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COMPARISON OF METHODS APPLIED TO MEASURING THE LIGHTNING IMPULSE BREAKDOWN VOLTAGE OF INSULATING PRESSBOARD IMPREGNATED WITH MINERAL OIL AND NATURAL ESTER

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Abstract

The aim of this paper is to compare three different methods of analysis of results of lightning impulse breakdown voltage measurements of solid materials such as insulating pressboard. These three methods are the series method, the step method and the up-and-down method which are applied to withstand voltage estimation commonly in high voltage engineering. To obtain the data needed for the analysis a series of experimental studies was carried out. It included studies of mineral oil and natural ester impregnating 1 mm of thick cellulose-based pressboard. In order to show the distribution of breakdown voltage the Weibull distribution was additionally applied in data analysis. The results were also assessed from the viewpoint of dielectric liquid used for impregnation. The studies carried out showed that series and step methods give comparable results opposite to the up-and-down method. The latest overstates the results for mineral oil impregnated pressboard and understates for natural ester impregnated pressboard when juxtaposing them with the rest of the methods applied. In addition, there is lack of possibility to assess the withstand voltage for the up-and-down method directly from the vector of random variable. It is possible only as a result of a specially developed equation which always arouses doubt. From the methods applied it seems that the step method can be a great substitution for the series method as intuitive, fast in application and limiting the number of samples in solid insulation material testing.

Keywords: lightning impulse voltage, high voltage, measurement methods, dielectric liquids, insulating pressboard, Weibull distribution.

1. Introduction

The phenomena concerning *lightning impulse* (LI) voltage based stresses have a strongly statistical nature [1–4]. For this reason, there is no straightforward and reliable way to estimate the flashover or breakdown voltage of a given dielectric under LI stress. Many methods have been elaborated that allow for estimation of LI breakdown voltage on the basis of experiments

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where a series of lightning impulses are applied to the insulating system tested. Among these methods there are the series method, the step method and the up-and-down method. Each of them is characterized by a specific approach to conducting the experiment aimed at obtaining data for further analysis. The characteristic measurement procedures have advantages and disadvantages and differ from each other as it comes to the calculation of accuracy and errors [5–8]. When data concerning breakdown voltage are obtained, the breakdown probability is determined on a given voltage level and for a given voltage polarity. The most often used value of breakdown probability is a median that represents a 50% breakdown probability. However, when statistical analysis is performed on the basis of a selected distribution function (usually the Normal or two-parameter Weibull distribution function is applied), the breakdown voltages corresponding to low levels of probabilities (1 or 5 %) are given as more reliable in assessment of dielectric properties of a given insulating system [2, 3, 8–10]. In selected cases more complicated distribution functions are applied such as the three-parameter Weibull distribution with which the withstand voltage may be directly evaluated on the basis of the location parameter U_0, also called 0% probability [3, 11].

Proper assessment of dielectric strength of solid materials exposed to lightning impulses is still a challenge due to the fact that testing solid insulation has a destructive nature. It means that each sample can be used only one time and the set of samples must be carefully prepared before the beginning of the experiment. For a small number of samples, the cost of destructive breakdown voltage tests usually is affordable, however, when testing more expensive materials, it is impossible to provide a large number of samples for the tests. In addition, there is no clearly defined method considering the standards. An existing description in [12] is of very general nature and does not indicate an exact procedure that should be applied on a large scale. In turn, the literature data do not discuss how to test solid materials suffering lightning impulses, especially whether the methods accepted for gaseous and liquid insulation can be successfully applied also to solid insulation.

Taking it all into consideration, the aim of the studies presented in this paper was to compare the above-mentioned experimental methods used in engineering and scientific practice to evaluate lightning impulse electric strength of high-voltage solid insulation material represented by insulating cellulose pressboard impregnated with two commercial dielectric liquids. This comparison was aimed at indicating the merits and deficiencies of the methods in order to propose the best approach whenever there a need to evaluate the LI breakdown voltage of solid materials. It is especially important in the case of making the tests under non-uniform fields and lightning impulses which refer to a local microdefect that can appear in a transformer insulation system [2, 7, 13]. In turn, the choice of pressboard was dictated by the fact that this is the material commonly applied in transformer insulation systems and its properties are significant for correct operation of transformer unit.

The paper compared also the influence of the kind of liquid used for impregnation of the LI electric strength of pressboard tested. This comes from the observed significant increase in the number of transformer units filled with natural ester worldwide [14–16]. Since the impregnation medium can influence the dielectric strength of pressboard at an AC voltage [3, 14, 16], the data concerning LI voltage seem to be worth to be evaluated.

Finally, considering the fact that insulation is the key element of every high voltage device, manufacturers need to know which of the method allows to reduce the costs of high voltage insulation tests without a significant loss in accuracy and reliability of the results obtained. This is another significant aspect discussed herein.

Hence, it can be stated that the above-mentioned elements of the studies constitute the novelty of the work in relation to the state-of-the-art concerning lightning impulse testing of solid insulation. In general, as the tests are time and material consuming, solid insulation like

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pressboard is not tested extensively. Hence, the authors approach propose an evaluation of the methods mentioned in order to determine a good and economical way of reliable testing solid materials suffering lightning impulse voltage.

2. A short review of testing methods of lightning impulse breakdown voltage determination

2.1. The series method

One of the most popular methods used in high voltage insulation tests is the series method [1, 5, 7, 15]. It involves a number of series with predetermined and constant standardized voltage peak value of the impulse for each set. For each of the series, i.e. for each voltage level, n_i shots are applied of which k_i lead to sample breakdown. From this data breakdown probability at a given voltage level can be simply calculated as per (1):

$$P_i = \frac{k_i}{n_i} \tag{1}$$

by summing up the probabilities from the individual levels the cumulative probability curve can be drawn.

The number of voltage tests per series is defined based on analysis of normal distribution estimation and expected error values. With an increase in the number of samples within a single series the errors decrease exponentially. The most rapid drop in error ends with the number of samples per series equal to 10 [5]. Hence, most of the tests using the series method assume the number of samples to be between 10 and 20, wherein for solid materials, due to the destructive nature of the tests, this number is lowered as low as possible. In turn, the number of voltage levels varies usually between 5 and 8, giving satisfying results at moderate efforts and use of samples.

A graphical representation of the example of series method is shown in Fig. 1.

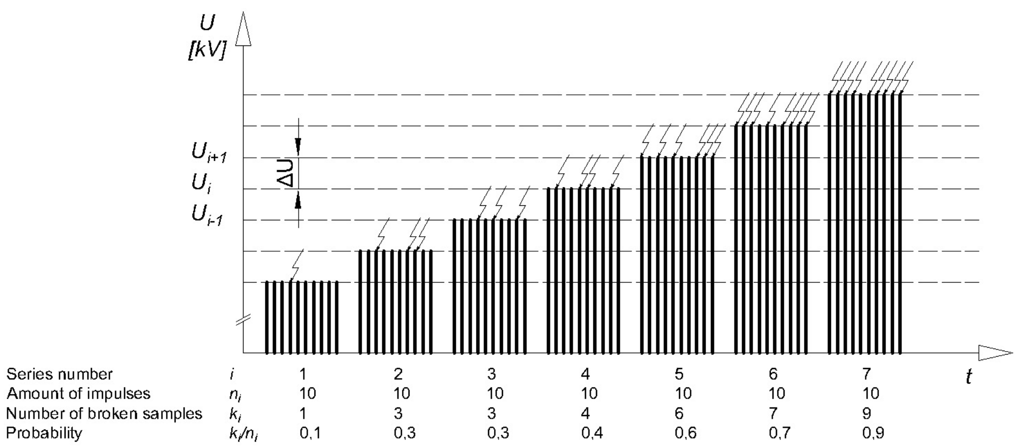

Fig. 1. Example of procedure of an insulation test using the series method.

The example presented consists of seven series with each series including ten shots. When considering peak values of standard lightning impulse voltages applied, they are obviously constant within one series. The voltage step between consecutive series is specified as ΔU and is fixed for the entire test. It is important in the series method not to consider the probability to be equal either to 0% and 100%. In other words, a series with no breakdown as well as one with breakdowns only are not taken into account.

Despite the simplicity of the series method, the application and working out the results of this method is problematic while testing non-regenerating insulation. This is due to its labor intensity and high costs of samples which can be used only once. The use of the series method is not possible with a low number of samples, thus research with this method is quite expensive.

2.2. The step method

The step method, also known as the Tetzner method from the name of its author, is a considerably cheaper way of conducting insulation tests at lightning stress comparing with the series method. It is widely used in maximum likelihood analysis in many fields of study [1,2,5,7,15,16]. In this method, the voltage is raised by step ΔU from starting value U_0 until the breakdown happens. After that, a next series begins from the same starting value of voltage as during the first series and with the same voltage step. It is expected in the measurement methodology of the method that minimum three levels of voltage before breakdown must be withstood if the measurement can be treated as true. An example of the use of step method is shown in Fig. 2.

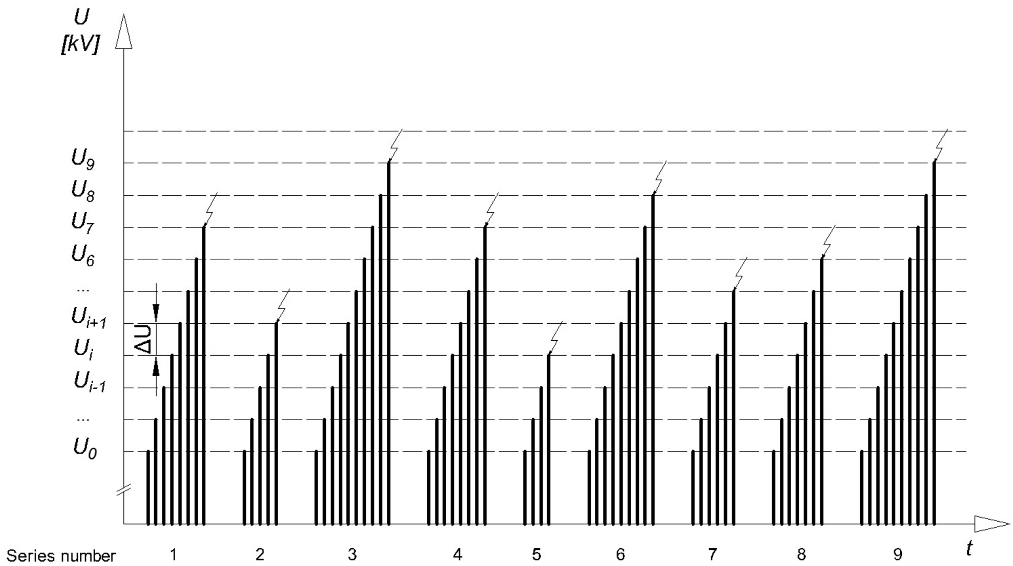

Fig. 2. Example of procedure of an insulation test using the step method.

The best practical approach for the results analysis is to evaluate the breakdown voltages from the assumed number of series and then subject them to the chosen statistical distribution. In other words, the values of breakdown voltages create the vector of random variables which can be analyzed using any known distribution function.

The step method can also be used with the number of impulses per step greater than one. In that case the procedure is similar to the one described above, but for each step a specific number of voltage impulses is applied to the sample. Three shots per step are typically applied when more than one shot is planned. If sample does not break down, next impulses are applied with the peak

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value raised by ΔU. Destruction of the sample means the beginning of a new series, starting again from U_0 level.

The main drawback of this method is, however that its results are strongly dependent on the starting voltage.

2.3. The up-and-down method

Another alternative for the series method is the so-called up-and-down method, which is also called the Dixon-Mood method, after the names of its inventors [5, 17]. Originally it was used in biological and medical data analysis, however, it has spread to other disciplines using maximum likelihood statistics [5,6,8]. It makes the peak voltage of every test conditional upon the preceding test following this algorithm:

– If at the previous voltage level a breakdown or a flashover took place, the subsequent level of voltage is lower by ΔU;
– If at the previous voltage level a breakdown or a flashover did not occur, the subsequent level of voltage is increased by ΔU.

An example of the use of up-and-down method is shown in Fig. 3.

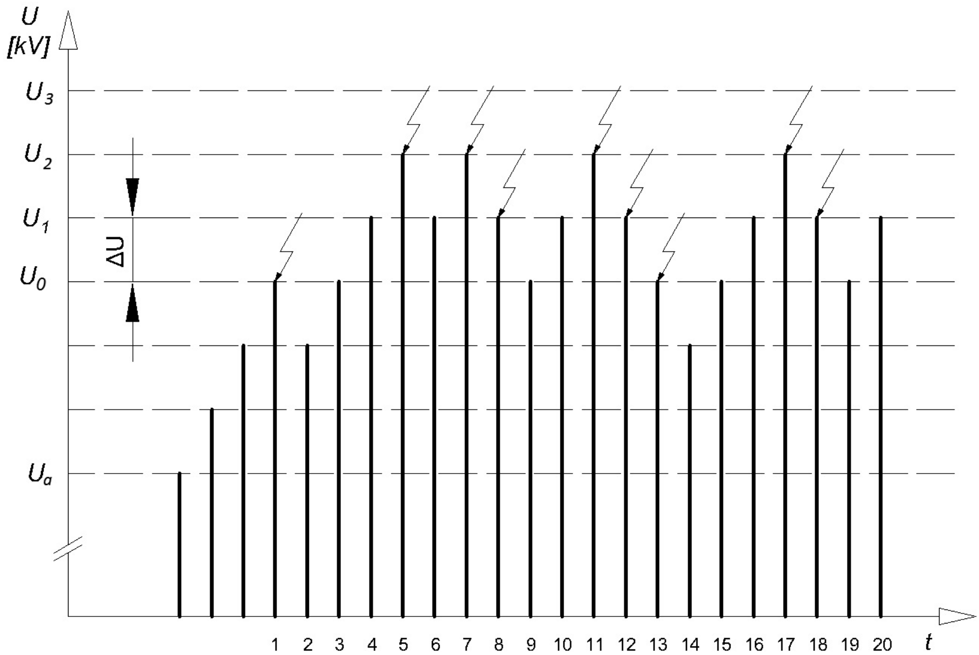

Fig. 3. An example of procedure of an insulation test using the up-and-down method.

The shots are counted from the one which causes a breakdown for the first time. After the required number of tests is conducted (which is usually around 20), breakdown events and no-breakdown events are summed as per (2):

$$k = \sum k_i, \quad q = \sum q_i , \tag{2}$$

where: k_i – tests resulting in a breakdown, q_i – tests without a breakdown.

Next, N number is calculated as:

$$N = \min(k, q). \tag{3}$$

Based on the calculated N, each voltage step of a valid test is indexed from 0 attributed to the lowest value. The 50% breakdown probability (U_{50}) and standard deviation (S) are calculated based on the following formulas:

$$A = \sum_{i=1}^{m} i l_i , \tag{4}$$

$$B = \sum_{i=0}^{m} i^2 l_i , \tag{5}$$

$$U_{50} = U_0 + \Delta U \left(\frac{A}{N} \pm 0.5 \right), \tag{6}$$

$$S = 1.62 \cdot \Delta U \left(\frac{NB - A^2}{N^2} + 0.03 \right), \tag{7}$$

where:
l_i – number of events related to the chosen N (breakdowns k_i or non-breakdowns q_i;
m – number of voltage steps;
"+" in formula (6) is taken when number N of breakdowns was greater than the number of no-breakdowns, otherwise "–" is taken;
U_0 in formula (6) means the lowest among the breakdown voltage values obtained from the measurement procedure performed.

The results achieved can be recalculated into the Weibull distribution location parameter (introduced later in this paper). According to literature [5], it is calculated from the following formula:

$$U_0 = U_{50} - 4.34S. \tag{8}$$

The up-and-down method is convenient, not labor-intensive and can be stopped at any time. 20 to 30 shots are typically enough to determine U_{50} with sufficient accuracy. Its drawback is that the standard deviation S determined from the tests is too large in relation to the real one. Therefore, it cannot be used for plotting the cumulative breakdown distribution P(U). This would entail significant errors in estimating the breakdown voltages related to low probabilities.

2.4. The three-parameter Weibull distribution function

Statistical analysis of the data obtained using the methods above should not be performed using normal distribution which, in the case of oil, paper-oil and sole paper/pressboard insulation, is treated typically as a false approach [3, 5, 7, 18]. Due to the fact that pressboard technical quality is the main factor affecting its dielectric strength, the theory of extreme values seems to be more suitable for analysis of breakdown voltage of pressboard. It is because of existence of small impurities and imperfections in the material leading to local reduction of its dielectric properties. Locally lower dielectric strength drastically affects the strength of the whole sample. Additionally, imperfection of pressboard concerns also its thickness which varies over the given sample. Thus, the extreme values theory should be applied during examination of breakdown voltage of solid insulating materials [5, 19, 20].

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One of the commonly applied extreme value based distribution functions is the Weibull distribution. It is exponential distribution widely used in statistical analysis including breakdown voltage determination, time-to-breakdown assessment and inception voltage of partial discharges evaluation [2,3,7,21]. Its three-parameter form in relation to the breakdown voltages is expressed by formula (9):

$$F(U) = \begin{cases} 1 - \exp\left[-\left(\dfrac{U - U_0}{U_m - U_0}\right)^k\right], & \text{for } U > U_0 \\ 0, & \text{for } U \le U_0 \end{cases}, \tag{9}$$

where:
U_0 – location parameter (expressed in kV) which means the value of voltage below which breakdown should not occur – the so-called 0% breakdown probability;
U_m – scale parameter (expressed in kV), which means the value of voltage for which probability of breakdown is equal to 63.2%;
U – random variable;
k – shape parameter.

3. Laboratory measurement methodology

The laboratory measurements were performed on pressboard samples of size 200 × 200 mm and 1 mm in thickness. For each sample four tests were conducted: each 5 cm away from the edges. The properties of the tested material, declared by manufacturer, are listed in Table 1.

Table 1. Properties of pressboard used during measurements.

Parameter	**Unit**	**Value**
Density	kg/dm^3	1.09
Dielectric permittivity	–	4.5
Tensile strength – longways	N/mm^2	107
Tensile strength – in breadth	N/mm^2	77
Conductivity of water extract	mS/m	3.3
Moisture content	%	4.2
Ash content	%	0.3

Before the tests the pressboard samples were separately impregnated with two dielectric liquids which differ in molecular structure and chemical properties. The properties of the liquids used (mineral oil and natural ester) are listed in Table 2.

The assumed drying and impregnation procedure, which based on our own experience and earlier works [3, 10, 14, 24], was as follows:

1. Drying the pressboard for 16 hours under vacuum < 100 Pa and in temperature of 105°C in a vacuum chamber.
2. Filling the vacuum chamber with a given dielectric liquid heated up to the temperature of 60°C.
3. Impregnation of the pressboard under vacuum in temperature of 80°C for 16 h.
4. Cooling the pressboard to ambient temperature while immersing it in the dielectric liquid.
5. Leaving pressboard samples in ambient temperature (around 20°C) for another 16 h.

Table 2. Properties of dielectric liquids used during measurements [22, 23].

Parameter	**Mineral oil**	**Natural ester**
Density at 20°C [kg/dm^3]	0.88	0.96
Viscosity at 40°C [mm^2/s]	10	50
Viscosity at 100°C [mm^2/s]	2.6	15
Fire point [°C]	191	300
Pour point [°C]	–42	–10
Biodegradability	non-biodegradable	readily biodegradable
Water content [ppm]	55	200
Dielectric strength [kV]	70	56
Dielectric dissipation factor at 90°C and 50 Hz	< 0.002	< 0.05
Dielectric permittivity at 20°C	2.2	3.2

During measurements the following equipment was used:
1) a 4-stages lightning impulse Marx generator capable of generating the standard (1.2/50 μs) lightning impulse of up to 400 kV in peak value;
2) an electrode system consisting of a flat grounded electrode and a sharp high-voltage (HV) point electrode representing non-uniform electric field distribution (see Fig. 4). The HV electrode was held with a non-conductive support arm which reduced pressure on the pressboard sample;
3) a DPO3054Tektronix digital oscilloscope for registration of voltage waveforms;
4) an MWS-2000AD peak value voltmeter and a resistive voltage divider of ratio equal to 500, both used for measurement of the peak value of the lightning impulse;
5) a FLUKE 117 true RMS multimeter working with a resistive voltage divider of ratio 1000 used to measure the DC charging voltage.

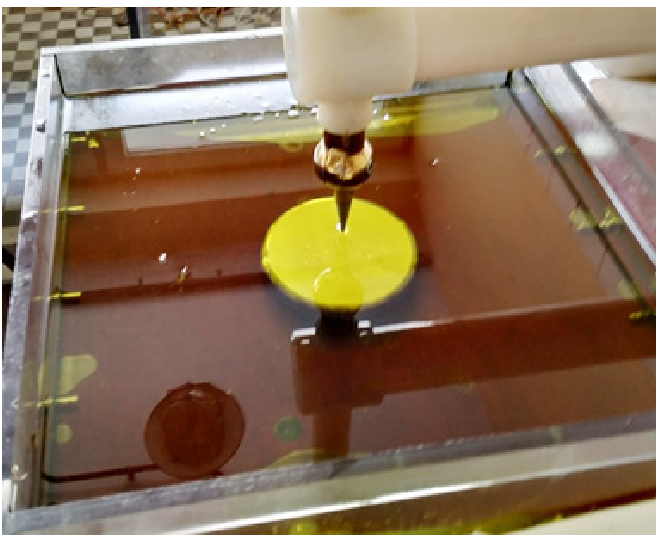

Fig. 4. Real view of the electrode system used in laboratory measurements.

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The generator was calibrated particularly for the measurement task which confirmed a linear correlation between the DC charging voltage and the peak value of the lightning impulse voltage. The result of the calibration is shown in Fig. 5. The negative polarity of the lightning impulse was applied as the commonly applied polarity in the industry based acceptance tests of power transformers [24].

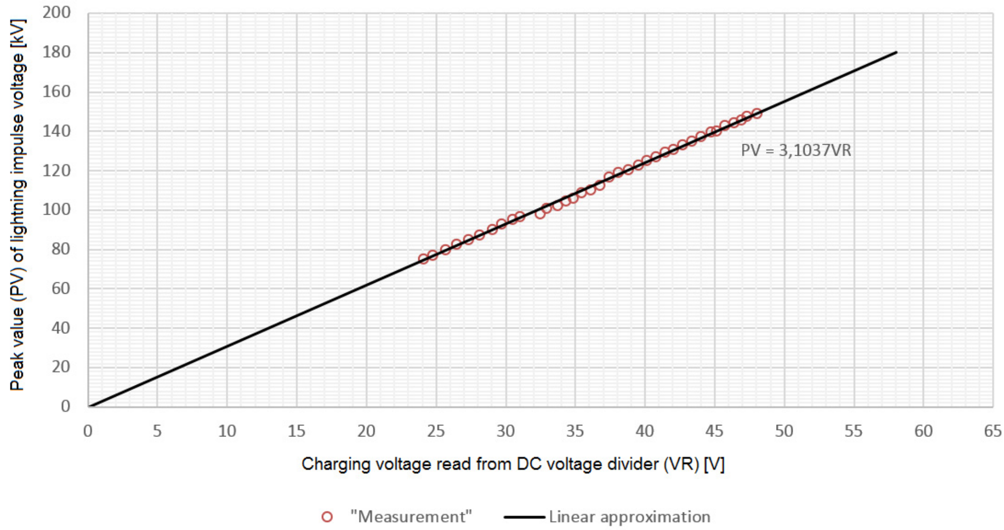

Fig. 5. Generator scaling curve.

As mentioned above, the dimensions of the sample allowed for conducting four measurements for one sample, each one in a different corner of the sample. The measurement point was changed both when the test did not result in a breakdown as well as when it did.

In order to evaluate the starting value of voltage for the main measurement procedure using the methods considered, pre-tests were firstly conducted with the following steps:

– A sample was prepared in the same setup the main procedure should be carried on;
– A first value of impulse voltage was chosen to be significantly lower than the expected breakdown voltage. The value chosen was 80 kV;
– Impulse voltage was increased by 4 kV until the breakdown of the sample was achieved. The sample was not replaced until the breakdown to save the amount of material to be tested;
– The procedure was repeated four times for each liquid considered.

The results of the pre-tests are listed in Table 3.

Table 3. Values of breakdown voltages in the pre-tests.

	Test 1	**Test 2**	**Test 3**	**Test 4**
Mineral oil impregnated pressboard	112 kV	116 kV	108 kV	112 kV
Natural ester impregnated pressboard	108 kV	108 kV	104 kV	104 kV

As it had been assumed that a value lower by 4 kV than the lowest value from the pre-tests would be chosen as the starting point, the starting voltages chosen for the series method were

104 kV for mineral oil and 100 kV for natural ester, respectively. The voltage step was equal to 2 kV in both cases as more proper from the statistical point of view. In testing the samples using series method five series were carried out for both liquids considered as the impregnating medium. Each series consisted of ten tests (ten lightning impulses of the same peak value applied to the pressboard under test).

In turn, for the step method six series were carried out for both considered liquids. The starting voltages were chosen as to fulfill the requirements related to three levels without a breakdown. Hence, these values were lowered in relation to the series method. Thus, the applied values were 100 kV and 96 kV respectively for mineral oil and for natural ester. The voltage step was, however, the same as in the case of series method.

In the case of the up-and-down method number of valid tests was set to 21. The starting voltages were assumed on the same levels as in the case of the step method. The voltage step was again equal to 2 kV.

4. Results

As a result of a single test the two possible events could occur: a breakdown of the sample, or lack of it. The recognition which of them took place was easy due to acoustic phenomena connected with a breakdown as well as voltage collapse visible in the registered voltage waveform. Additionally, the puncture on the surface of the sample was clearly visible when the breakdown happened. Fig. 6 shows two opposite situations; when the breakdown occurred and when it did not.

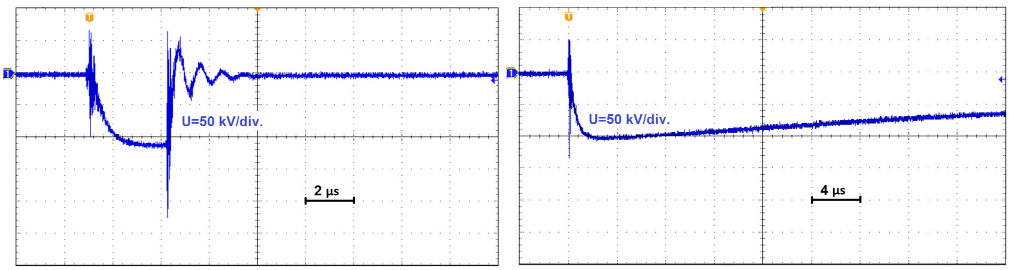

Fig. 6. Example of oscillograms of a voltage waveform: a) when a breakdown occurred, b) when a breakdown did not occur.

Further in this section the results of the measurements are presented separately for each of the methods applied. The raw data are quoted in distinctive tables. Next, these data are processed to obtain the characteristic parameters of the Weibull distribution function and the curves based on the parameters obtained are presented.

4.1. The series method

Tables 4 and 5 present the results of the measurements for mineral oil and natural ester impregnated pressboards respectively. As was indicated above, five series were carried out in each case. The distinctive series differ from each other by the number of breakdown events within ten applied lightning impulses.

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Table 4. Results of the series method for pressboard impregnated in mineral oil.

Index of test	**Series 1**	**Series 2**	**Series 3**	**Series 4**	**Series 5**
Voltage [kV]	108	110	112	114	116
No. of breakdowns	1	3	3	4	9
Probability	10%	30%	30%	40%	90%

Table 5. Results of the series method for pressboard impregnated in natural ester.

Index of test	**Series 1**	**Series 2**	**Series 3**	**Series 4**	**Series 5**
Voltage [kV]	100	102	104	106	108
No. of breakdowns	1	2	5	5	8
Probability	10%	20%	50%	50%	80%

Data received from experiments using the series method was analyzed with the use of the graphical method. To avoid complicated statistical difficulties of estimating parameter k of the Weibull distribution its value was assumed to be 3, which is an option commonly found in literature [10, 17]. For the Weibull distribution grid with $k = 3$, the sought function is a straight line described by (10):

$$\eta = a + b\zeta, \tag{10}$$

where:
$\eta = \sqrt[3]{-\ln(1 - F(u))}$,
$F(u)$ – distribution curve in a Cartesian coordinate system,
$\zeta = U$, meaning random variable.

To estimate a and b the least square method was applied.

Calculation of the parameters of the Weibull grid for $k = 3$ are shown in the Tables 6, 7 and 8 below.

Table 6. Calculations required to find parameters a and b for the Weibull grid ($k = 3$) for the results of the series method for mineral oil impregnated pressboard.

U_i	n_i	$\sum n_i$	$F(U_i)$	η_i	ζ_i	ζ_i^2	$\eta_i \zeta_i$
[kV]	[–]	[–]	[–]	[–]	[kV]	[kV^2]	[kV]
108	1	1	0.048	0.36	108	11664	39.46
110	3	4	0.190	0.60	110	12100	65.52
112	3	7	0.333	0.74	112	12544	82.90
114	4	11	0.524	0.90	114	12996	103.20
116	9	20	0.952	1.45	116	13456	168.12
			$\sum$	21.04	2274	258684	2410.64

Having values a and b, U_0 and U_m were estimated as the parameters of Weibull distribution function from the following formulas:

$$U_0 = -\frac{a}{b}, \tag{11}$$

$$U_m = U_0 + \frac{1}{b}. \tag{12}$$

Table 7. Calculations required to find parameters a and b for the Weibull grid (k = 3) for the results of the series method for natural ester impregnated pressboard.

U_i	n_i	$\sum n_i$	$F(U_i)$	η_i	ζ_i	ζ_i^2	$\eta_i \zeta_i$
kV	–	–	–	–	kV	kV^2	kV
100	1	1	0.045	0.36	100	10000	35.96
102	2	3	0.136	0.53	102	10404	53.78
104	5	8	0.364	0.77	104	10816	79.81
106	5	13	0.591	0.96	106	11236	102.11
108	8	21	0.954	1.46	108	11664	157.32
			$\sum$	21.72	2218	234380	2311.72

Table 8. Calculated parameters of the Weibull distribution function based on data from the series method.

	a	b	U_0	U_m	k
	[–]	[–]	[kV]	[kV]	–
Mineral oil impregnated pressboard	–15.21	0.143	106.3	113.3	3
Natural ester impregnated pressboard	–14.80	0.149	98.7	105.4	3

4.2. The step method

Tables 9 and 10 include the results of the measurements using the step method for mineral oil and natural ester impregnated pressboard respectively.

Table 9. Results of application of the step method for pressboard impregnated with mineral oil.

Index of test	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
Breakdown voltage [kV]	108	110	108	112	118	108
No. of tests till breakdown	4	5	4	6	9	4

Table 10. Results of application of the step method for pressboard impregnated with natural ester.

Index of test	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
Breakdown voltage [kV]	102	104	102	108	110	106
No. tests till breakdown	3	7	3	9	10	8

The data received from the step method were subjected to analysis using the Weibull distribution and the graphical method based on initial estimation applying the third central moment. The calculation were performed using Mathcad software where the grid with k constant was applied. The methodology used allowed to obtain the results which were included in Table 11.

Table 11. Calculated parameters of the Weibull distribution function based on data from the step method.

	a	b	U_0	U_m	k
	[–]	[–]	[kV]	[kV]	–
Mineral oil impregnated pressboard	–14.52	0.139	104.6	111.8	1.17
Natural ester impregnated pressboard	–8.84	0.092	95.8	106.7	2.46

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4.3. The up-and-down method

Tables 12 and 13 show the results of measurements using the up-and-down method for mineral oil and natural ester impregnated pressboard, respectively. In the column "Event" Y stands for occurrence of breakdown and N for lack of it. Since the first breakdown, according to the rules of the method, 21 shots were conducted.

Table 12. Results of the up-and-down method for pressboard impregnated with mineral oil.

Voltage [kV]	Event	Voltage [kV]	Event	Voltage [kV]	Event	Voltage [kV]	Event
102	N	114	N	110	N	114	Y
104	N	116	N	112	N	112	N
106	N	118	Y	114	Y	114	N
108	N	116	Y	112	N	116	N
110	N	114	Y	114	Y		
112	N	112	N	112	Y		
114	N	114	Y	110	N		
116	Y	112	Y	112	N		

Table 13. Results of the up-and-down method for pressboard impregnated with natural ester.

Voltage [kV]	Event	Voltage [kV]	Event	Voltage [kV]	Event	Voltage [kV]	Event
86	N	102	Y	106	N	110	Y
88	N	100	N	108	N	108	N
90	N	102	N	110	Y	110	N
92	N	104	N	108	Y	112	Y
94	N	106	N	106	Y	110	Y
96	N	108	Y	104	N		
98	N	106	Y	106	N		
100	N	104	N	108	N		

The results obtained were then processed as described above. The details of calculations are presented in Table 14.

Table 14. The results of calculations of breakdown voltage from the data received using the up-and-down method.

Parameter	U_0	ΔU	k	q	N	i	A	B	U_{50}	S	U_0(*Weibull*)
Unit	[kV]	[kV]	[–]	[–]	[–]	[–]	[–]	[–]	[kV]	[kV]	[kV]
Mineral Oil	112	2	10	11	9	4	14	24	114.1	0.9	110.2
Natural ester	102	2	9	12	9	6	27	100	107.0	6.9	76.9

5. Discussion and conclusions

In order to compare the results obtained by applying different testing methods the key parameters achieved from each of them are gathered in Table 15.

Table 15. List of key parameters received through analysis of measurement data.

Liquid	Method	U_0	U_m	k
Mineral oil	Series	106.3	113.3	3
	Step	104.6	111.8	1.17
	Up-and-down	110.2	114.1 (U_{50})	–
Natural ester	Series	98.7	105.4	3
	Step	95.8	106.7	2.46
	Up-and-down	76.9	107 (U_{50})	–

Based on the parameters of Weibull distribution obtained both for pressboard impregnated with mineral oil and that impregnated with natural ester, it can be noticed that parameters U_0 and U_m received from the series method and the step method are close to each other while in the case of the up-and-down method, where only U_0 can be compared, the values obtained differ significantly for both impregnating liquids. From these observations it can be assumed that the series and step methods give comparable results opposite to the up-and-down method. What is worth emphasizing with the results obtained is that the up-and-down method overstates the results for mineral oil impregnated pressboard and understates for natural ester impregnated one, when juxtaposing them with the rest of the methods applied. In addition, for the results received for natural ester impregnated pressboard it can be seen that they are more dispersed among the methods compared and U_0 parameter considered. The difference noticed in mentioned case reaches circa 20 kV the when up-and-down method is put together with the other methods used.

Since location parameter U_0 should be treated as the main indicator of dielectric properties of pressboards under test, deciding about insulation coordination of the insulating system, special attention must be directed solely on it. Hence, when a nearly 20% lower value of U_0 was evaluated from the up-and-down method with natural ester as the impregnating liquid, it is in all likelihood underestimating the actual value and such estimation will not result in catastrophic failures of electrical devices. However, it will lead to over-designing the device and financial mismanagement. In turn, when discussing the mineral oil impregnated pressboard, the U_0 parameter from the up-and-down method can cause the risk of unexpected failure in comparison with what is proposed by the other methods.

The differences that have emerged between the methods are, of course, natural due to specificity of each of them. It seems that the methods, whose results are subject of external statistical analysis (the series and step methods), give better results than the method based on an earlier elaborated equation for calculation of a given parameter. However, it is important to point out that, independently of the method applied, parameter U_0 obtained was lower than the lowest value received through the measurements and the difference between both values, excluding natural ester impregnated pressboard and the up-and-down method, did not exceed 6 kV (circa 5% in relative values).

Looking at the results from the viewpoint of the samples used for the measurements in series method the number of tested samples was 70 for mineral oil impregnated pressboard and 50 for natural ester impregnated pressboard, while for the up-and-down method the number of samples

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was only 28 and 29 respectively for mineral oil and natural ester. In turn, the step method used 32 samples for mineral oil and 40 for natural ester. These differences in the values of used samples for the up-and-down and step methods would further decrease in industrial-grade research due to not changing samples in the case of lack of breakdown. This would result in destroying 6 samples while testing them with the step method and 10/11 samples with the use of the up-and-down method. Whereas the application of the step method resulted in satisfying estimation of the breakdown voltage for such a low number of samples, the up-and-down method might still be viable with an increased number of samples used. While it would be more expensive than the step method, the main advantage of the up-and-down method is low labor intensity and lower sample requirements than the series method. Increasing the number of tested pressboard pieces to about 20 and changing them only after a breakdown might allow the up-and-down method to be a useful in-between way of testing insulation, being faster and easier to analyze than the series and step methods, while not consuming a significant number of samples.

Finally, it can be stated that the step method turned out to be great potential replacement for the series method. It is both inexpensive and less labor intense than the series method, while giving similar results. Its merit is also the fact that the vector of random variables obtained with this method is a clear group of data for which a comprehensive statistical procedure of parameters estimation can be applied. It means that in the case of application of the three-parameter Weibull distribution function, all three parameters are determined, which is not the case when the series method is considered (shape parameter $k = 3$ is imposed). In addition, the reliability of the step method would further increase with the increasing number of samples tested. After comparing 6 destroyed samples of the step method and 20/21 of the series method, it appears to be much better way of testing solid insulation materials. Hence, it may be suggested that in solid insulation materials testing at lightning impulse voltage the step method seems to be the best option, both as intuitive method for the measurements as well as economically justified. The statement above can be, however, generalized at this stage of the studies only for the conditions of experiment performed within this work, that is for the electrode arrangements representing non-uniform electric field distribution. Confirmation of the findings for other field distribution requires further work. The same concerns the issue of the number of samples required for testing and the number of series as well as the number of breakdown voltage lightning impulses necessary to obtain a reliable result – this should be verified, for example, by repetition of the tests or performing them for other pressboard thicknesses.

Apart from conclusions regarding the comparison of the statistical methods, it is clearly evident that natural ester provides lower breakdown voltage of pressboard impregnated with this liquid. However, the difference in the breakdown voltage expressed by location parameter U_0 is of about 10% (excluding the up-and-down method which was treated as not fully reliable in the analyzed case study), which leaves natural ester as quite viable substitution for mineral oil for locations in environmentally protected areas. A slight increase in costs connected with necessity of providing greater insulation levels may be enough compensation for potential damage to natural habitats caused, for example, by a mineral oil leakage. Moreover, in some locations the use of mineral oil may become prohibited, so in such the cases, the use of natural ester filled transformers would be an obvious choice.

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