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ALTERNATIVE METHOD FOR PROCESSING TAIL CHOPPED LIGHTNING IMPULSE WAVEFORMS

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Abstract – The International Electrotechnical Commission issued in 2010 a revision of the standards IEC 60060, describing how to calculate amplitude and time parameters used to evaluate high voltage tail chopped lightning impulse waveforms. However, the need for a full reference lightning impulse, in addition to the tail chopped impulse, creates difficulties for the tests and processing of the waveforms. This paper proposes an alternative method that precludes the need for the reference impulse.

Keywords: high voltage, impulse testing, measurement standards, measurement techniques, software.

1. INTRODUCTION

The International Electrotechnical Commission (IEC) issued in 2010 the third revision of standards IEC 60060-1 "High-voltage test techniques, Part 1: General definitions and test requirements" [1] and IEC 60060-2 "High Voltage Test Techniques - Part 2: Measuring Systems" [2]. These standards are the basis for the calibration and tests of high voltage equipment to be performed by industrial labs, power companies and high voltage research labs.

The previous standard IEC 60060-1:1989 [3] classified lightning-impulses in two types: "smooth" and "with damped oscillations". The latter case demanded the user to manually draw a mean curve through the oscillations, and the distinction between the two cases was based on the frequency of the oscillations, being 0.5 MHz the transition value.

This new standard IEC 60060-1:2010, based on experimental points from European experiments, defined the smooth function *k*(*f*), which represents the response of the equipment insulation to impulses with overshoot and is called test voltage function, in replacement of this abrupt transition:

$$k(f) = \frac{1}{1 + 2.2 f^2}, \qquad (1)$$

f being the frequency in MHz. The digital filter defined by *k*(*f*) is essentially a low-pass filter, as shown in Fig. 1.

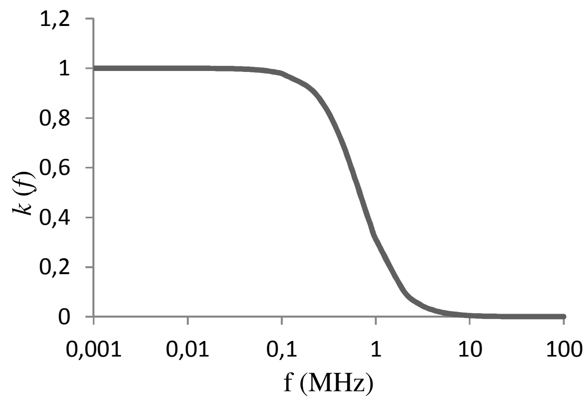

Fig. 1. Test voltage function *k*(*f*).

The signal processing necessary to estimate the time and amplitude parameters that characterize the high voltage impulses is described in the standards for full lightning impulses, and involves:

(a) fitting a double exponential curve to the recorded curve $U_0(t)$, in order to obtain the so-called base curve $U_m(t)$;

(b) calculating a residual curve $R(t)$ (which basically consists on the overshoot information) by subtracting the base curve $U_m(t)$ from the recorded curve $U_0(t)$;

(c) filtering this residual curve by a digital filter based on the test voltage function (1); and

(d) adding the filtered residual $R_f(t)$ to the base curve $U_m(t)$, thus obtaining the test voltage curve $U_t(t)$, from which the relevant amplitude and time parameters are estimated [4,5].

This processing also needs to be applied to tail chopped lightning impulses, but there are additional difficulties such as the need to acquire a full lightning impulse and a more complicated processing of the waveforms.

The next section briefly describes tail chopped lightning impulses and the relevant parameters, followed by an example of processing following literally the description of the IEC standard. Section 4 then describes in details the alternative processing herein proposed, followed by a brief conclusion.

2. TAIL CHOPPED LIGHTNING IMPULSES

Tail chopped lightning impulses (LIC) are based on a standard full lightning impulse, which rises to its peak value in (typically) 2 µs and slowly falls to zero. A chopping gap is used in the field and collapses the waveform after some preset time, subjecting the test object to an enormous stress.

If the chopping occurs before the peak value is reached (typically between 0.5 µs and 0.9 µs), the impulse is *chopped on the front*, otherwise it is *tail chopped* [6].

According to IEC 60060-1 standard, the two time parameters that need to be calculated in order to evaluate the tail chopped waveform are the front time T_1 and the time to chopping T_c, shown in Fig. 2. There is also one amplitude parameter, which is called the value of the test voltage (U_t) and is essentially the extreme value of the waveform.

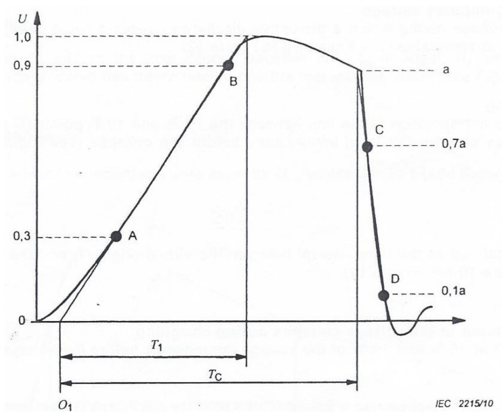

Fig. 2. Typical normalized tail chopped lightning impulse showing the relevant time parameters T_1 and T_c.

Referring to Fig. 2, initially it is necessary to find the virtual origin O_1, which is the intersection with the time axis of the line through points A (30% of peak value) and B (90% of peak value). The front time T_1 is then calculated as $(t_B - t_A)/0.6$. The time to chopping T_c is the time interval between the virtual origin O_1 and the instant of chopping t_c, which is the extrapolation of the line between the 70% and 10% points (C and D) on the voltage collapse.

IEC 61083-2:2013 [7] sets requirements for software for impulse voltage measurements, and provides standardized waveforms that can be used to test the processing algorithms, together with reference values and acceptance intervals for each amplitude and time parameter. Two tail chopped impulses, together with their full reference lightning impulses, are available, entitled "LIC-M4" and "LIC-M5", shown in Fig. 3 and Fig. 4, with the acceptance intervals shown in Table 1. The reference value for each case is the center of the respective acceptance interval.

Table 1. Acceptance intervals for 61083-2 LIC waveforms

Waveform	Parameter	Acceptance Interval
LIC-M4	Front time T_1 (µs)	1.279 to 1.331
	Time to chopping T_c (µs)	5.877 to 6.117
	Value of test voltage U_t (kV)	0.146 to 0.149
LIC-M5	Front time T_1 (µs)	0.840 to 0.874
	Time to chopping T_c (µs)	9.055 to 9.425
	Value of test voltage U_t (kV)	-393.8 to -386.0

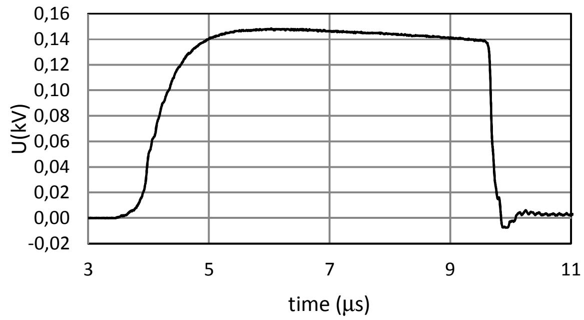

Fig. 3. Waveform LIC-M4 from standard 61083-2:2013.

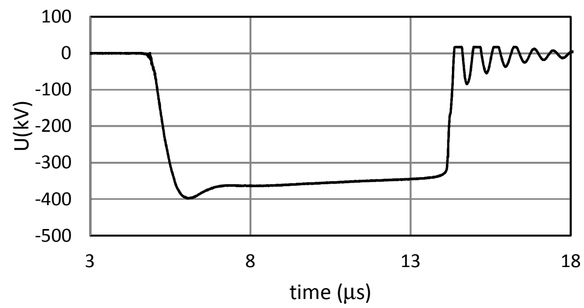

Fig. 4. Waveform LIC-M5 from standard 61083-2:2013.

3. STANDARD PROCESSING

The overshoot processing demands the fitting of a double exponential to the recorded curve, based on (2), whereas the nonlinear fitting algorithm aims at finding the parameters U, t_d, τ_1 and τ_2.

$$u_d(t) = U\left(e^{\frac{-(t-t_d)}{\tau_1}} - e^{\frac{-(t-t_d)}{\tau_2}}\right) \qquad (2)$$

However, this fitting in principle is not possible for a chopped waveform such as the one shown in Fig. 2. Thus, IEC 60060-1 indicates the need of two records for each test:

(a) the tail chopped lightning impulse $U_0(t)$; and

(b) a full reference lightning impulse $U_F(t)$, recorded using the same experimental setup, which allows the fitting of a standard double exponential, from which the base curve $U_m(t)$ is obtained.

For LIC impulses, IEC standard [1] defines that the test voltage curve $U_t(t)$ is to be calculated only up to the instant of chopping t_c. However, the time to chopping T_c is defined as the interval between the virtual origin O_1 and the instant of chopping t_c, and the latter is based on the extrapolation of the line between the points C and D. Thus, a test voltage curve defined as described in [1] would not allow these calculations. This issue has been dealt with [8,9] with good results, and Table 2 presents the time parameters obtained with the standard processing.

Table 2. Results of the standard processing

Waveform	Parameter	Value	Error
LIC-M4	Front time T_1 (µs)	1.306	0.08%
	Time to chopping T_c (µs)	5.977	0.33%
	Value of test voltage U_t (kV)	0.148	0.34%
LIC-M5	Front time T_1 (µs)	0.865	0.93%
	Time to chopping Tc (µs)	9.231	0.10%
	Value of test voltage U_t (kV)	-389.7	0.05%

Table 3 presents the results of the double exponential fit using the full reference lightning impulses provided by standard IEC 61083-2:2013 along with the tail chopped waveforms.

Table 3. Double exponential best fit parameters for the full reference lightning impulse

Waveform	τ_1 (μs)	τ_2 (μs)	t_d (μs)	U (kV)
LIC-M4	54.74	0.46	3.79	0.153
LIC-M5	90.79	0.26	4.99	-360.36

4. ALTERNATIVE PROCESSING

The need for a full reference lightning impulse is dictated by IEC 60060-1 due to the fact that a tail chopped waveform does not follow the smooth double exponential shape described by (2), and this would preclude a proper fitting.

However, as the test voltage curve $U_t(t)$ needs to be calculated only up to the instant of chopping t_c, the fitting of the double exponential also needs to be done only for this period. That is, if the recorded curve $U_0(t)$ is truncated at the instant of the voltage collapse, it should be possible to fit a double exponential and then proceed with the overshoot processing without the need of the full lightning impulse.

This approach has been tested in this work for both tail chopped waveforms from IEC 61083-2:2013 standard. Initially, Fig. 5 and Fig. 6 present the result of the double exponential fitting.

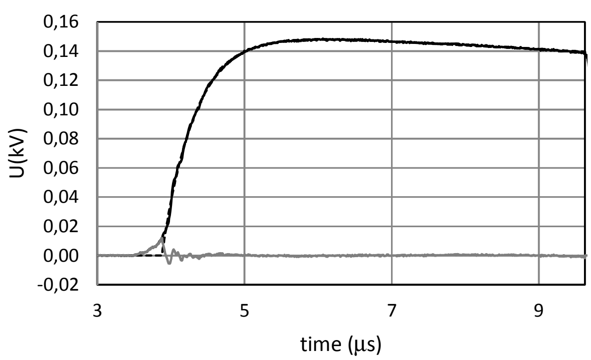

Fig. 5. Fitting of a double exponential to waveform LIC-M4 from standard 61083-2:2013 truncated at the instant of voltage collapse. The solid line is the tail chopped waveform, the dashed line is the fitted double exponential, and the gray line is the residual.

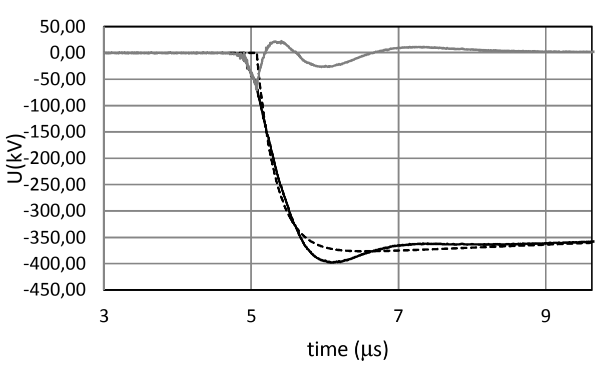

Fig. 6. Fitting of a double exponential to waveform LIC-M5 from standard 61083-2:2013 truncated at the instant of voltage collapse. The solid line is the tail chopped waveform, the dashed line is the fitted double exponential, and the gray line is the residual.

Both cases yielded good results with small residuals (RMSE = 0.28% for LIC-M4 and RMSE = 0.79% for LIC-M5). The larger residual near the wavefront is expected, as the double exponential needs to be truncated and filled with zeroes before the instant t_d. Also, LIC-M5 presents a larger overshoot than LIC-M4, and this affects the fit. Table 4 presents the results of the double exponential fit using the truncated tail chopped lightning impulses provided by standard IEC 61083-2:2013.

Table 4. Double exponential best fit parameters for the truncated tail chopped lightning impulse waveform

Waveform	τ_1 (μs)	τ_2 (μs)	t_d (μs)	U (kV)
LIC-M4	52.98	0.45	3.87	0.155
LIC-M5	64.07	0.27	5.07	-386.9

By comparing the results presented in Table 4 with Table 3, it can be noticed a good agreement between the results, with the exception of a larger discrepancy for the parameter τ_1 in the case of LIC-M5 waveform. This parameter τ_1 controls the rate of fall in the wavetail, while the parameter τ_2 controls the rate of rise in the wavefront. In both cases, the smaller the parameter, the steeper is the wave variation.

Nevertheless, the double exponential fitting is an auxiliary procedure employed in order to allow the test voltage function $k(f)$ to be applied on the overshoot information, separate from the smooth lightning impulse. Should the lowpass digital filter be applied directly to the high voltage impulse, full lightning or tail chopped, it would smooth the entire waveform and distort especially the time parameters, which depend heavily on the frequency content of the waveforms. Thus, the quality of the processing needs not to be assessed based on the double exponential fit parameters, but instead on the amplitude and time parameters that are defined by IEC 60060:2010 standards and which reference values and acceptance intervals are defined by IEC 61083-2:2013 standard for each waveform.

Table 5 presents the time and amplitude parameters calculated using the alternative processing above described for both waveforms LIC-M4 and LIC-M5.

Table 5. Results of the alternative processing

Waveform	Parameter	Value	Error
LIC-M4	Front time T_1 (μs)	1.306	0.08%
	Time to chopping T_c (μs)	5.953	0.73%
	Value of test voltage U_t (kV)	0.148	0.34%
LIC-M5	Front time T_1 (μs)	0.869	1.40%
	Time to chopping Tc (μs)	9.228	0.13%
	Value of test voltage U_t (kV)	-390.5	0.15%

By comparing Table 5 with Table 1, it can be seen that all amplitude and time parameters fall within the respective acceptance intervals, which is a good indicative of the feasibility of this alternative processing.

Also, by comparing Table 5 with Table 2, the differences between the parameters are quite small for the two methods. Some of the percentual errors in relation to the reference values for the alternative processing are larger than the standard processing, but the parameters still fall within their acceptance intervals.

4. CONCLUSIONS

This manuscript presented an alternative method for processing of tail chopped lightning impulse waveforms that has the potential to simplify the procedures for this type of high voltage testing.

The standard method requires, besides the tail chopped waveform, the acquisition of a full lightning waveform using the same experimental setup, to be used as a reference for the overshoot processing. The amplitude of this full lightning impulse waveform can be smaller than the tail chopped, but nevertheless it is still necessary to apply it separately, acquire the waveform, calculate a scale factor to correct the difference in amplitudes and align both waveforms in time, a procedure that might prove difficult in certain situations.

The alternative method relies solely on the tail chopped lightning impulse itself, and was tested in the 2 tail chopped waveforms included in the IEC 61083-2:2013 standard. The time and amplitude parameters were within the acceptance interval, providing a preliminary validation of the method.

Further studies are needed in order to verify any restrictions on the applicability of the alternative method, especially regarding the chopping time, as a waveform that is chopped too close to the peak value might originate difficulties for the fitting of the double exponential function.

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