PARAMETERS DETERMINATION OF TAIL-OSCILLATING LIGHTNING IMPULSE VOLTAGE WAVEFORM

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Abstract: This paper proposes an algorithm to distil waveform parameters according to IEC 60060-3 out of digitally measured data of tail-oscillating impulse voltage. IEC 60060-3 requires an envelope covering oscillatory waveform and the time to half-value, T_2, be determined from the envelope. Conventional technique, which cannot be carried out by computer, utilised a curved rule to draw the envelope on a measured waveform. Authors constructed a five-parameter base curve which is obtained from an equivalent circuit used in the on-site impulse tests. After determining the base curve variables using measured waveform data, one can derive analytical envelope from the base curve. The time to half-value can numerically be evaluated from the envelope without using a curved rule. The validity of the algorithm was confirmed by feeding all related TDG data into the programme in which the developed algorithm was embedded. The results were quite satisfactory in each case. The details of the algorithm and calculation results are to be demonstrated in the paper.

1 INTRODUCTION

Since the IEC 60060-1 Ed.2 [1] was introduced in 1994, definitions of waveform parameter of standard lightning impulse voltage have been recognised to have some difficulties. The situation invites modifications of the standards and the new 60060-1 Ed.3, which was an introduction of k-factor digital filter, was released in 2010 [2]. Important content of the new standards is the treatment of oscillation superposed on the wave-front. In the previous 60060-1, the oscillation, whose main component lower than 500 kHz, is accepted as an associated component with a generating circuit. In case the frequency component of superposed oscillation is higher than 500 kHz, the oscillation is judged as external noise and waveform parameters are derived from a smoothed mean curve. The difficulty in this case has been pointed that waveform parameters are to be computed differently depending on a judgement if a frequency component of the oscillation is close to 500 kHz. In order to compensate this drawback, the new IEC 60060-1 introduced the so-called k-factor, a digital low-pass filter, which can be applied to a residual component of recorded and base curves. The parameters are to be distilled from a synthetic curve called test curve which is made by superposition of the filtered curve over the base curve. With the k-factor, parameters determination of the oscillating lightning impulse waveforms becomes straightforward and no argument is now thought to be left.

It should however be emphasised that the k-factor smoothing technique can only be applied to a waveform which is superposed by oscillation appearing “from wave front to peak”. In fact no new treatment is made to a tail-oscillating waveform in both old and new IEC 60060-1. The parameters determination for the tail-oscillating impulse waveform is separately specified in a present IEC 60060-3 [3] and a definition of time to half-value is significantly different between IEC 60060-1 Ed.2 and 60060-3.

The TDG (Test Data Generator) accompanying with IEC 61083-2 [4] (to be approved in 2011) has been known to provide waveforms to be processed by not only IEC 60060-1 Ed.2 but also IEC 60060-3 procedures. The problem here is that whilst IEC 61083-2 is a software requirement to process digitally recorded waveform, the parameters evaluation in IEC 60060-3 is still have to be carried out in analogue manner.

Authors have developed a full digital technique in which base curve is defined for a tail-oscillating voltage waveform and parameters are derived from an envelope of the base curve as defined in IEC 60060-3. The technique was applied to the tai-oscillating waveforms generated by the forth coming TDG and satisfactory results were confirmed in each case. Details of the technique are to be described in this paper.

Unless otherwise mentioned, voltage waveform is simply noted as “waveform” and a polarity of the waveform is assumed positive throughout the paper.

2 TAIL-OSCILLATING IMPULSE WAVEFORM

2.1 Definition of waveform parameters according to IEC 60060-1

Lightning impulse time parameters according to the new IEC 60060-1 are derived from test curve: Let t_{30}, t_{90} and t_{50} be instants to reach 30, 90 and 50 % of the peak value, then time to half-value is evaluated as $T_2 = t_{50} - t_0$ (see, Figure 1) where t_0 is called virtual origin and easily computed as an external dividing point from t_{30} and t_{90} as a ratio of 0.3 to 0.9 or $t_0 = (0.9 \cdot t_{30} - 0.6 \cdot t_{90})/(0.9 - 0.3)$.

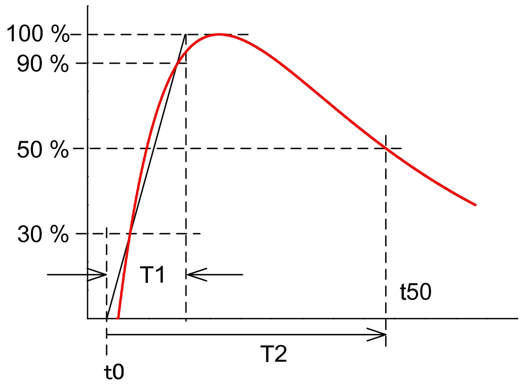


Figure 1: Waveform Parameter Definition by IEC 60060-1

2.2 Definition of waveform parameters according to IEC 60060-3

With waveforms defined by IEC 60060-1, oscillation component decreases to adequately small level around t_{50} and the determination of time to half-value is relatively easy as seen in the previous section. Contrary to this, waveforms appearing IEC 60060-3 typically have 15-400 kHz oscillating component and these components do not settle even at wave tail. In Figure 2, waveform parameter definitions are sketched and parameters are evaluated in the following manner.

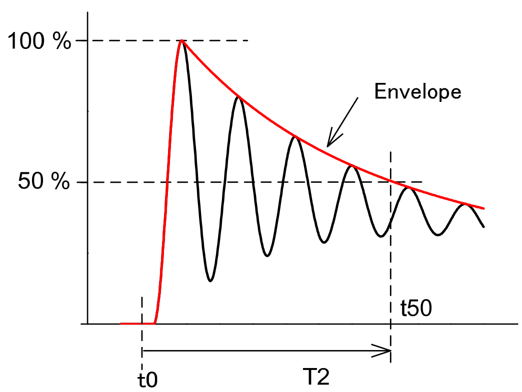


Figure 2: Waveform Parameter Definition by IEC 60060-3

1) Peak value is derived from recorded curve.

2) Front time T_1 is determined from the time to reach 30 and 90% of the peak value similar to IEC 60060-1 (identical to way shown in Figure 1).

3) Time to half-value T_2 is calculated as a time difference of t_{50} (half-value on envelope) and t_0 (calculable from t_{30}, t_{90} already determined in step 2)).

The analogue part of IEC 60060-3 is to draw an envelope from recorded data. If one can plot an envelope with an aide of computer, waveform parameter evaluation procedure in IEC 60060-3 should significantly become simplified and there should be small uncertainty in the obtained parameters. Moreover recorded curve with heavy internal noise would effectively be smoothed out.

3 INEVITABILITY OF TAIL-OSCILLATING IMPULSE

It is critical to construct an envelope with tail-oscillating impulse waveform. Authors have successfully determined envelope from base curve derived from generating circuit. Its background is briefly explained.

3.1 Smooth Lightning Impulse Circuit

Figure 3 shows typical L.I. generator circuit in frequency domain. Charged main capacitor is rewritten as a series connection of step voltage and non-charged capacitor. In normal circumstances, inequity $C \gg C_0$ (capacitance load) stands and residual inductance in the circuit can be neglected. It is well known that output waveform is analytically obtained as a superposition of two exponential functions, $e^{-\alpha t}$, $e^{-\beta t}$.

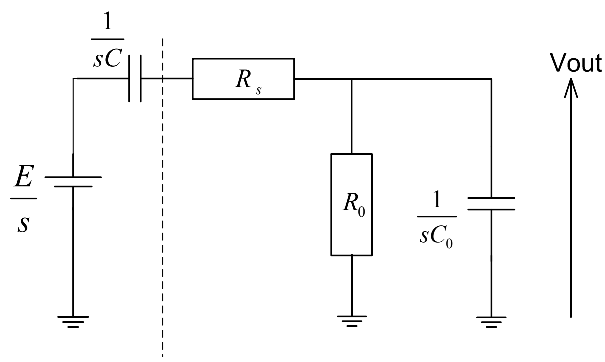


Figure 3: Standard Lightning Impulse Voltage Generator

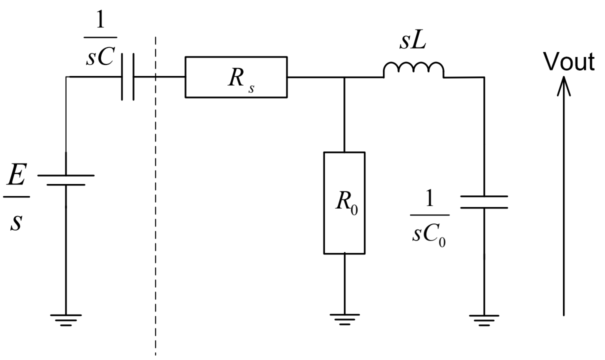
This can be written by eqn.(1).

$$V_{out}(s) = \frac{c}{s^2 + as + b} = \frac{c}{(s+\alpha)(s+\beta)} \qquad (1)$$
$$(a > 0, b > 0, c > 0)$$

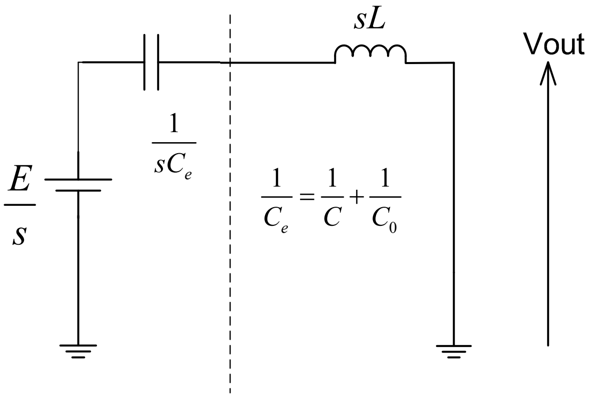
3.2 Tail-oscillating Lightning Impulse Circuit

IEC 60060-3 intends to define requirements for on-site test. Due to higher transmission voltage and consequential large size of high voltage apparatus, a value of C_0 tends to grow up. As a product of R_s and C_0 determins front time T_1, one has to select a small value for R_s, to maintain a value of T_1 between 0.84 and 1.56. Even in this case and inequity $C \gg C_0$ fails to become simply $C > C_0$ (for instance, $C/C_0 = 5$), a ratio of output peak to charged voltage, E, called efficiency, becomes small and it would be difficult to generate high voltage required for test. Moreover, it would also difficult to use C_0 in L.I. generator for on-site test as large as for laboratory level. Thus a condition of $C \gg C_0$ becomes hard to maintain from two reasons: increase of C_0 and decrease of C.

By inserting inductance L as shown in Figure 4 (a), this problem would be solved. Short R_s and disconnect R_0 (Figure 4 (b)) and one can obtain an ever oscillating output voltage of amplitude, $2EC/(C + C_0) = 1.667E > E$ for $C/C_0 = 5$. Even with a reconnection of two resistors, one can realise efficiency much larger than 100%.



(a) Tail-oscillating Lightning Impulse Voltage Generator



(b) Ever Oscillating Voltage Generator

Figure 4: Oscillating Voltage Generator

4 BASE CURVE DETERMINATION

After solving circuit transient for Figure 4 (a), the output voltage is given as

$$V_{out}(s) = \frac{d}{s^3 + as^2 + bs + c} \qquad (2)$$
$$(a > 0, b > 0, c > 0, d > 0)$$

In order to fulfil tail-oscillating condition, eqn. (2) should be rewritten as (2)'.

$$V_{out}(s) = \frac{d}{(s+\alpha)\left((s+\beta)^2 + \omega^2\right)} \qquad (2)'$$
$$(0 < \alpha < \beta)$$

Assuming obvious initial condition, $v_{out}(0) = 0$ and scaling (set coefficient of $e^{-\alpha t}$ to unity), eqn. (2)' can be converted into time domain as

$$v_{out}(t) = e^{-\alpha t} - \left(\cos\omega t + \frac{\beta - \alpha}{\omega}\sin\omega t\right)e^{-\beta t} \qquad (3)$$

Adding two variables (a virtual origin in time axis and a scaling factor of the measuring system), one can propose a base curve $f(A, \alpha, \beta, \omega, \tau; t)$ with five variables $A, \alpha, \beta, \omega, \tau$ for a tail-oscillating impulse waveform given by eqn. (4).

$$f(A,\alpha,\beta,\omega,\tau;t) = A\Big(e^{-\alpha(t-\tau)} - \left(\cos\omega(t-\tau) + \frac{\beta-\alpha}{\omega}\sin\omega(t-\tau)\right)e^{-\beta(t-\tau)}\Big) \qquad (4)$$

Variables, $A, \alpha, \beta, \omega, \tau$, can be determined to minimise the weighted (w_k) square sum of the difference between base curve and recorded curve at (x_k, y_k), $k = 1, 2, \cdots, n$.

$$S = \frac{1}{2}\sum_{k=0}^{n} w_k \left(f(A,\alpha,\beta,\omega,\tau;x_k) - y_k\right)^2 \qquad (5)$$

The technique to solve non-linear equation like eqn. (5) is already reported by authors [5]. Acceptable superposed oscillation frequency accepted in IEC

60060-3 is between 15 and 400 kHz and Initial value for ω is given as 80 kHz which is a rounded value of, 77.5 kHz, a geometrical mean of the two frequencies. With this initial value and ones, author successfully solved all variables for 4 curves generated by a new TDG.

Once the 5 variables $A, \alpha, \beta, \omega, \tau$ are determined, one can construct an analytical envelope for eqn. (4) using a well-known synthetic formula in trigonometric function.

$$\left|\cos\omega t + \frac{\beta-\alpha}{\omega}\sin\omega t\right| \leq \sqrt{1+\left(\frac{\beta-\alpha}{\omega}\right)^2} \qquad (6)$$

Two envelope curves (upper and lower) for eqn. (4) are possible but lower envelope should be discarded (see, Figure 2). Then one can obtain acceptable envelope function, f_e, as

$$f_e(A,\alpha,\beta,\omega,\tau;t) = A\left(e^{-\alpha(t-\tau)} + \sqrt{1+\left(\frac{\beta-\alpha}{\omega}\right)^2} e^{-\beta(t-\tau)}\right) \qquad (7)$$

Though it appears in Figure 2 that two curves given by eqn. (7) and eqn. (4) trace the same trajectory "until the peak", these two curves touch each other even at a moment slightly after the peak. Let the instant be t_x, then t_x is analytically obtained as

$$t_x = \tau + \frac{\pi + \tan^{-1}\left(\frac{\beta-\alpha}{\omega}\right)}{\omega} \qquad (8)$$

The above mentioned procedure can be summarised.

1) At the interval, $\tau < t < t_x$, peak value, t_{30}, t_{90} are evaluated. Determination of T_1 is possible at this stage. If recorded curve is superposed by measurable internal noise of the digital recorder, one can get rid of the noise by simply accepting base curve given by eqn. (4) as a test curve. This is the advantage of the proposed technique.

2) At the interval, $t > t_x$, t_{50} is determined from the envelope defined by eqn. (7) and time to half-value, T_2, can readily be evaluated.

5 TDG ANALYSYS

In the previous chapters, theoretical concept of algorithm capable to distil waveform parameters, from the digitally recorded tail-oscillating waveform for which IEC 60060-3 should apply, has been introduced. Authors now developed software which is implementing the proposed algorithm. The software now feeds TDG outputs and evaluates waveform parameters. If the computed parameters fall within acceptance limits specified in the new IEC 61083-2, the developed algorithm should prove its validity.

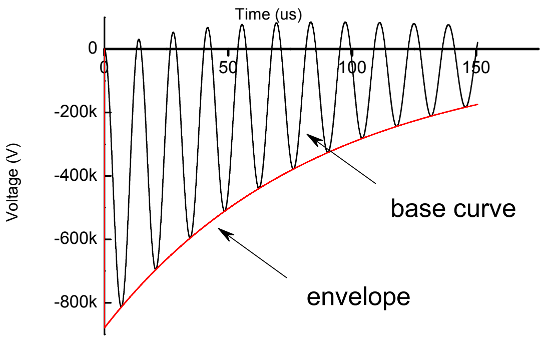
Table 1: TDG Waveform

TDG Designation	Features
OLI-M1	High frequency oscillation settles soon, Positive polarity
OLI-M2	High frequency oscillation, Positive polarity
OLI-M3	Low frequency oscillation, Positive polarity
OLI-M4	High Frequency oscillation, Polarity changes, Negative polarity

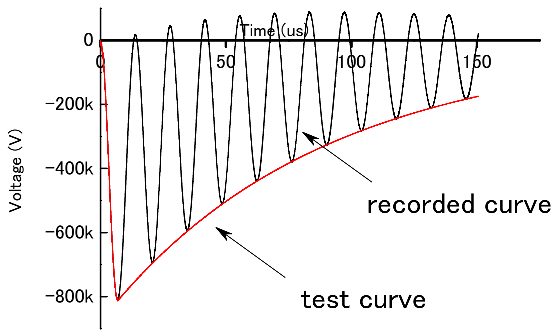
The TDG can generate four measured data, which are designated as OLI-M1~OLIM4 (OLI denotes "Oscillating Lightning Impulse" and M "Measured"). Features of these waveforms are briefly summarised in Table 1.

The software could successfully process all four waveform data and only OLI-M4's result is shown due to the limited allowed space of the paper. The reasons why OLI-M4 was selected are followings (see, Table 1).

- The feature of OLI-M1 is high frequency oscillation only, but the oscillation settles soon.
- Characteristics of OLI-M2 and OLI-M3 are almost identical. Only the difference of the two is oscillation frequency. One can select either of the two as a benchmark.
- Featured with negative polarity and long lasting oscillation, OLI-M4 was most challenging as a benchmark.



(a) Base Curve and Envelope



(b) Recorded Curve and Test Curve

Figure 5: Parameters Evaluation of TDG OLI-M4

Due to these backgrounds, OLI-M4 as well as OLI-M2 was selected for benchmark calculation. The result of OLI-M2 has already been seen in Figure 2 in which both recorded and test curves are drawn. Evaluated parameters of OLI-M2 are U_p=203170.76 V, T_1=5.799 µs, T_2= 51.872 µs, F (oscillation frequency)=60837.90 Hz. These values except frequency, whose value is not specified in IEC 61083-2, are well within the acceptance limits. Figure 5 shows detailed analysed results.

The base curve based on eqn. (4) and envelope given by eqn. (7) are plotted in Figure 5 (a) while recorded curve and test curve (recorded curve till t_x defined by eqn. (8) and envelope after t_x) are drawn in Figure 5 (b). Computed parameters are U_p=-810672.40 V, T_1=4.936 µs, T_2= 68.915 µs, F=72014.11 Hz. All of them are again within acceptance limits.

Although not demonstrated in the paper, other waveforms were also processed and calculated parameters were confirmed to be within the acceptance limits.

6 TAIL-OSCILLATING SWITCHING IMPULSE WAVEFORM

Parameter definitions in tail-oscillating switching impulse are partly different from those of tail-oscillating lightning impulse (see, Figures 1 and 2) but envelope is also introduced in evaluating waveform parameters. It should then be possible to use the proposed technique for parameter evaluation of the tail-oscillating switching impulse.

Author selected OSI-M4 from TDG as a benchmark for the proposed technique. Recorded, base and test curves are shown in Figure 6. As is expected, the proposed technique appears to fit recorded curve.

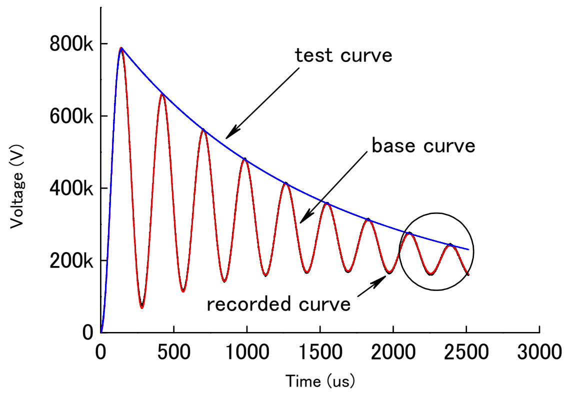


Figure 6: Parameters Evaluation of TDG OSI-M3

Evaluated parameters are U_p=785076.34 V, T_p(not T_1 !)= 144.687 µs, T_2= 1343.808 µs, F =3549.75 Hz. Those values are all within acceptance limits. Other three curves (TDG generates four such waveforms) were also analysed using the proposed technique and confirmed satisfactory results.

Although results were completely acceptable, calculated time to half-value, T_2, is always slightly smaller than reference value of the new IEC 61083-2 in each case. The reason for the minor disagreement can be explained in the followings.

The base curve described by eqn. (7) is derived from a transient of the circuit shown in Figure 4. The circuit consists of purely linear elements and ideal switch. The TDG, however, generates tail-oscillating waveform data measured in the test field. In the real circuit, switching is carried out by a spark gap whose operations are associated with arc between electrodes. This means real circuit uses a switch, which has a non-linear arc resistance connected in series to R_s in Figure 4 at closing state. Due to the existence of the resistance, energy should be dissipated along the arc and oscillation should settle sooner than with the ideal circuit (see, the area enclosed by a circle in Figure 6). This effect becomes more significant with switching impulse than with lightning impulse as the arc appears longer with the former than with the latter. This phenomenon leads to a fact that noticeable difference could not be recognised in time to half-value in the lightning impulse voltages, OLI-M1~ OLI-M 4.

7 CONCLUSION

Authors proposed algorithm to determine the parameters of tail-oscillating impulse waveform defined in IEC 60060-3 and 61083-2. This proposed technique was implemented in software package which fed TDG data and evaluated waveform parameters. From the results the following are elucidated.

- Base curve described by eqn. (4) was predicted from the circuit transient shown in Figure. 2. The estimation was proved to be acceptable.

- Envelope derived from eqn. (4) was used as a test curve for the tail-oscillating impulse voltage. As seen in the main text, one can compute waveform parameters using the test curve without involving manual work. This should improve accuracy and speed. Whole work can now be done automatically in a computer.

- The proposed algorithm can process not only lightning impulse voltage but also switching impulse voltage. The error in time to half-value, albeit insignificant, recognised in switching impulse waveform analysis was reasoned to be originated in non-linear characteristic of the spark gap.

8 REFERENCES

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