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STUDY OF STRUCTURAL DEGRADATION OF CERAMIC MATERIAL OF INSULATORS IN LONG TERM OPERATION

BADANIE DEGRADACJI CERAMICZNEGO MATERIAŁU IZOLATORÓW PO WIELOLETNIEJ EKSPLOATACJI

The paper presents ultrasonic method of investigations of long-rod line and post insulators, operated on 110/6 kV power engineering stations. Acoustic measurements were performed directly in place of exploitation for three groups of domestic insulators. They concerned 16 line insulators LP 75/17 from 1970s; 56 post insulators SWZPAK-110 from 1970s and 47 post insulators SWZP4-110/550 from 1980s. Worked out measurement technique enabled assessment of structure degradation degree without troublesome and expensive removal of insulators from operation. Nondestructive measurements were carried out using special apparatus, which was designed and constructed mainly for outdoor testing of operated objects and results were compared with non operated material. There was presented technology of fabrication of ceramic insulators, typical structure of their material and factors influencing operational durability. Experimental method of assessment of insulator material "life time" was described in brief.

All insulators were made of electrotechnical porcelain C 120 kind. There were performed detailed microscopic investigation of the material of operated line and post insulators. The results were compared with properties of the new porcelain. There was established correlation between the degree of the material degradation and the parameters of ultrasonic wave propagation and attenuation. Additionally there were used results of acoustic emission investigation of the material samples, which were subjected to slowly increasing compressive stress. On the basis of the study, advancement of ageing degradation of the material and the quality of tested insulators were assessed.

It was stated that advancement of aging effects in the material of exploited post insulators and non-operated ones, taken from station reserve, was approximately the same. External operational stresses seriously affected aging of porcelain only in case of the rods of line insulators. Significantly lower quality of post insulators, made in time of economic crisis in 1980s, was established. On the ground of performed study, earlier researches and data from exploitation there was ascertained operational durability as not exceeding 35 years. It concerns insulators made from C 120 kind material, which does not contain significant inhomogeneities or technological defects.

Keywords: electrotechical porcelain, long-rod insulators, aging processes, non-destructive ultrasonic testing, microscopic analysis

W pracy przedstawione zostały efekty degradacji materiału izolatorów liniowych i wsporczych, które od wielu lat eksploatowane były na stacjach energetycznych 110/6 kV. Pomiary akustyczne przeprowadzone zostały bezpośrednio w eksploatacji na trzech grupach krajowych izolatorów. Obejmowały one 16 izolatorów liniowych LP 75/17 z lat 1970-tych, 56 izolatorów wsporczych SWZPAK-110 z tego samego okresu oraz 47 izolatorów wsporczych SWZP4-110/550 z lat 1980-tych. Opracowana technika pomiarowa pozwala na ocenę stanu tworzywa izolatorowego bez uciążliwego i kosztownego zdejmowania obiektów z linii. Pomiary te mają charakter nieniszczący i wymagają jedynie krótkotrwałego wyłączenia napięcia z niewielkich odcinków sieci. Badania pracujących obiektów przeprowadzone zostały z wykorzystaniem specjalnego układu pomiarowego i porównane z parametrami nie eksploatowanego materiału. Przedstawiona została technologia produkcji izolatorów, budowa ich tworzywa oraz czynniki mające wpływ na strukturę materiału i jego trwałość eksploatacyjną. Opisano w zarysie eksperymentalną metodę oceny „czasu życia" tworzywa izolatorów.

Wszystkie badane w ramach pracy izolatory wykonane były z porcelany elektrotechnicznej rodzaju C 120. Przedstawiono wyniki badań mikroskopowych i ultradźwiękowych typowego tworzywa nowego oraz izolatorów liniowych i wsporczych po dłuższym okresie eksploatacji. Wykorzystano ponadto wnioski uzyskane w wyniku badań próbek porcelany C 120 metodą wolno narastającego naprężenia ściskającego z jednoczesnym monitorowaniem efektów degradacji techniką emisji akustycznej. Stwierdzono, że stopień zaawansowania procesów starzeniowych w porcelanie izolatorów wsporczych, które były w eksploatacji oraz pochodzących z rezerwy stacyjnej – pobranych z magazynów, był bardzo zbliżony. Obciążenia eksploatacyjne w poważnym

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stopniu wpłynęły jedynie na stan materiału pni izolatorów liniowych. Zaobserwowano wyraźnie niższą jakość izolatorów wsporczych z okresu kryzysowego lat 1980-tych. Obserwacje mikroskopowe pozwoliły na rozpoznanie etapów rozwoju procesów degradacji starzeniowej. Na podstawie przeprowadzonych badań, danych eksploatacyjnych oraz wcześniejszych prac określono trwałość eksploatacyjną izolatorów wykonanych z porcelany elektrotechnicznej rodzaju C 120. Nie przekracza ona 35 lat, pod warunkiem że izolator nie zawiera poważniejszych niejednorodności lub defektów technologicznych.

1. Introduction

Line insulators as well as post ones, belong to the group of especially important elements of the over-head transmission and distribution power lines. This concerns particularly the ceramic long-rod insulators. However, these constructions are resistant to electric breakdowns, but at the same time are mechanically fractureable. This means that in case of technological errors created during production, as well as due to long period of exploitation – when aging processes develop in the material, the probability of damage rises considerably.

Ceramics, in particular electrotechnical porcelain, is considered to be material 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 concerns the composition and grain-size distribution of raw mass, rheological flows during formation, as well as drying and firing (sintering) parameters. All technological inaccuracies formed during any stage of production can not be corrected anymore, and they worse final quality of the products. Technology of fabrication has essential influence on operational durability of power net insulators. Aluminosilicate ceramic materials, electrotechnical porcelain among them, are inhomogeneous in microscopic scale. This feature influences the parameters, especially mechanical strength, its dispersion and structural effects of aging degradation of the material [1,2].

Traditional and the most common course of production of long rod insulators consists of many stages [1,3]: selection of components, control and preparation of raw materials (weighing and milling), plasticization of raw material (mixing with water, filtration, seasoning), formation (deairing, pug pulling and profile turning), drying, glazing (marking), firing (sintering), final treatment (cutting and grinding), montage of fitting devices (assembling), tests of the object.

During this complicated and long lasting technological process different faults can be introduced into ceramic body [3]. The most important are:

– Alien inclusions, which can be brought in during preparation of components, plasticization or formation. Inclusions act as centers of internal stresses concentration. Broad zones of brittle cracks grow around them in the process of time. These zones are distinctly visible on fractures of insulator rods, as flat area called "mirror". This type of faults was one of the most important reasons of breakage of domestic line insulators LP 75/17 type.

– Textural defects, being consequence of improper work of vacuum deairing pug mills or inhomogeneous raw material composition (e.g. small drops of ceramic oil). During forming process disturbed texture can be introduced into material structure. As the effect strong internal stresses are present in the material. Relaxation of these stresses results in forming elongated, often round cracks or areas of elevated porosity as well as so called "dark bands". Textural defects were found both in line and post insulators of different type.

– Fissures, especially in the lowest part of post insulators of older generation, are the other kind of fault. These defects are result of irregularities of firing process. Fissures were the reason of numerous breakdowns of post insulators, especially SWZPAK-110 type.

Contemporary requirements concerning the certainty of supply, as well as security of exploitation of electrical power lines and stations, require using insulators of the highest durability and reliability. Reliability is defined as the probability of the object to work during 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 efficient and non-operational states. 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 [4]: .

$$Q_{(t)} = P(\tau > t). \tag{1}$$

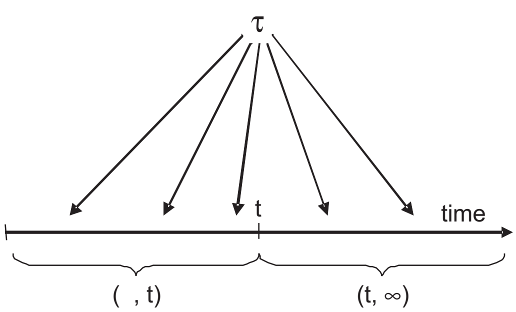

Fig. 1. Graphical description of reliability notion, explained in the text

Sometimes reliability is named 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 [4]. 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. The assumed time interval (0, t) of operation of the insulator without breakage can be considered as a so-called "life time". This is period of time is necessary for a subcritical crack to achieve the critical length, causing breakdown of a ceramic object under mechanical load. This period can be determined on the basis of complicated mechanical measurements of the ceramic material samples [5].

However, composition of raw aluminous material C 120 kind was worked out nearly 50 years ago, it is actual up to now. Composition of the material of investigated insulators was typical and comprised: kaolins 34 ÷ 36 %, feldspar fluxes 23 ÷ 26 %, refractory plastic clays 20 ÷ 23 %, metallurgical alumina 20 ÷ 25 %. Material after firing consisted of over 30 % of mullite in the form of precipitations, 20 ÷ 30 % of quartz grains, few percent of pores and the rest of glassy matrix – about 40 %. Contents of corundum can be omitted (below 1 %). Typical structure of C 120 porcelain material was presented in Fig. 2. Structure has suitable degree of sintering, homogeneity in micro-scale is satisfactory. Considerable part of quartz grains was however weakly bounded with matrix and partly separated from glassy phase. Total content of quartz grains in structure ranges from 19.8 to 23.9 %. Average size of grains equals to 29.6±12.4 μm. Precipitations of mullite are usually big – about 30 μm and randomly distributed. Porosity of the material is correct and does not overstep 2.0 %.

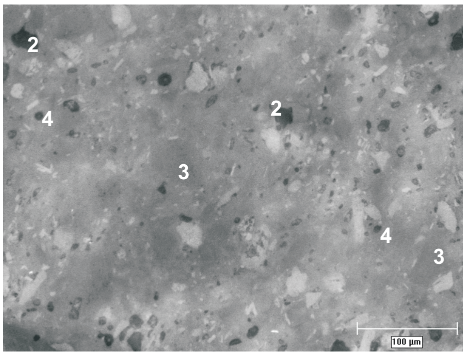

Fig. 2. Image of typical C 120 material structure, magnification 200×. Light fields of irregular shape represent quartz grains (19 %)-1, crushed out grains occupy 4 % (bigger black areas)-2, over 30 % of surface take up extensive dark areas of mullite precipitates-3. Porosity, illustrated by round, small, black spaces, take up below 1 %-4. Glassy matrix constitutes about 45 % of aluminous porcelain

There were performed ultrasonic measurements on the samples of the material, which structure was described above. Velocity of longitudinal waves propagation c_L was equal to 6360±20 m/s, transverse waves velocity equaled 3760±30 m/s. Taking into account density of the material — 2.53 g/cm^3, calculated Young's modulus amounted to 88±1 GPa. Amplitude damping coefficient α did not exceed 0.4 dB/cm.

On the material C 120 kind the authors performed mechanical-acoustic study of degradation processes [6]. Close similarity has been observed between the structural effects of slowly increasing compressive stress applied to the material sample and degradation processes, being the result of many years of exploitation on power line. The first stage of the material degradation occurs as a result of internal stresses existing in the ceramic body, mainly in the micro scale, created during the manufacturing processes. The process of the preliminary defects increase has a relatively low threshold energy and can develop already at lower stresses of acting on the sample. The process of their propagation under exploitation conditions, however, is not rapid and takes a few years. This stage corresponds to destruction of quartz grains and the beginnings of mullite phase damage – Fig. 3. The second effect takes place only in the central part of compressed samples, where the highest concentration of stress is present. Development of such effects in the material of working insulator, under operational stresses – static and especially dynamic - takes place in period of between 10 and 20 years.

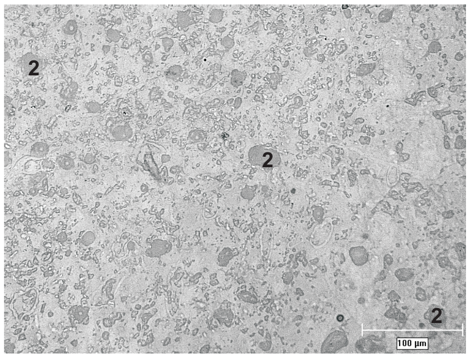

Fig. 3. Image of the structure of aluminous material after the preliminary stage of compressive stresses, magnified 200×. There appear the numerous separations of quartz grains and less often mullite precipitates from the matrix-1. Big black places (8 - 10 %) represent damaged and crushed out grains of quartz-2

The second stage of the structural degradation corresponds to long lasting development of subcritical defects. The microcracks, initiated at the boundaries of quartz grains or incidentally besides mullite precipitates are propagated in glassy matrix of the porcelain. This is simplified by densely distributed, cracked quartz grains. Subcritical stage of degradation is closely connected with homogeneity of the sample structure in micro and semi-macro scales. Both stages are strongly influenced by contents, size and spatial distribution of quartz grains as well mullite precipitates. During last – critical stage single cracks join together gradually and after branching out they lead to formation network of cracks (Fig. 4) and finally the breakage of the insulator.

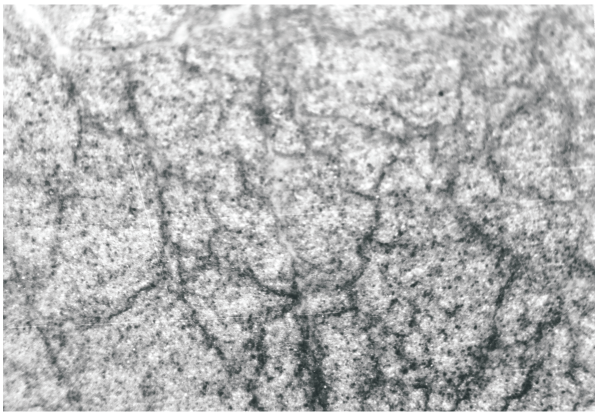

Fig. 4. Image of the structure of broken insulator SWZPAK-110 (1976) close to fracture place, magnification 20×. Process of degradation was accelerated by internal stresses resulted from textural defect

2. "Life time" and operational durability of ceramic insulators

The assumed time interval of work of the insulator without breakage (0, t) can be considered as a so-called "life time". 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, cut off from the insulator rod. The experimental technique includes the following quantities [7]:

– 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 small 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 σ/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.

Domestic insulators as well as imported ones, made of C 120 kind material were characterized by high failure frequency. Breakdowns were the consequence of relatively serious technological defects [8]. However, the other important factor was comparatively low resistance of the material to degradation effects, especially to cracks propagation as a result of internal stresses. These stresses were connected with high contents of quartz phase (primarily big plate grains) as well as technological inaccuracies or faults, described above. Serious defects caused breakdowns after a few years of exploitation, smaller flaws – after over ten years. Damages took place usually between November and March, when day and night amplitudes of temperature were the highest. As it was noticed, there is more important influence of period of exploitation than working load. This fact proofs role of long term aging processes, which proceed in particular in the neighborhood of faults and areas of increased internal stresses. Nondestructive ultrasonic method is specially useful to find these kind of structural flaws.

Operational durability – "life time" of C 120 kind material is all the time open problem. This is a consequence of varied properties of the material of older generation connected with non reproducible technological parameters. The other factor is occurrence of defects of diverse intensity. In the Institute of Fundamental Technological Research PAS in 1980s there were performed investigation of ceramic insulator materials of different kind [9]. This research demonstrated considerable dispersion of the materials parameters. So, unequivocal assessment of "life time" value was not possible.

As a part of work concerning application of modern C 130 kind material to produce insulators of the highest quality and reliability, there were performed complex comparative tests of aluminous porcelains, using different methods [10]. Complete procedure aimed to obtain "life time" of the material was performed only for C 130 kind porcelain. Nevertheless, on the basis of operational data and performed tests, especially of the mechanical strength of samples and insulators, there was roughly estimated operational durability of modern C 120 kind material. "Life time" of insulators made of this kind porcelain was near 35 years.

In this work examination concerned the groups of line and post insulators, which have been exploited on the power stations for 20 – 30 years long period. The ultrasonic method, as well as comparative research of microscopic structural analysis were used. The aim of the work was evaluation of the material state and possibilities of further exploitation.

3. Acoustic measurements

The nondestructive acoustic technique was in Poland applied to the insulator testing already in the early 1950s [11]. However, such tests at place of operation were introduced by the authors in the late 1990s. The acoustic method is based on the dependence of the parameters of waves' propagation on the properties of the medium, where the waves propagate. In case of a solid body they depend on the elastic properties of the material, as well as on its structural composition. The ultrasonic method has been widely applied in flaw detection. Detecting the discontinuities of the medium is performed by introducing a wave beam into investigated material and then recording its reflection from the boundary. Among possible applications of ultrasonic method, very important is elastometry. On the basis of experimentally determined values of the velocities of longitudinal – c_L and transverse – c_T ultrasonic waves, as well as known material density ρ, it is possible to obtain Young's modulus E and Poisson's ratio ν values [12]:

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

$$\nu = (c_L^2 - 2c_T^2)/2(c_L^2 - c_T^2). \tag{3}$$

One of the most important factors, proving the correctness of the ceramic material structure, is porosity. Porosity contents and its parameters have significant influence on the mechanical and electric properties of the insulator porcelain. This effect can be described by lowering of the elasticity modulus. The porosity changes the elastic Young's modulus of the material, and as a consequence decreases the longitudinal velocity c_L as well as transverse c_T. It was proven that velocities of ultrasonic waves' propagation decrease linearly with the growth of porosity contents [13].

An additional significant ultrasonic parameter, which above all allows evaluating the extent of the aging processes in ceramic material, is attenuation. Lowering and deformation of the signal amplitudes are a result of energy dissipation. This effect is due to the existence of numerous structural heterogeneities, such as micro-cracks, frequently spaced pores, larger crystalline phase precipitations, as well as areas where mechanical stresses appear and especially if the network of cracks is present. Measurement of the decrease of signal amplitudes, after passing through the insulator diameter in subsequent measured points, and observation of signal distortion enables evaluation the homogeneity, as well as the quality and degree of aging of the porcelain in the core. Due to complicated geometry of insulator rod and parameters of the ceramic material, measurements of amplitude attenuation coefficient are often difficult and not reliable. The attenuation of porcelain body can be assessed using indirect method. In such procedure amplitude of the signal passing through the rod diameter is registered. This value can be considered as inversely proportional to the attenuation of the medium. Methodology of ultrasonic measurements of ceramic materials was widely presented in the work [14].

Ultrasonic measurements of the insulators 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 equipment consisted of a set of ultrasonic piezoelectric transducers generating longitudinal and transverse waves, as well as a digital oscilloscope – Tektronix TDS 210 connected with a transmitting – receiving module. The latter was designed 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 transverse waves transducers of a 4.0 MHz frequency could only be used on the segments of rod near the fixing devices, because of an about 20 mm transducer diameter. Due to constructional restrictions it was impossible to make the transverse waves transducers of smaller dimensions. In dependence on the geometrical configuration of the intershed segments of the insulator rod, the measurements could be carried out using the transmission method – with two transducers or more accurate echo method – using only one transmitting-receiving transducer. The scheme of the measuring set has been presented in Fig. 5. 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. This mechanical-electronic construction allows a coaxial and repeatable acoustic coupling with the insulator rod being tested, and also a precise simultaneous measurement of the wave propagation path (insulator diameter).

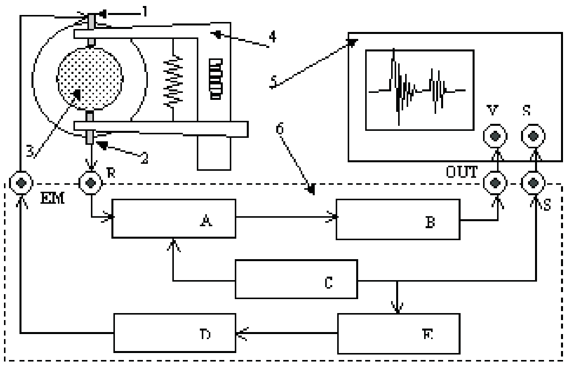

Fig. 5. Block diagram of the set used for measuring the time and the attenuation of ultrasonic wave propagation in the rod of insulators. Two-transducers transmission method is presented. Explanation in text below

The ultrasonic transducers are operated by 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 1. After going through the insulator rod 3, along its diameter the ultrasonic impulse reaches the receiving transducer 2, 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.

The measurement error, caused by the shape of the intershed segments of the insulator rods, as well as due to the evaluation of the passed impulse distance, 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 geometrical restrictions, 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. Accuracy of signal amplitude measurement was equal to ± 0.15 V.

4. Examination of line insulators

The authors investigated the group of domestic 16 LP 75/17 line insulators, made of C 120 kind porcelain in 1970s, which were in operation for about 30 years period. The procedure of ultrasonic measurements included tests done at consecutive points between the sheds, as well as next to both fixing devices of each insulator. In Fig. 6 there is presented diagram of tested line insulator. In Fig. 7 is shown dependence – range of c_L values measured along insulator rod versus average value of c_L for each insulator.

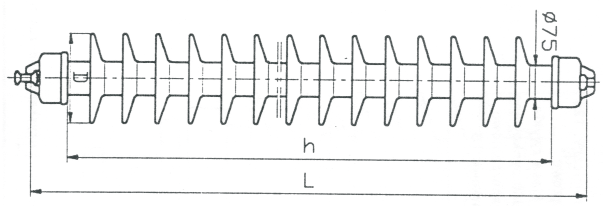

Fig. 6. Technical diagram of LP 75/17 insulator. Length h=895 mm, L=1080 mm, diameter of the rodø=75 mm, diameter of the shed D=175 mm, leakage path – 2100 mm, number of sheds – 17, weight – 28 kg, nominal tensile strength – 100 kN

Results of the ultrasonic measurements, obtained for tested insulators in place of operation, were collected in Table 1 [15]. In the table are put values of the velocity of longitudinal wave propagation c_L, signal amplitude A and calculated on the basis of equation (2) elastic Young modulus E. Density of the porcelain, determined using material of damaged insulators of the same type, was equal to ρ = 2.41 g/cm^3. Due to geometrical limitations, being the consequence of the insulators' rod shape, the measurement of the amplitude attenuation coefficient was difficult. The damping of ceramic body was determined using an indirect method, by registering of the signal amplitude in volts. As it was stated above, signal amplitude (in volts) is inversely proportional to the attenuation of the material of insulator rod in measuring point. The highest value of measured amplitude A about 4.5 V corresponds to attenuation coefficient α below 0.7 dB/cm. Exact recalculation of the all values A to α is not unequivocal.

TABLE 1

Results of the ultrasonic measurements of the group of domestic insulators LP 75/17 after about 30-years operation period

1	c_L [m/s]	5980	5790÷6180	6.5 %
2	A [V]	3.3	2.1÷4.5	73 %
3	E [GPa]	74	69÷79	13.5 %

Relative dispersion = 100 %×(value$_{max}$-value$_{min}$)/value$_{average}$

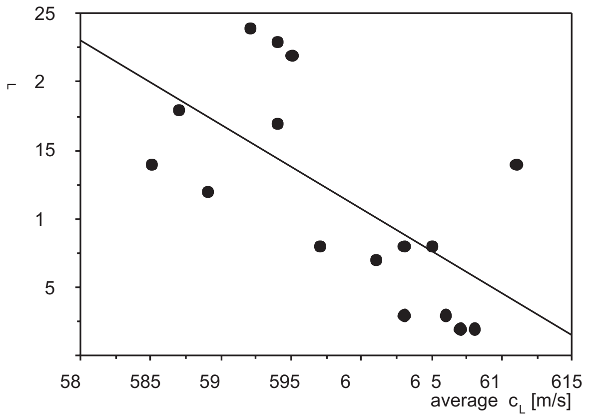

Fig. 7. Dependence of dispersion of velocity of longitudinal wave propagation c_L versus average value of c_L for the group of tested line insulators LP 75/17 from 1970s. Tested insulators can be divided in two groups. First group, upper, on the left – worse and less homogeneous, second, lower on the right – better and more homogeneous

Dispersion of c_L velocity for individual insulators was situated in the range from 20 to 240 m/s. Average value was equal to 120 m/s. Results indicated considerable diversity of the material inhomogeneity along insulator rod in tested group of objects. Dispersion was generally higher for insulators showing lower average c_L value of the material (Fig. 7). Elastic module and mechanical strength of these elements were poorer as well. Significant dispersion of the material parameters (Table 1) and its properties are the consequence of porcelain constitution and determined by raw material composition as well as technological factors. Advanced aging processes additionally amplified effect of dispersion. The presence of meaningful defects was not detected in tested group of insulators. Elements containing such faults must have already been broken.

Tested insulators LP 75/17 were characterized by generally moderate quality and homogeneity of the ceramic material. Constitution of the porcelain was typical for technology used in 1970s. After about 30 years' period of operation porcelain structure of insulators rods underwent advanced aging degradation processes. Degradation concerned quartz grains and in smaller degree glassy matrix as well as mullite precipitates – Fig. 8.

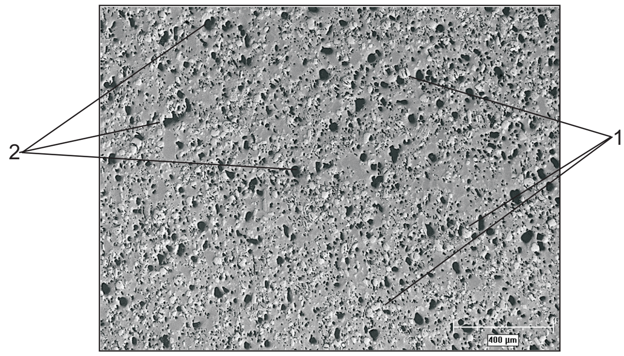

Fig. 8. Typical image of the material structure of LP 75/17 insulator rod from 1974, magnification 50×. Advanced aging processes, concerning primarily quartz phase are present. A lot of microcracks around and inside quartz grains are observable-1. Initial content of quartz – 24.3 %, about 8 % underwent crushing out-2

First of all, aging processes were a consequence of high and diversified contents of quartz phase in the material – between 20 and 37 %, average value 29 %. It was proved during microscopic analysis of the material of 3 selected insulators, which were taken off from operation. Quartz frequently occurred as bigger grains (over 20 μm). This phase was the main source of internal stresses, initiation and growth of cracks in the ceramic body. Almost all of grains were disconnected from matrix. Bigger grains of quartz showed also internal cracks. Significant part of the quartz grains fell out during preparation of the polished sections. Completely destroyed and crushed out quartz grains constituted at an average 8 % in the rod material and below 5 % in case of sheds. In the neighborhood of the quartz grains it was observed great number of small fractures (below 15 μm) and also sub-microscopic cracks, spreading out into the matrix. These effects were particularly intensive in the region of insulator rod - Fig. 8 and almost absent in the material of sheds.

The contents of the mullite phase was in the range 33 - 35 %. Relatively big precipitates of mullite (most often 25 ÷ 40 μm) were usually uniformly located in the material. They were well bounded with matrix and nearly did not contain internal cracks. Advancement of aging processes in mullite phase was much lower than in case of quartz. The corundum phase was present only incidentally as single smaller grains. The contents of pores was between 2.8 and 7.0 % (at an average 4.9 %). Size – below 10 μm – shape and distribution of pores in the ceramic body were acceptable. Porcelain material comprised 40 ÷ 60 % of glassy matrix (at an average 53 %). It was strongly bounded with precipitates of mullite. In neighborhood of the quartz grains small and very small cracks appeared, composing so called 'jet effect'. Microcracks coming out from the quartz particles developed in the stressed insulator and caused decrease of its strength. Material of the sheds contained much less number of fractures. Submicron cracks were present very rarely.

As a consequence of 30-years operation period, electrotechnical porcelain underwent advanced, but diversified aging processes. An essential influence on the degree of advancement of aging process, in case of the insulator rods, exerted static and dynamic operational loads. Relatively smooth surface of fractures of broken insulators gave evidence of low mechanical resistance of the material. Advancement degree of aging processes was to a great extent connected with content, size and spatial distribution of quartz grains. For insulators of higher quartz content, elevated damping - lower amplitude of ultrasonic signals were registered. Comparative structural research revealed not only high number of microcracks, but either areas with great number of crushed out quartz grains and probably parts of mullite precipitates too. Long, not branched cracks, belonging to subcritical effects, were observed infrequently. Subcritical effects of structure degradation, strongly influencing material damping, were registered in the areas of locally disturbed structure - Fig. 9.

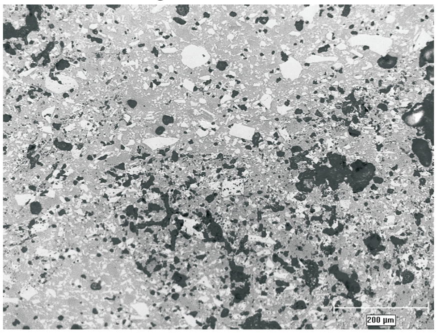

Fig. 9. Region of locally disturbed structure in the rod of insulator LP 75/17 (1973), magnification 100×. Numerous crushed out pieces of structure are visible (black areas)

Existence of all kinds of defects or inhomogeneities intensifies aging process of degradation, especially in case of strain insulators' material. Operational stresses have significant influence on intensity of degradation effect. Different material properties in the areas of rod and sheds confirm this observable fact. External loads result in considerable enlarging of degradation effects in the rods of line insulators. Similar effects the authors registered in case of Danish NORDEN insulators from 1960s. These elements were made from untypical mullite-spinel porcelain, produced in accord with using different technology (isostatic formation, firing in reducing atmosphere). The aging processes in the material of sheds of NORDEN insulators were not advanced and connected only with internal stresses. Degradation of the porcelain of rods was much stronger and mainly resulted from operational stresses.

5. Diagnostics of station post insulators

Besides line insulators, the ultrasonic investigations were also carried out on two groups of post insulators. The first constituted 56 objects SWZPAK-110 type, operated on industrial power engineering stations 110/6 kV [7,16,17]. These insulators, made in Poland in 1972 – 1976, underwent ultrasonic measurements. Tested insulators have been in exploitation for nearly 30 years' period. Measurements of 49 insulators were performed directly on the isolating switches, one was after breakdown. Further 6 objects came from the station reserve and were taken from the storehouse. Main technical parameters of SWZPAK-110 insulators were following: complete length – 1220 mm, length between fixing devices – 1000 mm, diameter of rod – 120 mm, diameter of sheds – 215 mm, leakage path – 2650 mm, number of sheds – 20, weight – 67 kg, nominal bending strength – 4 kN.

Considering geometrical restrictions, length of ultrasonic signal path and relatively high attenuation of the insulator material, it was necessary to perform series of comparative structural and acoustic tests. Such investigation allowed determining correlation between the degree of defectiveness in the ceramic body and amplitude of measured signal. Uncertainty of signal amplitude registration was equal to ± 0.15 V. The high amplitude values – over 2.2 V, indicated better material properties and lack of structural defects. Values below 1 V are not only the result of the advanced aging processes, but most of all, reveal the presence of faults such as cracks, delaminations or areas characterized by released texture and high, non-uniformly distributed porosity in the ceramic body. The most common range of amplitudes – from 1 to about 2 V – indicated lack of significant defects of the material, but at the same time the presence of fairly advanced aging processes. This dependence was confirmed by relatively low values of ultrasonic wave velocities. The experimental procedure included measurements at consecutive points between the sheds as well as under the upper and above the lower fixing devices of each insulator. The same method was used in case of line insulators. Density of the porcelain, determined using material of damaged post insulator was equal to ρ = 2.30 g/cm^3. Results of research of 56 SWZPAK-110 post insulators are presented in Table 2.

It should be emphasized that in the whole group of tested insulators high dispersion of the material properties was recognized. This comes not only from diversified degree of the material aging process advancement, but most of all from the differences of the initial parameters of the electrotechnical porcelain. However, a clear-cut assessment of the tested insulators is difficult, it can be stated that parameters of the material are generally low and significantly worse than in case of line insulators – Table 1.

TABLE 2

Results of ultrasonic measurements of the group of post insulators SWZPAK-110 after about 30-years' operation period

Ordinal Number	Measured Parameter	Average Value	Range of Value	Relative Dispersion
1	c_L [m/s]	5730	5360~6010	11.3 %
2	A [V]	1.7	0.3~3.5	188 %
3	E [GPa]	64.5	57~71	21.7 %

Relative dispersion = 100 %×(value$_{max}$-value$_{min}$)/value$_{average}$

On the basis of measurements there was ascertained similar advancement of ageing processes in the material of exploited insulators and non-operated ones – taken from the station reserve. This unexpectedly means that external – operational stresses had insignificant influence on the ageing effects in the material of post insulators. Due to this fact, properties and structure of the material in the area of rod and sheds of insulators were approximately the same. Typical structure of the material of exploited post insulator SWZPAK-110 was presented in Fig 10.

The phase analysis of broken SWZPAK-110 insulator material allowed formulating the conclusion that the material corresponds to typical electrotechnical porcelain of C 120 kind, of the older type. Material is characterized by an acceptable homogeneity. Average composition of the porcelain included about 24% of quartz, but 3 - 5 % of quartz phase was damaged and crushed out. The percentage of mullite phase exceeded 32 %. Precipitations of mullite had typical form and size of the order of tens of micrometers. Only 8.5 % was outside of distinct precipitations. The glassy matrix contents was about 40 %. The presence of corundum crystals in the ceramic body was not detected. Average porosity varied from typical value equal to 3 %, up to 9 ~ 12 % in defected areas – Fig. 11. An important material feature that was ascertained in all areas of the tested insulator – in the rod and sheds – is fairly advanced aging process. This effect is the consequence of internal quartz stresses in the material and almost not connected with operational load.

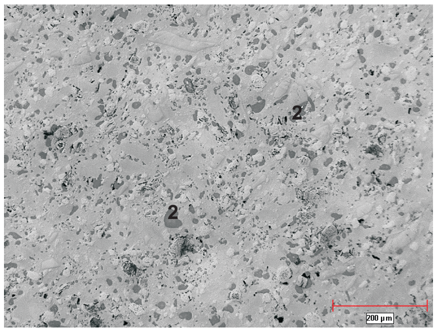

Fig. 10. Typical image of the material structure of the insulator SWZPAK-110 rod, produced in 1975, magnification 200×. Medium advanced ageing processes – numerous microcracks inside and around grains of quart, as well as crushed out grains-2 are visible. Degradation of the material of insulator sheds is comparable

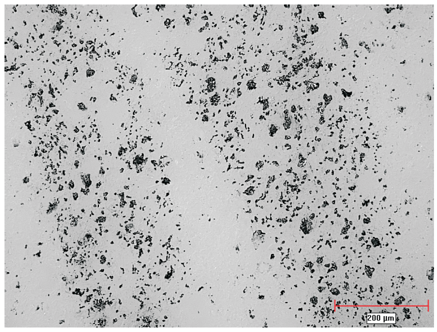

Fig. 11. Defective porosity taking form of elongated strips in the material of broken post insulator. Result of textural fault. Such structure is characterized by increased damping of ultrasonic waves. Amplitudes of passing signals were lower than 0.5 V. Image in polarized light, magnification 100×

Stage of advancement of degradation processes can be determined as advanced preliminary or early subcritical. Degradation concerns quartz phase and partly mullite precipitates. Cracks in the matrix are small and not numerous. Aging effects are similar as in case of the sheds of line insulators. "Jet effect" was almost absent, such as longer subcritical cracks propagating in glassy matrix. Degradation of mullite phase is present almost to small extend.

Part of tested insulators included regions, of frequently strongly elevated damping of ultrasonic waves. This resulted from the presence of technological defects, most often textural, in the material structure. It was confirmed by detailed structural study of several SWZPAK-110 insulators porcelain. These objects underwent breakdown in consequence of serious disturbance of raw material in a vacuum deairing pug mill – Fig. 11. In defected regions are present high internal stresses, resulting in amplifying degradation processes. Amplitude of passing ultrasonic signal is than decreased below 1 V or even 0.5 V. On the basis of the results of measurements of ultrasonic waves' propagation and their attenuation for a group of 56 SWZPAK-110 insulators from 1970s, the following notions were ascertained:

- 8 insulators (14.3 %) contained defects, which create high probability of breakdown, one of them underwent breakage;
- 11 insulators (19.6 %) had defects, which cause increased risk of breakdown;
- 37 insulators (66.1 %) did not contain detectable defects.

Apart from post insulators SWZPAK-110 from 1970s, there was tested plentiful group of domestic post insulators SWZP4-110/550 from years 1982 – 1987 [16,17]. Technical parameters of post insulators from both groups were nearly the same. Important problem was to compare quality and aging processes development of insulator porcelain of these two groups. It could be expected that state of the material of younger elements will be better. They were in operation about 10 years shorter then ones from 1970s.

There were investigated 47 insulators SWZP4-110/550. Collection of 43 elements was tested directly in operation, 4 objects came from the station reserve and were taken from the storehouse. Method of testing was the same as in case of SWZPAK-110 insulators. Results of ultrasonic study were presented in Table 3.

TABLE 3

Results of the ultrasonic measurements of the group of domestic post insulators SWZP4-110/550 after about 20-years operation period

Ordinal Number	Measured Parameter	Average Value	Range of Value	Relative Dispersion
1	c_L [m/s]	5580	5410~5840	7.7 %
2	A [V]	1.4	0.4~3.4	214 %
3	E [GPa]	61.5	58~67.5	15.4 %

Relative dispersion = 100 %×(value$_{max}$-value$_{min}$) /value$_{average}$

Results of measurements presented in table 3 revealed surprisingly lower parameters of the material of SWZP4 insulators in comparison to older elements from 1970s (table 2). Average value of c_L velocity was 150 m/s and Young modulus E – 3 GPa lower than in case of SWZPAK-110 elements. However, relative dispersion of these parameters was a few percent lower. Number of internal defects and regions of disturbed structure was higher. In tested group of 47 insulators SWZP4 – 19 objects (40.4 %) contained considerable defects, 9 (19.2 %) elements had smaller faults and 19 did not comprise detectable defects. Comparative tests performed on the pieces of material, cut off from the rods of insulators, enabled partial correlation between A – amplitude of ultrasonic signal and α – attenuation coefficient. Amplitude exceeding 3 V corresponds to α coefficient on the level 0.4 – 0.6 dB/cm. Average values – about 1.5 V suit over 1 dB/cm.

To explain lowering quality of SWZP4 insulators, exploited for shorter period, there were performed microscopic investigations of three elements of this type [17]. Structural study revealed contents of quartz phase between 21 and 23 % in the form of grains, most commonly sized 10 ~ 50 μm. About 1/4 part of quartz grains (4 - 6 %) was damaged and crushed out during preparation of surface for microscopic study. Best part of retained grains included internal and surrounding cracks. Particularly plate-shaped grains with distinct cleavage planes were weakly connected with matrix. The contents of such grains was much higher than in case of the material of line and post insulators from 1970s. Mullite phase constituted 31 ~ 35 % in the form of precipitates (usually 30 - 50 μm), usually uniformly distributed in the matrix. Porosity of the material was proper – at an average 4 ~ 5 % (incidentally up to 7.5 %). Pores size did not exceed 20 μm. The amount of glassy matrix was over 40 % and it did not show any longer subcritical cracks. The structure of the material of rod and sheds was the same – Fig. 12. In Fig. 13 is presented structure containing plate-shaped quartz grains with distinct cleavage planes and characteristic internal cracks. Their bonding with matrix is exceptionally weak.

Porcelain of SWZP4 insulators is considerably differentiated for particular elements. Advancement of aging processes is varied and closely connected with amount, distribution and form of quartz grains present in the material structure. Influence of mullite phase is not such important. Degradation achieved medium stage and is similar to the stage observed in older by decade post insulators SWZPAK as well as sheds of line insulators LP from 1970s. Internal quartz stresses were relatively high and resulted in aging effects, almost independent from operational stresses. Numerous areas of disturbed structure, in which amplitude of ultrasonic signal was frequently below 0.5 V, were recorded in the rods of insulators from 1980s.

Low parameters of the material and numerous defects and inhomogeneities of structure SWZP4 post insulators from 1980s are the consequence of economic crisis which then took place in Poland. As the result of shortage of foreign currency more expensive raw components were substituted by cheaper, with worse properties. Particular batches of production were not exactly the same. It was not possible to work out processing parameters for changing composition of raw porcelain material. This resulted in decrease parameters of porcelain and quality of insulators. As effect resistance to aging processes was lowered. Number of defects - textural and inclusions was higher. On the basis of performed investigations it was suggested to withdraw all theses insulators from operation and also from station reserve [16,17].

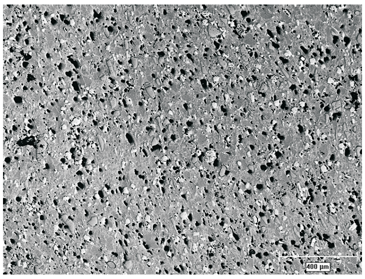

Fig. 12. Structure of rod material of post insulator from 1980s, magnification 50×. Homogeneity of structure components is proper. Aging processes concern quartz phase (bright fields) and partly mullite precipitates (darker grey areas). Degradation degree can be assigned as advanced preliminary or early subcritical

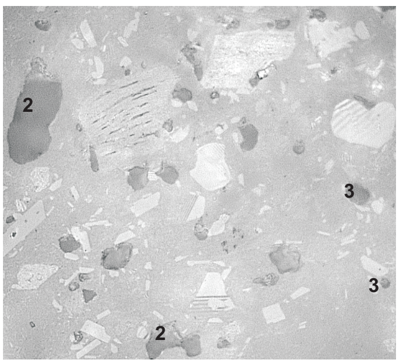

Fig. 13. Plate-shaped quartz grains-1 in structure of porcelain of post insulator from 1980s, magnification 500×. Dark areas illustrate spaces after crushed out grains-2 and smaller ones – pores-3

6. Conclusions

High failure frequency of insulators made from C 120 kind material constitutes important problem up to now. Decisive factor concerning breakdowns are technological faults. Being the source of high internal stresses, they lead in time to initiation and growth of cracks (even nets of cracks) having preliminary, subcritical and in the end – critical nature. This effect of the material degradation is amplified by ageing processes.

Results of performed tests prove serious weakening of parameters of C 120 kind material after long period of work. It concerns especially rods of line insulators, but as well post insulators, which porcelain have significantly worse properties. Material of insulators produced in 1980s, in time of economic crisis, has especially low parameters, includes more faults and inhomogeneities. It is more susceptible to ageing processes as well.

In case of post insulators, decisive influence on degradation processes, have internal stresses, quartz-related particularly. Degradation processes in the region of rods of line insulators are mainly result of operational load. However, ageing effects play important role as well. It is confirmed by number of breakdowns - similar of strain and suspension insulators. Technological defects are as a rule direct cause of damage just the same.

Material of tested insulators demonstrates high diversity of phase constitution and parameters. Ageing processes had further influence on properties variety magnification. Porcelain of post insulators, especially from 1980s, had generally worse parameters in comparison with the line ones. Surprisingly, high differences occurred for the groups of insulators of the same type. Line insulators LP 75/17 can be divided into two groups - better and more homogenous ones as well as poorer and less homogeneous. However, mention about variation of properties makes it difficult unequivocal assessment of the material of tested insulators, nonetheless it is possible to draw general conclusions. Performed investigation confirms in full limited resistance of C 120 kind material to degradation processes. On the ground of earlier researches, data from exploitation and presented examination, operational durability can be assumed as limited to no more than 35 years. This period of work can be believable on condition that insulator does not contain significant inhomogeneities or technological defects.

The most important result obtained on the basis of performed research is recommendation of replacement insulators made of C 120 kind porcelain exploited for about 30 years. Their further operation can cause frequent breakdowns. Younger insulators produced in crisis period of 1980s should be replaced in the first instance. Post insulators taken to examination from storehouse, showed unexpectedly similar degree of material degradation as in case of operated ones. Thus unused reserve objects should not be taken to exploitation.

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