International comparison of software for calculation of lightning impulse parameters based on a new processing algorithm


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Abstract: A new algorithm has been proposed to calculate the parameters of full lightning voltage impulses. The new algorithm enables the application of the test voltage factor (also referred to as k-factor in some literatures) for calculation of the equivalent test voltage of impulses with superimposed oscillations/overshoots. The new algorithm at the same time provides a robust procedure for obtaining time parameters of the impulses from not only smooth waveforms but also waveforms with varying degrees of distortions in the front part of the impulses. These distortions include oscillations on the impulse front and overshoots in the peak region. A critical part of the new algorithm is a 4-parameter fitting procedure to obtain the base curve, which is used for calculation of the test voltage curve. Another important part of the algorithm is applying a filtering procedure in the calculation of the test voltage curve.

The new algorithm was tested in different laboratories using different programming languages and different techniques for realising the fitting and filtering routines. The paper reports the results obtained from the participating laboratories using the proposed algorithm. The results obtained by the participating laboratories using existing software based on the requirement of IEC 60060-1:1989 were also compared. It is anticipated that the results can serve as a part of the basis for a new procedure for determination of lightning impulse parameters in the revised IEC 60060-1.

1 INTRODUCTION

The current version of IEC 60060-1 (1989) and IEEE Std 4 define that oscillations on lightning impulses with frequencies above 500 kHz should be disregarded, and that a mean curve should be drawn for the parameter evaluation. This definition has not been very practical, and it has led to ambiguity in the parameter evaluation of commonly recorded lightning impulses.

At the end of the 90’s, a European Project within the STM Program was developed by KEMA (Netherlands), Schering Institute (Germany), LCOE (Spain) and NGC (United Kingdom) in coordination with the CIGRE WG 33.03, in order to remove the present ambiguities in the evaluation of the test voltage when oscillations and/or an overshoot appear superimposed in a lightning impulse.

Within the project breakdown tests were performed on different materials (air, oil, XLPE, and SF₆) to study the influence of oscillations and overshoot superimposed on a full (close to double exponential) lightning impulse. The results showed that:

- All investigated materials showed similar behaviour.
- The results obtained match with earlier results [1].
- The 50% disruptive discharge voltage, $U_{50p}$, of the material under investigation for a full lightning impulse without oscillations, $U_i$, lies between the extreme value of the lightning impulse with superimposed oscillations, $U_e$, and the peak value of the mean curve of the impulse, $U_{mp}$. How far $U_i$ is placed from $U_e$ and $U_{mp}$ depends on the oscillation frequency. The higher the frequency of the oscillation or overshoot the smaller its influence on the breakdown voltage. This leads to the empirical equation with which the test voltage of a material subjected to a lightning impulse with oscillations or overshoot can be calculated by using a test voltage factor $k$ (or referred to as the k-factor in some early papers) which varies from 1 to 0 depending on the oscillation frequency:

$$U_i = U_{mp} + k\beta$$

where $\beta = U_e - U_{mp}$.

The result of the study was that in theory it should be possible to find a better evaluation method that gives more coherent results, which are more in agreement with the actual breakdown behaviour of the materials or devices under test.
2 PROPOSED NEW PARAMETER EVALUATION ALGORITHM

The procedure is an implementation of Equation 1, and it is used for computer aided calculation of digitally recorded impulses. The procedure is, in short, to obtain a test voltage curve from which the impulse parameters are calculated.

The proposed LI parameter definitions for the new IEC 60060-1 are listed in Appendix 1, and the algorithm proposed to be added as a normative annex is repeated in Appendix 2.

A number of alternative evaluation algorithms were studied before starting this round-robin, and the most promising one was selected for this study. Discussion on the alternative algorithms can be found on another paper [2].

A parallel round-robin has been carried out to study the applicability of the algorithm of equation 1 for manual evaluation of impulse parameters [3].

3 GUIDANCE FOR PROGRAMMING

This chapter summarizes our experience on implementing residual filtering algorithms [4], [5]. Here we concentrate on two steps of the algorithm that are not straightforward to implement: double exponential curve fitting and design of the k-factor filter.

3.1. Double exponential fitting

The double exponential function should include four free parameters (A, B, C and D):

\[ u(t) = A \left( e^{-\frac{(t-D)}{B}} - e^{-\frac{(t-D)}{C}} \right) \]  

(2)

The initial guess for the fitting algorithm could be for example:

A: The extreme value of the curve
B: 70µs
C: 0.4µs
D: True or virtual origin of the curve

Levenberg-Marquardt algorithm [6] and its derivatives have been used successfully for finding the best estimate in least squares sense. This algorithm is readily available in many programming environments [7].

Some software packages do not use partial derivatives during the optimization process. In the case of typical impulse voltage data, where the x- and y-values are of different magnitudes, time values in the order of 10^6 and voltage values of 10^5, omitting the derivatives leads to very poor convergence, or failure to converge at all. In this case normalizing the data (i.e. scaling it so that both voltage and time scales span approximately from 0 to 1) has been necessary.

3.2. Filtering

Either FIR or IIR type digital filter can be used. Both approaches described here lead to a linear-phase response.  

2.3.1. FIR

Typical number of coefficients needed to implement the k-factor using linear phase FIR approach range from 500 to 4000. Again, FIR filter design functions are available in many programming environments [8].

2.3.2. IIR

To obtain linear phase response, a dual pass (zero-phase) filtering approach has been proposed [9]. In this approach the attenuation of the filter is only half of what is needed, but the data is passed through the filter twice, first forward and then in reverse order.

It appears that in this case an IIR filter can be implemented by using only three coefficients:

\[ y(i) = b_0x(i) + b_1x(i-1) + a_1y(i-1), \]  

(3)

where \( x(i) \) is the \( i \)th input sample for the filter, and \( y(\hat{i}) \) is its \( \hat{i} \)th output sample. Here \( b_0, b_1 \) and \( a_1 \) are the filter coefficients.

The filter coefficients can be derived by a relatively simple forward calculation:

\[ x = \left( \frac{\pi T_s}{\sqrt{a}} \right), \]  

(4)

\[ b_0 = b_1 = \frac{x}{1+x}, \]  

(5)

\[ a_1 = \frac{1-x}{1+x}, \]  

(6)

where \( a \) is the -3 dB point of the K-factor filter, and \( T_s \) is the sampling interval used for recording the signal.

For example, 10 ns sampling interval leads to \( a_1 = -0.9585113 \) and \( b_0 = b_1 = 0.02074434 \).

The filtering is then performed twice (once in forward and once in backward direction) using the following difference equation:

\[ y(i) = 0.02074434(x(i) + x(i-1)) + 0.9585113y(i-1), \]  

(7)

where \( y \) is the output data vector and \( x \) the input data vector. In order to avoid numerical problems often typical for IIR filters, large enough number (in this case preferably \( \geq 7 \)) of decimals has to be used for filter coefficient.

4 RESULTS

The evaluation method was tested on 52 impulse waveforms. Their sources are summarised in Table 1. The waveforms vary a lot, and many of them are not considered as standard lightning impulses by the current IEC 60060-1.
Tab. 1: Origins of the 52 curves analysed by each round robin participant.

<table>
<thead>
<tr>
<th>Case</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 3, 4, 6, 8 and 9</td>
<td>From TDG (IEC 61083-2:1996).</td>
</tr>
<tr>
<td>A1 to A17</td>
<td>Created analytically.</td>
</tr>
<tr>
<td>B1 to B4</td>
<td>From transformer tests.</td>
</tr>
<tr>
<td>C1 to C4</td>
<td>Measured smooth waveforms.</td>
</tr>
<tr>
<td>D1 to D6</td>
<td>Measured waveforms with front oscillations.</td>
</tr>
<tr>
<td>E1 to E15</td>
<td>Misc. non-standard waveforms.</td>
</tr>
</tbody>
</table>

Each laboratory created their own software for evaluation of the parameters. All participants provided results calculated by the new method, and in addition four participants delivered parameters evaluated by a method fulfilling the requirements by the current version of IEC 60060-1.

The difference between the old method (as described in the current version of IEC 60060-1) and the proposed method (as described in the Appendices of this paper) are shown in Figs. 1 to 4. The relative overshoot values evaluated for each waveform according to the proposed new method are shown in Fig. 5.

The results are scaled so that the zero line of Figs. 1 to 3 ($U_t/U_p$, $T_1$, and $T_2$) is the mean value obtained by the proposed new method. In Fig. 4 ($\beta/\beta'$) the zero line means no overshoot. The error bars on the zero line of each figure show one standard deviation of the results (N=7) obtained by the proposed new method. The dots on these graphs show the results obtained by different software packages (N=4) fulfilling the requirements of the current version of IEC 60060-1.

5 CONCLUSIONS

A new method for evaluation of impulse voltage parameters has been proposed for the next revision of IEC 60060-1. The method has been tested by evaluating the impulse parameters of 52 impulses both by the new proposed method, and by the method of the current version of the standard.

Each participant of this comparison created their own software according to the algorithm proposed for the next revision of IEC 60060-1. These software packages (N=7) agree with very low standard deviations, when the test voltage value ($U_t$), front time ($T_1$), time to half value ($T_2$) or relative overshoot ($\beta$) is measured. The agreement is good even for the distorted waveforms e.g. from transformer testing.

The results obtained by the old method show, especially for front time evaluation, a large scatter: it has to be noticed, however, that several waveforms being proposed had parameters outside the range which could be considered acceptable: in fact, the largest systematic differences between the old and proposed new method were found while evaluating the analytical impulses with very large (typically 10%, and up to 30%) overshoot.

It seems that the scatter of the old method is larger than the systematic changes the introduction of the new method would cause to the parameter values.

Fig. 1 Peak value calculated according to current IEC 60060-1 ($U_p$) compared with the test voltage value ($U_t$) of the new proposal. The error bars around the zero line show one standard deviation of the test voltage value evaluations (N=7). Values obtained by software packages (N=4) according to the current IEC 60060-1 method is shown by dots.
Fig. 2 Front time ($T_1$) calculated according to current IEC 60060-1 compared with the value according to the new proposal. The error bars around the zero line show one standard deviation (N=7) of the front time evaluations with the proposed new method. Values obtained by software packages (N=4) according to the current IEC 60060-1 method is shown by dots.

Fig. 3 Time to half value ($T_2$) calculated according to current IEC 60060-1 compared with the value according to the new proposal. The error bars around the zero line show the standard deviation (N=7) of the front time evaluations with the proposed new method. Values obtained by software packages (N=4) according to the current IEC 60060-1 method is shown by dots.
Fig. 4 Overshoot ($\beta$) calculated according to current IEC 60060-1 compared with the relative overshoot ($\beta'$) according to the new proposal. The error bars around the zero line show the standard deviation (N=7) of the relative overshoot values. Values obtained by the software packages (N=4) according to the current IEC 60060-1 method is shown by dots.

Fig. 5 Relative overshoot magnitude evaluated using the proposed new method. Results of 7 evaluations are shown for each waveform.
6 APPENDIX 1, DEFINITIONS

Definitions in IEC60060-1 draft used for this work:
- test voltage value, \( U_t \)
- peak value of the test voltage curve
- overshoot magnitude, \( \beta \)
- difference in peak values between the recorded curve and the base curve
- front time, \( T_f \)
  of a lightning impulse voltage is a virtual parameter defined as \( 1/0.6 \) times the interval \( T \) between the instants when the impulse is 30 % and 90 % of the peak value on the test voltage curve.
- time to half-value, \( T_{\text{2}} \)
  of a lightning impulse voltage is a virtual parameter defined as the time interval between the virtual origin, \( O_t \), and the instant when the test voltage curve has decreased to half the peak value

7 APPENDIX 2, EVALUATION PROCEDURE

The guidance given to the comparison participants for creating their evaluation procedure:

a) remove voltage offset from the recorded curve \( U(t) \), and use that curve for the remaining steps;
b) find the extreme value \( U_e \) of the recorded curve \( U(t) \);
c) find the base level of the recorded curve by calculating the mean of the voltage values from the flat part in the beginning of the record;
d) find the last sample on front having a voltage value less than 0.2 times the extreme value \( U_e \);
e) discard data up to and including that sample;
f) find the last sample on the tail having a voltage value larger than 0.4 times the extreme value \( U_e \);
g) discard data after that sample;
h) fit the following double exponential function to the remaining data:

\[
u_d(t) = A \left( e^{-\frac{(t-D)}{\alpha}} - e^{-\frac{(t-D)}{\beta}} \right).
\]

Here \( t \) is time, \( u_d(t) \) is the double exponential voltage function, and \( A, \alpha, \beta \) are the parameters to be found by fitting;
i) construct the base curve \( U_b(t) \) of the waveform, by using the base level of the recorded curve for sample points up to time \( D \) (as defined in step hi) and values of \( u_d(t) \) for sample points from time \( D \) up to the instant of the last sample defined in step if;
j) subtract the base curve \( U_b(t) \) from the recorded curve \( U(t) \) to obtain the residual curve \( R(t) = U(t) - U_b(t) \);
k) create a digital filter with its transfer function \( H(f) \) equal to that defined by the test voltage factor function \( k(f) \);
l) apply the digital filter to the residual curve \( R(t) \) to obtain the filtered waveform \( R_f(t) \);
m) add the filtered residual curve \( R_f(t) \) to the base curve \( U_b(t) \) to obtain the test voltage curve \( U(t) \);
n) calculate the value of the test voltage \( U \) and time parameters from the test voltage curve;
o) find the peak value \( U_{\text{mp}} \) of the base curve \( U_b(t) \);
p) calculate the relative overshoot magnitude,
\[
\beta' = 100 \cdot \frac{U_e - U_{\text{mp}}}{U_e} \%
\]
q) display the recorded curve \( U(t) \) and the test voltage curve \( U(t) \);
r) report the value of the test voltage, front time, time to half value, and relative overshoot magnitude, \( \beta' \).

8 REFERENCES

[7] e.g. Matlab (lsqcurvefit), Octave (leasqr), Labview (Nonlinear Curve Fit) and LabWindows (NonLinearFit).
[8] e.g. Matlab (firl2), Octave (fir2).