IMPULSE CURRENT WAVEFORM PARAMETERS DETERMINATION WITH NON-LINEAR (ZnO) LOAD

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Abstract: This paper proposes numerical techniques to distil waveform parameters out of digitally measured data of oscillatory impulse current waveform. Firstly, the paper proposes ordinary curve-fitting technique for waveform generated by ICG with linear elements only. The so-called base curve is derived from an analytical solution of R-L-C series circuit. Using the base curve technique, one can distil waveform parameters from a noise superposed measured waveform data. Secondly, a novel technique, with which one can calculate waveform parameters from ICG with a non-linear load, is introduced in the paper. In case of ZnO arrester tests, transient current flowing in the circuit cannot analytically be defined and the base curve would not be defined. Authors focused on a fact that a non-linear element (ZnO) quickly turns on after a voltage application and its current-voltage relationship is characterised as $V_z(t) = V_{z0} + R_z \cdot i(t)$. Taking the characteristic into account, it turned out that ICG's output, even with a non-linear element, can be fitted by analytical base curve which is used for the linear circuit. The waveform parameters are then evaluated from the base curve like as it is with ICG with linear elements. The developed algorithm successfully handled relevant the waveform data provided by TDG (Test Data Generator), which is to be issued in 2011 as a part of IEC 61083-2 Ed.2. The details of the algorithm are to be clarified in the paper.

1 INTRODUCTION

After the release of IEC 60060-1 Ed.3[1] in 2010, IEC 61083-2 Ed.2[2], standards concerning the test voltage/current waveforms, are now under final revision and is scheduled to be issued in 2010. The conventional IEC 60060-1 Ed.2[3] also contains regulations concerning the high current tests but in the new version this part are to be deleted from IEC 60060-1 Ed.2 and summarised in a newly drafted IEC 62475[4]. The newly revised IEC 61083-2 Ed.2 still provides current waveforms as well as voltage waveforms of different kinds.

Typical waveform to be used in the high current tests are classified as three types: 1) a rectangular waveform which starts with a steep front followed by a relatively constant plateau and is terminated with a tail as sharp as its front.; 2) the so-called double-exponential function which is a superposition of two decreasing exponential functions of opposite polarities.; 3) a damped oscillating waveform which is a product of exponentially decreasing function and a sinusoidal function.

The generation of the rectangular waveform can be explained with the knowledge of travelling wave on a distributed line. Its applications are restricted within a special area and its details are hereafter not mentioned in this paper.

Both non-oscillatory and oscillatory waveforms are generated in the impulse current generator (ICG) whose equivalent circuit is composed of R-L-C series elements. When a value of R is much larger than that of $\sqrt{L/C}$, generated waveform then becomes non-oscillatory. The waveform is identical to the lightning impulse voltage waveform and waveform parameters evaluation can simply be performed according to IEC 60060-1. It is quite obvious that there are no chopping and oscillations superposing on wave's front~peak part (caused by a residual inductance) in a current waveform. The oscillations on voltage waveform have to be digitally filtered according to frequency characteristics called k-factor. This makes current waveform analysis much easier than voltage waveform analysis and this paper therefore does not treat non-oscillatory waveform either.

One, in general, wishes to generate a large current in ICG. This leads to a small value of series resistor, an element to restrict flowing current. As a result ICG generates a damped oscillating waveform.

Authors developed a technique which determines an analytical base curve for digitally recorded data including superposing noise. The waveform parameters are derived from the obtained smooth base curve. The former half of this paper introduces the details of the algorithm.

Even though ICG is composed of linear R-L-C elements, if non-linear load is connected as a test specimen, the generated current waveform cannot be given as an analytical function. This situation commonly takes place in a gapless arrester test as arrester (ZnO type) has non-linear V-I characteristics. Authors introduced a new technique based on curve-fitting algorithm used with current waveform generated in linear circuit. The proposed method comfortably processed TDG waveforms which are said to be measured during ZnO arrester test. The latter half of this paper explains the details on how to distil waveform parameters out of measured data recorded in ZnO tests.

2 ICG CIRCUIT AND BASE CURVE

Shown in Figure 1 is an equivalent circuit for ICG. Capacitor, C, is charged at E [V] and the accumulated charge in C is released to R-L series circuit after closing the switch. For simplicity the current flowing in the circuit is assumed positive (the arrow direction shown in the figure) unless otherwise specified.

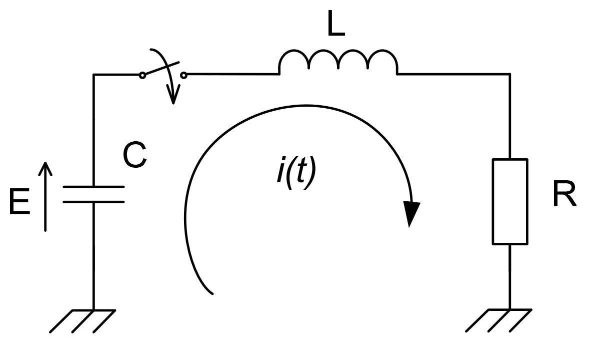


Figure 1: Equivalent Circuit for ICG

Let $i(t)$ be a current in the circuit, then its frequency domain function can be obtained as:

$$I(s) = \frac{E}{\omega L}\frac{\omega}{(s+\alpha)^2+\omega^2}$$
$$\alpha = \frac{R}{2L} \ll \omega = \sqrt{\frac{1}{LC}-\alpha^2} \simeq \sqrt{\frac{1}{LC}} \tag{1}$$

Solution in the time domain, *i(t)*, is given as:

$$i(t) = \frac{E}{\omega L} e^{-\alpha t}\sin(\omega t) = A\, e^{-\alpha t}\sin(\omega t) \tag{2}$$

Measured digital data should have a pre-trigger record and the base curve, $f(t)$, which fits a whole data, can be given as a four-parameter $(A, \alpha, \omega, \tau)$ function derived from eqn. (2) as:

$$f(t) = A e^{-\alpha(t-\tau)}\sin(\omega(t-\tau)) \tag{3}$$

The unknown parameters are determined from the condition on which the square sum (eqn. (4)) of n pairs of measured data, $(x_i,\ y_i),\ i = 1,\ 2,\ \cdots,\ n,$ and the base curve reaches the minimum value.

$$S = \frac{1}{2}\sum_{1}^{n} w_i\left(A e^{-\alpha(x_i-\tau)}\sin(\omega(x_i-\tau)) - y_i\right)^2 \tag{4}$$

In a practical calculation, the unknowns are solved from a set of four non-linear equations obtained by taking a partial derivative of eqn. (4) with respect to the four parameters.

Those non-linear equations are numerically solved by Levenberg-Marquardt method which combines the steepest descent method and Newton method.

The technique introduced here is completed as a Windows programme and used for practical applications (see, Figure 2).

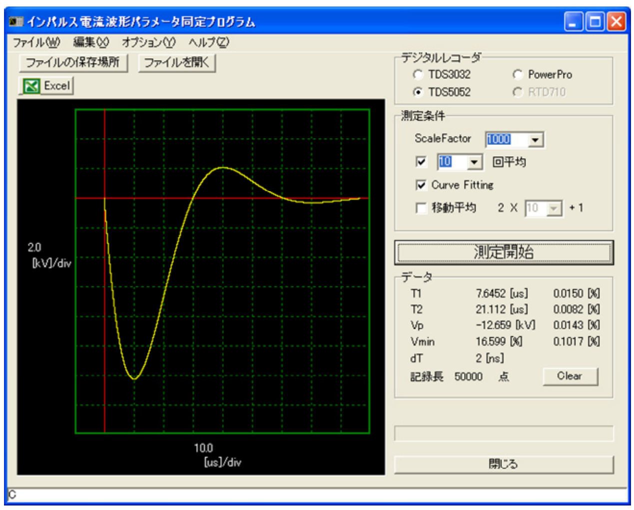


Figure 2: Impulse Current Waveform Calibrator's Output Analysis

Waveform in the figure is a voltage across resistor in the impulse current calibrator shown in Figure 1 and proportional to the circuit current, i(t). As the generator is now a calibrator, the value of C is selected smaller than that appearing in ICG while the value of R is much larger. Also a charging voltage is as low as 20~30 V and a whole generator can be put on a palm.

As recognised in Figure 2, the developed programme cannot only distil waveform parameters but also do statistical calculations on the derived values after processing series of measurements. That is one can set the number of measurements then programme iterates data analysis and computes the means value and deviation for each parameter after the iteration. The package also provides text-format outputs of measured data and base curve, which can be exported to a commercial graphic package and one can draw finer graphs.

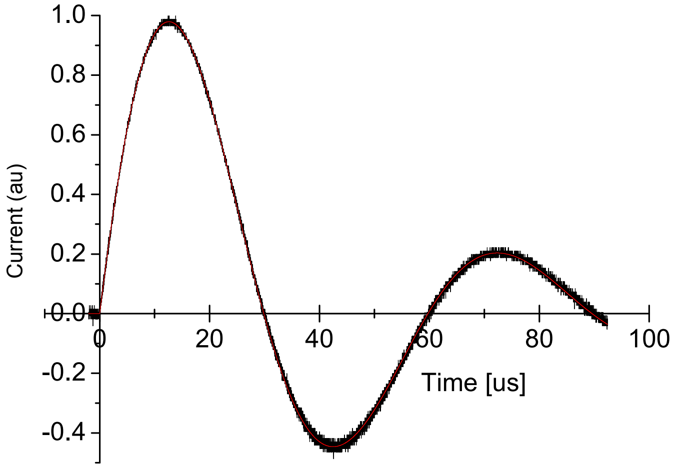


Figure 3: ICG's Output Analysis

A plot shown in Figure 3 is such example. Capacitor in Figure 1 was charged at 85 kV and the current was measured only once with a co-axial shunt (scale factor 1000:1). Curve is normalised by peak value (around 18 kA). It should be emphasised that the recorded data was superposed by digital recorder's internal noise but, with the introduction of base curve, waveform parameters can be determined smoothly. Values of circuit elements are summarised in Table 1.

Table 1: TDG Waveform

	R (Ω)	L	C
For Figure 2	25.51	2.157 mH	32.38 nF
For Figure 3	0.75	13 μH	5 μF

The circuit generating a waveform shown in Figure 2 is a calibrator as mentioned before and value of each element can then precisely be measured after disassembling the equipment. Contrary to this, ICG, whose output is shown in Figure 3, is a heavy equipment (weighting around 1500 kg transformer included). This makes dismantlement-and-measurement difficult and the values shown in Table 1 are simply transcribed from its specification sheet. Arc resistance of the spark gap in ICG is not taken into consideration.

For the waveform appearing in Figure 2, calculated waveform parameters were 7.69/21.21 impulse while close values (7.65/21.11 impulse) were measured. The corresponding parameters were 8.15/20.47 impulse and 9.97/23.65 impulse for the ICG output. This suggests that real ICG waveform parameters are difficult to predict in computation and paradoxically reminds an importance of the programme developed by authors.

3 ICG CIRCUIT WITH NON-LINEAR ELEMENT

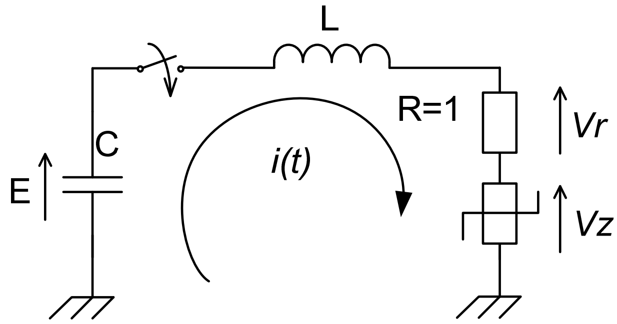


Figure 4: ICG with Non-Linear Element

Shown in Figure 4 is an equivalent circuit of ICG with non-linear element as a load. Voltage across the non-linear element is known to be described as:

$$v_z = V_0 \left(\frac{i}{I_0} \right)^{\beta} \quad (\beta = 1/20 \sim 1/12.5) \tag{5}$$

where I_0 is a constant to normalise a current i(t) and the value is known as 1 kA.

Characteristics given by eqn. (5) can be drawn in Figure 5.

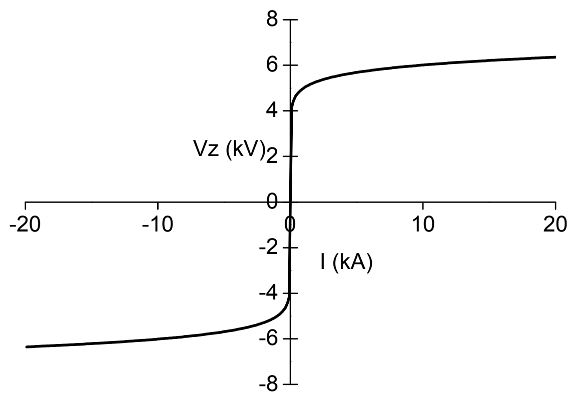


Figure 5: V-I Characteristic of Non-Linear Element

It should be emphasised in Figure 5 that the curve close to the vertical axis is almost perpendicular to the horizontal axis and if charged voltage of a capacitor exceeds V_0 appearing eqn. (5) upon switching, operating point should immediately jump from the origin to a certain point not on a perpendicular region.

This means that a trajectory of the working point moves on an approximated straight line shown in

Figure 6, which shows positive polarity of Figure 5 only.

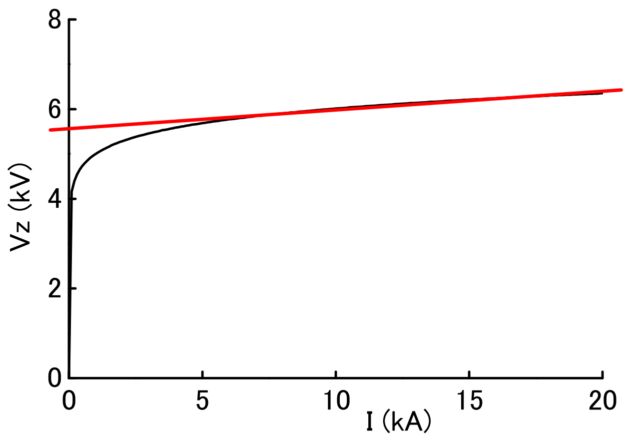


Figure 6: Effective Working area of Non-Linear Element

The straight line is approximated by:

$$v_z \simeq V_{z0} + R_z \cdot i(t) \tag{6}$$

Then a circuit equation, eqn. (7), can be rewritten by eqn. (8).

$$\frac{1}{C}\int_0^t i(t)\,dt + L\frac{d\,i(t)}{dt} + R \cdot i(t) + v_z = E \tag{7}$$

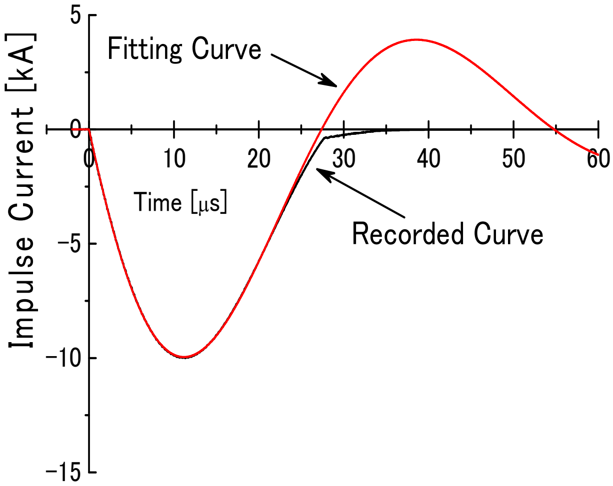
$$\begin{cases} \frac{1}{C}\int_0^t i(t)\,dt + L\frac{d\,i(t)}{dt} + R \cdot i(t) + \underline{V_{z0} + R_z \cdot i(t)} \simeq E \\ \Downarrow \\ \frac{1}{C}\int_0^t i(t)\,dt + L\frac{d\,i(t)}{dt} + (R + R_z) \cdot i(t) \simeq E - V_{z0} \end{cases} \tag{8}$$

Now one can redefine $R + R_z$ as R and $E - V_{z0}$ as E in eqn. (8), then eqn. (8) can be an approximated equation for a circuit shown in Figure 1. This means that a non-linear circuit in Figure 4 can be approximated by a linear circuit while a certain amount of current is flowing.

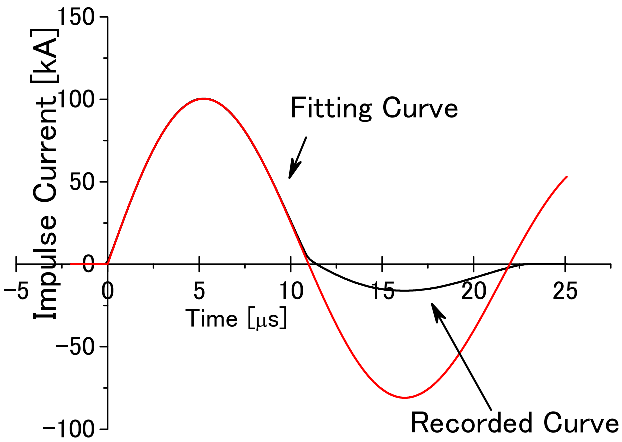
Then the objective function to be minimised is defined by eqn. (4) during the interval of the first swing of eqn. (3) and current value not close to zero (remind Figure 6). Authors therefore assigned weight, w_i, appearing in eqn. (4) in the following.

$$\begin{cases} w_i = 0 \ \cdots \ i(t)/i_{\max} < 0.05 \cap t < t_{\max} \\ w_i = 0 \ \cdots \ i(t)/i_{\max} < \ 0.4 \cap t > t_{\max} \\ w_i = 0 \ \cdots\cdots\cdots\cdots\cdots\cdots \ t < 0 \\ w_i = 1 \ \cdots\cdots\cdots\cdots\cdots \ any\ other \end{cases} \tag{9}$$

where $i(t)$ reaches peak value, i_{max} , at $t = t_{max}$



(a) TDG IC-M1 (Measured, No Undershoot)



(b) TDG IC-M2 (Measured, Slightly Undershoot)

Figure 7: Waveform Analysis by Analogous Circuit

As the time parameters in impulse current are determined from t_{10}, t_{90}, t_{50} (instants to reach 10% and 90% of peak value on front and half the peak on tail), unnecessary part of the data (for example, after crossing the time axis on tail) for the parameter evaluation are neglected if condition defined by eqn. (9) is introduced.

To confirm the effectiveness of the proposed technique, let us process two sets of test waveform data IC-M1 and IC-M2 (see, Figure 7 (a), (b)). Both are generated by TDG associated with the new IEC 61083-2 Ed.2. Although almost unrecognisable in the figures, two data were superposed by recorder's internal noise.

As can be recognised in Figure 7, two waveforms are characterised by no or small undershoot and were recorded under significantly non-linear condition. In each case, base curve completely fits recorded data in a dominant part (i.e. on the first swing centred on the peak).

Evaluated parameters for the two curves as well as IC-M3 (TDG generates three oscillating impulse current curves) are summarised in Table 2. These values are well within IEC 61083-2's acceptance limits.

Table 2: Computed Waveform Parameters

	Ip [A]	T1 [μs]	T2 [μs]
IC-M1	-10004.57	8.823	21.319
IC-M2	100420.70	4.237	9.128
IC-M3	64276.47	7.747	20.533

IEC 61083-2 Ed.2 proposes no true parameter value for a given waveform but recommended value (mean value collected from a round-robin evaluation) with acceptance limits as TDG waveforms (IC-M1~IC-M3) are measured data. Values of distilled parameters using newly developed algorithm all fall within the tolerances. That simply says the new algorithm is acceptable but does not tell how accurate it is.

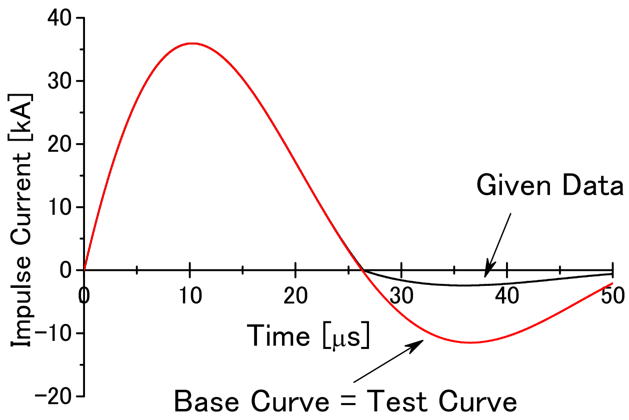


Figure 8: Simulated Waveform Superposed by No Internal Noise. Known Parameter Values

Table 3: Computed Waveform Parameters

	Ip [kA]	T1 [μs]	T2 [μs]
Reference	35.941	7.9290	19.979
Evaluated	35.943	7.9308	19.984
Error [%]	0.005	0.02	0.02

Authors hence generated ideal data of noise-free current waveform using a transient simulator. The data were fed into the programme. Both base curve and given data are plotted in Figure 8. It is possible to calculate very precise parameter values from ideal data. The distilled values can now be compared to the precise values and accuracy of the developed programme can be estimated.

Comparative results are summarised in Table 3. One can easily recognise in the table that disagreements both in time parameters and in peak value were negligibly small.

4 CONCLUSION

Authors developed a new algorithm which can distil waveform parameters from recorded data of ICG with non-linear element. The developed algorithm was applied to IEC TDG outputs and successfully computed each waveform parameters. The developed algorithm can process ICG waveform not only with non-linear element but also with linear element.

5 REFERENCES

[1] IEC 60060-1 Ed.3.0: "High-Voltage Test Techniques Part 1: General Definitions and Test Requirements", (2010)

[2] IEC 61083-2 Ed.2.0: "Instruments and Software used for Measurement in High-Voltage Impulse Tests, Part 2: Requirements for Software", (to appear in 2011)

[3] IEC 60060-1: "High-Voltage Test Techniques Part 1: General Definitions and Test Requirements", (1994)

[4] IEC 62475 Ed.1.0: "High-Current Test Techniques: Definitions and Requirements for Test Currents and Measuring Systems