14th International Conference on DEVELOPMENT AND APPLICATION SYSTEMS, Suceava, Romania, May 24-26, 2018

Design of Vertical Earth Grounding With Rectangular Outline by Minimizing Its Total Metal Mass

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Abstract—**The research continues applying optimal criteria for the design of earth grounding with vertical electrodes, placed around a rectangular contour. According to the minimum footprint area and to the total minimal volume criteria, the minimization of the conductive materials total mas, consisting of electrodes and strip-like steel conductor is approached. The minimum metal mass of the earth grounding is obtained for the smaller electrodes length and for the larger distances between them from the corresponding considered domains. The distortion of the objective function dependence has been eliminated by the non-tilting of the electrodes number to the even numbers. The comparison of the minimum earth grounding solutions determined with the three optimal criteria applied to date leads to a deepening of the specialists concept regarding the earth grounding design basis.**

Keywords—vertical earth grounding; earth grounding with electrodes placed on a rectangular outline; optimal criteria; minimum of the earth grounding total conductive mass; artificial earth grounding.

I. INTRODUCTION

In previous papers, the authors made nomograms for the calculation of the dispersion resistances for both simple and composite earth grounding, with several electrodes, and proposed to substantiate the design of the earth grounding on optimal criteria. At the same time, it was highlighted that the model of calculus of the earth grounding, contained in normative acts, presents nonlinearities and functions with implicit definitions.

Continuing the development of earth grounding sizing methods using optimal criteria, the algorithm for minimization of the total metal mass of the earth grounding is formulated and exemplified in the paper. The determination step of the electrodes number to achieve the maximum permissible dispersion resistance is simplified, the identified transcendence equation being based on the inequality corresponding to the dispersion resistance of the composite earth grounding.

The earth grounding (EGR) sizing is based on normative acts [1÷4], which specifies the size of the EGR earth dispersion resistance according to its purpose and indicates the calculation relations for the dispersion resistances of the simple and multiple EGR and for the utilization coefficients as well, in accordance with their specific construction. The nonlinearity of most relationships, the tabular indication of the correction function values of the utilization coefficient in relation to the electrodes number, as well as the implicit expressions have determined the stepwise development of the EGR design without the involvement of any optimal criterion. The merging of successive computational steps and function explanations is heavy due to the existing nonlinearities, which discourages the simplification of the EGR overall mathematical model.

The EGR rated earth resistance R_{Pn} must frame within the set $R_{Pn} \in \{1, 4, 5, 10\}$ Ω according to their destination [1÷3], the condition for the designers having the form:

$$R_P \leq R_{Pn} , \qquad (1)$$

given that the EGR realization at values lower than R_{Pn} is uneconomical and at higher values - not permitted. The designers and executors task should be to achieve just at the line as much as possible the condition expressed by the (1).

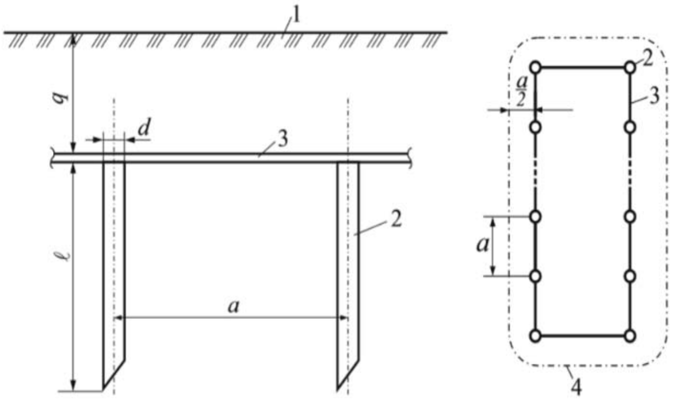
The reconsideration of the EGR design has led so far to the development of new nomograms, able to calculate the earth resistances for simple, vertical and multiple socket [11,12], as well as for the definition of EGR specific overall variables, which may constitute optimal (minimum) criteria in EGR dimensioning. These overall dimensions are as follows: EGR footprint area, total dispersion area, total volume, total conductive material mass and investment cost with the EGR [12,13].

The existence of optimal solutions has been highlighted in [14,15] and design algorithms have been proposed in [16] in order to obtain optimal solutions by applying the criteria of the EGR minimum footprint area and of the EGR total volume. The examples are oriented to the EGR with a rated dispersion resistance of 4 Ω, being realized with vertical pipe-type electrodes, located on the rectangular outline.

II. DIMENSIONAL CHARACTERISTICS OF THE VERTICAL EGR

A. *Geometry of The Vertical EGR With Rectangular Contour*

The constructive realization and the characteristic dimensional sizes of the vertical EGR with pipe electrodes are shown in Fig. 1, both in the form of a vertical section where only two of the adjacent electrodes (2) are represented (Fig. 1, *a*) and in an horizontal view like picture called EGR footprint (Fig. 1, *b*).



a *b*

Fig. 1. Construction and characteristic dimensions of a multiple, vertical EGR with pipe-type elctrodes: *a* – vertical representation; *b* – EGR footprint.

The meanings of the dimensional sizes are as follows: *d* – diameter of the pipe-type electrodes; *ℓ* – electrodes length; *q* – burial depth of the vertical electrode upper part in the soil (1); *a* – the distance between two electrodes in the horizontal plane; the pipe wall thickness is noted by *g*.

The connections (3) between the vertical electrodes (2) are carried out by galvanized strip-like steel conductors (Fig. 1, *b*) or by other types of conductors corresponding to the soil nature and to the EGR type.

B. *Simple EGR Dispersion Resistance*

The dispersion electrical resistance r_{pv} of a simple vertical electrode with the diameter *d* much smaller than the length *ℓ* ($d \ll \ell$) is given [1,3,7] depending on the electrode dimensions and the burial depth *q* from the soil surface (Fig. 1), by the relation:

$$r_{pv} = 0.366\frac{\rho}{\ell}\left[\lg\frac{2}{(d/\ell)} + 0.5\cdot\lg\left(1+\frac{1}{2(q/\ell)+0.5}\right)\right], \quad (2)$$

in which the dimensional variables (d/ℓ) and (q/ℓ) were highlighted, which increases the (2) degree of generality. The original calculation nomogram realized because of the (2) has been included in the works [12,13] and constitutes a particularly useful tool because it plays both qualitatively and quantitatively the r_{pv} size dependences of the variables highlighted by (2).

C. *Multiple EGR Dispersion Resistance*

The multiple EGR dispersion resistance R_P, realized through a parallel linking of the same type n_e electrodes, is determined by the general relationship [1]:

$$R_P = \frac{r_{pv}}{u_p \cdot n_e}, \ \Omega, \quad (3)$$

where r_{pv} is the dispersion resistance of a single EGR with one vertical electrode (2);

u_p - the utilization coefficient of the multiple EGR (in the concrete case, the complete notation will be u_{pd}), given by the relationship

$$u_{pd} = \left[1+\frac{\rho_p n_e f(n_e)}{2\pi p_{\mathrm{pv}}}\right]^{(-1)}, \quad (4)$$

in which $p=a\cdot n_e$ is the perimeter of the rectangle on the outline of which are placed the vertical electrodes, in m;

$f(n_e)$ - the function that introduces the dependence of the utilization coefficient on the electrodes number, given in [1] and for which the analytical expression was identified [14] as:

$$f(n_e) = 1.45\ \lg n_e + 0.1, \quad (5)$$

and the other sizes were previously explained.

Since in (3) the rated value R_{Pn} may be assigned to R_P ($R_P=R_{Pn}$), becoming a constant in this way, it means that the relationship can be used to determine the electrodes number n_e in terms in which the EGR characteristic dimensional sizes would be established [6].

III. EGR OPTIMAL DIMENSIONING

A. *Optimal Criteria for EGRs*

The following optimal criteria for EGRs sizing were proposed in [13], all based on the definition of some characteristic overall sizes for EGRs:

- the EGR footprint area;
- the EGR total volume;
- the EGR dispersion surface;
- the total mass of the conductive material used to realize the EGR;
- the EGR investment costs.

The first two optimal criteria have been addressed in [16], so that the achieved results are briefly presented in the following paragraphs. Due to the importance of the conductive materials total mass, this criterion will be approached as a priority in this work, the other criteria being the subject of future works.

B. *EGR Footprint Criterion*

The EGR footprint represents its image, seen from the top, highlighting the position and number of the vertical stakes, the distance between them and the geometrical figure described by all stakes. The electrodes emplacement after a rectangular outline (Fig.1, *b*) has been considered in this paper; so the EGR footprint area is given by:

$$A_{Pd} = n_e \cdot a^2 \text{ , m2,} \tag{6}$$

where n_e is the number of EGR vertical electrodes; relation (6) is valid for the case where on the width of the rectangle there are only two electrodes, which leads to the minimum area rectangle.

The analysis performed in [13,16] clearly showed that the minimum of the EGR footprint area is obtained for the longest lengths of the electrodes and for the smallest distances between them. Consequently, if the designer has to minimize the EGR footprint area, he has to follow the following steps:

- establishing, together with the manufacturer, the maximum length ℓ_M of the vertical electrodes, the minimum distance between them a_m and the buried depth q (e.g. q=0.8 m) technologically achievable accordingly the electrodes diameter d, with the thickness g, also agreed;
- measuring the soil resistivity ρ_p and determining the dispersion resistance r_{pv} of the single EGR, using the (2) or the appropriate nomogram;
- determination of the electrodes number n_e, required to achieve the nominal resistance R_{Pn}, imposed by the situation, solving the transcendent equation below, deduced by processing the (3):

$$n_e - \frac{\rho}{2\pi a\, R_{Pn}} \left(1.45 \cdot \lg n_e + 0.1\right) - \frac{r_{pv}}{R_{Pn}} \; ; \tag{7}$$

- determining the utilization coefficient u_{Pd} (rel. 4) for that integer electrodes number, lower than the decimal number, resulting from solving the equation (7);
- calculating the R_{Pe} component of the EGR resistance which is due only to the electrodes, with the relationship (3);
- determining the R_{Pc} component of EGR resistance, due to the conecting conductor between the electrodes, with the relation:

$$R_{Pc} = \frac{18.3}{a \cdot n_e} \lg(62.5 \cdot a^2 \cdot n_e^2) \; ; \tag{8}$$

- calculating the equivalent resistance of multiple EGR with the relationship below, checking that the condition is reached as close as possible with respect to R_{Pn}, to achieve:

$$R_{Pd} = \frac{R_{Pe} \cdot R_{Pc}}{R_{Pe} + R_{Pc}} \leq 4\Omega \, . \tag{9}$$

The minimum EGR footprint area is obtained for the greatest lengths of electrodes and for minimum distances between them, which are passable in the soil and with the contractor technology.

C. *EGR Total Volume Criterion*

The EGR total volume combines the characteristics of the horizontal plane, such as the distance a between the electrodes, the electrodes number n_e and the positioning system, with vertical dimensions, represented by the electrodes length ℓ and the burial depth q, given by the relation [16]:

$$V_P = a^2 n_e (q + \ell) \, , \tag{10}$$

which supports the statement above

The calculating method of the EGR dispersion resistance being relatively complicated (II, *C*), with implicit functions, the explanation of the volume V_P, given by (10) in relation with the dimensional parameters and then the optimal values identification was not applicable. For these reasons, the EGR total volume was determined for different values of the dimensional parameters and then identifying, from the set of obtained values, the corresponding solution to the EGR minimum volume V_P point.

The used calculation algorithm contains the same steps as the minimum area footprint criterion and the calculations show that the EGR minimum total volume also results for the minimum distance between the electrodes, but at their lower lengths from the considered lengths range [16].

IV. APPLYING THE EGR METAL MASS CRITERION

A. *EGR Metallic Mass Expression*

The conductive materials mass from the EGR composition, briefly referred as **EGR metallic mass**, is an overall size, characteristic for the EGR, because it combines sizes such as the diameter, length, thickness and electrodes number with the connecting conductor dimensions. The EGR metal mass M_P, which differentiates between possible constructive variants, comprises the pipes metallic mass and the strip connection mass between the pipes, so that the next relationship is obtained:

$$M_P = \gamma_m \left[\pi g (d - g) \ell n_e + (n_e - 1) a S_b \right], \tag{11}$$

where γ_m is the metal density, from which the electrodes and the connecting conductor are made;

S_b – the metal bar section, between electrodes, in m^2 and the other sizes have the meanings specified above.

Due to the determinant influence of the vertical electrodes length ℓ and the distance between them on the EGR dispersion resistance, these ones are to be considered as independent variables and the other variables that intervene being parameters. Thus, the following parameters are adopted: - the vertical electrodes diameter d; - the soil resistivity ρ_p; - the EGR rated resistance R_{Pn}; - the burial depth q; - the pipe wall thickness g; - the metal bar section S_b connecting the electrodes.

Consequently, the EGR metal mass M_P is considered to be a function of two independent variables, $M_P(\ell,a)$, so that its optimum is given by the annulment of the partial derivatives in relation to the two variables:

$$\frac{\pi g}{S_b}(d-g)\left(n_e+\ell\frac{\partial n_e}{\partial \ell}\right)+a\frac{\partial n_e}{\partial \ell}=0; \tag{12}$$

$$\frac{\pi g}{S_b}(d-g)\ell\frac{\partial n_e}{\partial a}+a\frac{\partial n_e}{\partial a}+n_e-1=0\ . \tag{13}$$

To be noted that these optimal conditions cannot be used in the initial design stage because the dependence of the electrodes number $n_e(\ell, a)$ is not yet explicit, being determined by the fulfillment of the condition (1), relative to finding the imposed value for the EGR rated resistance.

B. *Calculation Algorithm of the Total Metal Mass*

A simplification of the electrodes number n_e identifying algorithm has been conceived, in comparison with the one proposed in an earlier stage of the research [16], by including the dispersion resistance R_{Pc} of the connection conductor between the electrodes in the condition of achieving the EGR total dispersion resistance (9). Writing (9) as:

$$\frac{1}{R_{Pe}}+\frac{1}{R_{Pc}}\geq\frac{1}{R_{Pn}} \tag{14}$$

and replacing the expressions of the two components $\underline{P_{Pe}}$ and R_{Pc} of the EGR total dispersion resistance according to (3) and (8) respectively, the following transcendent equation is obtained:

$$\frac{2\pi a n_e}{2\pi a r_{pv}+\rho_P(1.45\cdot\lg n_e+0.1)}+\frac{a n_e}{18.3\cdot\lg(62.5\,a^2\cdot n_e^{\,2})}-\frac{1}{R_{Pn}}\geq 0\ . \tag{15}$$

whose solving leads directly to the required electrodes number, so that the equivalent dispersion resistance of the composite EGR is immediately below the imposed rated value R_{Pn}.

Solving the transcendent equation (15) replaces the solving of the transcendent equation (7) and the four next steps, referring to the use of (4), (8) and (9). Considering the left-hand side of (15) as a function, being it Y_e and assigning concrete values to the variables and parameters that intervene, excepting for the electrodes number n_e, the function $Y_e(n_e)$ may be graphically represented; observing a promising linearity of this function on the interest interval of the electrodes number, $n_e \in \{4\div12\}$ and taking into account the natural rounding to a whole even electrodes number, the next expression is proposed as a solution for the equation (15):

$$n_e=5+\frac{5}{1-Y_e(10)/Y_e(5)}\ , \tag{16}$$

wherein the introduced notations have the following meanings:

$$Y_e(5)=\frac{5an_e}{ar_{pv}+0.17722\cdot\rho_P}+\frac{5a}{58.447+36.6\cdot\lg a}-\frac{1}{R_{Pn}}\ ; \tag{17}$$

$$Y_e(10)=\frac{10a}{ar_{pv}+0.24668\cdot\rho_P}+\frac{10a}{69.465+36.6\cdot\lg a}-\frac{1}{R_{Pn}}\ . \tag{18}$$

Expression (16) was proposed as a solution to the transcendental inequation (15), based on the observation of a pronounced linearity of the function $Y_e(n_e)$ on a large part of the domain of interest and the subsequent necessity to round out, anyway, to a natural number the solution of (15).

The electrodes number n_e, determined as solutions of (15), as well as the EGR total masses M_P, calculated with (11), are given in Table I as n_e/M_P versus the considered values for the two independent variables, $\ell \in \{0,8; 1.0; 1.25; 1.5; 2.0; 2.5; 3.0; 4.0; 5.0\}$ m, $a \in \{0.3; 0.5; 0.7; 1.0; 1.5; 2.0; 2.5; 3.0\}$ m and for the parameters that intervene - $q = 0.8$ m, $\rho_P = 60$ Ωm, $d = 0.04$ m, $g = 0.004$ m, R_{Pn}=4 Ω, γ_m=7.8 kg/dm3.

To be emphasized that the electrodes numbers n_e obtained as solutions of (15) are rounded to the natural number immediately higher, but not until the even number immediately higher, as was done in previous works to meet the requirement of a rectangular placement. The aim was to stay around the analytical model solutions and not distorting the results by a visible increase of the electrodes number by the considered rounding.

TABLE I. Electrode Numbers/Total Metal Mass Of Conductive Materials For EGR With Vertical Electrodes Placed After A Rectangular Contour

Size, m		***a*, m**							
		0.3	0.5	0.7	1.0	1.5	2.0	2.5	3.0
ℓ, m	0.8	15/47.59	11/37.29	9/32.40	7/27.25	6/26.30	5/24.10	5/26.60	4/**22.52**
	1.0	14/54.27	10/40.90	8/34.34	7/32.19	6/30.53	5/27.63	4/23.48	4/25.35
	1.25	14/61.83	9/44.69	8/41.40	6/32.71	5/29.54	5/32.04	4/27.00	4/28.88

	1.5	13/73.3	9/52.63	7/42.29	6/38.00	5/33.95	4/28.66	4/30.53	4/32.40
	2.0	12/88.81	8/60.83	6/46.71	5/40.28	4/33.85	4/35.72	3/27.41	3/28.66
	2.5	11/100.8	7/65.50	6/57.30	5/49.10	4/40.90	3/31.46	3/32.71	3/33.95
	3.0	11/120.2	7/77.85	5/56.42	4/46.09	4/48.00	3/36.75	3/38.00	3/39.27
	4.0	10/144.5	6/87.81	5/74.07	4/60.20	3/46.09	3/47.34	3/48.58	2/31.97
	5.0	10/179.8	6/109.0	4/73.20	3/55.42	3/56.67	3/57.2	2/38.41	2/39.03

The electrodes number rounding to even numbers, due to the electrodes placement after a rectangular contour, can shift the local minima from the planes ℓ=constant to smaller values of a, such as in the case of ℓ=2.0 m, at the rounding to 4 of the electrodes number, for a=2.5 m, when the local minimum would move to a=2.0 m.

For a global perception of the function $M_P(\ell,a)$ variation, a 3D representation of the function was made, as can be seen in Fig. 2. The obtained surface waving, indicating local changes in the monotony character, is explained by rounding the electrodes number to natural ones, calculated as solutions of a transcendent equation. The surface $M_P(\ell,a)$ shape clearly highlights the absolute minimum, but also the small differences between this one and some local minima, located in the immediate vicinity.

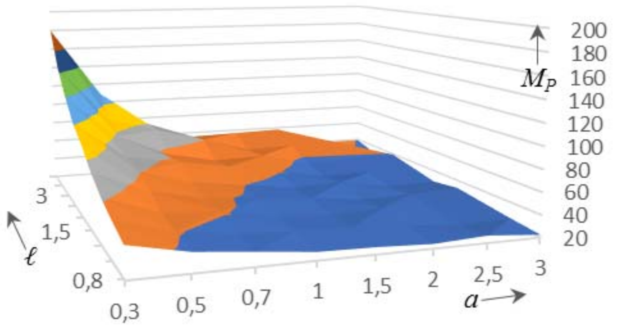


Fig. 2. Function $M_P(\ell$,a) representation of the EGR total metal mass versus the electrodes length ℓ and the distance a between the electrodes for the case ρ_p=50 Ωm and R_{Pn}=4 Ω.

Going through three methods of the EGR optimal design, focused on three minimal very different criteria, lead to the idea of a comparation between them. For this purpose, three solutions were chosen, the first three of those found in each of the applied performance criteria, which are presented in Table II.

The conditions for achieving the minimum of the three applied criteria, as well as the existence of some correlations between the minimum criteria, are the main objectives of the comparative analysis. It can be seen that both the footprint and the EGR volume are minimal at the lower considered values for the distance between electrodes, a=0.3 m, while the electrodes length ℓ minimizes the two criteria at the opposite limits of the considered range, as follows: to the largest limits, in the footprint case (ℓ=5 m), respectively to the smallest (ℓ=1 m) for the EGR total volume case.

TABLE II. COMPARISON OF THE FIRST THREE EGR MINIMUM SOLUTIONS, DETERMINED ACCORDINGLY THE ANALYZED THREE OPTIMAL CRITERIA

Performance criterion	**ℓ, m**	**a, m**	**r_{pv}, Ω**	**n_e**	**A_P, m2**	**V_P, m3**	**M_P, kg**	**R_P, Ω**
Footprint area	5.0	0.30	9.41	10	**0.90**	5.22	199.1	3.88
		0.50		6	1.50	8.70	120.6	3.75
		0.70		4	1.96	11.37	80.91	3.96
EGR volume	1.0	0.30	36.85	16	1.44	**2.59**	68.25	3.99
	1.1	0.30	34.43	16	1.44	2.74	74.51	3.92
		0.35		14	1.72	3.26	65.96	3.93
Conductive materials mass	0.8	3.0	38.32	4	36.0	57.60	**23.76**	3.79
		2.0		5	20.0	32.0	25.64	3.83
	1.0	2.5	32.64	4	25.0	45.0	25.02	3.91

Without calculating the correlation index values between the results of the three-minimum criteria application, it can be argued that there is a certain correlation between the footprint criteria and that of the EGR total volume regarding the distance a between electrodes, respectively between the total volume and the EGR metal mass criteria, regarding the electrodes length ℓ. These observations justify the assertion that the EGR total volume is practically somewhere between the other two mentioned optimal criteria.

It is furthermore considered to be fully significant to follow the evolution of the three sizes A_P, V_P și M_P, chosen as objective functions within each of the three applied criteria. The average of the three minimum solutions values, selected for the respective criterion (Table II) was considered as a characteristic value for each criterion. The following observations can be made:

- the footprint areas averages are almost identical when applying the minimum footprint criterion (A_{P1}=1.45 m2) and the EGR volume one (A_{P2}=1.53 m2), being about 18 times higher for the third criterion, the minimum conductive materials mass (A_{P3}=27 m2);
- the minimum, average volume recorded by applying the second criterion being V_{P2}=2.86 m3, it is found that it results almost 3 times multiplied to the minimum footprint criterion, (V_{P1}=8.43 m3) and close to 16 times greater to the minimum metallic mass criterion (V_{P3}=44.9 m3);
- if at the minimum metallic mass criterion the average value of the conductive materials total mass is M_{P3}=24.8 kg, there is an increase of this indicator at M_{P2}=69.6 kg, i.e. 2.8 times, to the EGR minimum volume criterion and to M_{P1}=133.5 kg, i.e. 5.4 times, to the minimum footprint criterion.

V. CONCLUSIONS

The EGR overall characteristic sizes proposed by the authors in a previous work, such as the footprint area, the EGR volume and the total metal mass of conductive materials, allow a synthetic appreciation of the possible solutions and provide a basis for defining some optimal criteria.

There is a non-linearity of the EGR sizing analytical model, so it was necessary to develop a computational algorithm to highlight the optimal solutions. Even if concrete applications were limited to EGR with the rated dispersion resistance of R_{Pn}=4 Ω, the calculation methodology has a general character and the stages of the process are clearly concretized in the paper. The variables involved were divided in two categories, the first one being of the independent variables, including the electrodes length ℓ and the distance a between the electrodes; the other sizes, such as soil resistivity, electrode diameter, EGR rated resistance and so on, have been included in the parameters category. The influences of the different parameters will be considered distinctly according to the priorities of each concrete application. The initially proposed algorithm was shortened by considering the resistance of both the electrodes and the connecting conductors, fact materialized in a new form of the transcendence inequation for the electrodes number determination.

Applying the first optimal criterion, of the EGR minimum footprint area, has led to the conclusion that deep EGR, which is having electrode lengths as large as possible and with electrodes as close as possible, determines small area footprints.

When applying the second optimal studied criterion of the EGR total volume, it can be stated that the EGR total minimum volume is obtained for the minimum considered lengths ℓ and distances a. This now seems normal, because the small distances between electrodes favor the obtaining of a footprint minimum area and the small electrodes lengths ℓ lead to low values of the EGR volume.

In principle, the EGR minimum metal mass is highlighted around larger distances between electrodes and especially in those areas where the electrodes number decreases by one unit owing to the increase of the EGR coefficient of use value and the decrease of the connecting conductors between electrodes equivalent resistance.

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