REGRESSION MODEL OF ARC OVERVOLTAGE DURING SINGLE-PHASE NON-STATIONARY GROUND FAULTS IN NEUTRAL ISOLATED NETWORKS

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Abstract

In order to perform insulation tests of electrical equipment under load in neutral insulated networks, it is necessary to create an artificial overvoltage, and at this time, it is necessary to determine the mathematical relationships between the single-phase non-stationary ground and the closing parameters. In the case of single-phase non-stationary earth faults, the dependencies between important parameters such as overvoltage frequency, earth fault resistance and earth fault angle obey complex laws. Therefore, for practical conditions, adequate mathematical models should be developed that allow to know the interdependencies of such parameters. In this work, the problem of analytical determination of the relationship between the overvoltage generated in neutral insulated networks as a result of non-stationary earth faults, the earth fault resistance and the earth fault angle was considered. For this purpose, a regression equation was obtained for the dependence of the overvoltage frequency on the ground fault resistance and the ground fault angle, and the corresponding spatial description was given. The obtained results confirmed the existence of a strong correlation between these parameters and can be used for practical purposes.

Keywords: isolated electrical network, non-stationary ground fault, overvoltage factor, ground fault resistance, ground fault angle, regression equation, correlation

I. Introduction

It is known that the failure of electrical equipment can cause various traumas of the staff, disruption of the technological process and serious accidents, so special tests are carried out to prevent such problems in advance. In general, such tests are carried out when one of the following situations occurs: equipment or installation is put into operation, after an accident, planned and unplanned repairs, a certain period of time has passed since previous inspections, etc. At the same time, high-voltage testing of electrical equipment insulation is mandatory for neutral-insulated electrical networks with a voltage of up to 35 kV [1, 2].

It is a very urgent issue to obtain preliminary information about the potential damage of electrical equipment in neutral insulated networks and to perform high-voltage tests of insulation under load in order to ensure the uninterrupted supply of electricity to electricity consumers [3, 4]. It is clear from the research works carried out in this direction that various methods and tools are proposed [5-8].

A method of testing the insulation under load in neutral-insulated networks was proposed [9]. According to this method, artificial non-stationary earth faults are created in the network based on Petersen's theory to test the insulation under load. It is possible to use the multifunctional high-voltage thyristor commutator device created in this regard. Using this device, it is possible to create an artificial single-phase non-stationary earth fault that obeys Petersen's theory in neutral-isolated networks. Thus, by providing different values of the phase angles through the control unit of the device, it is possible to create grounding of the phase of the network through the switching unit. Since switching processes are controlled by changing the grounding angle and resistance, it is possible to adjust its characteristic quantities (grounding current, arc output voltage). At the same time, since the quantities characterizing the switching process depend on the insulation resistance of the network with respect to ground, the artificial non-stationary ground faults created on the basis of Petersen's theory in neutral-isolated networks through the commutator allow both monitoring the insulation of the network with respect to ground and detecting damage in it.

The value of the arc overvoltage during the transition processes is of great importance when conducting the tests. The value of the arc overvoltage, as mentioned, depends on the ground fault resistance, the ground fault angle and the phase capacity of the network with respect to ground. Therefore, it is important to determine the ground fault resistance and the ground fault angle in advance in order to control the transient processes and determine the value of the test voltage accordingly. For this purpose, it is important to determine the dependence of the frequency of arc overvoltage in neutral insulated networks as a result of non-stationary earth faults, the dependence of the earth fault resistance, the angle of earth fault and the phase capacity of the network with respect to earth.

II. Statement of the problem for the regression model of arc overvoltage

In general, in order to determine the dependencies between the mentioned parameters, the numerical solution of the system of differential equations characterizing the transition process of the non-stationary earth fault created in neutral isolated networks should be performed using modern computing technologies. However, the numerical solution of the problem becomes much more difficult due to the "stiffness" of the mentioned differential equations. In other words, since the system of differential equations is non-linear, during their numerical integration, the stability of the solution is violated in some cases and the results are distorted. Therefore, in order to overcome such difficulties, it is important to obtain analytical expressions that determine the dependences between the frequency of the arc overvoltage (K) and the ground fault resistance (R_0), the ground fault angle (φ) and the phase capacitance (C_f) of the network with respect to the ground.

It should be noted that for the considered research question, in [10,11], the arc overvoltage ratio is determined from the ground fault resistance, in [12,13], the arc overvoltage ratio is from the ground fault angle, and in [14,15], the arc overvoltage ratio is determined from the derivation of analytical expressions for the dependences of the phase capacity of the network on the ground has already been considered. As a continuation of the conducted research, the regression model of the dependence of the single-phase arc overvoltage on the ground fault resistance and the ground fault angle in neutral-insulated networks is considered. The mathematical model to be obtained will allow to ensure the value of the arc overvoltage at the required value by controlling the transition processes that occur during the artificial earth-stationary earth faults created for the purpose of carrying out tests under load.

III. Problem solving method and algorithm

Obtaining an analytical expression for the dependence of the frequency of the arc overvoltage during single-phase faults on the neutral-insulated electrical network $(C_f = const)$ on the earth fault resistance and the earth fault angle 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 $(C_f = 1mkF)$ [8,9].

Table 1: $K = f(R_0, \varphi)$ *addiction*

R_0, Om	φ				
	30^0	60^0	90^0	120^0	150^0
5	2,45	3,16	3,30	3,10	2,16
10	2,29	2,91	2,96	2,86	2,03
15	2,16	2,69	2,77	2,66	1,93
20	2,05	2,51	2,62	2,49	1,84
25	1,96	2,35	2,49	2,35	1,76
30	1,88	2,22	2,38	2,24	1,69

As can be seen from Table 1, the relationship between the frequency of arc overvoltage and the ground fault resistance and the ground fault angle can be approximated by the following regression equation [16]:

$$K = \frac{a}{R_0} + b\sin\varphi + c, \tag{1}$$

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

If we accept substitutions $\frac{1}{R_0} = x$ and $\sin\varphi = y$ in equation (1), we can write the regression equation as follows:

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

In other words, the dependence between the frequency of arc overvoltage (K) and the conductance of the ground fault circuit (x) and the sine of the ground fault angle (y) can be approximated by a linear regression equation (table 2). In determining the type of the model, such a judgment was used that if the change of the result indicator is directly proportional to the change of the factor indicators, then the linear model is considered adequate [17].

Table 1: $K = f(x, y)$ *addiction*

x [Sm]	y				
	0,500	0,866	1,000	0,866	0,500
0,200	2,45	3,16	3,30	3,10	2,16
0,100	2,29	2,91	2,96	2,86	2,03
0,067	2,16	2,69	2,77	2,66	1,93
0,050	2,05	2,51	2,62	2,49	1,84
0,040	1,96	2,35	2,49	2,35	1,76
0,033	1,88	2,22	2,38	2,24	1,69

The regression coefficients of equation (2) are determined by the following well-known expressions [16]:

$$\left.\begin{aligned} a &= \frac{\sigma_K}{\sigma_x}\cdot\frac{r_{Kx} - r_{Ky}r_{xy}}{1 - r_{xy}^2}; \\ b &= \frac{\sigma_K}{\sigma_y}\cdot\frac{r_{Ky} - r_{Kx}r_{xy}}{1 - r_{xy}^2}; \\ c &= \overline{K} - a\overline{x} - b\overline{y} \end{aligned}\right\} \quad (3)$$

Here $\overline{x}-$ average value of quantity x; $\overline{y}-$ average value of quantity y; $\overline{K}-$ average value of quantity K; $\sigma_x -$ mean square deviation of quantity x from its mean value $(\overline{x})$; $\sigma_y -$ mean square deviation of quantity y from its mean value $(\overline{y})$; $\sigma_K -$ mean square deviation of quantity K from its mean value $(\overline{K})$; $r_{xy} -$ linear correlation coefficient between the quantities x and y; $r_{Kx} -$ linear correlation coefficient between the quantities K and x; $r_{Ky} -$ linear correlation coefficient between the quantities K and y.

IV. Modeling results

The numerical values of the statistical indicators necessary for the determination of the coefficients of regression dependence and the identification of the model sought are determined according to the correlation table given in table 3. According to Table 3, the following markings were adopted:

$$A = (x_i - \overline{x})^2;\ \ B = (y_i - \overline{y})^2;\ \ C = (K_i - \overline{K})^2;\ \ D = (x_i - \overline{x})\cdot(y_i - \overline{y});$$
$$M = (K_i - \overline{K})\cdot(x_i - \overline{x});\ N = (K_i - \overline{K})\cdot(y_i - \overline{y})$$

The data array consists of a sample, and the calculated values of the statistical indicators necessary for determining the coefficients are given below:

$$\sum_{i=1}^{n} x_i = 2{,}45;\ \ \sum_{i=1}^{n} y_i = 22{,}392;\ \sum_{i=1}^{n} K_i = 72{,}26;$$
$$\overline{x} = \frac{\sum_{i=1}^{n} x_i}{n} = 0{,}082;\ \ \overline{y} = \frac{\sum_{i=1}^{n} y_i}{n} = 0{,}746;\ \ \ \overline{K} = \frac{\sum_{i=1}^{n} K_i}{n} = 2{,}409;$$

$$\sum_{i=1}^{n}\left(x_i-\overline{x}\right)^2=0{,}09830667;\ \sum_{i=1}^{n}\left(y_i-\overline{y}\right)^2=1{,}2860832;\ \sum_{i=1}^{n}\left(K_i-\overline{K}\right)^2=5{,}390747;$$

$$\sum_{i=1}^{n}\left(x_i-\overline{x}\right)\left(y_i-\overline{y}\right)=0;\ \sum_{i=1}^{n}\left(K_i-\overline{K}\right)\left(x_i-\overline{x}\right)=0{,}4112667;\ \sum_{i=1}^{n}\left(K_i-\overline{K}\right)\left(y_i-\overline{y}\right)=1{,}998776;$$

Table 3: *Correlation table*

i	x_i	y_i	K_i	A	B	C	D	M	N
1	0,200	0,500	2,45	0,01400278	0,06071296	0,001708	-0,02915733	0,0048911	-0,0101845
2	0,200	0,866	3,16	0,01400278	0,01430416	0,564502	0,01415267	0,0889078	0,0898595
3	0,200	1,000	3,30	0,01400278	0,06431296	0,794475	0,03000933	0,1054744	0,2260421
4	0,200	0,866	3,10	0,01400278	0,01430416	0,477942	0,01415267	0,0818078	0,0826835
5	0,200	0,500	2,16	0,01400278	0,06071296	0,061835	-0,02915733	-0,0294256	0,0612715
6	0,100	0,500	2,29	0,00033611	0,06071296	0,014082	-0,00451733	-0,0021756	0,0292395
7	0,100	0,866	2,91	0,00033611	0,01430416	0,251335	0,00219267	0,0091911	0,0599595
8	0,100	1,000	2,96	0,00033611	0,06431296	0,303968	0,00464933	0,0101078	0,1398181
9	0,100	0,866	2,86	0,00033611	0,01430416	0,203702	0,00219267	0,0082744	0,0539795
10	0,100	0,500	2,03	0,00033611	0,06071296	0,143388	-0,00451733	-0,0069422	0,0933035
11	0,067	0,500	2,16	0,00021511	0,06071296	0,061835	0,00361387	0,0036471	0,0612715
12	0,067	0,866	2,69	0,00021511	0,01430416	0,079148	-0,00175413	-0,0041262	0,0336475
13	0,067	1,000	2,77	0,00021511	0,06431296	0,130562	-0,00371947	-0,0052996	0,0916341
14	0,067	0,866	2,66	0,00021511	0,01430416	0,063168	-0,00175413	-0,0036862	0,0300595
15	0,067	0,500	1,93	0,00021511	0,06071296	0,229122	0,00361387	0,0070204	0,1179435
16	0,050	0,500	2,05	0,00100278	0,06071296	0,128642	0,00780267	0,0113578	0,0883755
17	0,050	0,866	2,51	0,00100278	0,01430416	0,010268	-0,00378733	-0,0032089	0,0121195
18	0,050	1,000	2,62	0,00100278	0,06431296	0,044662	-0,00803067	-0,0066922	0,0535941
19	0,050	0,866	2,49	0,00100278	0,01430416	0,006615	-0,00378733	-0,0025756	0,0097275
20	0,050	0,500	1,84	0,00100278	0,06071296	0,323382	0,00780267	0,0180078	0,1401195
21	0,040	0,500	1,96	0,00173611	0,06071296	0,201302	0,01026667	0,0186944	0,1105515
22	0,040	0,866	2,35	0,00173611	0,01430416	0,003442	-0,00498333	0,0024444	-0,0070165
23	0,040	1,000	2,49	0,00173611	0,06431296	0,006615	-0,01056667	-0,0033889	0,0206261
24	0,040	0,866	2,35	0,00173611	0,01430416	0,003442	-0,00498333	0,0024444	-0,0070165
25	0,040	0,500	1,76	0,00173611	0,06071296	0,420768	0,01026667	0,0270278	0,1598315
26	0,033	0,500	1,88	0,00236844	0,06071296	0,279488	0,01199147	0,0257284	0,1302635

Continuation of table 3

27	0,033	0,866	2,22	0,00236844	0,01430416	0,035595	-0,00582053	0,0091818	-0,0225645
28	0,033	1,000	2,38	0,00236844	0,06431296	0,000822	-0,01234187	0,0013951	-0,0072699
29	0,033	0,866	2,24	0,00236844	0,01430416	0,028448	-0,00582053	0,0082084	-0,0201725
30	0,033	0,500	1,69	0,00236844	0,06071296	0,516482	0,01199147	0,0349751	0,1770795
$\sum$	**2,450**	**22,392**	**72,26**	**0,09830667**	**1,28608320**	**5,390747**	**0,00000000**	**0,4112667**	**1,9987760**

Thus, based on the data of table 3, mean square deviations and two-dimensional correlation coefficients for individual quantities are calculated based on known formulas. The numerical values obtained are as follows:

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}{n}} = 0{,}0572; \quad \sigma_y = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}{n}} = 0{,}207; \quad \sigma_K = \sqrt{\frac{\sum_{i=1}^{n}\left(K_i - \bar{K}\right)^2}{n}} = 0{,}4239;$$

$$r_{xy} = \frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{n\sigma_x\sigma_y} = 0; \; r_{Kx} = \frac{\sum_{i=1}^{n}\left(K_i - \bar{K}\right)\left(x_i - \bar{x}\right)}{n\sigma_K\sigma_x} = 0{,}5649; \; r_{Ky} = \frac{\sum_{i=1}^{n}\left(K_i - \bar{K}\right)\left(y_i - \bar{y}\right)}{n\sigma_K\sigma_y} = 0{,}7591.$$

Then, based on statements (3), the calculated values of regression coefficients of equation (1) or (2) are obtained as follows:

$$a = 4{,}18; \; b = 1{,}55; \; c = 0{,}91.$$

Thus, after determining the regression coefficients, the dependence (1) (or (2)) between the frequency of the arc overvoltage generated in neutral insulated networks during single-phase non-stationary earth faults and the earth fault resistance (or circuit conductance) and the sine of the earth fault angle can be written in the following obvious way:

$$K = \frac{4{,}18}{R_0} + 1{,}55\sin\varphi + 0{,}91 \tag{4}$$

or

$$K = 4{,}18x + 1{,}55y + 0{,}91 \tag{5}$$

As it can be seen, the regression model obtained in the form of (4) between the parameters during single-phase non-stationary earth faults is in a form that is simple and easy to implement in practice.

Let's check the adequacy of the obtained regression dependence (5) between the frequency of overvoltage and the conductance of the ground fault circuit and the sine of the ground fault angle during single-phase non-stationary ground faults. For this, by calculating the multivariate correlation coefficient, its significance can be checked with the Fisher criterion [16].

Based on the data, the value of the multivariate correlation coefficient is as follows:

$$R = \sqrt{\frac{r_{Kx}^2 + r_{Ky}^2 - 2r_{Kx}r_{Ky}r_{xy}}{1 - r_{xy}^2}} = 0{,}95.$$

We check the significance of the multivariate correlation coefficient with the $F-$Fisher test. It is known that the regression equation at the α significance level is considered adequate if the $F > F(\alpha, k_1, k_2)$ condition is met [17], here $k_1, k_2 -$ are the degrees of freedom.

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

$$F = \frac{\frac{1}{2}R}{\frac{1}{n-3}\left(1-R^2\right)} \approx 132.$$

The table value of the $F-$Fisher criterion is taken from the table depending on the significance level (α) and degrees of freedom (k_1, k_2) [17]:

$$\alpha = 0{,}05;\ k_1 = 2;\ k_2 = n-3 = 30-3 = 27;\ F(\alpha, k_1, k_2) = 3{,}35.$$

Since $F = 132 > F(\alpha, k_1, k_2) = 3{,}35$, the multivariate correlation coefficient $(R = 0{,}95)$ and the statistical significance of the regression equation is confirmed.

It should be noted that the multivariate correlation coefficient $(R = 0{,}95 \to 1)$ close to unity indicates that the dependence between the frequency of arc overvoltage and the conductance of the ground-fault circuit and the sine of the ground-fault angle can be considered a strong linear correlation relationship. It is recommended to use neutral-isolated networks when solving practical problems for organizing under-load tests of insulation of electrical equipment.

A 3D (spatial) image of the dependence of the frequency of the arc overvoltage on the earth fault resistance and the earth fault angle was constructed based on the regression equation (4) obtained using computer modeling reporting methods (Fig. 1). The numerical results of the regression model obtained between the parameters mentioned in Figure 1, in other words, the existence of a strong correlation relationship between the quantities are visually confirmed.

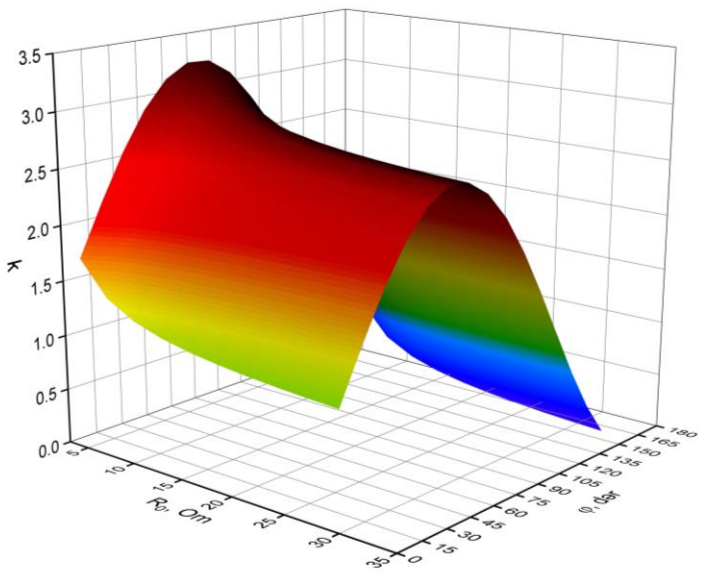

Figure 1. *Earth fault resistance times overvoltage and a 3D image of its dependence on the angle of closure with the ground*

VI. Conclusions

1. An easy-to-realize regression model was obtained between the frequency of arc overvoltage in neutral insulated networks as a result of non-stationary earth faults subject to Petersen's theory, the conductance of the earth fault circuit and the sine of the earth fault angle. The proposed analytical dependence between the mentioned parameters can be considered as a strong linear correlation relationship and based on this, the value of the test voltage can be determined.

2. The obtained results can be easily used during load tests of insulation of electrical equipment in the neutral isolated networks of the Azerenergy system, and at the same time, during the investigation and analysis of the results of non-stationary ground faults that occurred in the network.

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