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COMPARISON OF ACCURACY OF CONTROL SYSTEMS FOR VARIOUS FOCUSED-CURRENT LOGGING INSTRUMENTS

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This paper deals with the errors of the various types of focused-current (laterolog) control systems taking into account all the characteristic features of the control loop, as well as those of the borehole and bearing in mind the influence of the surrounding formations on the accuracy of the various controls.

The relationship is shown between the error of the measured apparent resistivity and the insufficient control, and their links with the main features of the control-loop and the four transfer functions representing the physical properties of the borhole and the surrounding formations.

It is emphasized that the applied theoretical treatment has less rigorous requirements than the real cases, as the ground contact resistance of the current electrodes are taken into account by that of the equipotential surfaces matching at the S_1 and S_2 electrodes. This involves neglecting the effect of the gaps (filled with low resistivity mud) between the current electrodes and the mentioned potential-surfaces. This results in no significant difference if the values of R_a are high enough while for low values of R_a it acts as if the output-resistivity of the control-loop in question was increased.

d: focused-current logging, control system, accuracy, I_1 control, I_0 control, I_1/I_0 ratio

1. Introduction

Focused-current (laterolog) well-logging methods have been used universally, in boreholes drilled with conductive mud, since the beginning of the seventies, pushing into background all the classical resistivity measurements. On the one hand this can be attributed to their having the deepest penetration of all logging methods, a good selectivity along the borehole and additionally, they are independent of the disturbances of mud-resistivity, as opposed to the conventional devices; on the other hand, with regard to their features and selectivity, they can better be associated with the other modern logging methods (sonic-, induction-, nuclear-) than the conventional ones. In the near future the focused method can look forward to a further boom as now this is perhaps the only one which offers the possibility of increasing its penetration and sensitivity. It is also likely that this method will play an important role in the planning of enhanced production methods. For these reasons it is necessary to get acquainted with some of the factors influencing its accuracy.

Among the well-known focused current tools (LL3, LL7, LL9 and DLL), those with seven or nine electrodes have so far proved the most useful because there is no flow either of I_0 measuring- or of I_1 focusing currents through the electrodes which give the control-signal and the measured information and this means that they are more accurate than the others. Moreover, one can form the

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shape of the I_0 current-beam by means of the I_1 current flowing through the properly located A_1 electrodes, to yield an advantageous measuring characteristic. Therefore this paper deals with the common effects of mud- and rock-resistivities and electrical parameters of the control circuit on the accuracy of control and measurement.

2. Errors of the control and measuring processes

Let us now consider the errors of the control and measuring process caused by these characteristic parameters, as a function of the current ratio $n = I_1/I_0$. We will find that not only the error of n is proportional to this influence, but that of the measured resistivity too.

Our intention is to examine this influence on the wellknown seven-electrode focused sonde *(Fig. 1/c)* but the same method is also suitable for the nine-electrode sonde as well as for dual types with elongated electrodes.

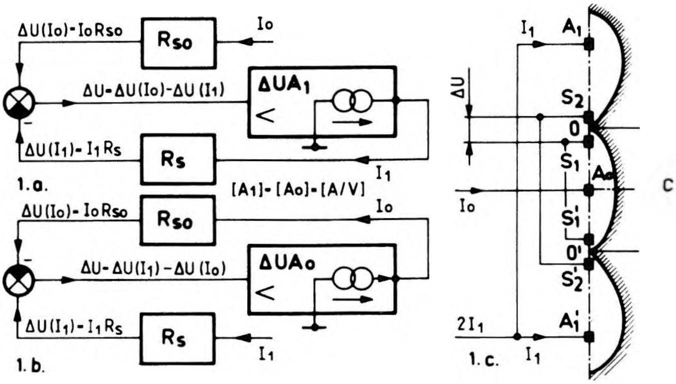

Fig. 1. Schematic diagrams of I_1 and I_0 control circuits (a, b) and an LL7 sonde (c)

1. ábra. Az I_0 és I_1 szabályozó egyszerűsített tömbvázlata és a hét elektródás szonda

Рис. 1. Упрощенная блок-схема регулирующего устройства I_0 и I_1
и семиэлектродный зонд LL7

One can read in *Fig. 1/a,* representing the simplified block-scheme of the I_1 control, the expressions

$$\Delta U = \Delta U(I_0) - \Delta U(I_1) = I_0 R_{so} - I_1 R_s \tag{1}$$

$$I_1 = \Delta U A_1 \tag{2}$$

If $\Delta U=0$, then (1) gives

$$I_1^*/I_0 = R_{so}/R_s = n_0 \tag{3}$$

where n_0 is the ideal I_1^*/I_0 ratio. The existing current ratio, if $\Delta U \neq 0$, using (1) and (2), is

$$n = I_1/I_0 = A_1 R_{so}/(1+A_1 R_s) \tag{4}$$

Let us define the error of the control as

$$h_{I_1} = (n-n_0)\,/n_0 = -1/\,(1+A_1 R_s) \approx -1/A_1 R_s \tag{5}$$

this is, in fact, the known expression for automatic control systems.

If the I_0 current is controlled, the expression of the error is

$$h_{I_0} = -1/(1+A_0 R_{so}) \approx -1/A_0 R_{so} \tag{6}$$

Thus in both cases the errors are functions of the gain of the control circuit as well as of the transfer functions, having values defined by $R_{so}=\Delta(I_0)/I_0$ and $R_s=\Delta(I_1)/I_1$, and they apparently depend on whether we control the I_1 or I_0. Our aim is to examine the effect on the control of these parameters. The characteristic features of these transfer-functions and those of the n ratio are shown in *Fig. 2* for a so called optimum-sonde and two-parameter resistivity-distribution in the direction perpendicular to the borehole axis.

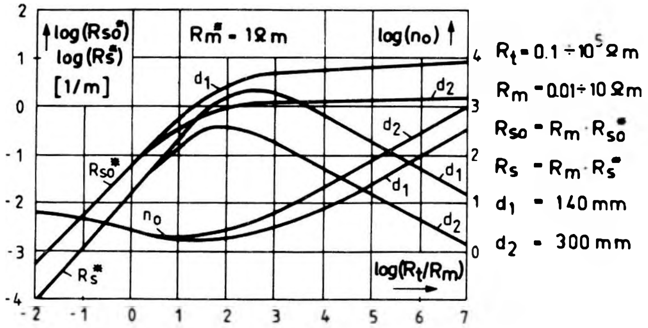

Fig. 2. R_{so}, R_s and n_0 as functions of rock- (R_t), mud-resistivity (R_m), and diameter of borehole *(d)*

2. ábra. A szabályozás transzfer-függvényei és az n_0 áramarány a kőzet- (R_t), az iszap-ellenállás (R_m) és a lyukátmérő *(d)* függvényében

Рис. 2. Функции передачи регулирования и соотношение токов n_0 в зависимости от сопротивления породы (R_t), раствора (R_m) и диаметра скважины *(d)*

The characteristic behaviour of R_{s0} and R_s in expressions (5) and (6) fosters the idea that the I_0 control needs far less gain (A_0) than does the control of I_1 (A_1), especially in cases demanding high n ratio. Some experts consider I_0 control to be more beneficial than the other, in particular if they wish to vary, beyond the controlled current, the n ratio too, e.g. so that the more the I_0 is decreased the more the I_1 is increased, or vice versa. One can achieve this process with an additional control circuit driven by the signal produced on R by the controlled current.

Unfortunately, these ideas are rather irrational since they do not take into account either the effects of the output resistances of the generators (R_0, R_1), or the ground contact resistances of the electrodes (R_{f0}, R_{f1}). The control schemes shown in *Figs. 1/a and b* serve for the study of the characteristics of functions R_{s0} and R_s only, they cannot be applied in the actual design of an instrument.

Next we use a general model which is suitable for studying the errors attributed to the inadequate control both of the n ratio and the R_a apparent resistivities. In both cases of the controls the R_0 and R_{f0} are connected series in the I_0 circuit as well as R_1 and R_{f1} in the I_1 circuit, see *Figs. 3 and 4*. The transfer functions make connections between the current flowing through two given points of the rock-space and the voltage caused by this current between another two points of the same space. They are fictitious, thus have no primary effect on the currents. Besides the transfers already defined, the other two are $R_k = U_M(I_1)/I_1$ and $R_{k0} = U_M(I_0)/I_0$.

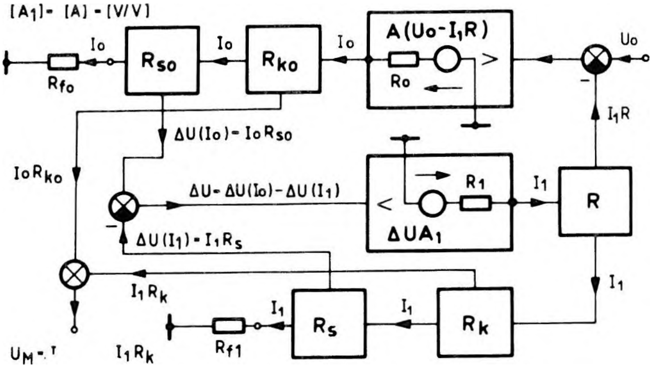

Fig. 3. Schematic diagram of I_1 control using all transfer-functions

3. ábra. Az I_1 szabályozás és a mérés transzfer-függvényes tömbvázlata

Рис. 3. Блок-схема регулирования I_1 и измерения с применением всех функций передачи

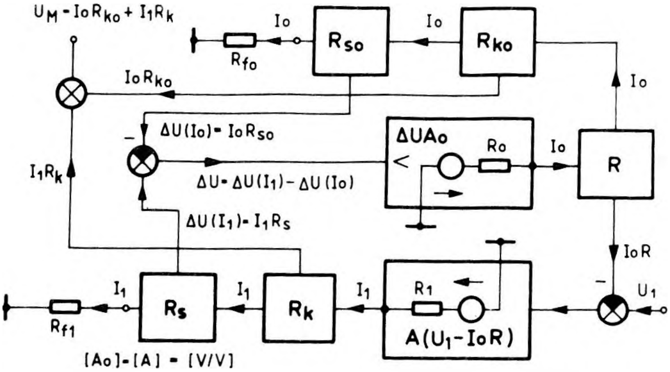

Fig. 4. Schematic diagram of I_0 control using all transfer-functions

4. ábra. Az I_0 szabályozás és a mérés transzfer-függvényes tömbvázlata

Рис. 4. Блок-схема регулирования I_0 у измерения с применением всех функций передачи

$$\Delta U = \Delta U(I_0) - \Delta U(I_1) = I_0 R_{so} - I_1 R_s \tag{7}$$

$$I_1 = \Delta U A_1 / (R_1 + R_{f1}) \tag{8}$$

Thus one can express the existing I_1 value and the n ratio as

$$I_1 = I_0 A_1 R_{s0} / [(R_1 + R_{f1}) + A_1 R_s] \tag{9}$$

$$n = I_1 / I_0 = A_1 R_{so} / [(R_1 + R_{f1}) + A_1 R_s] \tag{10}$$

The relative error of I_1 and the gain due to the parameters are given by:

$$\begin{aligned} h_{I_1} = (n - n_0)/n_0 = -(R_1 + R_{f1})/[A_1 R_s + (R_1 + R_{f1})] \leq \\ \leq -(R_1 + R_{f1})/A_1 R_s \end{aligned} \tag{11}$$

$$A_1 = [(1 + h_{I1})/h_{I1}] \,/\, [(R_1 + R_{f1})/R_s] \tag{12}$$

Accordingly, (11) and (12) show that the error and the gain are not only functions of R_s or h_{I_1} but also of R_1 and R_{f1}, however they are independent from the R_0, R_{f0}, R and A values. The error of R_a caused by I_1 is

$$h_{R1} = (R_a - R_a^*)/R_a^* \tag{13}$$

where R_a^* exists if $\Delta U = 0$, and R_a is measured if $\Delta U \neq 0$

$$R_a^* = k(R_{k0} + n_0 R_k) \tag{14}$$

$$R_a = k(R_{k0} + n R_k) \tag{15}$$

Equations (14) and (15) are merely modified forms of the basic equation of geophysical resistivity measurement:

$$R_a = kU_M / I_0, \tag{16}$$

if we consider the U_M value to be the superposition of the two potentials I_0R_{k0} and I_1R_k (fig. 3). From (14) and (15) one can express the error of resistivity:

$$h_{R1} = (n - n_0)R_k / (R_{k0} + n_0R_k) \tag{17}$$

Now, taking (3) and (10) one can reformulate (17), viz.

$$h_{R1} = -(R_1 + R_{f1}) / [(R_1 + R_{f1} + A_1R_s)] \cdot [n_0R_k / (R_{k0} + n_0R_k)] =$$

$$= h_{I1}n_0R_k/(R_{k0} + n_0R_k) = h_{I1}e_k \tag{18}$$

Hence the error h_{R1} is proportional to h_{I1}, moreover

$$e_k = n_0R_k / (R_{k0} + n_0R_k) \tag{19}$$

representing the influence of the rock- and mud-resistivities and their distribution always having a value less than unity. On the basis of (18) it can be stated that h_{R1}, the error of the apparent resistivity, is less than the error of I_1.

Similarly one can determine the characteristics of the I_0 control using Fig. 4.

$$\Delta U = \Delta U(I_1) - \Delta U(I_0) = I_1R_s - I_0R_{s0} \tag{20}$$

$$I_0 = \Delta UA_0/(R_0 + R_{f0}) \tag{21}$$

From these one gets the characteristic formulae

$$I_0 = I_1A_0R_s/[R_0 + R_{f0}) + A_0R_{s0}] \tag{22}$$

$$n = I_1/I_0 = (R_0 + R_{f0} + A_0R_{s0})/A_0R_s \tag{23}$$

$$h_{I0} = (I_0 - I_0^*)/I_0^* = -(R_0 + R_{f0})/[(R_0 + R_{f0}) + A_0R_{s0}] \approx$$

$$\approx -(R_0 + R_{f0})/A_0R_{s0} \tag{24}$$

$$A_0 = [(1 + h_{I0})/h_{I0}] \cdot [(R_0 + R_{f0})/R_{s0}] \tag{25}$$

If we consider (24) and (25) it can be seen that h_{I0} and A_0 depend on the parameters of the I_0 circuit. It soon becomes obvious that this apparent inequality between (11) and (24) covers a strict identity. Now, similarly to (14), the error of R_a is

$$h_{R0} = (R_a - R_a^*)/R_a^* = (n - n_0)R_k/(R_{k0} + n_0 R_k) \tag{26}$$

Using (3), (19) and the right side of (26) one can write

$$h_{R0} = [(R_0 + R_{f0})/A_0 R_k]\,[R_k/(R_{k0} + n_0 R_k)] \tag{27}$$

If we then multiply (27) by R_{S0}/R_{S0} and take (3), (19) and (24)

$$h_{R0} = [(R_0 + R_{f0})/A_0 R_{s0}]\,[n_0 R_k/(R_{k0} + n_0 R_k)] =$$

$$= [(R_0 + R_{f0})/A_0 R_{s0}]e_k \geq h_{i0} e_k \tag{28}$$

On comparing (24) and (11), the ratio of the errors from the controlled currents —supposing that h_{I0} and h_{I1} are small—is found to be

$$\frac{h_{I0}}{h_{I1}} = \frac{R_0 + R_{f0}}{R_1 + R_{f1}} \cdot \frac{R_1 + R_{f1} + A_1 R_s}{R_0 + R_{f0} + A_0 R_{s0}} \approx \frac{R_{f0}}{R_{f1}} \cdot \frac{1}{n_0} \tag{29}$$

This last approximation is derived by setting $A_0 = A_1$, $R_0 = R_1 = 0$ and using (3). The approximate values of R_{f0} and R_{f1} are obtained from (16) and Fig. 1/c, viz.

$$R_{f0} = U_M/I_0 = R_a/k \tag{30}$$

$$R_{f1} = U_M/I_1 = U_M/n_0 I_0 = R_a/k n_0 \tag{31}$$

Inserting (30) and (31) into (29) we find that the ratio is practically equal to unity, namely it does not depend on R_a. For this reason the accuracy of the current controls demands the same gain regardless as to whether we control I_0 or I_1. Making use of (18) and (28), the ratio of the measurement errors is

$$h_{R0}/h_{R1} = h_{I0}e_k/h_{I1}e_k = h_{I0}/h_{I1} \approx 1 \tag{32}$$

In *Fig. 5*, as further evidence, we present, on the basis of (12) and (25), the values of amplification A for both current controls, as a function of R_a, R_m and R_0 or R_1 respectively, using the transfer functions already presented in Fig. 2. The error of the control has a value as high as $h = 0.01$, the diameter of the borehole $d = 140$ mm, and $R_0 = 1\ \Omega$ or $R_1 = 0.1\ \Omega$

The continuous curves represent the cases of $R_0 = R_1 = 0$ and the dashed ones correspond to the real R_0 or R_1 values found in practice. The effect of the transitional impedances of the current electrodes is included in R_0 and R_1, respectively.

The figure shows the values of gain A necessary for measurements having an accuracy of $h = 0.01$ and the remarkable effect if R_0 or R_1 have values differing from zero.

It can thus be seen that there is no difference in the technical requirements if one controls I_1 or I_0. Consequently neither of the control ideas has the slightest advantage over the other. The main factor to be taken into consideration is which kind of measuring system gives the best solution for the most severe conditions, and the extremely high R_t and R_m dynamics occurring in oil and gas prospecting.

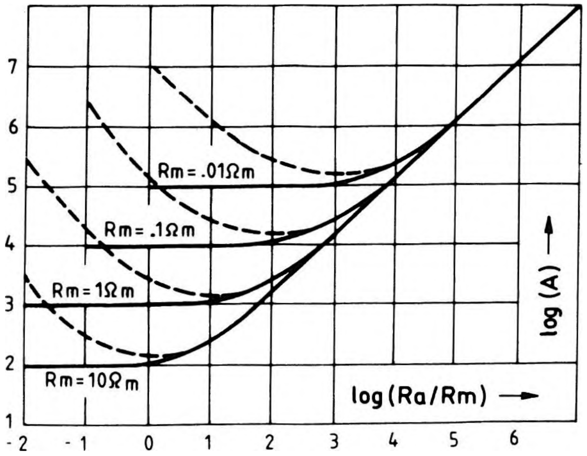

Fig. 5. Values of A versus R_a/R_m and R_0 or R_1 for an LL7 sonde. Continuous lines represent $R_0 = R_1 = C$

5. ábra. Az A értéke R_a/R_m és R_0 illetve R_1 függvényében egy LL7-szonda esetében. A folytonos vonal az $R_0 = R_1 = 0$ értéknek felel meg

Рис. 5. Значение A в зависимости от R_a/R_m и R_0 или R_1 для зонда LL7. Сплошная линия отвечает значению $R_0 = R_1 = 0$

3. Optimum system for focused-current control and measurement

A simple optimum system is shown in *Fig. 6*. The value of R_0 is chosen so that it keeps I_0 constant if R_a has low values; if R_a is high, then I_0 is in inverse ratio to R_a, advancing the realization of the n_0 requirement. We produce R_a as a quotient of U_M and I_0 being measured simultaneously while I_1 is controlled. The very advantage of the system is that it covers a high range of R_a resistivities while having possibly the least dynamics in the information channels. The value of U_M and I_0, that is $U(I_0)$, are shown as a function of R_a in Fig. 6/a.

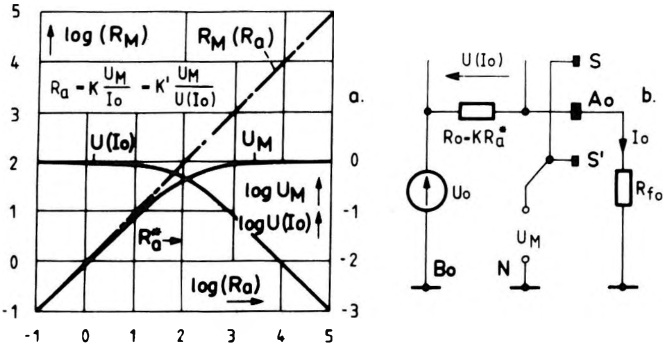

Fig. 6. Characteristics of the sonde measuring the U_M/I_0 ratio and its I_0 circuit

6. ábra. Az U_M/I_0 hányados mérésen alapuló mérőrendszer karakterisztikái és az I_0 áramkör

Рис. 6. Характеристики измерительной установки, основанной на измерении отношения U_M/I_0 и схема I_0

4. Combined controls

Let us consider the possibilities offered by the combined controlling. In the case of I_0 control (cf. Fig. 4) if h_{I0} (24) is small, supposing $R_0 = R_1 = 0$ and using (22), (23) and (30), one can write

$$I_0 - U_1 kA/(R_a + kAR) \tag{33}$$

$$I_1 - U_1 kAn/(R_a + kAR) \tag{34}$$

hence, I_0 does not depend on n,: it is only a function of R_a as well as of constants k, A, and R of the control circuit. If we choose k, A, and R properly, the current will have the same shape as that of the $U(I_0)$ curve shown by Fig. 6/a. The shape of the curve of the measured potentials is similar to that of curve U_M in Fig. 6/a. The position of the crossing point of the U_M and $U(I_0)$ functions depends on the values of R_a and $k\ A\ R$ product. Consequently the combined I_0 control, in spite of its having been complicated by using an additional control circuit, realizes only the simple optimum system shown by Fig. 6.

Likewise, we can write for the I_1 control shown in Fig. 3

$$I_0 \approx U_1 kA/(R_a + kAR) \tag{35}$$

$$I_1 \approx U_1 kAn/(R_a + kAR) \tag{36}$$

The currents as function of R_a and n are plotted in *Fig. 7.* The continuous curves show the I_0 values and the dashed ones those of I_1. One can see that the values of I_1 never exceed the maximum of the function $I_0(R_a, n_0)$. Theoretically this control would give the best solution—being both I_0 and I_1 maxima limited—if we did not consider the low values of I_0 i.e. the U_M voltage caused by this current. Whenever R_a is low we can see, bearing in mind expression (16), that U_M can have extremely low values, even lower that the noise level. Moreover the optimum U_M and $U(I_0)$ signal-dynamics is spoilt because the shape and relative values are not optimized as strictly as in the case of the system shown in Fig. 6. Thus, this control requires higher dynamics in each measuring channel than it does in the optimum system. Although the concept seems reasonable it is no more advantageous than the simple system.

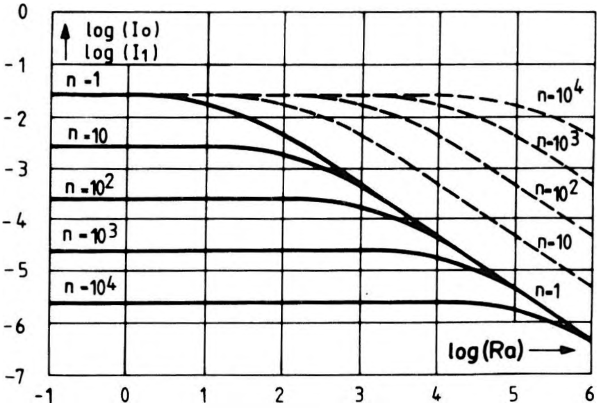

Fig. 7. Typical values of I_1 (dashed line) and I_0 (continuous line) versus R_a and n for I_1 control with additional I_1/I_0 ratio

7. ábra. I_1 (szaggatott vonal) és I_0 (folytonos vonal) jellemző értékei R_a és n függvényében, I_1 és járulékos I_1/I_0-szabályozás esetében

Рис. 7. Характерные значения I_1 (пунктир) и I_0 (сплошная линия) в зависимости R_a и n при регулировании I_1 и дополнительно I_1/I_0

5. Conclusions

Both cases of I_1 and I_0 controls demand identical control loop gain if the conditions are identical in the borehole. Thus it is not valid that the I_0 control demands less gain than that of the I_1(see equations (12) and (25)).

Consequently it is important for the highly demanding situation of oil and gas prospecting, especially in hostile environmental boreholes, that such control systems are realized which give adequate gain as well as stable and rapid operation.

The additional I_1/I_0 ratio adjusting cannot make it possible to decrease the gain of the control-loop for I_1 or I_0 control either, since neither gain A nor coupling-resistance R figuring in the expressions describes the error of the controlled current or that of the apparent resistivity (see equations (11) and (18), or (24) and (28)).

The error of the measured resistivity caused by insufficient control is proportional to the product of the error of current control and the factor depending on the resistivities of the borehole and rock-space and their geometrical distribution. This error is generally less than the error of the current control (see equations (18); (19), or (28)).

A KÜLÖNFÉLE TÍPUSÚ FOKUSZÁLT ÁRAMTERŰ SZELVÉNYEZŐ BERENDEZÉSEKBEN HASZNÁLT SZABÁLYOZÓ RENDSZEREK ÖSSZEHASONLÍTÁSA A PONTOSSÁG SZEMPONTJÁBÓL

KUBINA ISTVÁN

A cikk az irányított áramterű (laterolog) szelvényezés különféle változataival foglalkozik, figyelembe véve a szabályozó berendezés, a fúrólyuk és a kőzettér valamennyi jellemzőjét, amely befolyásolja a szabályozás pontosságát.

Bemutatjuk a mért látszólagos ellenállás hibájának és a szabályozás elégtelenségének összefüggését és azt, hogy ezek milyen kapcsolatban vannak a mérést meghatározó fő műszerjellemzőkkel, valamint a fúrólyukat és az azt körülvevő kőzetteret leíró négy átviteli függvénnyel.

СОПОСТАВЛЕНИЕ ПО ТОЧНОСТИ РЕГУЛИРУЮЩИХ СИСТЕМ РАЗЛИЧНЫХ ТИПОВ ДЛЯ БОКОВОГО КАРОТАЖА

И. КУБИНА

В работе дано сопоставление разных вариантов бокового каротажа с учетом всех характерных черт регулирующего устройства, скважины и вмещающих пород, которые производят влияние на точность регулирования.

Приводятся зависимость погрешности измеренного кажущегося удельного сопротивления от недостаточности регулирования и ее связь с определяющими измерение основными характеристиками аппаратуры, а также с четырьмя функциями передачи, описывающими скважину и окружающее ее пространство горных пород.