IEC 60060-1 Requirements in Impulse Current Waveform Parameters

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***Abstract*—There are IEC 60060-1 requirements on three impulse current waveforms. For the damped-oscillating waves, margins of the front time T1 and the time to half the peak T2 are 10 per cent whilst any value after the polarity reversal has to be less than 20 per cent of the peak value. Authors have tried to construct impulse current calibrator for reference measuring system, which would generate a waveform having the time parameters quite close to ideals. After numerous simulations in selecting values for circuit composing components, authors came to an impression that a damped-oscillating current generator whose output waveform has parameter values close to standard. In the paper, authors' "impression" is theoretically proved and mathematically possible margins are to be presented in detail.**

***Index Terms*—IEC 60060-1, Impulse current, Undershoot, Damped-oscillating waveform.**

I. Introduction

If one wishes to develop a code to analyse an impulse current waveform, it is necessary to build up a circuit which precisely generates pre-calculated output for the analysing programme. After numerous simulations in doing so, authors could unsuccessfully design an impulse current calibrator whose output's time parameters (front time, T_1 and time to half-value, T_2) are quite close to one of the standards defined in IEC 60060-1[1]. The investigation for the failed trial was commenced. The study revealed an important fact that one cannot realise a circuit whose output waveform's time parameters can exactly satisfy the IEC 60060-1 requirements. In the paper, possible time parameter combination, which falls within IEC 60060-1 requirements, is illustrated for a calibrator design.

II. Impulse Current Waveform

Fig. 1 shows definitions of parameters T_1, T_2, V_p for a damped-oscillating impulse current waveform appearing in IEC 60060-1. Polarity of the impulse current waveform is assumed to be positive throughout this paper unless otherwise mentioned.

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A front time and a time to half the peak are allowed to settle within 10% margin of the standard waveforms in the IEC norm. IEC 60060-1 specifies three damped-oscillating current waveforms as standard. These waveforms are summarised in Table 1.

TABLE I
IEC 60060-1 Impulse Current Waveforms

Identification	T_1 [μsec]	T_2 [μsec]
No. 1	4	10
No. 2	8	20
No. 3	30	80

Fig. 1 shows definitions of parameters for a damped-oscillating impulse current waveform appearing in IEC 60060-1[1].

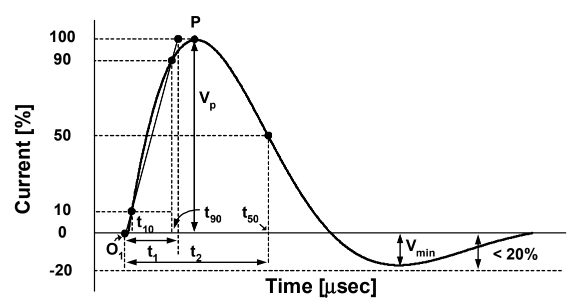


Fig. 1 Impulse current waveform and its parameters

A great concern in this paper is related to the IEC requirement with respect to under-shoot, saying "**Any polarity reversal after the current has fallen to zero shall not be more than 20% of the peak value.**" For simplicity, this requirement shall be called " 20% under-shoot" throughout this paper.

The time parameters, T_1, T_2, for impulse current waveform can be evaluated by (1) and (2) from the three time instants t_{10}, t_{90}, t_{50} at which value of the current curve reaches 10, 90 and 50% of the peak value.(see, Fig. 1)

$$T_1 = \frac{t_{90} - t_{10}}{0.8} \quad (1)$$

$$T_2 = t_{50} - \frac{9t_{10} - t_{90}}{8} \quad (2)$$

III. Impulse Current Generator Circuit and its Output Waveform

A. *Damped-oscillating Current Waveform*

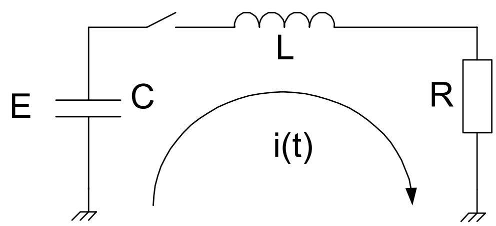


Fig. 2. Impulse current generator circuit

Shown in Fig. 2 is an equivalent circuit for a typical impulse current generator. The value of resistance R in the circuit is small so as to increase the generated current output. As a result, elements C, L become dominant in controlling the output waveform and damped-oscillating current shown in Fig. 1 is to be generated.

Analytical output formula for a circuit shown in Fig. 2 is easily obtained. Its simplified analogue form is given by (3).

$$V = e^{-\alpha t}\sin(\omega\ t) \quad (3)$$

Procedure to evaluate impulse current parameters are summarised in the followings:

1) From the circuit constants, R, L, C appearing in Fig. 2, it is possible to determine variables in (3).
2) Using (3), draw a curve shown in Fig. 1. If the under-shoot of the curve is less than 20% of the peak value, circuit constants are judged acceptable and one can calculate the impulse time parameters, T_1, T_2 and peak value, V_p, after evaluating variables, t_{10}, t_{90}, t_{50} which are obtained by solving a non-linear equation.

Authors planned to build an impulse current calibrator generating precisely 8/20 impulse to be used for impulse current parameters determination software. After numerous unsuccessful simulations, authors were decisively convinced that any combination of R, L, C in Fig. 2 cannot generate a current waveform quite close to 8/20 impulse.

Henceforth in this paper, it is to be clarified that why current waveform specified in IEC 60060-1cannot be generated as well as some discrepancy in IEC requirements. This paper may contribute as a useful guide for those who design a circuit generating IEC 60060-1 impulse current.

B. *Normalised Damped-Oscillating Waveform*

To analyse a damped-oscillating waveform given by (3) quantitatively, analogue waveforms are hereafter put together into a single form. For instance, a waveform function, which varies k-times as fast as (3) along the time-axis, is given by $e^{-k\alpha t}\sin(k\omega t)$. The accelerated function's time parameters, T_1, T_2 are calculable by multiplying those of originals' by factor $1/k$ as t_{10}, t_{90}, t_{50} for the accelerated form is just $1/k$ of the originals'. Then a ration of T_2/T_1 is obviously invariant. Also any two non-analogue waveforms given by (3) shall not have the same ratio of T_2/T_1.

One can generalise this fact as "Any damped-oscillating waveform given by (3) with a ratio ω/α constant has the same ratio of T_2/T_1". Conversely, any waveform described by (3) and having the same ratio of T_2/T_1 can be given by (4) by normalising the exponential part of (3).

$$V = e^{-t}\sin(\omega\ t) \quad (4)$$
$$(0 \le \omega < \infty)$$

Firstly, let us calculate a range for ω in (4) in which the under-shoot value is less than 20%. Assume that (4) reaches peak value at an instance (t_p, V_p) and minimum (negative maximum) at (t_b, V_b), then these variables are easily calculable by (5).

$$t_p = \frac{\tan^{-1}(\omega)}{\omega}, \quad V_p = e^{-\frac{\tan^{-1}(\omega)}{\omega}}\frac{\omega}{\sqrt{1+\omega^2}}$$
$$t_b = t_p + \frac{\pi}{\omega}, \quad V_b = -e^{-\frac{\pi}{\omega}}e^{-\frac{\tan^{-1}(\omega)}{\omega}}\frac{\omega}{\sqrt{1+\omega^2}} \quad (5)$$

Equating $|V_b/V_p| = 0.2$, a value for ω in (5) can analytically be determined as $\omega = -\pi/\log(0.2) = 1.95198126...$. The condition "under-shoot less than 20%" is satisfied with $\omega \ge 1.95198$. This leads to a condition of impulse current parameter $T_2/T_1 \ge 2.69570$.

Generally speaking, "damped-oscillating" waveform given by (3) should fall in the two extreme cases: critical-damping ($\omega/\alpha = 0$) and non-damped ($\omega/\alpha = \infty$).

These conditions can be achieved by selecting appropriate values for the parameters in Fig. 2. When two elements, L, C, are fixed constant and the value of R only can vary, the circuit generates various waveform.

For the value of R is large, then output waveform becomes "double-exponential function" known in lightning impulse voltage.

When the value of R decreases, the output waveform transforms to "damped-oscillating" via "critical-damping". The extreme case is "non-damped-oscillating" which is realised with $R = 0$.

Constraints of the ratio of the time parameters T_1 and T_2 for the two cases (critical-damping and non-damped) are now discussed.

C. *Critical Damping Waveform*

In case, a value of ω is enough small in comparison to that of α, then waveform given by (3) is called critical-damping and its curve, normalized by it peak value and peak instance, is provided by (6) (see, Fig. 3).

$$V = t\ e^{1-t} \quad (6)$$

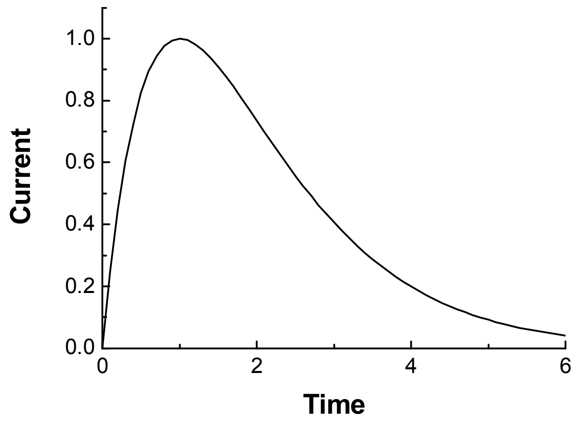


Fig. 3. Critical-Damping impulse waveform

Using Newton method, two variables T_1 and T_2 can be deduced from (1), (2) and (6). The ratio T_1 to T_2 is further determined as $T_2/T_1 = 3.80466\cdots$ (remark. the ratio for the lightning impulse voltage, whose time parameters are evaluated by the instances corresponding to 30, 90 and 50% of the peak value, is $T_2/T_1 = 3.46998$) . This fact leads to an inequality, $T_2/T_1 < 3.80466$,

D. Ever-Oscillating Waveform

There is the other extreme case with (3) in which a value of ω is much larger than that of α (i.e. time constant $1/\alpha$ is considered adequately longer than the period of sinusoidal part, $\sin(\omega t)$). Although any waveform with $\alpha = 0$ in (3) always satisfies non-damping condition no matter how $\omega(>0)$ takes any value, only the condition $\omega = 1$ is taken into account, for simplicity. With this particular case, a typical function to make the ratio T_2/T_1 =const. is given by the following equation (see, Fig. 4).

$$V = \sin(t) \quad (7)$$

The ratio T_2/T_1 can analytically be evaluated as 2.07554… using (1), (2) and (7).

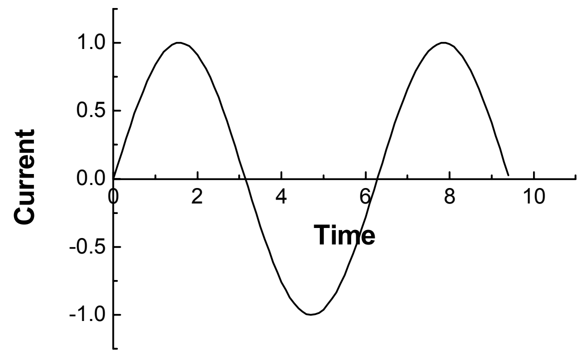


Fig.4. Ever-Oscillating Impulse Current Waveform

IV. Ratio of the Two Time Parameters

From the facts clarified in the previous chapter, the ratio of time parameters, T_2/T_1 , for any oscillating waveform must falls in the domain restricted by the ratios derived from (6) and (7).

The ratio T_2/T_1 is evaluated for the two extreme waveform: non-damping (100% under-shoot) and critical-damping (0% undershoot) and the ratio for any oscillating waveform is narrowed as $2.07554 < T_2/T_1 < 3.80466$. Of all oscillating waveform given by (4), the one with 20% under-shoot has the ratio $T_2/T_1 = 2.69570\cdots$ at $\omega = 1.95198\cdots$ Taking logical joint for the ratio, it becomes clear that any waveform satisfying the requirements in IEC 60060-1 must have its parameter ratio in the following range.

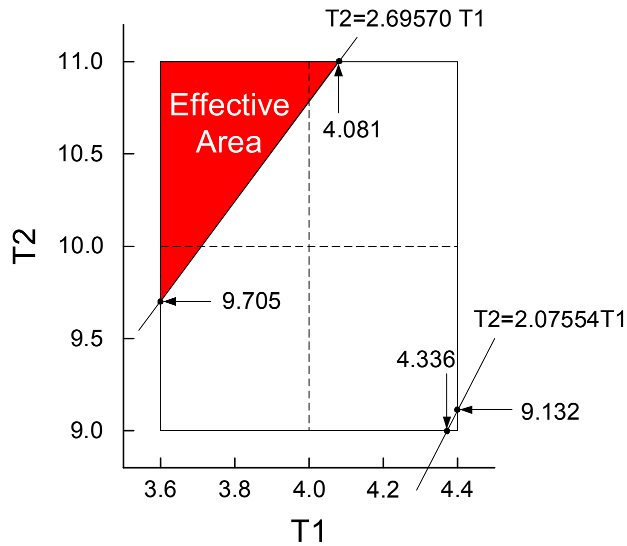
$$2.69570 < T_2/T_1 < 3.80466 \quad (8)$$

V. Standard Waveforms and Ratios of Time Parameters

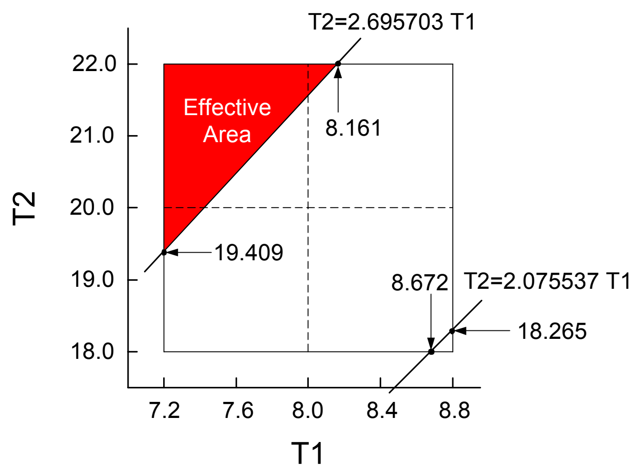
Using the knowledge introduced in the precedent chapters, three damped-oscillating current waveforms listed in Table 1 are now examined their feasibility.

Each graph in Fig. 5 is drawn with a horizontal axis corresponding to front time T_1 and a vertical axis a time to half the peak T_2 .

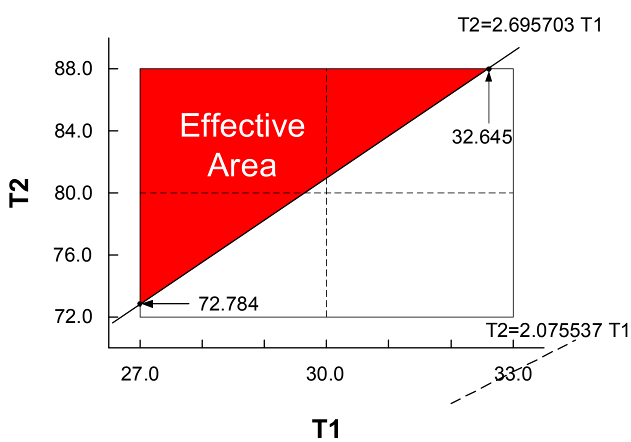
Rectangle with a solid line appearing in the figures shows acceptable waveform area for IEC 60060-1 which allows 10% margin for both T_1 and T_2 . Mathematically possible zone (itself makes a triangle) of the rectangle is shaded. Any damped-oscillating current waveform defined in IEC 60060-1 must therefore stay in the shaded area if its time parameters are plotted in the figure.



(a) 4/10 impulse



(b) 8/20 impulse



(c) 30/80 impulse

Fig. 5 Impulse current waveforms and their effective areas

The value of T_2/T_1 for the waveform of precise 4/10 impulse (see, a crossing point of the two dashed lines in Fig. 5(a)), for instance, is 2.5 which does not fulfil (8). The location corresponding to this waveform is obviously located outside the shaded region. This situation suggests that one cannot design a 4/10 impulse calibrator shown in Fig. 2, no matter how values for discrete elements are selected. Authors are, however, slightly certain if non-linear elements are implemented. It is also recognized from the figure that a 4.4/9.0 impulse (with 10% margin in T_1 and T_2) cannot be generated by a circuit composed of passive elements (this current impulse is possible only by a divergent-oscillating waveform).

As the waveform of an 8/20 impulse has the same ratio of T_2/T_1 as a 4/10 impulse, coordinates appearing in Fig. 5(b) are simply calculated after multiplying the numbers in Fig. 5(a) by factor 2.

An impulse current calibrator based upon the concept discussed in this paper was designed and constructed. As can be recognized in Table 2, measured time parameters, peak value (i.e. efficiency) and under-shoot value were precisely what were expected by a computer simulation.

TABLE II
COMPARISON OF WAVEFORM PARAMETERS

8/20 impulse	T_1 [μsec]	T_2 [μsec]	V_p [V]	V_{min} [V]
Simulation	7.6888	21.206	31.830	-9.9362
Measured	7.6835	21.224	31.874	-9.9972
Disagreement [%]	-0.069	0.085	0.138	-0.614

VI. CONCLUSION

Analysing time parameters of damped-oscillating current waveform defined in IEC 60060-1 and a calibrator circuit's output waveform, a feasible current waveform fulfilling IEC requirements is defined. Study clarified an important fact in designing current calibrator that only a waveform with front time slightly shorter than norm and half the peak slightly longer than the ideal can be generated in a feasible circuit

VII. REFERENCES

[1] IEC 60060-1: "High Voltage Test Techniques, Part 1, General Definition and Test Techniques", Geneva (1994)

VIII. BIOGRAPHIES

Shuji SATO (non-member) was born in Hiroshima, Japan. He graduated from the Kyushu University and started working in UHV Laboratory in Toshiba Co. Ltd.

While employed in Toshiba, he studied high voltage engineering at the Royal Institute of Technology in Stockholm. Upon leaving from Toshiba, he continued his research work in high voltage laboratory at the Swiss Federal Institute of Technology in Zürich. There he was awarded with a doctoral degree of science and technology before employed at Utsunomiya University, Japan. He is a member of Institute of Electrical Engineers of Japan.

Tatsuya HARADA (Life-Fellow member of IEEE) was born in Kofu Japan. He graduated from Tokyo Institute of Technology before starting his carrier in the Central Research Institute of Electric Power Industry, Tokyo. After leaving CRIEPI, he taught high voltage engineering as a Professor at Saga University and later at Nippon Institute of Technology.

He has been awarded six times for his works in high voltage measurement from IEEJ and medalled for his contribution to Japan's Technology from Japan's Ministry of Science and Technology.