

## BUILDING THE SURGE GENERATOR MODEL AND THE MULTI LAYER VARISTOR MODEL ACCORDING TO THE INTERNATIONAL STANDARDS

### XÂY DỰNG MÔ HÌNH MÁY PHÁT XUNG VÀ MÔ HÌNH BIẾN TRỞ PHI TUYẾN ĐA LỚP THEO CÁC TIÊU CHUẨN QUỐC TẾ

Le Quang Trung, Quyen Huy Anh, Dinh Thi Ngoan

Ho Chi Minh City University of Technology and Education

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#### ABSTRACT

*This paper presented the 1.2/50 $\mu$ s-8/20 $\mu$ s combination wave generator model and the low voltage multilayer varistor model which had the needed complexity and high precision compared to the models that have been proposed previously. The generator model is used to simulate and test the response of nonlinear model of low voltage voltage multilayer varistor with standard impulses as specified in the international standards. The voltage multilayer varistor model has similar characteristics as the actual low voltage multilayer varistor of manufacturers and the necessary input parameters such as rated surge current, residual voltage and the number of voltage multilayer varistor elements in parallel. The method of determining the repeated lightning impulse currents with waveform lightning 8/20 $\mu$ s that voltage multilayer varistor can withstand has also been mentioned will be the basis for research to determine the lifetime of the low voltage multilayer varistor in lightning protection against indirect lightning in the low voltage network.*

**Keywords:** impulse generator, low voltage multilayer varistor, lightning protection, residual voltage, impulse currents.

#### TÓM TẮT

*Bài báo trình bày mô hình mạch máy phát xung hỗn hợp áp dòng 1.2/50 $\mu$ s, 8/20 $\mu$ s và mô hình biến trở phi tuyến đa lớp hạ áp có độ phức tạp cần thiết và độ chính xác cao so với các mô hình đã được đề xuất trước đây. Mô hình máy phát xung được sử dụng để mô phỏng đánh giá và kiểm tra khả năng đáp ứng của mô hình biến trở phi tuyến đa lớp hạ áp với các xung sét như qui định trong các tiêu chuẩn quốc tế. Mô hình biến trở phi tuyến đa lớp hạ áp có đặc tính tương đồng như các biến trở phi tuyến đa lớp thực tế của các nhà sản xuất và có các thông số đầu vào cần thiết như: dòng xung sét định mức, điện áp dư và số lượng phân tử biến trở phi tuyến đa lớp mắc song song. Phương pháp xác định số xung sét lặp lại với dạng sóng 8/20 $\mu$ s mà biến trở phi tuyến đa lớp có thể chịu được cũng đã được đề cập sẽ là cơ sở để nghiên cứu xác định tuổi thọ còn lại của các biến trở phi tuyến đa lớp trong bảo vệ chống sét lan truyền trong mạng hạ áp.*

**Từ khóa:** máy phát xung, biến trở phi tuyến đa lớp hạ áp, bảo vệ chống sét, điện áp dư, dòng xung sét.

## 1. INTRODUCTION

The papers [1], [2], [3] presented the standard voltage impulse generator and the standard current impulse generator to generate the monopulses and the paper [4] presented the metal oxide varistor (MOV) model has the degree of detail and accuracy as required by the relevant standards [5, 6, 7]. However, the building of the 6kV 1.2/50 $\mu$ s-3kA 8/20 $\mu$ s CWG model and the low voltage MLV model have not been mentioned and fully analyzed [1].

This paper studied in depth and built the combination wave generator (CWG) model according to the ANSI/IEEE C62-41 standard [5] and the IEC 61000 standard [6]: 6kV 1.2/50 $\mu$ s, 3kA 8/20 $\mu$ s and MLV model in the Matlab environment. The accuracy of the CWG model proven through the waveform requirements of the relevant standards and the accuracy of multilayer varistor (MLV) model proven through the simulation result of residual voltage that is checked against the catalogue of manufacturers.

## 2. DEFINE THE PARAMETER ELEMENTS OF THE 6kV 1.2/50 $\mu$ s, 3kA 8/20 $\mu$ s CWG

The principle diagram of the CWG is presented in Figure 1.

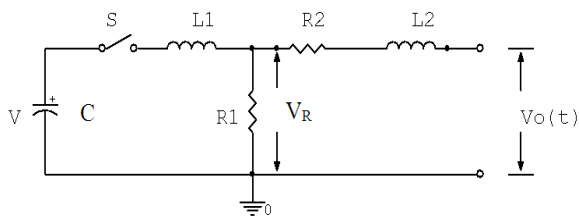


Figure 1. Principle diagram of the CWG.

By writing integro-differential equation describe the circuit and using Laplace transforms, the output voltage  $V_0(t)$  is given by:

$$V_0(t) = (VR_1C) \left( \frac{1}{\beta - \alpha} \right) (e^{-\alpha t} - e^{-\beta t}) \quad (1)$$

$$\text{Where: } \alpha = \frac{1}{CR_1} \text{ and } \beta = \frac{R_1}{L_1} \quad (2)$$

According to the standard [7] then

$$\beta \gg \alpha \text{ so } V_{0Max}(t) = (VR_1C) \left( \frac{1}{\beta} \right) \quad (3)$$

$$\frac{\beta}{\alpha} = e^{\beta t} \quad (4)$$

Then, the maximum value  $V_{0Max}(t)$  will decrease exponentially to 50%:

$$V_{0Max}(t) = (VR_1C) \left( \frac{1}{\beta} \right) = e^{-\alpha t_{decay}} \quad (5)$$

The coefficients  $\alpha$  is calculated as follows:

$$e^{-\alpha t_{decay}} = \frac{1}{2} \Rightarrow \alpha = \frac{-1}{t_{decay}} \ln\left(\frac{1}{2}\right) \quad (6)$$

Where:  $t_{decay}$  is time to half-value,  $t_{rise}$  is front-time of the wave, and at  $t_{decay}=50\mu$ s then  $\alpha=13.9 \times 10^3$ .

From Eq.(4) and  $t_{rise}=1\mu$ s then  $\beta = 6.1 \times 10^6$ .

According to the standard [7], the short-circuit current  $I(t)$  and the open-circuit voltage  $V_0(t)$  are determined by the expressions:

$$I(t) = AI_p t^3 e^{\frac{-t}{\tau}} \quad (7)$$

$$V_0(t) = AV_p (1 - e^{\frac{-t}{\tau_1}}) (e^{\frac{-t}{\tau_2}}) \quad (8)$$

From the Thevenin equivalent circuit the short-circuit current is calculated as follows:

$$I_{SC} = \frac{V_{oc}}{R_{th}} = \frac{V_{oc}}{2} \quad (9)$$

The charge in the circuit:

$$Q = \int i dt = \int \frac{V_0(t)}{2} = 0.7 \text{ (Coulomb)} \quad (10)$$

Where  $Q=C \times V$  and  $V=6000V$ , the value of capacitance  $C$  is:  $C=11.7\mu F$ .

With  $\alpha = 13.9 \times 10^3$  and  $\beta = 6.1 \times 10^6$  as calculated above, the values  $R_1 = 6.15 \Omega$  and  $L_1 = 1 \mu\text{H}$ .

From the Thevenin equivalent circuit ( $V_{oc}$ ,  $I_{sc}$ ), and according to IEEE standard the Thevenin impedance approximate  $2 \Omega (\pm 10\%)$ . Hence:  $Z_{th} = (Z_1 // R_1 + Z_2)$  (11)

$$\text{Where: } Z_1 = \frac{1}{sC} + sL_1; \quad Z_2 = sL_2 + R_2 \quad (12)$$

$$Z_{th} = \frac{(L_1 C s^2 + 1) R_1}{L_1 C s^2 + s R_1 C + 1} + R_2 + s L_2 \quad (13)$$

With waveform  $8/20 \mu\text{s}$ , and time to half-value  $t_{decay} = 20 \mu\text{s}$ , roughly half of the calculated wave cycle:  $t_{decay} = \frac{T}{2} = \frac{\pi}{\omega}$ , so

$$\omega = \frac{\pi}{t_{decay}} = \frac{3.14}{20} = 157 \text{ Krad/s}$$

Putting  $s = j\omega$ ,  $R_1 = 6.15 \Omega$ ,  $L_1 = 1 \mu\text{H}$  and  $C = 11.7 \mu\text{F}$  in Eq.(13) the value of  $Z_{th}$  is:

$$|Z_{th}| = 2 \Rightarrow |Z_{th}|^2 = 4 \quad (14)$$

The front-time constant for the short circuit current will approximate the value of  $L_2/R_2$ , thus:

$$L_2 = 3.9 \times 10^6 \times R_2 \quad (15)$$

Putting the value  $L_2$  in Eq.(13) and solving this equation results:  $R_2 = 1.8 \Omega$  and  $L_2 = 7.2 \mu\text{H}$ .

### 3. MODELING AND SIMULATION OF THE CWG

With the calculated values above, the CWG model in Matlab environment is shown in Figure 2.

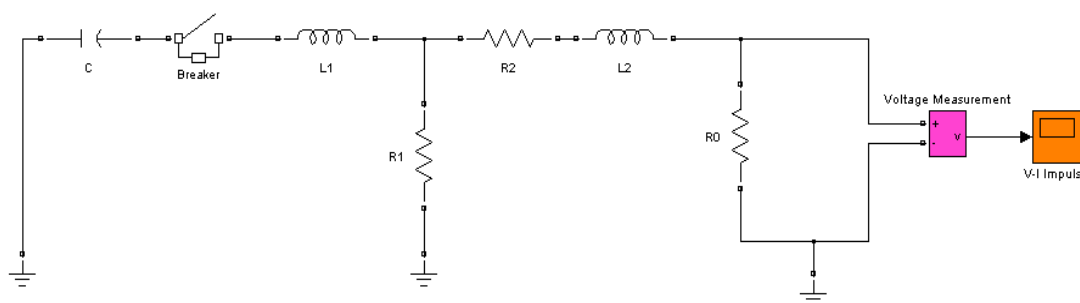


Figure 2. The 6kV 1.2/50 $\mu\text{s}$ -3kA 8/20 $\mu\text{s}$  combination wave generator model.

Simulation results of the open-circuit voltage and the short-circuit current are presented in Table 1.

Table 1. Simulation results.

A. Open-circuit voltage (voltage impulse)					
Parameter	$V_{peak}$ (V)	90% $V_{peak}$ (V)	$t_{90\%}$ ( $\mu\text{s}$ )	30% $V_{peak}$ (V)	$t_{30\%}$ ( $\mu\text{s}$ )
Value	5931	5338	0.35	1779	0.05
B. Short-circuit current (current impulse)					
Parameter	$I_{peak}$ (kA)	90% $I_{peak}$ (kA)	$t_{90\%}$ ( $\mu\text{s}$ )	10% $V_{peak}$ (V)	$t_{10\%}$ ( $\mu\text{s}$ )
Value	2.3	2.07	5.42	0.23	0.46

From the simulation results in Table 1, recognizing that:

- With voltage impulse: the voltage amplitude  $V_{peak} = 5.931 \text{ kV}$  meet the allowable tolerance:  $5.82 \text{ kV} < V_{peak} < 6.18 \text{ kV}$ ; the front-time  $\tau_1 = 1.67 (t_{90\%} - t_{30\%}) = 0.5 \mu\text{s}$  do not meet the allowable tolerance:  $0.84 \mu\text{s} < \tau_1 < 1.56 \mu\text{s}$ ; the time to half-value  $\tau_2 = 49.44 \mu\text{s}$  meet the allowable tolerance:  $40 \mu\text{s} < \tau_2 < 60 \mu\text{s}$ .
- With current impulse: the current amplitude  $I_{peak} = 2.3 \text{ kA}$  do not meet the allowable tolerance:  $2.7 \text{ kA} < I_{peak} < 3.3 \text{ kA}$ ; the front-

time  $\tau_1 = 1.25(t_{90\%} - t_{10\%}) = 6.2\mu\text{s}$  meet the allowable tolerance:  $6.4\mu\text{s} < \tau_1 < 9.6\mu\text{s}$ ; the time to half-value  $\tau_2 = 22\mu\text{s}$  meet the allowable tolerance:  $16\mu\text{s} < \tau_2 < 28\mu\text{s}$ .

- 3. Error correction: Due to a number of indicators on the voltage amplitude, current amplitude and time errors do not meet the requirements of international standards. Thus, should have the additional adjustments such as: increasing the capacitance of the capacitor C and reducing the value of  $R_1$ ,  $R_2$  and  $L_2$ . The re-selected parameters are  $C = 11.9\mu\text{F}$ ,  $L_1 = 2.45\mu\text{H}$ ,  $R_1 = 5.35\Omega$ ,  $L_2 = 3.45\mu\text{H}$ ,  $R_2 = 1.365\Omega$  and 6kV 1.2/50 $\mu\text{s}$ -3kA 8/20 $\mu\text{s}$  complete CWG model have the waveform meet the requirements of the amplitude and the time error of front-time and time to half-value according to the international standards. CWG model is shown in Figure 3 and the waveforms are shown in Figure 4.

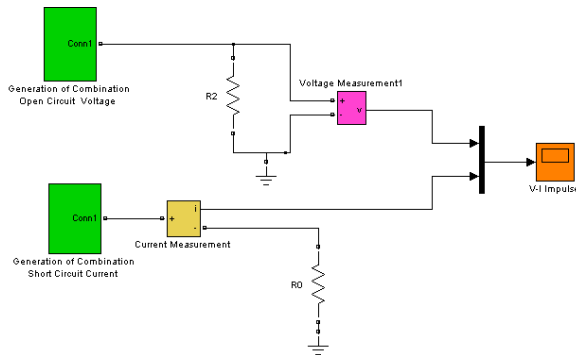


Figure 3. The combination wave generator model.

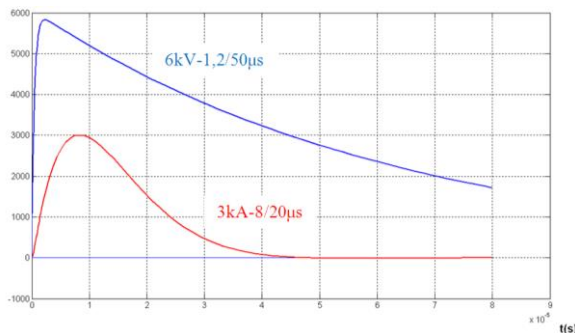


Figure 4. Lightning waveform 6kV - 1.2/50 $\mu\text{s}$  and 3kA - 8/20 $\mu\text{s}$ .

## 4. LOW VOLTAGE MULTILAYER VARISTOR MODEL

### 4.1 Building the low voltage multilayer varistor model

MLV is nonlinear multi-layer resistor (Figure 5), with symmetrical V-I characteristic (Figure 6). In normal working mode MLV regard as open circuit with extremely low leakage current and resistance of MLV will decreases when voltage exceeds the threshold voltage. Thanks to this characteristic, when transient voltage surge appears, MLV will quickly become a low impedance path to suppress the transient voltage surge.

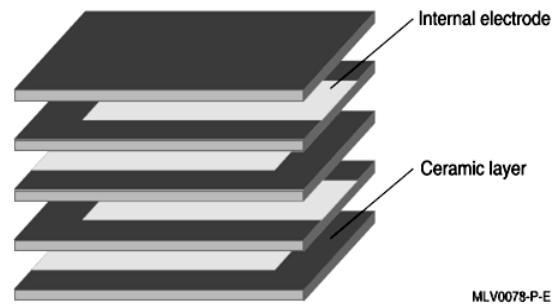


Figure 5. Structure of MLV.

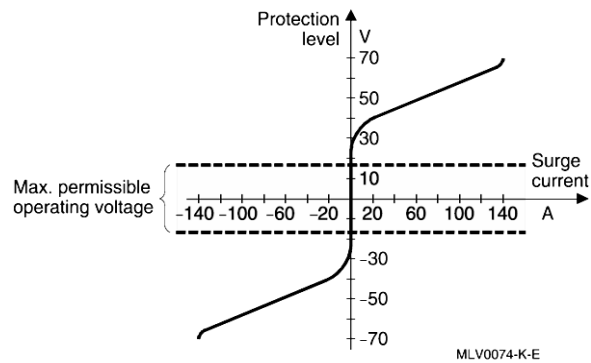


Figure 6. V-I characteristic of MLV.

The V-I characteristics of MLV is given by the relation:

$$I = KV^\alpha, \alpha > 1 \quad (16)$$

Where:  $I$ ,  $V$  are respectively current and voltage through the MLV;  $K$  is a constant of the ceramic and  $\alpha$  is nonlinear exponent.

The R-V characteristic shows the dependence of the voltage on the resistor value as follows:

$$R = \frac{V}{I} = \frac{V}{KV^\alpha} = \frac{V^{1-\alpha}}{K} \quad (17)$$

Taking the logarithm of two equations (16) and (17) results:

$$\log(I) = \log(K) + \alpha \log(V) \quad (18)$$

$$\log(R) = \log\left(\frac{1}{K}\right) + (1-\alpha) \log(V) \quad (19)$$

From the equations (16), (17), (18) and (19) the V-I characteristic of MLV can not be calculated. Therefore, using the equivalent Eq.(20) for calculating the value which as a function of V-I characteristic.

$$\log V = B_1 + B_2 \log(I) + B_3 e^{-\log(I)} + B_4 e^{\log(I)}, \quad I > 0 \quad (20)$$

Or:  $V = 10$

$$B_1 + B_2 \log(I) + B_3 e^{-\log(I)} + B_4 e^{\log(I)} \quad (21)$$

When considering the tolerance of the voltage across varistor TOL%:

$$V = \left(1 + \frac{TOL}{100}\right) 10$$

$$B_1 + B_2 \log(I) + B_3 e^{-\log(I)} + B_4 e^{\log(I)} \quad (22)$$

The parameters  $B_i$  are determined depending on each MLV. Furthermore, nonlinear regression model of mathematics can use to calculate the value  $B_i$  from the V-I characteristics of any MLV. With a pair of current and voltage value ( $V_1/I_1$  and  $V_2/I_2$ ) read from the V-I characteristic of MLV and put in Eq.(18), the value of exponential nonlinear  $\alpha$  will be calculated as follows:

$$\alpha = \frac{\log I_2 - \log I_1}{\log V_2 - \log V_1} = \frac{\log(I_2 / I_1)}{\log(V_2 / V_1)} \quad (23)$$

The input parameters of the MLV model is declared in the *Parameters* section of the

*Mask Editor* dialog box as shown in Figure 7, including: Max AC operating voltage ( $V_c$ ), Max impulse current ( $I_{max}$ ), Tolerance of varistor voltage % (TOL).

The input parameters of MLV model are declared in section *Initialization*:  $L_B$ , C,  $B_1$ ,  $B_2, B_3$ ,  $B_4$  and the program is written to retrieve the values and calculated values of the voltage array  $V\_array\_input$  according to current array  $I\_array\_output$  corresponding to all kinds of MLV. These parameters are provided from the data library of low voltage MLV (Figure 8).

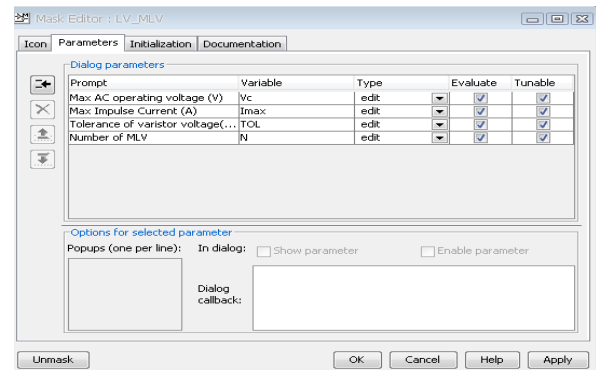


Figure 7. Input Parameters declared in the Mask Editor dialog box.

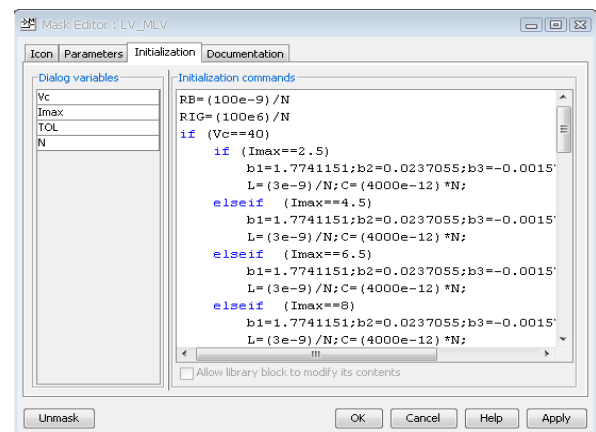


Figure 8. Dialog box Initialization of low voltage MLV model.

#### 4.2 Simulation the response of MLV

Enter the parameters of low voltage MLV of EPCOS manufacturer, type: CN1812K30G, CN2220K14G, CN2220K30G [8] (Table 2)

into MLV model built in Matlab and implement simulation of the residual voltage of this MLV corresponding to 0.8kA and 1.2kA-8/20 $\mu$ s current impulse. The results presented in Table 3.

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*Table 2. Parameters of low voltage MLV of EPCOS.*

Type of MLV	Maximum AC operating voltage (V)	Maximum current impulse 8/20 $\mu$ s (kAcrest)	Tolerance of MLV (%)	Maximum discharge voltage with 8/20 $\mu$ s impulse (Vcrest)	
				0.8kA	1.2kA
CN1812K20G	20	0.8	10	100	
CN1812K30G	30	0.8	10	149	
CN2220K14G	14	1.2	10		100
CN2220K30G	30	1.2	10		175

*Table 3. Simulation results.*

Residual voltage across the MLV (V)	Type of MLV of EPCOS manufacturer			
	CN 1812K20G	CN 1812K30G	CN 2220K14G	CN 2220K30G
	0.8kA	0.8kA	1.2kA	1.2kA
According to Catalogue	100	149	100	175
Simulation results	104	151	95	170
Tolerance (%)	4	1	5	3

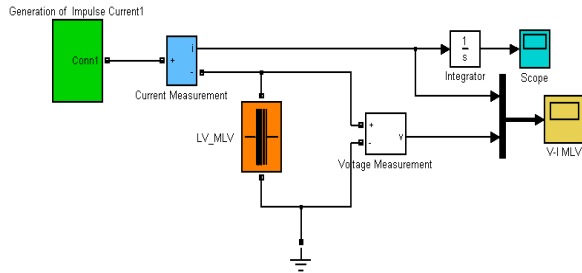
From the simulation results in Table 3. Recognizing that, the built low voltage MLV model have high precision. Residual voltage tolerance largest of the model is 5% while the tolerance by the manufacturer is 10%.

#### 4.5 Identify the repeated impulse with 8/20 $\mu$ s current impulse

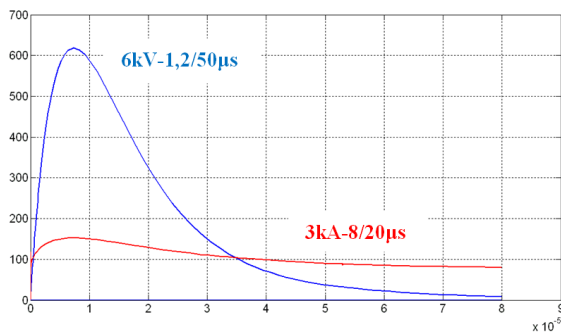
When determining the number of repeated impulse of MLV, manufacturers typically provide information in the form of

square-pulse 2m. While the lightning protection standards stipulate standard impulse is 8/20 $\mu$ s. This causes the difficulties for users. The following, presented the conversion method of 8/20 $\mu$ s standard impulse into 2 $\mu$ s square-pulse equivalent on the basis of the same level of lightning energy dissipation. From there, easily identify the number of repeated impulse of MLV when knowing the parameters the waveform 8/20 $\mu$ s.

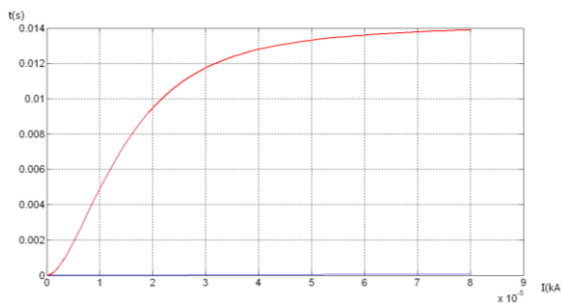
Circuit simulation as shown in Figure 9, including: 0.8kA 8/20 $\mu$ s lightning impulse generator waveform, MLV model CN1812K30G, integrator block, the scope. The waveform result and values of  $\int i^* dt$  are presented in Figure 10.



**Figure 9.** The circuit simulation determined the energy absorption of MLV type



a. Current and voltage waveform CN1812K30G



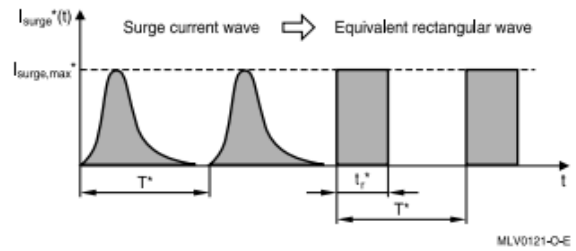
b. The value of  $\int i^* dt$

**Figure 10.** The waveforms and value of  $\int i^* dt$  of MLV type CN1812K30G.

From the simulation results, the value of the maximum amplitude of the current  $\hat{i}^*$  and  $\int i^* dt$  are given as follows:

$$\hat{i}^* = 0.618 \text{ kA}, \quad \int i^* dt = 14 \text{ mAs.} \quad (24)$$

From the simulation results the actual current waveform converted to equivalent rectangular waveform as shown in Figure 11:

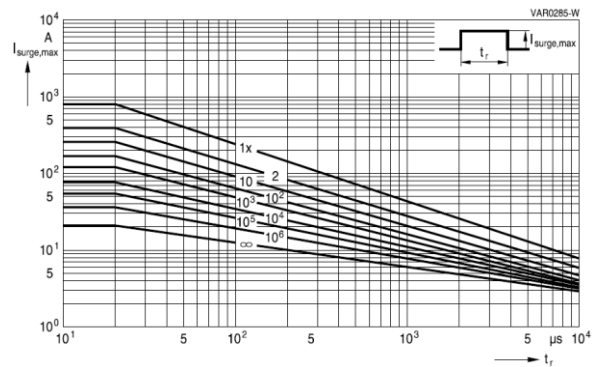


**Figure 11.** Convert the actual current waveform into equal rectangular waveform.

From Eq.(23), the value  $t_r^*$  is calculated as follows:

$$t_r^* = \frac{\int i^* dt}{\hat{i}^*} = \frac{14}{0,618} = 23 \mu\text{s} \quad (25)$$

From the values  $t_r^* = 23 \mu\text{s}$  and  $\hat{i}^* = 0,618 \text{ kA}$  and lookup in the graph in Figure 12 [8], the number of repeated impulse of CN1812K30G can withstand is  $n=1000$  times.



**Figure 12.** The time of repeated impulse can withstand of CN1812K30G MLV.

## 5. CONCLUSION

From the simulation results presented above, the following conclusion can be formulated:

- The 6kV 1.2/50 $\mu$ s-3kA 8/20 $\mu$ s CWG model that built in Matlab environment has enhanced compatibility according to the requirements of international standard.

- The MLV model that built in Matlab environment allowed integration multiple MLV in parallel and created favorable condition for transient studies in low voltage systems.
- To create favorable conditions for the users, the number of repeated impulse that MLV can withstand, is determined with a 8/20 $\mu$ s standard lightning surge rather with 2ms square pulse as manufacturers offered.

#### ACKNOWLEDGEMENTS

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#### Corresponding author:

Le Quang Trung

Lilama 2 Technical and Technology College

Email: [trungttc276@yahoo.com.vn](mailto:trungttc276@yahoo.com.vn)