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Durability forecast of long rod composite insulators operating under variable mechanical loading conditions

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Abstract: Suspension line insulators are during their operation subject to static forces and variable loads, usually of a cyclic character. These variable loads have a significant impact on the mechanical durability of composite insulators. A method of providing durability forecast for composite line insulators based on fatigue characteristics has been proposed. The method allows providing durability forecast of insulators in a wide range of variable loadings, i.e. from quasi-static to high amplitude loadings.

Key words: composite insulator, cyclic loads, fatigue strength, insulator testing, life estimation, mechanical strength

1. Introduction

The basic problem when selecting insulators is the assumption that exposures occurring during the expected operation time of an insulator will not cause such changes in its properties that could lead to its too rapid destruction, and thus to a failure of the power grid. Therefore, the correct selection of insulators requires the knowledge of their properties, not only those standardized or declared by the manufacturer, but also the ones expected by the line user (or investor), especially those related to the durability of the insulators used [1–5].

One of the most important properties of suspension line insulators, including composite ones, is their mechanical tensile strength.

Standardized mechanical strength tests of composite line insulators [6] are carried out under static load, whereas during operation the suspended in-line insulators are almost always subjected to variable forces, albeit at different intensities. In this context, it is important to mention the cyclic loads caused by the wind evoked vibrations of conductors. These loads overlap with the permanent static load (from the weight of the conductors and insulator strings, and from the conductor tension), forming a variable state of stress in the insulator.

Studies on the influence of variable (cyclic) loads on the mechanical strength of composite insulators [7–9] conducted at the Institute of Power Engineering (IEn) over the last several years have shown that such loads may lead to an accelerated damage of insulators. This depends on the parameters of the variable loading and the time of its influence. The construction and applied technology of the insulator is of paramount importance here. It was found that in high quality insulators the decrease of mechanical strength under variable loading was much slower [10, 11] than in insulators with an underdeveloped construction or manufacturing technology. Hence, the results of cyclic load tests of insulators and fatigue characteristics determined on their basis allow not only to compare the durability of line insulators from different manufacturers [8], but also to evaluate the stability of production and detect structural errors or technological failures [12].

Tests conducted so far at the Institute of Power Engineering (IEn) on composite line insulators under cyclic load have focused mainly on determining their limit strength parameters, and in particular on determining (and verifying) a mathematical model of long-term mechanical strength of these insulators [7]. This designated model is dramatically different from the long-term durability model of an insulator, which is included in the standard [6] and subjected mainly to the impact of static forces. Thus, the assessment of the durability forecast of composite line insulators based on the model in the standard may be incorrect, especially in the case of insulators operating under severe environmental conditions for many years.

Fatigue process studies have led to the current view that the decrease in the strength of a material strength subjected to variable load is associated with the formation of plastic strains in the material [4, 10, 13]. Similarly, in a composite insulator, the micro-cracks in the glass – epoxy resin core caused by these loads do not regenerate after the cyclic load has been removed, but propagate during the subsequent application of the variable tensile force. Such accumulation of damage leads to more and more changes in the structure of glass – epoxy resin and, consequently, to the destruction of the insulator by rupture of the core [8]. The accumulation of damage in the core of composite insulator leads to the conclusion that the durability of the insulator depends primarily on the time of variable load application and the value of its parameters, especially on the amplitude. Ignoring these facts may lead to an erroneous belief that under low variable loads there is no process of degradation of the glass – epoxy resin core of the insulator and its cracking [14]. Such a view is contradictory both to the model of long-term mechanical strength of composite insulators subjected to variable load [7] and to the theory of brittle materials cracking [13, 15].

The durability forecast of composite insulator in operation was based on its fatigue characteristics, determined as the dependence of time until the insulator deterioration on the value of amplitude of variable load. These characteristics allow to evaluate the durability of an insulator at any amplitude of load changes (including quasi-static) in any chosen period of insulator's life under this load.

The aim of the research paper discussed in this article was to develop a concept for the method of forecasting mechanical durability of composite line insulators, depending on the value and time of their variable (cyclic) load.

2. Concept for providing the durability forecast of composite line insulators based on their fatigue characteristics

The publication [10] describes the results of static strength tests of two composite insulators with a specified mechanical load (SML) of 160 kN, after 35 years of operation in a high voltage line. It was found that despite the positive result of the test, the glass – epoxy resin cores of these insulators were disintegrated. A similar phenomenon was observed in IEn laboratory tests of composite insulators subjected to variable tensile load [8, 9, 16].

It can be therefore said that the end of life of insulators, described in [10], was close, and the occurrence of an emergency state was more and more probable as they continued to be used. It can also be noted that, as shown in [8, 16], the complete disintegration of the glass – epoxy resin core is typical for brittle materials, i.e. it is not accompanied by a significant earlier decrease in the mechanical strength of the insulator.

Turning to the issue of mechanical durability forecast in terms of composite insulators, the following procedures can be indicated:

1. Use of the results from the operation of composite insulators in the power line, as described earlier, to determine their lifetime. Subsequently, testing the fatigue strength of the same insulators in storage under laboratory conditions (produced together with those removed from the line but not operated) and developing fatigue characteristics. Knowing their lifetime, the average amplitude of the cyclic load over the lifetime of these insulators on a given line can be determined from their fatigue characteristics.
2. Recording, due to wind, the variable loads of overhead line conductors over a period of at least 1 year. Due to the fact that these wind induced vibrations of conductors are transferred to insulators (mainly dead-end ones), the registration results obtained could be the basis for the selection of variable load parameters during laboratory fatigue tests of composite insulators [17]. The purpose of these laboratory tests would be to determine the durability of the insulators used in this line under operating conditions.

Knowing the value of the conductor tension and other parameters of the mechanical system of insulator conductors and strings together with their protection devices, it is possible – after conversion – to determine the course of amplitude changes affecting the insulator of variable load during the assumed period (for example, 1 year). Figure 1 shows a hypothetical course of amplitude changes of cyclic load over T_1 time during acting on the insulator suspended in the line.

Continuous line in Fig. 1. shows hypothetical course of amplitude A, acting on the cyclic load insulator (hypothetical real function) during T1 time, while intermittent line shows average amplitude A_1, obtained as a result of integration of real-valued function within limits from 0 to T_1.

Knowing the average amplitude of load variations A_1 and the maximum value of insulator load (including jointly static and variable loads), fatigue characteristics can be determined from the laboratory test results and durability forecast for a given type of line insulator can be provided.

It can also be added that the amplitude of vibration of conductors is most often below 1 mm under operating conditions, but amplitudes from a few millimeters to 10 mm have also been observed, especially at vibration of conductors of about 7 Hz [17].

It should also be noted that each type of conductor has its characteristic vibration frequency, i.e. a resonance frequency at which the conductor vibrates steadily and the resulting vibration amplitudes are relatively at the highest level. Tension strings are most exposed to vibrations.

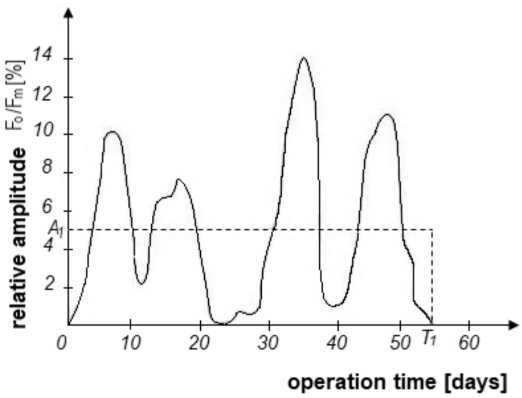


Fig. 1. Hypothetical course of amplitude changes, affecting the cyclic load insulator, in the contractual time T_1

The inertia forces generated in the vibration plane during the vibrations of the string elements create variable stresses in the insulators and protection device elements, which overlap with the existing static loads caused by the specific tensile force in the conductor.

At the time when first generation insulators (such as those discussed below, removed from 110 kV line, insulator – Fig. 2) were being produced, their tests were yet neither determined nor standardized, let alone the tests under variable load. Unfortunately, none of these insulators have been preserved in the storage resources – the entire batch of these insulators produced was intended for direct operation. Therefore, without a warehouse stock, it was not possible to carry out tests on them and determine their fatigue characteristics. For this reason, the concept of forecasting the durability of composite line insulators was discussed on the basis of the results of research conducted on insulators currently manufactured, also intended for the 110 kV line. The method used at the Institute of Power Engineering (IEn) to test and determine fatigue characteristics and to forecast the service life of insulators on this basis is the same for each type and family of long rod composite insulator.

3. Test objects and methodology of tests

3.1. Test objects

The test objects were suspension composite insulators, removed from the 110 kV line after approximately 35 years of operation (no longer manufactured), and composite insulators, designed for the 110 kV line, being currently manufactured.

Figure 2 shows such a composite insulator removed from the 110 kV line. It is a first-generation insulator, which consists of a glass – epoxy resin core with a non-pressure cast housing made of silicone elastomer RTV 1 and with metal end-fittings installed at the ends of the core.

Such insulators, in number of about 80 pieces, were constructed and produced in Poland [18]. They were installed in power line sections for the field tests in the early 1980s. In the period of more than 30 years of operation, no emergency conditions of the lines caused by these insulators

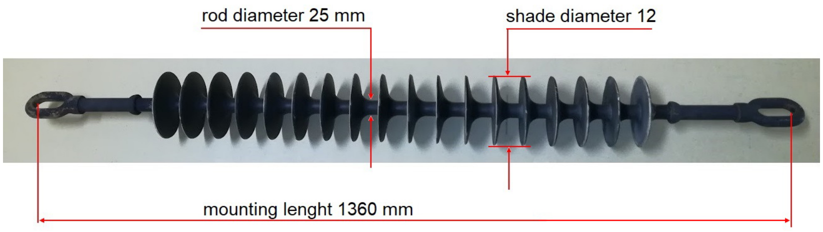


Fig. 2. Composite insulator removed from the line after 35 years of operation

were found. On the other hand, material testing of individual insulators of this type, removed periodically from the 110 kV line, confirmed the progressing aging of their housing material [19].

Laboratory tests, on the basis of which fatigue characteristics were determined and the concept of a durability forecast for composite insulators was described, were carried out on models (epoxy resin core with end-fittings mounted, without housing) of the line insulator type CS 120 C19L 550/3720 [20] currently produced – Fig. 3. The specified mechanical load (**SML**) of this insulator is 120 kN, the mounting length is 1270 mm and the rod diameter is 17 mm. At first these insulators (models) were tested for static mechanical strength [6]. The failure of the insulator (model) by its core pull out was recorded with a load of 177 kN.

Fig. 3. Composite insulator type CS 120 C19L 550/3720 with a housing of silicone elastomer LSR, whose models have been tested

The mechanical properties of the model are the same as those of the complete insulator, so the results also refer to the complete insulator of this type. Thanks to the use of models, it was also possible to observe the behavior of the core during the test.

3.2. Test methodology and test stand

All mechanical tests of composite insulators, both with static and cyclic loads, as shown in Fig. 2 and Fig. 3, were performed on the test stand shown in Fig. 4.

The static strength test of composite insulators under SML load was carried out in accordance with [6]. It was a one-minute tensile load test of 100% **SML**, which was continued by increasing the insulator load until it was destroyed.

Fatigue tests of insulator models were carried out under cyclic load, with the following basic parameters:

- average load (static load; fixed component) F_m,
- vibration amplitude F_a,
- maximum value of applied force $F_{\max} = F_m + F_a$,
- minimum value of applied force $F_{min} = F_m - F_a$.

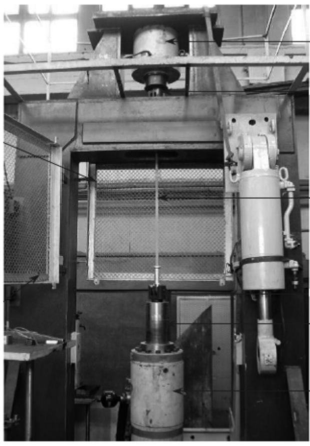


Fig. 4. Test stand with fatigue test-prepared composite insulator model CS 120 C19L 550/3720 for 110 kV line (glass – epoxy resin core without silicone elastomer housing)

With these cyclic loads parameters, the variable tensile force $\boldsymbol{F}$ (tensile load) applied to the insulator during the test can be simplified to [7–9, 16]

$$F = (F_m \pm F_a)\,, \tag{1}$$

or, assuming a uniform uniaxial loading state varying over time t, as

$$F(t) = F_m + F_a \sin \omega t, \tag{2}$$

where $\omega = 2\pi f$ is the frequency of load changes (f – vibration frequency).

Values of variable test load parameters are selected depending on rated (static) specified mechanical load (**SML**) of the insulator. The frequency of cyclic test load changes was assumed to be 7 Hz, which was demonstrated in [17].

Fatigue tests of insulator models were performed at four amplitudes: 25%, 20%, 15% and 10% of the average value of applied force $\boldsymbol{F}_m$.

It should be noted that the fatigue characteristics – determined on the basis of measurements made on a test stand as in Fig. 4, at the above mentioned amplitude values – make it possible to determine the mechanical durability of an insulator at any value of amplitude, which will be further demonstrated.

4. Test results

4.1. Results of mechanical strength tests of first-generation composite insulator

As already indicated in Section 3.1, the insulator shown in Fig. 2 was removed from the 110 kV line after 35 years of operation. This insulator was tested for static mechanical strength. The test was carried out in accordance with [6]. Diameter of the insulator core was 17 mm.

Figure 5 shows diagrams of load and elongation of the composite insulator presented in Fig. 2, in relation to time of the load application while in Fig. 6 the diagram of the insulator elongation in relation to applied tensile force is presented.

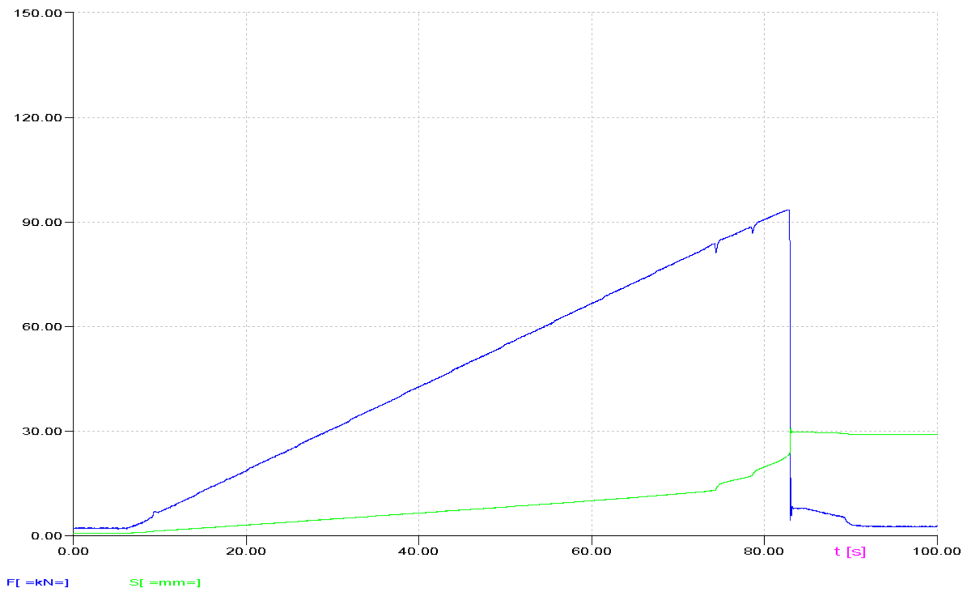


Fig. 5. Tensile force and insulator elongation in the static load strength test 1, tensile load F1 2, elongation E2

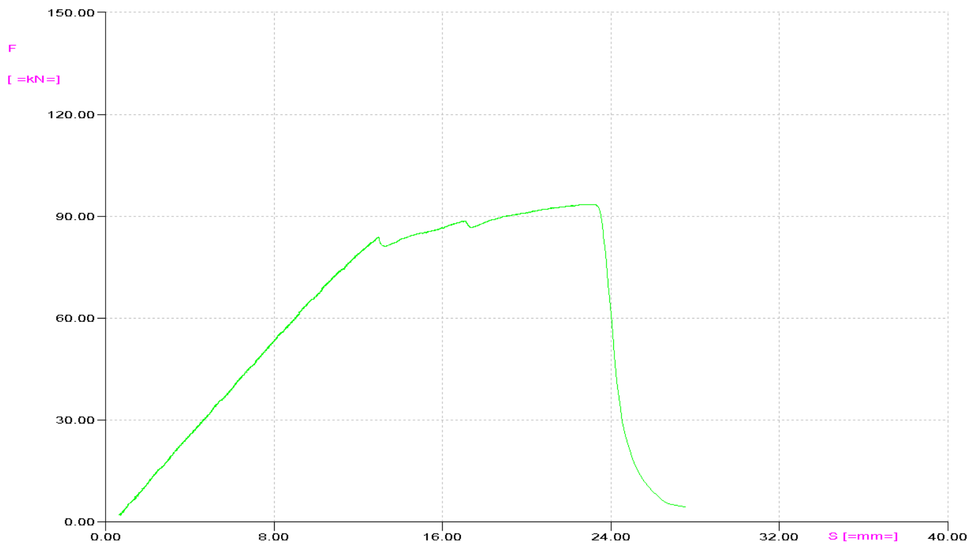
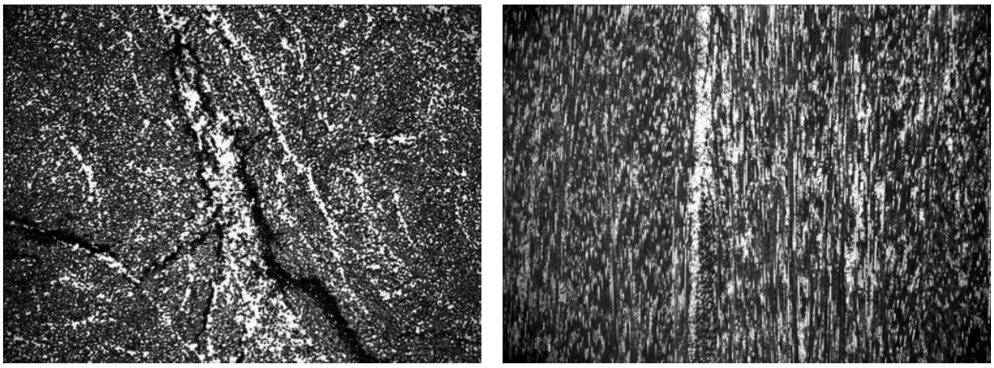


Fig. 6. Relationship between elongation and tensile load for insulator from Fig. 2 in mechanical strength test under static load

The test did not result in a tensile force of 100 kN, which was assigned to the insulator as a specified mechanical load (**SML**). Usually a real value of static mechanical strength for new insulators is at least 20% higher than a specified mechanical load (**SML**) declared by a manufacturer. The insulator core was finally removed from the end-fitting at a load of 92 kN, although the slip out process had already begun with a load of 86 kN (as shown in Fig. 6). One can estimate reduction of mechanical strength of this insulator in reference to its assumed real value (between 110 and 120 kN) in the range of 30 to 40%.

In order to explain the decrease in mechanical strength of the first-generation composite insulator tested (Fig. 2), its core was cut into cylindrical samples, and they were examined under a microscope.

It could have been observed that the surfaces of the samples were covered with cracks, which developed in the longitudinal direction (Fig. 7). These cracks were present on virtually all samples, regardless of where they were taken from the glass-epoxy resin core.



(a) (b)

Fig. 7. Microscopic photographs of samples taken from the core of the composite insulator from Fig. 2 after a destructive static load test (magnification ×50): (a) cracks observed at the cross-section area; (b) cracks observed on the surface of the right section

Core cracks, similar to those in Fig. 7, were also observed during fatigue tests of composite insulators, described in [8, 20]. The cores of these insulators were disintegrated due to the propagation of cracks. It can be assumed that the core of the tested insulator was also close to destruction, and the decrease of its mechanical strength could be related to changes in its structure as a result of micro-cracks caused during its operation.

4.2. Fatigue strength test results for composite insulator models

For fatigue strength testing, the models of composite line insulators (cores with end-fittings without housing) type CS 120 C19L 550/3720 were selected (see Fig. 3). The fatigue tests were carried out on the test stand shown in Fig. 4, and a summary of the results of the tests of insulator strength under cyclic load is presented in Table 1.

Table 1. Results of fatigue tests on insulator models

Load change amplitude F_a	Results of fatigue tests						
1	2	3	4	5	6	7	8
25% F_m	F_{max}	100%	88%	83%	67%	54%	–
	N	4600	16200	18400	87100	976700	–
20% F_m	F_{max}	100%	95%	90%	85%	70%	55%
	N	5200	10000	15500	18300	106500	1991×10^3
15% F_m	F_{max}	108%	100%	83%	70%	63%	–
	N	12100	12600	44200	393700	685000	–
10% F_m	F_{max}	110%	100%	83%	73%	–	–
	N	41100	94100	450200	1203400	–	–

F_{max} is the percentage value of maximum test load in relation to specified mechanical load of the insulator model
N is the number of load change cycles until the insulator model destruction

Fatigue characteristics were determined by an approximation of points, the coordinates of which were determined by pairs of numbers from Table 1 according to the following adopted rule:

– abscissa value is the number of cycles to model destruction, in Table 1 and Fig. 8, marked with N; and,
– ordinate value is the relative value (percentage) of maximum load in relation to **SML** (in Table 1 marked with F_{max} symbol).

The exponential function, which gives the best mapping accuracy, has been adopted as the approximation function. The logarithmic exponential function on both axes of the coordinate system is a straight line, which greatly simplifies its analysis.

Figure 8 shows the graphical form of the determined fatigue characteristics, with four characteristic maximum load levels marked. Table 2 shows the analytical form of these characteristics, the value of the coefficient of determination – as a measure of the mapping accuracy – and the value of the arbitrary angle of inclination of the characteristic to the $0 - x$ axis.

The characteristic four levels of maximum values of applied force $\boldsymbol{F}_{max}$ (total load: static + variable), for which fatigue characteristics were then determined as the relation between the amplitude of load changes and the number of cycles (time), were marked with letters in Fig. 8:

A – load F_{max} = 33.3% **SML** (assumed insulator design load),

B – load F_{max} = 40.0% **SML** (load level recommended by IEn for fatigue resistance assessment of composite insulator),

C – load F_{max} = 60.0% **SML** (so-called extraordinary load value according to standard [6]),

D – load F_{max} = 70.0% **SML** (elastic limit of end-fittings adopted in standard [6]).

Table 2. Analytical form of fatigue characteristics

Load change amplitude F_a	**Fatigue characteristic**	**Coefficient of determination R^2**	**Arbitrary characteristic inclination angle to 0–x axis**
1	2	3	4
25% F_m	$y_{25}(x) = 265x^{-0.12}$	0.98	6.7°
20% F_m	$y_{20}(x) = 239x^{-0.10}$	0.99	5.9°
15% F_m	$y_{15}(x) = 311x^{-0.12}$	0.96	6.7°
10% F_m	$y_{10}(x) = 394\,x^{-0.12}$	1.00	6.8°

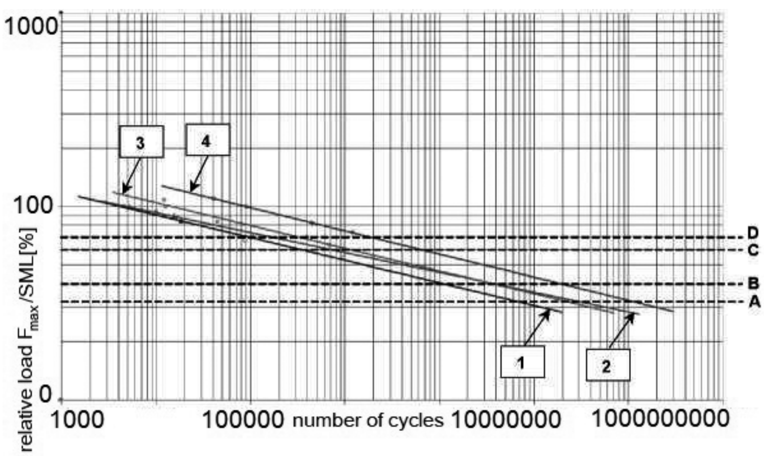


Fig. 8. Fatigue characteristics of composite insulators, determined for selected values of amplitudes of cyclic load changes (logarithmic scale on both axes):
characteristic for amplitude $F_a = 25\%F_m$, characteristic for amplitude $F_a = 20\%F_m$,
characteristic for amplitude $F_a = 5\%F_m$, characteristic for amplitude $F_a = 10\%F_m$

When analysing the obtained fatigue characteristics, both in graphical form (Fig. 8) and in analytical form (Table 2), it can be noted that they are practically parallel and that the arbitrary angles of inclination differ by no more than 0.9°.

The accuracy of the approximation expressed by the coefficient of determination R^2 is very high for of long-term these characteristics, i.e. close to unity. This confirms the (already proven) thesis that the model mechanical strength of composite line insulators subjected to the cyclic load is an exponential function [7].

4.3. Determination of fatigue characteristics of composite insulators in relation to the amplitude of load changes

Fatigue characteristics 1, 2, 3, and 4 in Fig. 8, and the data in Table 2 allow one to calculate the time to destruction (number of cycles) of the tested insulators at the assumed maximum load levels: A, B, C, and D. For each level of A, B, C, and D, four pairs of numbers shall be determined (four amplitudes were tested), which constitute the coordinates of the points in the following system:

– The abscissae values – the calculated number of cycles to the insulator destruction at the given level of A, B, C, or D; and,
– The ordinate values – relative (percentage) value of amplitude of changes in the insulator load in relation to average load.

The points thus determined and marked on the system of coordinates were approximated with an exponential function, obtaining high approximation accuracy (Table 3). In this way, fatigue characteristics were obtained depending on the amplitude of load changes, as shown in Fig. 9.

Table 3. Analytical form of fatigue characteristics in relation to amplitude of load changes

Level of load	**Fatigue characteristic**	R^2	**Arbitrary characteristic inclination angle**
1	2	3	4
A 33.3% **SML** ($F_{\max}$ = 40 kN)	$y_{33}(x) = 6631x^{-0.31}$	0.85	17.4°
B 40.0% **SML** ($F_{\max}$ = 48 kN)	$y_{40}(x) = 4458x^{-0.32}$	0.91	17.7°
C 60.0% **SML** ($F_{\max}$ = 72 kN)	$y_{60}(x) = 1256x^{-0.31}$	0.97	17.2°
D 70.0% **SML** ($F_{\max}$ = 84 kN)	$y_{70}(x) = 31x^{-0.30}$	0.98	16.7°

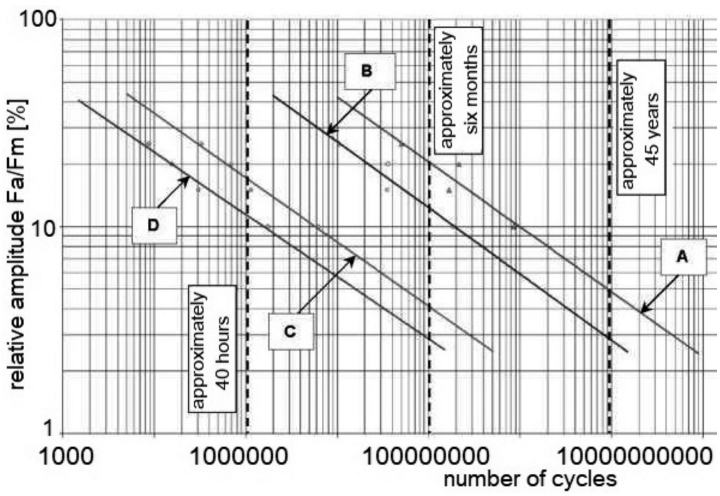


Fig. 9. Fatigue characteristics of composite insulators, determined for four values of maximum cyclic tensile load (logarithmic scale on both axes): $F_{\max}$ = 33.3% **SML**, $F_{\max}$ = 40.0% **SML**, $F_{\max}$ = 60.0% **SML**, $F_{\max}$ = 70.0% **SML**

Figure 9 shows fatigue characteristics diagrams on a double logarithmic scale. In this figure, the cyclic load time on the insulator is indicated by vertical, intermittent lines, converting the number of cycles of 7 Hz to hours or years. Three such times are shown in the figure, but any number of cycles can be converted in the same way. Table 3, on the other hand, presents the analytical form of these characteristics, also giving (as in Table 2) the coefficient of determination R^2 and the arbitrary angle of inclination of the characteristic to the $0 - x$ axis.

It can also be noted that, similarly to fatigue characteristics (Fig. 8 and Table 2), fatigue characteristics depending on the amplitude of load changes (Fig. 9 and Table 3) of the tested insulators are practically parallel, and they have a high degree of model fit (coefficient of determination R^2 close to unity).

5. Analysis of results and durability forecast of long rod composite insulators

When turning to the analysis of the results, it should be noted that the first-generation insulator (Fig. 2) was characterized by the worse quality of the core in relation to the insulator in Fig. 3 and insufficient repeatability of the crimping process, which at that time would be performed using a simple manual press. Therefore, it can be assumed with high probability that the currently manufactured insulator (Fig. 3) would last for more than 35 years under the same operating conditions.

On the basis of fatigue characteristics (Fig. 9 and Table 3), the following conclusions can be drawn concerning the operation time to failure (so called lifetime) of the tested insulators (models):

1. Assuming that the insulator load in service should not exceed the design load, 33.3% **SML** (total static and cyclic load) is assumed here, and the expected time of failure-free operation (time to destruction) of the insulator should be at the level of 45 years, then such an insulator may be exposed to continuous cyclic load with the amplitude F_a not exceeding 5% of the average load F_m.
2. However, if the insulator would be loaded at 40 per cent **SML** as a result of an underestimation of its design load, the amplitude F_a acting on the cyclic load insulator would have to be limited to 3 per cent of the mean load F_m, provided that the insulator failure-free operation time would be 45 years.
3. Extreme weather conditions, occurring even occasionally and briefly, causing an increase in the amplitude of cyclic loads acting on the insulator, even a load lower than the design load may cause a decrease in the insulator's strength, which will result in a reduction of its lifetime, because, as already mentioned, possible micro-cracks or preliminary damage to the core accumulate [8, 20].

It should also be noted that determination of fatigue characteristics, depending on the amplitude of load changes (Fig. 9 and Table 3) for a given composite insulator type, allows one to estimate its durability at virtually any amplitude of cyclic load that may affect the insulator as a result of the transmission of vibrations of conductors to the insulator string. A significant impact of variable loads on the durability of composite insulators can also be observed, because the more fatigue characteristics approach the abscissa axis, the more we approach the quasi-static load and extension of the insulator lifetime (however, this period always has a finite value, and can be estimated from the fatigue characteristics depending on the amplitude of load changes – this once again undermines the validity of the strength model according to the standard [6]).

If, as described, the approximate lifetime of a composite insulator, here the first generation, was known, the determination of the fatigue characteristic – depending on the amplitude of load changes – on the basis of the fatigue tests of the same insulators that were not in service (assuming the existence of storage resources) would allow for the following:

– The determination of the average amplitude of the variable load acting on the insulators in a given line during operation; and,
– The determination of the durability forecast for any composite insulator selected for operation in this line, on the basis of its fatigue characteristic, determined at design load and at the average amplitude of variable load, determined from the operating conditions of the previous insulator (here the first generation).

If the average amplitude of the variable load is determined directly from the measurements in the high voltage line (Fig. 1), its use to provide the durability forecast of composite insulators may be such as the amplitude determined on the basis of the actual time of failure-free operation of the composite insulator.

6. Conclusions

1. The long operation of composite line insulators in overhead power lines may result in the formation, accumulation, and propagation of micro-cracks in the glass-epoxy resin insulator core. These micro-cracks are the result of both static and, above all, variable loads acting on the insulators. This leads to fatigue changes in the core material, resulting in its disintegration and loss of mechanical properties.
2. Fatigue characteristics, determined depending on the amplitude of load changes, of a long rod composite insulator enable one to determine their durability during operation at any value of variable load (including quasi-static load).
3. Determination of fatigue characteristics of composite insulators, before their installation in a given power line, enables – in the case of the removal of any of them from the line, due to its end of life – the estimation of the average variable load to which this insulator, removed from the line, was exposed during its entire operation.
4. Knowledge of the average variable load acting on composite insulators in a given power line allows one to provide reliable mechanical durability forecasts (failure-free operation period) of any composite insulators used in this line, based on the fatigue characteristics determined for them.
5. For the construction of a new high-voltage power transmission or distribution line, the fatigue characteristics of the composite insulators used should be an integral part of the documentation. These reference characteristics may be referred to after many years of line operation to verify the average variable load on the line, and to correct, if necessary, the expected lifetime of the insulators.
6. If the insulators in the line are changed to, as before, composite insulators with different technical parameters than those originally used, the durability forecast of the new insulators

can be reliably provided on the basis of the fatigue characteristics determined for them and the values of variable loads determined for the insulators originally used.

The values of the average variable loads to which the composite insulators are subjected in high-voltage lines may be determined by direct measurement of the in-line vibrations of the conductors over a given period of time. Although the results of such measurements are highly desirable as a basis for providing the durability forecast of composite insulators, they are costly and difficult to perform in technical and organizational terms.

Acknowledgements

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