ADVANCED LIGHTNING CURRENT GENERATORS

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ABSTRACT: *Lightning current impulse circuit researches have used various schematics for diverse impulses, which makes several problems for lightning current impulse generator fabrication with a suitable cost. In addition, errors of several lightning current impulse math models have not met the standards. This work presents solutions to determination of parameters for a specific lightning current impulse circuit and a lightning current impulse math model which is in Matlab environment with high accuracy.*

Keywords*: Lightning current impulse generator*

1. INTRODUCTION

Researching on effects of lightning current impulses is important to selection of lightning-stroke-protective devices and overvoltage calculation on grid. Lightning current circuit researches have applied various schematics for diverse impulses, which makes several issues for lightning current impulse generator fabrication with a reasonable price. Furthermore, some of proposed lightning current impulse generator physical models have the front and half-value errors greater than the standard ones [2]. Therefore, it is necessary to research and propose a lightning current impulse generator model generating various wave shapes with high accuracy and suitable price.

This work presents the approximate method of quickly calculating basic parameters of lightning current impulse generator and the error-evaluating method of correcting the front error and the half-value error as the standards.

In addition, lightning current impulse math models for wave shapes 8/20µs and 4/10µs are proposed in Matlab environment.
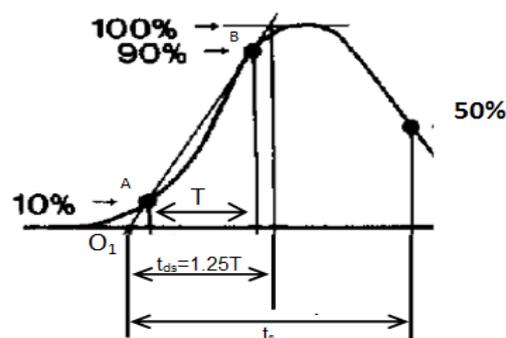
Figure 1. Standard wave shape

2. STANDARD LIGHTNING CURRENT IMPULSE WAVE SHAPES

Typical lightning current impulse wave shapes have been defined in the standards as Figure 1. Front error and half-value error are required less than 10%. [3].

Table 1 presents several universal lighting current impulses with front time t_{ds} and time to half value t_s.

Table 1. Standard lighting current impulses

Wave shape (µs)	t_{ds}(µs)	t_s(µs)	Wave shape (µs)	t_{ds}(µs)	t_s(µs)
10/700	10±10%	700±10%	1/200	1±10%	200±10%
1.2/50	1.2±10%	50±10%	10/350	10±10%	350±10%
2/25	2±10%	25±10%	1/5	1±10%	5±10%
2/50	2±10%	50±10%	4/10	4±10%	10±10%
0.25/100	0.25±10%	100±10%	8/20	8±10%	20±10%

3. LIGHTNING CURRENT CIRCUIT MODEL

3.1. Lightning current circuit schematic
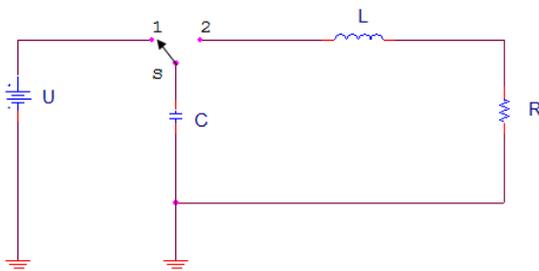
Figure 2. Lightning current circuit schematic

Front wave shape
Tail wave shape
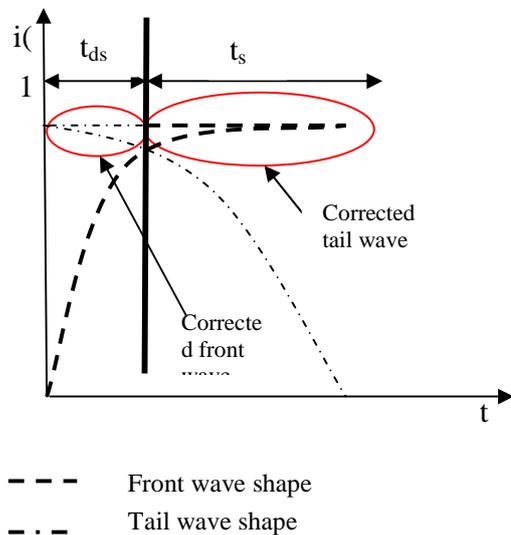
Figure 3. Front and tail wave shapes

By solving integral- differential equation and using Laplace transformation, the time dependent current passing through lightning current circuit can be obtained as equation (1):

$$i(t) = \frac{U}{RA}\left(e^{-\frac{t}{t_2}} - e^{-\frac{t}{t_1}}\right) \quad (1)$$

Where: $A = \sqrt{1 - 4Q^2}$, $Q = \omega_{ch}/2\alpha$

$\alpha = R/2L, \omega_{ch} = 1/\sqrt{LC}$

$$\begin{cases} \dfrac{1}{t_1} = \dfrac{R}{2L} + \sqrt{\dfrac{R^2}{4L^2} - \dfrac{1}{LC}} \\ \dfrac{1}{t_2} = \dfrac{R}{2L} - \sqrt{\dfrac{R^2}{4L^2} - \dfrac{1}{LC}} \end{cases}$$

Assigning $p = t_2/t_1$ and $I_m = U/RA$, equation (1) can be rewriten as equation (2):

$$i(t) = I_m \cdot e^{\frac{-t}{t_2}}\left(1 - e^{(p-1)\frac{-t}{t_2}}\right) \quad (2)$$

To achieve a standard lightning current, parameters p and t_2 must be selected correctly. Then based on equations (3) and (4), the resistance, inductance and capacitance of the circuit can be estimated.

$$\begin{cases} L = \dfrac{t_2^2}{pC} \quad (3) \\ R = \dfrac{(p+1)L}{t_2} = \dfrac{(p+1)t_2}{p^2 C} \quad (4) \end{cases}$$

3.2 Estimate parameters for lightning current impulse generator

3.2.1. Approximate method

The equation (2) shows that functions $e^{-\frac{t}{t_2}}$ and $\left[1-e^{-\frac{(p-1)t}{t_2}}\right]$ generate front and tail wave shapes, respectively.

When applied with the approximate method, the wave shapes can be presented in Figure 3.

In the period of tail time, it is assumed that $\left[1-e^{-\frac{(p-1)t}{t_2}}\right]=1$. Equation (2) can be rewritten as below:

$$i(t) = I_m e^{\left(\frac{-t}{t_2}\right)}$$

Therefore, $i(t) = 0,5.I_m$ if $t = t_s - t_{ds}$.

So: $I_m e^{\frac{-(t_s - t_{ds})}{t_2}} = 0.5 I_m$

Hence: $t_2 = \dfrac{t_s - t_{ds}}{\ln(2)}$ (5)

Similarly, in the period of front time, it is assumed that $e^{-\frac{t}{t_2}} = 1 = 1$, the time dependent current can be present as below:

$$i(t) = I_m \left[1 - e^{-(p-1)\frac{t}{t_2}}\right]$$

Table 2. Parameters R, L and C calculated by the approximate method

Standard(µs)		t_s/t_{ds}	t_2	p	R	L	C	Calculated(µs)		Error(%)	
t_{ds}	t_s							t_{ds}	t_s	Front wave	Tail wave
10	700	70	0.000995	274.406	9.9909	3.61E-05	0.0001	9.38E-06	0.00071	6.25	2.11
1.2	50	41.67	7.04E-05	162.1379	0.7084	3.06E-07	0.0001	1.13E-06	5.17E-05	6.25	3.44
2	25	12.5	3.32E-05	46.56767	0.3389	2.36E-07	0.0001	1.63E-06	2.67E-05	**18.75**	6.8
2	50	25	6.92E-05	96.09775	0.6997	4.99E-07	0.0001	1.75E-06	5.22E-05	**12.5**	4.4
0.3	100	400	0.000144	1582	1.44	1.31E-07	0.0001	2.50E-07	0.0001	0	0.63
1	200	200	0.000287	789.5188	2.8746	1.04E-06	0.0001	1.00E-06	0.0002	0	0.01
10	350	35	0.000491	135.7218	4.9413	1.77E-05	0.0001	9.00E-06	0.00036	**10**	3.49
1	5	5	5.77E-06	16.84963	0.0611	1.98E-08	0.0001	7.50E-07	5.60E-06	**25**	**12**
4	10	2.5	8.66E-06	6.943609	0.099	1.08E-07	0.0001	1.88E-06	1.06E-05	**53.13**	6
8	20	2.5	1.73E-05	6.943609	0.1981	4.32E-07	0.0001	3.75E-06	2.10E-05	**53.13**	5

The amplitude of current reaches $0.1 I_m$ at $t_{10\%}$ and $0.9 I_m$ at $t_{90\%}$. Therefore:

$$\begin{cases} 1 - e^{-(p-1)\frac{t_{10\%}}{t_2}} = 0.1 \\ 1 - e^{-(p-1)\frac{t_{90\%}}{t_2}} = 0.9 \end{cases}$$

Solving the system equations above, the parameter p can be estimated as equation (6):

$$p = \frac{\ln(0.9) - \ln(0.1)}{0.8 t_{ds}}(t_2) + 1$$ (6)

Based on equation 5 and 6, the result of estimating the parameters is shown in Table 2. The result shows that front and half-value errors of wave shapes having great fraction t_s/t_{ds} (10/700; 1.2/50; 0.3/100; 1/200; 10/350µs) meet the standards. On the other hand, wave shapes having low fraction t_s/t_{ds} (1/5; 4/10; 8/20; 10/350; 2/25; 2/50µs) do not satisfy the requirements.

3.2.2. Error-evaluating method

To estimate parameters of lightning current impulses generators with low fraction t_s/t_{ds}, the error-evaluating method is a better solution to reduce the front error and half-value error. The method is based on error deflection and relative error evaluation for current wave forms.

It is assigned that d_1, d_2 and d are front error deflection, half-value error deflection and accumulated error deflection, respectively.

Accumulated error deflection is estimated as equations below:

$d= d_1+d_2$

$$\begin{cases} d_1 =0 & \text{if } 0.9t_{ds}<t_a<1.1\ t_{ds} \\ d_1= 0.9t_{ds}-t_a & \text{if } t_a<0.9\ t_{ds} \\ d_1= t_a-1.1t_{ds} & \text{if } t_a>1.1t_{ds} \end{cases}$$

$$\begin{cases} d_2 =0 & \text{if } 0.9t_s<t_b<1.1\ t_s \\ d_2= t_b-1.1t_s & \text{if } t_b>1.1t_s \\ d_2=0.9t_s-t_b & \text{if } t_b<0.9\ t_s \end{cases}$$

Where: t_a is the estimated front time, $t_a=1.25*(t_{90\%}-t_{10\%})$; t_b is the estimated half value time, $t_b=t_{50\%} - t_{10\%}+0.1t_a$.

It is assigned e_1, e_2 and e are front error, half-value error and accumulated error, respectively. Then:

$e=e_1+e_2$.

Where: $e_1=|t_a-t_{ds}|/t_{ds}$;

$e_2=|t_b-t_s|/t_s$.

Parameters p and t_2 must reach the conditions (7) and (8):

$$1 < p < \frac{\ln(0.9) - \ln(0.1)}{0.8t_{ds}}\frac{t_s - t_{ds}}{\ln(2)} \qquad (7)$$

$$\frac{0.8.t_{ds}.(p-1)}{\ln(p)} < t_2 < \frac{1.1t_s - 0.9t_s}{\ln(2)} \qquad (8)$$

Among values (p,t_2) passing conditions (7) and (8), the values reaching the condition "d=0" mean the errors pass the standard. If "d=0"- reaching values are available, the value with the minimum accumulated error is the best option. In the case that no value (p,t_2) supports condition "d=0", the value having the minimum accumulated deflection will be chose as the best option.

Based on the error-evaluating method, round values R, L and C are presented in Table 3. Through this result, wave shapes 8/20µs and 4/10µs are only two conditions not achieving the requirements, and the errors are lower than proposed models [2].

4. HEIDLER MATH MODEL

4.1. Heidler equation

Heidler equation is one of equations that used to express lighting current impulses [4]:

$$i(t) = \frac{I_m}{\mu} \frac{\left(t/\tau_1\right)^{10}}{\left(t/\tau_1\right)^{10} + 1}\, e^{-\frac{t}{\tau_2}} \qquad (9)$$

Where: I_m is peak current (kA); τ_1 is increasing current time coefficient (µs); τ_2 is decreasing current time coefficient (µs) ; µ is peak-current-adjusting coefficient.

Applied with the approximate method, in the period of front time, it is assumed that $e^{-\frac{t}{\tau_2}} = 1$. Therefore, equation (9) can be rewritten:

$$i(t) = \frac{I_m}{\mu} \frac{\left(t/\tau_1\right)^{10}}{\left(t/\tau_1\right)^{10} + 1}$$

The amplitude of current reaches $0.1I_m$ at $t_{10\%}$ and $0.9I_m$ at $t_{90\%}$ .Therefore.

Hence:

$$\frac{\left(t_{10\%}/\tau_1\right)^{10}}{\left(t_{10\%}/\tau_1\right)^{10} + 1} = 0.1 \qquad (10)$$

$$\frac{\left(t_{90\%}/\tau_1\right)^{10}}{\left(t_{90\%}/\tau_1\right)^{10} + 1} = 0.9$$

Solving the systems of equation (10), parameter τ_1 can be estimated base on equation (11):

$$\tau_1 = \frac{0.8 t_{ds}}{\sqrt[10]{9} - \sqrt[10]{\frac{1}{9}}}$$ (11)

Similarly, in the period of tail time, assume that $\dfrac{(t/\tau_1)^{10}}{(t/\tau_1)^{10} + 1} - 1$, the Heilder equation can be rewritten as below:

$$i(t) = \frac{I_m}{\mu} e^{-\frac{t}{\tau_2}}$$

At $t = t_s - t_{ds}$ the current value reaches a half of the peak value.

Hence: $e^{-\frac{t_s - t_{ds}}{\tau_2}} = 0.5$

$$\tau_2 = \frac{t_s - t_{ds}}{\ln(2)}$$ (12)

Errors of the lightning currents based on equation (10) and (11) are shows in Table 4. Through this table, even if errors of wave forms 8-20, 4-10μs have been reduced in comparison with equation (1), they still do not pass for the requirements when the approximate method is applied.

Table 3. Parameters R, L and C estimated by the error-evaluating method

t_{ds} (μs)	t_s (μs)	R (Ω)	L (μH)	C (μF)	e_1 (%)	e_2 (%)
10	700	9.8	40	100	6.25	0.54
1.2	50	2.7	1.2	25	6.25	1.16
2	25	1.2	1.1	25	0	1.2
2	50	2.7	2.2	25	0	1.8
0.25	100	14.3	1.3	10	0	0.075
1	200	11.4	4.1	25	0	0.15
10	350	19	76.8	25	0	0.2
1	5	0.43	0.28	10	0	2
4	10	0.3	0.5	25	**37.5**	0.1
8	20	0.6	2.4	25	**29.7**	6

Table 4. The parameters of Heilder equation

t_{ds}	t_s	τ_1	τ_2	e_1(%)	e_2(%)
4	10	7.52E-6	8.6562E-6	**21.875**	**11**
8	20	1.504E-5	1.7312E-5	**21.875**	**10**

4.2. Parameters correction

To obtain a better result, a correction needs performing to compensate for assuming

$$x(t) = \frac{\left(\dfrac{t}{\tau_1}\right)^{10}}{\left(\dfrac{t}{\tau_1}\right)^{10} + 1} = 1 \quad \text{and} \quad y(t) = e^{\frac{-t}{\tau_2}}$$. The

correction of increasing current time coefficient and decreasing current time coefficient must be done to make functions x(t) and y(t) decrease because these functions are less than one before the approximate method is performed.

In the case of the functions, x(t) decreases when

$$\left(\frac{t}{\tau_1}\right)^{10}$$ decreases, which means that τ_1 increases.

On the other hand, function $y(t) = e^{\frac{-t}{\tau_2}}$

decreases if τ_2 decreases.

Correcting flowchart is presented in Figure 4, and Table 5 presents the parameters after correcting algorithm has been performed. Through this table, all wave shapes meet the standards.

Table 5. The corrected parameters of Heilder equation

tds (µs)	ts (µs)	τ_1	τ_2	e_1(%)	e_2(%)
4	10	1.0446E-6	5.885E-6	0	3
8	20	1.9898E-5	1.239E-05	1.5	2.5
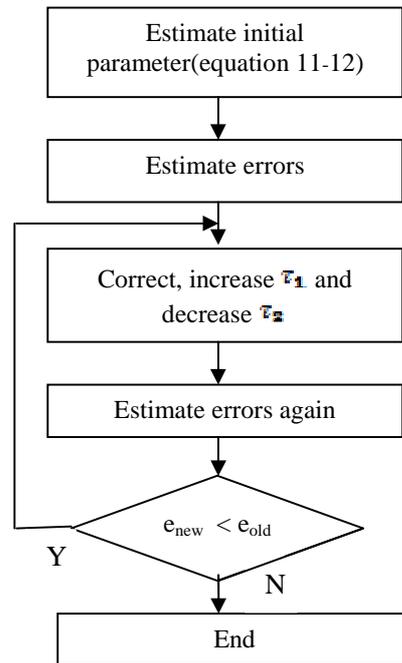
Figure 4. Correction flowchart

5. CONCLUSION

This work has estimated parameters R, L and C for lighting current generator available to generate various wave shapes 10/700, 1.2/50, 2/25, 2/50, 0.25/100, 1/200, 10/350, and 1/5µs which meet the standards.

Parameters R, L and C of lighting current generator 8/20µs have reduced errors of the wave shape in correlation with a proposed model from 39.06% to 29.7 %.

Math models for lighting current generator 8/20µs and 4/10µs have the errors lower than proposed researches from 6% to 3%.

CÁC MÔ HÌNH MÁY PHÁT XUNG SÉT CẢI TIẾN

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TÓM TẮT: *Những nghiên cứu về máy phát xung dòng sét trước đây sử dụng các cấu hình mạch riêng biệt để tạo ra các dạng xung dòng sét khác nhau, điều này gây khó khăn cho việc nghiên cứu chế tạo các máy phát xung sét với giá thành hợp lý. Bên cạnh đó, một số mô hình toán học mô phỏng dòng xung sét còn chưa đạt được độ sai số theo tiêu chuẩn. Bài báo này trình bày phương án thiết kế máy phát xung sét chỉ dùng một cấu hình mạch và mô hình toán học máy phát xung sét xây dựng trong môi trường Matlab có độ chính xác cao.*

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