Investigation of the throughput of nonlinear surge arresters using the MatLab software environment

N M Kuznetsov1, I N Morozov1,2 and S A Smirnov2

1Center for Physical and Technical Problems of Energy of the North of the Federal State Budgetary Institution of Science of the Kola Scientific Center of the Russian Academy of Sciences, Apatity, Russia
2Federal State Budgetary Educational Institution of Higher Education "Murmansk Arctic State University" Murmansk, Russia

E-mail: moroz.84@mail.ru

Abstract. This work is devoted to the topical issue of researching the throughput of nonlinear surge suppressors. The article discusses various options for test installations and offers simulation models. The MatLab environment, the Simulink simulation application, was chosen as the simulation software environment. The impulse current curve was calculated, after which the tests of nonlinear arresters using rectangular pulses were carried out. The simulation results of installations for operating tests of the surge arrester were compared with the real indicators of laboratory studies for arresters of the OPNp-110 UHL1 brand.

1. Relevance
Operational tests are the main type of tests for surge arresters (SPD), during which they are exposed to both currents and voltages of various types, most often simulating real operating conditions [1-5].

Operating experience shows that the continuous current flowing through the arrester does not significantly damage the protective characteristics. Nevertheless, the question of changing the characteristics after the flow through the varistors of large impulse currents of lightning overvoltages is not closed [7,8,10,11]. It can be assumed that the reason for the appearance of such changes is associated with the application of the operating voltage to the surge arrester, both immediately after the flow of the impulse current, and after seconds or even minutes. In such cases, the characteristics of the arrester become unstable, which can cause damage during further use.

2. Description of simulation models and the results of their work
In most operational tests of surge arresters, the test setups are very similar. They imply the application of an industrial combination of impulse actions and a certain combination of impulse actions that recreate a direct lightning strike, lightning impulses (normalized current pulses 8/20 μs) or switching overvoltages (rectangular pulses of a given current with a duration of 2–3.2 ms).

The normalized current pulse 8/20 μs is a unipolar current pulse with the conditional rise time Tf = 9 ± 1 μs and the pulse duration Ti = 20 ± 2 μs. The approximate rise time is the time that is 1/4 longer than the current rise time from 10% to 90% of the maximum value of the current impulse. The point of intersection of the time axis and the straight line drawn through the points where the impulse value is equal to 10% and 90% is considered to be the conditional beginning of the impulse (figure 1).
The time interval between the approximate beginning of the impulse and the moment of decay, when the current reaches half of the maximum, is taken as the duration of the impulse.

The calculation of the pulse current curve was performed using the Matlab application [6, 9, 12]. In this case, you can use only those points of the current-voltage characteristic that are within the calculated currents. For a varistor, whose current-voltage characteristic is shown in table 1, a current pulse “8/20” can be obtained in the circuit shown in figure 1.

Table 1. Calculated volt-ampere characteristic of the varistor.

| I, A | 0.003 | 35 | 75 | 165 | 1100 | 2000 |
|------|-------|----|----|-----|------|------|
| U, kV| 1.58  | 3.25 | 3.46 | 3.92 | 4.23 | 4.72 |

At the same time, as the analysis shows, the parameters of the circuit should have the following characteristics: C1 = 10 \( \mu \)F; L = 18 \( \mu \)H; R = 2.2 ohms. For these parameters, the duration of the leading edge of the pulse is \( T_f = 10 \mu s \) and the duration of the pulse is \( T_i = 30 \mu s \) (figure 2). With the battery charging voltage \( U_c = 11000 \text{ V} \), the maximum current impulse value is 2000 A. To obtain results with a different current value, the charging voltage value must be changed. The rectangular current pulse test is a type of test for non-linear surge arresters. Such tests also belong to one of the stages of operational tests of surge arresters with lightning impulses.

According to the recommendations of the International Electrotechnical Commission, a rectangular impulse wave is a wave with a rapid increase to a maximum value, holding at a constant value for a given period of time, and then a rapid drop to zero.
Parameters such as polarity, maximum value, nominal maximum value duration, and nominal total duration define a square wave pulse. For the conditional duration of the maximum value of the square wave \( T \) (figure 3) is taken the time in the duration of which the instantaneous value of the wave exceeds \( 9/10 \) of the maximum value. The total conditional duration of the wave \( T_p \) is the time during which the instantaneous value of the wave is greater than \( 1/10 \) of the maximum value. If there are minor fluctuations at the front of the wave, then an average curve should be drawn to determine when a value of \( 10\% \) is reached.

When tested in the switching mode of surge arresters with a nominal discharge current of 10 thousand and 20 thousand A, the pulse generator is a model of a power line, and the normalization of the charging voltage of the generators, the line impedance and the relative duration of the pulse amplitude is noticeable. During tests of arresters with a comparatively lower throughput, the parameters of the rectangular current pulse supplied to the samples are normalized, and not the parameters of the simulated power line. These pulses must meet the following requirements:

- the relative duration of the maximum value should be \( 100\% - 120\% \) of the normalized value;
- the relative total duration should not be \( \sim 150\% \) of the conditional duration of the maximum value;
- fluctuations or primary inrush should not exceed \( 10\% \) of the maximum current value; if there are fluctuations, an average curve must be drawn to find the maximum current value.
- The maximum current value should be \( 90\% - 110\% \) of the rated value.

A rectangular current pulse with a normalized conditional duration \( T = 30 \text{ ms} \) can be obtained in the circuit (figure 3) with the number of cells \( n = 7 \). For a varistor with a volt-ampere characteristic from table 2, the following circuit parameters are required:

**Table 2. Calculated volt-ampere characteristic of the varistor.**

| I, A | 185 | 285 | 440 | 5000 |
|------|-----|-----|-----|-------|
| U, kV | 8.1 | 8.4 | 8.7 | 11.1 |

Let us assume that \( L = 2.2 \text{ mH}; C = 15 \mu \text{F}; L_1 = 4 \text{ mH} \) and \( R = 82 \text{ ohms} \). To obtain a current pulse with a maximum value of \( 0.2 \text{ kA} \), the charging voltage of the capacitors in the chain must be \( 18.5 \text{ kV} \). As can be seen from figure 4, the conditional pulse duration is \( T = 0.03 \text{ s} \) and the total duration is \( T = 0.045 \text{ s} \), which is within the specified range. The resistor provides a drop in current to zero. At a higher value, the current pulse does not fall to zero, and at a lower value, a reverse pulse occurs (after the end of the pulse itself), which has a serious maximum value. Also, the resistor \( R \) shortens the leading edge of the pulse and at the same time lengthens its tail, which causes a sharp increase in the total pulse width.

The required parameters of the current pulse through the test sample are determined by the number of links in the chain circuit and the size of its individual components. Calculations show that the conditional pulse duration \( T \) and the total duration \( T_p \) increase in direct proportion to the inductance of the link \( L \) or its capacitance \( C \), as well as the number of links. A change in \( L_1 \) practically does not affect the relative and total pulse duration, although at small values of \( L_1 \), strong current fluctuations are observed at the front and the maximum value of the pulse, exceeding the permissible \( 1/10 \) of the maximum value. The pulse parameters corresponding to the norms, as a rule, can be obtained only for \( L_1 > L \) (figure 4). However, as the output inductance is increased, there is a large smoothing of the pulse edge, mainly at the level of \( 90\% - 100\% \) of the maximum value, and a noticeable current drop within the specified values. This drop can be leveled by reducing the capacity of the output link, as well as by shunting the two inductances closest to the surge arrester with resistors close in resistance to the characteristic impedance of the circuit circuit.

Tests of zinc oxide varistors in surge arresters with \( 8/20 \mu \text{s} \) current pulses and square wave currents help evaluate their carrying capacity. However, all information about the protective characteristics and
capacity of arresters can only be given by their operational tests. International standards provide for two types of operational tests for metal oxide arresters without spark gaps (arresters):

- working tests by lightning impulses;
- working tests with switching impulses.

During operational testing of surge arresters with lightning impulses, the tested models are tested with two high current impulses (from 10,000 to 100,000 A, depending on the class of the arrester) 4/10 μs. Between the first pulse and the second, the tested model is heated to a temperature of 55-60 degrees Celsius. Approximately 100 ms after the last high current impulse, the sample should be subjected to a power frequency voltage equal to the highest operating voltage Unb, which after 10 s should be reduced to the normalized voltage Unnorm. The last voltage is maintained on the sample for half an hour to confirm the thermal stability or thermal instability of the surge arresters. To monitor this stability, one of three sample parameters must be continuously recorded:

- active component of the current;
- temperature of varistors;
- power loss in varistors.

Figure 5 shows a diagram of a test bench during operational tests of surge arresters with lightning impulses as recommended by the International Electrotechnical Commission.
Figure 5. Schematic diagram of an arrester operational test setup.

The installation consists of a pulse current generator and a power frequency voltage source. The generator, in turn, consists of a capacitor bank C, a snubber resistor R, a reactor L and a spark gap F. To the test sample R03 through a transformer T from a shock generator or a powerful power supply network, which are connected to points a - b (see figure 3) power frequency voltage is applied. Reactor L1 and capacitor C1, as well as surge arrester R1 protect the transformer from impulse effects. Switch Q2, which bypasses the nonlinear resistor R2 at the right time, provides a step change in the power frequency voltage across the model under test. To measure currents in the corresponding circuits, low-resistance resistors are installed - shunts Rb1, Rb2 and Rb3. The supply voltage to the power transformer is supplied by the Q1 switch. To prevent overvoltage being applied to the recording device, switch Q3 shunts resistor Rbl for the duration of the pulse current. The operation of the switching devices is provided by a special automatic control device.

The simulation results of the installations for operational tests of the arrester were compared with the real indicators of laboratory research for the arresters of the OPNp-110 UHL1 brand. The comparison results showed the maximum deviation of the throughput values of the order of ± 0.15% from the physically measured values for all tests with different amplitudes.

Thus, the use of the simulation tools of the MatLab software environment lets to conduct laboratory studies of nonlinear surge arresters for throughput without physical tests.

References

[1] Veselov A E, Efimov B V, Kuznetsov N M, Nevretdinov Yu M and Tokareva E A 2008 Limiting arc overvoltages in power supply networks of mining enterprises Izvestia of higher educational institutions. Mining Journal 6 46-51
[2] Vlasko D I, Vostrikov A O, Domonov A P and Nevretdinov Yu M 2011 Problems and prospects of registration of lightning overvoltages in the operating network Proceedings of the Kola Science Center RAS 2(5) 54-65
[3] Efimov B V, Kuznetsov N M, Nevretdinov Yu M, Fastiy G P and Yaroshевич V V 2008 Arc overvoltages during the transition of single-phase earth faults in double Electrics 5 8-11
[4] Efimov B V, Nevretdinov Yu M, Vlasko D I and Vostrikov A O 2012 Registration of lightning overvoltages at a substation Proceedings of the Kola Scientific Center of the RAS 5(12) 29-38
[5] Khalilov F Kh et al. 2002 Protection of 6-35 kV networks from overvoltage (SPb.: Energoatomizdat) p 272
[6] Morozov I N and Kirillov I E 2019 Modeling the probability of overlapping a string of insulators during lightning strikes into lightning rods Industrial power engineering 9 10-4
[7] Nevretdinov Yu M, Tokareva E A and Vlasko D I 2008 Development of the method of
experimental studies of lightning protection of operating substations *Modeling of transient processes and steady-state modes of a high-voltage network: collection of articles. scientific. tr. Apatity* 96-110

[8] Novikova A N, Shmarago O V, Efimov B V, Danilin A N, Nevretdinov Yu M and Selivanov V N 2011 Issues of lightning protection of overhead lines in the north of the Kola Peninsula: requirements, operating experience of 110-150 kV overhead lines, calculation method Proceedings of the Kola Science Center of the Russian Academy of Sciences 2(5) 9-23

[9] Morozov I N, Kuznetsov N M, Belova L A and Borozdina E D 2020 Investigation of non-stationary modes of a 110 kV electrical substation using simulation in Matlab Vestnik Chuvash University 113-22

[10] Wu Z, Tian B, Xu A, Guo X, Cai Y and Wang G 2016 Analysis of overvoltage caused by intermittent earth fault and its suppression method China International Conference on Electricity Distribution, CICED 2016 China International Conference on Electricity Distribution, CICED 2016 – Proceedings 7576157

[11] Xiao H, Ding H, Peng T, Li L and Diangong Jishu Xuebao 2009 Constraining overvoltage existed in the power supply for the pulse magnetic field 24(1) 14-7

[12] Morozov I N et al. 2020 IOP Conf. Ser.: Earth Environ. Sci. 539 012148