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COMPARISON OF THE METHODS APPLIED FOR 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 the results of lightning impulse breakdown voltage measurements of solid materials such as insulating pressboard. These three methods are series method, step method and up-and-down method, which are applied commonly in high voltage engineering area for withstand voltage estimation. To obtain the data needed for the analysis the series of experimental studies were carried out. It included the studies on mineral oil and natural ester impregnated 1 mm in 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 method 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 specially developed equation, which always arouses a doubt. From the methods applied it seems that the step method may be a great substitution for the series method as intuitive, fast in application and limiting the number of samples, in terms of solid insulation materials testing.

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

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1. Introduction

The phenomena concerning *lightning impulse* (LI) voltage based stresses have a strongly statistical nature [1-4]. From 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 experiment, where the series of lightning impulses are applied to the insulating system tested. Among these method may be mentioned a series method, a step method or an up-and-down method. Each of them is characterized by a specific approach for the conducting the experiment aiming at obtainment the data for further analysis. The characteristic measurement procedures have advantages and disadvantages and differ from each other with approach to the calculation of accuracy and errors [5-8]. When the data concerning breakdown voltage are obtained, the breakdown probability is then 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 50% breakdown probability. However, when statistical analysis is performed on

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the basis of selected distribution function (usually Normal or two-parameter Weibull distribution function is applied), the breakdown voltages corresponding with 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 three-parameter Weibull distribution, for which the withstand voltage may be directly evaluated on the basis of the location parameter U_0, called also 0% probability [3, 11].

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

From above, the goal 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 on indication of the merits and deficiency of the methods in order to propose the best approach when the need for evaluation of the LI breakdown voltage of solid materials exists. It is especially important in the case of making the tests under non-uniform fields and lightning impulses, which are the reference to the situation of local microdefect that may appear in the 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 liquid kind used for impregnation on the LI electric strength of pressboard tested. This aspect results from the observed significant increase in a number of transformer units filled with natural ester worldwide [14-16]. Since the impregnation medium may influence the dielectric strength of pressboard at 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 significant loss in the accuracy and reliability of the results obtained. This is also the significant aspect discussed herein.

Hence, this may be stated that 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, due to time and material consuming tests the solid insulation like pressboard is not tested extensively. Hence, the author's approach proposes the evaluation of the methods mentioned in order to specify a good and economical way for reliable testing of solid materials at lightning impulse voltage.

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

2.1. Series method

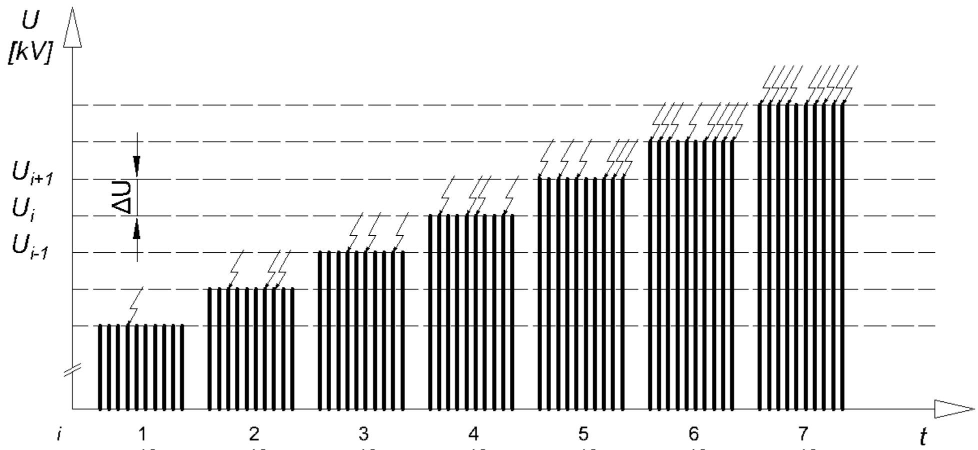
One of the most popular methods used in high voltage insulation tests is a series method [1, 5, 7, 15]. It involves a number of series with predetermined and constant standardized voltage impulse's peak value for each set. For each of series, that is for each voltage level, the n_i shots are supplied of which k_i lead to sample breakdown. From this data breakdown probability at given voltage level may 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 may be drawn.

The number of voltage tests per series is defined based on analysis of normal distribution estimation and expected error values. With the increase of 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 series method take the number of samples between 10 and 20, wherein for solid materials, due to destructive type of 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 within reasonable effort and use of samples.

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



Series number	i	1	2	3	4	5	6	7
Amount of impulses	n_i	10	10	10	10	10	10	10
Number of broken samples	k_i	1	3	3	4	6	7	9
Probability	k_i/n_i	0,1	0,3	0,3	0,4	0,6	0,7	0,9

Fig. 1. An example of procedure of insulation test using series method.

The example presented consists of seven series and each series includes 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 entire test. It is important for the series method that we cannot consider the probability equal to 0% and 100% respectively. In other words, the series with none of breakdown and with all breakdown within a given series is not taken into account.

Despite simplicity of series method application and working out of the results from this method is problematic while testing non-regenerating insulation. It is due to its labor intensity

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and high costs of samples, which will no more be used after tests. The use of series method is not possible with low number of samples, thus research with this method is quite expensive.

2.2. Step method

A step method, known also as Tetzner method from the name of its author, is considerably cheaper way of conducting the insulation tests at lightning stress comparing with the series method. It is widely used in maximum likelihood analysis among many disciplines [1, 2, 5, 7, 15, 16]. In this method, voltage is raised by step ΔU from starting value U_0 until breakdown happens. After that 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 withstand if the measurement may be treated as true. An example of the use of step method is shown in Fig. 2.

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 may be analyzed using any of known distribution functions.

The step method may also be used with number of impulses per step greater than one. In that case procedure is similar to this 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 shots are planned. If sample is not broke down, next impulses are supplied with peak value raised by ΔU. Destruction of sample means beginning of new series, started again from U_0 level.

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

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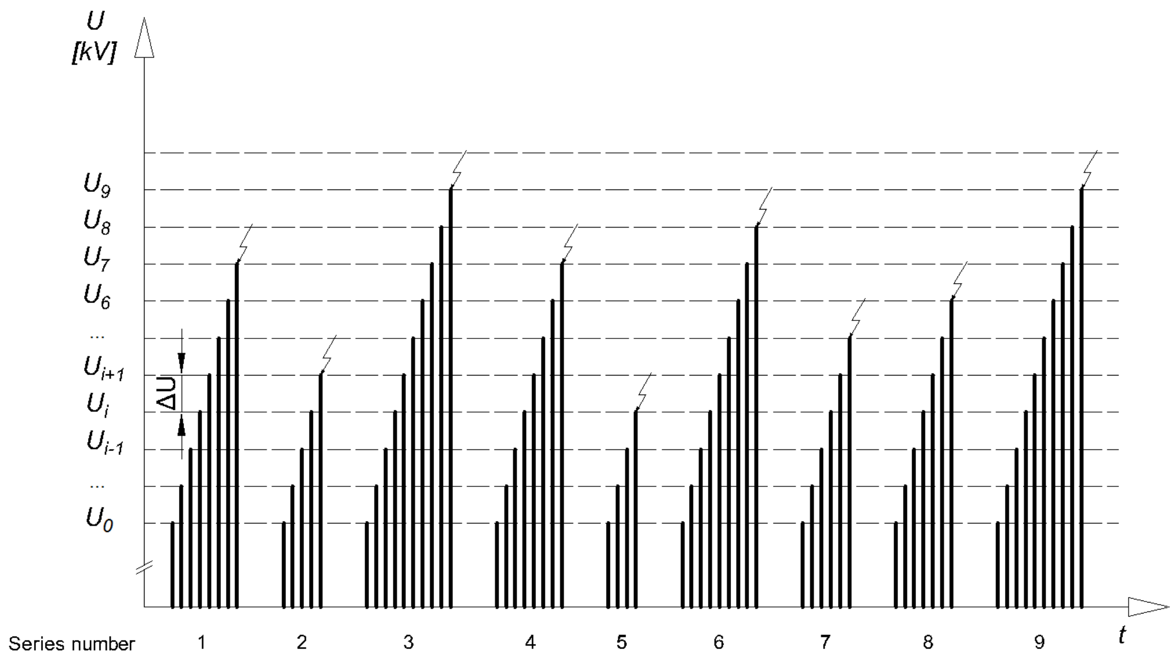

Fig. 2. An example of the procedure of insulation test using step method.

2.3. Up-and-Down method

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

- If at the previous voltage level breakdown or flashover took place, the subsequent level of voltage is lower by ΔU;
- If at the previous voltage level breakdown or 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.

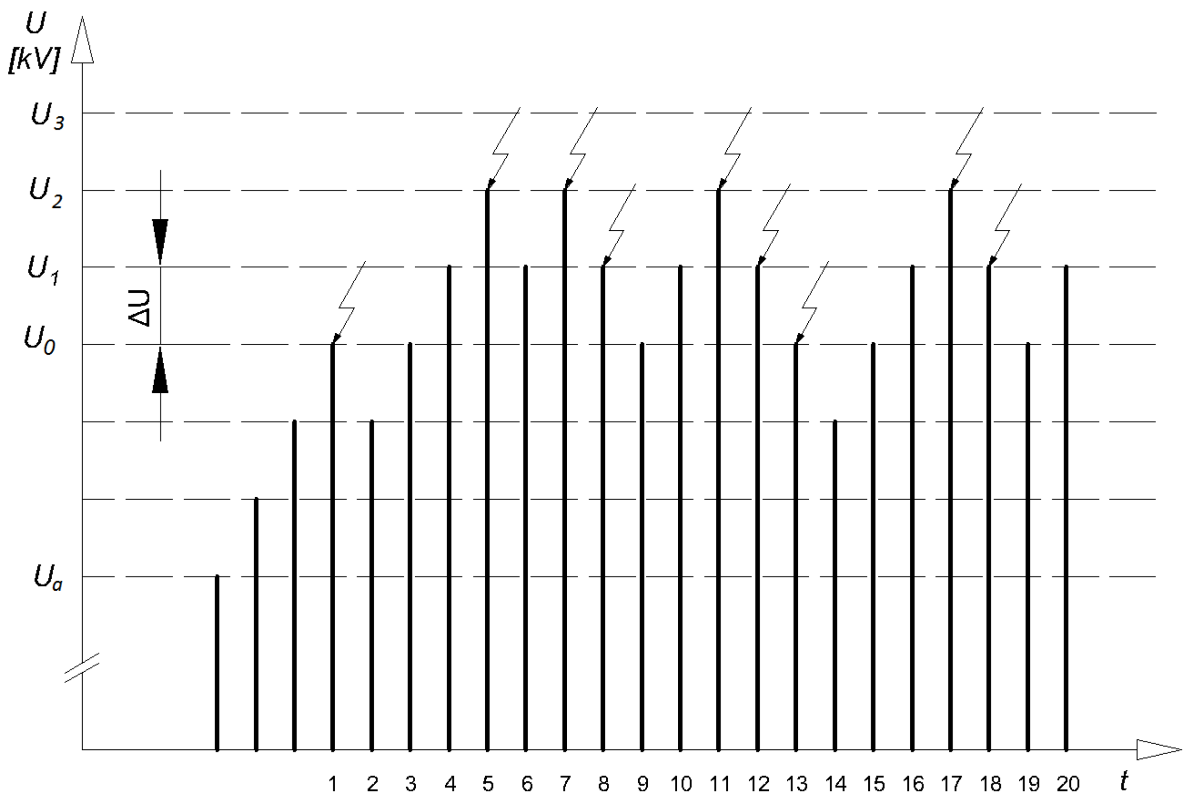

Fig. 3. An example of the procedure of insulation test using up-and-down method.

The shots are started to be counted from this, which causes 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):

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

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

Next, N number is calculated as:

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

Based on calculated *N*, each voltage step of valid test is indexed from 0 attributed for 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 chosen *N* (breakdowns k_i or non-breakdowns q_i;
m – number of voltage steps;
"+" in formula (6) – is taken when *N* number of breakdowns was greater than number of no-breakdowns, otherwise "-" is taken;
U_0 in formula (6) – means the lowest value among the breakdown voltage values obtained from the measurement procedure performed.

Achieved results might be recalculated into 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. The 20-30 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 a cumulative breakdown distribution P(U). This would be associated with significant errors in estimating the breakdown voltages related to low probabilities.

2.4. Three-parameter Weibull distribution function

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

One of the commonly applied extreme value based distribution function is Weibull distribution. It is exponential distribution used widely 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):

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

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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 concerned the pressboard samples of size 200 x 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.

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

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 containment	%	4.2
Ash containment	%	0.3

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 50Hz	<0.002	<0.05
Dielectric permittivity at 20 °C	2.2	3.2

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

1) Drying pressboard for 16 hours under vacuum <100Pa and in temperature of 105 °C in a vacuum chamber.

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

During measurements the following equipment was used:

1) 4-stages lightning impulse Marx generator able to generate the standard (1.2/50 μs) lightning impulse up to 400kV in peak value.
2) Electrode system consisting of flat grounded electrode and sharp high-voltage (HV) point electrode representing non-uniform electric field distribution (see Fig. 4). The HV electrode was held by non-conductive support arm, which reduced pressure towards pressboard sample.
3) Tektronix DPO3054 digital oscilloscope for registration of voltage waveforms.
4) MWS-2000AD peak value voltmeter and resistive voltage divider of ratio equal to 500, both used for measurement of peak value of lightning impulse.
5) FLUKE 117 true RMS multimeter working with resistive voltage divider of ratio 1000 used to measure DC charging voltage.

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

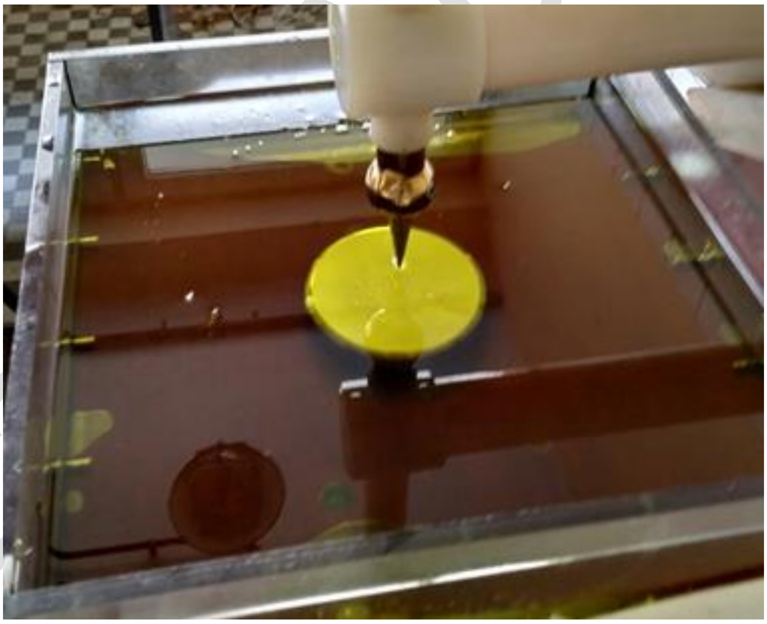

Fig. 4. Real view of electrode system used in laboratory measurements.

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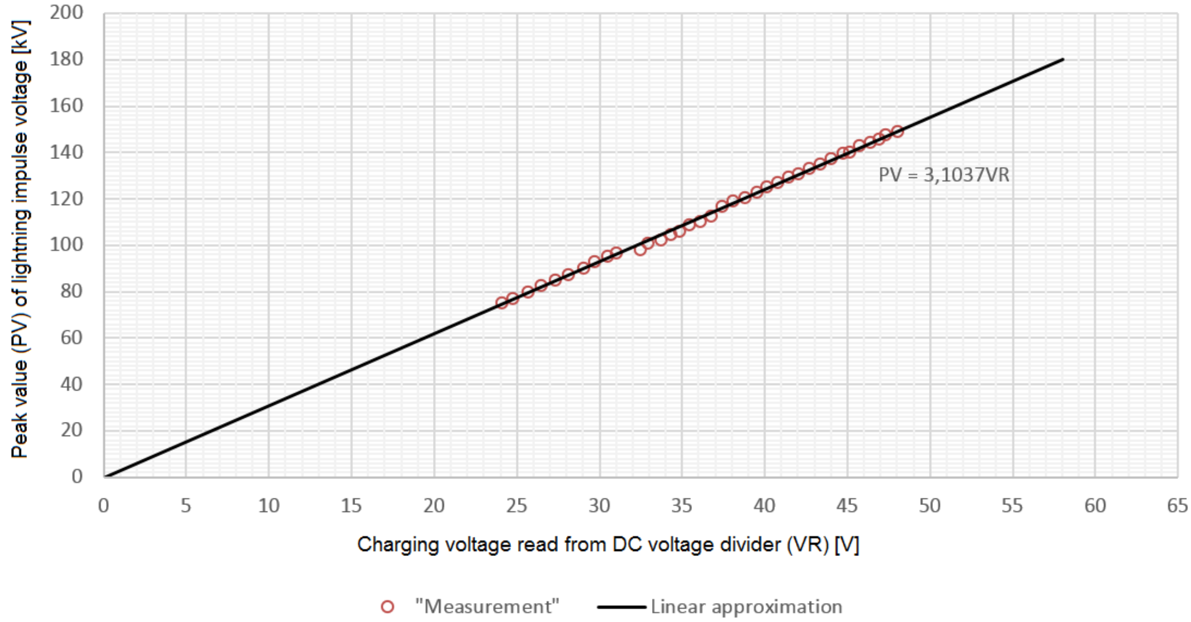

Fig. 5. Generator scaling curve.

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

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

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

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

Table 3. Results of breakdown voltage based on pre-tests.

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

From the above data the starting voltages chosen for the series method were 104 kV and 100 kV for mineral oil impregnated pressboard and for natural ester impregnated pressboard, respectively. It was assumed that 4 kV lower value then the lowest value from the pre-tests will be chosen as starting point. The voltage step was equal to 2 kV in both cases as more proper from statistical point of view. Testing the samples using series method the five series were carried out for both liquids considered as 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 the

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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 impregnated pressboard and for natural ester impregnated pressboard. The voltage step was however the same as in the case of series method.

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

4. Results

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

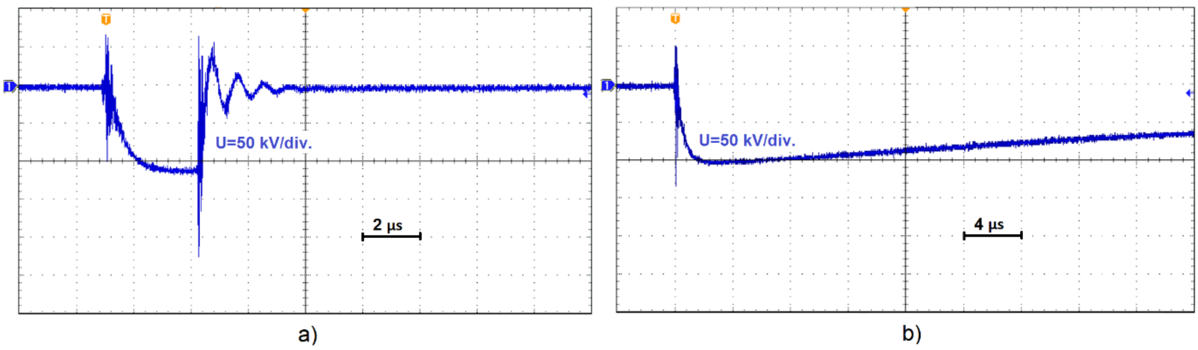

Fig. 6. Example of oscillograms of voltage waveform: a) when breakdown occurred, b) when breakdown did not occur.

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

4.1. 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 number of breakdown events within ten supplied lightning impulses.

Table 4. Results of 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%

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Table 5. Results of 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 series method was analyzed with use of graphical method. To avoid complicated statistical difficulties of estimating k parameter of Weibull distribution its value were assumed as k=3, which is commonly used option in literature [10, 17]. For Weibull distribution grid with k=3, the sought function is a straight line described by (10):

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

where:

$\eta = \sqrt[3]{-\ln\left(1 - F(u)\right)}$,

$F(u)$ − distribution curve in cartesian coordinate system,

$\zeta = U,$ meaning random variable.

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

Calculation of the parameters of Weibull's grid for k=3 are shown in the table below:

Table 6. Calculations required to find a and b parameters for Weibull's grid (k=3) for the results of 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

Table 7. Calculations required to find a and b parameters for Weibull's grid (k=3) for the results of 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

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

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

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

The results are set in Table 8.

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

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

Table 9. Results of application of 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 application of 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 step method were subjected to analysis using Weibull distribution and graphical method based on initial estimation applying third central momentum. Calculation were made 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 Weibull distribution function based on data from 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

4.3. Up-and-down method

Tables 12 and 13 show the results of the measurements using 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 first breakdown, according to the rules of the method, 21 shots were conducted.

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Table 112. Results of 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 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 up-and-down method application.

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

Table 1512. List of key parameters received after 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 pressboard impregnated with natural ester, this may be noticed that the

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parameters U_0 and U_m received from series method and step method are close to each other while in the case of up-and-down method, where only U_0 may be compared, the values obtained differ significantly for both impregnating liquids. From these observations this may be assumed simply that series and step method give comparable results opposite to the up-and-down method. What is worth to be emphasized within the results obtained that the up-and-down method 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, for the results received for natural ester impregnated pressboard it can be seen that they are more dispersed within the methods compared and U_0 parameter considered. The difference noticed in mentioned case reaches circa 20 kV when up-and-down method will be put together with other methods used.

Since location parameter U_0 should be treated as main indicator of the dielectric properties of the pressboards under test, deciding about insulation coordination of the insulating system, the special attention must be directed solely on it. Hence, when nearly 20% lower value of U_0 was evaluated from up-and-down method and natural ester as impregnating liquid, it is in all likelihood underestimating 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 mineral oil impregnated pressboard, the U_0 parameter from up-and-down method can cause the risk of unexpected failure in comparison what is proposed by other methods.

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

Looking at the results from the viewpoint of the samples used for the measurements for series method the number of tested samples was 70 for mineral oil impregnated pressboard and 50 for natural ester impregnated pressboard; for up-and-down method the number of samples was only 28 and 29 respectively for mineral oil and natural ester; the step method used in turn 32 samples for mineral oil and 40 for natural ester. These differences in the values of used samples for up-and-down and step method would be further decreased in case of industrial-grade research due to not changing samples in case of lack of breakdown. This would result in destroying 6 samples while testing them with step method and 10/11 samples with the use of up-and-down method. Whereas, step method resulted in satisfying estimation of breakdown voltage in such a low number of samples, the up-and-down method might still be viable with increase of number of used samples. While it would be more expensive than use of step method, the main advantage of up-and-down method is low labor intensity and lower sample requirements than series method. Increasing number of tested pressboard pieces to around 20, while changing it only after breakdown might allow up-and-down method to be useful in-between way of testing insulation, being faster and easier to analyze than series and step methods, while not consuming significant number of samples.

Finally, this may be stated that the step method turned out to be great potential replacement for series method. It is both inexpensive and less labor intense than series method, while giving similar results. Its merit is also the fact that vector of random variables obtained using this method is a clear group of data, for which a comprehensive statistical procedure of parameters estimation may 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

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applied when series method is considered (shape parameter k=3 is imposed). In addition, the reliability of the step method would further increase with increasing number of tested samples. After comparing 6 destroyed samples of step method and 20/21 of 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 in approach for the measurements as well as economically justified. Above statement 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 require further works. The same concerns also the aspect of the number of samples required for testing and the number of series as well as the number of lightning impulse breakdown voltage necessary to obtain a reliable result – this should be verified by repetition of the tests or performing them for other pressboard thicknesses for example.

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