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The ultrasonic method applied to diagnostic operational tests performed on long-rod post insulators

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In this contribution we present the control testing of a group of post insulators, which have been working for over 20 years on the 110/6kV station isolating switches of industrial power engineering. The research included 43 insulators of the SWZPAK-110 type, which were produced in Poland between 1972 and 1976. In order to elaborate the methodology of acoustic research, a detailed structural investigation of the insulator of this type, from the year 1975, was conducted. The insulator was broken, when being switched and has undergone tests, which were aimed to ascertain the causes of breakage as well as to determine the close correlations between the microstructure of the materials and the parameters of the ultrasonic wave propagation. On the basis of the measurements, the analysis of the quality of the tested group of insulators after long-term exploitation was carried out. This research, performed directly on the isolating switches, using a specially designed and constructed measuring unit, is innovative on a nationwide scale.

Key words: *long-rod insulators, ultrasonic testing, electrotechnical porcelain, and ceramic microstructure.*

1. Introduction

Suspension insulators as well as station-post insulators, belong to the group of especially important elements of the electroenergertic lines. This particularly concerns the ceramic solid core insulators. Although these constructions are resistant to breakdowns, they can easily undergo fracture. This means that in the case of technological errors arising during production process, as well as those due to years of exploitation – when the aging processes occur in the material, the probability of disruption rises considerably. Ceramic materials, electrotechnical porcelain in particular, are considered to be materials characterized by difficult and complicated technology. The information about the processes undergone by the material, is encoded in the structure of the porcelain. It especially effects the composition and grain-size distribution of the set of raw mass, reological flows during formation, as well as the drying and firing (sintering) parameters. All the technological inaccuracies made during any stage of production can not be corrected anymore, and lower the final quality of products. However, the present requirements concerning the certainty of supply, as well as security of exploitation of electrical power engineering lines and stations, require to use highest durability and reliability insulators. Reliability is defined as the probability of the object to work for a postulated period of time without breakdown. Durability is also the property of the object, which concerns the ability of retaining its properties with the passage of time [1]. In order to ensure the highest quality of the product most importantly its reliability and durability should be taken into account. In the case of long-rod insulators, these parameters are closely related to the aging processes of the ceramic material.

In this work, in order to evaluate the quality of a group of post insulators, which have been at work on the isolating switches for over 20 years, the ultrasonic method, as well as comparative research of microscopic structural analysis were used. The ultrasonic methods applied to the nondestructive insulator testing were already introduced in Poland in the early nineteen fifties [2]. The use of the acoustic technique is based on the dependence of the propagation of waves on the properties of medium, where the waves propagate. In the case of solid body they depend on the elastic properties of the material, as well as on its structural composition. The ultrasonic technique has been widely applied in flaw detection. Detecting the discontinuity of the medium is performed by introducing a wave beam into ceramic material and then finding out of the deflection of its part from the boundary of heterogeneity. If the discontinuity appears to be a gas cavity or a gap, in most cases, the sensitivity of the ultrasonic method is high. Therefore, the ultrasonic technique has been used in the production of electrotechnical porcelain for a long time, being one of the basic method of quality control.

Another important application of ultrasonic technique is a relatively not complicated possibility of calculating the dynamic values of elasticity modules. The most important quantity is longitudinal elastic constant – Young's modulus E, the value of which is proportional to the density of material ρ and the velocity of longitudinal ultrasonic wave propagation c_L as well as transversal c_T. Measuring both these velocities, and even the value c_L of itself (usually $c_T \approx 0.6c_L$), at a known density of ceramic material, the value of Young's modulus can be determined from the relation [3]:

$$E = \rho \frac{c_T^2(3c_L^2 - 4c_T^2)}{c_L^2 - c_T^2}. \tag{1.1}$$

Therefore, in order to perform elastometrical measurements it is not necessary to cut out accurately machined samples, as it is in standard mechanical methods. The porosity is one of the basic factors proving the correctness of the technological process of formation, as well as determining its mechanical and electrical properties. The influence of the contents of gas inclusions on the mechanical parameters of the material may be well described by lowering the elasticity modulus. The dependence between Young's modulus of the porous material – E and matrix without pores – E_0, is illustrated by the empirical equations:

$$E = E_0 \exp(-kp), \tag{1.2}$$

$$E = E_0(1 - k'p). \tag{1.3}$$

The influence of porosity on the modulus of elasticity of the material at the same time affects the velocity of ultrasonic wave propagation. The dependence of c_L on the porosity of material (presented in percentage) was determined based on the method, which substitutes the medium filled with inclusions with an equivalent continuous medium having effective moduli, given by MacKenzie [4]. It was proven [5] that the velocity of ultrasonic wave propagation decreases linearly (in the wide range of values from 2 to 15%) with the growth of porosity. For various materials only small deformations as well as small changes in slope are observed. Figure 1 presents examples of experimental dependencies $c_L = f(p)$, which the authors determined for electrotechnical porcelain of the older type. The above dependencies allow control research of the homogeneity of material through the length of the ceramic insulator cores. Such measurements were performed to a small extent in Poland in the 1990s [6, 7]. These results however, as expertise, have not been published. Due to technical difficulties only the velocity of longitudinal wave propagation was measured using the flaw detector apparatus. The authors applied a new methodology of ultrasonic research due to the constraints in the accuracy of measurements, impossibility to evaluate other acoustic parameters as well as common difficulties in measurement interpretation. Especially designed and constructed measuring equipment, which is described in detail in Sec. 3, was used. Besides allowing a high accuracy of

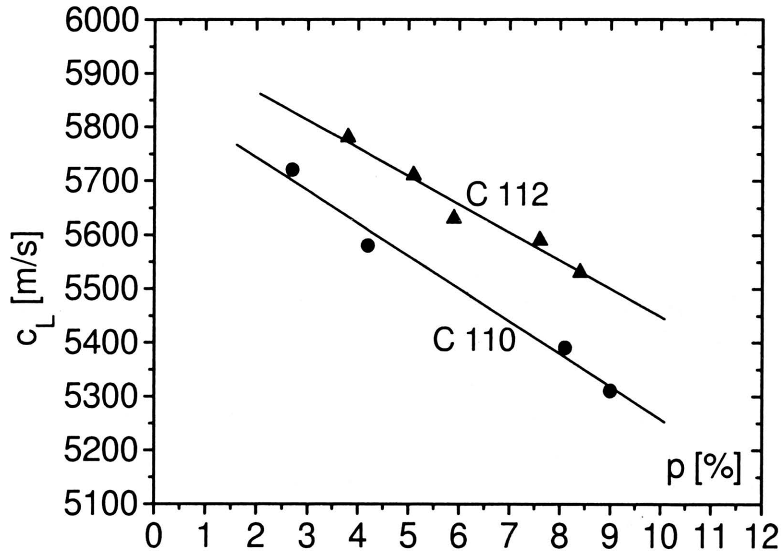


FIGURE 1. The dependence of the velocity of the longitudinal ultrasonic waves propagation versus porosity, determined experimentally for siliceous porcelain (C 110) produced in Poland, as well as cristobalite porcelain (C 112) produced in the former GDR.

measuring the impulse path and the time of its crossing through the diameter of the insulator, the unit enables the recording of ultrasonic wave attenuation value. This is a very significant parameter, which allows above all to evaluate the degree of the aging processes in ceramic material. The lowering and the distortion of the signal amplitudes are a result of a number of phenomena such as attenuation (absorbtion), which is caused by the thermal conductivity and radiation, as well as molecular relaxation. However, in the case of multiphase aluminasilicate materials, the diffraction effect, especially the dissipation effect is of the basic importance. This is due to the existence of numerous structural heterogeneities, such as micro-cracks, frequently spaced pores, larger crystalline phase precipitation as well as areas where mechanical stresses appear, and especially network of cracks. By measuring the lowering of signal amplitudes after passing through the insulator diameter in subsequent measured points and by observing the amplitude distortion, the homogeneity, as well as the quality and degree of aging of the porcelain at the core can be evaluated.

However, a number of comparative tests on insulators of the same type and produced from a similar material in laboratory conditions, were supposed to be made in order to conduct acoustic measurements of insulators in exploitation. The influence of various structural defects on the lowering of the ultrasonic wave propagation velocity and the increase of the attenuation had to be evaluated. In view of the fact that a group of 42 SWZPAK-110 insulators, produced in Poland between 1972 and 1976 was selected for measurement in exploitation conditions, analogous objects and material samples were used in comparative studies. A 1976 insulator, which was damaged in Żukowice [8], as well as a number of insulator core and shed samples, taken from insulators of the same type made in the 1970s, were used for detailed structural tests. A complex ultrasonic and structural testing of the SWZPAK-110 insulator from 1975, which represented investigated group of objects, was especially significant and defined precisely the earlier determined correlations. The failure of the insulator in year 2000 became an impact to carry out tests of major group of the insulators working on the isolating switches of the 110/6kV stations of industrial power engineering.

2. Structural testing of the isolating switch insulator

Apart from specifying the before mentioned correlations between the microstructure of the material and the parameters of ultrasonic wave propagation, the aim of research was to determine the causes of insulator failure. The study included the description of fracture, the microscopic evaluation of the polished sections in three planes of lateral transverse cutting of the core together with the porosity distribution, as well as the phase analysis of the ceramic material. Special attention was paid to the shape, size and distribution of pores as well as to noticeable effects of aging processes. In order to perform the microscopic tests it was necessary to make microsections of the lateral cross-section of the core of the damaged insulator, marked as PAK A, in several places. On the basis of ultrasonic measurements, presented in Table 1, the presence of the damaged area was observed only in the upper part of the insulator. It extended from the place of breakage under the upper fixing device – the measuring point labelled 0, up to the third shed. Therefore, a decision to perform three lateral cross-sectioning of the core was undertaken: right under the fracture in the point labelled 0, in the point labelled 1 – between the first and the second shed and between the third and fourth shed – the point labelled 3, where structural defects were not observed anymore.

The microsections were prepared following a standard procedure described in the relevant literature, cf. [9]. The surfaces of samples assigned for structural investigations were ground using special carborundum powders of granulation below 20 μm. The layers destructed during the grinding process were etched in 15% water solution of hydrogen fluoride acid. After etching process, the layers were polished in colloidal solution of silica of granulation of about 90 nm, in the presence of natrium chlorate (I) and stabilized in the weakly alkaline pH. During the polishing process system should be cooled down to temperature of about 15°C. After the latter process samples were rinsed in chemically active detergents and dried in ethyl alcohol vapour. In the structural research the optical microscope (MO), coupled with a Clemex image computer analyzer, was used applying 50 to 500 magnifications.

Figure 2 presents the image of the fracture of a part of the insulator from the metal fitting side. The fracture inspection indicates the presence of an area with an evidently disturbed surface in the central part. A large amount of small cracks and leaps, most of which are rounded, can be observed. Attention should be paid to the characteristic leap in the shape of letter "S", which joins with the furrow edges in the side-parts of the fracture. A typical shell fracture appears around the central area of disturbances, which constitutes about 25% of the cross-section area. Its only slightly corrugated surface, however, gives evidence to a low resistance of the material, indicating an advancement of aging processes. The furrow arrangement clearly proves that the defected central area was the source of cracks and their catastrophic growth. In the image of the microsection on the level labelled 0, directly

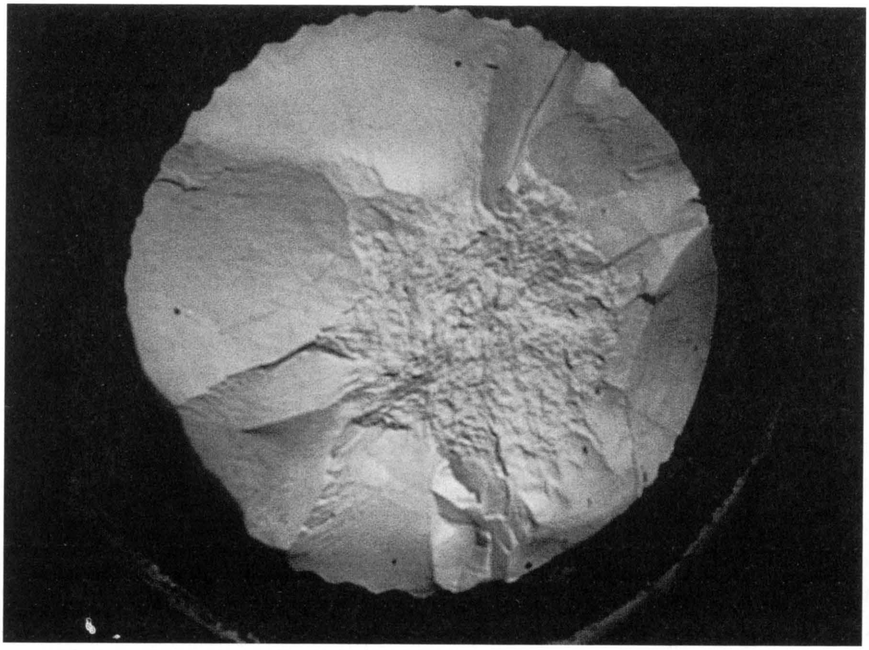
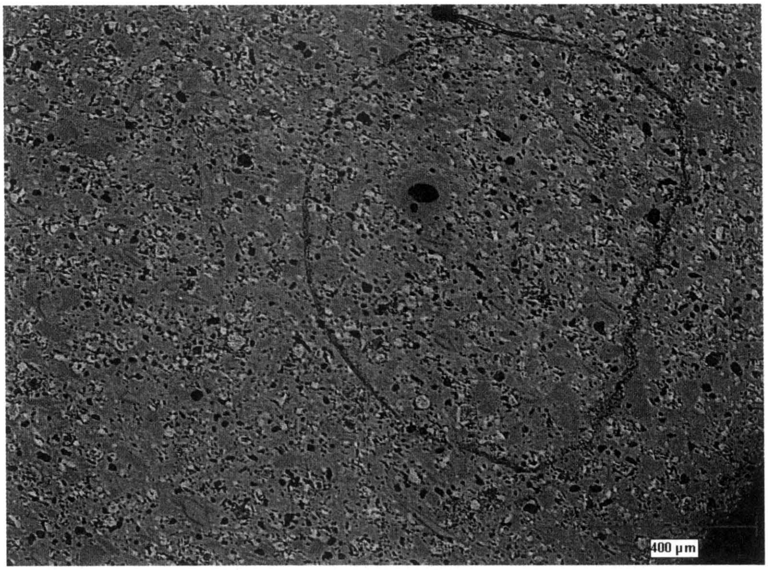


FIGURE 2. Image of the PAK A insulator fracture from the side of fixing device.

(a) 

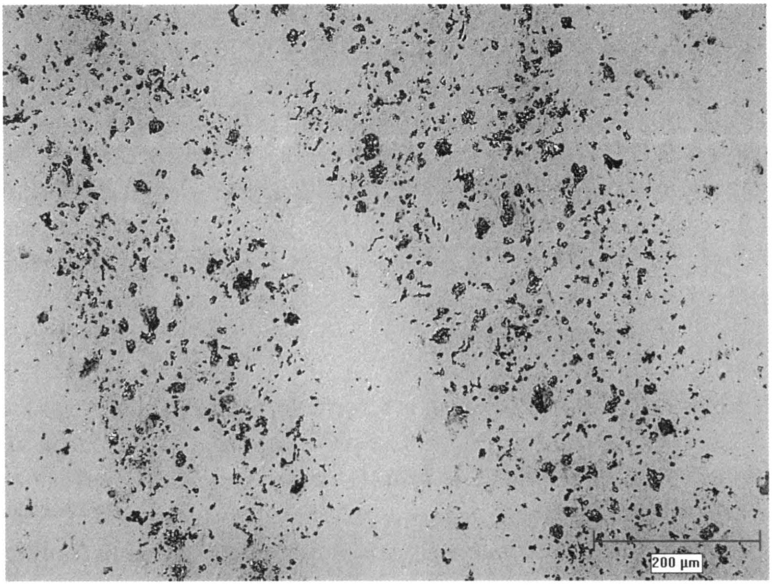
(b) 

FIGURE 3. Image of material on the level labelled as 0, in magnification: (a) 50×, and (b) 100×. In the central part of the rod – figure (a) – curved cracks and high porosity are visible; in the side part – figure (b) – characteristic elongated strips of defective structure are present.

below this area, characteristic circular cracks (Fig. 3a) as well as a high – up to 14% porosity in the greater part can be observed. Special attention should be directed to a great number of small micro-cracks, which are quite regularly distributed in the volume of material; however, usually are adjoining to bright grains of quartz. They are the result of advanced aging processes. Photographs of the material performed in polarized light (without interface-phase contrast) illustrated the presence of significant disturbances in the porosity distribution of the porcelain on the levels labelled as 0 and 1. The appearance of elongated areas, with a high porosity and inclusions forming strips was found, see Fig. 3b. Their clear presence, which indicates mass twirl is distinct on the level labelled 0, less numerous in area 1, and it absolutely disappears on the level labelled 3. There, the average porosity also goes down to 3.1%.

A phase analysis of the PAK A insulator material allowed to conclude that the material corresponds to the typical electrotechnical porcelain of the older 120 type, which is characterized by a acceptable homogeneity. The average composition of the material consists of about 24% quartz, over 32% mullite, where 8,5% has the form of needles. The glassy matrix content is about 40%. The presence of corundum crystals in the ceramic body was not detected. The average porosity varies from 3 to 9%. An important material characteristic that was ascertained in all the areas of tested insulator is its advanced aging process. This process manifests itself by a large amount of micro-cracks, which are usually adjacent to the numerous quartz grains. The latter usually show also cracks. However, the original cause, which in the process of time led to the critical propagation of cracks and breakdown, was a technological defect. The character of the fracture, the shape of cracks, as well as the visible areas characterized by a released defective texture and porosity, prove unsuitable pressing force and material swirl during the formation process in the pug mill. The wearing down by friction of the perpetual screw in the venting vacuum press was probably the direct cause of defects. This fault, which belongs to the textural ones, is often referred to as the "mass swirl". The fact that the core broke after an over 20-year period of exploitation was due to the mild working conditions. The switchovers were usually performed once in a very few months. Apart from these switchovers, the insulator, standing on the isolating switch, was practically not subjected to any mechanical loads.

3. The methodology of acoustic tests

Ultrasonic measurements of the post insulators chosen for the research were carried out using a specially constructed apparatus. The measuring set was adopted for the field tests, combining a small weight and size with a high accuracy of measurement, approximately ±0.6%. The system consisted of a set of ultrasonic piezoelectric transducers with an application on longitudinal and transverse waves, as well as a digital oscilloscope – Tektronix TDS 210 connected with a transmitting – receiving module. The latter was constructed in the Institute of Fundamental Technological Research PAS.

The transducers were assembled coaxially in the electronic slide caliper, in the appropriate jaw extension arms. The transducers for longitudinal waves of a 4.7 MHz frequency, which had an 8 mm diameter, were specially made for the intershed insulator tests in the Institute of Fundamental Technological Research PAS. The traversal waves transducers of a 4.0 MHz frequency, could only be used on the core segments near the fixing devices because of an about 20 mm transducer diameter. Due to constructional restrictions it is impossible to yield smaller dimensions of the transversal waves transducers. In view of geometrical configuration of the intershed segments of the core insulators, the measurements could be carried out only using the transmission method – with two transducers, transmitter and receiver. In the case of the echo method measurement, the signals were suppressed and distorted to a degree that did not allow a precise registration of neither the time of propagation, nor the ultrasonic wave attenuation. The measuring set is presented in Fig. 4.

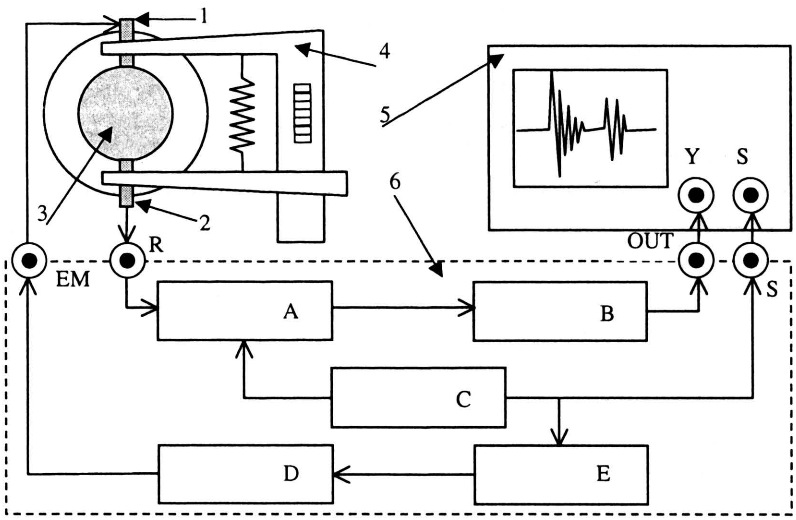


FIGURE 4. The block diagram of the set used for the measuring the time and the attenuation of ultrasonic wave propagation in the post insulators; explanation given in the text.

The transmitting probe 1 and the receiving transducer 2 were placed coaxially on the extension arms combined with jaws of the electronic slide caliper – 4. These mechanical-electronic construction allows a coaxial and repeatable acoustic coupling with the post insulator being tested, as also a precise simultaneous measurement of the wave propagation path (insulator diameter). The ultrasonic transducers are operated from the sending – receiving module 6. The impulse, which activates the transmitting probe is shaped in the key impulse generator E and after reinforcement in the power amplifier D, approaches the transducer. After going through the diameter of insulator 3, the ultrasonic impulse reaches the receiving transducer, then, after being amplified in the key signal preliminary amplifier A as well as in the voltage transducer B, it passes to the input of oscilloscope 5. The transmitting as well as receiving units are activated by a controlling and synchronizing system (timer) C. The timer signal is also used to synchronize the digital oscilloscope. The "time magnifier", available in the oscilloscope allows a precise measurement of the wave propagation time.

The measurement error caused by the shape of the intershed segments of the insulator cores and by the evaluation of the time of flight of the impulse was comparatively small. Its limit value was ±0.6%. The velocity of ultrasonic wave propagation was determined with accuracy of at least ±30 m/s. Due to the high attenuation of the ceramic medium, the measurement of the amplitude attenuation coefficient was not possible. Besides measuring the time of signal delay, the attenuation of ceramic body was determined using an indirect method, by registering signal amplitude in volts. The obtained value is inversely proportional to the medium attenuation. A series of comparative structural and acoustic tests were performed on porcelain samples as well as on insulator cores (the formerly described PAK A among them). This allowed the determination of accurate correlation between the degree of defectiveness in ceramic body and the signal amplitude, measured with a minimal accuracy of ±0.2 V on the oscilloscope screen. The high amplitude values (over 2.2 V) indicate the low degree of material aging apart from the lack of structural defects. The values below 1V are not only the result of the advanced aging processes, but first of all reveal the presence of faults as cracks, delaminations or areas characterized by a released texture and a high, non-uniformly distributed porosity in the ceramic body. The most common range of amplitudes – from 1.0 to about 2 V – indicates in spite of the lack of significant defects of the material, the presence of aging processes at various stages of advancement. This dependence is confirmed by relatively low values of ultrasonic wave velocities, which correspond in most cases to the values typical for the siliceous porcelain C 110, see Fig. 1; however, not to the aluminous porcelain of the 120 type.

4. The results of ultrasonic testing of switchgear insulators

Acoustic tests of insulator switches were performed using the apparatus and the methodology described in Sec. 3. The procedure included measurements done in consecutive points between the sheds as well as under the upper and above the lower fixing devices of each insulator. The measurement points were labelled with the numbers beginning from the top. The highest point under the upper fixing device was marked – 0, and the lowest under the twentieth shed – 20. Table 1 presents the results of acoustic measurements of insulator, which is marked PAK A, after breakdown, and its structural investigation was described in Sec. 2.

TABLE 1. The results of ultrasonic measurements of the insulator (PAK A) after breakdown. Next to every measuring point the velocity of longitudinal wave propagation, c_L, and the signal amplitude, A, are given.

Measuring point	c_L [m/s]	A [V]	Measuring point	c_L [m/s]	A [V]
0	5680	–	11	5670	1.2
1	5710	0.4	12	5640	1.2
2	5700	0.8	13	5600	1.4
3	5660	1.2	14	5560	1.6
4	5680	1.6	15	5580	1.5
5	5690	1.4	16	5580	1.4
6	5680	1.2	17	5600	1.4
7	5670	1.0	18	5600	1.8
8	5660	1.4	19	5560	2.2
9	5660	1.8	20	5570	2.2
10	5650	1.9			

In the measuring point labelled 0 – above the first shed, directly under the fracture – the measurement of the amplitude was impossible to be performed due to serious defects in the material structure. The presence of defects in the measuring points labelled 1 and 2 caused a reading of amplitude below 1 V. This was confirmed by way of structural tests.

Along with the PAK A insulator, whose breakdown led to the decision to perform tests, 43 insulators SWZPAK-110 made in Poland in 1972-1976, underwent ultrasonic measurements.

These insulators have been in use for over 20 years on 110/6kV stations in power industry. Measurements of 36 insulators were directly performed on the isolating switches, 6 objects came from the station reserve and were taken from the storehouse. Each of the tested insulators was given a symbol, in which the first letter denotes the station, the letters AK stand for the type (SWZPAK-110), the ordinal number allows a precise localization of the insulator on the isolating switch. An additional letter "r" indicates that the insulator was taken from the storehouse.

On the basis of ultrasonic tests the insulators were divided into three groups. In the case of 8 insulators, distinct structural defects, which were usually recorded on a certain segment of the core or in several places in the rod, were found. The presence of defects of this type, which were introduced into the material on the production process stage (usually forming and firing), causes a serious decrease in mechanical durability of the ceramic body and a high probability of breakdown. In the case of 11 insulators (including 3 reserve objects) the occurrence of smaller structural disturbances was ascertained. These defects are connected with material weakening, resulting among other from a higher porosity, heterogeneity in the phase distribution as well as the presence of areas of residual stresses. Such defects cause an increased probability of breakdown. The remaining 24 insulators (including 3 reserve insulators) have a quite homogeneous structure, which does not contain any defects that could be detected. However, one should emphasize a significant dispersion of material properties in the tested group of insulators, as well as a high, although diverse, level of the aging process advancement.

On the basis of the measured propagation velocity of ultrasonic longitudinal and transversal waves as well as known density of porcelain, the Young modulus of the material was calculated using Eq. (1.1). The average value obtained (68 ± 2 GPa) is compatible with the parameters of the 110 type siliceous material and does not meet the requirements for the aluminous porcelain of the 120 type – equal at least to 80 GPa [10]. A significant dispersion of the modulus value for the whole group of 43 insulators was ascertained. The modulus is contained within the range from 62 to 76 GPa. This proves the occurrence of the advanced aging processes in the material. Such a substantial dispersion is caused, however, not only by the varying degree of material aging, but first of all by different initial parameters of electrotechnical porcelain, produced in the 1970s. This was due to the production technology of that time. Apart from the variations of raw material composition, the firing process, which did not have fully repeatable parameters, had the greatest influence on the material properties.

Table 2 presents insulators with substantial structural defects, which creates a high probability of breakdown. Table 3 shows insulators with smaller defects, which cause an increased risk of breakage. Table 4 sets together insulators, in which no defects nor any heterogeneities which could cause a higher risk of breakdown were found.

TABLE 2. List of insulators with a high probability of breakdown.

No.	Design of insulator	Range of c_L [m/s]	Range of A [V]
1	PAK A	5450-5600	0.4-2.2
2	PAK 0	5680-5760	0.5-2.7
3	PAK 9	5560-5650	0.5-2.1
4	PAK 13	5650-5720	0.6-1.2
5	PAK 18	5750-5800	0.3-1.6
6	PAK 22	5690-5790	0.8-1.7
7	PAK 47	5760-5860	0.6-1.9
8	ZAK 5	5930-6010	0.7-1.7

TABLE 3. Specification of insulators with an increased probability of breakdown.

No.	Design of insulator	Range of c_L [m/s]	Range of A [V]
1	PAK 1	5750-5840	0.8-2.4
2	PAK 2	5620-5810	0.9-1.9
3	PAK 5	5620-5630	0.8-2.6
4	PAK 14	5420-5510	0.7-1.7
5	PAK 17	5550-5640	0.5-1.4
6	PAK 20	5670-5790	0.9-1.7
7	PAK 46	5700-5780	0.7-2.0
8	ZAK 4	5890-5960	0.7-1.6
9	GAKr 1	5530-5660	0.9-1.5
10	GAKr 2	5670-5790	0.9-1.6
11	GAKr 3	5640-5780	0.8-1.6

TABLE 4. Group of insulators in which no defects that could cause an increased risk of breakage were detected.

No.	Design of insulator	Range of c_L [m/s]	Range of A [V]
1	PAK 3	5650-5720	1.2-3.5
2	PAK 4	5760-5860	1.2-2.0
3	PAK 6	5700-5840	1.0-2.0
4	PAK 19	5790-5920	1.0-2.3
5	PAK 21	5630-5720	1.0-1.8
6	PAK 23	5760-5810	1.1-2.3
7	PAK 24	5670-5770	1.0-1.5
8	PAK 37	5460-5500	1.0-1.9
9	PAK 38	5440-5560	1.0-1.7
10	PAK 39	5690-5770	1.0-2.8
11	PAK 40	5730-5820	1.0-2.0
12	PAK 41	5670-5780	1.0-2.5
13	PAK 42	5750-5820	1.1-1.5
14	PAK 43	5810-5900	1.8-3.3
15	PAK 44	5920-5970	1.0-3.1
16	PAK 45	5480-5600	1.0-2.8
17	PAK 48	5700-5780	1.2-3.5
18	ZAK 1	5690-5840	1.0-1.8
19	ZAK 2	5690-5800	1.0-1.4
20	ZAK 3	5870-5920	1.0-1.9
21	ZAK 6	5920-6010	1.0-2.3
22	GAKr 4	5600-5660	1.1-1.5
23	GAKr 5	5640-5720	1.2-1.4
24	GAKr 6	5690-5740	1.0-1.3

5. Conclusions

As a result of comparative tests of the microscopic structural analysis as well as the ultrasonic method performed on samples and damaged insulators, close correlation between the microstructure of the electrotechnical porcelain and parameters of ultrasonic wave propagation and attenuation was established. The obtained results are reasonable. A full usefulness of the equipment and the methodology of ultrasonic measurements applied to nondestructive exploitation tests on the insulators from isolating switches were found out.

The structural and ultrasonic tests pointed out that the breakdown of the PAK A insulator was caused by a hidden technological fault of texture, called "mass twist". Nevertheless, apart from the faults introduced to the mass at the stage of production, the advanced aging process, after an over 20-year period of work had a significant influence on the lowering of mechanical strength. On the basis of the results of propagation parameter measurements as well as the measurements of ultrasonic wave attenuation parameters in a group of 43 SWZPAK-110 insulators from the years 1972-1976 the following facts were ascertained:

- 8 insulators (18.6%) contained defects, which create a high probability of breakdown,
- 11 insulators (25.6%) had defects which cause an increased risk of breakdown,
- 24 insulators (55.8%) contained no detectable defects.

However, it should be emphasized that in the whole group of tested insulators a significant distribution of material properties was observed. This results not only from the diversified degree of the material aging process advancement, but first of all from the differences in initial parameters of the electrotechnical porcelain. This fact seriously makes a clear-cut assessment of the tested insulators group difficult. However, it can be stated that mainly as a result of the aging processes, in all the tested objects material does not meet the technical requirements for the 120-type aluminous porcelain. The recorded acoustic parameters as well as the determined values of elasticity modulus of the insulator porcelain proved the above conclusions.

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