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REGRESSION MODEL OF THE DEPENDENCE OF ARC OVERVOLTAGE ON GROUND FAULT RESISTANCE AND NETWORK PHASE CAPACITANCE RELATIVE TO GROUND

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ABSTRACT

In neutral-isolated networks, testing insulation under load requires determining the dependencies between parameters characterizing single-phase non-stationary ground faults. Identifying such dependencies is often accompanied by a number of difficulties. Therefore, simple mathematical models that allow understanding the relationships between these parameters in practical conditions must be developed. This paper considers the issue of determining the relationship between the overvoltage arising in a neutral-isolated network as a result of non-stationary ground faults, the ground fault resistance, and the network phase capacitance to ground. For this purpose, a regression equation was obtained to describe the dependence of the overvoltage multiplicity on the ground fault resistance and network phase capacitance to ground, and the corresponding 3D visualization was constructed.

Introduction

Neutral-isolated networks play a significant role in supplying consumers with electrical energy. Such networks primarily perform the distribution of electrical energy among consumers, comprising numerous overhead and cable lines. During operation, the insulation of these lines, especially cable lines, deteriorates due to prolonged electrical, thermal, and mechanical impacts. This results in a decrease in insulation resistance and electrical strength, which can cause sudden damage and disrupt the power supply to consumers. Therefore, timely detection of weak insulation sections in networks and restoration of damaged areas is of great importance. For this reason, network equipment is periodically disconnected and subjected to insulation testing [1,2]. However, such tests are considered inconvenient as they require considerable time and labor. Consequently, methods for testing network insulation without disconnecting equipment have been proposed [3-5]. These methods are based on the principle of creating artificial ground faults under load conditions. However, the devices used in these methods cannot perform regulation and control functions. Therefore, a new method for testing insulation in neutral-isolated networks has been proposed [6]. According to this method, controlled and regulated artificial non-stationary ground faults are created in the network to test the insulation under load

conditions. It is important to note that the overvoltage value arising during such ground faults, based on Petersen's theory, depends on the network's phase-to-ground capacitance, ground fault resistance, and ground fault angle. Hence, determining the test voltage value requires prior identification of the ground fault resistance and ground fault angle. For this purpose, the dependence of arc overvoltage multiplicity on ground fault resistance, ground fault angle, and network phase-to-ground capacitance is determined based on non-stationary ground faults in neutral-isolated networks.

1. Problem statement

To determine the dependence of arc overvoltage multiplicity on ground fault resistance, ground fault angle, and network phase-to-ground capacitance, the numerical solution of the system of differential equations characterizing the transient process of non-stationary ground faults in neutral-isolated networks must be performed using modern computational technologies. However, the numerical solution of the problem is significantly complicated due to the "stiffness" of these differential equations, which in some cases disrupts the stability of the system solution and distorts the results. Therefore, to overcome such difficulties, it is necessary to obtain analytical expressions that define the dependencies between the arc overvoltage multiplicity (k), the ground fault resistance (R_0), the ground fault angle (φ), and the network phase-to-ground capacitance (C_f). It should be noted that analytical expressions for the dependence of arc overvoltage multiplicity on ground fault resistance were previously considered in [7,8], on ground fault angle in [9,10], on network phase-to-ground capacitance in [11,12], and on both ground fault resistance and ground fault angle in [13-16]. As a continuation of these studies, this work focuses on obtaining the regression model of the dependence of arc overvoltage multiplicity on ground fault resistance and network phase-to-ground capacitance.

2. Problem solving

The analytical expression for the dependence of the arc overvoltage multiplicity on the ground fault resistance and the network's phase capacitance relative to the ground in a neutral-isolated electrical network during single-phase ground faults is considered. For this purpose, the results of experimental studies carried out on a low-voltage model of a neutral-isolated network, presented in Table 1, are used $\left(\varphi = 90^\circ\right)$ [6].

Table 1. $k = f\left(R_0, C_f\right)$ **dependence**

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

As seen from Table 1, the dependence between the arc overvoltage multiplicity, the ground fault resistance, and the network's phase capacitance relative to the ground can be approximated by the following regression equation [17, p. 133-135]:

$$k = \frac{a}{R_0} + \frac{b}{C_f} + c, \quad (1)$$

Here, a, b, c – is referred to as the regression coefficients.

If we assume the substitutions in equation (1) as $\frac{1}{R_0} = x$ və $\frac{1}{C_f} = y$

$$k = ax + by + c, \quad (2)$$

Thus, the dependence between the arc overvoltage multiplicity (k), the conductance of the ground fault circuit (x), and the reciprocal value of the network's phase capacitance relative to the ground (y) can be approximated by a linear regression equation (Table 2).

Table 2. $k = f(x, y)$ **dependence**

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

Regression coefficients are determined by the following expressions [17, p.133-135]:

$$\left.\begin{aligned} a &= \frac{\sigma_k}{\sigma_x} \cdot \frac{r_{kx} - r_{ky} r_{xy}}{1 - r_{xy}^2}; \\ b &= \frac{\sigma_k}{\sigma_y} \cdot \frac{r_{ky} - r_{kx} r_{xy}}{1 - r_{xy}^2}; \\ c &= \bar{k} - a\bar{x} - b\bar{y} \end{aligned}\right\}, \quad (3)$$

Here, $\bar{x}$ – the mean value of the quantity x, $\bar{y}$ – the mean value of the quantity y, $\bar{k}$ – the mean value of the quantity k, σ_x – the root mean square deviation of the quantity x, σ_y – the root mean square deviation of the quantity y, σ_k – the root mean square deviation of the quantity k, r_{xy} – the linear correlation coefficient between the quantities x and y, r_{kx} – the linear correlation coefficient between the quantities k and x, and r_{ky} – the linear correlation coefficient between the quantities k and y are determined based on the correlation table (Table 3). The following notations are adopted according to the correlation table:

$$A_i = (x_i - \bar{x})^2;\ B_i = (y_i - \bar{y})^2;\ C_i = (k_i - \bar{k})^2;\ D_i = (x_i - \bar{x}) \cdot (y_i - \bar{y});$$

$$E_i = (k_i - \bar{k}) \cdot (x_i - \bar{x});\ F_i = (k_i - \bar{k}) \cdot (y_i - \bar{y});\ M_i = \left| \frac{ax_i + by_i + c - k_i}{k_i} \right|;\ N_i = (ax_i + by_i + c - k_i)^2.$$

$$n = 42;$$

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

$$\sum_{i=1}^{n}\left(x_i-\bar{x}\right)^2=0{,}13747222;\ \sum_{i=1}^{n}\left(y_i-\bar{y}\right)^2=3{,}35869048;\ \sum_{i=1}^{n}\left(k_i-\bar{k}\right)^2=5{,}259829;$$

$$\sum_{i=1}^{n}\left(x_i-\bar{x}\right)\left(y_i-\bar{y}\right)=0;\ \sum_{i=1}^{n}\left(k_i-\bar{k}\right)\left(x_i-\bar{x}\right)=0{,}6259;\ \sum_{i=1}^{n}\left(k_i-\bar{k}\right)\left(y_i-\bar{y}\right)=2{,}5669524;$$

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

Table 3. Correlation table

i	x_i	y_i	k_i	A_i	B_i	C_i	D_i	E_i	F_i	M_i	N_i
1	0,200	1,000	3,30	0,01400278	0,39960459	0,952018	0,07480357	0,1154595	0,6167908	0,013993	0,002132
2	0,100	1,000	2,96	0,00033611	0,39960459	0,404133	0,01158929	0,0116548	0,4018622	0,023350	0,004777
3	0,067	1,000	2,77	0,00022500	0,39960459	0,198661	-0,00948214	-0,0066857	0,2817551	0,011148	0,000954
4	0,050	1,000	2,62	0,00100278	0,39960459	0,087447	-0,02001786	-0,0093643	0,1869337	0,016503	0,001870
5	0,040	1,000	2,49	0,00173611	0,39960459	0,027461	-0,02633929	-0,0069048	0,1047551	0,051289	0,016310
6	0,033	1,000	2,38	0,00233611	0,39960459	0,003104	-0,03055357	-0,0026929	0,0352194	0,087125	0,042997
7	0,200	0,500	2,99	0,01400278	0,01746173	0,443176	0,01563690	0,0787762	0,0879694	0,008682	0,000674
8	0,100	0,500	2,74	0,00033611	0,01746173	0,172818	0,00242262	0,0076214	0,0549337	0,084398	0,053477
9	0,067	0,500	2,54	0,00022500	0,01746173	0,046533	-0,00198214	-0,0032357	0,0285051	0,072053	0,033494
10	0,050	0,500	2,38	0,00100278	0,01746173	0,003104	-0,00418452	-0,0017643	0,0073622	0,041553	0,009781
11	0,040	0,500	2,25	0,00173611	0,01746173	0,005518	-0,00550595	0,0030952	-0,0098163	0,006412	0,000208
12	0,033	0,500	2,15	0,00233611	0,01746173	0,030376	-0,00638690	0,0084238	-0,0230306	0,025684	0,003049
13	0,200	0,333	2,85	0,01400278	0,00119189	0,276376	-0,00408532	0,0622095	-0,0181497	0,004680	0,000178
14	0,100	0,333	2,59	0,00033611	0,00119189	0,070604	-0,00063294	0,0048714	-0,0091735	0,080552	0,043526
15	0,067	0,333	2,39	0,00022500	0,00119189	0,004318	0,00051786	-0,0009857	-0,0022687	0,067110	0,025726
16	0,050	0,333	2,24	0,00100278	0,00119189	0,007104	0,00109325	0,0026690	0,0029099	0,038516	0,007443
17	0,040	0,333	2,12	0,00173611	0,00119189	0,041733	0,00143849	0,0085119	0,0070527	0,005568	0,000139
18	0,033	0,333	2,02	0,00233611	0,00119189	0,092590	0,00166865	0,0147071	0,0105051	0,028635	0,003346
19	0,200	0,250	2,74	0,01400278	0,01389031	0,172818	-0,01394643	0,0491929	-0,0489949	0,012034	0,001087
20	0,100	0,250	2,47	0,00033611	0,01389031	0,021233	-0,00216071	0,0026714	-0,0171735	0,061668	0,023201
21	0,067	0,250	2,28	0,00022500	0,01389031	0,001961	0,00176786	0,0006643	0,0052194	0,050036	0,013015
22	0,050	0,250	2,13	0,00100278	0,01389031	0,037747	0,00373214	0,0061524	0,0228980	0,018763	0,001597
23	0,040	0,250	2,02	0,00173611	0,01389031	0,092590	0,00491071	0,0126786	0,0358622	0,012132	0,000601
24	0,033	0,250	1,93	0,00233611	0,01389031	0,155461	0,00569643	0,0190571	0,0464694	0,043603	0,007082
25	0,200	0,200	2,66	0,01400278	0,02817602	0,112704	-0,01986310	0,0397262	-0,0563520	0,028105	0,005589
26	0,100	0,200	2,39	0,00033611	0,02817602	0,004318	-0,00307738	0,0012048	-0,0110306	0,046248	0,012217
27	0,067	0,200	2,20	0,00022500	0,02817602	0,015447	0,00251786	0,0018643	0,0208622	0,032862	0,005227
28	0,050	0,200	2,06	0,00100278	0,02817602	0,069847	0,00531548	0,0083690	0,0443622	0,003970	0,000067
29	0,040	0,200	1,95	0,00173611	0,02817602	0,140090	0,00699405	0,0155952	0,0628265	0,028868	0,003169
30	0,033	0,200	1,88	0,00233611	0,02817602	0,197390	0,00811310	0,0214738	0,0745765	0,051032	0,009204
31	0,200	0,167	2,58	0,01400278	0,04047761	0,065390	-0,02380754	0,0302595	-0,0514473	0,050110	0,016714
32	0,100	0,167	2,33	0,00033611	0,04047761	0,000033	-0,00368849	0,0001048	-0,0011497	0,032622	0,005777
33	0,067	0,167	2,14	0,00022500	0,04047761	0,033961	0,00301786	0,0027643	0,0370765	0,017651	0,001427
34	0,050	0,167	2,01	0,00100278	0,04047761	0,098776	0,00637103	0,0099524	0,0632313	0,008132	0,000267
35	0,040	0,167	1,91	0,00173611	0,04047761	0,171633	0,00838294	0,0172619	0,0833503	0,037077	0,005015
36	0,033	0,167	1,84	0,00233611	0,04047761	0,234533	0,00972421	0,0234071	0,0974337	0,060035	0,012202
37	0,200	0,125	2,47	0,01400278	0,05897959	0,021233	-0,02873810	0,0172429	-0,0353878	0,083983	0,043031
38	0,100	0,125	2,21	0,00033611	0,05897959	0,013061	-0,00445238	-0,0020952	0,0277551	0,005496	0,000148
39	0,067	0,125	2,08	0,00022500	0,05897959	0,059676	0,00364286	0,0036643	0,0593265	0,004624	0,000092
40	0,050	0,125	1,92	0,00100278	0,05897959	0,163447	0,00769048	0,0128024	0,0981837	0,038803	0,005550
41	0,040	0,125	1,84	0,00173611	0,05897959	0,234533	0,01011905	0,0201786	0,1176122	0,059224	0,011875
42	0,033	0,125	1,80	0,00233611	0,05897959	0,274876	0,01173810	0,0253405	0,1273265	0,065899	0,014070
⚜	**3,430**	**15,450**	**97,62**	**0,13747222**	**3,35869048**	**5,259829**	**0,00000000**	**0,6259000**	**2,5669524**	**1,520226**	**0,448307**

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

$$r_{xy}=\frac{\sum_{i=1}^{n}\left(x_i-\bar{x}\right)\left(y_i-\bar{y}\right)}{n\sigma_x\sigma_y}=0;\ r_{kx}=\frac{\sum_{i=1}^{n}\left(k_i-\bar{k}\right)\left(x_i-\bar{x}\right)}{n\sigma_k\sigma_x}=0{,}736;\ r_{ky}=\frac{\sum_{i=1}^{n}\left(k_i-\bar{k}\right)\left(y_i-\bar{y}\right)}{n\sigma_k\sigma_y}=0{,}611.$$

$$\sum_{i=1}^{n}\left|\frac{ax_i+by_i+c-k_i}{k_i}\right|=1{,}520226;\ \sum_{i=1}^{n}\left(ax_i+by_i+c-k_i\right)^2=0{,}448307.$$

Based on the expressions (3), the regression coefficients are:

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

Thus, after determining the regression coefficients, the dependency (2) between the overvoltage multiplicity caused by non-stationary earth faults in isolated neutral networks and the inverse value of the phase capacitance of the network relative to the ground, along with the conductivity of the earth fault circuit, can be explicitly written as follows:

$$k=4{,}55x+0{,}76y+1{,}67 \quad (4)$$

Let us verify the adequacy of the obtained regression equation (4) between the overvoltage multiplicity during non-stationary earth faults, the conductivity of the earth fault circuit, and the inverse value of the phase capacitance of the network relative to the ground. To do this, the value of the multiple correlation coefficient can be calculated and its significance can be verified using the Fisher criterion [17, p. 133-135].

The value of the multiple correlation coefficient is determined by the following known expression:

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

The fact that the multidimensional correlation coefficient is close to unity $\left(R=0{,}96\to 1\right)$ indicates that the dependence between the conductivity of the ground closing cycle and the inverse value of the network's phase capacitance relative to the ground, with the variation of extreme voltage, can be considered a strong linear correlation.

We check the significance of the multidimensional correlation coefficient using the $F-$Fisher criterion. It is known that, at the significance level α, the regression equation is considered adequate if the condition $F>F(\alpha,q_1,q_2)$ is met [18, p.50], where q_1,q_2- the degrees of freedom.

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

$$F=\frac{R^2}{1-R^2}\cdot\frac{n-m-1}{m}, \quad (5)$$

Here, $n-$is the number of experiments, $n=42$; $m-$is the number of factors, $m=2$. Then, based on expression (5), $F=229{,}22$.

$F-$ Fisher criterion table value, is taken from the table depending on the significance level (α) and degrees of freedom (q_1,q_2) [18, p.370]:

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

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

The mean relative and mean square errors of the approximation are determined by the following corresponding expressions:

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

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

The determination index of $R^2 = 0{,}96^2 = 0{,}9216$ indicates that $92{,}16$ % of the change in the arc overvoltage multiplier (k) is due to the changes in the ground fault current (x) and the inverse value of the network's phase capacitance relative to ground (y), while the remaining $7{,}84$ % is caused by the changes in other factors not considered.

The average elasticity coefficients are determined by the following well-known expressions [18, p.102]:

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

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

From this, it can be concluded that a 1% increase in the ground fault current (x) results in a 0.16% increase in the arc overvoltage multiplier (k), while a 1% increase in the inverse value of the network's phase capacitance relative to ground (y) causes a 0.121% increase in the arc overvoltage multiplier (k). Since $\bar{E}_x = 0{,}16 > \bar{E}_y = 0{,}121$, the ground fault current (x) has a greater effect on the arc overvoltage multiplier (k) compared to the inverse value of the network's phase capacitance relative to ground (y). The fact that the average elasticity coefficients are smaller than 1% indicates that the arc overvoltage multiplier (k) is not elastic to changes in the ground fault current (x) and the inverse value of the network's phase capacitance relative to ground (y).

Thus, the dependency (1) between the arc overvoltage multiplier (k), ground fault resistance, and the network's phase capacitance relative to ground, resulting from non-stationary ground faults in neutral-isolated networks, can be expressed as follows:

$$k = \frac{4{,}55}{R_0} + \frac{0{,}76}{C_f} + 1{,}67, \quad (6)$$

Using the OriginLab [19] program, based on the regression equation (6) obtained, a 3D (spatial) plot was created showing the dependence of the arc overvoltage deflection on ground fault resistance and the network phase capacitance relative to ground (Figure 1).

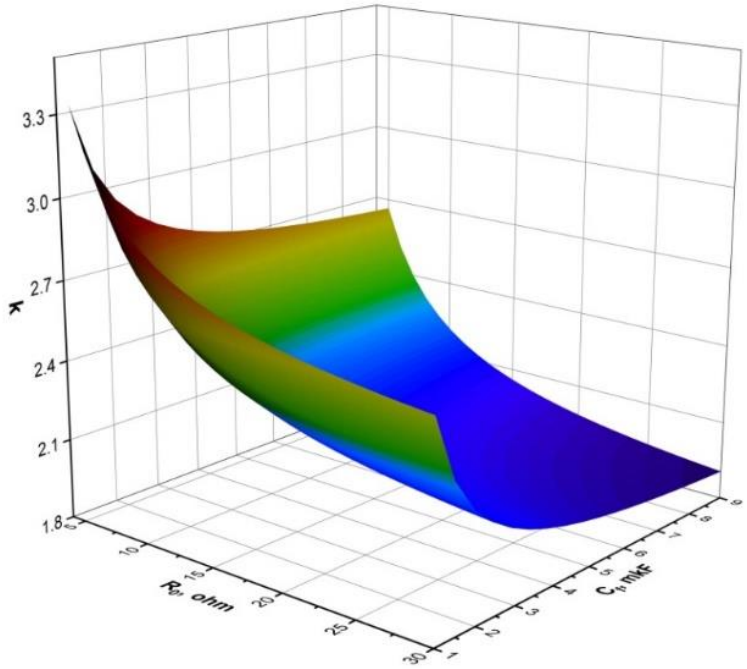

Figure 1. 3D plot of the dependence of arc overvoltage on ground fault resistance and network phase capacitance relative to ground.

3. Conclusion

Based on Petersen's theory, a regression model was developed, which shows the relationship between the overvoltage deflection of the arc due to non-stationary ground faults in neutral-isolated networks, the fault circuit's conductivity, and the inverse value of the network's phase capacitance relative to the ground. This model can be easily implemented in practice. The analytical dependence proposed between the mentioned parameters can be considered a strong linear correlation.

The obtained results can be used during the insulation testing of neutral-isolated networks in the Azerbaijani power system under load conditions.

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