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Determination of the scope of the experimental-calculation method for measuring the touch voltage

The work is devoted to the improvement of methods for determining the normalized parameters of the grounding system (GS) of operating power stations and substations. The ***aim*** *of the work is determination of the scope of the experimental-calculated method for measuring the touch voltage, depending on short-circuit (SC) current value for the given dimensions of the GS and the type of soil.* ***Methodology****. The study analyzed the non-linear effect of the SC current value on the touch voltage, taking into account such factors as the GS size and the soil type. The calculation used statistical data on the GS size and the characteristics of the soil obtained by monitoring the GS state of 585 operating electrical substations with a voltage class of 110-750 kV using the induction method and the method of vertical soil sounding, respectively. For the calculation, a mathematical model of a non-equipotential GS located in a three-layer semiconductor space with plane-parallel boundaries was used, this model was developed using the method of integro-differential equations.* ***Results****. To determine the scope of the method, in this work it is proposed to use the linearity criterion, which is determined due to the ratio of the constant of reduced touch voltage to the current value. The example shows the method for determining the threshold minimum and maximum values of the measuring current of the soil, in the range between which the measurements by experimental-calculated methods are impossible. A table of threshold current values has been formed and recommendations have been developed on the possibility of using experimental-measuring methods for determining the touch voltage depending on the GS size and soil characteristics.* References 22, tables 3, figures 7.

Key words: **electrical substations, grounding system, modeling of the electromagnetic processes, touch voltage, soil characteristics, short-circuit.**

Метою роботи є визначення області застосування експериментально-розрахункового методу вимірювання напруги дотику в залежності від значення струму короткого замикання для заданих розмірів заземлювального пристрою (ЗП) та типу ґрунту. В дослідженні було проаналізовано нелінійний вплив величини струму КЗ на напругу дотику з урахуванням таких факторів як розмір ЗП та тип ґрунту. Для розрахунку була використана математична модель нееквіпотенційного ЗП, розташованого у тришаровому напівпровідному просторі з плоско-паралельними границями поділу, що була розроблена за допомогою методу інтегро-диференційних рівнянь. Для визначення області застосування методу в роботі запропоновано використовувати критерій лінійності, який визначається через відношення сталої приведеної напруги дотику до поточного значення. Сформовано таблицю значень порогових струмів та розроблено рекомендації щодо можливості використання експериментально-вимірювальних методів визначення напруги дотику в залежності від розміру ЗП та характеристик ґрунту. Бібл. 22, табл. 3, рис. 7.

Ключові слова: **електрична підстанція, заземлювальний пристрій, моделювання електромагнітних процесів, напруга дотику, характеристики ґрунту, коротке замикання.**

Problem. The grounding system (GS) of power stations and substations is a branched complex system of horizontal ground electrodes and vertical electrodes. The main purpose of the GS is to ensure the electrical safety of both the operating personnel of the power facility and unauthorized persons, as well as the reliable operation of the equipment.

In all regulatory documents, electrical safety at a power facility is characterized by the value of the touch voltage (U_t). In Ukraine, the permissible value of U_t is regulated by [1], in the European Union it is regulated by [2]. Swiss standards [3, 4], as well as Austrian [5] generally meet European Union requirements.

The method of electromagnetic diagnostics (EMD) has become widespread for determining the GS current state of operating power facilities. It involves the implementation of three stages [6]: the experimental stage, the calculation stage, and the stage of developing recommendations for reconstruction aimed at bringing the GS in line with the requirements of the current regulatory documents to further perform the main functions.

Over past 20 years specialist of Research & Design institute «Molniya» was diagnosis of 585 objects with a voltage class of 110-750 kV (operating power stations, substations of energy systems, mining and processing plants, factories, oil pumping stations, etc.), and it was found that the design of 97 % before reconstruction of GS was not meet the requirements of regulatory documents , and for more than 75 % it was exceeds the allowable values of the touch voltage [7], which can to severe post-accident consequences and poses a threat to the safety of people and animals.

A number of factors that significantly affect the value of the touch voltage were determined in [8]: the design of the GS, the electrophysical characteristics of the soil (EPC) and the resistance of the base at the place of maintenance of the equipment, etc. In this work, we will consider in detail the dependence of the touch voltage on the value of the ground fault current.

Analysis. According to the method of determining the touch voltage, three methods can be distinguished: experimental, calculated, and experimental-calculated.

The experimental method for measuring the touch voltage is carried out in the field on an operating object directly at a short-circuit (SC) current. It is dangerous, expensive and can be justified only in isolated cases in exceptional situations; therefore, it is practically not used.

The calculated method is based on the results of the GS EMD: the current structural state [9], additional experimental characteristics of the GS for assessing the adequacy of the calculation model [10, 11], and the EPC found using vertical electrical sounding (VES) [12]. The advantages of the method are the ability to determine the normalized parameters of the GS in all modes with a real SC current on all equipment with high accuracy (94 %), as well as checking the effectiveness of the developed recommendations [9]. In addition, the calculation programs take into account the geometric, electrical and magnetic parameters of ground electrodes. The disadvantages of the calculated method are the laboriousness of the work to determine the initial data (the actual state of the GS, the carrying out of the VES, etc.), the need for specialized expensive devices and software, as well as highly qualified scientific and technical personnel.

The experimental-calculated method has received the greatest distribution both in Ukraine and in the world. His varieties and analysis are considering in sufficient detail in [13]. The general principle is to measure U_t while simulating a SC mode on substation equipment. With the help of a sinusoidal current generator, a voltage is applied to the circuit (see Fig. 1) with a frequency close to the industrial one, but different from it and its harmonics. The current measuring electrode C is on distance L_C, which is, as a rule, 2–3 times greater than the diagonal GS (D). In this case, the current value in the circuit I_m is fixed using an ammeter A, and the measured touch voltage U_m is fixed using a voltmeter V connected in parallel with the resistor R_B, simulating the resistance of the human body (usually equal to 1000 Ω). The horizontal distance L_p from the contact point to the plate is assumed to be 0,8 m [1, 9] or 1,0 m [14, 15]. As a potential electrode P imitating two human feet, a plate with a contact surface of 25×25 cm^2 is used, which is loaded with a weight of at least 25 kg. To simulate the most unfavorable seasonal conditions, the place of potential electrode installation is moistened.

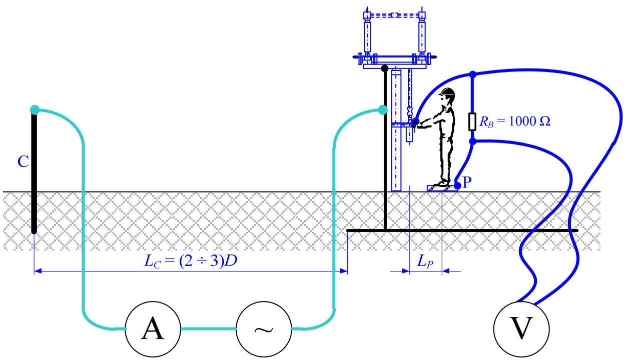

Fig. 1. The measurement circuit of touch voltage

In Ukraine and other countries of near and far abroad, a method of measuring at a low current value (up to 10 A) with subsequent reduction of the measured touch voltage in proportion to the real SC current has become widespread [9]:

$$U_t = U_m \frac{I_{SC}}{I_m}, \quad (1)$$

where I_{SC} is the SC current calculated according to the energy system data.

In the international standard IEEE [15], the determination of the touch voltage is performed at a current of 0,1–0,2 kA (method of current input or high current method), after which the measured values of the touch voltage are found by expression (1). In [16], it is indicated that a value ~ 0,1 kA is necessary to ensure the best signal-to-noise ratio. Thus, none of the analyzed sources considered the issue of the influence of the SC current value on the normalized parameters of the GS when carrying out the measurements.

In Ukraine, as in some other countries, the GS of power stations and substations are made of hot-rolled steel (coated or uncoated). When high currents of a single phase-to-earth fault (their value for power facilities in Ukraine can reach up to 60 kA) [17] flow by the elements of GS, the inductive component of the self-resistance of the ground electrodes is not a constant, which is explained by the nonlinear dependence of the magnetic permeability of steel on the strength of the magnetic field around, hence the magnitude of the current flowing through the ground electrode (see Fig. 2). It is assumed that the nonlinear dependence is more pronounced at low and medium currents.

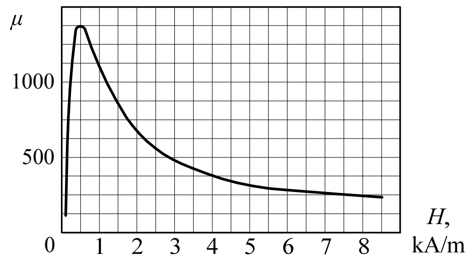

Fig. 2. The dependence of the magnetic permeability μ on magnetic field strength for steel BSt3SP (Fe37-3FN) [16]

Because of the type of dependence, it can be argued that the influence of the SC current or measuring current on the value of the normalized GS parameters is non-linear. Thus, the disadvantage of the experimental-calculated method for determining the touch voltage is the methodological error, which is associated with the neglect of the dependence of the magnetic permeability of the ground electrode material on the flowing current.

In addition, such measurements require the installation of a measuring electrode in the zone of zero potential, the distance to which L_C in 2-3 diagonals of the GS D (see Fig. 1) is valid only for homogeneous soil, for a two-layer soil such a distance can be in the range of 3-40 diagonals, as indicated by the data given in [14, 18, 19]. In conditions of dense buildings or developed infrastructure, this is almost impossible to achieve. Also, during a short-circuit, as a rule, part of the current flows in the neutral, which is not taken into account when measuring by this method. This component of the methodological measurement error is considered in detail in [8].

Nevertheless, there are current values at which magnetic saturation of the GS elements occurs and the dependence of the touch voltage on the SC current can be considered linear, and the GS resistance can be considered as a constant. In addition, the ascending part of the dependence in Fig. 2 is conditionally linear.

Thus, it can be assumed that there are such values of the measuring current and SC current for which expression (1) will be valid. At the same time, the main factors that affect the limit values of the above currents are the parameters that are individual for each power facility: the size of the GS and the EPC of the soil.

The aim of the work is determination of the scope of the experimental-calculated method for measuring the touch voltage, depending on SC current value for the given dimensions of the GS and the type of soil.

Research materials.

It is known that there are four types of VES curves, each of which is characterized by the ratio of the resistivity of the layers: Q – $\rho_1 > \rho_2 > \rho_3$; A – $\rho_1 < \rho_2 < \rho_3$; H – $\rho_1 > \rho_2 < \rho_3$; K – $\rho_1 < \rho_2 > \rho_3$. Taking into account the previously obtained statistical distribution of EPC [20], it is advisable to carry out the study for the data given in Table 1.

Table 1

Typical EPC of the soil

Soil type	ρ_1, Ω×m	ρ_2, Ω×m	ρ_3, Ω×m	h_1, m	h_2, m
Q	100	50	10	0,8	6,3
H	100	50	100	0,8	6,3
K	10	100	10	0,8	6,3
A	10	50	100	0,8	6,3

As part of the GS EMD of 585 power facilities of Ukraine with a voltage class of 110-750 kV, the distribution of the GS size *S* was obtained (see Fig. 3,*a*) and it was determined that its value varies in the range from 122 m^2 to 436158 m^2.

This approximately corresponds to the GS size from 11 m × 11 m to 660 m × 660 m. Figure 3,*b* shows the distribution of the SC current value for the selected database. The database of SC was formed on the basis of responses to requests to operating organizations, similarly to [17]. In this case, the current value is in the range from 0,74 kA to 59,995 kA, and the median is 8,47 kA. In Fig. 3,*a*,*b*: *f* is the number of energy facilities as a percentage of all selected ones.

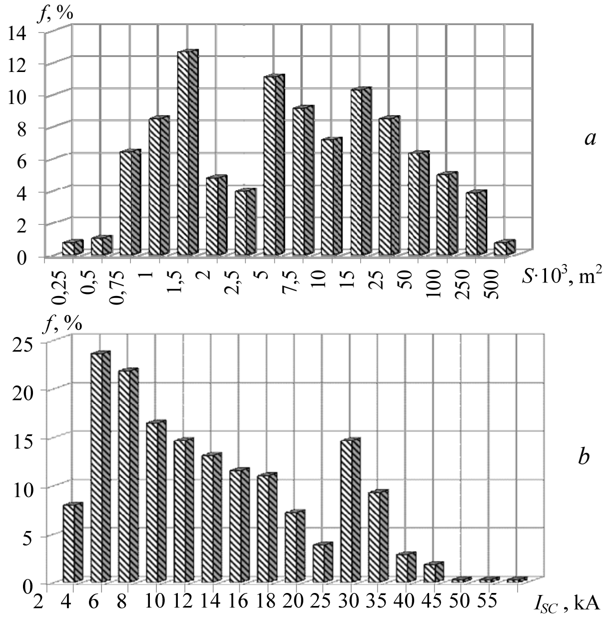

Fig. 3. The number of energy facilities as a percentage: *a* – GS size distribution of; *b* – SC current distribution

To carry out the study, the range of GS size *S* is [30×30; 156×156] m^2 was chosen, and the value of the SC current I_{SC} is [0,2; 20] kA, which allows covering about 75 % of cases. For the calculation, a mathematical model of a non-equipotential GS located in a three-layer semiconductor space with plane-parallel separation boundaries was used, developed using the method of integro-differential equations [10, 11, 21]. The determination of the normalized parameters was carried out for the specified current ranges, while the GS was located at a depth of 0,5 m, the size of its cell was 6 m × 6 m, and the cross section was ∅14 mm.

It should be noted that the dependence of the touch voltage value or the reduced touch voltage on the SC current is inconvenient for analysis, since visually the curves look close to straight lines (see Fig. 4), which does not allow determining the linear section of the dependence for direct recalculation using the expression (1).

Current and voltage are generally vector values. According to the theorem on the linear dependence of vectors, vectors will be linearly dependent if and only if at least one of them is a linear combination of others [22]. As can be seen from Fig. 4, there are the following SC current values, starting from which the reduced touch voltage $U'_t = U_t / I_{SC}$ is almost constant (U'_{tconst}). Therefore, to determine the range at which the touch voltage can be considered linearly dependent on the SC current, it is proposed to use the linearity criterion K_{con}, the value of which should be less than the engineering error of 10 %:

$$K_{con} = \left(\frac{U'_{ti}}{U'_{const}} - 1 \right) \times 100\% < 10\% . \quad (2)$$

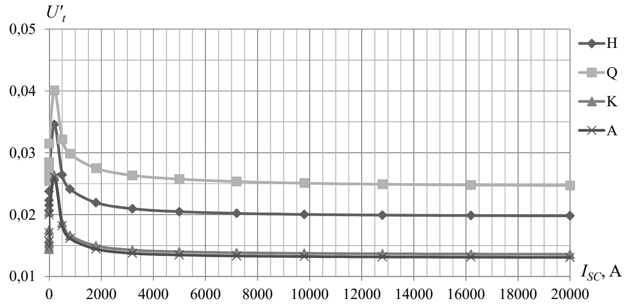

Fig. 4. The dependence of reduced touch voltage on the SC current for the steel GS, *S* = (156×156) m^2 and soil (Table 1)

As a result of the calculations, a number of dependences of the values of the GS normalized parameters on three factors were obtained: the SC current value, the GS size, and the soil type (see Table 1). For example, Table 2 shows the characteristic points of such a dependence for the area *S* = (30×30) m^2. As a steady value of the reduced touch voltage, we consider one that does not change with increasing current. For example, for soil type A and GS with 30×30 m^2, U'_{tconst} = 0,025 V/A.

The data obtained indicate that there are intervals before and after the threshold values of the currents $I_{\min}$ and $I_{\max}$, respectively, where the criterion K_{con} is less than 10 %, therefore, a directly proportional recalculation can be applied. Based on the calculated data, it is possible to construct a family of curves for the corresponding areas. Their general view is shown in Fig. 5.

It should be noted that the use of other values of specific resistances, sizes of GS and sizes of GS cells can affect the absolute values of the calculated parameters, but does not change the general appearance of the curves.

Consider the method for finding the values of the currents $I_{\min}$ and $I_{\max}$ using the example of GS with an area of 30×30 m^2. Fig. 6 shows the ascending and descending part of the curves for different soil types. In Table 2 (soil type K) we find that with an increase in current from 0,05 A to 0,50 A, the coefficient K_{con} increases from 1,188 % to 10,163 %, therefore, the corresponding current value determined by interpolation for K_{con} = 10 % can be considered as the lower limit of applying the techniques of linear recalculation for GS of the specified area and soil type: $I_{\min}$ = 0,48 A.

Table 2

The dependence of the calculated GS parameters on the SC current

SC current I_{SC}, A	Voltage on the GS U_G, V	Touch voltage U_t, V	Reduced touch voltage U'_t	Linearity criterion K_{con}, %	Voltage on the GS U_G, V	Touch voltage U_t, V	Reduced touch voltage U'_t	Linearity criterion K_{con}, %
	Soil type K				**Soil type A**			
0,05	0,02	0,0017	0,035	1,188	0,0421	0,0013	0,025	1,758
0,10	0,04	0,0035	0,035	2,361	0,0842	0,0026	0,026	3,496
0,30	0,12	0,0109	0,036	6,467	0,2531	0,0081	0,027	9,598
0,35	0,15	0,0128	0,037	7,431	0,2954	0,0096	0,027	10,983
0,45	0,188	0,017	0,037	9,302	0,38	0,01	0,028	13,603
0,50	0,209	0,019	0,038	10,163	0,42	0,01	0,028	14,851
16,0	7,012	0,934	0,058	71,286	13,840	0,805	0,050	103,30
54,0	23,55	2,99	0,055	62,509	46,63	2,55	0,047	90,985
549,3	230,2	20,7	0,038	10,431	465,2	15,7	0,029	15,590
686,0	286,9	25,2	0,037	7,870	580,3	19,0	0,028	11,811
843,8	352,3	30,6	0,036	6,196	713,1	22,8	0,027	9,299
2000,0	830,9	69,6	0,035	2,038	1686,0	51,0	0,026	3,092
3041,8	1262,0	104,7	0,034	0,956	2562,0	76,4	0,025	1,517
20000	8279,0	681,9	0,034	0,000	16830	494,9	0,025	0,000
	Soil type Q				**Soil type H**			
0,05	0,03	0,013	0,256	0,118	0,0645	0,0100	0,201	0,150
0,10	0,06	0,026	0,256	0,274	0,1290	0,0201	0,201	0,349
6,8	4,174	1,836	0,272	6,541	8,825	1,467	0,217	8,504
16,0	9,974	4,426	0,277	8,353	21,000	3,551	0,222	10,803
31,3	19,490	8,646	0,277	8,371	41,020	6,937	0,222	10,826
54,0	33,55	14,81	0,274	7,426	70,760	11,860	0,220	9,650
2000,0	1202,0	512,4	0,256	0,353	2581,0	402,4	0,201	0,449
4920,8	2953,0	1257,0	0,255	0,058	6345,0	986,8	0,201	0,119
5488,0	3293,0	1402,0	0,255	0,065	7076,0	1100,0	0,200	0,069
16200	9716,0	4136,0	0,255	0,003	20880	3245,0	0,200	0,004
20000	11990,0	5106,0	0,255	0,000	25780	4006,0	0,200	0,000

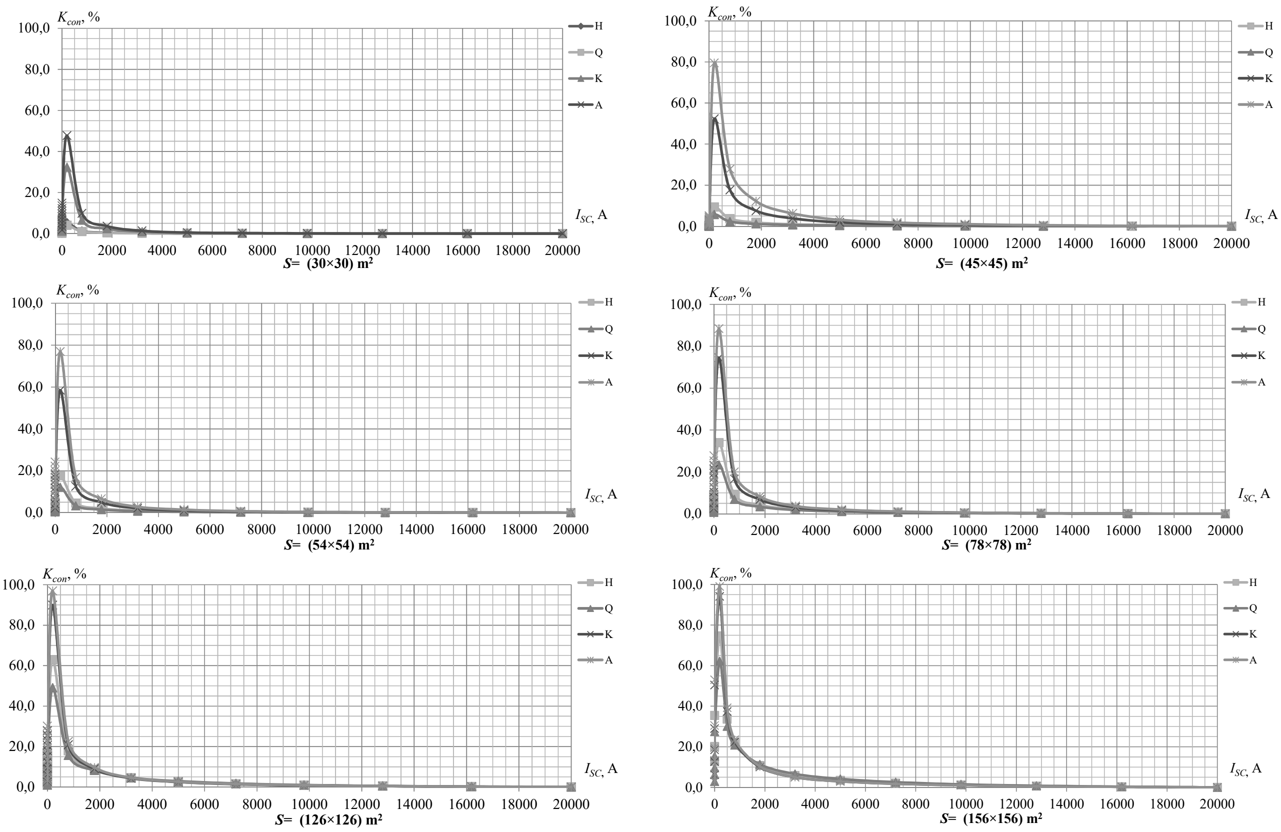

Fig. 5. The dependence of the linearity criterion on the current simulating a SC for a GS of a given area for different soil types

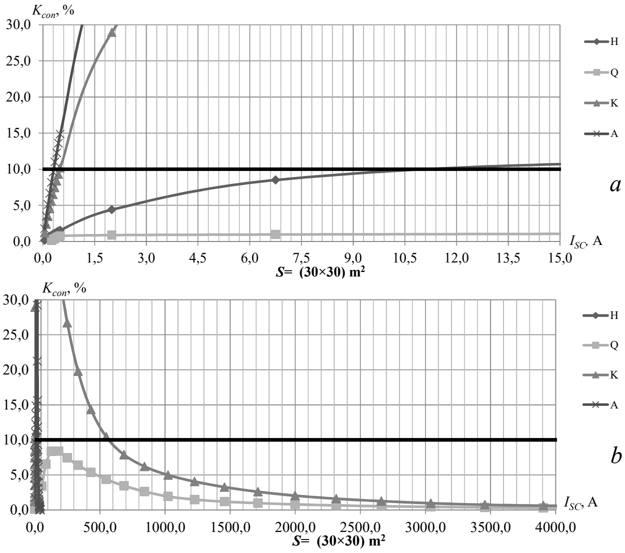

Fig. 6. The dependence of the linearity criterion K_{con} on the current simulating a SC: *a* – ascending; *b* – descending

Then follows the non-linearity section caused by the dependence of the magnetic permeability of the ground electrode material on the magnetic field strength and, accordingly, on the SC current (see Fig. 2). Starting from the value of 16 A, the value of the criterion K_{con} passes to the descending part, and at a current of approximately 550 A, it crosses the 10 % boundary, then gently decreases to 0. Thus, in this case, we accept $I_{\max}$ = 550 A.

Similarly, the corresponding values of the boundaries of the currents $I_{\min}$ and $I_{\max}$ were found for all soil types and the considered sizes of the GS. The data obtained are summarized in Table 3.

Table 3

Threshold current values for using the experimental-calculated method for determining the touch voltage

GS area S, m^2	Low current method $I_{\max}$, A				High current method $I_{\min}$, A			
	H	Q	K	A	H	Q	K	A
30×30	12,7	–	0,48	0,32	32	–	550	800
45×45	12,1	–	0,4	0,3	149	–	600	820
54×54	3,5	100	0,25	0,17	525	350	900	1050
78×78	0,6	25	0,19	0,16	900	650	1050	1400
126×126	0,27	0,39	0,16	0,15	1500	1300	1700	1800
156×156	0,24	0,3	0,13	0,13	1900	2000	1800	1850

In Table 3 for soil type Q and GS areas 30×30 m^2 and 45×45 m^2 the lines with the sign «–» mean that there are no restrictions on the measuring current, because in all cases, the linearity criterion is less than 10 %.

The obtained dependencies form the limits of application of the experimental-calculated method for determining the touch voltage, because the criterion for the possibility of linear recalculation allows the possibility of measurement under the following condition:

$$I_m \le I_{\min} \quad \text{or} \quad I_m \ge I_{\max} . \qquad (3)$$

That is, for GS with an area of 30×30 m^2 located in soil type A, the measuring current must meet the following requirements: $I_{\min} \le$ 0,32 A and $I_{\max} \ge$ 800 A.

The use of a measuring current of more than 800 A threatens sensitive microprocessor technology, expensive high-voltage equipment, and the relay protection system.

Provided that all soil types are covered and for considered dimensions of GS substation, the measurement requires a current with a value of at least 2000 A. The use of such a current for the considered soil types with the resistance of the feet R_f = 100 Ω and GS with S = 156×156 m^2 will lead to a touch voltage from 219 V up to 495 V (you can get the indicated values from the graph in Fig. 4 by multiplying the corresponding current value by the reduced touch voltage). Furthermore, such a current is dangerous.

In addition, it follows from this that a proportional recalculation of the touch voltage value measured by the low current method for GS of arbitrary size with an arbitrary soil type is possible only for substations in which the SC current will exceed 2000 A.

The use of the experimental-calculated method with a low current value is acceptable for GS with the area 30×30 m^2 and 45×45 m^2 located in the soil type Q, and for the IEEE method – GS with the area 30×30 m^2 and 45×45 m^2 for soil types H and Q and 54×54 m^2 – for soil type Q.

The carrying out measurements using the low current method, even for GS with the area S = 30×30 m^2, requires a measuring current not exceeding 0,32 A (to cover all possible soil types). Such a current, subject to the resistance of the feet R_f = 100 Ω, creates a touch voltage not exceeding 8,1 mV (type A), and for large substations, the value of U_m will be even less. Taking into account that measurements are carried out at an operating power facility, with electric field strength of up to 30 kV/m and a measuring current with a frequency close to the industrial one, there are only two options for determining the touch voltage:

- the use of an experimental-calculated method using the existing fleet of instruments for some soil types and GS sizes, according to the restrictions given in Table 3 and expression (3), or the creation of new instruments that can measure U_m with a value of less than a few millivolts at a frequency close to the industrial one, in a complex electromagnetic environment;
- the use of the calculated method based on the data obtained using the GS EMD with the verification of the adequacy of the calculated model [10].

An alternative is relevant to develop devices with the ability to measure units of millivolts, provided that they operate at a frequency close to an industrial one and external electric field strength of up to 30 kV/m for determining the touch voltage by using the experimental-calculated method.

It should be noted that such dependence is not observed for GS made of a diamagnetic or paramagnet, which makes it possible to use the experimental-calculated method for measuring the touch voltage for GS made, for example, of copper (see Fig. 7) without restrictions.

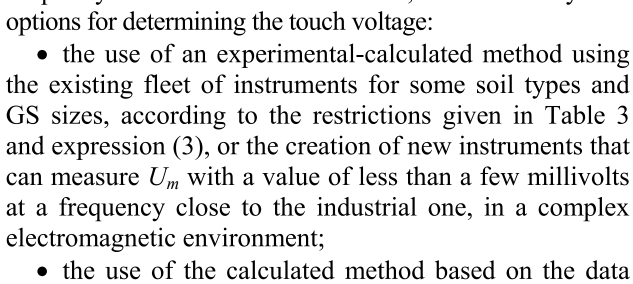

Fig. 7. The dependence of the reduced touch voltage value on the SC current for GS made of a copper at S = (30×30) m^2 and given soil parameters from Table 1

Conclusions.

1. For the first time, it was proposed to set the minimum and maximum threshold values of the measuring current for determine of the scope application of the experimental-calculated method for measuring the touch voltage. It has been proved that a proportional recalculation of the measured touch voltage value is possible only for the GS of substations, in which the SC current will exceed 2000 A.

2. It was found that using of the experimental-calculated method for GS made of steel (or other ferromagnetic material) with:

- low measuring current is limit for GS with the area 45×45 m^2 (and less) located in soil type Q;
- high measuring current (IEEE method) is limit for GS with the area 30×30 m^2 and 45×45 m^2 for soil types H and Q, 54×54 m^2 – for soil type Q.

3. Determining the touch voltage by the experimental-calculated method for GS of other sizes located in soil types H and Q, as well as soil types K and A types with the modern level of instruments is impossible with an error of less than 10 %.

Conflict of interest. The authors declare that they have no conflicts of interest

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