Electric strength of air and sulphur hexafluoride in the system with electrodes covered with dielectric double layer

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The paper presents the results of the study on the effect of dielectric double layer at electrode surface on electric strength of compressed air and compressed sulphur hexafluoride. The research has been carried out at alternate voltage of 50 Hz frequency. It was found that thin insulation coating laid on electrode surface, composed of aluminum oxide layer with a layer of electro-insulation polyester lacquer significantly improves electric strength of air and sulphur hexafluoride. It was found that maximum growth of electric strength of these gases was caused by the coating under their pressures exceeding the atmospheric one ($3 \cdot 10^5$ and $5 \cdot 10^5$ Pa). The changes in configuration of electrode surface of the insulation systems caused by sparking over have been examined with scanning laser confocal microscope.

1. Introduction

High-voltage electric insulation of cumulative busducts, enclosed switchgears, and heavy current busducts is often ensured by compressed gases, i.e. air or sulphur hexafluoride (SF_6). One of main factors affecting electric strength of an insulation system, using compressed gases as the insulation medium, is the condition of the parts composing the insulation system. For example, microroughness of larger dimension or material particles that are weakly joined with the electrode and might by detached by the electrostatic force, significantly reduce the electric strength of insulation system. Additionally, mechanical fatigue resulting from alternate voltage and electrostatic force, and thermal fatigue caused by increased temperature, gradually worsen mechanical strength of the parts of electrode material. This may lead to detaching the microroughness regions of the electrode surface at lower and lower voltage values. Therefore, our study has been aimed at searching such methods of surface processing of these elements that improve resistance of the surface to mechanical damage leading to microroughness generating the particles weakly joined with the surfaces. At the same time these methods should increase electric strength of the insulation system.

Former research of the effect of coating the surface of aluminum electrode of the insulation system with oxide layer has shown that the coating may increase the electric strength by more than ten percent, at alternate voltage (50 Hz), in case of the insulation system based on compressed air [4] and compressed SF_6 [5].

The present paper is a continuation of the research and is devoted to influence of the insulation coatings composed of double dielectric layers, i.e. aluminum oxide and insulation lacquer, on electric strength of the above mentioned systems.

2. Description of the measuring stand and the research method

For purposes of the research a cylindrical chamber of stainless steel was used, of 0.40 m diameter and 0.70 m height. Detailed description of the chamber is shown in the paper [6].

Compressed air was delivered by an oil-free compressor. Compressed air and SF_6 were pressed into the chamber through a silica gel filter. Before filling the chamber with SF_6 it was pumped out with a vacuum pump down to the pressure of about 0.1 Pa.

The insulation system was designed in the form of planar aluminum electrodes of 50 mm diameter, with rounded edges, according to the Rogowski formula. The process of electrode surface preparation and creation of the oxide coating is described in [4].

For purposes of the research the electrodes coated with aluminum oxide of the thickness of 5…10 μm were used. Once the layer on the electrode surfaces was ready [4], the electrodes were washed several times in distilled water, with the use of an ultrasonic washer. Afterwards, the electrodes were dried in laboratory dryer in temperature 110°C. After cooling, the next insulation lacquer layer was laid by spraying on the oxide layer. The electrodes prepared this way were dried in room temperature for several hours. Then the lacquer layer was hardened in a laboratory dryer, under the temperature and duration specified by the lacquer manufacturer. Thickness of the lacquer layer laid on the oxide one amounted to 30…40 μm.

Specification of the lacquers used in the studies is shown in Table 1. Most of these materials are quick-drying lacquers designed for electric equipment protection, particularly the one subject to hazard of humidity. They are designed for use under various temperature ranges and various electric voltage values.

AC High voltage of 50 Hz frequency was obtained from a resonance current test system RSZ-700-30-50 (700 kV, 500 kVA) from Haefely Trench Company, supplied from medium voltage distribution network (15 kV).

One of the test transformer terminals was earthed and connected to the test chamber connected to the bottom electrode of the insulation system. The other was connected to the upper electrode through a resistor of 40 kΩ resistance and the lead-in insulator located in upper cover of the chamber. High voltage was measured by means of an electrostatic kilo-voltmeter.

Electric strength of the systems with compressed air and SF_6 was examined for the following pressure values: $1 \cdot 10^5$, $3 \cdot 10^5$ and $5 \cdot 10^5$ Pa.

Table 1. Specification of materials used for coating the aluminum oxide layer on the aluminum electrode surfaces

Coating symbol	**Name/Manufacturer**	**Type**	**Electric strength kV/mm**
A	Urethan 71/Kontakt-Chemie	polyurethane lacquer	40
B	FSC/Electrolube	silicon	80
C	Elektro 101/Elantas	vinyl resin	100
D	Ultimeg 2000-380-45/AET	alkyd phenolic resin	120
E	Dolphon CC 1105/Synflex	polyester lacquer	160

The examined systems have been subject to sparkles conditioning, as in case of the systems including coated electrode sparking would damage them. The conditioning consisted in very slow voltage increase, with the rate about 1 kV/min, until a spark jump. Voltage value corresponding to the first jump was assumed to be equal to electric strength of the system.

Mathematical processing of the test results has been made with the Statistica software [1]. Arithmetic average of five values measured under equal experimental conditions was considered as a representative value of multiple measurements of the jump voltage. On the other hand, standard deviation and 95% confidence interval were assumed to be a measure of a spread of the results around the average.

Surface condition of the electrodes before placing them in the chamber and after the spark jumps has been assessed with the help of a scanning laser confocal microscope LEXT from Olympus [7] – Fig. 1. The microscope enables 3D analysis of the electrode surfaces with extremely high resolution.

Fig. 1. View of the scanning laser confocal microscope LEXT from Olympus [7]

3. Measurement results and their analysis

The studies were carried out in laboratory and in the field. During the laboratory tests carried out for steady heat exchange five measuring sensors have been used, one of them being an active sensor. As a principle it was assumed that the active sensor is located in the middle of the cylindrical container with the soil – Fig. 2.

In order to minimize disturbance of temperature distribution in one sensor caused by another, the passive sensors were so placed as to preclude location of any sensor between the active sensor and any of the passive ones, since this could change the thermal energy flux.

Table 2. Results of the measurements of peak jumping voltage for the insulation systems subject to alternate voltage, with air pressures of $1\cdot10^5$, $3\cdot10^5$ and $5\cdot10^5$ Pa and with the electrodes without surface coating, with oxide coating, and with double coats composed of aluminum oxide and insulation lacquer layers, the inter-electrode distance being equal to 3 mm

The tested insulation system		Pressure	Average value of peak jumping voltage	Standard deviation	95% confidence interval for the average value
		Pa	kV	kV	kV
without the coating		10^5	7.23	0.32	6.79-7.67
		$3\cdot10^5$	21.00	1.57	18.82-23.18
		$5\cdot10^5$	36.00	1.16	34.39-37.61
with Al_2O_3 coating		10^5	7.60	0.35	7.11-8.09
		$3\cdot10^5$	25.50	1.67	23.18-27.82
		$5\cdot10^5$	39.75	1.39	37.82-41.68
with double coating – Al_2O_3 + insulation lacquer layer marked with the symbol:	A	10^5	8.50	0.31	8.07-8.93
		$3\cdot10^5$	27.11	1.85	24.54-29.68
		$5\cdot10^5$	45.89	1.37	43.98-47.8
	B	10^5	8.73	0.64	7.84-9.62
		$3\cdot10^5$	28.29	1.54	26.14-30.44
		$5\cdot10^5$	46.01	1.64	43.73-48.29
	C	10^5	8.78	0.85	7.6-9.96
		$3\cdot10^5$	30.00	1.18	28.36-31.64
		$5\cdot10^5$	49.78	2.21	46.71-52.85
	D	10^5	8.99	0.46	8.35-9.63
		$3\cdot10^5$	30.78	2.48	27.34-34.22
		$5\cdot10^5$	49.99	1.21	48.3-51.68
	E	10^5	9.02	0.94	7.71-10.33
		$3\cdot10^5$	31.01	1.66	28.7-33.32
		$5\cdot10^5$	51.32	1.55	49.17-53.47

Table 2 gives evidence that the use of double dielectric layer at the electrode surface, that is composed of aluminum oxide and insulation lacquer layers, enables significant increase in the electric strength of the insulation system operating with compressed air. For example, the increase in electric strength of the system, with reference to the systems with bare electrodes and air pressure equal to $3 \cdot 10^5$ and $5 \cdot 10^5$ Pa and insulation lacquer layer marked with E symbol exceeds 40 percent.

Results of the measurements of peak jumping voltage at ac voltage of the insulation systems with SF_6 under the pressures of $1 \cdot 10^5$, $3 \cdot 10^5$ and $5 \cdot 10^5$ Pa and with the electrodes without surface coating, with oxide coating, and with double coats made of aluminum oxide and insulation lacquer layers, are shown in Table 3. In these tests the inter-electrode distance amounted to 3 mm.

Table 3. Results of the measurements of peak jumping voltage for the insulation systems subject to alternate voltage, with SF_6 pressures of $1 \cdot 10^5$, $3 \cdot 10^5$ and $5 \cdot 10^5$ Pa and with the electrodes without surface coating, with oxide coating, and with double coats composed of aluminum oxide and insulation lacquer layers, the inter-electrode distance being equal to 3 mm

The tested insulation system		**Pressure**	**Average value of peak jumping voltage**	**Standard deviation**	**95% confidence interval for the average value**
		Pa	**kV**	**kV**	**kV**
without the coating [5]		10^5	18.89	0.30	18.47-19.31
		$3 \cdot 10^5$	49.00	2.36	45.72-52.28
		$5 \cdot 10^5$	75.03	2.72	71.25-78.81
with Al_2O_3 coating [5]		10^5	21.58	1.45	19.56-23.6
		$3 \cdot 10^5$	62.04	2.60	58.43-65.65
		$5 \cdot 10^5$	83.72	2.54	80.18-87.26
with double coating – Al_2O_3 + insulation lacquer layer marked with the symbol:	A	10^5	24.81	1.87	22.22-27.4
		$3 \cdot 10^5$	67.00	2.24	63.89-70.11
		$5 \cdot 10^5$	100.42	3.47	95.59-105.25
	B	10^5	25.15	2.06	22.28-28.02
		$3 \cdot 10^5$	71.21	2.44	67.82-74.6
		$5 \cdot 10^5$	106.60	2.16	103.6-109.6
	C	10^5	25.02	0.67	24.1-25.94
		$3 \cdot 10^5$	76.45	4.72	69.88-83.02
		$5 \cdot 10^5$	117.12	4.54	110.81-123.43
	D	10^5	24.45	2.20	21.39-27.51
		$3 \cdot 10^5$	80.34	2.54	76.81-83.87
		$5 \cdot 10^5$	121.80	3.84	116.46-127.14
	E	10^5	26.09	3.05	21.84-30.34
		$3 \cdot 10^5$	81.89	5.33	74.48-89.3
		$5 \cdot 10^5$	122.23	4.13	116.49-127.97

Table 3 gives evidence that the use of double dielectric layer at the electrode surface, that is composed of aluminum oxide and insulation lacquer layers, enables significant increase in the electric strength of the insulation system operating with compressed SF_6. Maximum increase in electric strength of the system caused by the double dielectric layer placed at the electrode surfaces occurred for the coating with insulation lacquer marked with E symbol. It amounted to 52% in case of SF_6 pressure equal to $3 \cdot 10^5$ Pa and 67% for SF_6 pressure equal to $5 \cdot 10^5$ Pa.

Electrode surface condition of the tested insulation systems was checked with scanning laser confocal microscope, both before and after measuring of their electric strength. This gave 2- or 3-D views of selected parts of the electrode surfaces. Moreover, the 3D analysis allowed to scan both the shape of the surface defect and its dimensions, inclusive of its depth.

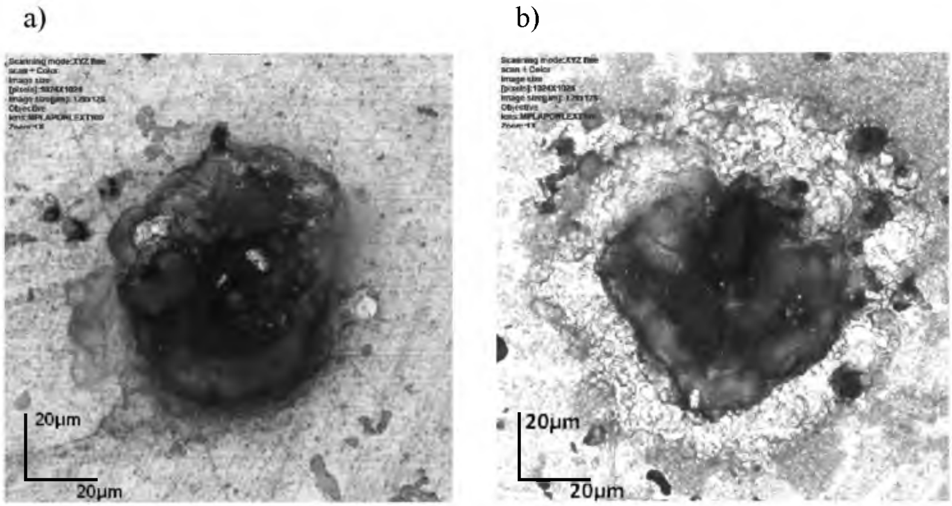

Fig. 2. 2D view of the damage trace caused by the spark-over to aluminum electrode surface without the coating (a) and with aluminum oxide layer on it (b)

Example results of the tests are shown in Figs 2, 3, and 4. Figure 2 presents a 2D, while Fig. 3 a 3D view of the damage trace caused by the spark-over to aluminum electrode surface without the coating (a) and with aluminum oxide layer on it (b). On the other hand, Fig. 4 presents an example profile of the crater arising in results of the spark-over on the aluminum electrode without the coating (a) and with aluminum oxide layer on it (b).

a) b)

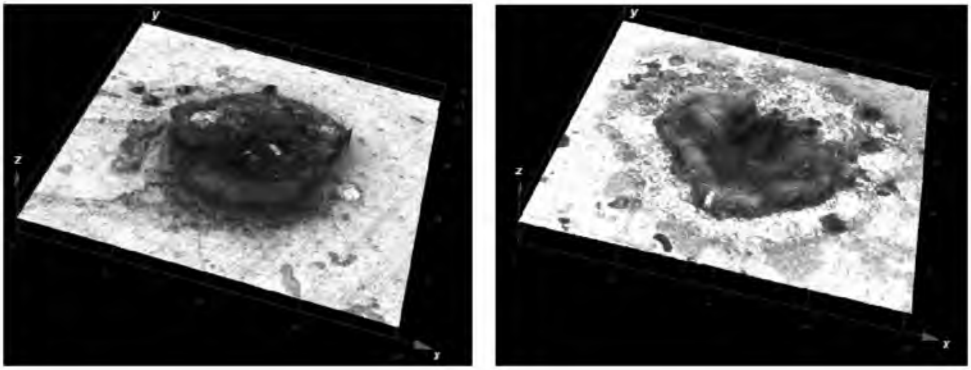

Fig. 3. 3D view of the damage trace caused by the spark-over to aluminum electrode surface without the coating (a) and with aluminum oxide layer on it (b)

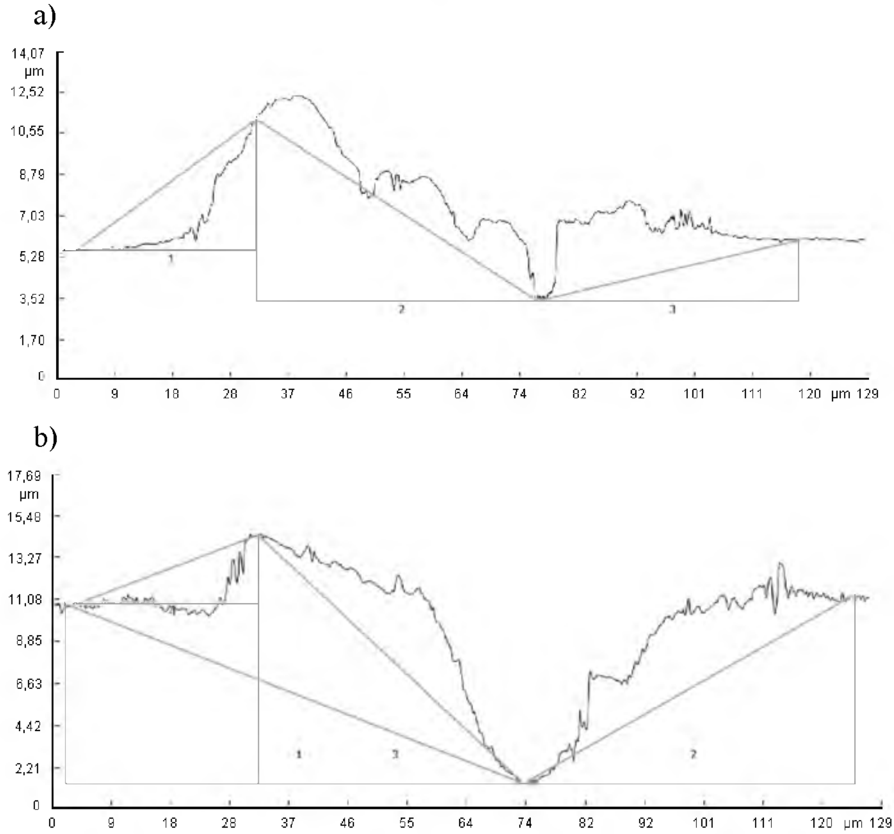

Fig. 4. Example profile of the crater arising in results of spark-over on the aluminum electrode without the coating (a) and with aluminum oxide layer on it (b)

4. Conclusions

Recapitulating, one can state that in result of coating electrode surfaces of the insulation system with double dielectric coat composed of aluminum oxide and insulation lacquer layers a significant increase in electric strength of the insulation system with compressed air and compressed SF_6 may be achieved, at alternate voltage of rated network frequency. Maximum increase in electric strength of the considered insulation systems occurred in case of the coating composed of aluminum oxide and polyester lacquer layers. The experiments have shown that minimum percent increase in electric strength of the tested insulation systems caused by the double dielectric coat on the electrode surfaces occurred at the lowest pressure of the insulating gases ($1\cdot10^5$ Pa). Significantly higher growth was observed for higher pressures ($3\cdot10^5$ and $5\cdot10^5$ Pa).

Microscopic analysis of the damage traces caused by spark-over to the electrode surfaces has shown that the dimensions of the craters arising on electrode surfaces covered with aluminum oxide are usually remarkably smaller than those generated at the uncoated electrodes. It means that the aluminum oxide layer, distinguished by good mechanical strength, protects the electrode surface not only against mechanical damage, e.g. while assembling the device, but also reduces the extent of surface damage caused by electric discharge.

Mechanical damage to a polished electrode surface usually results in worsening of electric strength of the gas insulation system. Therefore, the use of these coatings of high mechanical strength as insulation coverage of current conducting elements may be considered to be advisable. It should be noticed that the coating composed of aluminum oxide and insulation lacquer layers significantly increases, at the same time, electric strength of gas insulation system, particularly at the pressure significantly exceeding the atmospheric one.

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