ACOUSTIC EXAMINATION OF EPOXY-GLASS INSULATOR MATERIAL

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Ultrasonic, microscopic and acoustic emission (AE) methods were applied to investigate the microstructure of composite rods, used as a carrying element of the medium voltage insulators. Such features of material structure as homogeneity level and the appearance of defects were discussed. The research was aimed at determining the influence of the technology of epoxy-glass fabrication on quality parameters of the insulator rods. The results of acoustic testing were compared with the effects of microscopic investigation.

Key words: composite insulator, epoxy-glass material, nondestructive ultrasonic measurements, acoustic emission.

1. Introduction

Electrotechnical porcelain is considered as the most commonly applied in the industry high-voltage insulating material. The variety of its advantages makes the porcelain one of the leading materials applied in engineering. The essential properties of this material are its high resistance to corrosion and to thermal damage, high electrical resistance and mechanical strength at acceptable values of density. The parameters stated above, in correlation with the practice gained over a hundred years of application, are the reason of domination of long-rod porcelain insulators – especially in Europe – in voltage transmission and distribution systems. The other kind of insulating elements in operation are the glass cap and pin (disc) insulators. They show some drawbacks leading to some limitations of their application. Among disadvantages the most significant

are: high weight of the insulator sets, no uniform electric field distribution along the string, poor resistance to pollution, partial discharges and gradual ageing processes in the structure and on the glass surface. Nevertheless, the disc insulators are inexpensive and resistant to mechanical rupture. This kind of insulation is dominating on domestic 400 kV extra-high voltage (EHV) overhead lines.

The fundamental factor considered when taking a decision, which type of insulator should be preferred, is the quality and operational reliability of the elements of electricity transmission or distribution systems. The consequences of the failure and the maintenance of a high voltage (HV) line considerably exceed the costs of purchasing the insulating elements. Modern projects of HV line should also take into account the problem of climate hazards and air pollution. However, the costs of the energy transmission and distribution influence the total cost of line insulation. The rapid demand for energy supplies dated to early fifties of the XX-th century has led to the growth of projects of ultra-high voltage power systems, even beyond the limit of 1000 kV (in North America). The weight of the insulators, either glass or porcelain, has turned out to be the major problem for the enterprise. That was the cause of growing attention to the synthetic substances, especially epoxy-glass composites. First light insulators with sheds made of epoxide material are dated to 1959 [1].

The progress of the composite insulators construction can be divided into the following periods. The insulators fabricated in 1960–1975 are considered as the first generation. The eighties are the years of introducing the second generation. Wide application of the new technology is related to the third one, appearing in early nineties. Only that generation seemed to be competitive enough in terms of technical and economical aspects. Several different designs of the insulation arrangements (i.e. post and hollow insulators, cross-bar and separating equipment) have been introduced during the last decade, especially in the United States. In this country it is widely understood that application of the composites as the insulating elements results in reduction of both the investing and maintenance costs. EHV lines with composite insulation used solely have been built since 1994 [2].

When compared to the ceramic elements, the composite insulators have significantly smaller diameter and weight. The production method enables easy adaptation of the product dimensions to the particular requirements, eliminating troublesome formation of insulator strings. The new material characterizes the endurable and renewable hydrophobic properties and thus, it is recommended to operate in highly polluted environment. The costs of launching a new product are acceptable and the production itself requires less energy than technology of the ceramics, especially considering the firing process. Due to its elasticity and reduced mass, the composite insulators are also resistant to mechanical shocks and vibrations. Assembly of composite insulators is easy and its maintenance costs are low. It is worth mentioning that in the USA, the overhead line operators suffer from the losses caused by the gunshot attacks on the line insulators. The composite elements are also less sensitive to that kind of hazard. The composite insulators are gradually introduced in Polish medium- and high-voltage networks, especially on 110 kV overhead distribution lines.

2. Construction and degradation hazards of composite insulators

The typical line composite insulator consists of three elements, as it is shown in Fig. 1: metal fixing devices situated at both ends; the polymer cover with disc sheds and the glass-epoxy insulating rod. The rod acts as a hard core to endure the mechanical load and voltage gradient. The synthetic rubber cover with sheds ensures the desired leakage path and rain spark-over voltage [3, 4].
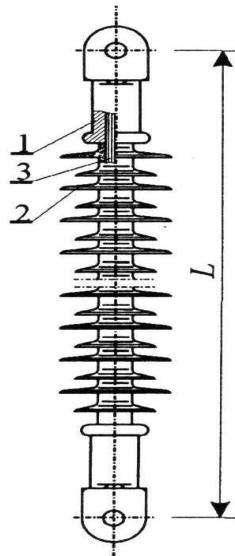

Fig. 1. The typical line composite insulator: 1 – metal fixing devices situated at both ends, 2 – the polymer cover with formed sheds, 3 – the glass-epoxy carrying rod [4].

Although the composite insulator can be considered as a relatively simple object, the design and technological problems are still present. The endurance and reliable operation of composite insulator highly depends on firm and tight coupling of its elements. The critical region is the triple junction of the rod, fixing device and the polymer cover. Special attention should be paid to avoid the moisture leak here. When the junction is insufficiently hermetic, the chemical corrosion process could appear at the place of the rod and fixing device connection and it could also result in electrical breakdown what would lead to rod damages. The electrical breakdown effects in the border area of the rod and polymer cover have been definitely eliminated only in the third generation products. The synthetic rubber cover is exposed to such ageing factors like: aggressive gases (ozone and nitride oxides), ultraviolet radiation, temperature changes, moisture, industrial pollution, mechanical stress and voltage gradient. The occurrence of electric fields exceeding the level of 5–7 kV/cm can be a cause of partial discharge effect, which devastates the surface of the rubber cover [5]. To limit these harmful processes, the best synthetic compositions (most frequently silicone rubber) should be applied to form the insulator cover with sheds and perform its proper adhesion to the carrying rod.

The other process resulting in insulator degradation is the brittle fracture of the carrying rod. It can be caused by different factors: corrosion of the fiberglass (action of nitride acid), inappropriate transportation, improper line support assembly and structure overload occurring during compression of the metal fixing devices. The corrosion effects can be reduced by a proper overall shape design to diminish the electrical field strength level (corona effect reduction), especially close to the core-fixing device junction.

The triple point core-fixing device-polymer cover should be protected with a very high accuracy. Also, a very delicate dealing with composite insulators is necessary during its transportation and installation. The control of the pressure acting on the carrying rod of an insulator during the process of setting up the metal fixing devices can be nondestructively performed by the acoustic emission method.

3. Structural and ultrasonic investigation

The object of analysis in this work were two types of epoxy-glass rods, produced in Poland. Both the types had the same dimensions but they were prepared using different forming processes. The rods of type A were made using continuous drawing process. The rods of type B were obtained using the analogous method with additional tightening (wrapping round by an elastic fiber). In the case of type A material the density was $d_A = 1.9$ g/cm^3 and contents of roving fibres – about 70%. The B composition had higher density $d_B = 2.1$ g/cm^3 and contents of roving fibres – over 80%. To make the microscopic inspection, the rods were cut into pieces at different locations and then the surface of the samples was properly prepared. At first the surfaces were ground using SiC powder of 10 μm grain size. Polishing process, using colloidal solution of silica, was performed on a special fabric of 90% porosity. After rinsing in chemically active detergents and drying in alcohol vapors, the microsections were ready for microscopic investigation.

The microscopic analysis revealed sufficient homogeneity of both composite materials. No major pore cavities and surrounding crack areas were noticed. These kinds of defects have been found in epoxy-glass insulator composites of older generations – Fig. 2. It has been found a little poorer roving filling of the matrix and more areas with no roving contents in samples of type A. The maximal pore diameters were approximately calculated to some scores of micrometers in both compositions. In composition A a small pore amount was detected. In material B the contents of pores was even smaller. The average fiber roving diameter in composition A was 11.2 μm, while in composition B the average fiber roving diameter was 6.3 μm, with remarkable presence of a population of greater fibers – analogous to those used in composition A. In both materials were revealed the cracks situated along the fibers.

However, these defects occurred more frequently in composition A and only incidentally in material B. The typical microscopic images of both materials are shown in Fig. 3 – composition A and in Fig. 4 – material B.
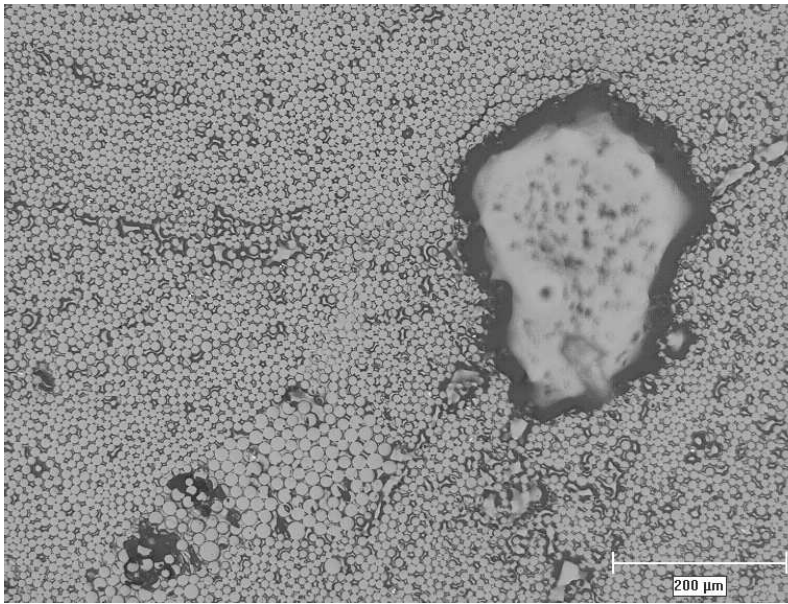
Fig. 2. An example of great pore cavity and other inhomogeneities found in epoxy-glass insulator rod of elder generation. Magnification × 50.
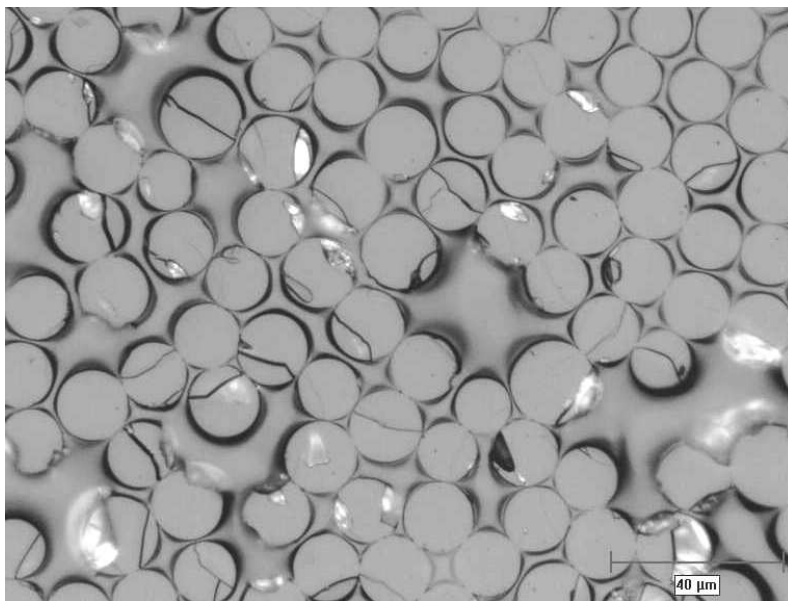

Fig. 3. The typical microscopic image of composition A structure. Faults in roving filling of the matrix and internal cracks of roving fibres are visible. Magnification × 200.
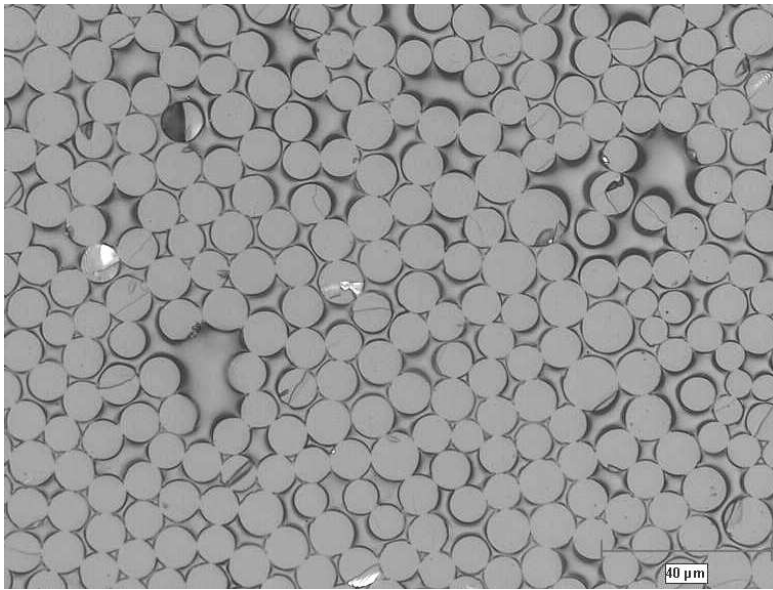
Fig. 4. The typical microscopic image of composition B structure. Sufficient homogeneity and small
number of internal cracks of roving fibres are visible. Magnification × 200.

The ultrasonic measurements were carried out using standard procedures with application of the set-up presented in papers [6, 7]. These works were related to similar problems of ceramic insulators testing. In the case of epoxy-glass composite material, the echo-method and an ultrasonic 4.7 MHz transducer were used. The longitudinal wave propagation velocity and the amplitude attenuation coefficient were measured in two directions – parallel and perpendicular to the core axis. Four samples of 40 millimeters length of both the A and B materials were prepared for this investigation. The results of measurement are presented in Table 1.

Table 1. The results of ultrasonic longitudinal wave measurements of the composite insulator core rods, performed parallel and perpendicular to the core axis. The following ultrasonic wave parameters were presented as upper and lower limits of four measurements: $c_{L||}$ – longitudinal mode wave velocity parallel to the core axis, $c_{L\perp}$ – longitudinal mode wave velocity perpendicular to the core axis, α_c – amplitude wave attenuation coefficient parallel to the core axis in central part of the core, α_p – amplitude wave attenuation coefficient parallel to the core axis in peripheral region of the core, $\alpha_\perp$ – amplitude wave attenuation coefficient perpendicular to the core axis – across the core diameter.

Measured parameter	Material of type A	Material of type B
$c_{L||}$ [m/s]	4960 ÷ 5090	5220 ÷ 5350
$c_{L\perp}$ [m/s]	3230 ÷ 3360	3490 ÷ 3600
α_c [dB/cm]	3.02 ÷ 4.67	2.89 ÷ 4.75
α_p [dB/cm]	1.35 ÷ 3.87	1.72 ÷ 3.82
$\alpha_\perp$ [dB/cm]	6.81 ÷ 8.46	3.80 ÷ 5.71

Wave velocity measurements were carried out with accuracy of ±15 m/s and amplitude wave attenuation coefficient measurements were performed with an estimated error of ±0.15 dB/cm.

Results of the longitudinal mode wave velocity measurements indicated relatively low dispersion in both investigated compositions. This revealed sufficient material homogeneity. The remarkable difference between $c_{L||}$ and $c_{L\perp}$ is a consequence of anisotropy of the roving fiber packing. Cracks appear in considerable part of the fibers, especially in epoxy-glass of type A. There are areas without roving presence, high density of phase borders and low contents of pores. Some fibers are also twisted, what additionally increases the amplitude wave attenuation coefficient. Thus, wave attenuation in the investigated material is characterized by a complex mechanism. The factors listed above result in high variations of the attenuation coefficient, even when it is determined in the same section of the rod. The higher level of attenuation coefficient measured parallel to the core axis in central part of the core in comparison to the peripheral core region can be caused by different pressure level during material formation in those regions. The wave energy absorption in the material is of minor importance when compared to the scattering effects. The structural differences between both compositions are more evident when the average longitudinal wave velocities are compared. In B type material the average wave velocity measured parallel to the core axis $c_{L||}$ has the value of 5280 m/s and the average wave velocity measured perpendicular to the core axis $c_{L\perp}$ has the value of 3540 m/s. In A type material the corresponding values are lower: 5040 m/s and 3290 m/s. The values of attenuation coefficient (α_c and α_p) are slightly lower in type B epoxy-glass, than in that of type A – measurements parallel to the rod axis. In the case of measurements performed perpendicular to the rod axis, the differences in attenuation coefficient are greater. Mean value of $\alpha_\perp$ in type B material is equal 4.76 dB/cm and mean value of $\alpha_\perp$ in type A composite – 7.64 dB/cm.

4. Acoustic emission investigation

Besides microstructural and ultrasonic measurements, the process of compression of the fixing devices on the carrying rod was investigated. This process was performed by a hydraulic press. Compression was realized by automatic multi-element jaw. Direct on-line control of the pressure acting on the carrying rod is difficult. Compressive forces acting on both ends of the rod are analogous. Therefore only one end of the rod was controlled during compression, while to the other end the wideband acoustic emission sensor WD Physical Acoustic Corporation type was coupled. The passband of AE transducer was between 80 and 1000 kHz. Transducer was connected with a preamplifier and AE analyzer, coupled with the computer. The applied instrumentation is shown in Fig. 5, presenting the composite medium voltage line insulator with installed fixing devices. In the central part of the picture there is a carrying rod with fixing device placed in the jaws of the hydraulic press. To the other end of the rod the acoustic emission sensor is connected.

The preliminary test was performed to estimate the proper compressive force, to obtain a good connection without any damage of the rod material. The suitable compression load was determined in the range 17–21 MPa. The group of three rods of type A and three rods of type B were taken to measure AE effects during fitting of the fixing
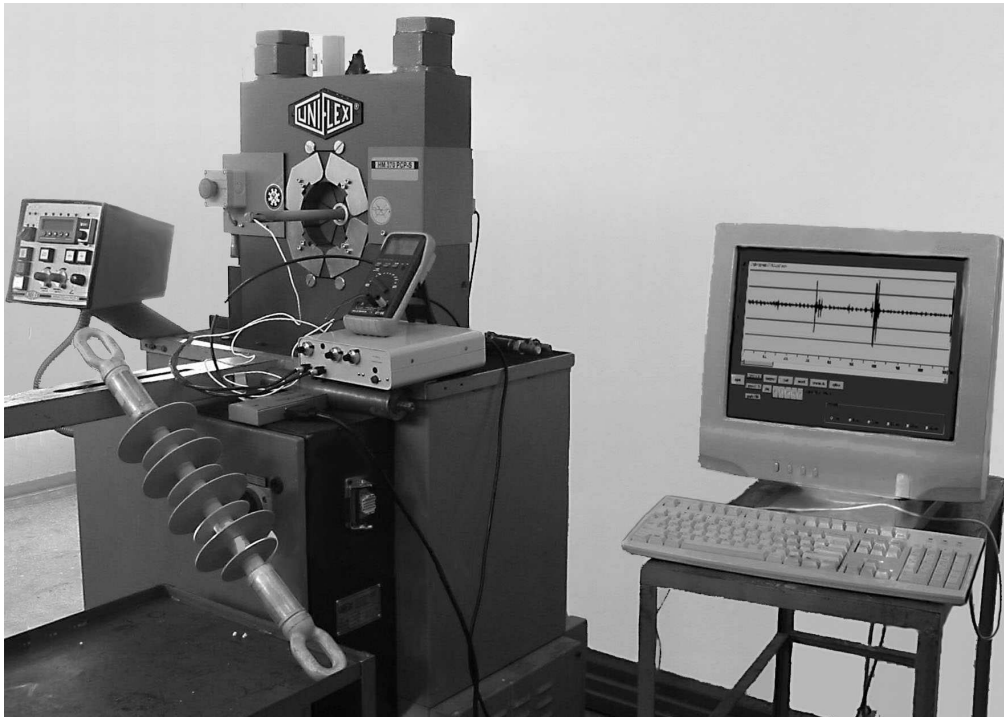
Fig. 5. View of the experimental set-up used to AE control the process of compressing the fixing devices on the medium voltage insulator rod.

devices. Experiments were carried out using pressure 17 MPa. The effective values of acoustic emission signals (RMS) generated during compression were registered. The typical time dependence of RMS signal is shown in Fig. 6 (epoxy-glass A) and in Fig. 7 (material B). The whole process can be divided into three stages. During the first stage of the process (4–4.5 s) the compression increased linearly to the value of 17 MPa. During this preliminary stage, a high acoustic activity was generated. Course of the AE activity in this stage was similar for all experiments. This is a consequence of the analogous effect of plastic deformation of metal fixing device. Metal deformation has been recognized as the source of AE signals. In two next stages the compression was maintained at constant level 17 MPa. During the second stage, AE activity remained at low level. The strong acoustic signals were generated in the last stage – after eleventh second. They originated from the deformed structure of the epoxy-glass rod. The high RMS value of AE signals can be result of cracking of roving fiberglass in the structure of composite material. Experiments showed a remarkable difference in the course of acoustic energy emission generated by the rods of type A and B. The amplitude of the signal generated by the structure of type A – two bursts, was approximately two times greater than that of type B – one burst. These results indicate lower mechanical strength and higher number of structural inaccuracies of epoxy-glass material of type A.
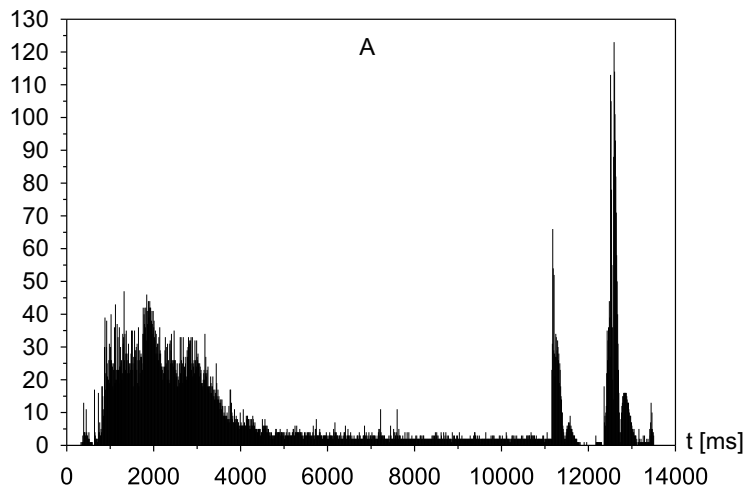
Fig. 6. Time dependence of AE RMS signals, generated in material of type A during fixing device assembly to the insulator rod.
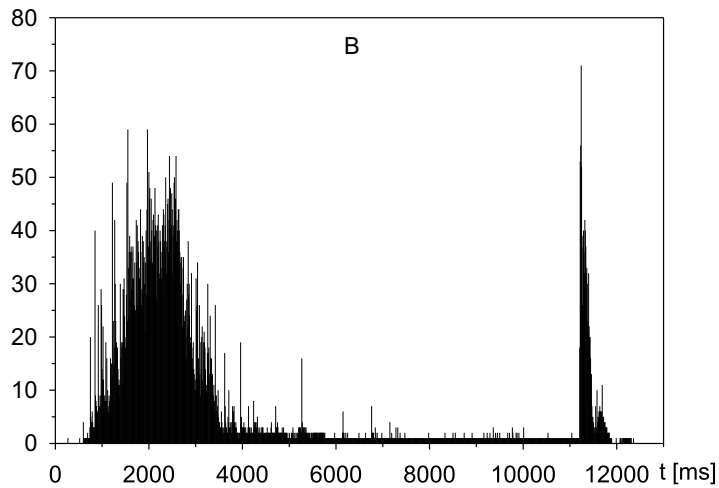
Fig. 7. Time dependence of AE RMS signals, generated in material of type B during fixing devices assembly to the insulator rod.

5. Conclusions

The paper presents the results of ultrasonic, microscopic and acoustic emission research of carrying rods of medium voltage composite insulators. Investigation was performed for two types of epoxy-glass materials, denoted A and B. The A – type composition was fabricated using continuous drawing process. For B composition additional

tightening method was applied. The measurements revealed higher ultrasonic wave velocities and lower levels of attenuation coefficients measured in B type composition in comparison to material A. These findings are the consequences of differences in microstructure of the materials. There is a higher amount of roving fibers per unit volume and denser structure in B type composition. The concentration of defects was greater in type A material, what considerably influenced the results of the measurements, obtained using both acoustic methods. It seems, that cracks of roving fibres have greater influence on mechanical and acoustic parameters of the epoxy-glass materials, while the pores and roving missing spaces are of less importance. Acoustic emission method confirmed lower mechanical strength of A type epoxy-glass material. This nondestructive technique can be helpful in testing the quality of the rod material and accuracy of the fitting process.

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