BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Volumul 62 (66), Numărul 1, 2016
Secţia
ELECTROTEHNICĂ. ENERGETICĂ. ELECTRONICĂ

SPECIAL DIELECTRIC TESTS FOR COMPOSITE INSULATORS

BY

MARIAN COSTEA*, ILEANA BĂRAN and TUDOR LEONIDA

Politehnica University of Bucharest

Received: February 15, 2016
Accepted for publication: February 29, 2016

Abstract. The manufacturing of composite insulators has matured in recent decades and their use has become an increasingly widespread due to the advantages involving primarily low weight and very good behavior in terms of pollution. In order to detect hidden defects, the laboratory tests are specific and require special facilities. The paper focuses on the issue of steep-front impulse tests, with a slope of at least 1,000 kV/µs, describes the possibilities to obtain such a shape using a classic impulse generator (with or without intervention in the shaping circuit) and presents the obtained results. To frame these results in the general category of insulation performances to fast and very fast front durations, comparison have been made with breakdown voltage-time characteristics to standardized lightning impulse.

Key words: composite insulator; impulse generator; steep-front impulse test; voltage-time characteristic.

1. Introduction

The composite insulators are used nowadays on a large scale because of certain advantages comparing to ceramic insulators and not only in terms of prices. After estimation made by Pigini (2014), there were about 20 million composite high voltage line insulators in operation at the end of 2010. But it is a roughly information obtained by using various sources. It may be mentioned

---

*Corresponding author : *e-mail*: marian.costea@upb.ro

also that the widespread use of these insulators started only after 1980. The main reason for this large use widespread is the low weight (about only one tenth from an equivalent string made from glass or porcelain) and the good performances in polluted areas (because of the so-called lotus effect). There are also other features which recommend their use both in AC and DC applications, mainly in the high voltage transmissions lines, for long insulators strings. Many works were dedicated to their characteristics, manufacturing processes or behavior in operation (Papailiou *et al.*, 2013; Gubanski, 1992; Farzaneh *et al.*, 2009).

But there are not only advantages regarding the manufacturing, testing, storage, installation or operation of composite insulators.

Because of their composite structure regarding the insulating part (two insulating materials with different roles and properties), high exigencies are imposed during manufacturing process, and also special laboratory tests to verify the quality of components and of whole assembly.

Among the specific electrical tests must be mentioned, for silicone rubber the "erosion test" and for finished product the "tracking and erosion test" and "steep-front test" (IEC 60587:2007 Std; IEC 62217:2012 Std). Generally, there are four types of tests: design, type, sample and routine test.

The design tests are intended to verify the design, the used materials and the manufacturing technology. The type tests are intended to verify the main characteristics of the insulator, which depend primarily of its shape and dimensions. The sample tests are used to verify the characteristics of insulators which depend on the manufacturing quality and of materials. These tests are performed on insulators randomly extracted from the lots offered to the customer. And finally, the routine tests are aimed to eliminate the insulators which have manufacturing defects. They are performed for each insulator which will be supplied.

Regarding the dielectric tests, specific tests for composite insulators are, as might easily presume, the design tests.

2. Failures and Causes which Produce Them

Composite insulators can be affected by a number of defects related to their structure, the materials they are made, the manufacturing process quality and external factors acting during operation. As presented by Pigini (2014), an overall failure rate for composite insulators ranges from 10^{-5} to 10^{-4} the mechanical failures being predominant, and this is with one order of magnitude higher than that of ceramic insulators strings, considered to lie between 10^{-6} and 10^{-5}. The difference is justified by the different degree of maturity of the two technologies, but continuous improvement of the reliability of composite insulators is a recognized fact.

Under the combined influence of the electric field and of atmospheric pollution on the housing and sheds, cracks, tracks or erosions may occur. According the IEC 62217, a crack is an internal fracture or surface fissure with a depth greater than 0.1 mm. Not only can the electric field produce such a failure. A track is a conductive path, even in dry conditions, developing on the surface of insulating material. The erosion is an irreversible loss of material on the insulator's surface, but without conductive properties. These kinds of problems may lead in time to flashover or puncture of insulation. The main contribution to the development of such a phenomenon has the electric field which determines corona discharges on the end fittings or on the water droplets of the surface of the insulator.

The attack of rodents to the silicone rubber during the storage or of some birds species during operation are other problems which must be avoided. Moisture in certain locations is likely to lead to the developing on the surface of mosses and lichens, which not only retain water, but also affects the insulator housing, changing its color and decreasing the hydrophobic properties.

Brittle fracture is also a dangerous phenomenon which destroys the insulator due to the sudden breaking of the core. Although the rate of failure is very low, this process was systematically studied in laboratory to identify the causes. The majority of above presented problems can be technically solved and the laboratory design tests have the goal to identify them in this phase.

3. Considerations About the Special Electrical Tests

The test methods for evaluating resistance of insulating material to tracking and erosion, under severe ambient conditions and power frequency are described by IEC 60587 standard. The goal of this test is to classify the insulating material. The test is performed using parallelepipedic specimens having a thickness (recommended) of 6 mm and at least 50 mm × 120 mm in surface. With the help of stainless steel flat electrodes, the specimen is installed on an inclined plane (at an angle of 45°). By means of a filter paper pad clamped under the top electrode, a contaminant liquid solution with a controlled drop wise flow on the specimen is applied. A power frequency stabilized source (up to about 6 kV and with a rated current not less than 0.1 A) is used to apply the voltage between the electrodes. There are two methods to evaluate the specimen behavior: one of them using a constant voltage and the other by applying a stepwise voltage. Each method has a corresponding end-point criterion. After reaching this point the depth of the tracks is measured using a special gauge and the material is classified accordingly.

The quality of the interfaces and connections of end fittings and respectively the compliance of shed and housing material to the standard prescriptions must be verified according IEC 62271 (IEC 62217:2012 Std).

Regarding the shed and housing material tests, the last edition of standard has kept as normative only 1,000 h salt fog test. It must be mentioned that the first edition of IEC 62217 has included two other alternative tests: a 5000 hour multi-stress test and a tracking wheel test. Now, these tests are described in a technical report (IEC TR 62730:2012) in order to be used mainly for research purposes.

Among the design tests, the steep-front impulse can be considered one of the most difficult (Gorur, 2015) but relevant test (providing most information) regarding the interfaces and connections of end fittings. It is considered (Gorur, 2015) that "the probability of puncture in a steep front test increases with defects and with the steepness of the applied voltage" (in this case an upper limit of the steepness must be considered or stipulated in the standard? Or, what is the limit to produce a puncture in a healthy insulator?).

The test is mentioned in IEC 61109 (IEC 61109:2008 Std) and fully described in IEC 62217 (IEC 62217:2012 Std). It succeeds after the reference dry power frequency test and pre-stressing tests (mechanical and thermal ones). After that the insulators must be subjected to water immersion pre-stressing: they will be kept in boiling de-ionized water (or tape water) with a prescribed content of NaCl for 42 h. After this conditioning the insulator must be allowed to cool in the water and then the test could be started. Each specimen must be inspected and no cracks are allowed.

The steep-front impulse test consist in applying a voltage whose rise slope is at least 1,000 kV/µs to the whole insulator (if the distance between its metal fittings does not exceed 500 mm) or, for longer insulators, to a segment of at most 500 mm length. This insulator segment is bounded by strips of copper (usually) with a width of approx. 20 mm and thickness up to 1 mm and the tests must be performed, successively, over the entire insulator length. The voltage must be applied between two such successive clips firmly fixed to the surface of the insulator. The steepness of 1,000 kV/µs is being understood as the average slope of impulse (a more specific requirement is not stipulated in the standard).

Because each interval defined in the manner stated above must be subjected of 25 impulses with positive and negative polarity, it is a time consuming test especially for long insulators.

The condition relating to the voltage to be applied is that each impulse must have a front which fulfills the requirement of steepness and to result an external flashover between electrodes every time. (In the case of hollow insulators the standard specifies that measures must be taken to prevent internal flashovers.) Criterion for acceptance: no puncture of any part of the insulator shall occur.

4. Generator Setting and Test Arrangement

To perform the steep front impulse voltage test it is necessary to set the impulse generator to produce an impulse having the required steepness of the front and to charge adequately the shaping circuit in order to obtain a flashover each time that the generator is triggered.

An impulse having such a slope can be obtained basically in these ways: (1) with a classic impulse generator set to obtain disruptive discharges in the highest portion of voltage-time characteristic of the tested insulation; (2) by appropriate designing of the shaping circuit of an impulse generator in order to obtain a shorter front time; (3) using an auxiliary output circuit ("peaking circuit", (Schon, 2013)) usually containing an additional spark gap (singular or multiple) between the output of generator and the object under test. Hence, we used the first two methods.

It would be possible to reach an impulse front with the required magnitude (1,000 kV/µs) with a generator which produce a standardized lightning impulse (1.2/50 µs) if the amplitude of the output voltage would be enough high compared to the insulation withstand voltage. Regarding the calculation mode of the impulse voltage slope, the dedicated standard does not offer other details. As a result we considered the front time as is determined for the standardized lightning impulse (LI).

The resizing of the shaping circuit is other feasible solution if the existing elements of a classic generator can support without degradation the new stress.

For this second case, we calculated for an existing generator with given capacitors, the necessary values of series resistances in order to produce an impulse with a front shorter than 1.2 µs (the proposed time front value was under 0.8 µs). We used six stages of an impulse generator (of 14 stages) having the maximum each stage charging voltage of 250 kV. Reducing the series resistance of the shaping circuit at about 2/3 of initial value, the front time was reduced practically in the same ratio. The excessive reduction of series resistance can lead to oscillations even on the front of impulse because of the inherent inductance of the components of a stage (the circuit damping is reduced) and cause to it unacceptable thermal stress. On the other hand, the approved measuring system for a LI (full or chopped) remains able to evaluate correctly such a signal. The shape of a new obtained full impulse is shown, for negative polarity, in Fig. 1.

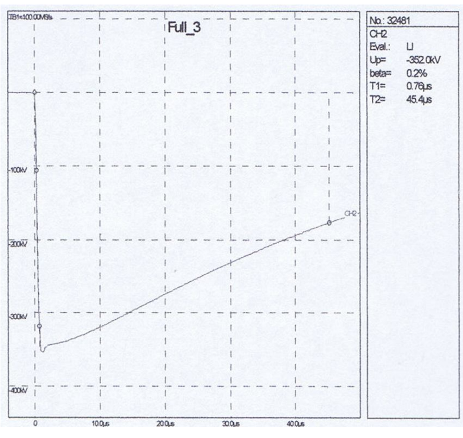

Fig. 1 – The full impulse with front time shorter than standardized LI.

This impulse was measured with the generator loaded with the composite insulator prepared for the test (with 50 cm between electrodes, as presented above). The flashover occurs with about 50% probability, at a peak value of about 345 kV for positive polarity and about 385 kV for negative polarity, but the impulse slope doesn't comply with the standard requirement.

As a result, the impulse amplitude must be increased until the slope condition will be satisfied.

5. Experimental Results

5.1. Lightning Impulse Voltage-Time Characteristics

In order to obtain a full description of the insulation performance to fast rising impulse voltages, the voltage-time characteristic of the 50 cm section of the insulator string under test was determined using lightning impulse voltage provided by the impulse generator in standard configuration. The samples acquired in order to determine the voltage-time characteristics for positive and negative polarity were obtained using standard lightning impulses with crest value going from U_{50} to (2…3) × U_{50}.

The data were fitted with a nonlinear model inferred using a least-squares formulation. A nonlinear model is defined as an equation that is nonlinear in the coefficients or a combination of linear and nonlinear in the coefficients.

Nonlinear models are more difficult to fit than linear models because the coefficients must be estimated using an iterative approach. The technique used to obtain estimations for the model coefficients was the so called "Trust-region" that can solve difficult nonlinear problems more efficiently than other algorithms. The model used for the voltage-time characteristics was the following:

$$U_A = a\left(1+\frac{b}{T_A}\right)+\varepsilon\,, \tag{1}$$

where: U_A is breakdown voltage, [kV], T_A – time to breakdown, [μs], ε – error in [kV].

The estimated coefficients and their 95% confidence limits are given in Table 1.

Table 1
Results of the Fitting Procedure

	a, [kV]	b, [μs]	R^2
Positive polarity	285.7 (280.2, 291.2)	1.551 (1.496, 1.605)	0.993
Negative polarity	329.2 (324.0, 334.4)	1.264 (1.221, 1.307)	0.991

The quantity R^2 is the coefficient of multiple determinations and its value measures the success of the model in explaining the variability of the data. For the models in Table 1 the R^2 values are very close to 1 which indicates the suitability of the model to the sample data analyzed.

Also in Fig. 2 two types of prediction bounds are represented: 95% prediction bounds for new observations and 95% prediction bounds for the fitted function, the prediction interval for new observations being larger than the prediction interval for the function itself. As the time to breakdown goes towards small values both prediction intervals become narrower indicating that the upper part of the voltage-time characteristic is better defined than the lower part.

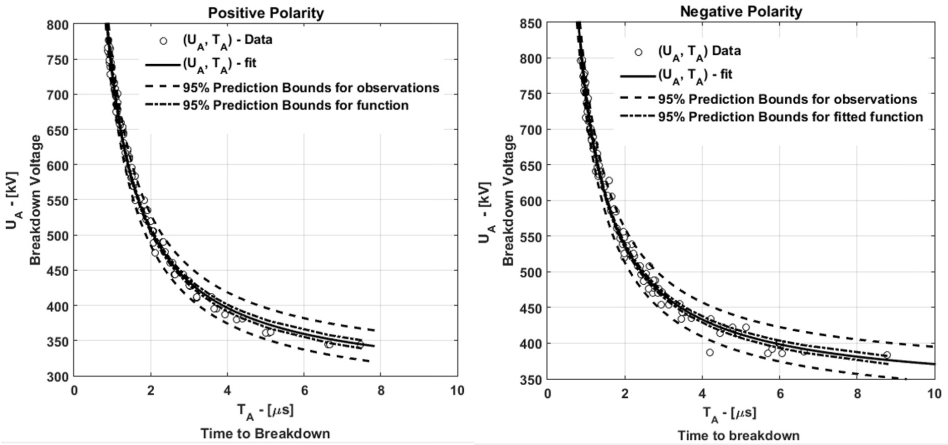

Fig. 2 – Voltage – time characteristics for positive and negative polarity for standardized lightning impulse.

For non-linear fitting, the computation of confidence intervals is not an easy task, especially when both predictor and predicted variables are subject to statistic variability. The procedure used to infer the coefficients given in Table 1 allows also getting equations for the prediction bounds. The general expression fitting the prediction bounds is given:

$$U_A\big|_{\mathrm{INF\,or\,SUP}} = \alpha \exp(\lambda_1 T_A) + \beta \exp(\lambda_2 T_A) \qquad (2)$$

The values of the coefficients allowing computing the 95% prediction bounds for new observations are summarized in Table 2. They can be used to calculate a confidence interval associated to the predicted variable (*i.e.* U_A) given a value of the predictor (*i.e.* T_A). The difference between the inferior (INF) and superior (SUP) prediction bounds represents the width of the confidence interval.

Analyzing the voltage-time characteristics one can see that due to the values of the inferred coefficients, the two curves intersect in a point having the coordinates T_A = 0.62 μs and U_A = 1,000 kV.

If the breakdown voltage overcomes this value, the polarity effect experiences a reversal, the positive polarity breakdown voltage becoming higher than the negative one.

Table 2
95% Prediction Bounds for New Observations

	Bound	α [kV]	λ_1 [1/µs]	β [kV]	λ_2 [1/µs]
Negative	INF	861.4	–1.11603	439.7	–0.02863
	SUP	865.4	–1.11757	498.8	–0.02441
Positive	INF	919.6	–1.12197	409.4	–0.03406
	SUP	921.8	–1.12179	463.4	–0.02887

The 1000 kV/µs is reached for the peak voltages which exceed at least 762 kV (T_1 = 0.76 µs) for negative polarity and respectively 752 kV (T_1 = = 0.75 µs) for positive polarity. Keeping in mind these values we proceed to the second method.

5.2. Lightning Impulse Voltage-Time Characteristics

For this tests, we used a reduced series resistor in the shaping circuit of generator and the front time of full impulse became 0.76 µs. If the charging voltage was increased up to 130 kV/stage, the peak voltages which ensure the required slopes were over 700 kV as presented in the Fig. 3, but considering as front time the conventional front time as it has been defined for the standardized LI, and not as time to crest. As it can be observed, the impulse front is almost linearly, smooth, without oscillations. The chopping time is about 1 µs and it is very close to the time to crest. A series of 25 impulses were applied for each polarity and after each set the state of the insulator was verified.

The variables observed during the experiment were those provided by the transient analyzer, namely:

U_A, [kV] – breakdown voltage defined as the peak voltage value (for breakdowns occurring on the tail of the wave) or as actual voltage value (for breakdowns occurring on the front of the wave),

T_1, [µs] – front time (defined as for lightning impulse),

T_A, [µs] – time to breakdown (time to chopping),

all measured values complying with the provisions in IEC 60060-1:2010 Std.

To the variables directly observed such as those quoted above, we have added an indirect observable variable, *i.e.* the average slope *S*, [kV/µs], computed as the ratio of the breakdown voltage U_A to the conventional front time T_1.

A quick view on the procedure’s results is offered by the quantities summarized in Table 3.

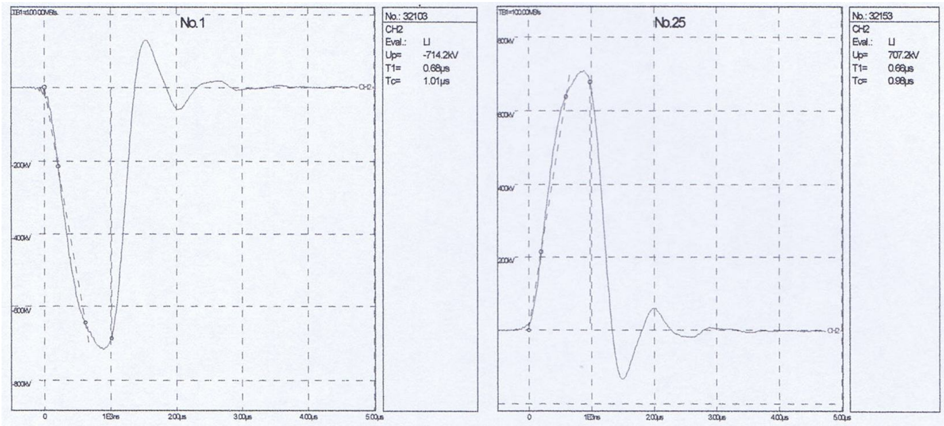

Fig. 3 – Examples of steep-front impulses (negative and positive) applied during specific test on a 110 kV rated voltage composite insulator.

Table 3
Basic Descriptive Statistics

			Mean	Median	Min	Max	SD	CV=SD/Mean
Positive polarity	U_A	kV	711.5	712.0	706.0	715.0	2.8	0.00396
	T_A	μs	0.98	0.98	0.94	1.03	0.02	0.02344
	S	kV/μs	1044.4	1045.0	1020.0	1070.3	12.1	0.01156
Negative polarity	U_A	kV	703.5	704.0	696.0	710.0	3.8	0.00541
	T_A	μs	0.95	0.95	0.90	0.99	0.02	0.02386
	S	kV/μs	1073.7	1072.1	1050.7	1094.7	12.4	0.01157

SD – Standard deviation; CV – coefficient of variation.

As it can be observed, the scatter of the observed variables around the central values of their respective distributions are small, both in terms of absolute (SD – sampling standard deviation) and relative value (CV).

The time sequences of slope values evaluated for each steep-front impulse applied during the test procedure are represented in Fig. 4 for both polarities. The slope values are randomly spread around the sample mean without highlighting trends.

For every steep-front impulse applied during the test procedures the slope had values higher than 1,000 kV/μs as the standard requires.

The corresponding time sequences of the breakdown voltage exhibits weak, but statistical significant, ascending trends for both polarities as it can be seen in Fig. 5 *a*.

In addition, the breakdown voltage values for positive polarity are higher than those measured for negative polarity, contrary to the known polarity effect on voltage breakdown in non-uniform asymmetrical electric fields which places the negative breakdown voltage over the positive one.

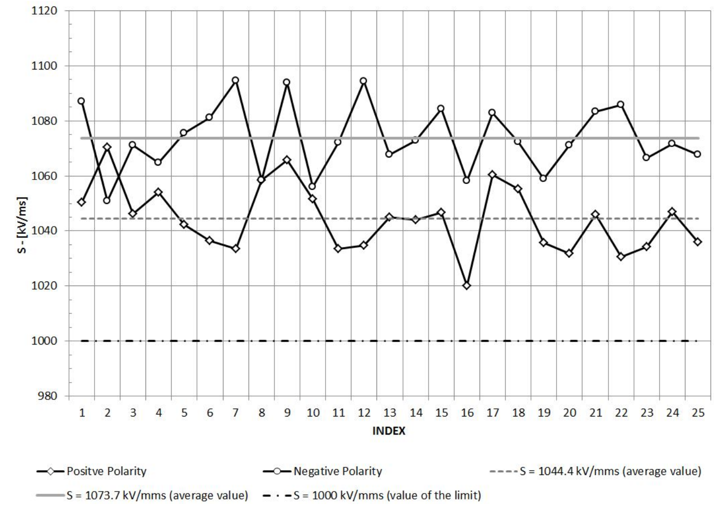

Fig. 4 – Time sequences of actual slope values *S* during the test procedures.

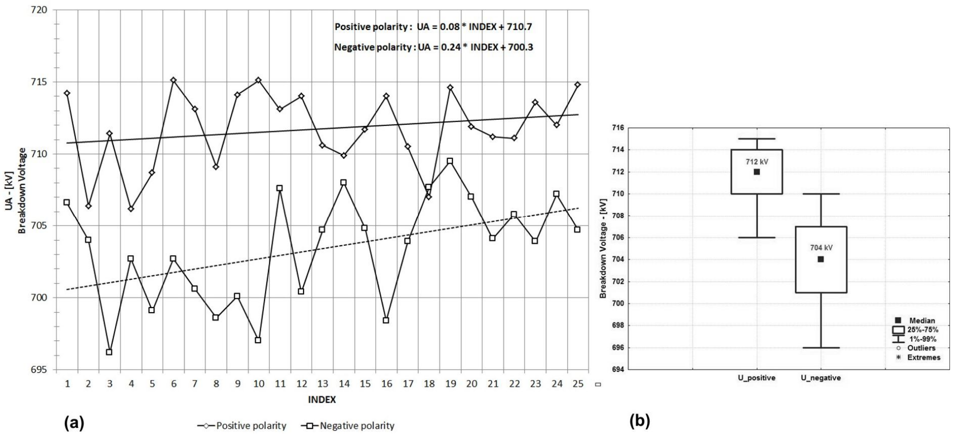

Fig. 5 – Features of actual breakdown voltages recorded during the test procedures: (*a*) Time sequences and (*b*) Boxplot representation of distributional characteristics and levels.

The difference is reduced (8 kV as it can be seen in Fig. 5 *b*) but was confirmed by applying a two-side *t* – test with the null hypothesis that the data in the two independent random samples (positive and negative breakdown voltages) come from normal distributions with equal means and equal but unknown variances. The alternative hypothesis is that the data come from populations with unequal means. The test has rejected the null hypothesis at the 5% significance level; consequently the samples come from populations with different means.

To end the analysis of the results, and to provide a comparison between the two types of impulse voltages used, a brief analysis of the dependency between the average slope of the applied voltage (S) and the corresponding time to breakdown recorded was plotted in Fig. 6. As it can be seen, the steep-front impulse is associated to shorter time to breakdown than the lightning impulse for the same values of the average slope, and also to smaller breakdown voltages.

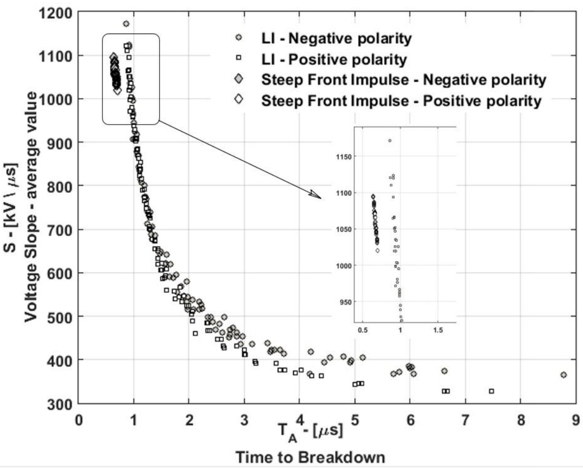

Fig. 6 – Voltage slope and time to breakdown correlation for lightning impulse and steep-front impulse.

6. Conclusions

The paper presents the possibilities to obtain steep-front impulses, as stipulate the IEC 62217 standard, using a usual impulse generator, without "peaking circuit". To reach the desired slope of impulse in order to comply with standard requirement two methods are used and compared. The method based on a classic LI generator charged to reach disruptive discharges on upper part of voltage-time characteristic of tested insulator require a higher voltage for the same slope, comparing with the steep-front method. This last method is suitable to be applied because a lower charging voltage is necessary to obtain the desired impulse slope.

Because the differences between shed shapes and diameters of different composite insulators are reduced, the necessary voltages for this kind of tests are almost the same to the given values in this paper.

As secondary results of the research, voltage-time characteristics of the tested insulator section have been obtained. They can be used not only as a comparison term for insulation behavior when stressed with steep-front impulse voltage, but also as a quantitative descriptor for the insulation performance to standard lightning impulse, mainly if we look at those characteristics not in terms of breakdown voltage but in terms of average breakdown voltage gradient. This approach will allow the extension of these particular results to other similar insulators but with different lengths.

Part of research from this article was presented at the 7th International Conference on Energy and Environment, CIEM 2015, a joint event organized by University Politehnica of Bucharest, "Gheorghe Asachi" Technical University of Iasi, WEC-Romanian National Committee and the Academy of Romanian Scientists.

REFERENCES

Farzaneh M., Chisholm W.A., *Insulators for Icing and Polluted Environments*. Wiley, New York, 2009.

Gorur R., *Steep-Front Impulse Test for Insulators*. INMR, March 6, 2015.

Gubanski S.M., *Properties of Silicone Rubber Housings and Coatings*. IEEE Transactions on Electrical Insulation, **27**, *2* , 374-382 (1992).

Papailiou K., Schmuck F., *Silicone Composite Insulators - Materials, Design, Applications*. Springer-Verlag, Berlin, 2013.

Pigini A., *HV Composite Insulators: Market Size & Reliability*. INMR **7**, 2014.

Schon K., *High Impulse Voltage and Current Measurement Techniques*, Springer International Publishing Switzerland, 2013.

* * * *Electrical Insulating Materials Used under Severe Ambient Conditions – Test Methods for Evaluating Resistance to Tracking and Erosion*. IEC 60587:2007 Std.

* * * *High-Voltage Test Techniques.* Part 1: *General Definitions and Test Requirements*. IEC 60060-1:2010 Std.

* * * *Insulators for Overhead Lines – Composite Suspension and Tension Insulators for AC Systems with a Nominal Voltage Greater than 1,000 V – Definitions, Test Methods and Acceptance Criteria*. IEC 61109:2008 Std.

* * * *Polymeric HV Insulators for Indoor and Outdoor Use – General Definitions, Test Methods and Acceptance Criteria*. IEC 62217:2012 Std.

ÎNCERCĂRI DIELECTRICE SPECIALE ALE IZOLATOARELOR COMPOZITE

(Rezumat)

Procesul de fabricație a izolatoarelor compozite a ajuns la maturitate în ultimele decenii, acestea fiind utilizate pe scară tot mai largă datorită avantajelor pe care le implică: în primul rând masă redusă şi o comportare foarte bună în condiții de poluare. În vederea detectării defectelor ascunse, izolatoarele de acest tip sunt supuse unor încercări de laborator dedicate, care necesită facilități speciale. Lucrarea se concentrează asupra încercărilor la impuls de tensiune cu front rapid, având o pantă de cel puțin 1000 kV/μs, descrie posibilitățile de obținere a unei astfel de tensiuni cu ajutorul unui generator de impuls clasic (cu sau fără intervenție în circuitul de formare) şi prezintă rezultatele obținute. Pentru a încadra aceste rezultate în categoria generală a performanțelor dielectrice la solicitări cu front rapid, au fost făcute comparații cu caracteristicile tensiune-timp, la impuls de tensiune de trăsnet standardizat, ale aceleiaşi izolații.