Convert the Amplitudes of Different Surge Waves Based on Equivalent Energy

Minh Vu Nguyen Hoang[1,*]

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ABSTRACT

Damaged medium voltage lighting arresters (MVLA) are often caused by the energy dissipation generated by the surge current exceeding the allowable absorbed energy. Allowable absorbed energy of MVLA depends on amplitude and waveform of surge current. However, manufacturers of MVLA usually only provide a surge current amplitudes of 8/20µ**s** wave form. This causes many difficulties for users in choosing the appropriate MVLA for each surge protection problem in the distribution system and transformer station. This paper presents a method to convert the amplitudes of different surge waveforms based on the equivalent energy to assist designers and users to evaluate and select suitable medium voltage lighting arrester which have the highest protection performance in each case. The 8/20us waveform, 10/350us waveform, and 4/10us waveform generator models are all checked for errors of amplitude, of wave front time and of tail time. The model of the medium voltage lighting arresters is checked for residual voltage errors with standard surge amplitudes of typical surge waveforms provided by the manufacturers. All errors of the above models are satisfactory. The problem is solved through modeling and simulation methods with the help of Simulink-Matlab tool. The research results provide the conversion coefficients of 8/20us surge waveform amplitude to 10/350us surge waveform amplitude and 4/10us surge waveform amplitude with errors within the allowable range of the current standards.

1. INTRODUCTION

Currently, on the power grid, overvoltage often occurs due to lightning strikes directly on the line (10/350µs pulse wave), induced lightning to the line (8/20µs pulse wave), line switching (4/10µs pulse wave) [1]. The solution of placing lightning protection devices on high voltage [2, 3] or low voltage lines [4] is used to protect the equipment and the stable operation of the electrical system.

To protect the insulation of distribution transformers, as well as distribution equipment in substations, Medium Voltage Lighting Arresters (MVLA) are often used on the high-voltage side and the low-voltage side. The MVLA shall be able to rapidly dissipate the surge current energy to ground and to provide a relatively low residual voltage relative to the allowable impulse insulation withstand level The studies [5, 6, 7] address solving the problem of overvoltage protection by using the MVLA model of ATP-Draw software, optimizing the installation location of MVLA, and stating the conditions for selecting MVLA for transformers overvoltage protection. But it has not been mentioned that damage to MVLA depends mainly on the energy dissipated by surge currents generated with different amplitudes and waveform of surge current.

Currently, most MVLA catalogs usually give the allowable power dissipation of surge current corresponding to the surge current of 8/20µs waveform [8, 9]. This causes many difficulties for users when interested in the ability to dissipate energy with different surge current waveforms.

Therefore, it is necessary to conduct research to propose a method of converting surge amplitudes to different waveforms based on the equivalence of the allowable absorption energy announced by the manufacturers [10, 11].

However, to solve the above problem according to modeling and simulation methods, it is necessary to build standard surge generator models, model MVLA with errors within the allowable range of current standards.

2. STANDARD SURGE GENERATOR MODEL

2.1. Mathematical surge generator model

The IEC 61000-4-5 standard specifies the standard current surge wave shown in Figure 1 [12].

The mathematical equation describing the surge current has the form:

$$i(t) = I.k_1.k_2.\left(e^{-at} - e^{-bt}\right) \tag{1}$$

[1]*University of Architecture Ho Chi Minh City, 72407, Vietnam.*
**Corresponding author:* Minh Vu Nguyen Hoang; Phone: +84-903-676-968; Email: vu.nguyenhoangminh@uah.edu.vn.

here, *I* is the amplitude of the exponential surge current; k_1 is the amplitude correction factor; k_2 is the surge correction factor; *a* and *b* are coefficients determined by the graphical method.

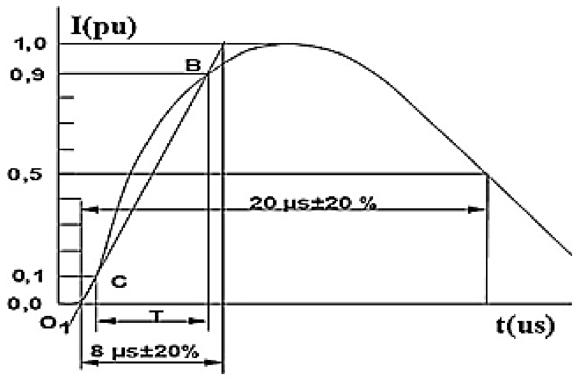

Fig. 1. Standard current surge wave

Currently, there are a number of MVLA models built in EMTP, ATP software [13, 14, 15, 16], while the MVLA model in Matlab software is simple and needs improvement [17].

2.2. Mathematical equation of current surge wave

Figure 2 shows the current surge model in MATLAB.

The functions of the blocks in Figure 2 are as follows:

- Time block t_1 and Time block t_2: enter wave front time and wave tail time;
- Gain block 4: input factor k_2;
- Multiplier block: create the ratio t_2/t_1 after adjusting the t2I value;
- F_{cn} block b/a: determine b/a value from the ratio t_2/t_1;
- F_{cn} block u_1/u: determine the value of I_1/1 from the ratio b/a;
- Multiplier block a: determine the value of a from the value at1;
- Multiplier b: determine the value of b from the ratio b/a;
- The Clock block is the block that creates the time variable: t;
- bt multiplier block: determine bt value from b value and t value;
- Gain, Gain 1, Gain 2 blocks are reversed sign blocks;
- Exponential blocks eu assign exponential functions to the variables -at and -bt;
- Add block: is the block that adds two variables e-at and -e-bt;
- Block I: is the input block of the maximum amplitude I_1 of the current pulse;
- F_{cn} block: is the block that converts the value of kA to A;
- Voltage amplitude multiplier block: is the block that determines the maximum amplitude of the pulse exponential current I;
- Gain block 3: input correction factor k_1;
- Controlled Voltage Source block: is a voltage signal generator block;
- Block r_1: is a current limiting resistor, which turns the voltage signal into a current signal when the output is shorted.

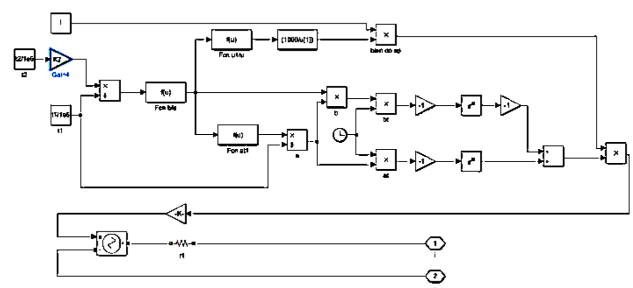

Fig. 2. Current surge model in Matlab.

The current surge generator interface is shown in Figure 3.

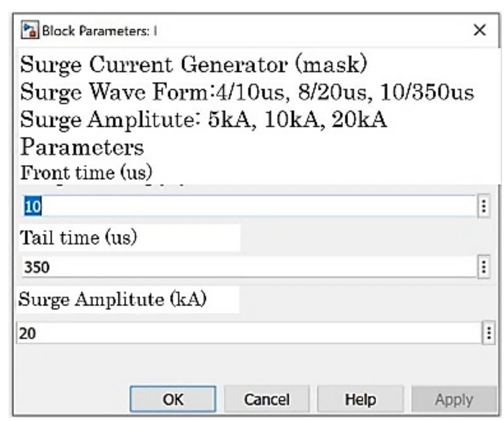

Fig. 3. The current surge generator interface.

Current surge simulation circuit with amplitudes of 5kA, 10kA, 20kA with different surge waveforms is shown in Figure 4.

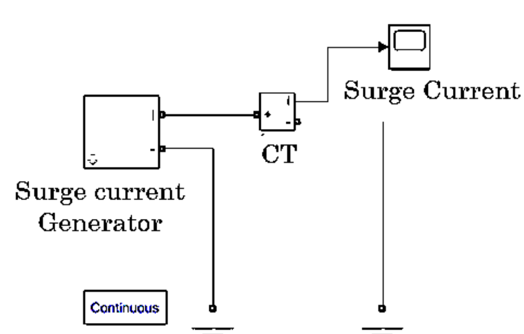

Fig. 4. Surge current simulation circuit.

Simulation results of 4/10µs, 8/20µs and 10/350µs surge current waves are presented in Figure 5, Figure 6 and Figure 7 respectively.

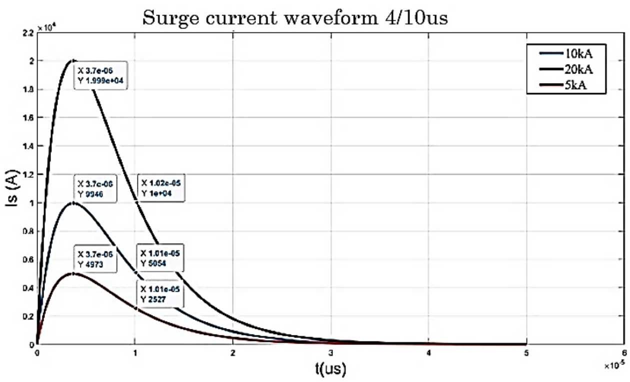

Fig. 5. Simulation results of surge current 4/10µs with amplitudes of 5kA, 10kA, 20kA.

Analysis of 4/10µs waveform simulation results, found that:

- Amplitude errors from 0÷0.6%, negligible;
- Wave front error 7.5% < 20%, satisfactory;
- Wave tail error from 1÷2% < 20%, satisfactory.

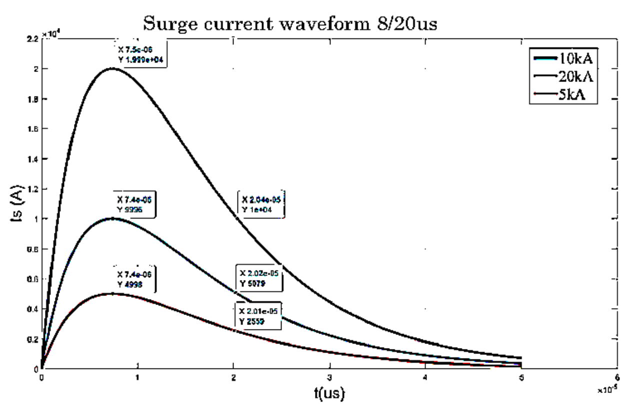

Fig. 6. Simulation results of surge current 8/20µs with amplitudes of 5kA, 10kA, 20kA.

Analysis of 8/20µs waveform simulation results, found that:

- Amplitude errors from 0÷0.2%, negligible;
- Wave front error 6.25÷7,5%< 20%, satisfactory;
- Wave tail error from 0,5÷2% < 20%, satisfactory.

Analysis of 10/350µs waveform simulation results, found that:

- Amplitude errors from 0,5÷0.6%, negligible;
- Wave front error 0% < 20%, satisfactory;
- Wave tail error from 1,25÷1,31% < 20%, satisfactory.

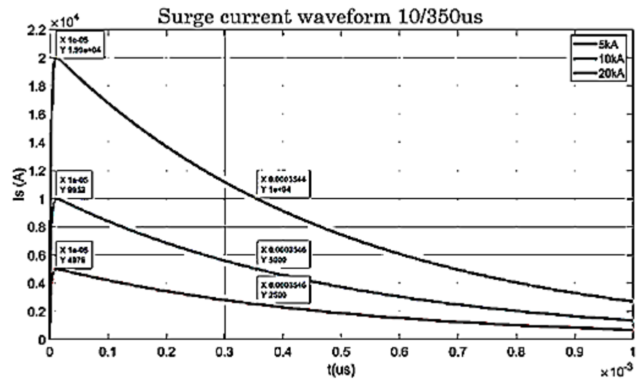

Fig. 7. Simulation results of surge current 10/350µs with amplitudes of 5kA, 10kA, 20kA.

3. PINCETI MVLA MODEL

3.1. Mathematical MVLA model

Pinceti's MOV MVLA model is a model developed based on the frequency-dependent model proposed by IEEE with block diagrams of elements shown in Figure 8 [6].

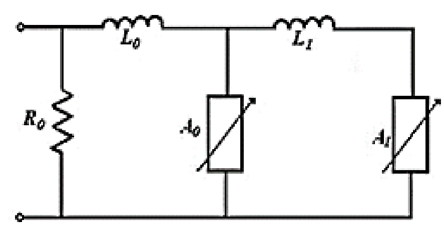

Fig. 8. Pinceti MVLA model.

In this model, two nonlinear resistor blocks A_0 and A_1 are built based on the V-I characteristics proposed by IEEE and R_0=1MΩ.

The L_0 and L_1 values of Pinceti's MOV-type SPD model are calculated from expressions (2) and (3):

$$L_0 = \frac{1}{12}\frac{V_{r1/T2} - V_{r8/20}}{V_{r8/20}} \cdot V_n \tag{2}$$

$$L_1 = \frac{1}{4}\frac{V_{r1/T2} - V_{r8/20}}{V_{r8/20}} \cdot V_n \tag{3}$$

here, *Vn* is the rated voltage of the MOV MVLA; V_{r1}/T_2 is the residual voltage for fast lightning current 10kA at ($1/T_2$); *Vr*8/20 is residual voltage for 10kA lightning current with 8/20µs waveform.

3.2. Pinceti MVLA model in Matlab

Using Simulink in Matlab build a complete MVLA model as shown in Figure 9, with note that two resistors R_0=R_1=1MΩ are added to avoid current pulses in series with the inductance component when simulating in Matlab.

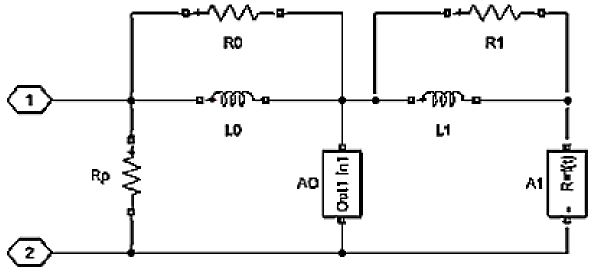

Fig. 9. Pinceti MVLA model in Matlab.

The interface of the Picenti MVLA model in Matlab is shown in Figure 10.

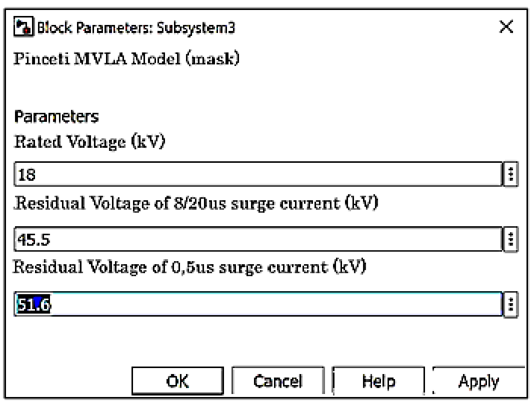

Fig. 10. Interface of Pinceti MVLA model in Matlab.

3.3. Simulate operation of MVLA

To evaluate the accuracy of the Pinceti MVLA model, simulate the residual voltage of the model with standard current pulse of 5kA 8/20µs, 10kA 8/20µs and 20kA 8/20µs. These residual voltage values are compared with the residual voltage values provided in the manufacturer's catalogue.

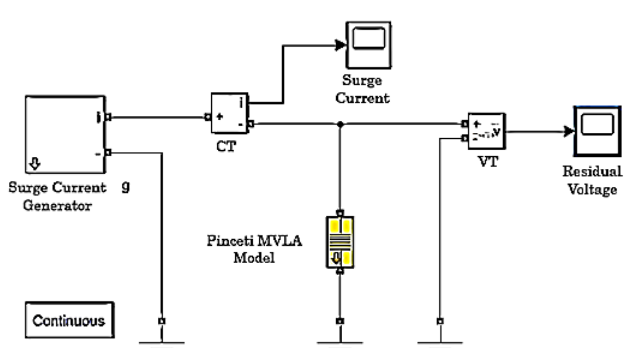

Fig. 11. Simulation circuit of MVLA.

Here will test with MVLA 3EK7 180 4AE4 of Siemens [8] and AZG2 of Copper [6].

Simulated residual voltage waveforms of MVLA 3EK7 180 4AE4 Siemens for 5kA 8/20µs, 10kA 8/20µs and 20kA 8/20µs surge currents are shown in Figure 12.

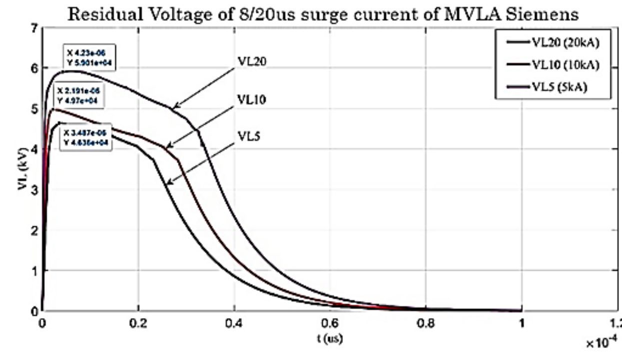

Fig. 12. The simulated residual voltages of MVLA 3EK7 180 4AE4-Siemens.

Simulated residual voltage waveforms of MVLA AZG2 – Cooper for 5kA 8/20µs, 10kA 8/20µs and 20kA 8/20µs surge currents are shown in Figure 13.

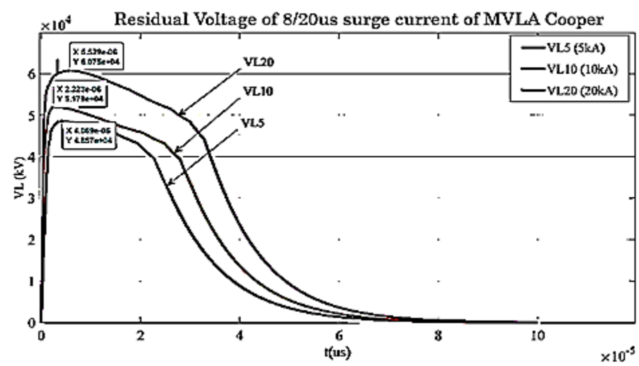

Fig. 13. The simulated residual voltages of MVLA AZG2 – Cooper.

Table 1 presents the residual voltage values through simulation (V_{sim}), the residual voltage value provided by the manufacturer (V_{cat}) and the E_{rr} model error.

Note: Err (%) = ((|Vcat – Vsim|)/Vcat) 100%.

Analysis of residual voltage simulation results of Pinceti MVLA model corresponding to 5kA, 10kA, 20kA surge currents with residual voltage values provided by the manufacturer (Siemens and Cooper), found that:

- The Pinceti MVLA model is very convenient for users because the input parameters can be looked up from the manufacturer's catalogue;

- The residual voltage error of the Pinceti MVLA model has the lowest value of 2.15% and the highest value of 7.9%, both lower than the allowed residual voltage error of 10%.

4. CONVERT THE AMPLITUDES OF DIFFERENT SURGE WAVEFORMS

4.1. Absorbed energy

The MVLA is damaged due to many reasons, but the main cause is the absorbed energy exceeding the allowable level of the MVLA corresponding to the standard current pulse waveforms specified by the manufacturers.

The absorbed energy of the MVLA can be determined graphically with acceptable accuracy using the rectangular conversion method, according to IEC 60060 standard [18]. However, this method is mainly to check the allowable absorbed energy of MVLA and does not mention the determination of absorbed energy of MVLA under different surge waveforms.

When using modeling and simulation methods, the absorbed energy of MVLA is determined by the expression [9]:

$$W = \int_{t_0}^{t_1} v(t)i(t)dt \tag{4}$$

This method has the advantage of high accuracy, no special equipment is required, but the disadvantage is that a surge generator model and MVLA model are required to be compatible with the prototype.

To convert surge amplitude to different waveforms, below presents the equivalent method of absorbed energy through modeling and simulation.

The simulation circuit to determine the absorbed energy of the MVLA is shown in Figure 14. Simulation results of absorbed energy and pulse current amplitude of SPD 3EK7 180 4AE4 (Siemens) with different surge waveforms are presented in Table 2.

Simulation results of absorbed energy and pulse current amplitudes of MVLA AZG2 (Cooper) with different surge waveforms are presented in Table 3.

Analysis of the simulation results of absorbed energy of MVLA 3EK7 180 4AE4 - Siemens and SPD AZG2 - Copper found that:

1. The pulse amplitude conversion factor from 8/20μs waveform to 10/350μs waveform can be approximated as 0.15;

2. The pulse amplitude conversion factor from 8/20μs waveform to 4/10μs waveform can be approximated as 1.7.

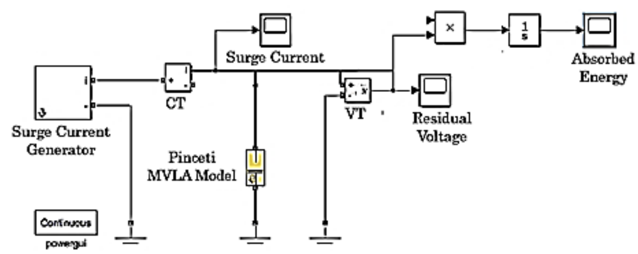

Fig. 14. Simulation circuit to determine the absorbed energy of the MVLA.

Table 1. Summarize residual voltage value of MVLA

Product code	Rated Voltage (kV)	Residual Voltage of 8/20μs surge current								
		5kA			10kA			20kA		
		Vcat (kV)	Vsim (kV)	Err (%)	Vcat (kV)	Vsim (kV)	Err (%)	Vcat (kV)	Vsim (kV)	Err (%)
3EK7 108 4AE4	18	44.5	46.36	4.18	47.8	49.7	3.97	55	59.01	2.29
AZG2	18	46.9	48.57	3.56	50.7	51.79	2.15	56.3	60.75	7.9

Table 2. Simulation results of absorbed energy and surge current amplitudes of MVLA 3EK7 180 4AE4

Parameters	8/20μs surge waveform		
Surge current (kA)	5	10	20
Absorbed Energy (J)	2612	6865	18450
Parameters	10/350μs surge waveform		
Surge current (kA)	0.868	1.564	2.792
Absorbed Energy (J)	2663	6862	18490
Conversion Factor	0.173	0.156	0.140
Parameters	4/10μs surge waveform		
Surge current (kA)	8.57	17.23	34.72
Absorbed Energy (J)	2675	6883	18450
Conversion Factor	1.71	1.72	1.73

Table 3. Simulation results of absorbed energy and surge current amplitudes of MVLA AZG2

Parameters	8/20µs surge waveform		
Surge current (kA)	5	10	20
Absorbed Energy (J)	2730	7198	18880
Parameters	10/350µs surge waveform		
Surge current (kA)	0.864	1.585	2.793
Absorbed Energy (J)	2714	7198	18710
Conversion Factor	0.173	0.158	0.140
Parameters	4/10µs surge waveform		
Surge current (kA)	8.55	17.2	34.57
Absorbed Energy (J)	2770	7194	18740
Conversion Factor	1.71	1.72	1.73

5. CONCLUSION

This paper delves into the research and solves the following issues:

- Research and build standard surge generators for different surge waveforms in Matlab, especially 10/350µs and 4/10µs surge currents with negligible amplitude error (<0.6%), wave front time error (< 7.5%) and wave tail time error (<2%);

- Building a MVLA model as suggested by Pinceti in Matlab, easy to use because only input parameters are required in the manufacturer's catalogues. The proposed MVLA model has an error of 7.3% lower for Siemens's MVLA and 7.9% lower for Cooper's MVLA;

- Research on the method of converting the rated surge amplitude of the MVLA in the distribution grid to different surge wave forms based on energy equivalence. Specifically, the surge amplitude conversion factor from 8/20µs waveform to 10/350µs waveform is 0.15 and the pulse amplitude conversion factor from 8/20µs waveform to 4/10µs waveform is 1.7.

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