New proposal for manual and automatic evaluation of lightning impulse test voltages with oscillations

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Abstract: The automated evaluation of lightning impulses with oscillations or overshoot superimposed near the peak might cause some problems due to the weak definition of the mean curve and due to the stringent 500 kHz limit. Based on the results of an European Research Project the contributions describes a new proposal for the evaluation procedures. Different methods using a frequency dependent test voltage factor for manual as well as for automated evaluation of the test voltage of lightning impulse tests are described. By comparing the influence of various evaluation parameters for fitting and digital filtering algorithms it can be demonstrated that different methods lead to comparable results. Thus the reproducibility and reliability of lightning impulse test might be increased.

1. Introduction

Measured lightning impulses often show oscillations or overshoot near the peak. Especially when performing lightning impulse tests on power transformers such oscillations might be superimposed. In order to evaluate such curves the current standards like e.g. the IEC 60060-1 [1] require a so called mean curve for the evaluation procedure which is illustrated in Figure 1.

![Figure 1: Standard lightning impulses with superimposed oscillations and overshoot](image)

The mean curve should represent a smooth standard lightning impulse. Comparing the measured curve and the drawn mean curve the frequency and the amplitude of the superimposed oscillations can be determined. Evaluating oscillograms from analogue oscilloscopes the evaluation with the mean curve gives reliable results as experienced specialists know how to draw the mean curve manually. But using the advantages of digital measuring systems and automated evaluation procedures some problems arise as there are no exact definitions for an automated construction of the mean curve. Due to this weak definition of the mean curve an automated evaluation is not unambiguous and in many cases it becomes difficult to compare the test results. Further more the stringent frequency limit of 500 kHz might lead to a variation of test results. As the IEC 60060-1 allows a maximum oscillation amplitude of only 5 % a deviation of 5 % in the test voltage would not lead to different test results, but a deviation of the test voltages during a test series could cause discussions between the two engaged parties. This problem stimulated several investigations [2-5]. Further a Test Data Generator (TDG) [6] with predefined curves of lightning impulses was introduced more for the comparison and qualification of evaluation software. Finally the physical background of the 500 kHz limit and alternative methods for the evaluation were investigated in an European Research Project [7].

2. Results of experimental investigations

Within the European Project the influence of oscillations or overshoot superimposed near the peak was investigated. A special two stage generating circuit was used in order to adjust the amplitude, the time parameters and the frequency/duration separately in a wide range [7]. The partners engaged in the project tested materials like air, SF₆, oil and PE [7-10]. Based on the experimental results the influence of the frequency or the duration of oscillations/overshoot, respectively, can be described in the following way: Superimposed oscillations/overshoot with low frequencies have a strong influence on the breakdown voltage and in this case the test voltage is the extreme value of the measured curve. Superimposed oscillations of high frequencies have no influence on the breakdown voltage and the corresponding test voltage is the peak voltage of the mean curve i.e. the lightning impulse without the superimposed oscillation. For oscillations with frequencies between this two extreme cases the influence of the superimposed oscillations decreases continuously with increasing frequency. Thus the problems with the stringent frequency limit of 500 kHz in the current standards could be avoided by using a frequency dependent correction function which decreases continuously with increasing frequency and which has no stringent step in the function [10].
3. New proposal for evaluation

The results of the breakdown test lead to a new evaluation proposal which uses a frequency dependent test voltage factor $k$ as shown in Figure 2. According to the proposal of the Joint Task Force between CIGRE WG 33-03 “High Voltage Testing and Measuring Techniques” and SC 12 “Transformers” the highest amplitude of the measured curve is called extreme voltage $U_{\text{extr}}$. Then with the amplitude $\beta$ of the superimposed oscillation the test voltage $U_t$ can be calculated using the following equation:

$$U_t = U_{\text{extr}} - (1-k(f)) \cdot \beta \quad (1)$$

**Figure 2** Test voltage factor $k$ as function of frequency of superimposed oscillation

Using the dashed line for the function $k$ the evaluation procedure corresponds with current IEC 60060-1 with a test voltage step at 500 kHz. Using the continuously decreasing function $k(f)$ the problems with the frequency step at 500 kHz are avoided and the determined test voltages takes the physical behavior in a better way into account. The analysis of the investigated breakdown tests showed that a good fit of the $k$-function could be reached with a linear regression line in a logarithmic frequency scale between 300 kHz and 1600 kHz as illustrated in Figure 2 [7, 10].

4. Evaluation using the $k$-factor method

For the calculation of the test voltage using (1) still a mean curve would be necessary for the determination of the oscillation amplitude $\beta$. In order to avoid the problems with the ambiguous construction of a mean curve alternative methods were tested and compared.

The proposed methods should increase the test reproducibility and it should be able to use the procedures for manual as well as for automated evaluation. This lead to the following proposed methods:

- Fitting of the impulse tail with a single exponential function. This can be done manually as well as automatically.
- Implementation of digital filters with filter functions adapted to the function of the $k$ factor.

**Single exponential fitting of tail**

The evaluation with a single exponential fitting will be demonstrated in the following. The proposal is to evaluate the impulse with a single exponential function which fits the tail of the measured impulse. This can be done manually using a curve template or with free hand lines as well as automated by using regression algorithms which fit the tail of the measured impulse. The evaluation with a single exponential fitting of the tail will be demonstrated in Figure 3 with the example of the impulse ‘case 9’ (lightning impulse with oscillation $\approx 600$ kHz) from the IEC TDG [6].

**Figure 3** Impulse ‘case 9’ (TDG) with double exponential (DE) and single exponential (SE) fitting

After drawing the single exponential fitting of the tail the amplitude of the oscillation $\Delta U$ can be determined by calculating the difference between the extreme value $U_{\text{extr}}$ and the value of the fitted curve. Afterwards the frequency of the superimposed oscillation or the duration of the overshoot, respectively, can be calculated from the time difference between the peaks or by the time difference between the interconnection points of the measured and the fitted curve. Having determined $\Delta U$, $U_{\text{extr}}$ and the frequency $f$ the test voltage can be calculated analogous to (1):

$$U_t = U_{\text{extr}} - (1-k(f)) \cdot \Delta U \quad (2)$$

Comparison tests with five engineers and with different parameters for automatic regression algorithms showed that both methods, the manual as well as the automated regression, lead to reproducible and comparable results [11].

**Digital filters for the evaluation**

Another way for the determination of the test voltage with the $k$ factor method is the use of digital filters. The transfer function of the filters can be adapted to the function $k(f)$ and after the filtering of the measured original curve the peak value of the filtered curve represents the test voltage. The filtering can be done in the frequency domain using FFT algorithms as well as by the implementation of FIR filters which are also
used for the noise reduction of measured lightning
impulse curves [12].

As the philosophy of standardization prefers
definitions of limits and not of detailed algorithms or
filter coefficients it has to be shown that different filter
algorithms and implementations fit the requirements
and lead to comparable results. In the following FIR
filters designed as multiband FIR filters with an
arbitrarily shaped piecewise linear frequency response
[13] and FIR filters optimized with the Parks-
McClellan algorithm [13, 14] are compared. Also the
influence of the number of filter coefficients is
demonstrated.

In Figure 4 the magnitude responses for FIR filters
designed as multiband filters with arbitrarily shaped
piecewise linear frequency response which are
adapted to the function \(k(f)\) according to Figure 2 are
illustrated for several numbers of filter coefficients.
All results are presented for a sampling frequency of
100 MHz. It can be seen that the correspondence be-
tween the realized magnitude response and the ideal
function \(k(f)\) increases with growing number of filter
coefficients.

For the evaluation of the filters some test impulses of
the IEC TDG [6] were filtered with the realized FIR
filters. Table 1 shows the results and the deviation to
the true test voltage value \(U_{\text{true}}\), which was calculated
by (1) using a double exponential mean curve [11].
Two contrary effects can be observed: As for small
filter lengths \(n\) the realized magnitude response for
low frequencies (up to 500 kHz) is lower than the
desired function, the filters with small filter lengths \(n\)
\((n = 256, 512)\) lead to test voltages which are slightly
too low. The other effect can be observed with the
impulse ‘case1’ which is a smooth lightning impulse
without oscillation/overshoot with a fast front time
\(T_1 = 0.84\) µs. The evaluated test voltage for this
impulse grows with increasing filter length \(n\). Due to
the fast front time \(T_1\), the frequency spectrum of this
impulse contains some high frequency components
which are reduced by the filter. Thus, due to the Gibbs
phenomenon there is a slight overshoot in the filtered
curve which leads to test voltages which are slightly
higher than the true value. This effect can be observed
especially with high filter lengths \(n\) \((n = 1024, 2048,
4096)\) as for small filter lengths the effect is compen-
sated due to the deviation between desired and
realized magnitude response for frequency compo-
nents up to 500 kHz. Nevertheless for all used filter
lengths there are only small deviations to the true
value \(U_{\text{true}}\) and all deviations are within the uncertainty
limit of ±3 % required by the IEC 60060-2 [15].

Taking into account the described contrary effects
optimal filtering results could be achieved with a filter
length of \(n = 1024\) coefficients.

**Table 1:** Test voltages as function of filter length \(n\) for FIR filters
with piecewise linear frequency response

<table>
<thead>
<tr>
<th>(n)</th>
<th>(U_{\text{true}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>256</td>
<td>1050</td>
</tr>
<tr>
<td>512</td>
<td>1057</td>
</tr>
<tr>
<td>1024</td>
<td>1059</td>
</tr>
<tr>
<td>2048</td>
<td>1068</td>
</tr>
<tr>
<td>4096</td>
<td>1068</td>
</tr>
</tbody>
</table>

For comparison also FIR filters optimized with the
Parks-McClellan algorithm [13] were realized and
tested. Examples for the magnitude response in de-
cendency of the filter length \(n\) are illustrated in
Figure 5.

The optimization algorithm generates filter responses
which fit for low frequencies up to 500 kHz in a better
way with the desired magnitude response. Thus even
for small filter lengths \(n\) a good fitting between the
realized and the desired magnitude response can be
achieved. The voltages evaluated with this kind of FIR
filters are shown in Table 2. Also for this filter reali-
zation there are only minor deviations to the true value
\(U_{\text{true}}\) and also for this filter design a filter length of
\(n = 1024\) coefficients leads to an optimum.
reliability of lightning impulse tests. It prevents and might help to increase the reproducibility and the suitability for manual as well for automated evaluation procedures. The proposed evaluation methods are a smooth transition between low and high frequency oscillations. The current problems with the stringent frequency limit of 500 kHz in the IEC 60060-1 can be avoided due to the current problems with the stringent frequency limit test voltage factor $k$. Using this test voltage factor $k$ frequency dependent influence can be described with a polynomial method. For the FIR filter the Parks-McClellan realization with $n = 1024$ coefficients is used. The results show that the frequency of the oscillations or the waveform of the currents depends on the waveform of the test voltage. The results of breakdown tests with lightning impulses further more a spread in the test voltage evaluation during a test series.

Table 2: Test voltages as function of filter length $n$ for FIR filters optimized with Parks-McClellan algorithm

<table>
<thead>
<tr>
<th>$n$</th>
<th>256</th>
<th>512</th>
<th>1024</th>
<th>2048</th>
<th>4096</th>
<th>$U_{\text{true}}$ [kV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>case 1</td>
<td>1058</td>
<td>1059</td>
<td>1065</td>
<td>1070</td>
<td>1069</td>
<td>1050</td>
</tr>
<tr>
<td>case 8</td>
<td>1041</td>
<td>1043</td>
<td>1049</td>
<td>1055</td>
<td>1053</td>
<td>1043</td>
</tr>
<tr>
<td>case 9</td>
<td>1004</td>
<td>1005</td>
<td>1010</td>
<td>1015</td>
<td>1014</td>
<td>1008</td>
</tr>
<tr>
<td>case 11</td>
<td>958</td>
<td>959</td>
<td>962</td>
<td>970</td>
<td>969</td>
<td>960</td>
</tr>
<tr>
<td>case 13</td>
<td>-1045</td>
<td>-1037</td>
<td>-1046</td>
<td>-1052</td>
<td>-1051</td>
<td>-1054</td>
</tr>
<tr>
<td>case 14</td>
<td>-1030</td>
<td>-1028</td>
<td>-1035</td>
<td>-1041</td>
<td>-1040</td>
<td>-1033</td>
</tr>
</tbody>
</table>

Table 3 shows the test voltages for several impulses from the IEC TDG evaluated with different evaluation procedures using the $k$ factor method. The results show that different procedures lead to the same results within reasonable uncertainty limits. Thus it is only necessary to define the test voltage factor $k$ as function of the frequency and the user can chose suitable procedures for manual as well as for automated evaluation procedures which fulfill the requirements.

Table 3: Test voltages in dependency of used method

<table>
<thead>
<tr>
<th>DE function $U_{\text{true}}$ [kV]</th>
<th>FFT filter [kV]</th>
<th>FIR filter [kV]</th>
<th>SE function $U_{\text{true}}$ [kV]</th>
<th>IEC 60183-2 (TDG) [kV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>case 8</td>
<td>1043</td>
<td>1051</td>
<td>1049</td>
<td>1049</td>
</tr>
<tr>
<td>case 9</td>
<td>1008</td>
<td>1011</td>
<td>1010</td>
<td>1011</td>
</tr>
<tr>
<td>case 11</td>
<td>960</td>
<td>965</td>
<td>964</td>
<td>960</td>
</tr>
<tr>
<td>case 13</td>
<td>-1054</td>
<td>-1049</td>
<td>-1046</td>
<td>-1057</td>
</tr>
<tr>
<td>case 14</td>
<td>-1033</td>
<td>-1036</td>
<td>-1035</td>
<td>-1038</td>
</tr>
</tbody>
</table>

5. Conclusion

The results of breakdown tests with lightning impulses have shown that the frequency of the oscillations or overshoot influences the breakdown voltage. The frequency dependent influence can be described with a test voltage factor $k$. Using this test voltage factor $k$ the current problems with the stringent frequency limit of 500 kHz in the IEC 60060-1 can be avoided due to a smooth transition between low and high frequency oscillations. The proposed evaluation methods are suitable for manual as well for automated evaluation and might help to increase the reproducibility and the reliability of lightning impulse tests. It prevents

References


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