An Improvement of the Evaluation of Lightning Impulse Test Voltages using the k-factor

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Abstract: The evaluation of lightning impulses with oscillations or overshoot near the peak suffers from the definition in the actual recommendation. The breakdown behaviour depends on the frequency of the oscillation and the amplitude. The results of a European Research Project have shown, that the influence of the superimposed oscillations can be described with a frequency dependent factor which is valid for oscillations and overshoot. The evaluation with this factor leads to a remarkable increase of the reproducibility. The use of filtering technique prevents furthermore the discussion concerning the determination of the test voltage and overshoot duration. Evaluation methods and an example of transformer test impulse are presented with a proposal for a future change of the recommendations concerning impulse evaluation and software check.

1. Introduction

The evaluation of the test voltage of lightning impulses with oscillations or overshoot in the peak area is difficult due to the ambiguous definition in the existing recommendation [1]. This problem is well known and was solved in the past by the experience of the test engineers in the laboratories world-wide. The analogue measuring technique and partly also the transfer behaviour of the impulse voltage dividers has sometimes covered the evaluation problems. The problem arises more pronounced with the introduction of the digital measuring technique also in the field of high voltage measurements and with the automatic evaluation of the test voltage by the incorporated computer. In order to carry out appropriated lightning impulse evaluations during testing practice, the real stress caused by oscillations superimposed on a smooth impulse should be distinguished from others measuring difficulties (divider bandwidth, dynamic response of digital recorder, etc). In this paper the influence of lightning impulses with superimposed oscillations is studied for different insulating materials.

2. Experimental investigations

Within an European research projects 5 research institutes took part on the investigation of the breakdown behaviour of some basic insulation material as function of the superimposed oscillations or overshoot [2]. The investigated materials were air, oil, SF₆, polyethylene and oil/paper. Even if the results were published in numerous contributions to international conferences [3, 4], the basic ideas and assumption should be explained here. The fundamental shape of a lightning impulse is characterised by a double exponential function and this shape is called „mean curve“, even if a lightning impulse, generated in a high voltage laboratory, is not a double exponential function due to the existing inductance, which leads to a smooth increase of the voltage at the beginning. The points for the evaluation of the front time are therefore and for some other reasons chosen at 30 % and 90 % of the highest measured value of the impulse.

In order to be able to change the amplitude of the fundamental impulse and the superimposed oscillations or overshoot a test circuit with two impulse generators was established. A further advantage of this test circuit was the possibility to measure separately the two impulses, which were superimposed on the test object.

Another assumption was made, that the investigations should be carried out on material specimens with a relatively small thickness in order to reduce the required voltage amplitude for the breakdown tests. The main task of the research program was the investigation of the material behaviour and not the behaviour of a system where the voltage distribution depends on the resistive, capacitive or inductive voltage grading.

The breakdown behaviour was checked by the determination of the 50 % breakdown voltage, which is a typical value for the characterisation of the insulation performance of materials. The results have shown that the 50 % breakdown voltage depends on the frequency and the amplitude of the superimposed oscillations or overshoot and it would be assumed that the breakdown behaviour at lower probabilities is similar.

The results of the European Research Project have also shown that is no difference in the breakdown voltage between superimposed oscillations and overshoot with the corresponding frequency.

3. Introduction of the k-factor

The breakdown voltage for the investigated materials depends on the oscillation frequency of the superimposed part, but there was no stringent
frequency at which the breakdown behaviour changes remarkable. The evaluation of the test experiments showed that the breakdown voltage at the superposition with lower frequencies are close to the highest measured value which is roughly the sum of the fundamental (double exponential) impulse and the superimposed oscillation. During the tests it was also recognised that in the case of the two impulse generating circuits the trigger point of the oscillation generator is important. In order to get comparable results the front time was more or less kept constant and this defines the trigger point. With increasing frequencies the breakdown voltage comes closer to the peak value of the fundamental (double exponential) impulse and therefore the so-called k-factor was introduced. The k-factor should represent the influence of the oscillating frequency on the breakdown voltage. The measurements on the different materials and also with uniform and non-uniform field configurations showed that the influence depends a little bit on the electrode or field arrangement and also on the investigated materials. Regarding the uncertainty in the measurement and the existing evaluation procedure a mean curve for the k-factor was generated with the value of k = 1 up to frequencies of 300 kHz and a value of k = 0 at 1.6 MHz, with a logarithmic frequency scale [5].

The test voltage was then calculated by the following steps. The highest measured voltage was determined as extreme value, according to a proposal of a CIGRE Joint Task Force 33-03/12. The peak of the fundamental impulse was determined as peak value of the mean curve. The difference between these two values is given by the variable θ. It should be noted, that the value of θ is not identical with the overshoot according to the existing recommendation except when the time of extreme value is identical with the time of the peak value of the fundamental impulse, but the deviation is small. Within the experiments the calculation of the test voltage could be carried out by the following equations:

\[ U_t = U_{\text{extr}}(1-k)^{\theta} \quad \text{or} \quad U_t = U_{\text{pmc}} + k^{\theta} \quad (1) \]

with \( U_{\text{extr}} \) the highest measured voltage and \( U_{\text{pmc}} \) the peak value of the fundamental (mean) impulse, because the different measuring systems for the fundamental impulse and the superimposed oscillations show the single components of the complete impulse.

However the measurement of a lightning impulse in a high voltage laboratory does not allow this calculation in a simple way, because the extreme value will be recorded, but the peak value of the fundamental part is not available and shall be again evaluated by a „mean curve“. Concerning a new proposal for an IEC recommendation it should be taken into account, that the evaluation of a lightning impulse with oscillation shall be possible manually as well as automatically be a computerised evaluation procedure. Under these conditions two ways seems to be reasonable for the improvement of the evaluation of lightning impulses, the calculation or drawing of a mean curve in order to use (1) or the filtering of the impulse with a filter having the same frequency characteristic as the k-factor and then determine the extreme value of the filtered curve as the test voltage.

**„Mean curve“ procedure**

The mean curve can be calculated using mode-based curve fitting [6] or applying Fast Fourier Transformation to determine the oscillation frequency and to remove the superimposed oscillation. Both methods needs the data in digital form and a computerised evaluation procedure. If the data are only available in form of a diagram or a plot other method are necessary. In case of oscillations the frequency can be evaluated by the time difference between characteristic points, e.g. two consecutive peaks. In case of overshoot a simple evaluation of the exponential characteristic as the k-factor and then determine the impulse with the characteristic of the k-factor. The extreme value of the filtered curve as the test voltage.

**Filtering procedure**

The test voltage can be determined by using a filter with the characteristic of the k-factor. The extreme value of the filtered curve is then the test voltage and the shape of this curve may show some oscillations with low frequencies, which is again not in line with the actual recommendation. The amplitude limitation of the superimposed oscillations can be done by a limitation of the voltage difference between the extreme value of the measured and filtered curves [5]. This procedure seems to be very helpful, because nowadays analogue-digital converter with computeri-
sed evaluation procedures are available in most of the high voltage laboratories. In order to check the correct evaluation the impulse shapes in the IEC recommendation can be used, where the data are digital available [8]. If necessary further impulse examples can be added. The advantage of this method is the simple determination of the test voltage (extreme value of the filtered curve) and the notice of other frequencies than the dominant frequency. Figure 2 shows an lightning impulse with oscillations and the different evaluation procedures.

**Figure 2**: Impulse with double exponential (DE) and single exponential (SE) fitting

### Evaluation examples

The verification of the two procedures can be demonstrated by two impulses shapes of the IEC recommendation. These two impulses A and B (case 13 and 14 of [8]) are measured impulses from transformer tests. Table 1 shows the characteristic data and the evaluation results for a manual evaluation procedure with a mean curve. The results show clearly the large difference in the test voltage evaluated by the actual recommendation due to the fixed frequency limit of 500 kHz where the test voltage changes from the extreme value of the measured curve to the extreme value of the mean curve. The proposed procedure reduces this effect dramatically and it is clear that from the physical point of view, the behaviour of an insulation breakdown will be influenced by the frequency of the superimposed oscillations and this influence decreases with increasing frequency. However the influence has no discontinuity at the frequency of 500 kHz and therefore the existing IEC recommendations seems to be wrong in this respect. For comparison Table 2 shows the results of a filtering evaluation procedure and the agreement between the manual and automated procedure is very high.

### 4. Transformer testing

A CIGRE Joint Task Force 33-03/12 has evaluated the procedure and main parameters of lightning impulses used by the transformer manufacturer and customer during the impulse tests. The particular point in these tests is the fact, that the oscillations are not caused by the impulse generating circuit alone, but by the test object and the mutual influence of test circuit and test object. A modification of the test circuit arrangement will not solve the problem as it is the case for many other test objects. The result was that the extreme value of the recorded impulse and the rate of rise dU/dt are important for the stress of the transformer or transformer winding. Therefore their proposal is the use of the extreme value and the calculation of a mean steepness using the 30 % and 90 % value of the extreme value. Furthermore the time near the peak, that means in the range above 90 % should be long enough to generate the expected stress on the tested insulation. The use of the k-factor take these requirements into account and leads to the notice of the voltage stress and the voltage distribution within the windings given by the extreme value of the applied voltage and the mean steepness of the voltage and is therefore in a good agreement with the used evaluation procedure.

### 5. Proposal for future recommendation

The actual fixed frequency of 500 kHz for the determination of the test voltage, either the extreme value of the measured curve or the extreme value of the mean curve, should be replaced by the k-factor as function of the frequency. The k-factor can be used for manual and automated evaluation of the test voltage. In case of computerised procedure additional test impulses should be generated in order to check the correct evaluation of the test voltage according to the changed recommendation. The test impulses can be

<table>
<thead>
<tr>
<th>impulse</th>
<th>( U_{\text{extr}} ) in kV</th>
<th>( U_{\text{pmc}} ) in kV</th>
<th>( \beta ) in kV</th>
<th>( f ) in kHz</th>
<th>( U_t ) in kV</th>
<th>( U_{\text{IEC}} ) in kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-1069</td>
<td>-964</td>
<td>105</td>
<td>388</td>
<td>-1052</td>
<td>-1070</td>
</tr>
<tr>
<td>B</td>
<td>-1074</td>
<td>-964</td>
<td>110</td>
<td>582</td>
<td>-1030</td>
<td>-960</td>
</tr>
</tbody>
</table>

**Table 2**: Results of evaluation with filtering procedure

<table>
<thead>
<tr>
<th>impulse</th>
<th>( U_{\text{extr}} ) in kV</th>
<th>( U_{\text{pmc}} ) in kV</th>
<th>( \beta ) in kV</th>
<th>( f ) in kHz</th>
<th>( U_t ) in kV</th>
<th>( U_{\text{IEC}} ) in kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-1072</td>
<td>-957</td>
<td>115</td>
<td>390</td>
<td>-1048</td>
<td>-1070</td>
</tr>
<tr>
<td>B</td>
<td>-1071</td>
<td>-960</td>
<td>111</td>
<td>590</td>
<td>-1028</td>
<td>-960</td>
</tr>
</tbody>
</table>
incorporated in the existing standard or in an additional part which should then also contain a number of typical transformer impulses.

The advantages of the proposal can be demonstrated on two examples. For test circuits where the oscillations are mainly caused by the test circuit arrangement the amplitude of the oscillations are limited to 5 % according to the actual recommendation. The influence on the test results by the proposed evaluation procedure with the k-factor has therefore a very small influence on the test object, because the voltage difference are limited up to maximum 5 %. However the reproducibility will be increased remarkable and the test procedure improved.

For test circuits where the oscillations are caused mainly be the test object the limitations of the oscillation amplitude up to 5% is very often technical not possible. Already the test impulses in the actual recommendation shows amplitudes higher than 10 % (see Table 1 and 2). Here the proposal will reflect much better the stress in the test object and the physical behaviour of the insulation.

The investigation on the different material has shown the breakdown behaviour as function of the frequency of the superimposed oscillations and this behaviour can be transferred also to insulation system. The change of the actual recommendation has a small influence on the test results, because the stress e.g. for a transformer winding is mainly given by the extreme value and by the steepness of the applied impulse voltage. In addition, the test voltage determined by the k-factor approach gives a complementary information of a specific stress condition.

Finally in both cases the extreme sensitivity of analogue-digital converters to small changes in the complete measuring chain and to internal and external noises can be avoided concerning the determination of the test voltage depending on the frequency of oscillation or shape of the overshoot. A small jitter in the sampling rate, even for very high sampling rates, may lead to a change in the calculated frequency and to a step in the evaluated test voltage in the order of the allowed amplitude of the superimposed oscillations.

The examples in Table 1 and 2 shows clearly that a change in the frequency of the superimposed oscillations from about 400 kHz to about 600 kHz leads to a change in the test voltage of about 10 % \((U_{\text{IEC}}\) in Table 1 and 2 for impulses A and B) according the IEC recommendation but only to about 2 % according to the new proposal for the manual as well as for the automated evaluation. The small change in the test voltages represents also the small changes in the voltage stress of the test object in a more realistic way. This advantage would be much more supported, if the frequency of the oscillations would be very close to the frequency limit of 500 kHz, given in the actual recommendation [1].

6. Conclusions

The investigations on the breakdown behaviour have shown, that the oscillation frequency or the equivalent overshoot duration have an influence on the breakdown voltage of insulating materials. The existing evaluation procedure takes this into account but with a discontinuity at 500 kHz. The proposal of a frequency dependent k-factor for the evaluation of the test voltage takes the physical breakdown behaviour of the materials into account without any discontinuity. The manual and the described automated evaluation lead to reproducible results which are much less sensitive to changes in the frequency of the superimposed oscillations. Therefore the proposal prevents discussion at the determination of the test voltage which are mainly based on the ambiguous definition of the test voltage and not on the behaviour of the object under test. Furthermore the evaluated test voltage represents better the voltage stress of the tested object and increases the test reproducibility.

7. References


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