METHOD OF THE CONTROLLED CURRENT REGULATION – LATEROLOG

METODA KONTROLOVANÉ REGULACE PROUDU – LATEROLOG

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Abstract

Every focused electric field can be regulated either with the guard electrodes, or with the central electrode. There exist double conditions of regulation: $U_N = U_M$ and $U_N = 0$. The first one presents Laterolog-normal Log, whereas, the second one is for Laterolog-lateral Log. The focused electric field is characterized by two factors; the coefficient of focusing and the constant of the electrode tool. The coefficient of focusing determines whether focusing is positive or negative, whereas, the constant of tool is positive only. The best variances of the electrode tool are for the 9-electrode Laterolog, the 7-electrode Laterolog and the 3-electrode Laterolog. Regulation is always made with the guard electrodes for condition that $U_N = U_M$. It holds for standardly-manufactured equipments.

Abstrakt

Každé usměrněné elektrické pole může být regulováno buď stínícími elektrodami, nebo centrální elektrodou. Existují dvojí podmínky regulace: $U_N = U_M$ a $U_N = 0$. První představuje potenciálové měření Laterologu, zatímco ta druhá gradientové měření Laterologu. Usměrněné elektrické pole charakterizují dva faktory: koeficient fokusace a konstanta hlubinné sondy s elektrodami. Koeficient fokusace určuje, zda je fokusace pozitivní či negativní, ale konstanta hlubinné sondy musí být jen pozitivní. Nejlepšími variantami elektrodového uspořádání hlubinné sondy je devítielektrodový, sedmielektrodová a tříelektrodový Laterolog. Reguluje se vždy stínícími elektrodami za podmínky, že $U_N = U_M$. To platí pro standardně vyráběná zařízení.

Keywords

focused electric field, the coefficient of focusing, the constant of electrode tool, the controlled current regulation, well-logging

Klíčová slova

usměrněné elektrické pole, koeficient fokusace, konstanta hlubinné sondy s elektrodami, kontrolovaná regulace proudu, karotáž

1 Introduction

This theory published by MARUŠIAK (1968) and (1969) seemed to be very hopeful, however, due to interpretation of well-logging data registered it has been found that the focused electric field cannot be simulated virtually on a computer, but, such focused electric field must really exist. The failure of this way of interpretation was interpreted as an error of theory and next investigation had been abandoned. Leaving away out of theory published by MARUŠIAK was not the best decision, because the theory of controlled current regulation remains permanently alive and informative. The theory offers us various arrays of electrodes, different focusing and exact and simple calibration of the Laterolog methods. This paper has aim to prove that.

2 Shortly about Laterolog

Focused electric methods began to be used when high salinity of mud obstructed to electric direct current to penetrate inside of geologic formation. The electric current flew almost all by highly conductive mud. Operator registered only resistivity of mud. It was reason for development of new generation of electric equipments on basis of focusing electric field.

There were formed new electrode arrays of tool. Central current electrode received two and more guard electrodes having the same polarity as the central one. It is important for focusing of electric field that is formed like wide fantail entering perpendicularly into the borehole wall. This effect is made by the guard electrodes being close to central current electrode. Next guard electrodes make form and range of electric field. If they have an inverse polarity than the feeding (central) electrode the current contours are intensively curved towards the tool; such tools have shallower range what is important for study of invasion zone.

The first equipments were constructed on basis of direct current. The one is still used, however, in the recent time prevails using of altering current. The direct current has only zero-frequency, there is impossible to register simultaneously more currents having various frequencies, has high noise and high Groningen effect, when thin permeable beds with high resistivity make force the current contours to return and flow through conductive mud. Such thin beds are little distinct, sometimes they are not there and concurrently can be the source of hydrocarbons.

In praxis there began to be used three variances of Laterolog: Pseudolaterolog which has 9 electrodes, Classical Laterolog with 7 electrodes and, finally, Guard Log having 3 electrodes. Very soon there was formed necessity to register Pseudolaterolog and Classical Laterolog simultaneously; therefore Dual Laterolog (DLL) created. It was on basis of the direct current. Two all identical the electrode array tools with 9 electrodes were jointed one another and so operator was able to register two curves at the same time. Each of arrays has different result thanks to the peripheral electrodes B and B´. The variance DLL-d (deep range) has these with the polarity as the feeding electrode A and the guard electrodes E and E´ have. The contours going out from the electrodes enter almost perpendicularly into the borehole wall. The next variance DLL-s (shallow range) has the same array but electrodes B and B´ have inverse polarity as electrodes A, E and E´. It has consequence that the contour fantail of electrode A is more curved and contours going out of electrodes E and E´ go rapidly to electrodes B and B´.

Dual Laterolog presented progress but has too failings. Beside Groningen effect and high noise there was an influence of contact resistance being between both tools and too between tool and cable. And the main; because both tools are enough long it is impossible to register both curves in the last metres over the borehole bottom. This all was why the altering current is more and more used. In such case you can register on basis frequency spectrum several currents simultaneously and each of them can be focused in other way and degree.

The lower frequency presents deeper range, the higher frequency shallower range. If you measure simultaneously with 5 frequencies it offers interpretation such factors as R_m, R_{x0}, R_t and D_i are. Moreover, the Groningen effect is almost eliminated, the curves are divided into more thin beds, and influence of contact resistance is none. And the all is done with the only electrode array.

In the recent time it is very often used DDL on basis altering current. It works with two frequencies, low for DLL-d and high for DDL-s. The registering is supplemented by record of Microlaterolog. The most complete equipment in the recent time is the one of firm Schlumberger remarked as High-Resolution Laterolog Array tool, HRLA Schlumberger. It uses altering currents having 6 frequencies, Mode 0, Mode1…, and Mode 5. Each of currents is in other way focused. The equipment registers simultaneously all frequency spectrums. The records emphasize thin beds and one can easy interpret factors as R_m, R_{x0}, R_t and D_i are. Also is possible to make 3d-display of the complete borehole. From the next many equipments is the interesting one remarked like the Spherically Focused Log (SFL) determined for shallower range, mainly for interpretation R_{x0}. The tool has again 9 electrodes, focusing is done not to be too deep.

From the older authors I can mention paper by CHEN, Y.H., CHEW, W.C. AND ZHANG, G.J. (1998), where are studied new arrays of Laterolog. The next authors concentrated their effort over investigation which has something common with horizontal drilling. They are ANDERSON, B., BARBER, T. AND GIANZERO, S. (2001), further, YANG, W., TORRES-VERDÍN, C., AKKURT, R., AL-DOSSARI, S., AL-TOWIJRI, A. AND ERSOZ, H. (2007). The Groningen effect was studied by LACOUR-GUYET, P. (1981). It needs to say that within inclined and horizontal drilling interpretation of Laterolog must reply on new geological factors which for horizontal formations played rather marginal role. However, during inclined drilling it is completely new situation. Here is big influence of anisotropy for resistivity, higher influence has invasion zone, adjacent rocks and too angle being between the borehole axis and formation. Of course, more is influenced Laterolog with deep range than with shallow range. More is in papers of the above authors.

I should like to say that all me known works supposed always real focusing of electric field; MARUŠIAK, I. had selected false way when expected real focusing of non-focused curves through computer. On the other side principles of the controlled current regulation are permanently interesting and can a lot of say to methods based on focusing of electric field. It holds not only for focusing using direct current, but maybe too for focusing with altering current. I think so.

3 Theory of the controlled current regulation

Very important is the electrode tool. Number of electrodes can be various. There can be 9 electrodes there and then it is the 9-electrode Laterolog also called as Pseudo-Laterolog. If the electrode tool has 7 electrodes only – it will be the 7-electrode Laterolog known as Classical-Laterolog. And for 3 electrodes only, you will get the 3-electrode Laterolog – Guard-Log. It is possible to identify the current and potential electrodes as one common electrode too. All mentioned variances are depicted in figures 1, 2 and 3.

The electrode tool is characterized by two factors. The first is the coefficient of focusing remarked as η. This can be positive or negative. It holds that $\eta > 0$ or $\eta < 0$. The positive value presents identical polarity of the feeding electrode and the guard electrodes. Direction of the electric contours of field is perpendicular to the borehole wall what means that an influence of the salt mud is restricted.

The negative value presents that direction of electric contours is parallel to the electrode tool; the electric field is collected into nearest area around the tool where the salt mud is dominating. We register in such case much lower values.

The second factor is the constant of the electrode tool. This can be positive only as I think; negative value can present an error of enumeration, however, can be too indication of some unknown phenomenon. We remark it like K. Both factors K and η are dependent on partial constants. They are four: k_{AM}, k_{AN}, k_{EM} and k_{EN}. This holds for the 7-electrode Laterolog and for the 3-electrode Laterolog having their electrode B on the earth surface. For 9-electrode Laterolog there are moreover constants k_{BM}, k_{BN} .

4 Variances of the 9-electrode Laterolog

The 9-electrode Laterolog named as Pseudo-Laterolog has electrode B and B’ on the electrode tool and that is why that the partial constants are six. To the mentioned four ones there are next two remarked as k_{BM} and k_{BN}. All partial constants are positive only. Their calculation is directed with formulas being different for the case when there is a distance between the current and potential electrodes and for the case when both above electrodes present the only common electrode.

Theory distinguishes two conditions of regulation. The first is that $U_N = U_M$ and the second is $U_N = 0$. Both can be realized in two ways of regulation. The first one is that the current electrode A is the feeding one, whereas, electrodes E and E’ present the guard electrodes. The second one is that electrodes E and E’ are feeding electrodes and the electrode A is the guard one.

For condition $U_N = U_M$ it holds that you register the voltage being between electrode M and electrode N_0 on the earth surface. Condition $U_N = 0$ says that you register voltage between M and N electrodes on the tool. It seems condition $U_N = U_M$ presents Laterolog-normal Log, whereas, condition $U_N = 0$ rather Laterolog-lateral Log.

4.1 The 9-electrode Laterolog – regulation by the guard electrodes on condition $U_N = U_M$

It needs to define the voltages being on electrodes M and N.

$$U_M = R \times \frac{I_A}{k_{AM}} + R \times \frac{I_E}{k_{EM}} - R \times \frac{I_A}{k_{BM}}\text{, and} \tag{1}$$

$$U_N = R \times \frac{I_A}{k_{AN}} + R \times \frac{I_E}{k_{EN}} - R \times \frac{I_A}{k_{BN}}. \tag{2}$$

Both equations will be adjusted on this form:

$$U_M = R \times I_A \times \left\{ \left(k_{AM}^{-1} - k_{BM}^{-1} \right) + k_{EM}^{-1} \times \left(\frac{I_E}{I_A} \right) \right\}\text{, and} \tag{3}$$

$$U_N = R\times I_A \times\left\{ \left(k_{AN}^{-1} - k_{BN}^{-1}\right) + k_{EN}^{-1}\times\left(\frac{I_E}{I_A}\right)\right\}, \tag{4}$$

where R = the resistivity of rocks [Ωm],

I_A = the feeding current streaming through electrodes A and B [mA], and

I_E = the regulative current flowing through electrodes E and E’ [mA].

The coefficient of focusing η is defined as current ratio:

$$\eta = \frac{I_E}{I_A}. \tag{5}$$

Due to formula (5) it is possible to record the regulative current like this:

$$I_E = \eta \times I_A. \tag{6}$$

The current I_A is constant and stabilized. The current I_E is constant too, because simultaneous condition that $U_N = U_M$ forms coefficient of focusing like constant. Equations (3) and (4) will change their form on this:

$$U_M = R\times I_A \times\left\{\left(k_{AM}^{-1} - k_{BM}^{-1}\right) + k_{EM}^{-1}\times\eta\right\}, \text{ and} \tag{7}$$

$$U_N = R\times I_A \times\left\{\left(k_{AN}^{-1} - k_{BN}^{-1}\right) + k_{EN}^{-1}\times\eta\right\}. \tag{8}$$

If you substitute those formulas into condition $U_N = U_M$, you will receive factor η.

$$\eta = \left(\frac{k_{AN}^{-1} - k_{AM}^{-1}}{k_{EM}^{-1} - k_{EN}^{-1}}\right) + \left(\frac{k_{BM}^{-1} - k_{BN}^{-1}}{k_{EM}^{-1} - k_{EN}^{-1}}\right). \tag{9}$$

Now, it is the resistivity R that needs to be expressed. It is made with the help of voltage U_M registered between electrode M on the tool and electrode N_0 being on the earth surface.

$$R = K\times\frac{U_M}{I_A}, \text{ and} \tag{10}$$

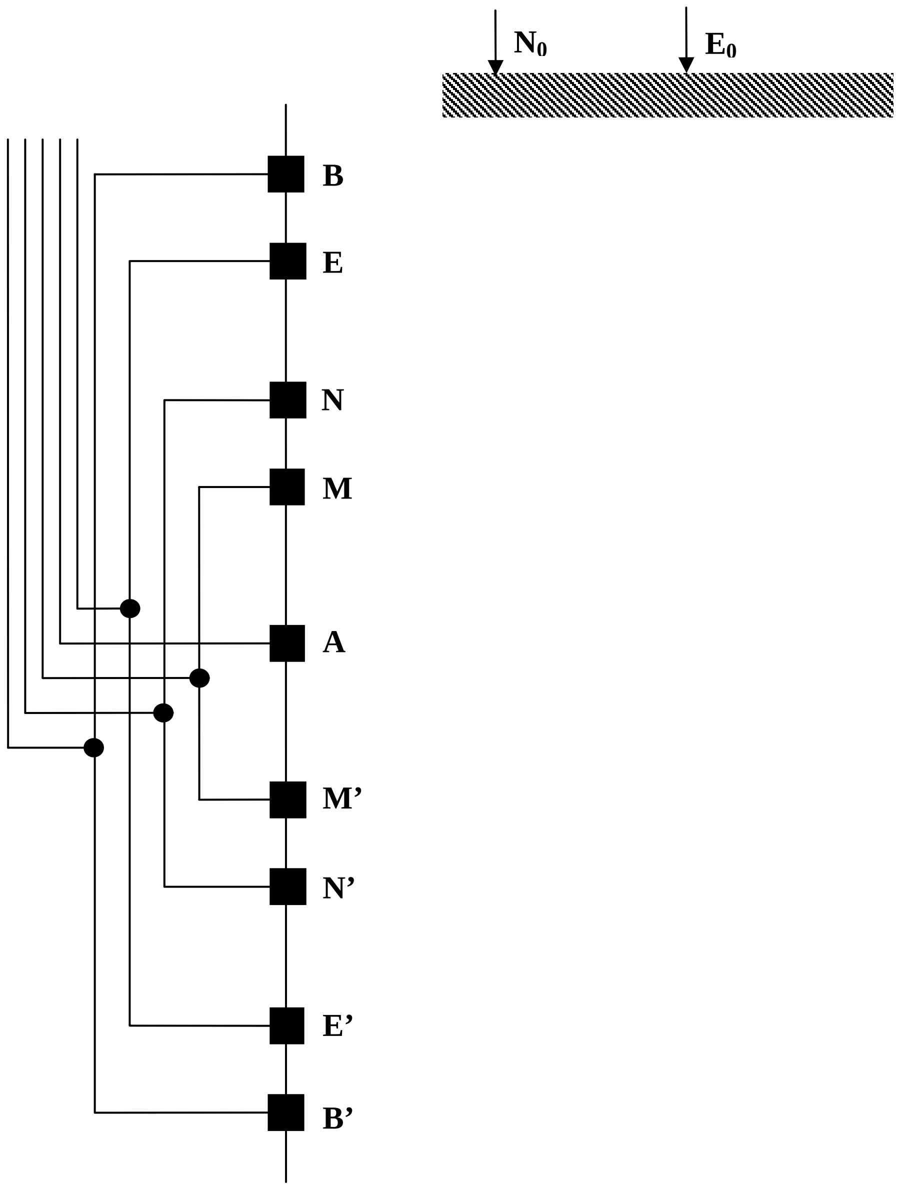

Fig.1 Scheme of the electrode tool of the 9-electrode Laterolog

$$K = \left\{ \left(k_{AM}^{-1} - k_{BM}^{-1} \right) + k_{EM}^{-1} \times \eta \right\}^{-1}, \tag{11}$$

where K = the constant of the electrode tool for Pseudo-Laterolog.

From fig.1 it is confirmed that estimation of the size for each of partial constants is directed with formula:

$$k = 4\pi \times L\,, \tag{12}$$

where L = the electrode spacing, i.e., the distance between centres of the current and potential electrodes expressed in [m].

Now, all is about spacing of partial constants. It holds that:

$$\overline{\mathrm{AM}} < \overline{\mathrm{AN}} \Rightarrow k_{AM} < k_{AN}\,,\ \overline{\mathrm{BM}} > \overline{\mathrm{BN}} \Rightarrow k_{BM} > k_{BN}\ ,\ \overline{\mathrm{EM}} > \overline{\mathrm{EN}} \Rightarrow k_{EM} > k_{EN} \text{ and } \overline{\mathrm{AM}} < \overline{\mathrm{BM}} \Rightarrow k_{AM} < k_{BM}\,. \tag{13}$$

Owing to inequalities (13) you get next relations:

$$k_{AM}^{-1} > k_{AN}^{-1}\ ,\ k_{BM}^{-1} < k_{BN}^{-1}\ ,\ k_{EM}^{-1} < k_{EN}^{-1} \text{ and } k_{AM}^{-1} > k_{BM}^{-1}\ . \tag{14}$$

Next inequalities are these:

$$\frac{k_{AM}}{k_{AN}} < 1,\ \frac{k_{BM}}{k_{BN}} > 1 \text{ and } \frac{k_{EM}}{k_{EN}} > 1\,. \tag{15}$$

Inequalities (14) enable us to express the following relations:

$$\left(k_{AN}^{-1} - k_{AM}^{-1} \right) < 0,\ \left(k_{BM}^{-1} - k_{BN}^{-1} \right) < 0\ ,\ \left(k_{EM}^{-1} - k_{EN}^{-1} \right) < 0 \text{ and } \left(k_{AM}^{-1} - k_{BM}^{-1} \right) > 0\,. \tag{16}$$

Then hold following relations:

$$\frac{k_{AN}^{-1} - k_{AM}^{-1}}{k_{EM}^{-1} - k_{EN}^{-1}} > 0 \text{ and } \frac{k_{BM}^{-1} - k_{BN}^{-1}}{k_{EM}^{-1} - k_{EN}^{-1}} > 0.$$

From these it results that $\eta > 0$ and $K > 0$, too.

This way of regulation is best of all. The electric contours are directed perpendicular to the borehole wall. However, because of electrodes B and B’ being on the electrode tool focusing of electric field is not too deep. The characteristic section of electric contours looks like a bud of tulip having relatively low penetration into bed. Therefore Pseudo-Laterolog is used for investigation of invasion zone.

4.2 The 9-electrode Laterolog – regulation by the guard electrodes on condition $U_N = 0$

We use the same equations (7) and (8) but condition for regulation is $U_N = 0$. Then coefficient of focusing will be negative and its form derived is as follows:

$$\eta = -\,k_{EN} \times \left(k_{AN}^{-1} - k_{BN}^{-1} \right)\ . \tag{17}$$

$$\overline{AN} < \overline{BN} \Rightarrow k_{AN} < k_{BN} \ \text{ and } \ \overline{AM} < \overline{BM} \Rightarrow k_{AM} < k_{BM}\ .$$

Then you can have that

$k_{AN}^{-1} > k_{BN}^{-1}$ and $k_{AM}^{-1} > k_{BM}^{-1}$.

It results in the relations:

$\left(k_{AN}^{-1} - k_{BN}^{-1} \right) > 0$ and $\left(k_{AM}^{-1} - k_{BM}^{-1} \right) > 0$.

That confirms that η < 0. For the tool constant we start from formula:

$$K = \left\{ \left(k_{AM}^{-1} - k_{BM}^{-1} \right) + k_{EM}^{-1} \times \eta \right\}^{-1} = \left\{ \left(k_{AM}^{-1} - k_{BM}^{-1} \right) - \frac{k_{EN}}{k_{EM}} \times \left(k_{AN}^{-1} - k_{BN}^{-1} \right) \right\}^{-1}. \tag{18}$$

In this case it is dilemma, because mathematically the tool constant can be positive, negative or even zero. And all is defined with spacing of partial constants. So you can differ:

- For $K > 0$ holds that $\left(k_{AM}^{-1} - k_{BM}^{-1} \right) > \frac{k_{EN}}{k_{EM}} \times \left(k_{AN}^{-1} - k_{BN}^{-1} \right)$.
- For $K = 0$ holds that $\left(k_{AM}^{-1} - k_{BM}^{-1} \right) = \frac{k_{EN}}{k_{EM}} \times \left(k_{AN}^{-1} - k_{BN}^{-1} \right)$.
- For $K < 0$ holds that $\left(k_{AM}^{-1} - k_{BM}^{-1} \right) < \frac{k_{EN}}{k_{EM}} \times \left(k_{AN}^{-1} - k_{BN}^{-1} \right)$.

As the tool constant ought to be always positive, I decided for condition that K > 0. However, I am not all sure whether there is not some phenomenon being reflected with K < 0. It could depend in a way with the electrode array of tool and focusing of electric field.

The fact that η < 0 means, too, the regulative current has contradictory polarity to I_A. Simply speaking, the current I_E flows in the contradictory direction than is direction for the current I_A. It holds again that:

$$I_E = \eta \times I_A \ldots \text{for } \eta < 0. \tag{19}$$

Consequence of that is the electric contours of field are collected in the area close to electrode tool in the direction being parallel to the electrode tool. The investigated area is mud and invasion zone, in particular. Best registration is for fresh and half-fresh mud; worse it is for salt mud. The feeding current I_A is stabilized and the regulative current I_E is then stabilized too. You register voltage being between electrodes M and N on condition $U_N = 0$; both are on the electrode tool. Such registration can be remarked as Laterolog-lateral Log.

4.3 The 9-electrode Laterolog – regulation by the central electrode on condition $U_N = U_M$

The central electrode of tool is electrode A. In this case the feeding electrodes are E and E’ and the guard electrode is A; in fact it is actually A, A’ and further E. The basic equations remain those remarked as (1) and (2). These have to be adjusted in other way, because the feeding current flows through electrodes E and E’.

$$U_M = R\times I_E\ \times\left\{\ k_{EM}^{-1} + \left(\ k_{AM}^{-1} - k_{BM}^{-1}\ \right)\times\left(\ \frac{I_A}{I_E}\ \right)\right\}, \text{ and} \tag{20}$$

$$U_N = R\times I_E\ \times\left\{\ k_{EN}^{-1} + \left(\ k_{AN}^{-1} - k_{BN}^{-1}\ \right)\times\left(\ \frac{I_A}{I_E}\ \right)\right\}\ . \tag{21}$$

If regulation is made with electrode A, the coefficient of focusing will be defined like this:

$$\eta = \frac{I_A}{I_E}\,. \tag{22}$$

This ratio has always in numerator the regulative current; it is I_A.

$$I_E = \eta\times I_A \ldots \text{for } \eta > 0\,. \tag{23}$$

Expression (23) will be substituted into formulas (20) and (21):

$$U_M = R\times I_E\ \times\left\{\ k_{EM}^{-1} + \left(\ k_{AM}^{-1} - k_{BM}^{-1}\ \right)\times\eta\ \right\}, \text{ and} \tag{24}$$

$$U_N = R\times I_E\ \times\left\{\ k_{EN}^{-1} + \left(\ k_{AN}^{-1} - k_{BN}^{-1}\ \right)\times\eta\ \right\}\ . \tag{25}$$

After implement of condition $U_N = U_M$ you can express the coefficient of focusing:

$$\eta = \frac{\left(\ k_{EM}^{-1} - k_{EN}^{-1}\ \right)}{\left(\ k_{AN}^{-1} - k_{BN}^{-1}\ \right) - \left(\ k_{AM}^{-1} - k_{BM}^{-1}\ \right)} \ = \ \frac{\left(\ k_{EM}^{-1} - k_{EN}^{-1}\ \right)}{\left(\ k_{AN}^{-1} - k_{AM}^{-1}\ \right) + \left(\ k_{BM}^{-1} - k_{BN}^{-1}\ \right)}\ . \tag{26}$$

Formula (26) is reciprocal to formula (9). That presents that $\eta > 0$.

Now, you are able to write the resistivity registered on condition regulation $U_N = U_M$.

$$R = K\times\frac{U_M}{I_E}\ , \text{ and} \tag{27}$$

$$K = \ \left\{\ k_{EM}^{-1} + \left(\ k_{AM}^{-1} - k_{BM}^{-1}\ \right)\times\eta\ \right\}^{-1}. \tag{28}$$

We register voltage U_M being between electrodes M and N_0. This record is named as Laterolog-normal Log. New way of regulation presents relatively deep penetration of electric contours into rocks; however, the way of regulation, when the feeding electrode is A, the guard electrodes is E and E’, is better. This way of regulation means that electric contours enter perpendicularly to the borehole wall, nevertheless, the bunch of contours is widely open, namely, in direction to electrodes B and B’, whereas, around the central electrode the contours are directed perpendicularly inwards the borehole in narrow bunch. You can probably expect bigger influence of invasion zone and mud.

4.4 The 9-electrode Laterolog – regulation by the central electrode on condition $U_N = 0$

It hold formulas (22), (23), (24) and (25); however, the condition of regulation is $U_N = 0$. The coefficient of focusing is following:

$$\eta = -\frac{1}{k_{EN} \times \left(k_{AN}^{-1} - k_{BN}^{-1} \right)} . \tag{29}$$

Formula (29) is reciprocal value of the formula (17); it means that $\eta < 0$. The resistivity of rocks is defined with the help of equations (27) and (28):

$$R = K \times \frac{U_M}{I_E} \text{, and}$$

$$K = \left\{ k_{EM}^{-1} + \left(k_{AM}^{-1} - k_{BM}^{-1} \right) \times \eta \right\}^{-1} . \tag{30}$$

The constant K is again positive. There is registered voltage U_M being between electrodes M and N on condition $U_N = 0$; both on the tool. This log can be remarked as Laterolog-lateral Log.

It ought to be remembered that this registration is not too convenient for the boreholes with salt mud. Most of electric contours of field are concentrated into close surroundings of tool, even if they too penetrate into rocks. Their direction tries to be parallel to the tool. Such way of focusing can be classified as an anti-focusing. And this area is domain of mud; if mud is salt you will record very low values.

5 Variances of the 7-electrode Laterolog

Scheme of the electrode tool is a partial case of Pseudo-Laterolog; fig.2. The electrode B is not on the electrode tool, but, on the earth surface. This is infinitely far of the electrode tool and just that is why that there holds condition:

$$k_{BM}^{-1} = k_{BN}^{-1} = 0 . \tag{31}$$

The above condition results from formula (12). The all former formulas will get easier. We have again four variances of the 7-electrode Laterolog; for two various ways of regulation $U_N = U_M$ and $U_N = 0$ and for an electrode exchange. The variance of 7- electrode Laterolog is classical one and too the deepest of all. The current contours penetrate very deep into bed and because they are perpendicular to the borehole wall an influence of salt mud is minimal; one can say that none.

5.1 The 7-electrode Laterolog – regulation by the guard electrodes on condition $U_N = U_M$

As electrode B is located on the earth surface penetration of the electric contours perpendicular to the borehole wall is much deeper than it is for Pseudo-Laterolog. It is bunch of electric contours mutually almost parallel entering perpendicularly into rocks. You register an influence of the non-invaded zone. Effect of invasion zone and, namely, of mud is suppressed. This presents the best variances of all four. The formulas needed for calculation are these:

$$\eta = \left(\frac{k_{AN}^{-1} - k_{AM}^{-1}}{k_{EM}^{-1} - k_{EN}^{-1}} \right), \qquad (32)$$

$$R = K \times \frac{U_M}{I_A}, \text{ and}$$

$$K = \left\{ k_{AM}^{-1} + k_{EM}^{-1} \times \eta \right\}^{-1}. \qquad (33)$$

The coefficient of focusing is positive, η > 0; the constant of electrode tool is positive too, K > 0.

5.2 The 7-electrode Laterolog – regulation by the guard electrodes on condition $U_N = 0$

For this variance we shall use the adjusted formulas:

$$\eta = -\frac{k_{EN}}{k_{AN}}, \qquad (34)$$

$$R = K \times \frac{U_M}{I_A}, \text{ and}$$

$$K = \left\{ k_{AM}^{-1} + k_{EM}^{-1} \times \eta \right\}^{-1}.$$

It holds that η < 0 and K > 0.

5.3 The 7-electrode Laterolog – regulation by the central electrode on condition $U_N = U_M$

This variance is characterized by these formulas:

$$\eta = \frac{\left(k_{EM}^{-1} - k_{EN}^{-1} \right)}{\left(k_{AN}^{-1} - k_{AM}^{-1} \right)}, \qquad (35)$$

$$R = K \times \frac{U_M}{I_E}, \text{ and } \; K = \left\{ k_{EM}^{-1} + k_{AM}^{-1} \times \eta \right\}^{-1}. \qquad (36)$$

It is valid that η > 0 and K > 0.

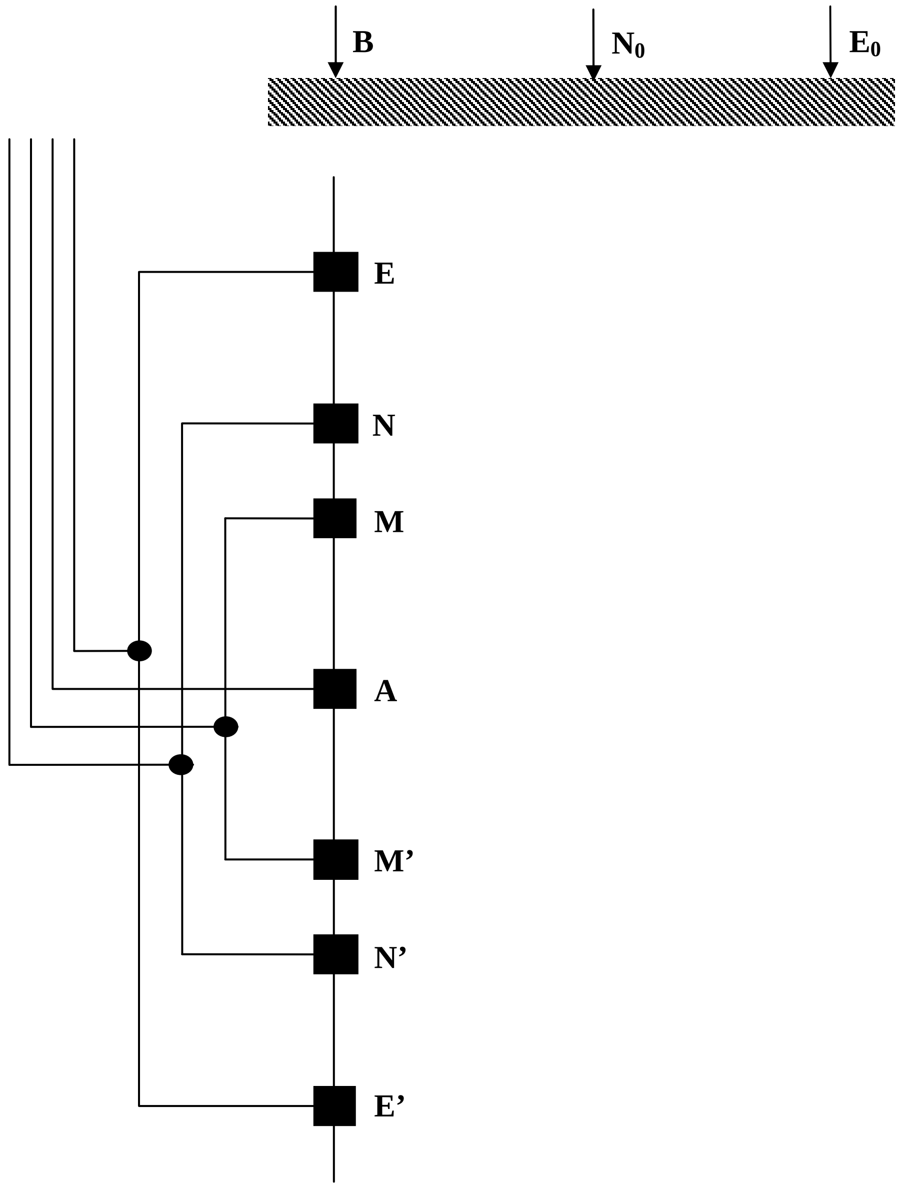

Fig.2 Scheme of the electrode tool of the 7-electrode Laterolog

5.4 The 7-electrode Laterolog – regulation by the central electrode on condition $U_N = 0$

We attain these formulas:

$$\eta = -\frac{k_{AN}}{k_{EN}}, \tag{37}$$

$$R = K \times \frac{U_M}{I_E}, \text{ and}$$

$$K = \left\{ k_{EM}^{-1} + k_{AM}^{-1} \times \eta \right\}^{-1}.$$

It holds again that $\eta < 0$ and $K > 0$.

6 Variances of the 3-electrode Laterolog

The electrodes B and N_0 remain on the earth surface. Electrodes A and M are identical and electrodes E and N are too. It is depicted in fig.3. There exist again four possible variances when the variance characterized by registration with the help of the guard electrodes on condition $U_N = U_M$ is best of all. As there hold again that $k_{AM} < k_{AN}$,and $k_{EM} > k_{EN}$ the inequalities (14) and (15) are valid too. In spite of that the 3-electrode array tool has its uniqueness.

As you see in fig.3 there holds that A≡M, E≡N and E´≡N´. That presents that $\overline{AM} = 0 \Rightarrow$ however $k_{AM} \neq 0$. It is similarly with electrodes E and E´. There hold $\overline{EN} = \overline{EN'} = 0 \Rightarrow$ however $k_{EN} \neq 0$. Both partial constants are not dependent on the distance between them, but only on length and diameter of electrode. If they have not the same dimensions then $k_{AM} \neq k_{EN}$.

Next uniqueness is that $\overline{AN} = \overline{EM}$, however, because electrodes E and E´are much longer than electrode A, there holds that $k_{AN} \neq k_{EM}$. Both mentioned particularities influence the following counting.

6.1 The 3-electrode Laterolog – regulation by the guard electrodes on condition $U_N = U_M$

Here hold formulas (10), (32) and (33). However, because there are identities A ≡ M and E ≡ N calculation of partial constant will use adjusted formulas in comparison to Laterolog for 7 or 9 electrodes. This variance belongs to best one of all four.

$$\eta = \left(\frac{k_{AN}^{-1} - k_{AM}^{-1}}{k_{EM}^{-1} - k_{EN}^{-1}} \right) = \left(\frac{k_{AM}^{-1} - k_{AN}^{-1}}{k_{EN}^{-1} - k_{EM}^{-1}} \right),$$

$$R = K \times \frac{U_M}{I_A}, \text{ and } K = \left\{ k_{AM}^{-1} + k_{EM}^{-1} \times \eta \right\}^{-1}.$$

It is valid that $\eta > 0$ and $K > 0$.

6.2 The 3-electrode Laterolog – regulation by the guard electrodes on condition $U_N = 0$

This variance is characterized with formulas (10), (33) and (34).

$$\eta = -\frac{k_{EN}}{k_{AN}}, \; R = K \times \frac{U_M}{I_A}, \text{ and } K = \left\{ k_{AM}^{-1} + k_{EM}^{-1} \times \eta \right\}^{-1}.$$

It holds that $\eta < 0$ and $K > 0$.

6.3 The 3-electrode Laterolog – regulation by the central electrode on condition $U_N = U_M$

For this variance there are valid formulas (27), (35) and (36).

$$\eta = \frac{\left(k_{EM}^{-1} - k_{EN}^{-1} \right)}{\left(k_{AN}^{-1} - k_{AM}^{-1} \right)} = \left(\frac{k_{EN}^{-1} - k_{EM}^{-1}}{k_{AM}^{-1} - k_{AN}^{-1}} \right), \quad R = K \times \frac{U_M}{I_E}, \text{ and}$$

$$K = \left\{ k_{EM}^{-1} + k_{AM}^{-1} \times \eta \right\}^{-1}.$$

It is valid that $\eta > 0$ and $K > 0$.

6.4 The 3-electrode Laterolog – regulation by the central electrode on condition $U_N = 0$

Here are formulas used for calculation: (27), (36) and (37).

$$\eta = -\frac{k_{AN}}{k_{EN}},$$

$$R = K \times \frac{U_M}{I_E}, \text{ and}$$

$$K = \left\{ k_{EM}^{-1} + k_{AM}^{-1} \times \eta \right\}^{-1}.$$

It holds again that $\eta < 0$ and $K > 0$.

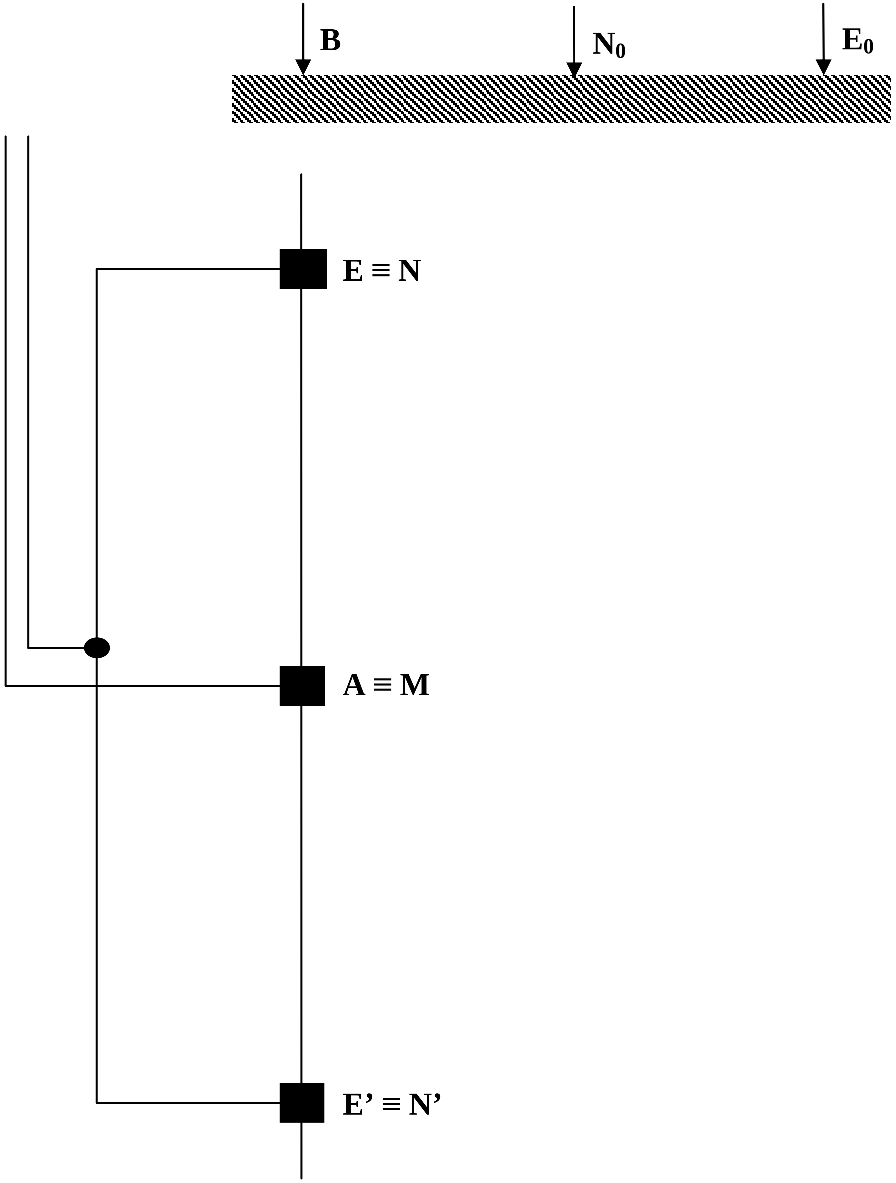

Fig.3 Scheme of the electrode tool of the 3-electrode Laterolog

7 Formulas used for calculation of the partial constants

The derived formulas were published in other paper. They suppose the cylindrical electrodes which are used for Laterolog, induced polarization or for static and selective SP-potentials. If the current and potential electrodes **are not identical**, we shall use such formulas:

$$\left(\frac{k}{a_L}\right)=\frac{1}{F_1+F_2}\,, \tag{38}$$

$$F_1=\frac{1}{8}\times\left(\frac{n}{a_n}\right)^{-1}\times\left\{\ln\left[\left(\frac{\sqrt{2}}{2}\right)\times\sqrt{\left(\frac{2L}{a_L}+\frac{m}{a_m}\right)^2+1}+\frac{n}{a_n}\right]-\ln\left[\left(\frac{\sqrt{2}}{2}\right)\times\sqrt{\left(\frac{2L}{a_L}+\frac{m}{a_m}\right)^2+1}-\frac{n}{a_n}\right]\right\}, \tag{39}$$

$$F_2=\frac{1}{16}\times\left(\frac{n}{a_n}\right)^{-1}\times\left\{\mathrm{Argsinh}\left[\left(\frac{\sqrt{2}}{2}\right)\times\sqrt{\left(\frac{2L}{a_L}+\frac{m}{a_m}\right)^2+1}+\frac{n}{a_n}\right]-\mathrm{Argsinh}\left[\left(\frac{\sqrt{2}}{2}\right)\times\sqrt{\left(\frac{2L}{a_L}+\frac{m}{a_m}\right)^2+1}-\frac{n}{a_n}\right]\right\} \tag{40}$$

where L = distance being between both centres of the current and potential electrodes [m],
m = length of the current electrode [m],
n = length of the potential electrode [m],
a_L = diameter of the tool body [m],
a_m = diameter of the current electrode [m], and
a_n = diameter of the potential electrode [m].

Those six variables can be reduced only on three ones. They are these:

(L/a_L) = slenderness ratio of the electrode tool,
(m/a_m) = slenderness ratio of the current electrode, and
(n/a_n) = slenderness ratio of the potential electrode.

All new variables are dimensionless.

If the current and potential electrodes **are identical**, we shall attain the following formulas:

$$\left(\frac{k}{a_n}\right)=\frac{1}{F_1+F_2}\,, \tag{41}$$

$$F_1=\frac{1}{8}\times\left(\frac{n}{a_n}\right)^{-1}\times\left\{\ln\left[\left(\frac{\sqrt{2}}{2}\right)\times\sqrt{\left(\frac{n}{a_n}\right)^2+1}+\frac{n}{a_n}\right]-\ln\left[\left(\frac{\sqrt{2}}{2}\right)\times\sqrt{\left(\frac{n}{a_n}\right)^2+1}-\frac{n}{a_n}\right]\right\}, \tag{42}$$

$$F_2 = \frac{1}{16} \times \left(\frac{n}{a_n} \right)^{-1} \times \left\{ \operatorname{Argsinh}\left[\left(\frac{\sqrt{2}}{2} \right) \times \sqrt{\left(\frac{n}{a_n} \right)^2 + 1} + \frac{n}{a_n} \right] - \operatorname{Argsinh}\left[\left(\frac{\sqrt{2}}{2} \right) \times \sqrt{\left(\frac{n}{a_n} \right)^2 + 1} - \frac{n}{a_n} \right] \right\}. \tag{43}$$

For A ≡ M and E ≡ N there holds simplification characterized with relations: L = 0 and m = n. If it holds that $(n / a_n) \rightarrow 0$ then you will get that $(k / a_n) \rightarrow \infty$. And for $(n / a_n) \rightarrow \infty$ you will receive that $(k / a_n) \rightarrow 0$. It is evident that it is only and only about an influence of the diameter and length of electrode. For the 3-electrode Laterolog it is characteristic that the central electrode A ≡ M is much smaller than the guard electrodes E ≡ N and E' ≡ N'. The constant of the central electrode will be higher than it is for the guard electrodes. It is time to say which of the formulas are used for relevant type of Laterolog.

For the 9-electrode Laterolog when regulation is made with the help of the guard electrodes on condition that $U_N = U_M$ the partial constants k_{AM}, k_{AN}, k_{BM}, k_{BN}, k_{EM} and k_{EN} are calculated through formulas (38), (39) and (40).

For the 7-electrode Laterolog when regulation is made by the guard electrodes on condition $U_N = U_M$ the partial formulas k_{AM}, k_{AN}, k_{EM} and k_{EN} are calculated again thanks to formulas (38), (39) and (40).

For the 3-electrode Laterolog when regulation is made by the guard electrodes on condition $U_N = U_M$ the partial constants k_{AN} and k_{EM} are calculated after formulas (38), (39) and (40), whereas, the partial constants k_{AM} and k_{EN} after formulas (41), (42) and (43).

I have to add that all resting and less useful variances are directed with the same formulas as these useful, however, their disadvantage in worse focusing of electric field presents big handicap for them. The worst of all is when focusing is parallel to axis of tool; in such case electric contours are concentrated in higher quantity in the mud, in particular, when it is salt mud. All quoted formulas from (38) up to (43) are from paper presented to publication, RYŠAVÝ, F. (2013).

8 Discussion over focusing of electric field

As you can have seen variances of focusing are enough large. Usually feeding electrode is electrode A and the guard electrodes are electrodes E and E´. However, it can be too contrariwise when feeding electrodes are E and E´, whereas, the guard electrode is A. If to that you add conditions of regulation $U_N = U_M$ and $U_N = 0$, there exist four variances for the only electrode array. Next possibilities carry various electrode array of tool when you can have 9-electrode tool, 7-electrode tool and 3-electrode tool.

I am sure you noticed too that favourable condition is when $U_N = U_M$, whereas, when holds that $U_N = 0$ it is less favourable condition. In both cases you have electric field that is focused, however, variants of focusing are different. In the first variant the current contours are perpendicular to the borehole axis and go perpendicularly into the borehole wall. They penetrate deeply inwards rocks and in big distance from the wall they are curved and return to electrode B. The second variant offers too focused electric field. The current contours go too into rocks but because are intensively curved at once in the direction being parallel to the borehole axis, they stretch mainly invasion zone and mud.

Let suppose the following relation which is similar to relation for pseudo-static and static SP-potentials for voltage; SCHLUMBERGER (1989), *Log Interpretation Principles /Applications*. The formula is following:

$$U_M = \frac{R_t \times I_A}{K} \times \left\{ 1 + \frac{R_i}{R_m} + \frac{R_s}{R_m} + \frac{R_t}{R_m} \right\}^{-1} ,$$

If you adjust this equation for resistivity, you will receive this relation:

$$R = K \times \frac{U_M}{I_A} = R_t \times \left\{ 1 + \frac{R_i}{R_m} + \frac{R_s}{R_m} + \frac{R_t}{R_m} \right\}^{-1} , \tag{44}$$

where R_m = the mud resistivity [Ωm],

R_s = the resistivity of adjacent beds [Ωm],

R_i = the resistivity of invasion zone [Ωm], and

R_t = the resistivity of non-invaded bed [Ωm].

If we are able to simulate virtually the mud column having infinite resistivity, i.e., $R_m \rightarrow \infty$, and it is with the help of the electrode array and focusing electric field always possible, equation will gain the following form:

$$R = K \times \frac{U_M}{I_A} = \lim_{R_m \rightarrow \infty} R_t \times \left\{ 1 + \frac{R_i}{R_m} + \frac{R_s}{R_m} + \frac{R_t}{R_m} \right\}^{-1} \approx R_t \quad \text{for } \mathrm{U_N} = \mathrm{U_M} . \tag{45}$$

In this case we are possible to create non-conductive mud column with the help of electric field focusing, even if the real mud column is conductive sometimes highly conductive. The registered resistivity equals almost the resistivity of non-invaded bed.

If it is possible to simulate virtually the mud column having zero resistivity, i.e., $R_m \rightarrow 0$, and it is the second case, equation will have definition like this:

$$\begin{gathered} R = K \times \frac{U_M}{I_A} = \lim_{R_m \rightarrow 0} R_t \times \left\{ 1 + \frac{R_i}{R_m} + \frac{R_s}{R_m} + \frac{R_t}{R_m} \right\}^{-1} \approx R_t \times \left\{ \frac{R_i}{R_m} + \frac{R_s}{R_m} + \frac{R_t}{R_m} \right\}^{-1} = \\ \frac{R_m \times R_t}{R_i + R_s + R_t} = \frac{R_m}{\left(1 + \dfrac{R_i + R_s}{R_t} \right)} \approx R_m \quad \text{if holds that } \mathrm{R_t} \rangle\rangle \left(\mathrm{R_i} + \mathrm{R_s} \right) \text{and for } \mathrm{U_N} = 0 . \end{gathered} \tag{46}$$

This event shows that when the current contours are focused parallelly to the borehole axis, the registered resistivity is strongly influenced by invasion zone, adjacent beds and mud, in particular.

Main request is to focus the current contours to be perpendicular to the borehole wall. The contours going out of feeding electrode A form section like a low and wide glass for champagne; it is for 7-electrode tool. If it is 9-electrode tool, the section looks like a bud of tulip, because electrodes B and B´ form the electric field not to be too deep. This holds for feeding electric current remarked as I_A.

The regulative electric current I_E have contours going out of both guard electrodes E and E´. The contours flow through mud to electrode A which curves them up to measure that they come perpendicularly into the borehole wall. The contour's section presents thin electric ray; in the space it looks like thin and straight disc embedded on axis when both ends of axis present electrodes E and E´.

The before description was when I_A and I_E flow in the same direction; it holds that $I_A > 0$, $I_E > 0$ or $I_A < 0$, $I_E < 0$. However, the currents can flow too against one another, i.e., $I_A > 0$, $I_E < 0$ or $I_A < 0$, $I_E > 0$. It is given with the coefficient of focusing η after its sign.

This has two basic values; positive and negative. It determines direction of the regulative current. The final electric current is sum of both mentioned currents.

$$I = I_A + I_E = (1+\eta)\times I_A \qquad (47)$$

The final electric current can be positive, negative and zero.

- For $\eta > 0$ it holds that $I > 0$.
- For $-1 < \eta < 0$ it holds that $I > 0$
- For $\eta = -1$ it holds that $I = 0$.
- For $\eta < -1$ it holds that $I < 0$.

It was said the coefficient of focussing η to be positive, negative, possibly too zero. The higher the coefficient of focussing is the deeper penetration of the current contours in the rock is. For negative η it presents much weaker penetration.

The constant of electrode tool remarked as K ought to be only positive. It is condition going out of empirical knowledge. However, this theory offers some cases when K can be negative too. I am not able to explain that now; it seems that it is connected with the electrode array of tool. Here is opened field of investigation for younger scientists.

9 Calibration of resistivity

Calibration of resistivity is very simple. You can use formulas (10) or (27).For calibration in the linear scale one etalon is enough, however, for the non-linear scale you will need to have all set of etalons. As etalons there are used resistors having their values of electrical resistance in [Ω]. These are defined with certain error. Such resistor simulates the resistivity of rocks according to formula:

$$R^* = R_0 \times K\,, \qquad (48)$$

where R_0 = the electrical resistance of resistor [Ω],
K = the constant of the electrode tool [m], and
R^* = the simulated resistivity of rocks [Ωm].

Deflection of record remarked as l^* answering to R^* you receive from the next formula:

$$l^* = \frac{R^*}{n}, \qquad (49)$$

where n = the step of linear scale [Ωm/ 1cm], and

l^* = deflection for R^* [cm].

I should like to note that the simulated resistivity R^* will be for various tool arrays too various, because the constant K will be different. It holds for Pseudolaterolog, Classical Laterolog, Guard Log and all next arrays.

Resistors present the primary etalons which can be easy under metrological control. They serve for calibration of equipment only. Verification of right activity of all equipment including the electrode tool is made with the help of the test pit filled with fresh water. Such pit of small radius, it can be a borehole, presents secondary etalon of resistivity. Thanks to registration of measured values after two or more electrode tools you will be able to determine an interval of allowed deflections expressed in the resistivity for the before-selected step of linear scale. Such electrical surrounding is possible to inspect within time and to define its new allowed resistivity, as well.

10 Metrological controls

We have to distinguish two different controls. The first is the control of standard that in this case is a resistor having known value in ohms, [Ω]. The value has too its error; so we can say that there exits an interval of admitted values so called the confidence interval. If you have as a standard the resistor having 100 Ω ± 5%, it means that holds 100 Ω ± 5 Ω. The second is the control of the all registering system. For that you must have an environment with known resistivity. It can be very thick bed, big rock block, however, the easiest of all is big reservoir filled with fresh water. You have regularly to take samples of water, to record their resistivity, to count the mean and to determine the middle square error. Then it is possible to define the confidence interval for resistivity of fresh water. Observations are made with the gauge having two times higher accuracy than the field/laboratory gauge. And now a bit more about both controls.

Control of standard

The standard for registering of resistivity is a resistor/ set of resistors having its value in ohms, [Ω]. As we know too its error it is possible to determine the confidence interval as was said yet. The controlling gauge in this case it is ohmmeter must have its accuracy, at least, two-times higher than the field/laboratory gauge. The controlling gauge is calibrated in interval two years in the accredited laboratory having valid licence just in recent time. It receives the stick-on calibre label and if you wish the certificate about calibration too. With the help of this gauge you will make, at least, ten records of electric resistance of the controlled resistor. Then you will count the mean. If the mean is in the confidence interval, the standard is constant and for field calibration holds the value from producer. If the mean is out of the above interval you have to exchange the resistor, because is disrupted.

All observations are recorded and they present the controlled documents. Therefore they must have all needed requisites. The records are archived for some years and can have analogue or digital forms.

Control of the registering system

As it was said the fundament is an environment having known resistivity. Here is not controlled electric resistance in ohms, [Ω], but resistivity of environment in ohmmeters, [Ωm]. Such environment presents standard value of resistivity. If you have a reservoir with fresh water you can take samples of water and record their resistivity. You can use for the control the same gauge like it is for the control of standard, but now you register resistivity. You will take ten samples, at least, register their resistivity, determine mean and count the middle square error. In such case you are able to say what the confidence interval is.

The next step is to dip the field tool in the reservoir and register resistivity of fresh water. If the value is in the above interval, the system is stable. If it is not, system must be restored and will go over by new control. For records there hold the same principles like it is for the control of standard.

11 Conclusions

Thanks to analysis having been made before here are these conclusions:

- The 9-electrode Laterolog remarked as Pseudo-Laterolog has electrodes B and B’ on the electrode tool, whereas, the 7-electrode Laterolog and the 3-electrode Laterolog have their electrode B_0 on the earth surface. Both have deeper penetration of the electric contours of field into beds than it is for Pseudo-Laterolog.
- Regulation is possible either by the guard electrodes, or by the central electrode. Both sorts of regulation have two different ways how to do it; either on condition that $U_N = U_M$, or that $U_N = 0$.
- The 3-electrode Laterolog has the current and potential electrodes identical. It holds that $A \equiv M$ and $E \equiv N$.
- We distinguish positive and negative focusing of the electric field. The positive focusing has electric contours oriented perpendicularly to the electrode tool and to the borehole wall. Coefficient of focusing is positive. The negative focusing has the above electric contours oriented parallelly to the electrode tool; coefficient of focusing is negative. Such focusing ought to be never used for salt mud.
- The constant of the electrode tool is always positive.
- Partial constants are enumerated after the before-published formulas. We have to distinguish whether or not the current and potential electrodes are identical.

References

ANDERSON, B., BARBER, T. and GIANZERO, S., *The effect of crossbedding anisotropy on induction tool response*: Petrophysics, v.42, no.3, 2001, p.137 - 149

CHEN, Y.H., CHEW, W.C. and ZHANG, G.J., *A novel array Laterolog method*: The Log Analyst, v.39, no.5, 1998, p. 23 - 33

KAROUS, M. *Geoelektrické metody průzkumu*, SNTL/ALFA, Praha, 1989,423 p

LACOUR-GUYET, P., *The Groningen effect, causes and partial remedy*: Schlumberger Technical Review, v.29, no.1, 1981, p. 37 - 47

MARUŠIAK, I. *Princip kontrolirovannoj reguljacii toka mnogoelektrodnych karotažnych zondov.* 1. část, Užitá geofyzika, 7, Brno, 1968

MARUŠIAK, I., TĚŽKÝ, A., JONÁŠOVÁ, V. *Princip kontrolirovannoj reguljacii toka mnogoelektrodnych karotažnych zondov.* 2. část, Užitá geofyzika, 8, Brno, 1969

RYŠAVÝ, F. *Method of the controlled current regulation – calculation of partial constants for cylindrical electrodes*, presented to publication on conference OVA 13, 2013

SCHLUMBERGER, *Log Interpretation Principles /Applications,* Schlumberger Well Wireline & Testing, Sugar Land, 1989

YANG, W., TORRES-VERDÍN, C., AKKURT, R., AL-DOSSARI, S., AL-TOWIJRI, A. and ERSOZ, H., *Interpretation of frequency-dependent dual-Laterolog measurements acquired in middle-east carbonate reservoirs using a second-order finite-element method*, SPWLA 48th Annual Logging Symposium, June 3-6, 2007

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