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ACOUSTIC METHOD OF ON-SITE EXAMINATION OF CERAMIC LONG-ROD INSULATORS

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This paper presents the new nondestructive ultrasonic method for investigation of long-rod insulators working as the element of station isolating switches. The 110/6kV stations belonged to domestic industrial power engineering. The main aim of the research was to establish a close correlation between the degree of defectiveness of electrotechnical porcelain and parameters of ultrasonic wave propagation and attenuation. In addition, the causes of breakage of insulator SWZPAK-110 from the year 1975 were ascertained. This ceramic element underwent detailed structural and comparative acoustic measurements. The experimental investigations were performed using a specially designed and constructed measuring equipment. Besides founding the original technological and also direct causes of breakage of the insulator mentioned above, the most significant achievement of the work was elaboration of the methodology of ultrasonic measurements applied directly to objects in exploitation. The presented method was used for the analysis of quality of the group of 43 insulators after long-term exploitation on isolating switches.

Key words: ultrasonic measurement, ceramic insulator, electrotechnical porcelain, microstructure.

1. THE BASIS OF ULTRASONIC MEASUREMENTS OF INSULATOR CERAMICS

Suspension insulators as well as station-post insulators, belong to the group of especially important elements of the over-head transmission lines. This particularly concerns the ceramic long-rod insulators. However, these constructions are resistant to electric breakdowns, but at the same time mechanically fractureable. This means that in case of technological errors created during production, 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 which the material has undergone, is encoded in the structure of the porcelain. It especially affects the composition and grain-size distribution of the set of raw mass, rheological 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 they lower the final quality of the products. However, the present requirements concerning the certainty of supply, as well as security of the 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 the postulated period of time without breakdown. To define the notion of reliability it is necessary to specify the range of time $(0, t)$, which indicates the postulated work period of an object. Symbol τ determines the transition moment between efficiency and non-operational states. This transition can take place in the postulated interval $(0, t)$ or outside (t, ∞) – Fig. 1. Therefore, reliability marked by $Q(t)$ denotes the probability of damage beyond the postulated period of work [1]:

$$Q(t) = P(\tau > t). \tag{1.1}$$

Sometimes reliability is known as the probability of success. 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 assure the highest quality of the product, 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.

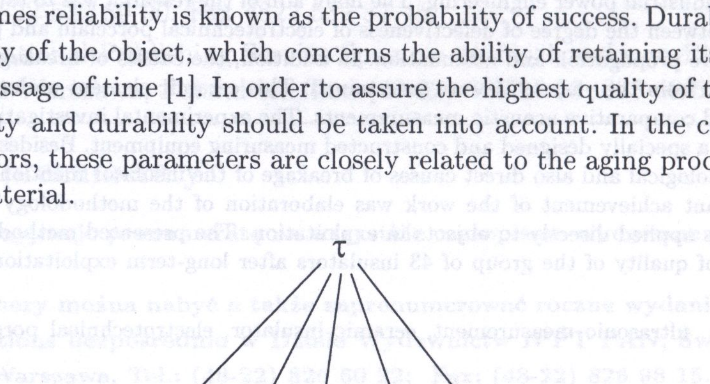

FIG. 1. Graphical description of reliability notion, explained in the text.

The assumed time interval $(0, t)$ of work of the insulator without breakage can be considered as a so-called "lifetime". It is the time necessary for a subcritical crack to achieve the critical length causing breakdown of a ceramic object under the mechanical load. This period can be determined on the basis of complicated mechanical measurements of the ceramic material samples. The experimental technique includes the following quantities [2]:

- Weibull's parameters (m, J) of the probability distribution of short-term mechanical strength. These parameters are obtained from the three-point bending strength tests of standard samples without notches and the displacement rate growth during a test should be constant and equal 1 mm/min. To determine the other parameters, the three-point bending strength test should be made for four groups of samples (at least 30 samples in one group), strained at a constant velocity growth equal to 0.001, 0.01, 0.1 and 1 mm/min.
- Next to bring about as the result, the three parameters (n, B, A) appearing in relations necessary to evaluate the velocities of stress growth $d\sigma/dt$ [MPa/s] and the medians of strength distribution $\sigma_{0.5}$ [MPa] for each group of measured samples.
- The critical value of stress intensity factor K_{Ic} at the instant of time when the greatest crack starts to grow catastrophically in the material. This coefficient is a material constant and can be an estimate of material toughness to a brittle fracture process under tensile load. The K_{Ic} value can be determined using the Vickers indentation method or three-point bending of standard notched samples.

In the following work, in order to evaluate the quality of a group of post insulators, which have been exploited 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 [3].

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 recording the reflection from the boundary of heterogeneity. If the discontinuity appears to be a gas cavity or a gap, generally, 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 methods of quality control.

Another important application of ultrasonic technique is a relatively simple possibility of calculating the dynamic values of elasticity moduli. The most important quantity is the 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 velocity c_T.

Measuring both velocities, and even the value c_L only (usually $c_T \approx 0.6c_L$), at a known density of the ceramic material, the value of Young's modulus and Poisson's ratio can be determined from the relations [4, 5]:

$$E = \rho c_T^2 \left(3c_L^2 - 4c_T^2\right) / \left(c_L^2 - c_T^2\right), \tag{1.2}$$

$$\nu = \left(c_L^2 - 2c_T^2\right) / 2\left(c_L^2 - c_T^2\right). \tag{1.3}$$

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

$$E = E_0 \exp(-kp) \tag{1.4}$$

and

$$E = E_0(1 - k'p). \tag{1.5}$$

The porosity affects the modulus of elasticity of the material and at the same time, changes the velocity of ultrasonic wave propagation. The dependence of c_L on the porosity of material (presented in percents) was determined basing on the method, which replaces the medium filled with inclusions with an equivalent continuous medium having effective moduli given by MacKenzie [6]. It was proven that the velocity of ultrasonic wave propagation decreases linearly in the wide range of porosity values from 2 to 15% with the growth of this parameter [7]. For various materials only a displacement of straight lines in linear relation to each other, as well as small changes in slope are observed. Figure 2 presents examples of experimental dependences $c_L = f(p)$, which the authors determined for electrotechnical porcelain of the older type. The above dependences enable examination 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 [8, 9]. These results however, as expertises, have not been published. Due to technical difficulties, only the velocity of longitudinal wave propagation was measured using the defectoscope. The authors were induced to apply 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 measuring the impulse path and the time of its crossing through the diameter of the insulator, the unit enables recording of the ultrasonic wave attenuation value. This is a very significant parameter, which above all allows to evaluate the extent of the aging processes in ceramic material. Lowering and the distortion of the signal amplitudes are a result of energy dissipation. These phenomena are connected with absorption and scattering processes. Absorption is caused by the thermal conductivity and radiation, as well as by molecular relaxation.

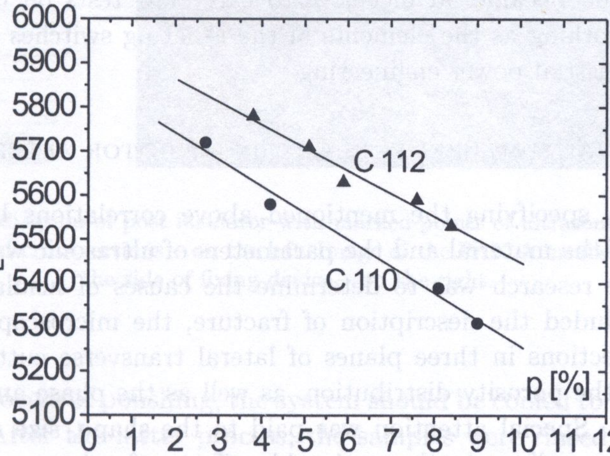

FIG. 2. Dependence of velocity of the longitudinal ultrasonic waves propagation versus porosity, determined experimentally for quartz porcelain (C 110) produced in Poland, as well as cristobalite porcelain (C 112) produced in the former GDR.

The scattering processes, including diffraction, are of basic importance in the case of multiphase materials like aluminosilicate ceramics. 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 a network of cracks. By measuring the decrese 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 an analogous material in laboratory conditions, were supposed to be made in order to conduct acoustic measurements of insulators in exploitation. The influence of the presence of various structural defects on 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 [10], as well as a number of insulator core and shed samples, taken from insulators of the same type made in the 1970s, were used in the detailed structural tests. A complex ultrasonic and structural testing of the SWZPAK-110 insulator from 1975, which represented the investigated group of objects, was especially significant and verified the earlier determined correlations. The breakdown of the insulator in the year 2000 became an incentive to carry out tests on the major group of insulators working as the elements of the isolating switches of the 110/6 kV stations of industrial power engineering.

2. Structural measurements of the insulator after breakdown

Apart from specifying the mentioned above correlations between the microstructure of the material and the parameters of ultrasonic wave propagation, the aim of the research was to determine the causes of insulator breakdown. 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 the pores, as well as to the 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 PAK A, in several places. On the basis of ultrasonic measurements, presented in Table 1, the presence of the defected area was detected only in the upper part of the insulator. It extended from the place of breakage under the upper fixing device – the measuring point labeled 0, up to the third shed. Therefore, a decision to perform three lateral cross-sections of the core was taken: right under the fracture in the point labeled 0, in the point labeled 1 – between the first and the second shed and between the third and fourth shed – the point labeled 3, where structural defects were not found anymore – Fig. 3. The microsections were prepared following a standard procedure described in professional literature, for example [11]. The surfaces of samples assigned for structural investigations were ground using the special carborundum powders of granulation below 20 μm. The layers damaged in consequence of the grinding process were etched in 15% water solution of hydrogen fluoride acid. After the etching process, layers were polished in the colloidal solution of silica of granulation about 90 nm, in the presence of natrium chlorate (I) and stabilized weakly alkaline reaction.

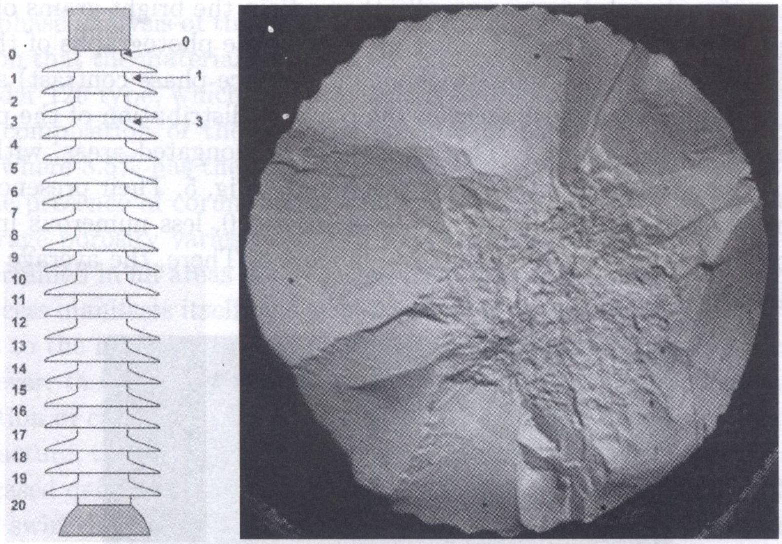

FIG. 3. Schematic diagram of post insulator with marked points of ultrasonic measurements and places of the rod cross-sections – on the left. Image of the PAK A insulator fracture from the side of fixing device – on the right.

During the process of polishing, the system should be cooled to a temperature of about 15°C. After the latter process, the 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 magnification from 50 to 500.

Figure 3 presents an 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 of a low mechanical resistance of the material, indicating an advancement of the aging processes. The arrangement of furrows clearly reveals that the defected central area was the source of cracks and their catastrophic growth.

In the image of the microsection on the level labeled 0, directly below this area, characteristic circular cracks – Fig. 4, as well as a high – up to 14% porosity in the greater part can be observed. Special attention should be focused on the great number of small micro-cracks, which are quite regularly distributed in the volume of material, however usually they adjoin the bright grains of quartz. They are the result of advanced aging processes. The photographs of the material performed in polarized light (without interference-phase contrast) show the presence of significant disturbances in the porosity distribution of the porcelain on the levels labeled 0 and 1. The appearance of elongated areas, with a high porosity and inclusions forming strips was found – Fig. 5. Their presence, which uncover mass twirl, is distinct on the level labeled 0, less numerous in area 1, and it absolutely disappears on the level labeled 3. There, the average porosity also goes down to 3.1%.

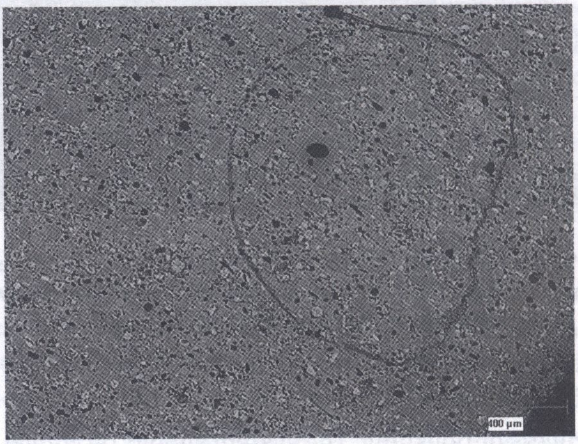

FIG. 4. Image of the central part of the rod on the level labeled 0, in magnification 50 ×. Photograph with interference-phase contrast. Curved cracks and high porosity are visible.

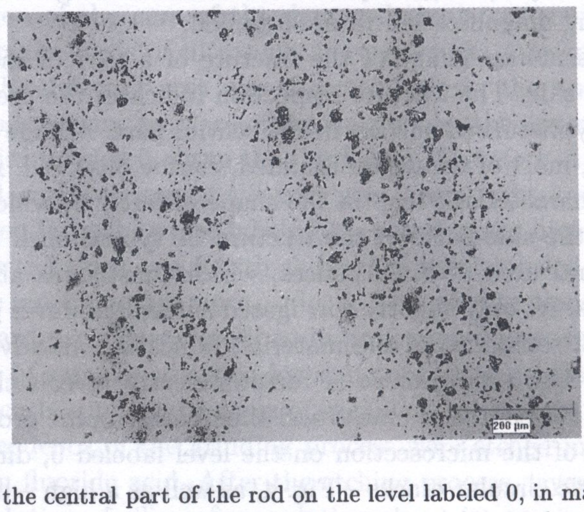

FIG. 5. Image of the central part of the rod on the level labeled 0, in magnification 100 ×. Photograph performed in polarized light. Characteristic elongated strips of defective structure are present.

The phase analysis of the PAK A insulator material allowed to formulate the conclusion that the material corresponds to the typical electrotechnical porcelain of the older 120 type, which is characterized by an 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 feature, that was ascertained in all areas of the 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 also show 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 the 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 the defects. This fault, which belongs to the textural ones, is often referred to as the "mass swirl". The twist of the material texture can be observed in semi-micro scale as well – Fig. 6. 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 every few months period. Apart from these switchovers, the insulator standing on the isolating switch was practically not subjected to any mechanical loads.

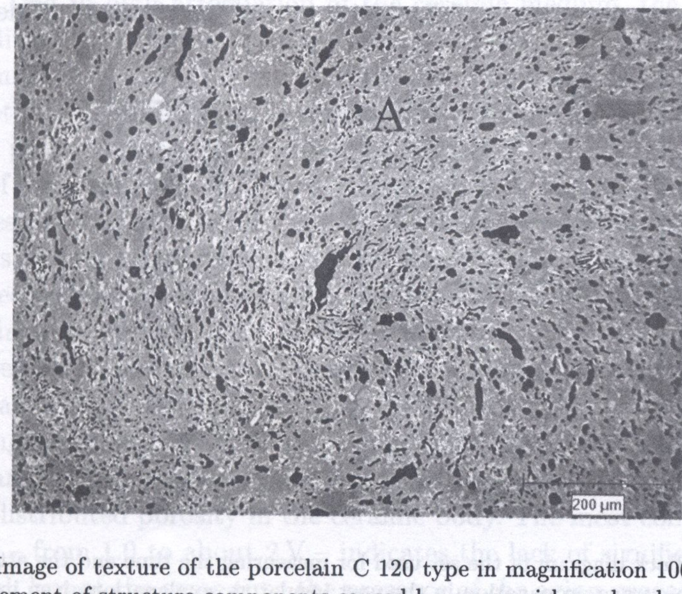

FIG. 6. Image of texture of the porcelain C 120 type in magnification 100 ×. Spiral placement of structure components caused by mass swirl can be observed.

3. Equipment constructed for ultrasonic testing of insulators

Ultrasonic measurements of the post insulators chosen for the research were carried out using a specially constructed apparatus. The measuring set was adapted 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 of 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 of 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 IFTR PAS. The transversal 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 the transversal waves transducers of smaller dimensions. In view of the geometrical configuration of the intershed segments of the insulator core, 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 deformed to a degree that did not allow a precise registration of neither the time of propagation, nor the ultrasonic wave attenuation. The measuring set has been presented in Fig. 7. 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.

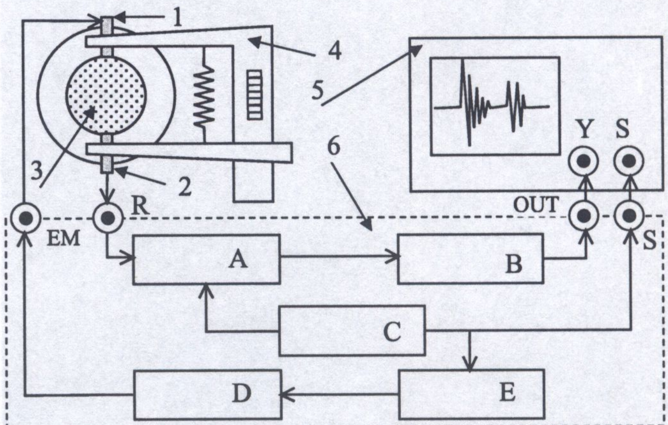

Fig. 7. Block diagram of the set used for measuring the time and the attenuation of ultrasonic wave propagation in the post insulators; explanation given in the text.

This mechanical-electronic construction allows a coaxial and repeatable acoustic coupling with the post insulator being tested, and also a precise simultaneous measurement of the wave propagation path (insulator diameter).

The ultrasonic transducers are operated from the sending-receiving module – number 6. The impulse which activates the transmitting probe is shaped in the key impulse generator E and after strengthening 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 is passed 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.

4. Ultrasonic measurements of insulators at the exploitation place

Acoustic tests of insulator switches were performed using the apparatus described in Sec. 3. The measurement error caused by the shape of the intershed segments of the insulator cores, as well as due to the evaluation of the impulse distance covered, was comparatively small. Its limit value was ± 0.6%. The velocity of ultrasonic wave propagation was determined with an accuracy of at least ± 30 m/s. Due to 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 the signal amplitude in volts. The obtained value is inversely proportional to the medium attenuation.

Series of comparative structural and acoustic tests were performed on porcelain samples, as well on insulator cores (the formerly described PAK A among them). This allowed the determination of accurate correlation between the degree of defectiveness in the ceramic body and the signal amplitude, measured with a minimal accuracy ± 0.1 V on the oscilloscope screen. The high amplitude values – over 2.2 V, indicate a low degree of material aging apart from the lack of structural defects. The values below 1 V are not only the result of the advanced aging processes, but most of all they reveal the presence of faults such as cracks, delaminations or areas characterized by a released texture and a high, no uniformly distributed porosity in the ceramic body. The most common range of amplitudes – from 1.0 to about 2 V – indicates the lack of significant defects of the material, but at the same time the presence of the aging processes at various stages of advancement. This dependence is confirmed by the relatively low values of ultrasonic wave velocities, which correspond in most cases to the values typical for the quartz porcelain C 110 – Fig. 2, not the aluminous porcelain of the 120 type.

The procedure included measurements done at consecutive points between the sheds as well as under the upper and above the lower fixing devices of each insulator. The measurement points were labeled with the numbers beginning from the top – Fig. 3. 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 the insulator, which was marked PAK A, after breakdown; its structural investigation was described in Sec. 2. In the measuring point labeled 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 labeled 1 and 2 – a below 1 V amplitude – was confirmed by structural investigations.

Table 1. The results of ultrasonic measurements of the insulator (marked 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	<u>0.4</u>	12	5640	1.2
2	5700	<u>0.8</u>	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			

Together with the PAK A insulator, whose breakdown led to the decision to perform the 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 110/6 kV stations in the 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 at the production process stage (usually forming and firing), causes a serious decrease of 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, being a result of, among other, a higher porosity, heterogeneity in the phase distribution, as well as the presence of the areas of residual stresses. Such defects cause an increased probability of breakdown. The remaining 24 insulators (including 3 reserve insulators) showed a quite homogeneous structure, which did 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 longitudinal and transversal ultrasonic waves, as well as the known density of the porcelain, Young's elasticity modulus of the material was calculated, using the dependence (2.1). The obtained average value 68 ± 2 GPa is compatible with the parameters of the quartz material 110 type and does not meet the requirements for the aluminous porcelain of the 120 type – equal at least to 80 GPa [12]. Attention should be paid to a significant dispersion of the modulus value for the whole group of 43 insulators. The modulus is contained within the range from 62 to 76 GPa. This proves the occurrence of an advanced aging processes in the material. Such a substantial dispersion is caused however not only by the varying degree of material aging, but most 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 create 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 or any heterogeneities, that 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 – 3.3

5. Final comments

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.

As a result of comparative investigations of the microscopic structural analysis, as well as the ultrasonic tests performed on samples and defected insulators, close correlation between the microstructure of the electrotechnical porcelain and parameters of ultrasonic waves propagation and attenuation was established. The obtained relations allowed a confirmation of the reliability of the results. A full usefulness of the built equipment and the methodology of ultrasonic measurements applied to nondestructive exploitation tests on the insulators from isolating switches were stated.

On the basis of the results of propagation parameter measurements, as well as the measurements of ultrasonic wave attenuation parameters for 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.

Figure 8 presents the quality classification of investigated insulators versus the year of production. However, it should be emphasized that in the whole

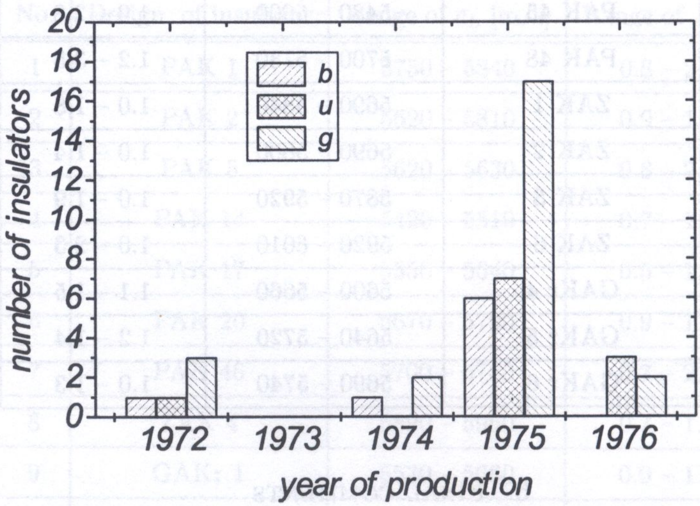

FIG. 8. Quality classification of the group of 43 insulators after ultrasonic measurements. The symbol **b** denotes insulators with defects creating high probability of breakdown; **u** – with an increased possibility o breakage; **g** – without detectable defects.

group of the tested insulators a significant dispersion of material properties was observed. This results not only from the diversified degree of the material aging process advancement, but most of all from the differences in initial parameters of the electrotechnical porcelain. This fact seriously makes a clear-cut assessment of the tested insulators difficult. However, it can be stated that mainly as a result of the aging processes, in all the tested objects the material does not meet the technical requirements for the 120-type aluminous porcelain. The recorded acoustic parameters, as well as the determined elasticity modulus values of the insulator porcelain attempt to prove the above stated conclusions. On the basis of measurements similar advancement of ageing processes in exploited insulators material and from reserve ones was ascertained.

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