Analysis and design of an impulse current generator

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Abstract: - This paper presents an analytical method for the design and analysis of impulse current generators according to the requierements of the international standard IEC 60060-1. The circuit of the generator is analyzed and mathematical expressions for the most important circuit and impulse current parameters are included. The analytical expression of the impulse current waveform in the distinct operation conditions of the generator, as well as expressions for the calculation of the time constants of the waveform are computed. Moreover arithmetic expressions concerning the range of the generator element values are derived, ensuring that the characteristics of the generated current are in accordance with the limitations of IEC 60060-1. These expressions can well fasilitate the correct design of the impulse current generator taking under consideration the international standard. A computer programme has been also developed to support the complex calculations in the impulse current generator circuit. The programme has the ability to calculate the desired configuration and the characteristics of the generated current.

Key words: - Impulse current, impulse current generator, IEC 60060-1

1 Introduction

Lightning as an electrical phenomenon has got very disturbing and destroying consequences for human lives and installations. Telecommunication, navigation and electrical power systems are mainly these, which suffer most from lightning currents. Many lightning current tests, which simulate the real lightning conditions, are conducting on these systems in order to observe their performance. The production of such impulse currents requires impulse current generators with the ability to produce impulses of definite amplitude and waveshape. Therefore, it is well understood that the careful and correct design of impulse current generators plays an important role in the systems lightning protection.

The performance of impulse current tests requires the design of generators that will produce impulses of the correct amplitude and waveshape. In this paper a mathematical analysis of the generator circuit is performed and the dinstict operation conditions of the generator are analysed. Analytical expressions concerning the impulse current waveform are stated and the peak value as well as the time to peak are estimated.

The values of the time parameters of the impulse and the elements of the generator are expressed with analytical and arithmetic expressions ensuring that the characteristics of the generated current are in accordance with the limitations of the international standard IEC 60060-1 [1].

A computer programme has been also developed in order to combine the mathematical analysis with the limitations of the international standard. It introduces flexible solutions which take advantage the laboratory equipment and maximize the efficiency of the generator. At the same time, it gives the opportunity the configuration of the generator to be freely designed according to the demands of the experiment, ignoring the limitations of the standard. The computer programme analyses the defined configuration or alternatively proposes possible configuartions which offer the desired characteristics. Finally a sensitivity analysis of the generator characteristics for all possible operation conditions is included in this paper.

This work forms a useful tool in the development of impulse current generators considering that the international bibliography is quite limited in this particular subject [2, 3, 4]. It must be mentioned that computational approaches to this problem has also been performed in the past [5, 6, 7].

2 Analysis of the generator circuit

Discharging a capacitor to the test object through an inductive circuit (Fig.1) performs impulse current tests. The capacitor, or a row of capacitors, is charged by a DC high voltage supply U_o. The total capacitance C of the circuit includes also the capacitive component of the test object. The inductance L includes an inductive air-core coil L_1

that is added to the circuit for the regulation of the damped oscillation, the inductance L_2 of the test-object and the stray inductance of the circuit conductors.

Generally, the resistance of the discharge loop is very low. However, the resistive components of the circuit elements should be determined. The total resistance R of the loop includes the measuring resistor R_3, the resistance R_2 of the test-object and the circuit conductors as well as any other resistance R_1 that is added to the circuit for the attenuation of oscillations. The charging resistances R_{p1} and R_{p2} of the circuit do not contribute to the resistance of the discharge loop. Although the circuit of Fig.1 is very simple, it is not flexible and independent to regulate the shape of the current waveform.
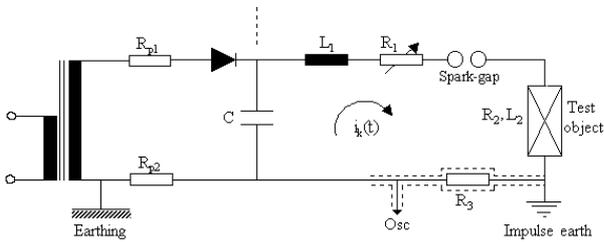
Fig.1 Current generator for exponential impulses (C: capacitor, L_1: inductance, L_2: inductance of the test object, R_1: damping resistance, R_2: resistance of the test object, R_3: measuring resistance, R_{p1}, R_{p2}: charging resistances, Osc: impulse oscilloscope).

The generator consists also of a variable spark-gap which, when fired, discharges the capacitor to the test object loop resulting in the formation of the impulse current. The discharge current $i_k(t)$ can be determined from the system equation at the instant of triggering of the spark gap:

$$U_0 = Ri_k(t) + L\frac{di_k(t)}{dt} + \frac{1}{C}\int i_k(t)\,dt \qquad (1)$$

This equation has three solutions which, correspond to three distinct discharge conditions of the impulse current. The type of the discharge condition is determined by the value of the term R^2-4L/C. If the resistance R is adjusted exactly to nullify the term, then the oscillation is damped. With smaller resistance, the term takes negative values and the oscillation in the current is under-damped. For higher magnitude of the resistance, the term becomes positive and the oscillation is over-damped. These types of discharge of the impulse current generator are shown in Fig.2. The resistance R is the varying element of the generator while the capacitance C and the inductance L are assumed to be constant.
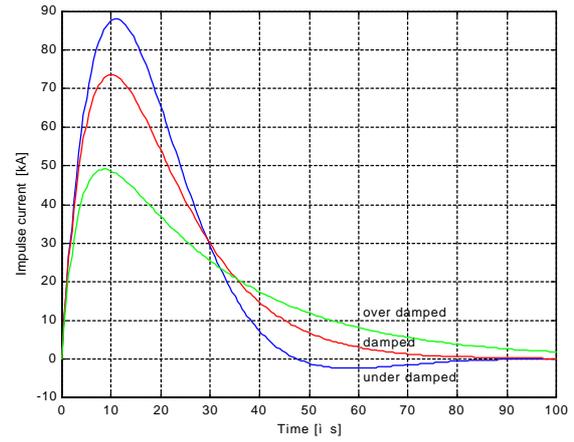
Fig.2 Distinctive discharge conditions of the exponential impulse current generator (over-damped: R=1.5 Ω, damped: R=1 Ω, under-damped: R=0.75 Ω, U_o=100kV, C=20$\mathbf{m}$F, L=5$\mathbf{m}$H).

Solving Eq.(1) by putting:

$$Z = \sqrt{\left| R^2 - 4L/C \right|} \qquad (2)$$

results in three solutions that correspond to the three types of the discharge.

If the resistance is adjusted to damp the oscillation, R^2=4L/C, then the impulse waveform is given by the relation:

$$i_k(t) = \frac{U_0}{L} t e^{-\frac{R}{2L}\cdot t} \qquad (3)$$

The time taken for the damped oscillating current to rise from zero to the peak is:

$$T = \frac{2L}{R} \qquad (4)$$

The amplitude of the current at peak is calculated as follows:

$$I_{max} = \frac{2U_0}{eR} \qquad (5)$$

If R^2>4L/C, the oscillation is over-damped and the current waveform is given by the formula:

$$i_k(t) = \frac{U_0}{Z}\left(e^{-\frac{R-Z}{2L}\cdot t} - e^{-\frac{R+Z}{2L}\cdot t} \right) \qquad (6)$$

The time taken for the current to rise from zero to the peak is:

$$T = \frac{L}{Z}\ln\left(\frac{R+Z}{R-Z} \right) \qquad (7)$$

Thus, the amplitude of the current is calculated as:

$$I_{max} = \frac{U_0}{Z}\left(e^{-\frac{R-Z}{2L}\cdot T} - e^{-\frac{R+Z}{2L}\cdot T} \right) \qquad (8)$$

If $R^2 < 4L/C$, the oscillation is under-damped and the current can be shown to vary with time according to the relation:

$$i_k(t) = \frac{2U_0}{Z} e^{-\frac{R}{2L}t} \sin(w \cdot t) \qquad (9)$$

where ω is the angular frequency of the oscillation:

$$w = \frac{Z}{2L} \qquad (10)$$

Since the current waveform is oscillating it will show more peaks than one, some of them with inverse polarity. The time taken for the oscillating current to rise from zero to the first peak is given by the expression:

$$T = \frac{2}{w} \arctan \frac{\sqrt{R^2 + (2wL)^2} - R}{2wL} \qquad (11)$$

The amplitude I_{max} of the current wave at this peak is calculated as:

$$I_{max} = \frac{2U_0}{Z} e^{-\frac{R}{2L} \cdot T} \sin(w \cdot T) \qquad (12)$$

The respective time T′ from zero to the first peak of the inverse polarity is:

$$T' = T + \frac{p}{w} \qquad (13)$$

Putting t= T′ in Eq.(9) results the minimum amplitude I_{min} of the current waveform.

$$I_{min} = -I_{max} \cdot e^{-p\frac{R}{Z}} \qquad (14)$$

3 Design considerations

The front-time t_f of the impulse current is defined as 1.25 times the interval between the instants when the impulse is 10% and 90% of peak value. The time to half-value t_h of the current is defined as the time interval between the virtual origin and the instant at which the current has decreased to half the peak value. The time parameters t_f/t_h of the four standard, exponential impulse currents, according to IEC 60060-1, are the following: 1/20μs, 4/10μs, 8/20μs, 30/80μs. A ±10% tolerance is accepted between the specified values for these standard impulse currents.

The front-time and the time to half-value of the impulse current can be controlled for a given capacitance with the simultaneous variation of the R and L values. The front-time can be determined with suitable selection of the inductive coil, while the time to half-value with the added resistance.

Solving Eq.(3) for the pairs of values of the damped oscillating current at the points of 10%, 90% and 50% of peak value, the following expressions for the time parameters are derived:

$$t_f = 1.43 \frac{L}{R} \qquad (15)$$

$$t_h = 5.42 \frac{L}{R} \qquad (16)$$

Thus, the ratio of those parameters for the damped oscillation, results to be independent from the circuit elements R, L and C:

$$\frac{t_f}{t_h} = 0.26 \qquad (17)$$

Considering the ±10% tolerance for t_f and t_h, the upper and lower limit of the ratio t_f/t_h for the standard, exponential impulse currents of IEC60060-1 may lie in the intervals of Table 1. It is obvious that the determined value for the ratio t_f/t_h in Eq.(17) lies outside the defined limits. This means that critical damping of the oscillation in the standard impulse currents is impossible. Inevitably, tests with the standard impulses have to be performed either with under-damped oscillating currents or with over-damped ones. A disadvantage of over-damping of the oscillation is the decrease of the current amplitude and, consequently, of the utilisation factor I_{max}/U_o of the impulse generator.

Table 1 Limits for the time parameters of standard impulse current waveforms.

Impulse	1/20μs	4/10μs	8/20μs	30/80μs
t_f/t_h	0.04-0.06	0.33-0.49	0.33-0.49	0.31-0.46

The under-damped oscillation maximises the utilisation factor but attention should be paid to the amplitude of the oscillation. According to IEC 60060-1, any polarity reversal after the current has fallen to zero shall not be more than 20% of the peak value. Thus, the ratio of the peak value I_{min} of the inverse polarity to the value I_{max} of the first peak must be:

$$\left| \frac{I_{min}}{I_{max}} \right| \le 0.2 \qquad (18)$$

Putting the values of I_{min}, I_{max} from Eq.(12), (14) results:

$$Z \le \frac{p}{\ln 0.2} R \qquad (19)$$

Substituting Z from Eq.(2) results the minimum magnitude of the resistance:

$$R \ge 1.1 \cdot \sqrt{L/C} \qquad (20)$$

This is the lower limit for the magnitude of the resistance of the discharge loop in order to meet the requirement of IEC 60060-1 referring to the amplitude of the oscillation in the impulse current.

4. Computer design of the generator

The computer programme of this paper has been developed for the analysis and design of impulse current generators. The computation algorithm runs either for the calculation of the impulse current if the elements of the generator are given or for the calculation of the elements of the generator if the user defines the constants of the current. Following the first procedure, the initial conditions of the impulse generator are entered and the programme calculates the full waveform of the impulse current. For a pre-defined test current waveform, the programme follows the inverse procedure to calculate the elements of the generator.

In the first procedure, the user defines the impulse capacitance C, the inductance L and the total resistance R of the discharge unit of the generator as well as the D.C. charging voltage U_o. From these, result the impulse current waveform and the respective voltage waveform across the test-object.

The programme calculates all the parameters of the impulse current waveform like the front-time t_f, the time to half-value t_h and the ratio t_f/t_h. If the wave-front is oscillating, it is smoothed using a mathematical routine embedded in the programme. Then, the time parameters of the modified waveform are determined.

If either the front-time or the time to half-value fall outside the ±10% limits of the pre-selected standard waveform, then the user is warned to change the values of R, L and C. The divergences are displayed and modified values of the electrical elements are recommended. The same fine-tuning is performed if the inverse peak of the oscillating current exceeds the specified limits of 20%.

Other parameters which are also calculated are the maximum and minimum value I_{max}, I_{min} of the current waveform and the time to maximum T, as well as the ratio I_{min}/I_{max} that is an important parameter for the under-damped oscillation.

Following the inverse procedure, the programme calculates the elements R, L and C of the generator using as input the front-time and the time to half-value. The user is also asked to enter the values of the available impulse capacitors. This facilitates the design because the number of available capacitors in the high voltage laboratories is always limited. The capacitors are bulky equipment and more expensive than the widely available spare resistances.

The designer may also control the oscillation in the current by putting a limit to the amplitude of the inverse peak. In this way, he directs the programme to a more desirable configuration and restricts the number of solutions. All the acceptable solutions give impulses with front-time and time to half-value within the permissible limits of ±10%. The optimised configurations are displayed, together with the impulse parameters, giving the ability to the user to select the most suitable and economical solution.

On the other hand, the user may select an impulse other than the standard ones. This procedure requires more input data since there are no limitations. Generally, the designer has the freedom to pre-define any desirable characteristic of the generator or of the impulse. These characteristics could be either the charging energy generator, the charge voltage of the impulse capacitor, the peak amplitude of the impulse current or even any one of the front-time and the time to half-value.

Finally the programme displays the results i.e. the resistance R, the inductance L and the capacitance of the impulse capacitor. It also displays the front-time and the time to half-value, the current peak, the charge voltage of the impulse capacitor, the charging energy of the generator and draws the current waveform, which obtained for each solution.

5. Sensitivity analysis

The utilisation factor I_{max}/U_o of the impulse generator for over-damped oscillating currents is maximised with large capacitance and small inductance (Fig.3a). Very important parameter is also the resistance of the discharge loop; increase of the resistance attenuates the impulse current (Fig.3b). Moreover, variations in the magnitude of the inductance and of the capacitance slightly affect the impulse current when the resistance is higher than 6 Ohm (Fig.3c). However, the current is too small. In this case it is quite unlikely to operate the generator at so low utilisation factor. On the other hand, the cost and the size of the construction in this case increase significantly.

It has been observed that by increasing the resistance, the front-time decreases while the time to half-value increases. The opposite results arise increasing the inductance i.e. the front-time increases and the time to half-value decreases. Finally both of these time parameters increase by increasing the impulse capacitance.

When operating the generator with under-damped oscillations, the utilisation factor is maximised for high values of the impulse capacitance and for low values of the inductance (Fig.4a). The impulse current in this condition is more sensitive to the magnitude of the elements of the generator, especially to the resistance of the discharge loop that is very small. Slight increase of the resistance causes a significant attenuation of the impulse current (Fig.4b).

R=3 Ù

I [kA]

L = 12 ì H
L = 24 ì H
L = 36 ì H
L = 48 ì H
L = 60 ì H

C [ì F]

C=20 ì F

I [kA]

R = 2 Ù
R = 3 Ù
R = 5 Ù
R = 7 Ù
R = 10 Ù

L [ì H]

L=5 ì H

I [kA]

C = 30 ì F
C = 15 ì F
C = 10 ì F
C = 5 ì F

R [Ù]
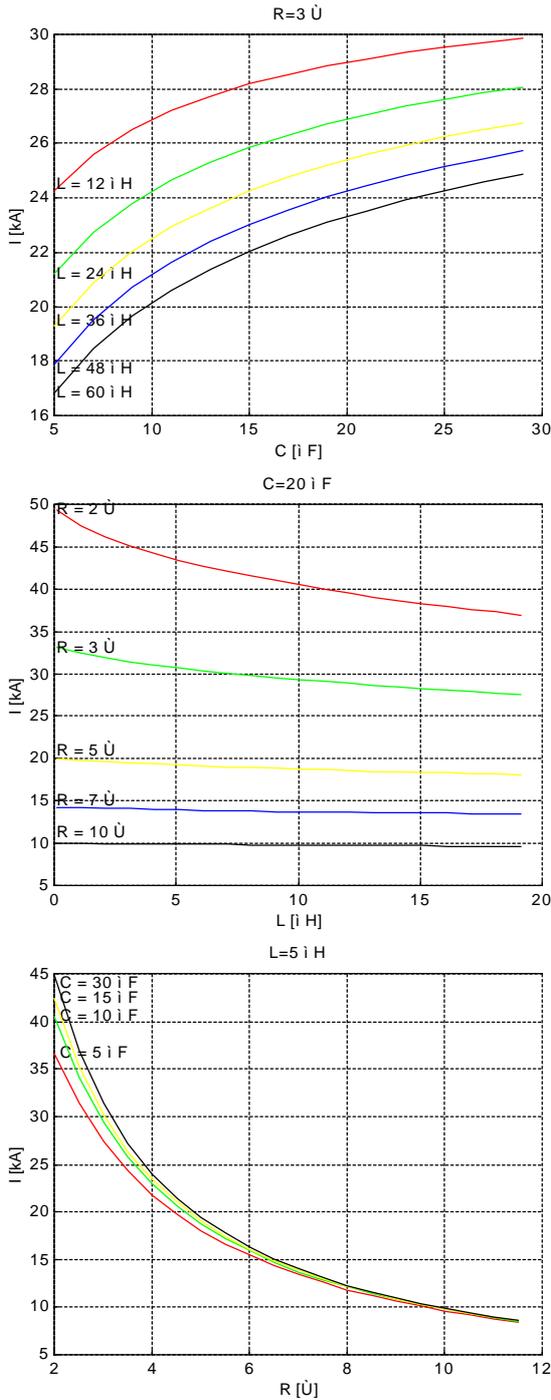
Fig.3 Sensitivity of the peak of impulse current in the over-damped oscillation.

It seems that with a high resistive component, the current is not affected by variations of the magnitude of the inductance and the capacitance (Fig.4c). This is rather unlikely to occur because the utilisation factor of the generator is very low and the size of the elements as well as their cost is increasing significantly.

When the generator is operating in the under-damped oscillation, increment of the total resistance results in the decrease of the front-time and increase of the time to half-value similar as in the over-damped oscillation. On the other hand increment of either the inductance or the capacitance of the generator will result not only in the increase of the front-time but in the increase of the time to half-value as well.

R=2 Ù

I [kA]

L = 20 ì H
L = 29 ì H
L = 41 ì H
L = 50 ì H

C [ì F]

C=10 ì F

I [kA]

R = 1 Ù
R = 1.8 Ù
R = 2.6 Ù
R = 3.4 Ù

L [ì H]

L=25 ì H

I [kA]

C = 9 ì F
C = 7.5 ì F
C = 5 ì F
C = 2.5 ì F
C = 1 ì F

R [Ù]
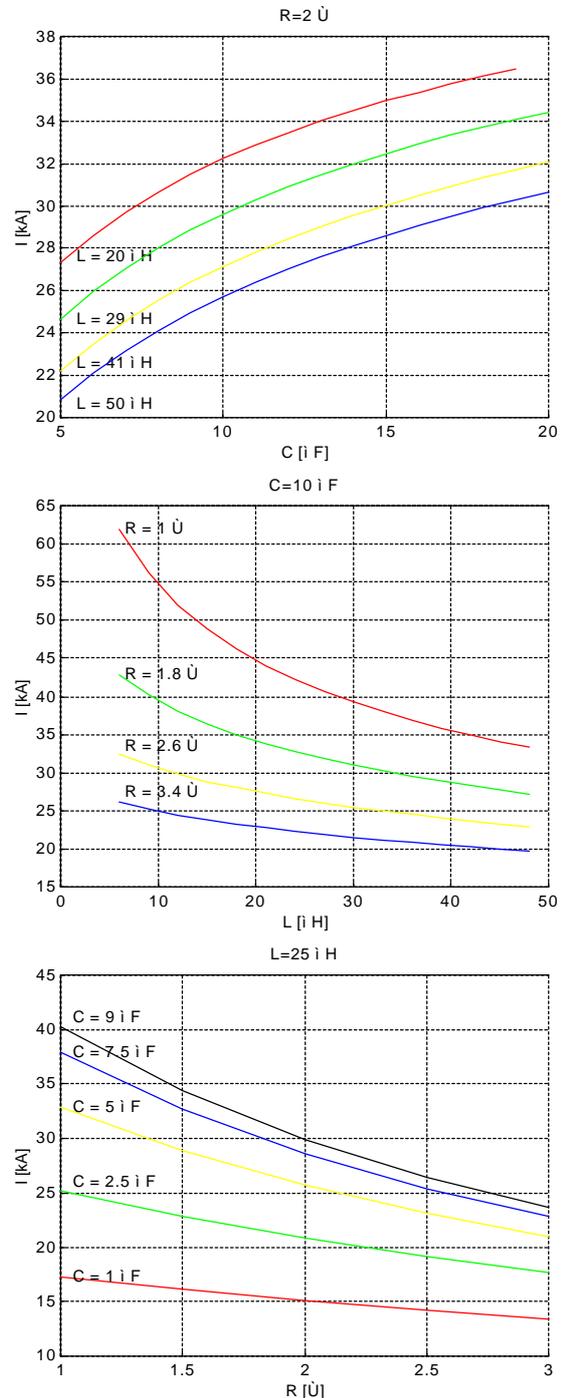
Fig.4 Sensitivity of the peak of impulse current in the under-damped oscillation.

The condition $R^2=4L/C$ for critical damping of the oscillating current restricts the possibility of changing the elements of the generator. Therefore, it is not possible to obtain the desirable values of the

front-time and of the time to half-value by varying one and only element (R, L, C) of the generator. When changing one element it is required to change at least one of the others in order to meet the requirements for damped oscillation, otherwise the current tends to the over-damped oscillation ($R^2>4L/C$) or to the under-damped ($R^2<4L/C$). In order to retain the damped oscillation, it is required to change the magnitude of two elements simultaneously. Such a modification tends to alter the time parameters t_f and t_h. Consequently, a modification to the generator elements is restricted by the upper and lower limit of the time parameters of the required current waveform.

The determination of the optimum combination between L, C and R, under the condition for critical damping, results to a higher value of the current and, therefore, to a better utilisation factor. The computer programme optimises the circuit configuration even after restrictions have been applied to some elements.
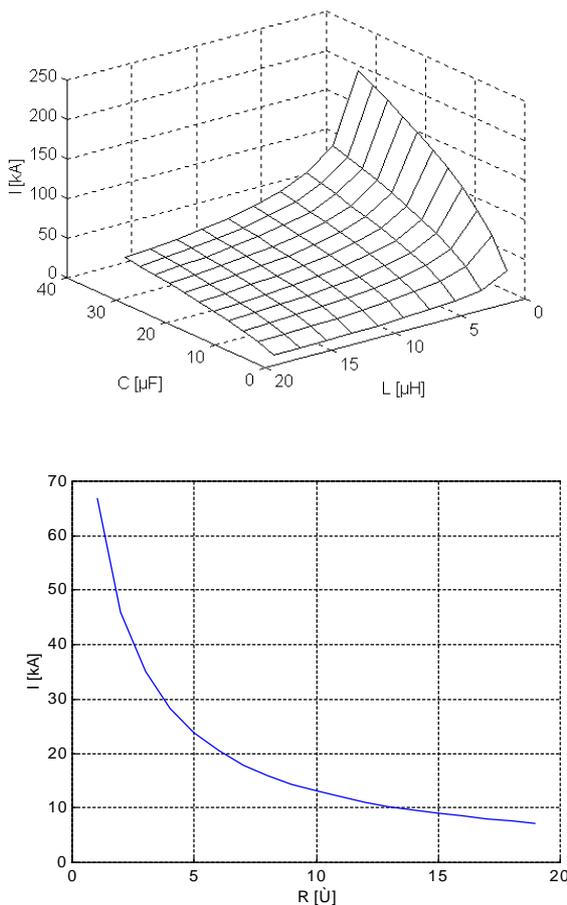
Fig.5 Sensitivity of the peak of impulse current in the damped oscillation.

6. Conclusions

The paper presented an analytical method in conjunction with a computer programme for the design of an impulse current generator. With the proposed method the parameters of the impulse current and the elements of the generator are calculated and several considerable conclusions concerning the configuration of the system are extracted. With the computer programme, which is very flexible and user friendly, the designer determines the circuit elements, entering the desired waveform. Inversely, given all or some of the circuit elements, the impulse current waveform, as well as the time parameters are evaluated. The limits defined by the international standards and the permissible tolerances are taken in account through the calculations something, which makes the method very accurate. Conclusions are also extracted testing the developed method and using several element values. The method can greatly assist to the construction and use of impulse current generators in research, work and testing.

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