Professional article

Informacije MIDEM
Journal of Microelectronics,
Electronic Components and Materials
Vol. 42, No. 3 (2012), 197 – 204

Aging Of Overvoltage Protection Elements Caused By Past Activations

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Abstract: This paper investigates the ageing process of some common elements used for overvoltage protection. Tested elements are overvoltage diodes, varistors and gas filled surge arresters. Ageing process is considered as a function of previous number of element activations. Experiments are performed both with voltage and current transients. Statistical analysis of experimental data has shown that all elements investigated are subjected to the ageing during their functional operation. After 1000 overvotage diode activations, the volt-ampere characteristic curve "breaking" has been noticed in the range of higher currents, while the breakdown voltage value is reduced. In the case of varistor, it is determined that with higher number of activations comes an increase in the value of breakdown voltage and the shift of volt-ampere characteristics in the field of higher voltage. As for the aging of gas filled surge arresters, it has been shown that past activations reduce the value of dc breakdown voltage and lead to narrowing the area bounded by the 0.1% and 99.9% quintiles of the impulse characteristics.

Key words: overvoltage diodes, varistors, gas filled surge arresters, ageing, transients.

Staranje elementov za prenaptostno zaščito zaradi premostitev

Povzetek: V članku je raziskan proces staranja nekaterih tipičnih elementov za prenapetostne zaščite. Testni elementi so prenapetostne diode, varistorji in plinsko polnjeni prenapetostni odvodniki. Proces staranja je upoštevan kot funkcija števila predhodnih aktivacij. Opravljeni so bili testi tako napetostnih kot tokovnih prehodov. Statistične analize merilnih podatkov so pokazale, da so vsi elementi podvrženi staranju v obdobju normalnega obratovanja. Po 1000 aktivacijah diode je bil opažen »zlom« tokovno-napetostne karakteristike v območju velikih tokov in znižanje prebojne napetosti. Pri večkratnem proženju varistorja je bil opažen dvig prebojne napetosti in premik napetostno-tokovne karakteristike pri višjih napetostih. Pri plinsko polnjenih prenapetostnih odvodnikih je bilo opaženo, da predhodne aktivacije znižujejo prebojno DC napetost in vodijo v oženje območja omejenega med 0.1 % in 99.9 % kvantila karakteristike impulza.

Ključne besede: prenapetostne diode, varistorji, plinski polnjeni prenapetostni odvodniki, staranje, prehodi.

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1. Introduction

All the overvoltage protection elements are subjected, to a lesser or greater extent, to the changes of operational characteristics under the influence of overvoltages which occur during the exploitation of the protective circuit. Effects of aging occur because of the design and materials imperfection, while the changes of elements' parameters in this process are irreversible. The nature of the aging effect is cumulative as well as the damages caused by radiation [1]. Initial element damages may not always significantly degrade the functional characteristics of the circuit, however, their accumulation during the time degrade characteristics of protection elements to a grater extent, so that protective circuit can eventually become completely dysfunctional. Duration of the proper functioning of protective circuit depend not only on the properly selected protective elements (in terms of nominal voltage), but on the design of protective circuit which must be adapted to conditions in which the protected device operate (number of overvoltages in the time unit, their expected values and shapes). In term of determining the optimal design of the protective circuit, it is of interest to investigate the basics of elements aging process, exposed to current or voltage transients, so that is the subject and the aim of this paper.

2. The aging of overvoltage diode

Overvoltage diode combining in itself the three parts: contact systems, crystal of semiconductor and polarization conjunction. Degradation phenomena during exploitation are caused by the processes at phase boundaries. Degradation of the contact system is caused by the phenomena such as electromigration, creation of intermetallic phases and chemical compounds on the contact points between the metallization and the adsorbed components, etc [2]. The reasons that lead to changes in diode characteristics can be very different. When forming the diode structure, many processes of interaction and redistribution of generic defects, which are introduced in the process of technological operations, flow in the crystal. The result of these operations is the occurrence of certain defect structures whose evolution during exploitation causes aging and degradation characteristics of such specific components. These defects are: distributed and associated point defects, the local mechanical stresses and dislocated systems.

In the general case, defective structure, created in the technological cycle, is metastable and relaxes during the time. The basic physical mechanisms that cause its relaxation processes are generation and migration of lattice defects as well as specific processes of structural transformation in the boundary layers [3].

The process of exploitation (effects of overvoltages) results in a spatial redistribution of electrical charge and electrical field, changes of polarity centers as well as continuous relaxation and the generation of electronic excitation. The changed defect atomic configurations, impurity profile, and other structures of various complexes appear as a result of aforementioned processes. In the bases of these processes are micro-mechanisms such as the type “electronic excitation - atom-displacement”. Specific outcome of these mechanisms, in the diode aging process, determines the diode functional characteristics. The formation of electronic excitation in the case of overvoltage diodes is caused by the striking ionization processes. The described changes in the electronic subsystem lead to deformation of the charge density image for atoms displacement, while in certain cases lead to barriers reduction or elimination for atomic transition. If the mechanical stress gradients exist in certain parts of the semiconductor then a directed movement of point defects occurs, which cause the redistribution of impurities. In the same time, different transformation processes of point defects occurs: formation and deformation of the complex composed of displaced atoms vacancy, creation and annihilation of fine precipitates [4]. In this way, the aging kinetics is determined by the nature of low-temperature mechanisms, in this case by the number of activations, which cause changes in defect structure of materials [5,6].

In this paper, the aging of the overvoltage diode was measured against the influence of previous number of activation on its volt-ampere characteristic, volt-ohm characteristics and the breakdown voltage value. Tested overvoltage diodes were with nominal breakdown voltage of 250 V and with the maximum dc current of 1 A. Diodes were tested with 1000 current pulses ($I_{max} = 13A$, $T_1/T_2 = 8/20\mu l$). Measurements of diode characteristics were performed in its inverse polarization, within the plateau area of volt-ampere characteristics. Experiment was performed at temperature of 20°C in well-controlled laboratory conditions. For all tests the type B measurement uncertainty was less than 5 % [7,8].

Figure 1 shows the diode volt-ampere characteristics at the beginning and the end of the experiment, while the corresponding volt-ohm characteristic is given in Figure 2. Based on the results shown in Figures 1 and 2 it can be noticed that the diode aging process is weakly expressed. The breakdown voltage at start was 259.4 V, while at the end of testing, the value was 262.2 V. In the volt-ampere characteristics, after 1000 activations, "breaking" the curve was observed in range of high currents, which can be explained by degradation of the diode electrodes (metallization). Figure 2 shows the increase of dynamic resistance after the test completion.

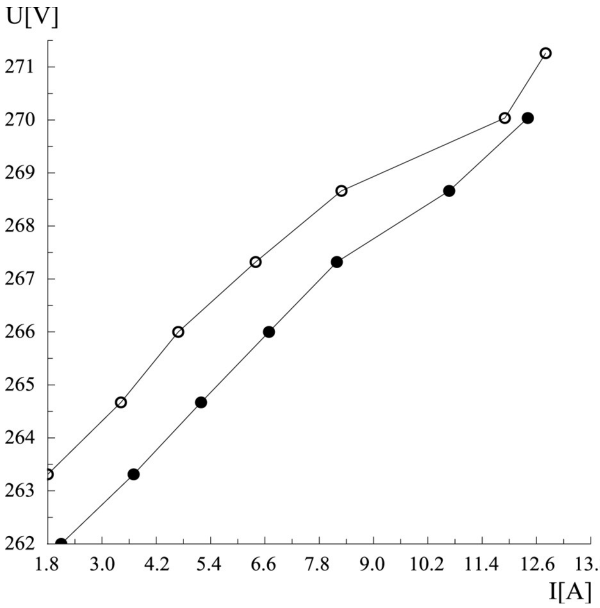

Figure 1: Volt-ampere characteristics depending on the diode activation number (● – 1 pulse; ○ – 1000 pulses).

3. Aging of the varistor

The aging process of the varistor can be described by the irreversible changes of its volt-ampere characteristics. There are two basic causes of varistors aging, and that are the constant current through the varistor, which exists when the voltage is loaded, and the pulse current due to occurrence of overvoltage pulses. These facts indicate that the aging process of varistor begins with its connection in the circuit, regardless whether the overvoltage pulses occur or not. The temperature has a great influence on the aging process caused by the loaded voltage, while the process is less expressed in case of the overvoltage occurrences. Due to the continuous flow of direct current through the varistor the resistance drop can be observed, resulting from the merging of the elementary grains of zinc-oxide, which occurs due to thermal effects [9]. This effect is already noticeable with the current of 1 mA. Specifically, the varistor subjected to the mentioned current value at the temperature of 40°C has the operating voltage reduction of 80%. Research showed [3,4] that varistor exposed to the critical overvotage impulse remains in the circuit brake while the varistor exposed to the long-term effect of constant current, at destruction, act as a short circuit.

It is necessary to say that the effect of varistors aging, which is caused by the influence of constant current, can be effectively minimized by selecting the proper varistor for a protected device. However, changes in varistor characteristics caused by the transients are the real interest, and that was examined within this paper.

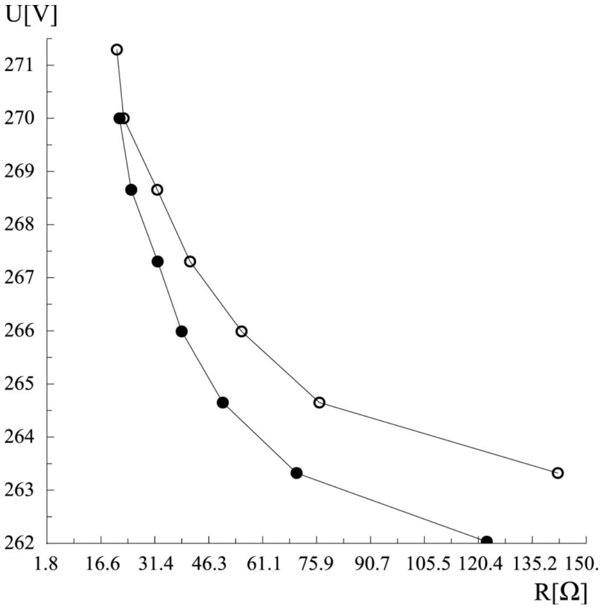

Figure 2: Volt-ohmic characteristics depending on the diode activation number (● – 1 pulse; ○ – 1000 pulses).

Two different types of varistor were investigated, with disc diameter 10 mm and 14 mm, respectively. Both varistors were designed for permanent alternating voltage load V_{eff} = 230 V, with a maximum current value (8 X 20μs) 2500 A for the first varistor, and 4500 A for the other. Varistors were subjected to 1000 current test pulses, while after the sequence of 100 test pulses the recording of varistor characteristics was done (by using the same test pulse). For both type of varistors, changes in volt-ampere and volt-ohmic characteristics were measured, as well as changes in the breakdown voltage value. All these changes are given as a function of previous varistor activations. Since the varistors with smaller disc diameter are more susceptible to aging, shown diagrams are related to this type of varistor.

The Figure 3 shows the volt-ampere characteristics changes, while the changes in volt-ohmic characteristic are given in Figure 4, both depending on varistor activation number. The Figure 5 shows the change of varistor breakdown voltage value in dependence of varistor activation number. From the results obtained, it can be concluded that the increase of varistor activations imply increase in the breakdown voltage and the shift of volt-ampere characteristics in the range of higher voltages. From the diagram shown in Figure 4 it can be concluded that the slope change of volt-ampere characteristic is relatively low, i.e. that the coefficient of nonlinearity α is not changed significantly. Change of the varistor coefficient of nonlinearity α depending on the varistor activation number is shown in Figure

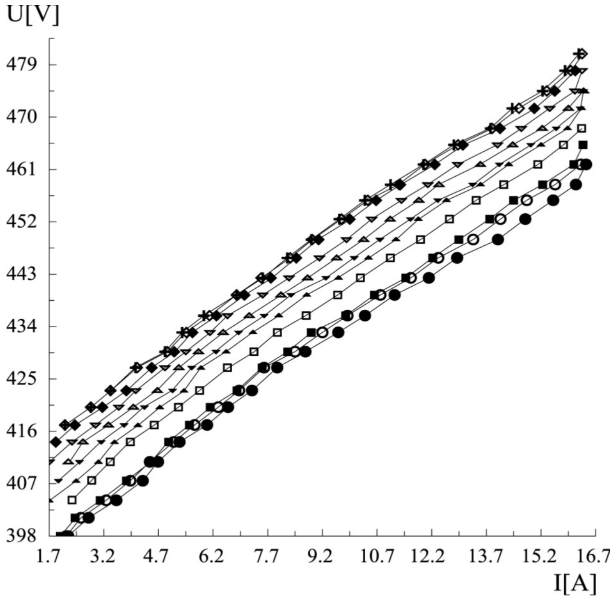

Figure 3: Volt-ampere characteristics depending on varistor activation number (● – 1 pulse; ○ – 100 pulses; ■ – 200 pulses; □ – 300 pulses; ▲ – 400 pulses; ▼ – 500 pulses; Δ – 600 pulses; ∇ – 700 pulses; ♦ – 800 pulses; ◊ – 900 pulses; + – 1000 pulses;).

6. These changes can be explained by "breaking" some elementary chains at position of elementary varistor with a minimal dissipation, due to the effect of current pulses, which reduces the effective varistor surface for current conducting, and thereby its resistance and breakdown voltage increase. So, therefore, the noticeable effects in decreasing of the nonlinearity coefficient α with the number of activation could be expected in the current domain.

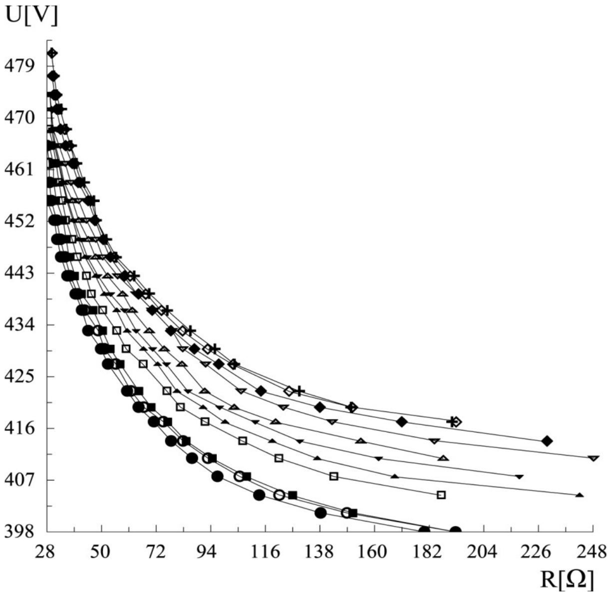

Figure 4: Volt-ohmic characteristics depending on varistor activation number (● – 1 pulse; ○ – 100 pulses; ■ – 200 pulses; □ – 300 pulses; ▲ – 400 pulses; ▼ – 500 pulses; Δ – 600 pulses; ∇ – 700 pulses; ♦ – 800 pulses; ◊ – 900 pulses; + – 1000 pulses).

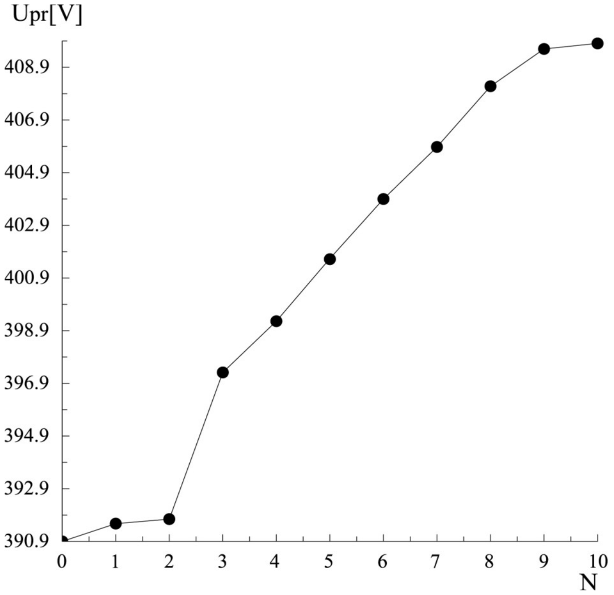

Figure 5: Varistor breakdown voltage depending on activation number (number of pulses =N*100).

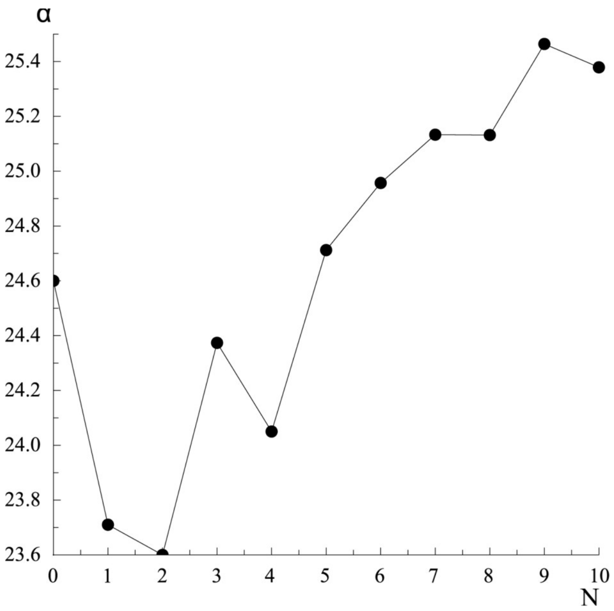

Figure 6: Varistor coefficient of nonlinearity α depending on activation number (number of pulses =N*100).

4. Aging of gas filled surge arresters

For gas filled surge arresters the characteristic process of aging (irreversible changes) arises due to changes of electrode topography [10,11].

Testing the irreversible characteristics of gas filled surge arresters was performed on arresters with the nominal voltage of 470 V, 230 V and 145 V. The aim of the test performed was to determine the change in the statistical sample of the random variable impulse breakdown voltage depending on the number of past breakdowns. This effect was investigated on a series of 1000 measurements both with dc breakdown voltage and pulse breakdown voltage. During the experiments the discharge energy was constant. The results are divided into 20 successive groups with 50 measurements of breakdown voltage. Each of these groups was tested statistically. By using the graphic, χ - square, and Kolmogorov test the random variable belonging to one of the following distributions was examined: normal, exponential, double exponential and the Weibull distribution [12-15]. By using the U-test each group was tested on belonging to the same random variable, with a 5% significance level [16].

The influence of past breakdowns on the volt-second characteristic was tested in the same way. Measurements were divided in 20 successive groups with 50 values of impulse breakdown voltage. Then, for each group the theoretical statistical distribution was determined with 99.9% and 0,1% quintiles ($U_{99,9}$, and $U_{0,1}$).

Starting from the values of $U_{99,9}$, and $U_{0,1}$ and the corresponding values of dc breakdown voltage the volt-second characteristic is constructed based on the Area law [17-19]. Comparisons of pulse characteristics of the experimentally obtained values, divided in successive groups, allowed the determination of past impulse breakdown effects on the volt-second characteristic.

Figure 7 shows chronological range of the first series of measurement values of dc breakdown voltage of the gas filled surge arrester with nominal voltage 470V. Figure 8 provides chronological range of the last series of measurements. Figure 9 shows the values of the U-test variables, with the 5% level of significance, depending on the random variable dc breakdown voltage. Based on results presented, it is clear that during the exploitation of the gas surge arresters the irreversible changes have been manifested. Statistical analysis showed that groups of measurements with lower number follow the normal distribution. With the increasing of the group number the distribution becomes Weibull. This effect is more pronounced if the discharge energy increases. The observed effect of irreversible changes of the gas filled surge arresters with dc breakdown voltage can be explained by changes within the topography of electrode surface. Small changes of the interelectrode gap distance can greatly affect the value of dc breakdown voltage (in the case of gas filled surge arrester, since its interelectrode gap is small). As a result of breakdown there is a decrease in the interelectrode gap distance as a consequence of the breakdown craters on the electrode surface. Reducing the interelectrode gap distance causes the decrease of dc breakdown voltage value.

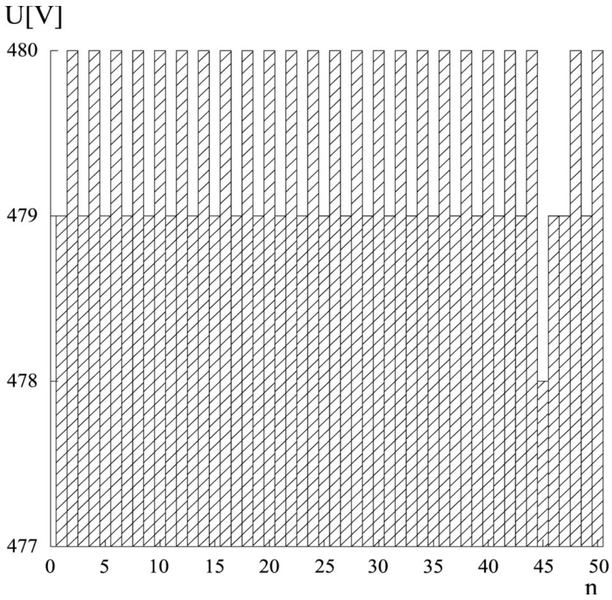

Figure 7: Chronological range of the first series of measurement values of dc breakdown voltage.

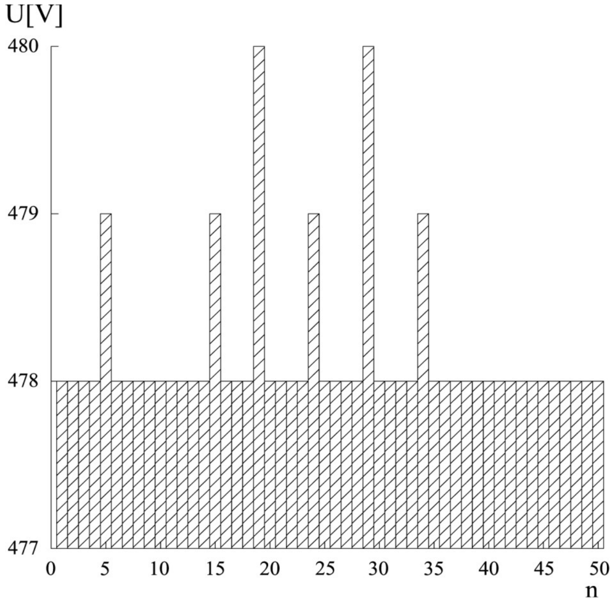

Figure 8: Chronological range of the last series of measurement values of dc breakdown voltage.

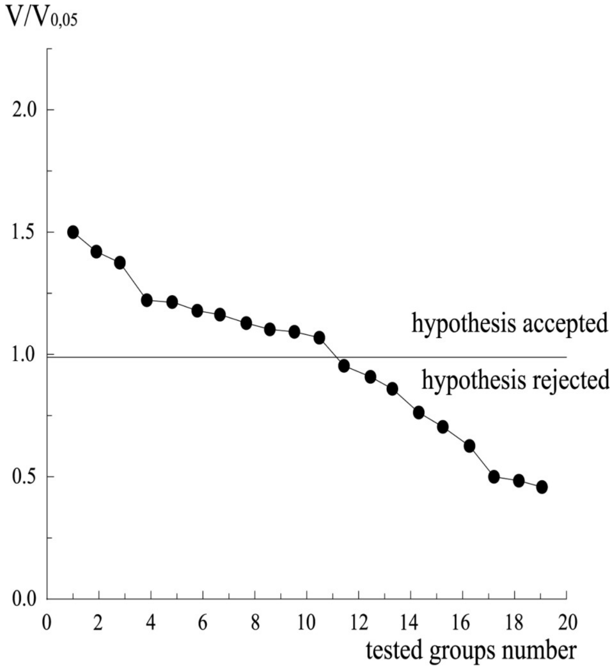

Figure 9: Value of the U-test variables with the 5% level of significance depending on the random variable dc breakdown voltage.

Decreasing the dc breakdown voltage value (Figures 7 and 8) is the consequence of increased number of initiation centers caused by past breakdowns. The change of the random variable distribution, what is noticeable with increasing the group number of measurements, i.e. transition from normal to Weibull distribution, can be explained by the phenomenon of "weak spots" in the electrodes surfaces. These weak spots are not in equilibrium with the "strong spots" so that there is a loss of distribution symmetry, so it becomes asymmetric Weibull distribution [20].

Similar irreversible effect was observed in the case of a random variable "impulse breakdown voltage" which is reflected in the change of pulse characteristics. The consequence of the previous discharges in this case is the smoothing and narrowing of the volt-second characteristic, Figures 10 and 11. Figures 12 and 13 shows photos of electrode surface after the 1000 impulse breakdowns voltage.

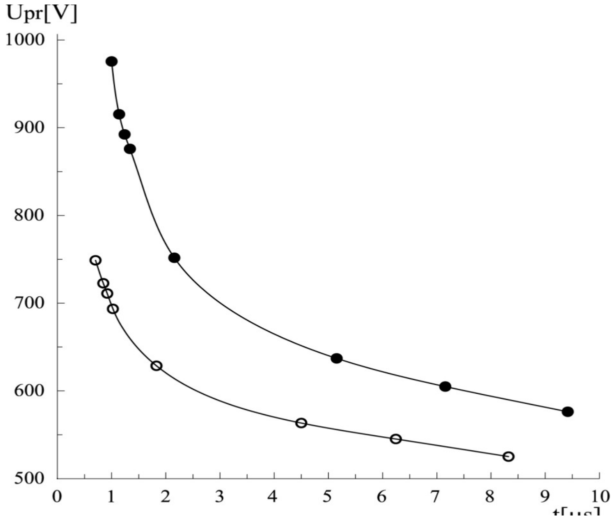

Figure 10: Volt-second characteristics after first series of breakdowns.

Based on the obtained results it can be concluded that the gas filled surge arresters are exposed to the irreversible changes during their exploitation. These changes are caused by changing the topography of electrode surfaces during operation.

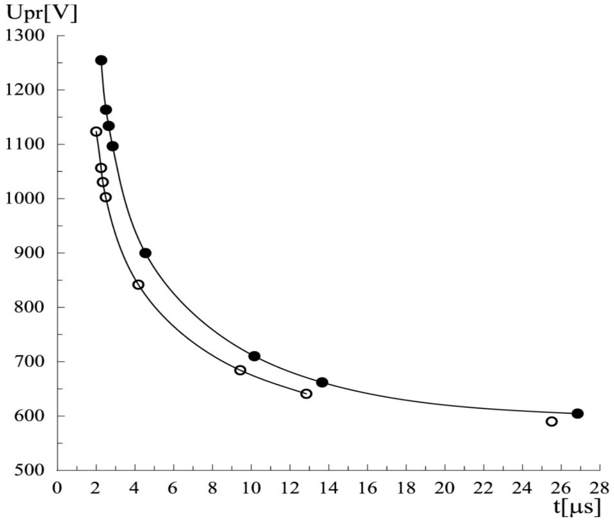

Figure 11: Volt-second characteristics after last series of breakdowns.

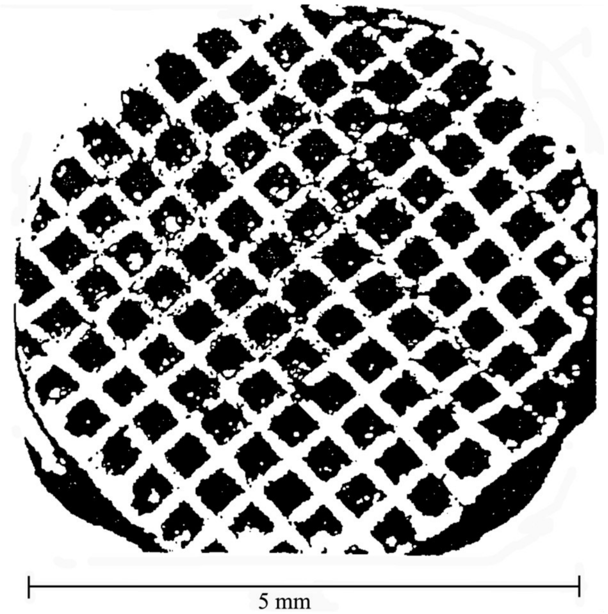

Figure 12: Topography of the electrode surface after 50 completed impulse voltage breakdowns.

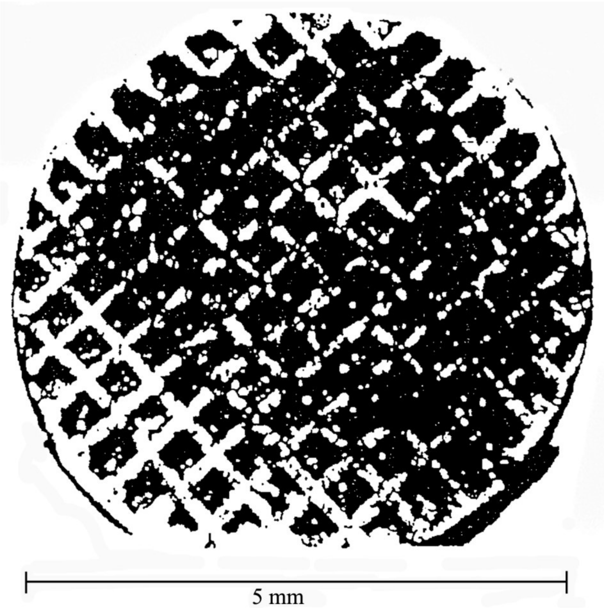

Figure 13: Topography of the electrode surface after 1000 completed impulse voltage breakdowns.

5. Conclusion

This paper presents the results obtained within the functional ageing investigation of elements for overvoltage protection. It has been shown that the past activations reduce the breakdown voltage value of the overvoltage diode. It was noticed that there is an increase in dynamic resistance after larger number of activation. After 1000 activations, the volt-ampere characteristic curve "breaking" can be noticed in the range of higher currents, which can be explained by degradation changes in diode electrodes.

In the case of varistor, it is shown that with higher number of activations comes an increase in the value of breakdown voltage and the shift of volt-ampere characteristics in the range of higher voltage. Also, it is found that the number of previous activations does not significantly affect the varistor coefficient of linearity. This phenomenon can be explained by "breaking" some chains of elementary varistor at the place of elementary varistor with the lowest power dissipation due to the effects of current pulses, which reduces the effective varistor surface for electricity conducting, and thereby its resistance and breakdown voltage increase.

As for the aging of gas filled surge arresters, it has been shown that past activations reduce the value of dc breakdown voltage and lead to narrowing of the area bounded by the 0.1% and 99.9% quintiles of the impulse characteristics. This phenomenon is explained by the created craters caused by previous activations. The resulting craters significantly reduce the interelectrode distance of the order of 0.1 mm and lead to increased electronic emission centers. As a result, there is reduction in the dc breakdown voltage value, i.e. increase in the number of free electrons, which leads to said consequences on the macroscopic characteristics. Established irreversible changes in characteristics of elements for overvoltage protection due to previous activations are of concern in designing and life assessment of overvoltage protection in conditions of high electromagnetic contamination.

Acknowledgment

The Ministry of Education and Science of the Republic of Serbia supported this work under contract 171007.

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Arrived: 16. 08. 2012
Accepted: 31. 10. 2012