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Summary

The study of the basic electrophysical parameters of thin Mo films obtained by magnetron sputtering depending on the conditions of deposition was made. It is shown that the films obtained at deposition rate about 4 nm/s and at less than 1 Pa Argon pressure to the substrates heated up to temperature over 450°C have the best reproducibility.

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THE INFLUENCE OF POLUTION ON THE ELECTRICAL INSULATORS

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Introduction

The pollutant agents that are present in the environmental air have a direct influence on the electrical properties of insulators. The surface properties of the insulators are the first ones to be affected.

Test conditions

A study on the influence of some pollutant agents on the electrical insulator was done. Electrical insulator types 2025, 2026, PSG6, PSG12 and VLKS were tested individually or in groups of two or more elements, in gradually increasing pollution conditions.

Nitrogen oxide, chlorine and sodium chloride were used as pollutant agents, because, these gases usually are emitted by chemical plants. Electrical insulators with a clean surface as well as covered with silicone vaseline were used. These insulators were exposed during a six month period to polluted medium with nitrogen oxides and sulfuric anhydride.

The tests were performed in the following conditions:

– The insulators were tested individually or in groups, in conditions of constant humidity and constant applied voltage while the concentration of pollutant agent in the environment air was gradually increasing.

– The insulators were tested individually or in groups in conditions of constant pollutant agent concentration in environmental air and constant applied voltage while relative air humidity was gradually increasing.

– The insulators were tested individually or in groups in conditions of constant pollutant agent concentration in environmental air and constant humidity while applied voltage was gradually increasing.

Theoretical considerations

Applied voltage and humidity effects on the polluted surface of insulator results in the appearance of leakage currents. The values of these currents are determined by the conductivity of superficial film on the surface. This leads to the conclusion that the dependence of leakage current on conductivity and applied voltage is as follows:

$$I = f(\gamma, U) \quad (1)$$

As it can be seen from the above expression, if the continuity conditions of the film are realized the voltage gradient remains constant, the film voltage influences like a linear element. In these conditions the current keeps a sine waveform shape on the insulator surface and depends on conductivity variation, pollution and humidity degree.

If the continuity and uniformity aren't assured on the length of the leakage pass, the current depends on even more factors such as: conductivity, shock ionization, voltage and the film uniformity degree.

To clarify this function lets consider time period t_1 in which the current keeps a sine waveform shape on the insulator's surface. In this case the expression will be as follows:

$$i(t)_1 = f\left(\frac{u}{R}\right) \quad \text{or} \quad i(t)_1 = f(\gamma, U) \quad (2)$$

Due to physical and chemical conditions, an increase in the pollution phenomenon will lead to the forming of shock ionization current in addition to the one leaking through the film.

In the subsequent time period t_2 an equivalent scheme of insulator can be considered as two elements, linear and nonlinear ones, connected in parallel. During this period, the expression for current is presented as equation (3).

$$: i(t)_2 = G(\alpha, U) + F(\gamma, U) \quad (3)$$

where α is the shock ionization coefficient.

It is clearly seen that the resistance increases with the increase of leak current *i*(*t*) so:

$$\text{if} \quad R \to \infty \quad \text{then} \quad \gamma \to \infty \quad \text{and} \quad F(\gamma, U) \to 0$$

In the period t_2 , the current is, in fact, the ionization current according to the following expression:

$$I(t)_2 = G(\alpha, u) \quad (4)$$

This current influences the deformed character of the *i*(t) function. This happens because of the fact that the discharges take the form of electric arc discharges, which extend on the insulator's surface and the following expressions are valid:

$$Y = C_0 + \sum_{1}^{\infty} C_k \sin(k\omega t - \varphi_k) \quad (5)$$

$$i(t) = C_0 + \sum_{1}^{n} A_k \sin k\omega t + \sum_{1}^{n} B_k \cos k\omega t \quad (6)$$

where A_k and B_k are Fourier coefficients, which can be determined by decomposing of the function into simple wave forms. Because the leakage current depends both on the humidity and pollution degree it is important to know its variation according to these factors.

Experimental results

Statistical analysis of the measurements

This relation shows the interdependence between the leakage currents from the insulator surface and the pollution degree and the humidity determined by conductivity modifications. The analysis of experimental data dispersion presented in table 1 shows a linear relation between the leakage current (*y*) and the humidity degree (named *x*) as the following function:

$$\overline{y}_x = b_0 + b_1 \cdot x \quad (7)$$

By statistical processing of the measurement data, which are shown in table 1, the following solution for b_0 and b_1 in the matrix form was obtained:

$$B = \begin{vmatrix} b_0 \\ b_1 \end{vmatrix} = \begin{vmatrix} 0.03 \\ 0.0054 \end{vmatrix} \quad (8)$$

The theoretical regression function y_x, which has the nearest values to the effective values *y* is:

$$\bar{y}_x = 0.03 + 0.0054 \cdot x \tag{9}$$

In this formula $b_0 \neq 0$, though it is very small. This can be accounted for the fact that a small leakage current exists even in the absence of pollution when the insulator is subjected to a voltage.

In figure 1 the dependence between the leakage current and the pollution degree is presented. In table 2 the results of the statistical processing for the determinations of the leakage current are presented, the humidity being variable while voltage is constant.

The dispersion diagram for these data reveals a relation between the leakage current and humidity, as:

$$\bar{y}x = b_0 - b_1 x^2 \tag{10}$$

To calculate parameters b_0 and b_1 the data from table 2 were used. The solution in matrix form is:

$$B = \begin{vmatrix} b_0 \\ b_1 \end{vmatrix} = \begin{vmatrix} 0.12 \\ 0.00074 \end{vmatrix} \tag{11}$$

The final expression for regression function is:

$$\bar{y}_x = 0.12 - 0.00074 x^2 \tag{12}$$

Table 1. Measurement results

Y \ X	0	550	900	1250	1460	f_y	yf_y	y^2f_y	xf_x	x^2f_x	xyf_{xy}
0.01	5					5	0.05	0	0	0	0
3		4				4	12	36	2200	1210000	6600
5			2			2	10	50	1800	1620000	9000
7				2		2	14	98	2500	3125000	17500
7.5					1	1	7.5	57.25	1460	2131600	10950
f_x	5	4	2	2	1	14	43.55		7960	8086600	44050
xf_x	0	2200	1800	2500	1460	7960	$\sum xf_x = (x_1+x_2+x_3+x_4+x_5)\cdot f_x$				
x^2f_x	0	1210000	1620000	3125000	21316000	8086600	$\sum yf_y = (y_1+y_2+y_3+y_4+y_5)\cdot f_y$				
yf_y	0.05	12	10	14	7.5	43.55	$\sum x^2 f_x = (x_1^2+x_2^2+x_3^2+x_4^2+x_5^2)\cdot f_x$				
y^2f_y	0	36	50	98	7.5		$\sum xyf_{xy} = (x_1y_1+x_2y_2+\ldots+x_5y_5)\cdot f_{xy}$				
xyf_{xy}	0	6600	9000	17500	10950	44050					
Information matrix			$\lvert x^* x\rvert = \begin{vmatrix} 14 & 7960 \\ 7960 & 8086600 \end{vmatrix}$								
Inverse information matrix			$\lvert x^* x\rvert^{-1} = \begin{vmatrix} \frac{8086600}{113212400-63361600} & \frac{-7960}{113212400-63361600} \\ \frac{-7960}{113212400-63361600} & \frac{8086600}{113212400-63361600} \end{vmatrix}$								
Factor matrix			$\lvert x^* y\rvert = \begin{vmatrix} 43.55 \\ 44050 \end{vmatrix}$								
System solution			$\lvert x^* y\rvert^{-1} x^* y = \begin{vmatrix} b_0 \\ b_1 \end{vmatrix} \begin{vmatrix} 0.03 \\ 0.0054 \end{vmatrix}$								
Regression function			$\bar{y}x = b_0 + b_1 x = 0.03 + 0.0054x$								

This function can be made linear by taking logarithm, because the coefficient b_1 is very small, that is why the regression line can be approximated by a straight line. The approximation will simplify the calculations, which are necessary for the determination of the regression function in the case when both pollution and humidity influences are taken into consideration.

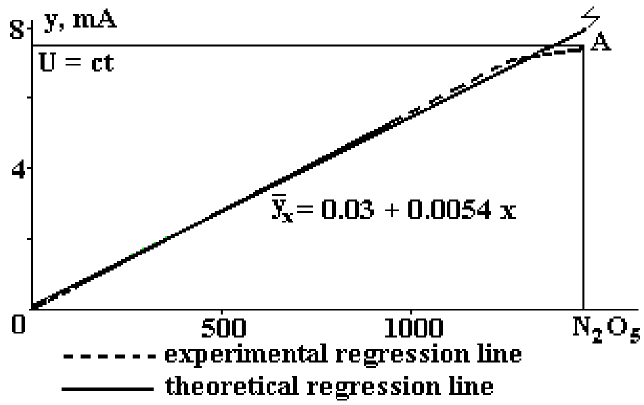

Fig. 1. The leakage current variation vs N_2O_5 quantity

Using the experimental data from table 3 and by denoting the leakage current by y and the humidity and pollution with x_1 and x_2, respectively, the relation function can be approximated with a straight line that has the expression:

$$y(x_1, x_2) = b_0 + b_1 x_1 + b_2 x_2 \tag{13}$$

Table 2. The result of the statistical processing for the determination of the leakage current

	x	Y	x^2	x^3	x^4	xy	x^2y
1	0	0.1	0	0	0	0	0
2	68	3	4624	314432	21381376	204	13872
3	74	4	5476	405224	29986576	296	21904
4	81	4.5	6561	531441	43046721	364.5	29524.5
5	92	6.5	8464	778688	71639296	598	55016
6	100	7.5	10000	1000000	100000000	750	75000
Σ	415	25.5	35125	3029785	$2.66 \cdot 10^8$	2212.5	195316.5
Information matrix			$\left\lvert x^* x \right\rvert = \begin{vmatrix} 6 & 35125 \\ 415 & 3029785 \end{vmatrix}$				
Inverse information matrix			$\left\lvert x^* x \right\rvert^{-1} = \begin{vmatrix} \frac{3029785}{18178710 - 14576875} & \frac{-35125}{18178710 - 14576875} \\ \frac{-415}{18178710 - 14576875} & \frac{6}{18178710 - 14576875} \end{vmatrix}$				
Variable matrix			$\left\lvert x^* y \right\rvert = \begin{vmatrix} 25.5 \\ 2212.5 \end{vmatrix}$				
Normal system solution			$\left\lvert x^* y \right\rvert^{-1} x^* y = \begin{vmatrix} 0.12 \\ 0.00074 \end{vmatrix}$				
Regression function			$\bar{y}x = b_0 - b_1 x^2 = 0.12 - 0.00074 x^2$				
Sum			$\sum x = x_1 + x_2 + x_3 + x_4 + x_5$ $\sum y = y_1 + y_2 + y_3 + y_4 + y_5$ $\sum xy = x_1 y_1 + x_2 y_2 + x_3 y_3 + x_4 y_4 + x_5 y_5$				

Using the experimental data from table 3 the matrix solution can be obtained as:

$$B = \begin{vmatrix} b_0 \\ b_1 \\ b_2 \end{vmatrix} = \begin{vmatrix} 0.1 \\ 0.0082 \\ -0.017 \end{vmatrix} \tag{14}$$

The theoretical regression function is:

$$\bar{y}_x = 0.1 + 0.0082x_1 - 0.017x_2 \tag{15}$$

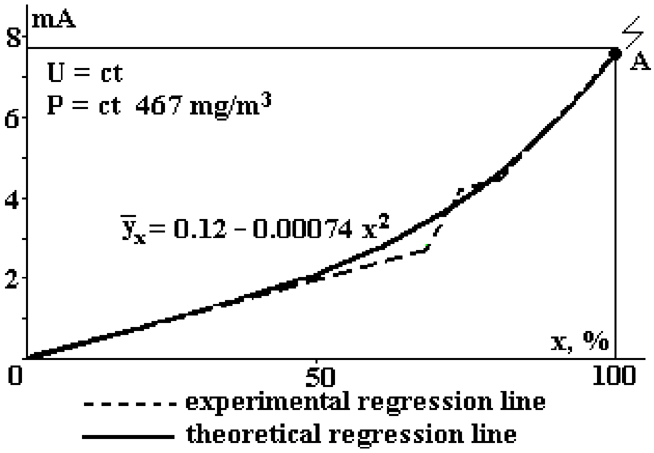

Fig. 2. The leakage current variation vs. humidity

Table 3. Leakage current vs. humidity x_1 and pollution degree x_2

	y	x_1	x_2	x_1^2	x_1^2	x_1y	$x_2 y$	x_1x_2
1	0.1	0	0	0	0	0	0	0
2	0.75	170	44	28900	1938	127.3	33	7480
3	1	440	68	193600	4624	440	68	29920
4	2.4	650	83	637000	6889	1560	1560	53950
5	5.5	980	100	360400	10000	5390	5390	98000
Σ	9.65	2240	295	1246600	23449	7517.5	7051	189350

Relation between leakage current and both pollution and humidity is presented in figure 3.

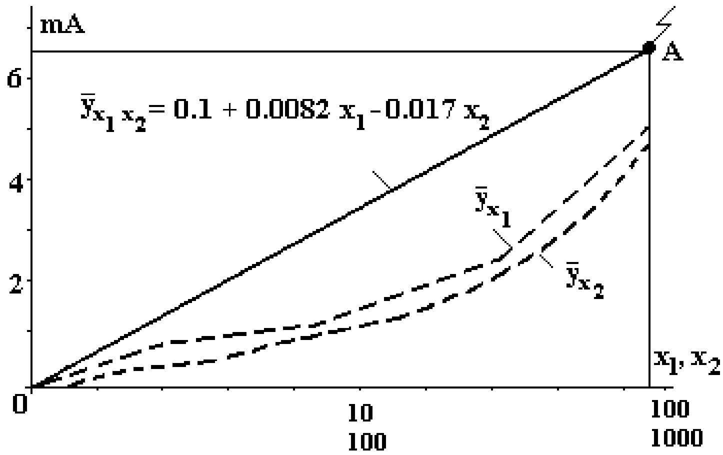

Fig. 3. The leakage current vs. humidity and pollution degree

This variation shows that on an OA part of the leakage current curve is directly proportional with the pollution and humidity. Experimental data show that after the point A on the leakage current curve is no longer directly proportional to pollution degree, instead it has disorderly values. Superficial discharges appear on the insulator surface in this area.

Using the electrical insulator subjected to working voltage is dangerous at this level of pollution as soon as electric breakdown can occur at any time.

A small increase of working voltage at this level of pollution or humidity will result in acceleration of partial discharges and electric breakdown through insulation may start unless preventive actions are taken.

In the most unfavorable cases (extremely high humidity or intense pollution) the electric breakdown through the insulation takes place much earlier and leakage current increases up to hundreds of mA.

The minimum value of the leakage current, at which the electric breakdown begins, determines the security level at which the insulator can be used.

Table 4. Leakage current values for insulator type 2025

			Formula and results			
y	X	Relative humidity	$(x^{*}x)^{-1}$	$(x^{*}y)$	$(x^{*}x)^{-1}(x^{*}y)$	$\overline{y}x$
0.1	0	44	$\begin{vmatrix} \frac{16225616}{43340544} & \frac{-6244}{43340544} \\ \frac{-6244}{43340544} & \frac{5}{43340544} \end{vmatrix}$	$\begin{vmatrix} 13.1 \\ 32531 \end{vmatrix}$	$\begin{vmatrix} 0.217 \\ 0.0018 \end{vmatrix}$	$0.217 + 0.0018x$
0.75	170					
1.25	570					
4.6	2150					
6.5	3354					
1.5	460	74	$\begin{vmatrix} \frac{6725700}{12006000} & \frac{-4650}{12006000} \\ \frac{-4650}{12006000} & \frac{5}{12006000} \end{vmatrix}$	$\begin{vmatrix} 14.9 \\ 21958 \end{vmatrix}$	$\begin{vmatrix} 0.15 \\ 0.0033 \end{vmatrix}$	$0.15 + 0.0033x$
2.6	810					
3.7	1420					
7.1	1960					
0.1	0	83	$\begin{vmatrix} \frac{5721000}{9333400} & \frac{-4390}{9333400} \\ \frac{-4390}{9333400} & \frac{5}{9333400} \end{vmatrix}$	$\begin{vmatrix} 15.4 \\ 20394 \end{vmatrix}$	$\begin{vmatrix} 0.15 \\ 0.00358 \end{vmatrix}$	$0.15 + 0.00368x$
1.5	460					
3.2	950					
3.8	1250					
6.8	1750					
0.1	0	100	$\begin{vmatrix} \frac{3244797}{-9450172} & \frac{-3563}{9450172} \\ \frac{-3563}{9450172} & \frac{3}{-9450172} \end{vmatrix}$	$\begin{vmatrix} 19.5 \\ 20938 \end{vmatrix}$	$\begin{vmatrix} 0.14 \\ 0.005 \end{vmatrix}$	$0.14 + 0.005x$
2	320					
4	799					
5.5	980					
8	1464					
0.1	0	100	$\begin{vmatrix} \frac{25392814}{-119716916} & \frac{-8531}{119716916} \\ \frac{-8531}{119716916} & \frac{5}{-119716916} \end{vmatrix}$	$\begin{vmatrix} 16.9 \\ 50975.5 \end{vmatrix}$	$\begin{vmatrix} 0.04 \\ 0.0009 \end{vmatrix}$	$0.04 + 0.0009x$
0.8	450					
1.2	1160					
6.5	3354					
7.4	3459					
0.1	0	100	$\begin{vmatrix} \frac{8212561}{38380601} & \frac{-5179}{38380601} \\ \frac{-5179}{38380601} & \frac{5}{-38380601} \end{vmatrix}$	$\begin{vmatrix} 14 \\ 22909 \end{vmatrix}$	$\begin{vmatrix} 0.09 \\ 0.001 \end{vmatrix}$	$0.09 + 0.001x$
1.5	592					
2	851					
4	1586					
6.5	2150					

$$(X'X) = \begin{vmatrix} \frac{\sum x^2}{\det|x'x|} & \frac{-\sum x}{\det|x'x|} \\ \frac{-\sum x}{\det|x'x|} & \frac{\sum f}{\det|x'x|} \end{vmatrix} \quad (x'y) = \begin{vmatrix} \sum y \\ \sum xy \end{vmatrix} \quad (X'X)(X'Y) = \begin{vmatrix} \frac{\sum x^2 \sum y - \sum x \sum xy}{\sum x^2 \sum f - \left(\sum x\right)^2} \\ \frac{\sum f \sum xy - \sum x \sum y}{\sum x^2 \sum f - \left(\sum x\right)^2} \end{vmatrix} = \begin{vmatrix} b_0 \\ b_1 \end{vmatrix}$$

$$\overline{y}x = b_0 + b_1 x$$

The variation curves of the effective values of the leakage current for insulator type 2025 in the different test conditions are shown in figure 4 using data from table 4. It is seen from figure 4 that the behavior of the insulators during the pollution process and its effect on them can be characterized by the curves gradient. Worth to note that the values of the leakage current are close one to another at the beginning of the dangerous areas even though the pollution values that determine these areas are very different. This way, the difference in leakage current for points A_1, A_3, exposed for 6 months to pollution, and points A_2, A_4 points, unexposed to pollution, is only 1 mA.

The oscilloscope visualization is another way to show the existence of two areas, safe and unsafe, in the process of insulation pollution. We observed that in the first part (OA area) leakage current waveform is sine, while after point A it is deformed. This area is characterized by the appearance of some harmonics. Figure 5 shows the curves shape obtained by oscilloscope visualization in two areas.

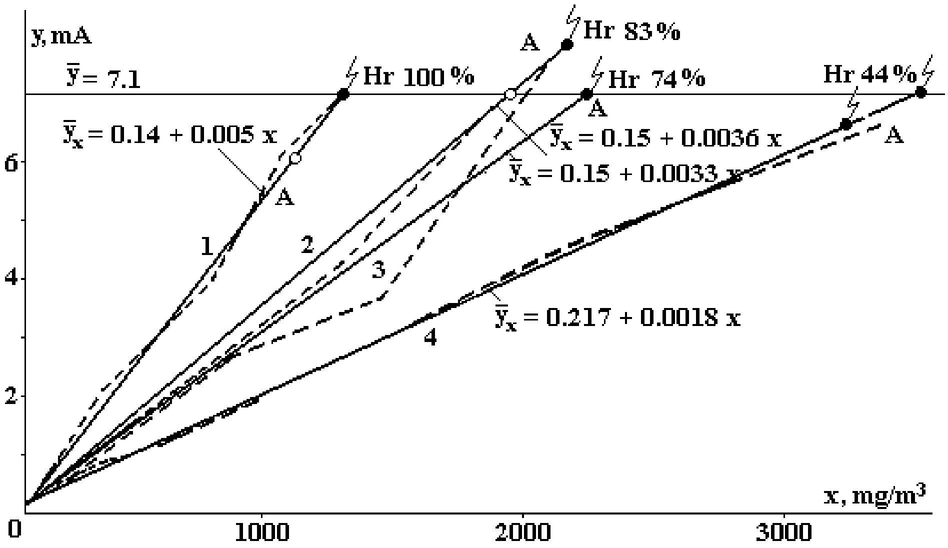

Fig. 4. The leakage current vs. pollution degree: 1.Insulator with vaseline, after 6 month exposure; 2. Clean insulator; 3.Greased insulator, after 6 month exposure; 4. Recently greased insulator

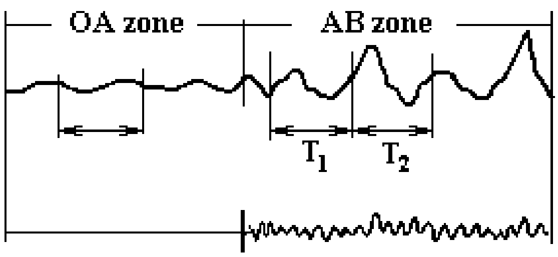

Fig. 5. Leakage current on the surface of insulator

Conclusions

The presence of pollutant agents, the relative humidity and the applied voltage have a different influence on the leakage currents.

In the most unfavorable cases (extreme humidity or intense pollution) the electric breakdown through the insulation takes place much earlier. The same can be said about appearance of partial electric breakdowns. Leakage current during electric breakdown increases very fast and can achieve values as high as hundreds of mA.

The dependence of leakage current intensity on the content of pollutant agents, the relative humidity and the applied voltage for different insulator types can be expressed by some analytical expressions.

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Summary

The different pollution agents, which are present in the environmental air, influence the electrical insulators properties. In this essay, the way in which pollution agents influence the electrical insulators properties at working voltage and different humidity was studied. Analytical relations were obtained. Using these relations, the evolution of electrical insulator properties in the presence of pollution agents can be determined.