

P. PAPLIŃSKI¹, H. ŚMIETANKA¹, P. RANACHOWSKI^{2*},
Z. RANACHOWSKI³, K. WIECZOREK³, S. KUDELA JR⁴

DEGRADATION PROCESSES IN SHIELD-CENTRING ELEMENTS OF SURGE ARRESTERS

This paper presents the results of testing samples of shield-centering elements from medium-voltage surge arresters. The elements were made of TSE glass textolite. The elements have been dismantled from different operated surge arresters, which were subjected to discharge currents (short-circuit currents) of different intensity and duration. The discharge currents led to degradation of the tested elements with various degrees of advancement. The degradation was investigated using microscopic methods and energy-dispersive X-ray spectroscopy (EDS). Changes in the content of elements of the surface of textolite materials – as the degradation progresses – were documented.

It was found that high discharge current flows resulted in melting of the organic binder, epoxy resin, especially its surface layer. Partial charring and even burning of the resin was noticeable. Furthermore, it was found that with increasing degradation on the surface of the TSE laminate, the carbon and oxygen content, which are part of the organic resin, decreases. Simultaneously the amount of silicon, calcium and aluminium, which are present in the glass fibres, increases. The charring effect of the resin and the formation of conductive paths result in a decrease in the performance of surge arresters and their subsequent failure.

Keywords: surge arrester; TSE glass textolite; discharge (short circuit) current; EDS method

1. Introduction

The issue of surge protection for electrical and electronic systems, networks and equipment is of particular importance. Overvoltage damages the insulation of equipment and other components of the electricity network and cause disruptions in their operation. As a result significant economic costs are incurred.

Power systems and supporting equipment, which include surge arresters, are exposed to overvoltages during operation. This is caused by a voltage rise above the rated voltage. The uncontrolled voltage rise can be the result of environmental disturbances (lightning), switching and casual surges generated in the system, as well as other disturbances during system operation. The above-mentioned voltage rise cannot be predicted and avoided [1,2]. Yet, the devices installed in substations should operate faultlessly also under disturbance conditions. Especially sensitive to overvoltage are transformers, which play a key role in the power system. They are threatened with breakdowns in the winding insulation, which entails costly repairs. The economy and safety of this equipment requires extended protection against unacceptable high surges. Overvoltage protection has been

used in various forms for about 120 years [3]. Since the 1970s, non-directional surge arresters based on ZnO varistors, which are essentially resistors with strongly nonlinear voltage-current characteristics, have been widely used [4,5].

Typical surge arresters, in particular medium voltage surge arresters, have a closed design and have a uniform polymer housing around the internal components. The varistor pile is enclosed in a tube-shaped shield-centering element, usually made of glass textolite [5,6]. The advantage of such a design is high mechanical durability, with relatively low mass, while the disadvantage is poor varistor cooling. In addition, if no suitable countermeasures are provided in the design, there is a risk of exposing the polymeric material to the effect of partial discharges, which may occur between the inner wall of the shield-centering element and the varistor pile under the influence of external contamination. Long-term practice proves that short-circuit currents cause partial discharges inside surge arresters. As a result, inside the structure of surge arresters the temperature rises high locally. It causes mainly degradation of glass textolite, which is used for construction of the tube being the shield and setting element of the device.

¹ INSTITUTE OF POWER ENGINEERING – RESEARCH INSTITUTE, 8 MORY STR., 01-330 WARSAW, POLAND

² INSTITUTE OF FUNDAMENTAL TECHNOLOGICAL RESEARCH PAS, 5B PAWIŃSKIEGO STR., 02-106 WARSAW, POLAND

³ WROCLAW UNIVERSITY OF SCIENCE AND TECHNOLOGY, FACULTY OF ELECTRICAL ENGINEERING, WYBRZEŻE WYPIAŃSKIEGO 27, 50-370 WROCLAW, POLAND

⁴ INSTITUTE OF MATERIALS AND MACHINE MECHANICS SLOVAK ACADEMY OF SCIENCES, DÚBRAVSKÁ CESTA 9/6319, 845 13 BRATISLAVA, SLOVAKIA

* Corresponding author: pranach@ippt.pan.pl



2. Subject and methodology of tests

This paper presents the results of investigations into the stages of degradation of the shield-centering elements of surge arresters, under the influence of the flow of high short-circuit currents. The research is a continuation of tests carried out by the authors since 2012 [7]. The tested elements, made of glass-epoxy laminate, i.e. glass textolite TSE, were taken from medium voltage (MV) surge arresters. The textolite elements, which are the subject of these investigations, were dismantled from various operating surge arresters, through which flowed discharge (short-circuit) currents of different intensity and duration. They have caused observable and documentable degradation in the material of shield-centering elements with various degrees of advancement.

Optical microscopy (OM), scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) were used in this study. The EDS method allowed to record and document the changes in the elemental composition (elemental content) of the textolite surface layer as the degradation progressed. In order to make the results of the research reliable and fully comparable, the analyses were carried out on the same surface areas, 4.0 mm^2 , for all the samples with different degrees of degradation.

The textolite roving support was made of fibre bundles of special ECR glass. This type of glass is characterised by good electrical properties such as low conductivity and high chemical resistance. Typical glass of this type contains more than 58% SiO_2 , about 22% CaO , less than 12% Al_2O_3 and smaller amounts of other additives (ZnO , MgO , TiO_2 and other metal oxides) [8]. The calcium present in the elemental composition comes from CaCO_3 , a flux and stabiliser, while aluminium comes from Al_2O_3 , improving chemical resistance, which are used in the glassmaking set. The presence of mobile sodium ions Na^+ (e.g. from a flux like Na_2CO_3) is minimised. Glass fibres with diameters ranging from 3 to 20 μm (usually between ten and twenty micrometres) are used [9].

TSE glass textolite has a relatively high resistance to elevated temperatures – up to about 180°C . The roving support fibres have a much higher temperature resistance than the laminate binder – an organic epoxy resin. Under the influence of high temperature, the degradation of the textolite material should therefore mainly concern its organic phase.

Fig. 1 shows not operated domestic (Polish) surge arrester whose shield-centring element has become a reference sample.

3. Tests results

Fig. 2 shows the reference sample for the material under investigation. The fibres of the textile support were covered with a layer of transparent epoxy resin and were under the surface of the textolite. Fig. 3 shows the EDS test results of the surface of the initial material, for which the elemental composition was determined. The epoxy resin, the laminate binder present on the surface of the material, contained 76.6% carbon (C) and 23.4%

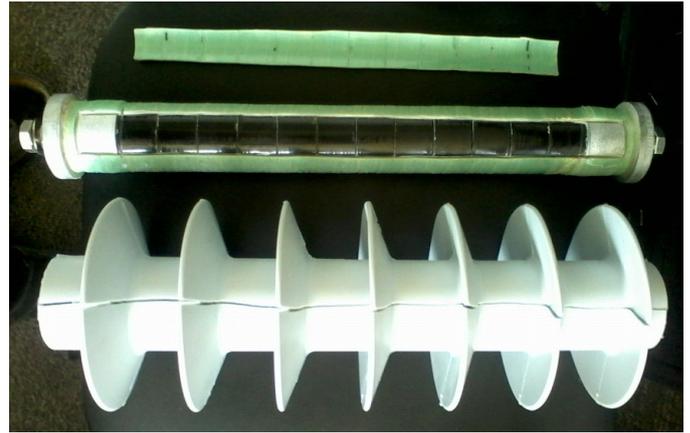


Fig. 1. Unexploited domestic MV surge arrester from 2018, after sectioning and removing the silicone elastomer cover – at the bottom. The cut-out fragment of the shield-centering element served as a reference sample – at the top. In the centre, the pile of varistors is visible

oxygen (O) by weight; the hydrogen (H) content was omitted – as it cannot be recorded using the EDS technique. The elements present in the fibreglass textile support – primarily silicon (Si) and calcium (Ca) – were not recorded, because they were covered with the organic resin layer.

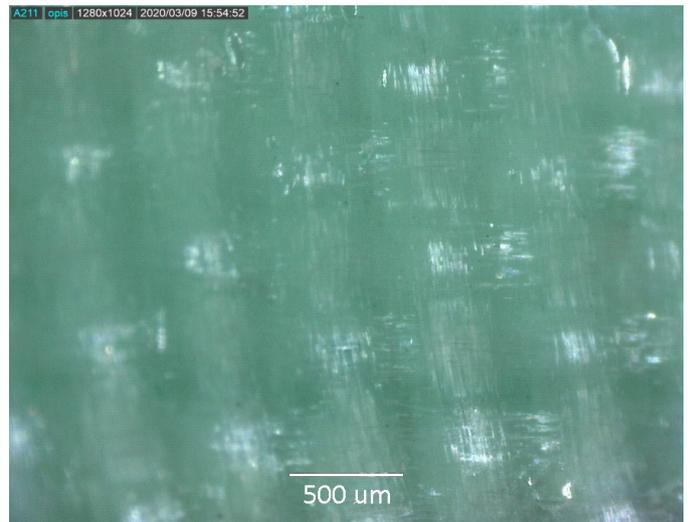


Fig. 2. OM image of the surface of textolite taken from an unexploited surge arrester, magnified 40 times. The textile weave made of fibreglass under the transparent resin layer can be seen

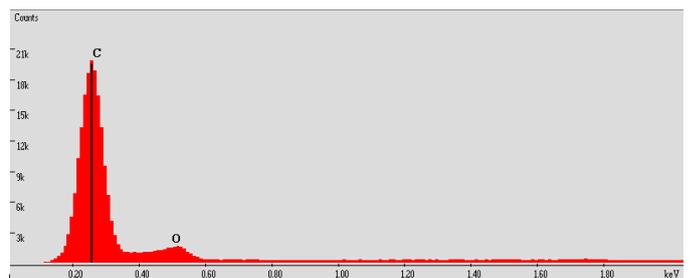


Fig. 3. EDS spectrum obtained for the textolite surface from an unexploited surge arrester. Only carbon and oxygen, derived from the organic epoxy resin, were recorded

The flows of discharge currents cause a local rise in temperature inside the surge arresters. A number of flows of such currents, in certain areas of the shield-centring elements, lead to increasing the degradation of the laminate. This was expected to be particularly true for the organic phase – epoxy resin. During the examination of the components of the operated surge arresters, many areas affected by degradation were identified. However, it was found that, depending on the intensity and duration of the discharge currents – and therefore the generated temperature – there were significant differences in the images of the microstructures and the degree of degradation of the laminate.

As a result of the flow of discharge currents and a local rise in temperature, the organic binder – epoxy resin – was melted and charred in some areas of the shield-centring elements. After the surface layer of resin has melted, fibre bundles from the textile support appeared on the surface of the material – Fig. 4. Fig. 5 presents the results of EDS analysis of the material surface in the area of slight degradation, with determined elementary composition. The surface of the material contained, besides carbon (78.0%) and oxygen (18.6%), also 1.6% of silicon and 1.0% of calcium, which came from these roving glass fibres on the surface of the laminate. Also minor admixtures of aluminium (Al) and magnesium (Mg) came from the glass. The degree of textolite degradation was not yet high and hence a small proportion of silicon and glass admixtures.

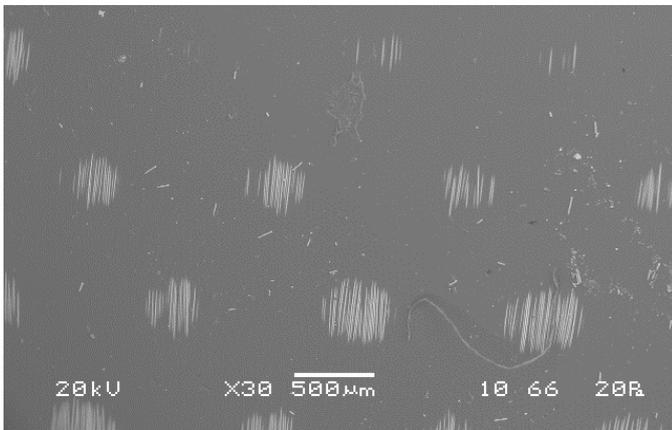


Fig. 4. SEM image of the textolite surface with weak degradation, magnified 30 times. Bundles of light-coloured roving fibres can be seen, which appeared on the surface of the laminate after the top layer of epoxy resin has melted

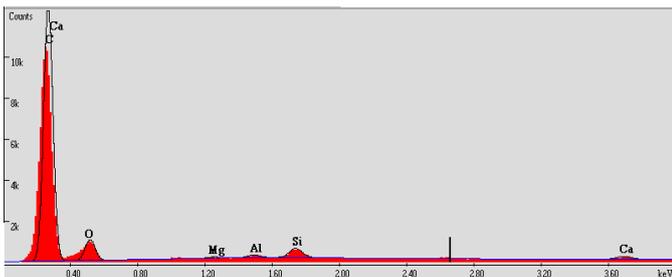


Fig. 5. EDS spectrum recorded for the textolite with slightly visible degradation in the form of a small content of elements present in the glass roving support (silicon, calcium, aluminium and magnesium)

As the degradation effects progressed, more and more areas of charred epoxy resin were observed as a result of the discharge currents – Fig. 6. These areas kept increasing and the degree of charring of the organic phase intensified. Even where the resin was not yet heavily carbonised, its outer layer was melted to such an extent that the textile support was more and more noticeable on the surface. The fibre bundles can be seen particularly well in the SEM images – Fig. 7.

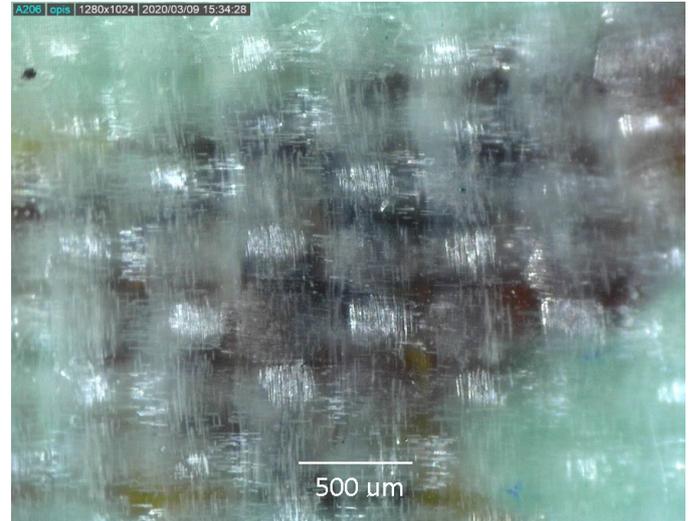


Fig. 6. OM image of the surface of the textolite with visible degradation, magnified 40 times. A part of the sample is clearly charred, and the shining fibre bundles of the roving support emerged on the surface after melting of the top resin layer

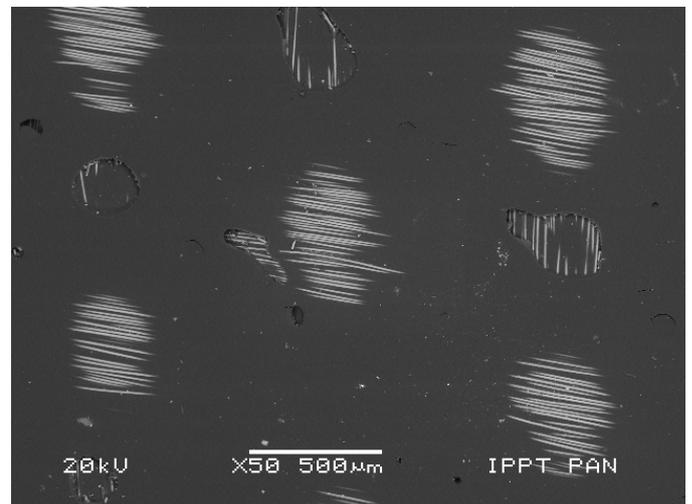


Fig. 7. SEM image of the textolite surface with advanced degradation, magnified 50 times. In the top layer of the material the resin is melted to a large extent. Bundles of bright roving fibres emerge from under it. There are also melted indentations in the resin

EDS analysis of the textolite with advanced degradation – Figs 6 and 7 – indicated an already pronounced content of the glass roving in the elemental composition of the material surface. The content of carbon (74.1%) and oxygen (16.9%) were reduced by several percent. This proves a significant loss of

the organic phase – epoxy resin in the top layer of the textolite. At the same time, the amount of elements present in the glass increased: silicon to 4.6%, calcium to 2.9% and aluminium to 1.4% – Fig. 8. In total, they accounted for about 9% by weight of the laminate surface, excluding the oxygen part. The temperature rise resulting from the discharge currents, in some areas of the shield-centring elements, must therefore have been large, exceeding 200°C.

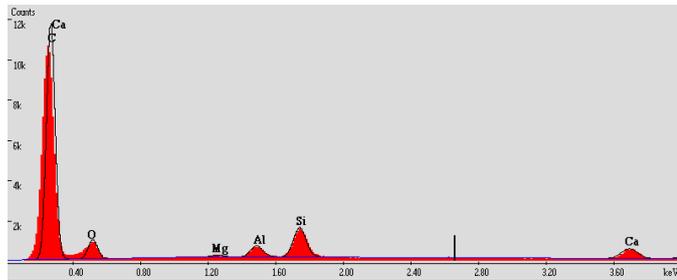


Fig. 8. EDS spectrum recorded for the textolite with advanced degradation effect. Significant proportion of elements present in the glass textile support: silicon, calcium and aluminium is visible

As a result of the flow, especially over a long period of time, of strong discharge currents, there must have been a large local growth in temperature – even reaching 300°C. As a consequence, the degradation of the organic epoxy resin increased in some areas of the shield-centring elements. Fig. 9 shows an OM image of the textolite from an operated surge arrester, where the charring of the resin has reached a high level. This is evidenced by the change in colour of the textolite to much darker. Fragments of the material showed a high variation in the degree of degradation. The temperature was then only high in specific areas of the shield-centring elements. In these areas, strong or even very strong degradation of the laminate effects were observed.

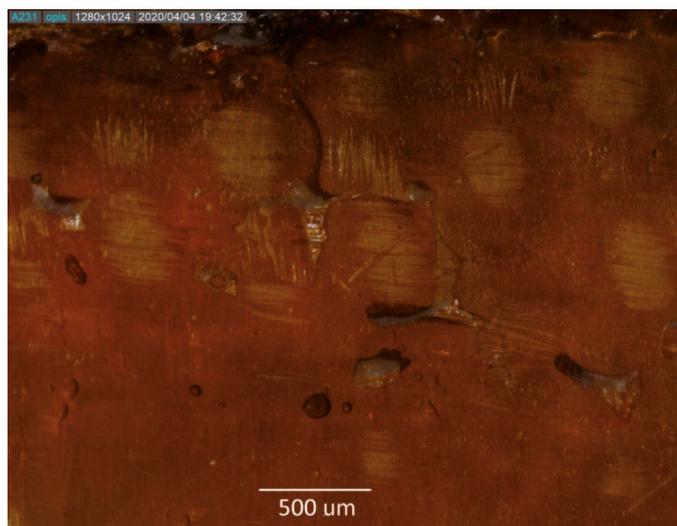


Fig. 9. OM image of the textolite surface with strong degradation, magnified 40 times. A fragment of the sample material has been considerably charred – the colour of the textolite has changed. Bright fibre bundles of the roving textile support can be seen. When the top layer of resin melted, these were found on the surface of the laminate

A number of flows of high discharge currents led to significant melting of the organic epoxy resin, especially of its top layer partial charring and even burning. As a result, numerous fibre bundles from the roving textile support are clearly visible in the SEM images – Fig. 10. Consequently, elements from the glass are a significant component in the elemental composition of the surface layer of the material.

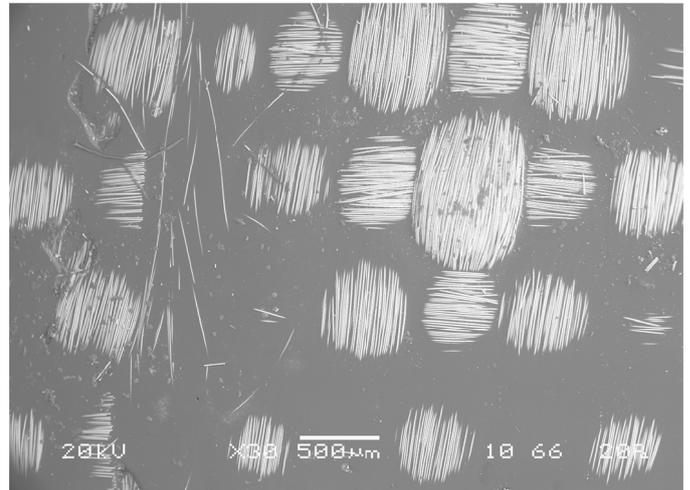


Fig. 10. SEM image of the surface of the textolite with very strong degradation, magnified 30 times. The resin on the top layer has been considerably melted. Numerous bright bundles are visible on the surface, as well as individual glass fibres with areas of damaged roving

Fig. 11 shows EDS analysis of a very heavily degraded surface of the textolite. The carbon content remained at 68.0%, compared to the original value of 76.6%. The amount of elements present in the glass increased significantly: silicon to 8.4%, calcium to 5.5% and aluminium to 2.6% – a total of 16.5% (excluding oxygen). The epoxy resin from the surface layer of the laminate has melted and has been partially charred and burnt.

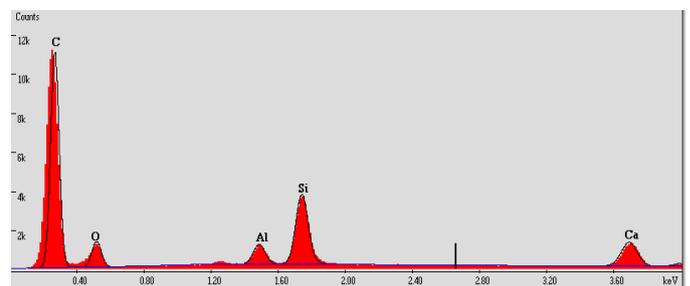


Fig. 11. EDS spectrum recorded for the textolite with very strong degradation. There is a significant proportion of elements present in the glass roving: silicon, calcium and aluminium. Oxygen is present in both – organic and inorganic phases

High local temperature rise led to very strong degradation of the laminate in some areas of the shield-centring elements of surge arresters. In extreme cases, the organic epoxy resin melted and was charred, cracked or even burnt out. An example of very

severe damage to the textolite structure and exposure of the textile roving support is shown in Fig. 12.

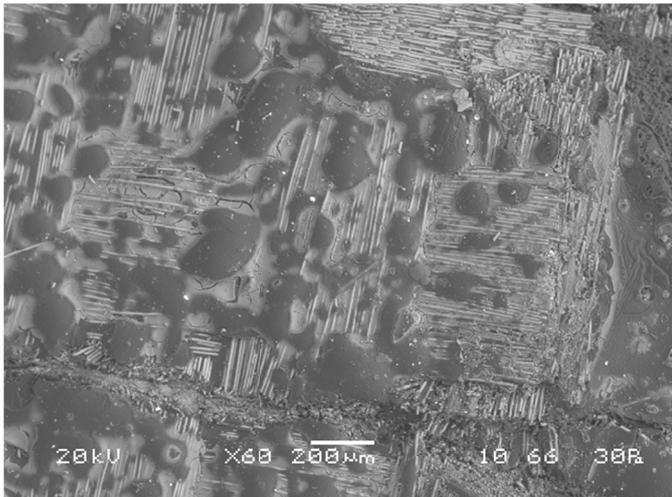


Fig. 12. SEM image of the textolite surface with very strong degradation, magnified 60 times. The resin on the top layer of the material has largely melted; it is charred and burnt. As a result, the roving support has become visible

Changes in the elemental composition (content of elements) of the textolite surface layer for successive stages of the material degradation are presented in TABLE 1. The data were obtained on the basis of EDS X-ray spectroscopy, without taking hydrogen into account. The decreasing content of carbon and oxygen, which are included in the epoxy resin, is evident. This is a consequence of its loss from the top layer of the laminate as degradation processes increase. At the same time, the amount of silicon, calcium and aluminium, which are components of the inorganic glass roving support of the laminate, rises. It is increasingly exposed on the surface of the textolite as the degradation of the organic binder progresses.

It should be emphasised that despite the loss of total carbon on the laminate surface, it becomes conductive. The resin – which is a dielectric – becomes increasingly carbonised, creating longer and more effective conductive paths at the surface of the varistors in the surge arrester. This results in a reduction of the operating parameters, and, after some time, a failure of this device may be expected.

3. Conclusions

Tests have been carried out on shield-centring elements of various MV surge arresters, through which discharge (short-circuit) currents of varying intensity and duration flowed. They caused degradation of varying intensity in the textolite elements. Six stages of degradation were distinguished. They were defined as: initial, weak, visible, moderately strong, strong and very strong. Both microscopic observations of the sample surface and EDS X-ray spectroscopy showed that the degradation mainly affects the organic binder – epoxy resin. It melts and is gradually carbonised, cracked or even burned out. As a result, the glass textile support of the laminate is exposed. It was found that as the surface degradation of the shield-centring element increases, the amount of carbon and oxygen, which are part of the epoxy resin as an organic binder, decreases. On the other hand, the content of silicon, calcium and aluminium, which are the components of the inorganic textolite roving support, increases.

From the point of view of the function of a surge arrester, the charring of the epoxy resin is particularly undesirable. Conductive paths are then formed at the surface of the varistor pile. It causes shunting of varistors and, consequently, lowering of operating parameters of the device, such as continuous operating voltage and rated voltage [5]. The progressing degradation processes of the shield-centring elements lead to the damage of the surge arrester.

Further work of the authors will be focused on finding countermeasures to limit the epoxy resin degradation process caused by the flow of high currents that char the inner parts of the centring elements.

REFERENCES

- [1] Working Group Report, Calculating the lightning performance of distribution lines, IEEE Trans. on Power Delivery **5**, 1408-1417 (July 1990). DOI: <https://doi.org/10.1109/61.57983>
- [2] E. Anderson, Internal overvoltages in the medium voltage networks and their limitation. Selected issues related to the method of neutral point earthing of 6 kV industrial networks and power plants networks, (in Polish), Series: Postępy techniki wysokich napięć **22**, 1997 Institute of Power Engineering, Warsaw.

TABLE 1

Changes in elemental composition – the content of elements of surface layer of textolite material in weight percent, for consecutive stages of progressive material degradation. Data were based on EDS X-ray spectroscopy; hydrogen was not included. Carbon and oxygen are the components of the epoxy resin (organic binder), while silicon, calcium and aluminium (also part of oxygen) are the components of the glass roving – the inorganic textile support of the laminate

Element content by weight [%]	Referential value	Initial degradation	Weak degradation	Visible degradation	Moderately strong deg.	Strong degradation	Very strong degrad.
Carbon C	76.6	80.0	78.0	76.6	74.1	66.6	68.0
Oxygen O	23.4	18.2	18.6	19.0	16.9	17.8	15.5
Silicon Si	—	1.0	1.6	2.4	4.6	7.8	8.4
Calcium Ca	—	0.9	1.0	2.0	2.9	5.5	5.5
Aluminium Al	—	—	0.5	~1.0	1.4	2.3	2.6

- [3] A.R. Hileman, *Insulation Coordination for Power Systems*, 2018 CRC Press. DOI: <https://doi.org/10.1201/9781420052015>
- [4] Z. Woynarowski, Zinc oxide varistor, (in Polish), *Wiadomości Elektroenergetyczne* **4**, 1982.
- [5] K.L. Chrzan, *High-voltage surge arresters*. (in Polish), 2003 Dolnośląskie Wydawnictwo Edukacyjne, Wrocław.
- [6] *High-voltage surge arresters, the buyer's guide*. ABB 2019. <https://library.e.abb.com/public/ba61a5f190bf46fe8676554e-0a2e9e4a/Buyer%27s%20Guide%20Surge%20Arresters%202019-10-17.pdf>
- [7] P. Papliński, P. Ranachowski, Investigation of surfaces of internal elements of surge arresters, (in Polish), *Przegląd Elektrotechniczny* **88** (5a), 73-76 (2012). ISSN 0033-2097
- [8] I. Plesa, P.V. Notingher, S. Schlögl, Ch. Sumereder, M. Muhr, Properties of Polymer Composites Used in High-Voltage Applications, *Polymers* **8** (5), 173 (2016). DOI: <https://doi.org/10.3390/polym8050173>
- [9] Standard PN-EN ISO2078:2011, Glass textiles – Threads – Markings.