Electrical insulation for non standard wave
shape lightning impulses

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Summary

Material and equipment used in electrical installations are
designed and constructed under the objective of being
capable of withstanding different dielectric stresses: e.g.
very fast transients, lightning impulses, switching
impulses and power frequency. To check the design,
materials and equipment are subjected to several tests.
One of these tests is a lightning impulse (LI) test.

The stresses occurring in practice differ from the standard
wave shapes that have to be applied during tests carried
out in laboratories. This problem particularly affects the
transformer-manufacturing sector. Even in laboratories it
is not possible to generate a smooth standard 1,2/50 LI,
due to resonances between the impulse generator and the
transformer to be tested.

The present IEC 60060-1 allows different interpretations
in the evaluation of measured lightning impulse wave
shapes. These different interpretations can lead to
discrepancies in insulation dimensioning. Consequently, it
would be difficult to judge the insulation co-ordination for
LI if some equipment is tested with smooth 1,2/50 impulses
and others with non-standard impulses, when the
dielectric stress equivalence between both is not known.
This fact has provoked the start of a project in 1997, in
which five testing laboratories participated. The main
results of the work performed are presented in this paper.

Keywords: lightning impulse, IEC 60060-1,
oscillations, overshoot, non-standard wave shapes.

1 Introduction

The current standard IEC 60060-1 defines the lightning
impulse 1,2/50 as smooth impulse or impulse with
superimposed oscillations with an amplitude of not more
than 5% of the peak. It is not known in sufficient depth
what the behaviour of different dielectric media is when
the applied impulse is non-standard. It would be possible
to consider the test voltage as the maximum voltage level,
taking into account the superimposed oscillations.
Alternatively it is possible to suppose that for certain
frequencies and oscillation amplitudes, these oscillations
do not significantly affect the dielectrics and in
consequence the test voltage should correspond to the
peak value of the mean or filtered curve ignoring the
superimposed oscillations.

These different interpretations can lead to big
discrepancies in insulation dimensioning. Consequently, it
would be possible to difficult to judge the insulation co-
ordination for lightning impulses if some equipment is
tested with smooth impulses 1,2/50 and others with non-
standard impulses, when the dielectric stress equivalence
between both is not known.

The aim of the project was to study the influence of the
U_{50%} for different electrical media (air, SF₆, oil and
XLPE) when oscillations of up to 20% amplitude and up
to 5 MHz frequency are superimposed on a smooth 1,2/50
lightning impulse.
2 Problems with evaluation of measured lightning impulses

In order to point out the problems with the evaluation of the test voltage of measured impulses, a brief revision of the definition of the test voltage as described in IEC 60060-1 is given. For the definitions of the front time and the time to half value a reference is made to the standard itself [1]. In the second paragraph the theoretical problems with the interpretation are listed. To demonstrate the reality of the problems with the interpretation of the standard, a summary is given of the results of a questionnaire held amongst many laboratories world-wide about the current practice.

During testing of actual specimens, impulses of different shapes can occur. Besides the standard full lightning impulse (Figure 1), also impulses with wave shapes as illustrated in Figure 2, Figure 3 and Figure 5 can occur.

2.1 Definition of the test voltage in IEC 60060-1

For a lighting impulse without oscillation or overshoot, the value of the test voltage is its peak value. For lightning impulse with oscillation or overshoot the evaluation method to determine the test voltage is depending on the amplitude and duration of the overshoot or frequency of the oscillation (and is either the peak value or the peak value of the mean curve). In any case, a mean curve, that has neither overshoots nor oscillations should be drawn. For the purpose of measurement, the maximum amplitude of this curve is chosen as the peak value defining the value of the test voltage. In the cases of Figure 2 c) and d) the peak value of the original wave is considered to be the test voltage.

![Figure 1: Evaluation rules for a full lightning impulse according to IEC 60060-1](image)

![Figure 2: Evaluation rules for lightning impulses with overshoot or oscillations](image)

![Figure 3: Examples of non-standard lightning impulses](image)

![Figure 4 Filter characteristic according to present IEC 60060-1](image)

2.2 Problems with the interpretation

Independent if manual or digital evaluation methods are used, there are problems with the interpretation of IEC 60060-1. The following list shows some of the problems associated with the definitions and interpretation of the standard.

If the amplitude of the oscillations or overshoot is not larger than 5%, the duration of the overshoot or the frequency of the oscillation has to be determined. If the frequency of such oscillations is not less than 0.5 MHz or the duration of overshoot not more than 1 µs, as in Figure 3 a) and b), a mean curve that has neither overshoots nor oscillations should be drawn. For the purpose of measurement, the maximum amplitude of this curve is chosen as the peak value defining the value of the test voltage.
What is the definition of the mean curve, especially for impulses with both overshoot and oscillations? 

How to determine the $T_{30\%}$ and $T_{90\%}$ when there are oscillations close to these times?

Which peak value (real peak or peak of the mean curve) for calculation of the front time should be used?

How should the amplitude and duration or frequency of overshoot and oscillations be calculated?

How should a non-standard wave shape, for instance those that occur during real testing, be evaluated?

What is the physical background that supports the “magical 0,5 MHz value” for the frequency of oscillations and the “1 µs value” for the duration of the overshoot?

Could other parameters, than the one used in IEC 60060-1, describe the breakdown process better?

Should the same parameters be used for all materials (air, XLPE, SF₆, oil, vacuum, etc.)?

**Figure 5: Typical lightning impulses in transformer testing**

### 2.3 Current practice in laboratories

In order to know how the high-voltage laboratories around the world are facing the evaluation problems and to note which evaluation methods are used, two different questionnaires (one for manufacturers and testing laboratories and another one for calibration laboratories) were prepared. Questions were asked, amongst others, how these laboratories evaluate voltage and time parameters in the cases of full and chopped impulses with oscillations superimposed ($f \geq 0,5$ MHz) and/or overshoot ($d \leq 1$ µs). Only manufacturers and testing laboratories were asked about the possible influence on the breakdown behaviour of dielectric materials of these overshoots and/or high frequency oscillations with small amplitude superimposed to the lightning impulse.

Answers came from 23 manufacturer’s laboratories, 8 testing laboratories, and 12 calibration laboratories, all over the world. The main conclusions are summarised below, a more detailed summary can be found in [5].

The main conclusion of the questionnaire is that different laboratories are using different algorithms and evaluations methods. Some of them are quite far of the IEC 60060-1 rules, as for power transformer manufacturers. The majority of manufacturers of power transformers and cables uses the maximum value as the test voltage (not in accordance with IEC 60060-1), while the majority of manufacturers of other high voltage equipment and independent test laboratories considers the peak value of the mean curve. The differences in the obtained parameters when evaluating the same impulse are large, because of the evaluation methods.

Besides this, there is not a well-established physical background of the relevancy of the parameters, and the information supplied by the laboratories on this subject is contradictory. About 30% of the manufacturer laboratories supplied information of the possible influence on the breakdown behaviour of different dielectric materials, when overshoots and/or high frequency oscillations are superimposed on the lightning impulse. There was no agreement between the received answers.

### 3 Summary of the work and the results obtained during the research

#### 3.1 Introduction to the work

To test the relevancy of $U_p$, $T_1$, and $dU/dt$, tests mentioned in Table 1 have been performed for homogeneous and non-homogeneous fields with both positive and negative polarities.

The aim of the project is to study the influence of the $U_{50}$ for different dielectric media (air, SF₆, oil and XLPE) when oscillations of up to 20% amplitude and up to 5 MHz frequency are superimposed on a smooth 1,2/50 LI.

### Table 1 Tests to be performed

<table>
<thead>
<tr>
<th>Determination of the $U_{50}$-Breakdown</th>
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<tbody>
<tr>
<td><strong>Parameter to vary</strong></td>
</tr>
<tr>
<td>Configuration</td>
</tr>
<tr>
<td>Positive polarity</td>
</tr>
<tr>
<td>Negative polarity</td>
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<td>Homogeneous field</td>
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<td>Non homogeneous field</td>
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Another aspect of the project was a deep literature investigation towards the influence of parameters to the breakdown behaviour for different insulating materials and towards the possible introduction of new parameters.

The literature investigation did not show that the parameters used today are the only right ones, but
information obtained was not enough to support the use of other or alternative parameters. Therefore it is necessary to investigate the impulse breakdown behaviour of different insulating materials, while varying the parameters considered relevant.

### 3.2 Description of the test set-up

For the purpose of investigation of the relevancy of parameters a test set up has been designed and built. The test set-up comprises of several parts, the generating circuit, the test vessels, the measuring systems and the evaluating systems. All partners built their own test set-up. They are described in detail in [6].

The special generating circuit, as shown in Figure 6, comprises of two parts that are independent. One part generates a smooth standard lightning impulse and the other part generates oscillations or overshoot. The test object is placed between the generation parts. In Figure 7 an example of a generated impulse is shown. It can be seen that this looks similar to the impulses in Figure 5. The generators built covered a range up to 500 kV for tests in air and up to 100 kV for tests in oil, SF₆, and XLPE.

With the system used, two measuring systems are needed, one for the smooth impulse and the other for the oscillations/overshoot. The difference is the impulse applied to the test cell. The measuring system for smooth lightning impulses must be capable to measure standard lightning impulses ($T_1$ between 0.84 and 1.56 µs and $T_2$ from 40 to 60 µs). A conventional resistive or capacitive divider is suitable for this kind of measurement. The requirements to measure the oscillations and overshoot are more restrictive. Measurements of oscillation frequencies from several hundred kHz to some MHz with voltage amplitudes between 5 kV and 20 kV must be made. A bandwidth of approximately 35 MHz is required. No commercial dividers or voltage probes with this specifications could be found so special dividers were built.

For the measurements a special software package was developed by LCOE. This program carries out the following two functions: Control of the digital recorder and calculation of parameters of lightning impulses. The detailed description of the software is given in [7]. The parameters calculated by the software have been validated. The validation was carried out using mathematical wave shapes (double exponential + damped oscillations + noise) and comparing the software results with the other ones obtained by analytical calculation.

### 3.3 Results of the test performed

The investigations were carried out for four different materials: XLPE, oil, SF₆ and air. The 50% breakdown voltage change and a number of parameters, as shown in Figure 9 and Table 1 were studied.

For air a special analysis was carried out of the disruptive affect area as a new parameter for the evaluation of lightning impulses, in addition to the analysis of the $U_{50}$ breakdown voltage, and the results were quite promising [8].

The influence of oscillations and overshoot were similar, but not identical for all materials studied. In general no difference could be obtained for oscillations and overshoot ($T = 1/(2 \pi f)$) of equal amplitude., therefore in this paper only the results of the influence of oscillations is given.
The influence is similar for oscillations of small amplitude (5%) and large amplitude (20%). At low frequencies there is large influence of the oscillations but at high frequencies there seems to be no influence of the oscillations. For frequencies in between the upper and lower limits the relation is dependant of the frequency as shown in Figure 9. For 5% oscillations the value range from 0.95 to 1.05 instead of 0.8 to 1.2 in Figure 9. The main difference is that for 5% oscillations a larger part of the frequency band is within the ± 3% tolerance for peak value measurements.

Figure 9: $U_{50\%}$ as function of the frequency of the superimposed oscillations of 20% amplitude

4 Proposal for new impulse evaluation procedure

The general conclusion is that for oscillations of low frequency, the test voltage should be the peak value of the total curve and for oscillations of high frequency, the test voltage should be the peak value of the mean curve. For oscillations of frequency in between these two, the test voltage is a value in between the peak value of the mean curve and the peak value of the total curve, according to the formula below.

$$U_{\text{test}} = k \cdot U_{\text{total curve}} + (1 - k) \cdot U_{\text{mean curve}}$$

For low frequencies, $k = 1$ and for high frequencies $k = 0$. $k$ as function of the frequency can be represented in a graph as well, as given in Figure 10. The function might differ slightly for different insulating materials, and this has to be investigated in more detail.

The proposal for the evaluation of impulses is to use the tolerance band method to determine whether a full impulse is a standard impulse or a non-standard impulse. For non-standard impulses the test voltage is a function of the peak value of the mean curve and the peak value of the total curve. The new evaluation procedure can be summarised using the flowchart on the next page.

Figure 10: $k$ as function of the frequency of the oscillation.

5 Conclusions

The research carried out in the framework of the European project for different dielectric media (air, SF₆, oil and XLPE) has solved many of the open questions and a new evaluation procedure (as described in the previous paragraph) will be proposed to CIGRE WG33-03 and IEC TC 42 in order to modify the standard IEC 60060-1.

Acknowledgements

The authors thank the European Community for financial support of the project "Digital Measurement of Parameters used for Lightning Impulse Tests for High Voltage Equipment" that is within the scope of the SMT-programme contract no. PL-95120-SMT4-CT96-2132 and the institutions involved in this project: KEMA (Netherlands), FFII-LCOE (Spain), NGC (UK), Schering-Institute (Germany). The authors also thank all laboratories who filled in the questionnaire.

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Note 3: The calculated test voltage ($U_{\text{test}}$) using the filter is in the scope of the research carried out in the European Project only when this condition is satisfied:

$$U_p - U_{\text{test}} < A(f) \cdot U_{\text{test}}$$

Where the value of $A$ is obtained from the figure below:

Note 4: This parameter represents the mean curve slope in the front of the impulse and it can be specially relevant for transformer testing. Maximum instantaneous values of $dU/dt$ could be also considered and studied in future researches.