New Procedure in Impulse Evaluation -
a Change in the Electrical Breakdown Test Results?

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Abstract: The actual recommendation is ambiguous concerning the evaluation of the test voltage of lightning impulses with oscillations or overshoot near the peak. Based on measurements within an European Research Project a new evaluation procedure is proposed using the k-factor as a measure of the influence of the superimposed oscillating voltage on the breakdown behavior of insulating materials. The k-factor is frequency dependent and a function is developed which can be used as filter characteristics. Some examples show the evaluation procedure and the results in comparison with the actual evaluation recommendation. Assuming the same behavior at withstand tests the k-factor can be used for the evaluation of the test voltage during withstand or breakdown tests. A comparison between the results using the actual procedure and the results using the new proposed method on lightning impulses applied on a power transformer shows clearly that the new procedure is reliable, reproducible and will not lead to changes in withstand voltage and test results.

INTRODUCTION

The existing evaluation procedure for lightning impulses with oscillation or overshoot is ambiguous and not well described in the relevant recommendation [1]. Fig. 1 shows the actual situation concerning the determination of the test voltage.

![Fig. 1 Standard lightning impulses with super-imposed oscillations and overshoot](image)

Depending on the frequency of the oscillation or duration of the overshoot the test voltage is determined by the peak value of the measured impulse in case of an oscillation frequency below 500 kHz resp. an overshoot duration longer than 1 µs or by the peak value of the so called mean curve, shown in Fig. 1 as dotted lines, in case of an oscillation frequency equal or above 500 kHz resp. an overshoot equal or shorter than 1 µs. With the introduction of digital measuring equipment combined with an automatic evaluation of the impulse parameters the discussion concerning impulse evaluation becomes stronger, because small deviations in the impulse record leads to different peak values within one test period, particularly if the oscillation frequency or overshoot are close to the given limit. Even with a limitation of 5 % overshoot in the amplitude the deviation in the peak values could lead to an extensive discussion concerning the reasons of the deviation. Therefore a number of investigations within the European Union and CIGRE were carried out to find the physical background of the existing frequency limit and to develop a unambiguous evaluation procedure for lightning impulses [2-5].

EXPERIMENTS

The most extensive measurements were carried out by 4 laboratories within the European Union dealing with the main insulating material for high voltage equipment like air, SF₆, polyethylene and oil. All laboratories used a test circuit with two impulse generators, where one generates a smooth double exponential lightning impulse, representing the so called mean curve, and the oscillating impulse with variable amplitude and frequency to represent the oscillation or overshoot superimposed on the smooth lightning impulse. Further details are well described in [6]. This arrangements allow the determination of the 50 % breakdown voltage of the tested insulating materials as function of the amplitude and the frequency of the superimposed oscillation. The main results are the following:

- The influence of the oscillation and the overshoot on the breakdown behavior are equal.
- The frequency of the oscillation influences the breakdown voltage depending on the frequency.
- Below 300 kHz the breakdown voltage is very close to the peak value of the recorded impulse.
- Above 1.600 kHz the breakdown voltage is close to the peak value of the smooth impulse, which means not influenced by the oscillation.
- All investigated materials show a similar behavior.
From these test results the group of laboratories proposes the introduction of the so called k-factor, which should consider the frequency dependent breakdown voltage of insulating materials in case of superimposed oscillations on smooth lightning impulses. This factor should not consider the voltage distribution within a high voltage equipment as function of the frequency of the applied voltage. Fig. 2 shows in a simplified diagram the basic results and the comparison with the recommendation.

![Fig. 2: Test voltage factor k as function of frequency](image)

The consequence of these results was a proposal to the relevant IEC Technical Committee TC 42 to delete the stringent frequency requirement for the test voltage determination and to replace it by a smooth transition function, as generally shown in Fig. 2. Working Groups within CIGRE and IEC figure out a quite simple function which describes very well the shape of the experimentally determined curve. The k-factor can be expressed by the following equation:

\[
k = \frac{1}{1 + a f^2}
\]  

(1) 

with \( a = 2.2 \) and Fig. 3 shows the result.

![Fig. 3: k-factor as function of the frequency in MHz](image)

The high voltage community agrees that the introduction of the k-factor is an improvement of the impulse parameter evaluation and reflects the physical behavior of the insulating material better than the stringent frequency limit at 500 kHz. The next step should be the establishment of the k-factor in the IEC recommendations, but several procedures are possible and it should be checked which procedure should be preferred and recommended [7].

**IMPLEMENTATION OF THE k-FACTOR**

There are mainly two procedures which can be used for lightning impulse evaluation with the help of the k-factor. The first one is the so called global filtering method. The k-factor function, shown in Fig. 3, describes a kind of filter which can be applied on the recorded impulse. The outcome is an impulse with reduced but remaining oscillations and the peak value of this curve gives the test voltage amplitude. Due to the fact, that also the smooth part of the applied impulse contains frequency amplitude above 300 kHz the front time of the impulse was influenced and increased by the evaluation procedure. This is may be not acceptable.

The second procedure is the residual filtering method which separates the two components of the impulse, the smooth double exponential and the superimposed oscillation. It contains four steps. The first one is the generation of a smooth double exponential curve, similar to the former mean curve shown in Fig. 1, which shows the best fit with the recorded impulse. The second step is the set up of the so called residual curve, which is the difference between the recorded impulse and the smooth double exponential curve. The third step is the filtering of this residual curve with a filter characteristic according to the function shown in Fig. 3. The fourth and last step is the addition of the smooth double exponential curve and the filtered residual curve and the peak value of this curve gives the amplitude of the test voltage. The resulting curve has an acceptable change in the time parameter even if it is not decided, if the time parameter should be evaluated from the original recorded curve or form the evaluated curve. The preparation for the revision of IEC 61083-2 “Digital recorders for measurements in high-voltage impulse tests - Part 2: Evaluation of software used for the determination of the parameters of impulse waveforms [8]” which contains test impulses for the check of the software showed that the second procedure gives some problem in the reproducibility due to different starting points of the double exponential curve depending on the evaluation procedure. With a given starting point for the smooth double exponential curve and the filtered residual curve and the peak value of this curve gives the amplitude of the test voltage. Therefore the new edition of IEC 60060-1 [1] includes the residual filtering method with the k-factor method for the evaluation of lightning impulses with oscillations or overshoot near the peak.
Fig. 4 shows for instance the evaluation of a lightning impulse voltage applied on a power transformer with the typical impulse shape, influenced by the test object in two steps. The first step is the evaluation of the mean curve and the calculation of the residual curve. After filtering of the residual curve with a filter function shown in Fig. 3 the second step is the addition of the mean curve and the filtered residual curve, shown together with the recorded impulse in Fig. 5.

Fig. 4: Recorded impulse, mean curve and residual curve

Fig. 5: Recorded impulse and evaluated test voltage curve

The evaluated test voltage curve shows also some oscillation, but the peak value of this curve gives the amplitude of the test voltage and there is no further interpretation.

CONSEQUENCES ON THE IMPULSE TESTS

The evaluation of the k-factor is based on breakdown tests of different materials. According to the relevant standards the 50 % breakdown voltage was determined. Depending on the investigated material the standard deviation was different, for gases small and for solid material like polyethylene large. The general behavior was comparable and the 50 % breakdown voltage shows a clear dependence on the frequency of the superimposed oscillation at the same amplitude of the applied voltage. The peak value of the smooth double exponential part is called $U_{\text{mean}}$, the peak value of the recorded impulse $U_{\text{extr}}$. The difference between these two peak values is named $\beta$. The k-factor expresses the portion of the oscillating part which contributes to the breakdown voltage $U_{\text{break}}$ according to the following equation:

$$U_{\text{break}} = U_{\text{mean}} + k \beta$$

Fig. 5 shows the normalized breakdown voltage as function of the frequency of the superimposed oscillation. It should be noted, that an overshoot can be handled was a strongly damped oscillation.

Fig. 5: 50 % breakdown voltage as function of the oscillation frequency of the superimposed voltage

For frequencies up to 300 kHz the breakdown voltage is the sum of the amplitude of the mean curve plus the full amplitude of the superimpose oscillating part, expressed by the value of $k = 1$. With increasing frequency the breakdown voltage comes nearer to the amplitude of the mean curve and at 1.600 kHz the oscillation part does not contribute to the breakdown voltage, expressed by the value of $k = 0$.

It can be assumed that the breakdown behavior of insulating materials can be transferred to the withstand behavior of insulating materials and that the relation between smooth double exponential curve and superimposed oscillating voltage is also valid for withstand tests.

Besides this assumption the introduction of the k-factor in the evaluation of the amplitude of the test voltage at lightning impulses with oscillation will definitely improve the reproducibility and the reliability of lightning impulse withstand or breakdown tests and the uncertainty concerning the test voltage amplitude will be reduced. A comparison between the test results of lightning impulses on transformers shows clearly that the new proposed procedure has no in influence on the test results and that no change is caused by the evaluation procedure. Fig. 6 shows a typical lightning impulse shape of a power transformer with a relative high oscillation amplitude.

The frequency of the oscillation is above 500 kHz and therefore according the actual recommendation the test voltage is the peak value of the mean curve, which is not shown in Fig. 6 because it depends how much the oscillation amplitude should be taken into account.
Regarding the mean curves in Fig. 1 the test voltage amplitude will be below 1000 kV, if a smooth double exponential curve is drawn through the recorded curve.

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The new procedure was also tested by the evaluation of lightning impulses applied to power transformers in a transformer manufacturer laboratory in order to check the applicability of the procedure. Table 1 shows the results for the actual and the new procedure.

### Table 1: Comparison of test voltages as function of the evaluation procedure for lightning impulses

<table>
<thead>
<tr>
<th>( U_t ) in kV</th>
<th>( U_{\text{IC}} ) in kV new procedure</th>
<th>( ?U ) in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEC procedure</td>
<td>new procedure</td>
<td></td>
</tr>
<tr>
<td>813</td>
<td>789</td>
<td>3,0</td>
</tr>
<tr>
<td>1310</td>
<td>1274</td>
<td>2,7</td>
</tr>
<tr>
<td>809</td>
<td>792</td>
<td>2,1</td>
</tr>
<tr>
<td>1300</td>
<td>1270</td>
<td>2,3</td>
</tr>
</tbody>
</table>

The difference in the test voltage amplitude is between 3 % and 2 %, similar to the results shown in Fig. 6. The lower test voltage, given by the new proposed procedure, reflects the voltage stress of the insulation due to the lightning impulse stress. The higher test voltage, given by the IEC procedure, gives the peak value of the recorded impulse and takes not into account the influence of the frequency of the superimposed oscillation on the breakdown or withstand behavior. If a customer now requires a higher test amplitude in order to reach the required test voltage amplitude, than the stress on the insulation will increase, but this represents the required stress of the insulation regarding the test purpose.

### CONCLUSIONS

The actual problem with the ambiguous evaluation of lightning impulses with oscillations or overshoot near the peak can be solved by the new proposed procedure. The procedure has been checked by several measurements of the transformer manufacturer laboratory and the results are satisfactory. Anyhow some checks concerning the sensitivity of extreme cases may be necessary. The evaluation procedure is simple, well described and reflects the physical behavior of the insulating material. It can be carried out automatically or manually. The procedure will be now included in the revision of the relevant IEC 60060 Part1 and will improve lightning impulse tests on apparatus where oscillations can normally not be prevented.

### REFERENCES