The Influence of Magnetic Field Shape on Dielectric Characteristics of Vacuum Switches

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The aim of this paper is to examine the influence of the magnetic field shape in the inter-contact space in the context of contact degradation during the switching operation of circuit-breaking with current. The results of measuring the AC breakdown voltage and pulse breakdown voltage are statistically analyzed for that purpose. The experiments are carried out on the commercial switching elements with CuCr contact. The experiment parameters are the current breaking voltage value and inter-electrode distance. Results showed that switches with radial magnetic field suffer less irreversible changes during the breaking operation such as circuit-breaking with nominal current and circuit-breaking with short-circuit current.

Keywords: *Vacuum switch, CuCr contacts, radial magnetic field, axial magnetic field, current breaking operation, irreversibility, dielectric characteristics.*

1. INTRODUCTION

The basic characteristics of vacuum switches are the following: high reliability, mechanical and electric durability, easy maintenance (no requirement for replacing or refilling the media intended for arc quenching, small dimensions and weight, the current being interrupted at the first zero phase without being accompanied by the repeated arc ignition, safety in terms of explosion and fire and zero environment pollution) [1-3].

The phenomenon of electric arc occurs in the course of the switching operation circuit-breaking with current. If this operation breaks the nominal current, the electric arc is wide (the diffuse arc). In case of short-circuit current breaking, the electric arc is narrow. The wide electric arc leads to contacts conditioning and increasing the value of breakdown voltage of the switch with open contacts. The narrow concentrated electric arc leads to considerable topography change of electrode surfaces thereby decreasing the breakdown voltage value of the switch with open contacts [4-7].

The concentrated arc oscillates under the influence of electromagnetic forces along the electrodes' edge. In modern vacuum switches, the magnetic field in inter-contact space is used for quenching the electric arc. The shape of magnetic field is obtained by contact geometry. The most commonly used shape is that of radial or axial magnetic field [8-10]. The aim of this paper is to examine the influence of the magnetic field shape in the inter-contact space in the context of contact degradation during the switching operations of circuit-breaking with current.

Received: January 2016, Accepted: February 2016
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doi:10.5937/fmet1701135T

2. SWITCHING OPERATIONS OF CIRCUIT-BREAKING WITH CURRENT

Current breaking in the vacuum switching element cause the contact changes by means of the following mechanisms: 1 – cathode erosion (in the course of cathode spot movement of the electric arc); 2 – explosion of the conducting metal bridge in arc expanding; 3 – condensing of neutral metal vapor at contacts, and 4 – micro spikes emission from the melted surface parts of anode and cathode. Mechanisms 1, 2 and 3 are dominant for the diffuse arc (i.e. in case of such vacuum arc operation in which several parallel small current arcs exists with the order of magnitude being 100 A and that do not form consolidated anode spot), and are practically negligible for the narrow arc (i.e. in case of such vacuum arc operation in which anode spots of several parallel arcs are unified into a consolidated cathode spot). The diffuse arc occurs with small current, and is converted into a narrow arc for certain values of the current, which depends on contact geometry, a type of contact material and the shape of magnetic field in the inter-contact distance. The diffuse one has typical voltage values of 30 V while for the narrow arc, these values exceed 100 V. The transition of a diffuse arc into a narrow arc does not occur instantaneously, but rather, transitional shape can be brought about.

Cathode erosion for relatively small arc current originates from melted material in the cathode spot (which is constantly stochastically moving) thereby leaving the trace on the cathode surface. However, these are not traces with sharp craters, but rather the sharpest micro-bulges on a cathode are being destroyed and thereby the layer of impurities from the cathode can be removed. This conditioning of contacts leads even up to improving of dielectric strength. The explosion of the conducting bridge is mostly responsible for deterioration of dielectric characteristics in the diffuse arc operation. Namely, in the course of breaking operation, at one moment, the only contact between electrodes is a small surface in which the material melts and explosively evaporates due to significant Joule's effect. At the explosion spot sharp craters and micro-spikes remain and lead to the electric field intensifying. The sole influence of the condensed metal vapours upon the dielectric strength of the inter-contact space is practically insignificant. Such condensation can lead to improvement of dielectric properties of the inter-contact space by means of the two mechanisms: 1 – condensing on micro-spikes and increasing the radius of their curvature and 2 – gathering the metal vapours on the screens after gathering the molecules of residual gas thereby enhancing the vacuum level.

Narrowing of arc and formation of a single anode spot leads to intensive melting of anode and increases micro-spikes emission. These micro-spikes collide with electrodes where they unify and become solid. Part of these micro-spikes remains loosely connected with the base, so that after the subsequent impact of sufficiently strong electric field their breaking off can initiate the vacuum breakdown by micro-particle mechanism [11-14]. The other part of micro-parts remains connected with the surfaces of electrodes thus representing the micro roughness. It may occur that they contain micro-spikes, which if acted on by sufficiently strong electric field can initiate emission mechanisms of the breakdown [15-17].

3. EXPERIMENT AND EXPERIMENTAL DATA PROCESSING

The investigation, which is the subject of this section, was carried out on two types of commercial vacuum switching elements that are hereinafter referred to as A and B, respectively. All switching elements were furnished with the cylindrically shaped insulating cover made of Al_2O_3 ceramic. More specifically, the contacts of elements A and B were made of sintered CuCr according to the manufacturer's specification. The contacts were not visible. Namely, the type A element pertains to transverse magnetic field contacts, while, at the same time, the type B element pertains to axial magnetic field contacts. Figure 1 displays the photos of switches of type A and type B. Furthermore, the examined switching elements' parameters abiding to the manufacturer specifications are provided in Table 1.

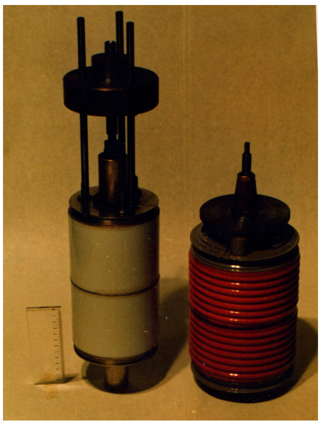


Figure 1. Photos of switches type A (left) and type B (right).

The utilized device that converted the rotation of its movable part into the movable contact translation (1 mm = 360°) was the pneumatic cylinder, which represented a drive for a movable contact of vacuum switching element. Additionally, measuring the Ohmic resistance between contact carriers determines the zero distance of the contact.

Placing the switching element into a vessel filled with SF_6 gas under a pressure of 2 bar was prevented by outside flashovers. Radiation measurement performed at the rear of the shield was compliant with the level of the natural background radiation. In addition to this, the vacuum chambers, the thickness of which equalled 4 mm and the aim of which was to provide protection from X-rays, were located behind a lead shield.

Both types of vacuum switching chambers underwent dielectric examination, which was accomplished by means of ac and pulse voltages. The applied pulse voltage had negative polarity, the shape of which totalled 1.2/50 µs, while the amplitude equalled 250 kV. A rise rate of the applied ac voltage totalled 20 kV/s.

Table 1. The examined switching elements' parameters.

Type of switching element	A	B
Rated line voltage [kV]	12	14
Rated continuous current [kA]	2	2
Rated short-circuit breaking current [kA]	20	20
DC percentage [%]	50	40
Rated short-circuit making current [kA]	50	50
The contact gap [mm]	8	10
Average opening speed [m/s]	1	1

The pulse voltage source was in the form of a four stage Marx generator with capacitors of 70 kV/200 nF per degree. Furthermore, a voltage shape of 1.2/50 µs was provided by adjusting the generator. The breakdown occurred always at the wave front due to adjusting the amplitude of the breakdown voltage [18, 19].

A source of *ac* voltage was provided in the form of a high-voltage test transformer of 130 kV_{eff} / 30 kVA with the transfer ratio of 1:300. The regulating transformer of 220 V/(0–500) V furnished the test transformer.

A series of dc measurement was performed by means of a dc supply source, which had the maximum 30 kV output. The ripple of the output voltage was stable and smaller than 5%. A regulating transformer adapted the value of the *dc*, which was carried to the tested object with a rise rate totalling 20 kV/s. A spark gap provided protection for the diode of the output part.

Moreover, the *dc* voltage was generated through a high-ohmic divider of 132 MΩ/23.4 kΩ with the transfer ratio of 5600. More specifically, a capacitive divider with a high-voltage gas capacitor the transfer ratio of 8000 was utilized so as to measure the *ac* voltage.

The emission current was measured via a shunt of 1500 Ω placed in a series along with the object that was being tested.

The series with the tested object was supplied by the thyristor protection aimed at detecting voltage greater than 50 V after the breakdown that eventually led to the current being turned off.

A source of high current was provided through the short-circuit current generator of 2×40 MVA and generator voltages of 1080, 625, and 540 V. While the pre-coding arc duration was controlled not to surpass (8 ± 1) ms, both the short-circuit interrupters and generator actuating change limited the current in the generator circuit. The elements requiring to be accurately switched on were connected to synchronous switching equipment the type B measurement uncertainty of which was less than 1%.

Additionally, a voltage divider was used for measuring the high voltage. The pulse voltage required the utilization of a low-ohmic resistor divider (R_0 = 10 kΩ) the transfer ratio of was 273. Briefly, the signal was carried from its low-voltage part into the digital oscilloscope via a coaxial cable. On the one hand, the ohmic divider of 8 kΩ/2 kΩ with a transfer ratio of 5:1 was utilized for measuring the electric arc voltage. While, on the other hand, a coaxial shunt of 0.1 mΩ with a maximum current of 40 kA_{eff} provided a series of measurement of the electric arc current.

Two different switching operations were involved in experimental procedures, both switching operations being circuit-making circuit-breaking: (1) with nominal current and (2) with short-circuit current. These operations were hereinafter specified as the operation 1 and 2, respectively.

The formation of statistical samples pertaining to pulse and ac breakdown random variables was the ultimate goal of the experiment. As the flow chart of experiment displayed in the form of Figure 2 shows, statistical samples were taken for: conditioned contacts and switching operations 1 and 2.

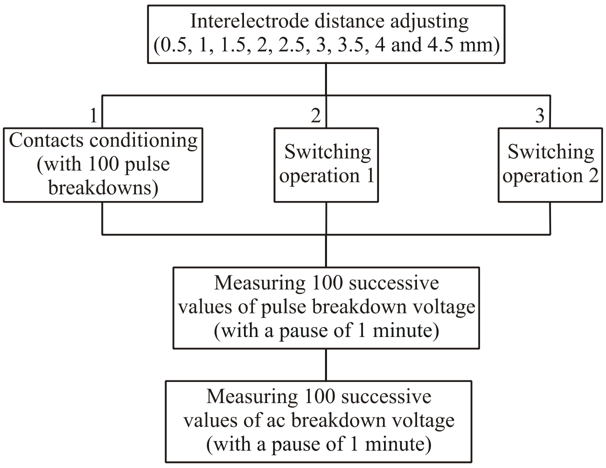


Figure 2. The experiment's flow chart.

Concisely, the measurement uncertainty totalled 4.6% (combined uncertainty) for the *ac* measurement. Simultaneously, the measurement uncertainty equalled 4.8% (combined uncertainty) for the pulse measurement and 3.6% (uncertainty type B) in the case of a series of measurements that were carried out for nominal and short-circuit current and being less than 0.5% (uncertainty type B) for the inter-electrode distance [22].

Statistical samples of breakdown voltage variables were statistically processed as following:

(1) The statistical sample was deprived of the spurious values,

(2) In order to check whether two sub-samples belong to the same sample irrespective of their distribution function [23], the U-test was implemented. A statistical sample comprising 100 random variables was divided into 20 chronological sub-samples of five random variables, which were subsequently tested by means of U-test.

(3) Each statistical sample exhibited somewhat random variable tendency that was examined by theoretical distribution functions (normal, Weibull, and exponential [20, 21]).

4. RESULTS AND DISCUSSION

Figures 3 and 4 display the oscillographs of voltage and current in the course of the switching operation "circuit-breaking with nominal current" and "circuit-breaking with short-circuit current", respectively. The diagrams shown in the figure 3 illustrates that in case of nominal current breaking the diffuse arc phenomenon occurs (regardless of the shape of magnetic field in the inter-contact space).

The diagrams shown in Figure 4 illustrates that in the course of short-circuit current breaking the phenomenon of narrow arc occurs thereby proving the sudden increase of arc voltage (also, this phenomenon does not depend on the shape of magnetic field in the inter-contact space).

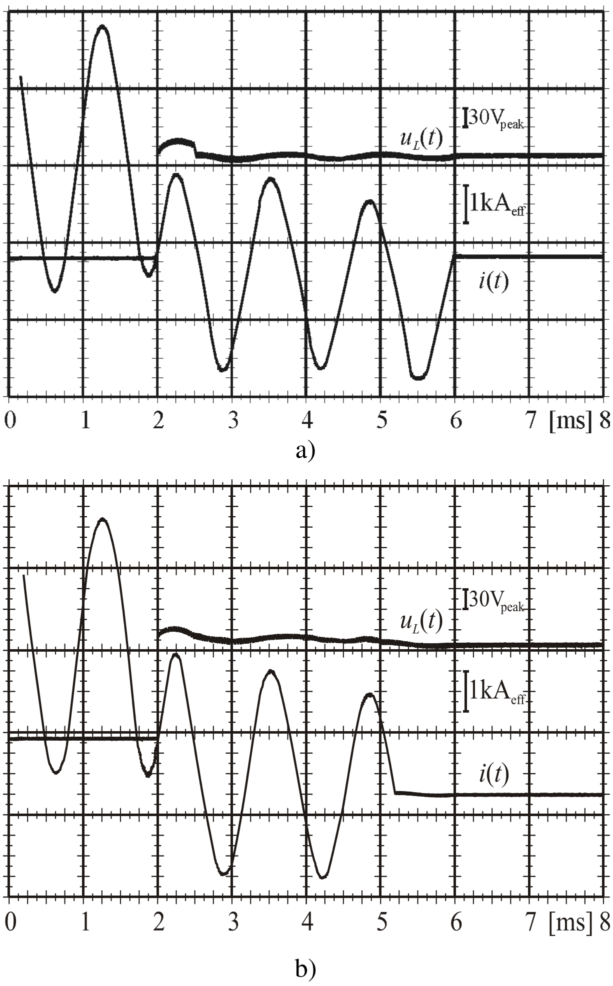
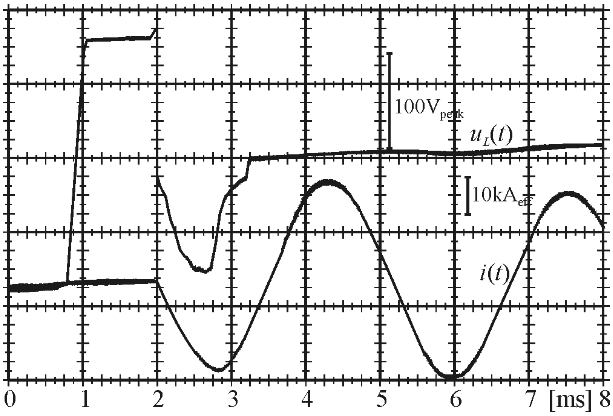
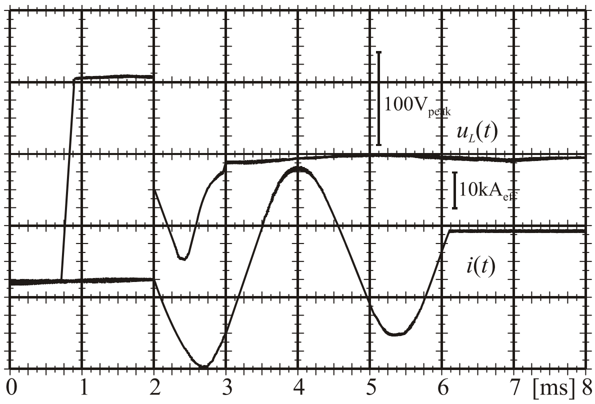


Figure 3. Oscillogram of the current and voltage during the operation 2: a) switching element type A; b) switching element type B.



a)

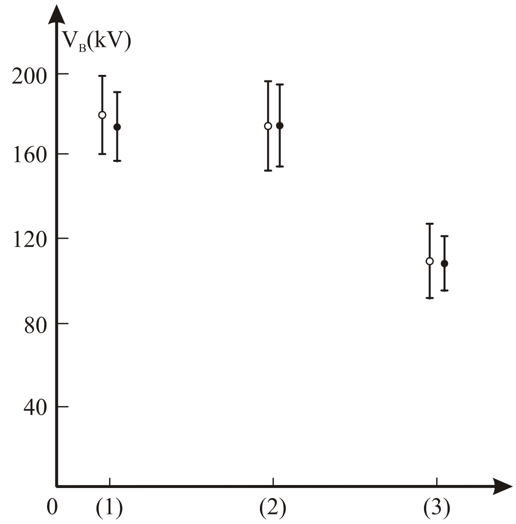


b)

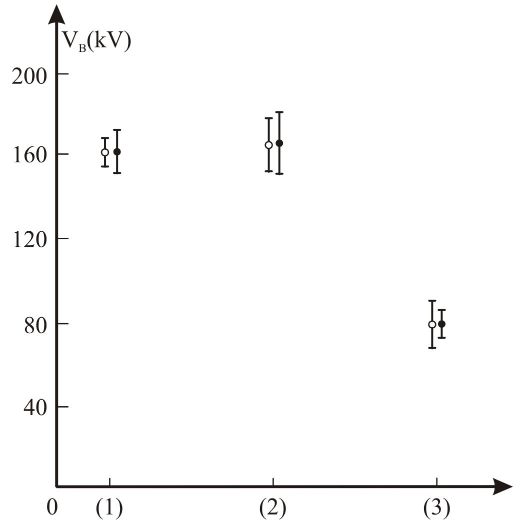
Figure 4. Oscillogram of the current and voltage during the operation 3: a) switching element type A; b) switching element type B.

4.1 Conditioned contacts

The results obtained with conditioned contacts show:
- In case of contacts with radial magnetic field for distances less than 2 mm, there is no difference between values of ac and pulse breakdown voltage. For inter-electrode distance larger than 2 mm, values of pulse breakdown voltage are somewhat higher. This phenomenon can be accounted to the ratio of the time necessary for the evaporated electrode material to fill in the inter-electrode space to the time of the pulse rise, Figure 5.
- In case of a contact with axial magnetic field, ac and pulse breakdown voltage have the same value up to the inter-contact distance totaling 2.5 mm. The difference between the contacts with the radial and axial magnetic field lies in the concentration of micro-spikes in the central part of contact surfaces in case of axial magnetic field, which all leads to the faster filling of the inter-contact space with the contact material vapors, Figure 5.
- The linear increase of the values of ac and the pulse breakdown voltage was established with the inter-electrode distance in case of contact with the radial field.
- At higher inter-contacts values, the linear increase of ac and pulse breakdown voltage is disturbed in case of contact with the axial field.
- Random variables ac and pulse breakdown voltage ultimately belong to the Weibull distribution, Figure 6.
- If the breakdown field is taken as a random variable instead of the breakdown voltage, then all statistical samples of that random variable, for different *d*, can be displayed by the unified Weibull distribution. According to the theory of weak spots, this means that there is only one type of weak spots, which is described by the macroscopic electric field.
- The results of the U-test show that *ac* and pulse breakdown voltage random variables belong to a unified statistical distribution with less than 5% statistical uncertainty.
- A significant influence of the vacuum chamber type on the corresponding values of *ac* and pulse breakdown voltage was not noticed, Figure 7.



a)



b)

Figure 5. Dependence of the pulse (•) and ac (○) break–down voltage on the switching operation (1) conditioned contacts, (2) circuit breaking with nominal current, (3) circuit breaking with short-circuit current for: a) switch type A; b) switch type B

4.2 Circuit-breaking with nominal current

After the switching operation of nominal current breaking, the results are almost identical to the results obtained with conditioned contact, independently of the shape of the magnetic field and the inter-contact space.

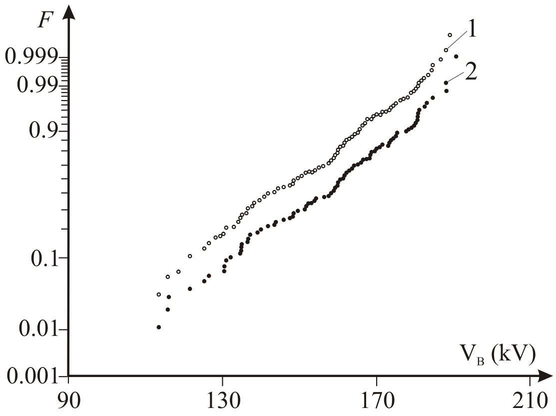


Figure 6. Pulse breakdown voltage shown in the Weibull probability paper after the switching operation 1 for the switch type B (1) and A (2).

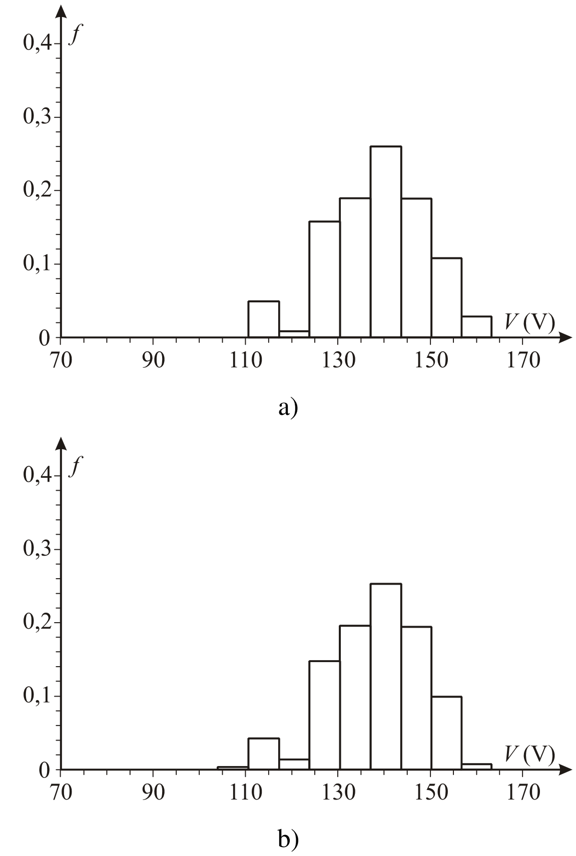


Figure 7. Histogram of breakdown voltage for inter-contact distance of 4mm, switch type B: a) ac breakdown voltage; b) pulse breakdown voltage.

4.3 Circuit-breaking with short-circuit current

After the switching operation of short-circuit current breaking, the following was established:

- In case of contact with radial magnetic field there is no difference between statistical samples of random variables ac and pulse breakdown voltage.
- In case of contacts with the axial magnetic field, values of random variable ac breakdown voltage are higher than values of the pulse breakdown voltage.
- In case of contacts with the radial magnetic field, the mean values of ac and pulse breakdown voltage increases with $d^{0.6}$, Figure 8.
- In case of contacts with the axial magnetic field, the mean values of ac and pulse breakdown voltage increases with $d^{0.45}$, Figure 8.
- In case of contact with the radial magnetic field, random variables ac and pulse breakdown voltage belong to the complex distribution of additive type that comprises two distributions of the Weibull type. The values of ac and pulse breakdown voltage are lower than the corresponding values obtained for conditioned contacts, Figure 9.
- In case of contacts with axial magnetic field, random variables ac and pulse breakdown voltage belong to the complex distribution of additive type that comprises two Weibull distribution types. By comparing the figures, it becomes evident that the contribution of additive distribution is equal in case of contact with the axial magnetic field.

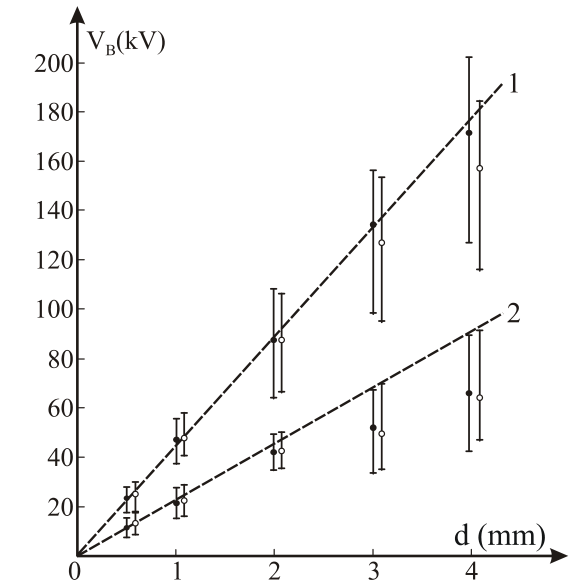


Figure 8. Dependence of mean value and standard deviation of pulse (●) and ac (○) breakdown voltage on the inter-contact distance for: (1) switch type A and (2) switch type B.

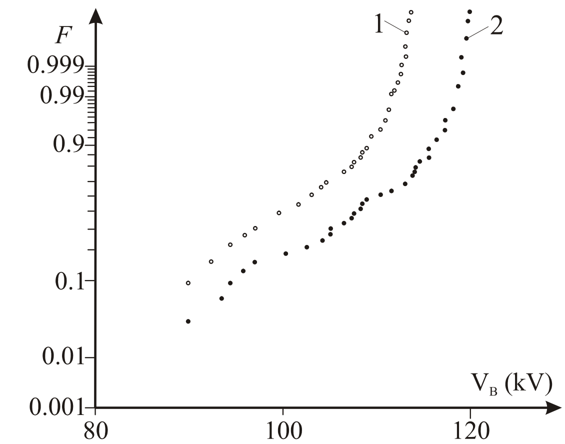


Figure 9. Pulse breakdown voltage shown in the Weibull probability paper after the switching operation 3 for the switch type B (1) and A (2).

5. CONCLUSION

Based on examination of dielectric characteristics changes of vacuum switches with CuCr contacts and different shapes of magnetic field in the inter-electrode space, the following can be concluded: 1 - In switches with axial field, substantially larger changes of contact surfaces' topography occur during the switching operations of current breaking; 2 – This effect is particularly striking during the short-circuit current breaking; 3 – Due to these effects the significant decrease of dielectric strength was observed for the switches with axial field; 4 – These effects can affect the power system, which contains vacuum switches of this type and 5 – Switches with axial magnetic field should be avoided whenever it is possible.

ACKNOWLEDGMENT

This work was partly supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia under contract no. 171007.

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УТИЦАЈ ОБЛИКА МАГНЕТНОГ ПОЉА НА ДИЕЛЕКТРИЧНЕ КАРАКТЕРИСТИКЕ ВАКУУМСКИХ ПРЕКИДАЧА

Р. Тодоровић, Д. Шкатарић, З. Бајрамовић, К. Станковић

Циљ овог рада је испитивање утицаја облика магнетног поља у међуконтактном простору у смислу деградације контаката током склопних

операција исклопа под оптерећењем. У том смислу статистички су анализирани резултати мерења наизменичног пробојног напона и импулсног пробојног напона. Експерименти су спроведени на комерцијалним прекидачима са CuCr контактима. Параметри у експерименту били су вредност напона приликом прекидања струје и међуконтактно растојање. Установљено је да прекидачи са радијалним магнетним пољем у међуконтактном простору трпе мање иреверзибилне промене током прекидања номиналне струје и номиналне струје кратког споја.