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INVESTIGATION OF EXPLOSION SAFETY OF DC POLYMER SURGE ARRESTERS 3.3 KV FOR TRACTION NETWORK OF RAILWAY TRANSPORT

In the testing laboratories of Ukraine, there is no high-voltage equipment of the necessary energy for testing surge arresters for explosion safety, which does not allow to estimate this indicator at the stage of development of prototypes. In view of this test, the polymer prototypes of the DC surge arresters in polymer case (SAp) 3.3 kV were tested under the operating conditions of the equipment of the operating substation with short-circuit currents of 8.3 kA and a current time of 0.02 seconds, close to the recommended by Standard of IEC 60099-4:2014 values. 8 samples of surge arresters were tested. A sample of the surge arrester was mounted on one of the metal supports at a height of 5.5 m located in the substation and connected to the 3.3 kV traction substation buses through disconnectors and a high-speed switch. After the short-circuit breaker was closed through a column with a pre-punched or shunted copper wire varistor, a short-circuit current flowed to form an electric arc inside the arrester samples. During the tests video samples were recorded using a video recorder installed in close proximity to the test sample. The frame of the SAp samples in which the varistors were enclosed was performed either by winding the fiberglass tape on a varistor column, or from rods arranged in the form of a squirrel cage, or in the form of a fiberglass tube with a hole for gas ejection during a short circuit inside the SAp. The destruction of the hull occurred without scattering of the fragments in seven cases from the eight samples tested. In seven samples, a local rupture of the silicone shell occurred in the varistor zone, a gas ejection and an arc discharge occurred through this gap. The exception was sample No. 2, made by a continuous winding of a glass-banding tape on a varistor column, in which, during the explosion, the upper electrode exploded with the simultaneous expansion of fragments of the varistor in a radius of 3-5 m. Due to the white smoke accompanying the explosion, it was not possible to fix on the frame whether the arc output from the case to the outside, despite the fact that on the next frame (in 33 ms.) the arc was no longer fixed. In the tests of eight of the presented designs, none of them ignited the hull. If the tests were carried out on the surge arresters assembled with pre-punched varistors (electrothermal breakdown), the varistors during the tests split, remaining inside the frame. From the action of the arc in the contact zone of the aluminum electrodes with varistors, a deep burn-out of the electrodes was observed, in some cases, the burnup was up to 7 mm deep and up to 8 mm wide. If the varistors were shunted by a copper wire, they remained intact. If the varistors were shunted by a copper wire, they remained intact und melting and burning out a part of the aluminum electrodes in the area of connection with the copper wire were smaller sizes. The samples showed a completely satisfactory ability to withstand large pulse currents without dispersing dangerous fragments for personnel and surrounding equipment. However, polymer designs, the frame of which is made by continuous winding, require reinforcement of the connection zone of the carcass with electrodes to exclude the break-out of electrodes during the accumulation of gases during a short circuit inside the shell of the SAp. For such designs, an additional test for mechanical strength in the longitudinal direction with a predetermined norm is required in the acceptance test program. References 11, tables 1, figures 5.

Key words: **electrical equipment of traction network, direct current, overvoltage protection, surge arrester, explosion safety, test procedure, explosive destruction, fragment separation.**

Проведено випробування полімерних зразків ОПН-3,3 кВ в експлуатаційних умовах на обладнанні діючої підстанції, при токах короткого замикання 8,3 кА і часу впливу струму 0,02 с, близьких за величиною до рекомендованих стандартом IEC 60099-4:2014 значень. Випробувано 8 шт. обмежувачів перенапруг. Каркас, в якому були укладені варистори, виконувався або шляхом намотування склопластикової стрічки на варисторну колонку, або стрижнів, розташованих у вигляді «білячої клітини», або склопластикової труби з отвором для викиду газів при короткому замиканні всередині ОПН. Зразки показали цілком задовільну здатність витримувати великі імпульсні струми без розльоту небезпечних для персоналу і навколишнього обладнання фрагментів. Полімерні конструкції, каркас яких виконаний суцільним намотуванням, вимагають посилення зони з'єднання каркаса з електродами для виключення вильоту електродів при скупченні газів при короткому замиканні всередині корпусу ОПН. Для таких конструкцій потрібне введення в програму приймально-здавальних випробувань додаткової перевірки на механічну міцність в поздовжньому напрямку з заздалегідь встановленої нормою міцності. Бібл. 11, табл. 1, рис. 5.

Ключові слова: **електрообладнання тягових пристроїв, постійний струм, захист від перенапруг, обмежувачі перенапруг, вибухобезпечність, методика випробувань, вибухове руйнування, розліт фрагментів.**

Проведены испытания полимерных образцов ОПН-3,3 кВ в эксплуатационных условиях на оборудовании действующей подстанции, при токах короткого замыкания 8,3 кА и времени воздействия тока 0,02 с, близких по величине к рекомендуемым стандартом IEC 60099-4:2014 значениям. Испытано 8 шт. ограничителей перенапряжений. Каркас, в котором были заключены варисторы, выполнялся либо путём намотки стеклопластиковой ленты на варисторную колонку, либо из стержней, расположенных в виде «беличьей клетки», либо в виде стеклопластиковой трубы с отверстием для выброса газов при коротком замыкании внутри ОПН. Образцы показали вполне удовлетворительную способность выдерживать большие импульсные токи без разлёта опасных для персонала и окружающего оборудования фрагментов. Полимерные конструкции, каркас которых выполнен сплошной намоткой, требуют усиления зоны соединения каркаса с электродами для исключения вылета электродов при скоплении газов при коротком замыкании внутри корпуса ОПН. Для таких конструкций требуется введение в программу приёмо-сдаточных испытаний дополнительной проверки на механическую прочность в продольном направлении с заранее установленной нормой прочности. Библ. 11, табл. 1, рис. 5.

Ключевые слова: **электрооборудование тяговых устройств, постоянный ток, защита от перенапряжений, ограничители перенапряжений, взрывобезопасность, методика испытаний, взрывное разрушение, разлёт фрагментов.**

Introduction. To protect against overvoltages the electrical equipment of traction devices, electric locomotives and electric trains dischargers or surge arresters (SA) are used.

Currently, in most cases, dischargers РМВУ-3,3; РВКУ-3,3 А 01 [1-3] on electrical equipment are installed, made of vilite disks and spark gaps, as well as surge suppressors in porcelain cases. Vilite dischargers are morally obsolete and are in fact out of production; porcelain surge arresters have several disadvantages: insufficient tightness of the connection between a porcelain tire and a metal flange, high explosion hazard, large dimensions and weight. To eliminate the above disadvantages, for the replacement of porcelain structures for the DC railroad surge arresters in a polymer case (SAp) are designed and mastered. When developing new SAp, it is taken into account that their most important indicator is explosion safety. Surge arresters, like any apparatus, can be damaged in operation, for example, due to internal breakdown of varistors, which can lead to short circuit and electric arcs inside the case, a sharp increase in internal gas pressure from thermal decomposition of materials caused by an electric arc. If damage to the SA is accompanied by an explosive destruction of the case, then this is a danger to the substation personnel and the equipment located near it, since the explosion can fragment the varistors and the hard parts of the exploded case at high speed. Metal flanges can also escape from the SAp case. When installing the SAp on electric locomotives and electric trains, the danger of explosive destruction of the SA is aggravated by the fact that the fragmentation of fragments can occur in crowded places. According to [4], for all types of SA, explosion safety is defined as the absence of an explosive destruction of a case with fragmentation in the normalized zone when tested, and the absence of case ignition during destruction and, if it occurs, followed by flame attenuation during a time not longer than 30 s.

For a SA of a DC network, test modes for confirming the explosion safety are defined in [5]. In the Ukrainian testing laboratories there is no high-voltage equipment for high currents for testing the SA for explosion protection in short-circuit modes. At the same time, when preparing the Specifications for these products, confirmation of compliance with the requirements of [6] is required, in which the explosion safety of the apparatus is the most important indicator.

The goal of the work is the determination of the explosion safety of SAp-3.3 kV samples with a polymer case on the equipment of an operating DC traction substation under conditions as close as possible to operation.

Samples for testing. 8 samples of surge arresters SAp-3.3/4.5 /10/550 of the contact network, consisting of a column «varistor + aluminum inserts + aluminum electrodes», fiberglass frame and silicone organic ribbed protective shell passed the necessary electrical and mechanical tests, were tested.

In samples No. 1-3, the frame is made by continuous winding of a glass band tape impregnated with a thermosetting binder. In samples No. 4-6, the frame is made by winding glass band tape, providing for the presence of sections with incomplete closure by the glass band tape of the lateral (cylindrical) surface of the varistor column. After the tape was applied, the frame was baked at temperature of 165 °C, then its surface was sanded and coated with a special primer for strong bonding of silicone rubber with glass tape before applying the silicone shell.

In sample No. 7, the frame is made in the form of a «squirrel cage» consisting of thin fiberglass rods located around the varistor and firmly fixed by molding in aluminum electrodes.

In sample No. 8, the frame is assembled from a prefabricated fiberglass pipe with two holes in the side surface, designed to release gas pressure during the breakdown of SAp; the flanges were fixed on a fiberglass pipe using a glue-thread connection.

To create a short circuit in samples No. 3-6, 8, the varistor was shunted by copper wire with cross section of 0.62 mm^2; in samples No. 1, 2, 7, the varistor experienced preliminary electrothermal breakdown, but was not destroyed.

Figure 1 shows schematically columns of samples with varistors prepared for the application of a silicone protective shell.

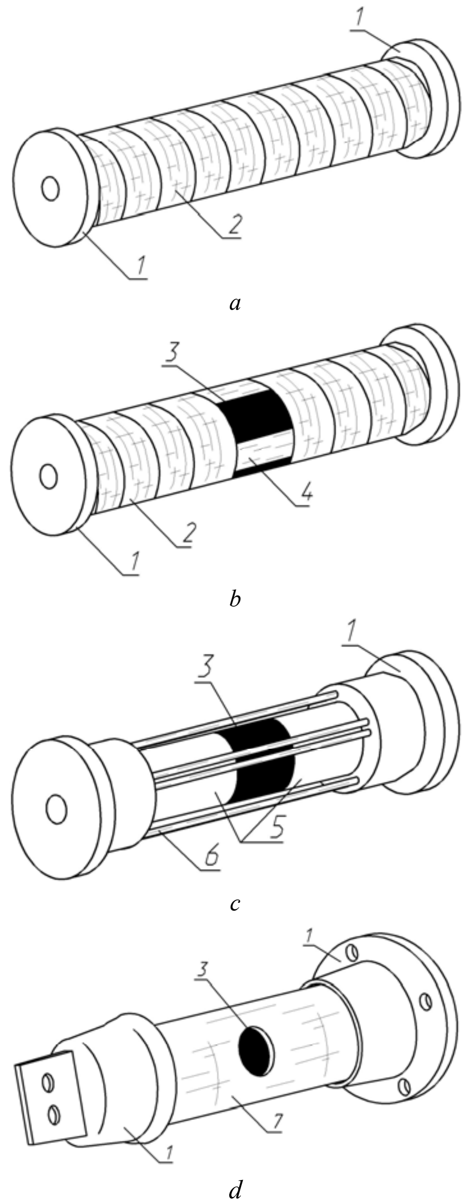

Fig. 1. Column sketches: *a* – with winding; *b* – with winding and with a hole; *c* – with rods; *d* – with a pipe and two holes (1 – aluminum flange, 2 – hardened fiberglass tape, 3 – metal oxide varistor, 4 – longitudinally positioned glass band tape, 5 – aluminum inserts, 6 – fiberglass rod, 7 – fiberglass pipe with holes)

A technique of testing for explosion safety. Tests for explosion safety of surge suppressors were carried out on the basis of the Slavyansk traction substation according to the program agreed with the JSC «Ukrainian Railways». The electrical circuit of tests is shown in Fig. 2.

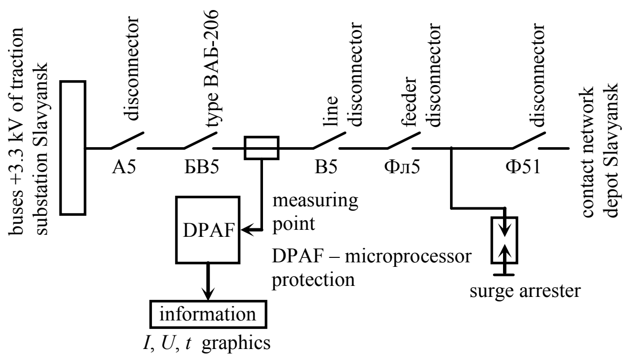

Fig. 2. Electrical circuit of testing sections of the SAp on the traction substation of Slavyansk city

The sample of the surge arrester was mounted on one of the metal poles at height of 5.5 m located on the territory of the substation and connected to the traction substation buses of 3.3 kV via disconnectors A5, B5, Фл5 and high-speed circuit breaker ВАБ-206 (Fig. 3).

Fig. 3. Sample of SAp prepared for testing

The test circuit was separated from the contact network by a Ф51 disconnector. After the ВАБ-206 circuit breaker was closed, a short circuit current flowed through a column with a experienced preliminary breakdown or shunted by a copper wire varistor with the formation of an electric arc inside the SAp section.

The process associated with the flow of short-circuit current was monitored using the control complex of the digital protection and automation of feeder (DPAF) 3.3, the instantaneous values of the current and voltage in the circuit were recorded and current and voltage oscillograms through the arc were recorded.

During the tests, samples were video-recorded using a DVR installed in close proximity to the sample under test. After the tests, each SAp sample was inspected, the samples were photographed, the weight of the sample was determined after the tests and, if the shell ruptured, the dispersion of the SAp fragments was evaluated.

Figure 4 shows the oscillogram of current and voltage at the moment of arc discharge inside the case of the sample No. 2.

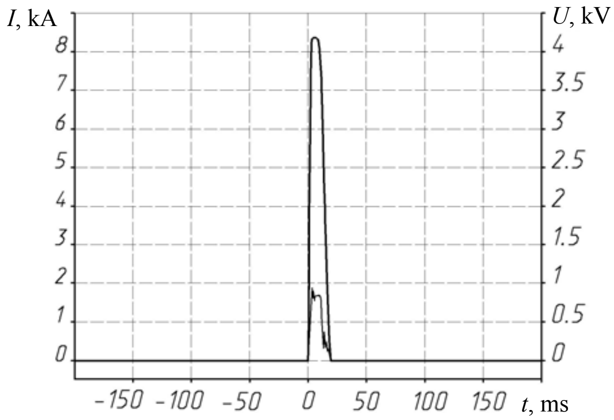

Fig. 4. Oscillogram of current and voltage at the moment of arc discharge inside sample case No. 2: a high peak corresponds to the arc current; lower peak – to voltage; abscissa – time in ms

The test results for SAp-3.3 kV for explosion safety are presented in Table 1.

For the evaluation of explosion safety of the SA, the Standard [4] establishes the following criteria:

1. A surge arrester is considered to be explosion-proof if fragments of a structure that fell to the ground after the destruction of the SA are left in a circle with a diameter of not more than $D = 1.2\cdot(2\cdot H_{sa} + D_{sa})$, where H_{sa}, D_{sa} are the height and diameter of the Sa, respectively; for devices of small height, it is assumed that $D = 1.8$ m.
2. It is considered permissible to depart from a circle of fragments of a damaged structure weighing up to 60 g each.

The area of hot gases coming from the SA is not standardized.

Additionally, we note that if, as indicated in [7-11], the electric arc from the SA case will come out, then explosive destruction will not occur over the entire period of arc burning. However, if the arc remains inside the case, explosion proof cannot be guaranteed.

From Table 1 it follows that of the 8 tested structures in 7 cases, the destruction of the case occurred without scattering of the fragments. In the area of placement of the varistor, there was a local break of the silicone shell with the release of gas and exit to the outside of the arc discharge. The exception was sample No. 2, in which, during an explosion, the upper electrode was broken out with simultaneous scattering of fragments of a split varistor within a radius of 3-5 m.

Analysis of research results.

1. From Table 1 it is seen that from 8 tested structures in 7 cases the destruction of the case occurred without scattering of the fragments. In 7 samples, in the zone of the varistor placement, there was a local break of the silicone shell with the release of gas and exit of the arc discharge. The exception was sample No. 2, which was made by continuous winding of the frame with a glass banding tape, which had a tearing out of the upper electrode during the explosion and simultaneous scattering of fragments of a split varistor within a radius of 3-5 m. Because of the white smoke accompanying the explosion, it was failed to record on the frame whether the arc exit from the case to the outside, despite the fact that in the next frame (after 33 ms) the arc was no longer recorded.

Table 1

Test results of SAp-3.3 kV for explosion safety

SA No.	short-circuit current through SA (A); maximum voltage fixed by DPAF (V); full time of the short circuit switching off (s)	Type of damage to the case	Varistor state after testing	State of aluminum liners adjacent to varistors
1	I = 8130; U = 800; t = 0.02	Shell rupture in the varistor placement zone without fragmentation	Varistor cracking	Deep erosion of aluminum liners in the zone of cracks in the varistor
2	I = 7178; U = 1120; t = 0.02	Tearing the top electrode; destruction and expansion of varistor fragments for 3-5 m	Varistor cracking	Erosion of aluminum liners in the zone of cracks in the varistor
3	I = 8640; U = 800; t = 0.02	Shell rupture in the varistor placement area without fragmentation	Varistor cracking	Erosion of aluminum liners in the zone of cracks in the varistor
4	I = 7890; U = 1000; t = 0.02	The rupture of the shell in the zone of placement of the weakened place in the winding of glass band tape	Varistor, shunted by copper wire, without destruction	Erosion of aluminum liners in the zone of copper wire
5	I = 7245; U = 800; t = 0.02	2 tears and 3 shell punctures	Varistor, shunted by copper wire, without destruction	Erosion of aluminum liners in the zone of copper wire
6	I = 8153; U = 800; t = 0.02	8 point punctures	Varistor, shunted by copper wire, without destruction	Erosion of aluminum liners in the zone of copper wire
7	I = 7238; U = 900; t = 0.02	Shell rupture in the varistor placement area without fragmentation	Varistor cracking	Erosion of aluminum liners in the zone of cracks in the varistor
8	I = 7890; U = 1000; t = 0.02	The rupture of the shell in the zone of the location of the round hole in the fiberglass pipe, glue-threaded connection of aluminum flanges with fiberglass pipe is not broken	Varistor, shunted by copper wire, without destruction	Erosion of aluminum liners in the zone of copper wire

2. In two other samples No. 1 and No. 3, made similarly by a continuous winding with a glass banding tape, a local gap of the frame and the silicone coating was observed with the arc going out. Scattering of dangerous fragments was absent. In about 100 ms, the electric arc reached the surface was completely extinguished, this can be seen on the freeze frames received every 33 ms (Fig. 5). For the remaining 5 samples, the observed arc burning pattern was similar, as for samples No. 1 and No. 3 (Fig. 5).

3. When testing the 8 presented structures, in none of them the case did not ignite.

4. If the tests were carried out on SAp, assembled with experienced preliminary breakdown varistors (electrothermal breakdown), the varistors during the tests broke apart, remaining inside the frame (except sample No. 3). From the action of the arc in the zone of contact between aluminum electrodes and varistors, a deep burnout of the electrodes was observed; in some cases the burnup was up to 7 mm deep and up to 8 mm wide.

5. If the varistors were shunted with copper wire, they remained intact, while melting and burning out part of the aluminum electrodes also occurred in the zone of connection with the copper wire, but in smaller sizes.

arc in 33 ms — arc in 66 ms — arc in 99 ms — sample No. 1 after voltage off

Fig. 5. Freeze frames of the arc exit from the SAp case after ВАБ-206 switching on

Conclusions.

1. Conducted tests of polymer samples of SAp-3.3 kV under operating conditions on the equipment of the operating substation, with short circuit currents of 8.3 kA and current exposure time of 0.02 s, close in value to ones recommended by IEC 60099-4:2014 Standard, showed quite satisfactory ability to withstand large pulse short-circuit currents without scattering fragments dangerous to personnel and the surrounding equipment.

2. Polymer structures, the frame of which is made of continuous winding, require strengthening the zone of connection between the frame and the electrodes. For

such structures, it is required to introduce an additional test for mechanical strength in the longitudinal direction with a predetermined strength limit into the acceptance test program of the SAp.

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