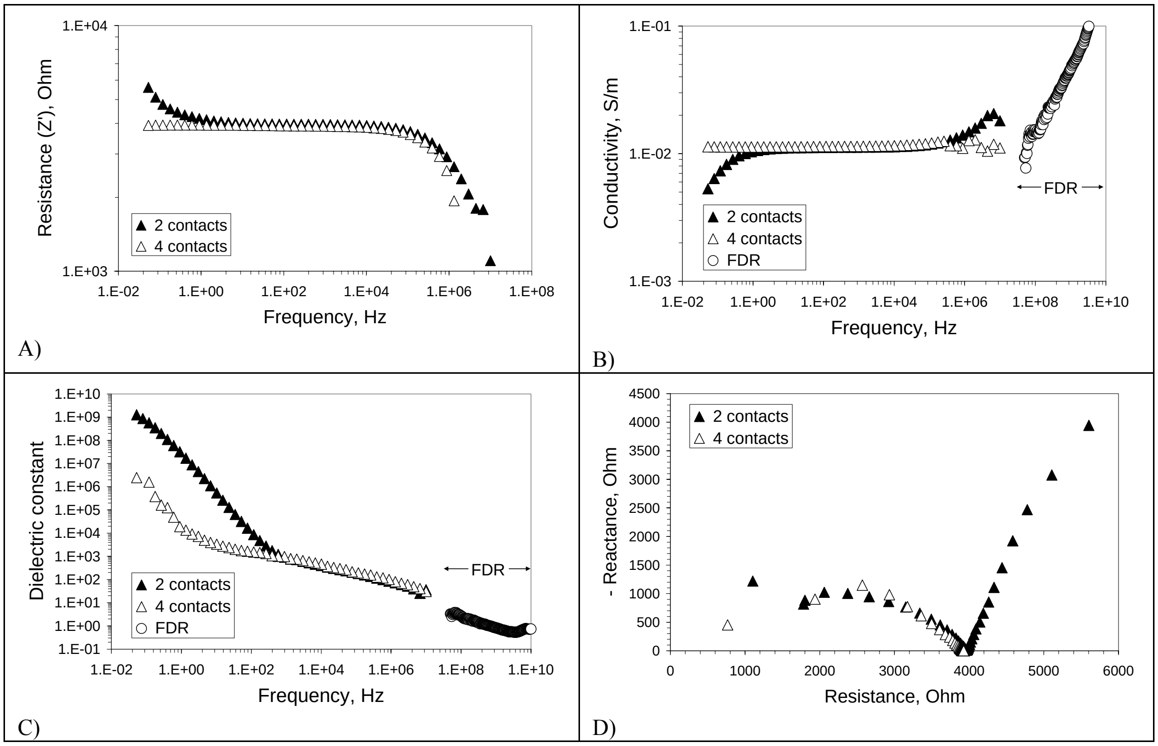


Fig.6: Measurements carried out on a carbonate sample (porosity = 6%, Sw = 100%) as a function of frequency. A) 2- and 4-contact impedances. B) and C) Conductivities and dielectric constants from 2-contact, 4-contact and Frequency Domain Reflectometry measurements. D) Argand plot.