RT&A, No 4(80)
Volume 19, December, 2024

MODELING OF ARC OVERVOLTAGE DEPENDENCE ON GROUND CIRCUIT RESISTANCE AND PHASE CAPACITANCE

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Abstract

The need to control the arc overvoltage during the insulation under load test in neutral insulated networks requires the determination of dependencies between single-phase non-stationary ground and parameters characterizing the faults. In most cases, the identification and realization of such dependencies is observed with a number of difficulties. Therefore, for practical conditions, simple mathematical models should be developed that allow knowing the dependencies between these parameters. In this work, the problem of determining the relationship between the overvoltage generated in the neutral isolated network as a result of artificial non-stationary earth faults, the earth fault resistance and the phase capacitance of the network with respect to the earth was considered. For this purpose, using the least squares method, a regression equation was obtained for the dependence of the frequency of overvoltage on the ground fault resistance and the phase capacitance of the network with respect to the ground, and a corresponding 3D image was constructed.

Keywords: neutral isolated network, non-stationary earth fault, earth fault resistance, frequency of overvoltage, regression equation, 3D modeling

I. Introduction

Neutral isolated networks play an important role in uninterrupted supply of electricity to operators. Since such networks mainly carry out the distribution of electric energy between operators, they include a large number of transmission overhead and cable lines. In the process of operation, the insulation of these power lines, especially cable lines, is subjected to long-term electrical, thermal and mechanical effects, so the dielectric properties deteriorate, in other words, the insulation resistance and electrical strength decrease. For this reason, it is important to detect parts of networks with poor insulation before damage occurs and to restore damaged areas.

Therefore, network equipment is periodically taken out of service and its insulation is tested [1,2]. Due to the large number of equipment, such tests are not considered convenient as they require a lot of time and labor. For this reason, various methods have been proposed to test network insulation under load without opening the equipment [3-5].

Insulation under load testing with the above-mentioned methods is based on the principle of creating artificial earth faults in the network. However, the devices used during the application of these methods cannot perform regulation and control functions. For this reason, new test method of insulation in neutral insulated networks was proposed [6]. According to the proposed method, controlled and adjustable artificial non-stationary earth faults are created in the network to test the insulation under load without disconnecting the equipment from the network. It should be noted that the value of the arc overvoltage generated during such earth faults based on Petersen's theory depends on the phase capacity of the network with respect to the earth, the earth fault resistance and the earth fault angle. Therefore, for the determination and control of the value of the test voltage, the preliminary determination of the values of the ground fault resistance, the ground fault angle and the capacitance of the network with respect to the ground is of particular importance and is an urgent issue.

For this purpose, in the previous works of the authors, the frequency of arc overvoltage generated in neutral insulated networks as a result of artificial non-stationary earth faults was determined separately and some pair correlation dependences on earth fault resistance, earth fault angle and phase capacity of the network with respect to earth [7-14]. As a continuation of the studies mentioned in the present study, the correlation dependence of the frequency of artificial earth fault arc overvoltage on the earth fault resistance and the phase capacity of the network with respect to earth is studied, and based on this dependence, an effective, easy-to-realize regression model is proposed for the purpose of controlling the arc overvoltage.

II. Problem statement for arc overvoltage regression model

In order to determine the dependencies of the artificial earth fault arc overvoltage frequency, the earth fault resistance, the earth fault angle and the phase capacity of the network with respect to the earth, using one of the numerical methods of the system of differential equations characterizing the transition process of the non-stationary earth fault created in the neutral isolated networks, with the application of modern computing technologies solution must be performed. However, the solution of the problem by numerical methods becomes much more difficult due to the greater non-linearity of the mentioned differential equations, "stiffness" due to the impossibility of determining certain parametric quantities, due to the mentioned reasons, in certain cases, the stability of the solution of the system of differential equations is violated and the results are distorted. Therefore, to overcome such difficulties, the frequency of arc overvoltage (k) with ground fault resistance (R_0), angle of closure with the ground $(\varphi)$and the phase capacitance of the network with respect to ground (C_f) Obtaining analytical expressions that determine the dependencies between them is one of the important issues.

It should be noted that in relation to the above-mentioned issues, in [7,8], the arc overvoltage ratio is determined from the ground fault resistance, in [9,10], the arc overvoltage ratio is determined from the ground fault angle, and in [11,12], the arc overvoltage ratio is determined. In [13,14], the dependence of the frequency on the phase capacity of the network with respect to the ground, and in [13,14], the analytical expressions for the dependences of the arc overvoltage on the resistance of the network to the ground and the angle to the ground have already been considered.

The compact regression models of arc overvoltage obtained in the mentioned works practically simplify the process of controlling its value during equipment tests. It is important to obtain dependences on other parameters for adjusting the value of arc overvoltage and to continue research in this direction. As a continuation of the conducted research, the regression model of the dependence of the ground fault resistance of the non-stationary arc overvoltage and the phase capacity of the network with respect to the ground is considered.

III. Problem solving method and algorithm

During single-phase earth faults in the neutral isolated electrical network obtaining an analytical expression for the dependence of the frequency of the resulting arc overvoltage on the ground fault resistance and the phase capacitance of the network with respect to the ground is considered. For this purpose, the results of the experimental studies carried out in the low-voltage model of the neutral-isolated network, given in table 1, are used $(\varphi = 90^\circ)$ [6].

Table 1: $k = f(R_0, C_f)$ *addiction*

R_0, Om	C_f, mkF						
	1	2	3	4	5	6	8
5	3.30	2.99	2.85	2.74	2.66	2.58	2.47
10	2.96	2.74	2.59	2.47	2.39	2.33	2.21
15	2.77	2.54	2.39	2.28	2.20	2.14	2.08
20	2.62	2.38	2.24	2.13	2.06	2.01	1.92
25	2.49	2.25	2.12	2.02	1.95	1.91	1.84
30	2.38	2.15	2.02	1.93	1.88	1.84	1.80

It should be noted that the proposed forms of regression models of arc overvoltage in [13,14] greatly simplify the issues of its management from the point of view of its technical implementation, and therefore it was proposed to use that form in the work under consideration. The data in Table 1 and the conducted analyzes showed that the dependence between the frequency of the earth fault arc overvoltage and the earth fault resistance and the phase capacity of the network with respect to the earth can be approximated by the hyperbolic regression equation expressing the following theoretical-probability scheme (NES) [7-14,15]:

$$k = \frac{a}{R_0} + \frac{b}{C_f} + c, \tag{1}$$

Here a, b, $c-$ called regression coefficients.

(1) to simplify the matter in $\frac{1}{R_0} = x$ and $\frac{1}{C_f} = y$ if we accept substitutions (1), NES is expressed by the following equation:

$$k = ax + by + c, \tag{2}$$

In other words, the frequency of arc overvoltage (k) with the conductance of the ground fault circuit (x) and the inverse value of the phase capacitance of the network with respect to earth (y) NES between can be approximated by the linear regression equation. The values of the new (x, y) quantities are given in table 2.

Table 2: $k = f(x, y)$ *addiction*

x	y						
	1.00	0.50	0.333	0.250	0.200	0.167	0.125
0.200	3.30	2.99	2.85	2.74	2.66	2.58	2.47
0.100	2.96	2.74	2.59	2.47	2.39	2.33	2.21
0.067	2.77	2.54	2.39	2.28	2.20	2.14	2.08
0.050	2.62	2.38	2.24	2.13	2.06	2.01	1.92
0.040	2.49	2.25	2.12	2.02	1.95	1.91	1.84
0.033	2.38	2.15	2.02	1.93	1.88	1.84	1.80

In this case, the least squares method is used to determine the regression coefficients [15, p.55-59].

It is known that, according to this method, it is required to choose the values of the regression coefficients in such a way that the sum of the squares of the errors between the approximating function and the experimental values is the smallest or minimum:

$$S(a,b,c) = \sum_{i=1}^{n} (ax_i + by_i + c - k_i)^2 \to \min, \tag{3}$$

$S(a,b,c)$for the function to get the smallest (minimum) value a, b and $c-$ according to which the special derivatives given below must be equal to zero:

$$\begin{cases} \dfrac{\partial S(a,b,c)}{\partial a} = 0; \\ \dfrac{\partial S(a,b,c)}{\partial b} = 0; \\ \dfrac{\partial S(a,b,c)}{\partial c} = 0. \end{cases} \tag{4}$$

$S(a,b,c)$ from the function$a, b$and$c$ –taking special derivatives according to (4), taking into account in the system of equations, the following system of linear equations is obtained:

$$\begin{cases} a\sum_{i=1}^{n} x_i^2 + b\sum_{i=1}^{n} x_i y_i + c\sum_{i=1}^{n} x_i = \sum_{i=1}^{n} k_i x_i; \\ a\sum_{i=1}^{n} x_i y_i + b\sum_{i=1}^{n} y_i^2 + c\sum_{i=1}^{n} y_i = \sum_{i=1}^{n} k_i y_i; \\ a\sum_{i=1}^{n} x_i + b\sum_{i=1}^{n} y_i + cn = \sum_{i=1}^{n} k_i. \end{cases} \tag{5}$$

To solve the system of equations (5), the correlation table given in table 3 is used. In Table 3, the following notations are adopted:

$$A_i = \left| \frac{ax_i + by_i + c - k_i}{k_i} \right|; \quad B_i = (ax_i + by_i + c - k_i)^2$$

Optional data array: $n = 42$;

$$\sum_{i=1}^{n} x_i = 3{,}43; \ \sum_{i=1}^{n} y_i = 15{,}45; \ \sum_{i=1}^{n} k_i = 97{,}62;$$

$$\sum_{i=1}^{n} x_i^2 = 0{,}4176; \ \sum_{i=1}^{n} y_i^2 = 9{,}0421; \ \sum_{i=1}^{n} k_i^2 = 232{,}157;$$

Table 3: *Table showing correlation report sequence*

i	x_i	y_i	k_i	x_i^2	y_i^2	k_i^2	$x_i y_i$	$k_i x_i$	$k_i y_i$	A_i	B_i
1	0.200	1,000	3.30	0.040	1.000	10.890	0.200	0.660	3,300	0.0139930	0.0021323
2	0.100	1,000	2.96	0.010	1.000	8.762	0.100	0.296	2,960	0.0233497	0.0047769
3	0.067	1,000	2.77	0.004	1.000	7.673	0.067	0.185	2,770	0.0111477	0.0009535
4	0.050	1,000	2.62	0.003	1.000	6.864	0.050	0.131	2,620	0.0165034	0.0018696
5	0.040	1,000	2.49	0.002	1.000	6.200	0.040	0.100	2,490	0.0512890	0.0163098
6	0.033	1,000	2.38	0.001	1.000	5.664	0.033	0.079	2,380	0.0871247	0.0429969
7	0.200	0.500	2.99	0.040	0.250	8.940	0.100	0.598	1,495	0.0086820	0.0006739
8	0.100	0.500	2.74	0.010	0.250	7.508	0.050	0.274	1,370	0.0843982	0.0534770
9	0.067	0.500	2.54	0.004	0.250	6.452	0.033	0.169	1,270	0.0720532	0.0334945
10	0.050	0.500	2.38	0.003	0.250	5.664	0.025	0.119	1,190	0.0415534	0.0097806
11	0.040	0.500	2.25	0.002	0.250	5.063	0.020	0.090	1,125	0.0064117	0.0002081
12	0.033	0.500	2.15	0.001	0.250	4.623	0.017	0.072	1,075	0.0256842	0.0030494
13	0.200	0.333	2.85	0.040	0.111	8.123	0.067	0.570	0.950	0.0046799	0.0001779
14	0.100	0.333	2.59	0.010	0.111	6.708	0.033	0.259	0.863	0.0805520	0.0435263
15	0.067	0.333	2.39	0.004	0.111	5.712	0.022	0.159	0.797	0.0671103	0.0257261
16	0.050	0.333	2.24	0.003	0.111	5.018	0.017	0.112	0.747	0.0385159	0.0074435
17	0.040	0.333	2.12	0.002	0.111	4.494	0.013	0.085	0.707	0.0055683	0.0001394
18	0.033	0.333	2.02	0.001	0.111	4.080	0.011	0.067	0.673	0.0286348	0.0033457
19	0.200	0.250	2.74	0.040	0.063	7.508	0.050	0.548	0.685	0.0120339	0.0010872
20	0.100	0.250	2.47	0.010	0.063	6.101	0.025	0.247	0.618	0.0616676	0.0232011
21	0.067	0.250	2.28	0.004	0.063	5.198	0.017	0.152	0.570	0.0500364	0.0130149
22	0.050	0.250	2.13	0.003	0.063	4.537	0.013	0.107	0.533	0.0187629	0.0015972
23	0.040	0.250	2.02	0.002	0.063	4.080	0.010	0.081	0.505	0.0121316	0.0006005
24	0.033	0.250	1.93	0.001	0.063	3.725	0.008	0.064	0.483	0.0436026	0.0070817
25	0.200	0.200	2.66	0.040	0.040	7.076	0.040	0.532	0.532	0.0281050	0.0055890
26	0.100	0.200	2.39	0.010	0.040	5.712	0.020	0.239	0.478	0.0462479	0.0122174
27	0.067	0.200	2.20	0.004	0.040	4.840	0.013	0.147	0.440	0.0328621	0.0052268
28	0.050	0.200	2.06	0.003	0.040	4.244	0.010	0.103	0.412	0.0039702	0.0000669
29	0.040	0.200	1.95	0.002	0.040	3.803	0.008	0.078	0.390	0.0288678	0.0031688
30	0.033	0.200	1.88	0.001	0.040	3.534	0.007	0.063	0.376	0.0510316	0.0092044
31	0.200	0.167	2.58	0.040	0.028	6.656	0.033	0.516	0.430	0.0501100	0.0167143
32	0.100	0.167	2.33	0.010	0.028	5.429	0.017	0.233	0.388	0.0326216	0.0057773
33	0.067	0.167	2.14	0.004	0.028	4.580	0.011	0.143	0.357	0.0176506	0.0014267
34	0.050	0.167	2.01	0.003	0.028	4.040	0.008	0.101	0.335	0.0081322	0.0002672
35	0.040	0.167	1.91	0.002	0.028	3.648	0.007	0.076	0.318	0.0370767	0.0050150
36	0.033	0.167	1.84	0.001	0.028	3.386	0.006	0.061	0.307	0.0600346	0.0122022
37	0.200	0.125	2.47	0.040	0.016	6.101	0.025	0.494	0.309	0.0839834	0.0430309
38	0.100	0.125	2.21	0.010	0.016	4.884	0.013	0.221	0.276	0.0054964	0.0001476
39	0.067	0.125	2.08	0.004	0.016	4.326	0.008	0.139	0.260	0.0046235	0.0000925
40	0.050	0.125	1.92	0.003	0.016	3.686	0.006	0.096	0.240	0.0388026	0.0055504
41	0.040	0.125	1.84	0.002	0.016	3.386	0.005	0.074	0.230	0.0592238	0.0118749
42	0.033	0.125	1.80	0.001	0.016	3.240	0.004	0.060	0.225	0.0658995	0.0140705
⚜	**3.430**	**15.450**	**97.62**	**0.4176**	**9.0421**	**232.157**	**1.2618**	**8.5982**	**38.477**	**1.5202260**	**0.4483068**

$$\sum_{i=1}^{n} x_i y_i = 1{,}2618; \ \sum_{i=1}^{n} k_i x_i = 8{,}5982; \ \sum_{i=1}^{n} k_i y_i = 38{,}477;$$

$$\sum_{i=1}^{n} \left| \frac{ax_i + by_i + c - k_i}{k_i} \right| = 1{,}520226; \ \sum_{i=1}^{n} (ax_i + by_i + c - k_i)^2 = 0{,}4483068.$$

(5) the system of linear equations is solved by one of the known methods and the regression coefficients are found, and the following values were obtained in the considered sample:

$$a = 4{,}55; \ b = 0{,}76; \ c = 1{,}67.$$

Thus, after determining the regression coefficients, the NES (2) between the frequency of the arc overvoltage generated in neutral insulated networks as a result of non-stationary earth faults and the conductance of the earth fault circuit and the inverse value of the phase capacitance of the network with respect to earth is written in the following obvious way:

$$k = 4{,}55x + 0{,}76y + 1{,}67 \tag{6}$$

Pairwise linear correlation coefficients are defined by the following well-known expressions:

$$\left.\begin{aligned} r_{xy} &= \frac{\overline{xy} - \bar{x} \cdot \bar{y}}{\sigma_x \sigma_y}; \\ r_{kx} &= \frac{\overline{kx} - \bar{k} \cdot \bar{x}}{\sigma_k \sigma_x}; \\ r_{ky} &= \frac{\overline{ky} - \bar{k} \cdot \bar{y}}{\sigma_k \sigma_y}. \end{aligned}\right\} \tag{7}$$

Here $\bar{x}, \bar{y}, \bar{k}$ – properly x, y, k average prices of quantities; $\overline{xy}, \overline{kx}, \overline{ky}$ – properly average prices of products; $\sigma_x, \sigma_y, \sigma_k$ – properly x, y, k mean square deviations of their quantities are determined according to the correlation table (Table 3):

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} = 0{,}082; \quad \bar{y} = \frac{\sum_{i=1}^{n} y_i}{n} = 0{,}368; \quad \bar{k} = \frac{\sum_{i=1}^{n} k_i}{n} = 2{,}324;$$

$$\overline{xy} = \frac{\sum_{i=1}^{n} x_i y_i}{n} = 0{,}03; \quad \overline{kx} = \frac{\sum_{i=1}^{n} k_i x_i}{n} = 0{,}205; \quad \overline{ky} = \frac{\sum_{i=1}^{n} k_i y_i}{n} = 0{,}916;$$

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n} x_i^2}{n} - \bar{x}^2} = 0{,}057; \quad \sigma_y = \sqrt{\frac{\sum_{i=1}^{n} y_i^2}{n} - \bar{y}^2} = 0{,}283; \quad \sigma_k = \sqrt{\frac{\sum_{i=1}^{n} k_i^2}{n} - \bar{k}^2} = 0{,}354;$$

Then according to statements (7):

$$r_{xy} = 0; \ r_{kx} = 0{,}736; \ r_{ky} = 0{,}611.$$

After that, no-conductivity of the earth fault circuit with the frequency of overvoltage during stationary earth faults and the inverse value of the phase capacitance of the network with respect to earth it is required to check the adequacy of the NES regression equation obtained between (6). For this, by calculating the multidimensional correlation coefficient, its significance can be checked with the well-known Fisher criterion [15].

The value of the multivariate correlation coefficient is determined by the following well-known expression:

$$R = \sqrt{\frac{r_{kx}^2 + r_{ky}^2 - 2r_{kx}r_{ky}r_{xy}}{1 - r_{xy}^2}} = 0{,}96.$$

The multivariate correlation coefficient is close to unity $(R = 0{,}96 \to 1)$ indicates that the dependence between the frequency of arc overvoltage and the conductance of the ground fault circuit and the inverse value of the phase capacitance of the network with respect to ground can be considered a strong linear correlation relationship.

Determining the significance of the multivariate correlation coefficient and the full adequacy of the model in general is traditional $F-$Fisheris checked with the criterion. It is known that α at the level of significance, the regression equation is considered adequate if $F > F(\alpha, q_1, q_2)$ be paid conditionally [16], here $q_1, q_2 -$are the degrees of freedom.

$F-$Fisher the reporting value of the criterion is determined as follows based on the data:

$$F = \frac{R^2}{1 - R^2} \cdot \frac{n - m - 1}{m}, \tag{8}$$

Here $n-$number of experiments, $n = 42$; $m-$is the number of factors, $m = 2$. Then according to statement (8). $F = 229{,}22$.

$F-$Fisher the table value of the criterion is the level of significance (α) and degrees of freedom (q_1, q_2) depending is taken from the table [16]:

$$\alpha = 0{,}05;\ q_1 = m = 2;\ q_2 = n - m - 1 = 42 - 2 - 1 = 39;\ F(\alpha, q_1, q_2) = 3{,}24.$$

$F = 229{,}22 > F(\alpha, q_1, q_2) = 3{,}24$ since multivariate correlation coefficient $(R = 0{,}96)$ and the statistical significance of the regression equation is confirmed.

The mean relative and mean square errors of the obtained approximation are determined by the following well-known expressions, respectively:

$$\bar{\varepsilon} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{ax_i + by_i + c - k_i}{k_i}\right| \cdot 100\% = 3{,}62\%;$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(ax_i + by_i + c - k_i)^2}{n}} = 0{,}103.$$

Let's calculate the determination index to determine the degree of change (variability) of the arc overvoltage depending on the mentioned quantities for the particular sample under consideration. The price of the determination index $R^2 = 0{,}96^2 = 0{,}9216$ presence indicates that the frequency of arc overvoltage (k) of change $92{,}16\ \%$- is the conductance of the ground fault circuit (x) and the inverse value of the phase capacitance of the network with respect to ground (y) at the expense of change, the rest 7,84 %- occurs due to the change of other random factors that are not taken into account, and this case k, x, y It once again confirms that the obtained correlation relationship between the quantities is great and the possibility of being used successfully during management.

We use average conductivity coefficients to separately determine the degree of influence of ground fault circuit conductance and network phase capacitance to ground on the frequency of arc overvoltage. Average elasticity coefficients are determined by the following well-known expressions [16]:

$$\overline{E}_x = \frac{\partial k}{\partial x}\frac{\overline{x}}{\overline{\overline{k}}} = a\frac{\overline{x}}{\overline{\overline{k}}} = 0{,}16;$$

$$\overline{E}_y = \frac{\partial k}{\partial y}\frac{\overline{y}}{\overline{\overline{k}}} = b\frac{\overline{y}}{\overline{\overline{k}}} = 0{,}121.$$

It follows that the conductivity of the ground fault circuit (x) 1% increase in the frequency of arc overvoltage (k) 0,16 % increase, the inverse value of the phase capacity of the network with respect to the ground (y) 1% increase in the frequency of arc overvoltage causes (k) an increase of 0.121% . $\overline{E}_x = 0{,}16 > \overline{E}_y = 0{,}121$ since the conductance of the ground fault circuit (x) to the inverse value of the phase capacitance of the network with respect to ground (y) relative to the frequency of arc overvoltage (k) has more effect. Average elasticity coefficients less than 1% of the arc extreme stress (k) conductance of the ground fault circuit (x) and the inverse value of the phase capacitance of the network with respect to ground (y) shows that it is not flexible to change. However, the obtained expression (6) can be effectively used during load tests of network isolation, and its validity is not in doubt.

IV. Results of computer modeling of regression dependence

Based on the obtained results, the dependence (1) between the frequency of the arc overvoltage and the ground fault resistance and the phase capacity of the network with respect to the ground in neutral insulated networks as a result of non-stationary earth faults can be written in the following obvious hyperbolic way according to the expression (6):

$$k = \frac{4{,}55}{R_0} + \frac{0{,}76}{C_f} + 1{,}67 \quad (9)$$

Based on the regression equation (9) obtained using the OriginLab [17] software complex, a 3D (spatial) image of the dependence of the frequency of arc overvoltage on the ground fault resistance and the phase capacity of the network with respect to the ground was constructed (Figure 1). As can be seen from the figure, the value of the arc overvoltage during artificial earth faults, depending on the earth fault resistance and the capacity of the network, for the organization of tests of electrical equipment under load in networks with neutral isolation, is controlled in the (1.9-3.3) U_{nom} interval, depending on the nature of the test problem. can be done.

(9) regression dependence, figure 1 and the dependences obtained in the authors' previous works [7-14] can be used practically and effectively during load tests of electrical equipment and network insulation, while the reliability of the obtained results is ensured.

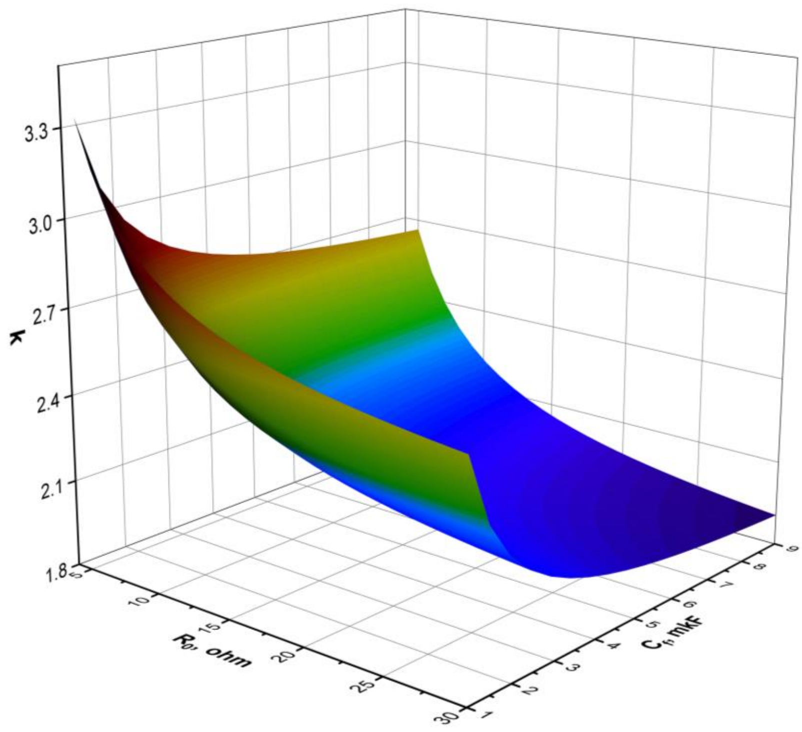

Figure 1: *Earth fault resistance and network overvoltage frequency 3D image of phase capacitance dependence with respect to ground*

IV. Conclusion

1. An adequate hyperbolic regression model, which can be easily implemented in practice, has been obtained between the frequency of arc overvoltage generated in neutral insulated networks as a result of non-stationary earth faults subject to Petersen's theory, the conductivity of the earth fault circuit and the inverse value of the phase capacitance of the network with respect to earth. The model adequacy test results confirm that the mathematical model expressing the proposed analytical dependence between the mentioned location and the closure parameters has a strong linear correlation relationship.
2. The obtained regression dependence and theoretical results can be successfully and easily implemented in the management of non-stationary earthing arc overvoltage during isolation under load in the neutral insulated networks of the Azerbaijani power system in transformation conditions.

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