Analysis of current distribution among long-flashover arresters for 10 kV overhead line protection against direct lightning strikes

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***Abstract* — The paper presents ATP-EMTP software simulation of a direct lightning strike (DLS) into the one phase conductor of 10 kV overhead line (OHL). The model takes into account the influence of induced overvoltages (IOV) from the lightning leader. There have been obtained distributions of surge current among modular long-flashover arresters (LFA-M) mounted on the poles depending on the lightning strike location and pole footing resistance. The three principal types of impulses flowing through the arresters of each phase have been revealed. It has been discovered that a current impulse shape at arresters can greatly differ from that of lightning.**

Keywords: direct lightning strike; induced overvoltage; lightning protection; current through the arresters; 10 kV distribution line.

I. Introduction

6-10 kV overhead distribution lines (OHLs) are exposed to frequent lightning strikes that can cause short circuits and tripping of the line. Traditionally, in order to protect lines of 110 kV and higher against direct lightning strikes (DLS), overhead shielding wires are applied. However, in case of 6-35 kV lines, this method is not used, as a rule, since upon lightning strike into the conductor the back-flashover occurs due to low strength of air insulation [1]. In order to ensure the required lighting protection, it is possible to use shielding wires jointly with nonlinear surge arresters [2], but the cost of such technical solution is rather high.

For protection of 10 kV OHLs against DLSs, modular long-flashover arresters (LFA-M) shown in Fig. 1 can be recommended [3, 4].

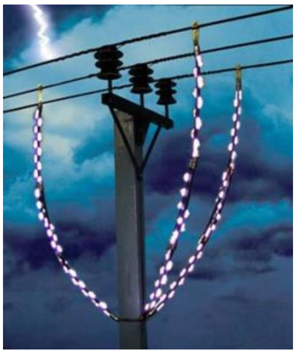

Figure 1. LFA-Ms on 10 kV OHL

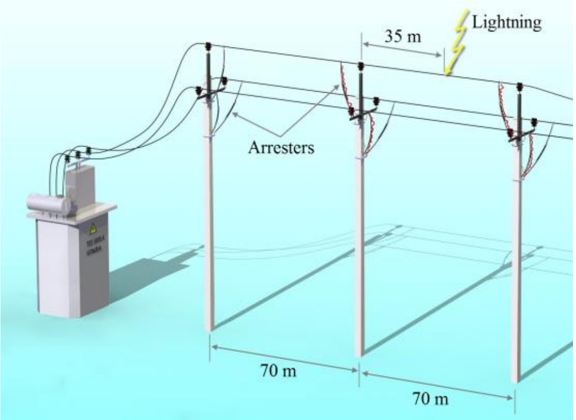

Figure 2. Arrangement of LFA-Ms on poles near substation for protection against DLS

Voltage-time curve (VTC) of a LFA-M lies lower than the one of an insulator (e.g, ShF20 being used in Russia), that is why upon lightning strike into the phase conductor the arrester flashes over earlier and undertakes the whole surge effect, thus protecting the insulator. After establishment of the impulse arc and passage of the short circuit follow current, the arc will be quenched upon the first current zero crossing, thus protecting the line from tripping.

To ensure the high-quality protection, it is required to mount a LFA-M on each phase of each pole (Fig. 2).

The objective of the analysis is the search of adequate actions in order to test arresters for quenching (breaking capability). After lightning strike into the conductor, the current passes along the line being distributed per phases and poles unevenly. At that, the impulse shape (front time and time to half-value) of the current passing through the arresters differs from the lightning current impulse shape.

II. Design Model Description

As a calculation tool for the current distribution analysis, ATP-EMTP (Electromagnetic Transients Program) software package was used. The advantages of ATP-EMTP are its reputation, friendliness and powerful capabilities. It provides a possibility of assembling calculation models on the basis of programming of totally new elements and modules that allowed considering the arresters' VTCs required for the lightning overvoltage analysis and statistical data of lightning impulse parameters.

The design models are shown in Fig. 3. The study covers the DLS cases off (a) and near (b) the substation. The model represents a series connection of three-phase line's integral units with pole branches and LFA-M arresters mounted on each phase. The lightning, represented as a source of surge current and the lightning channel surge impedance, strikes into the conductor of one phase. At the same location, the neighboring conductors are supplemented with branches with surge voltage sources imitating induced overvoltages. The study does not consider a three-phase sinusoidal voltage supply, since it will have little effect on the results upon direct lightning strike. At the ends of line 400 Ω active resistances equal to the surge impedance are added, in order to exclude impact of the reflected surges. The length of the whole line is 10 km.

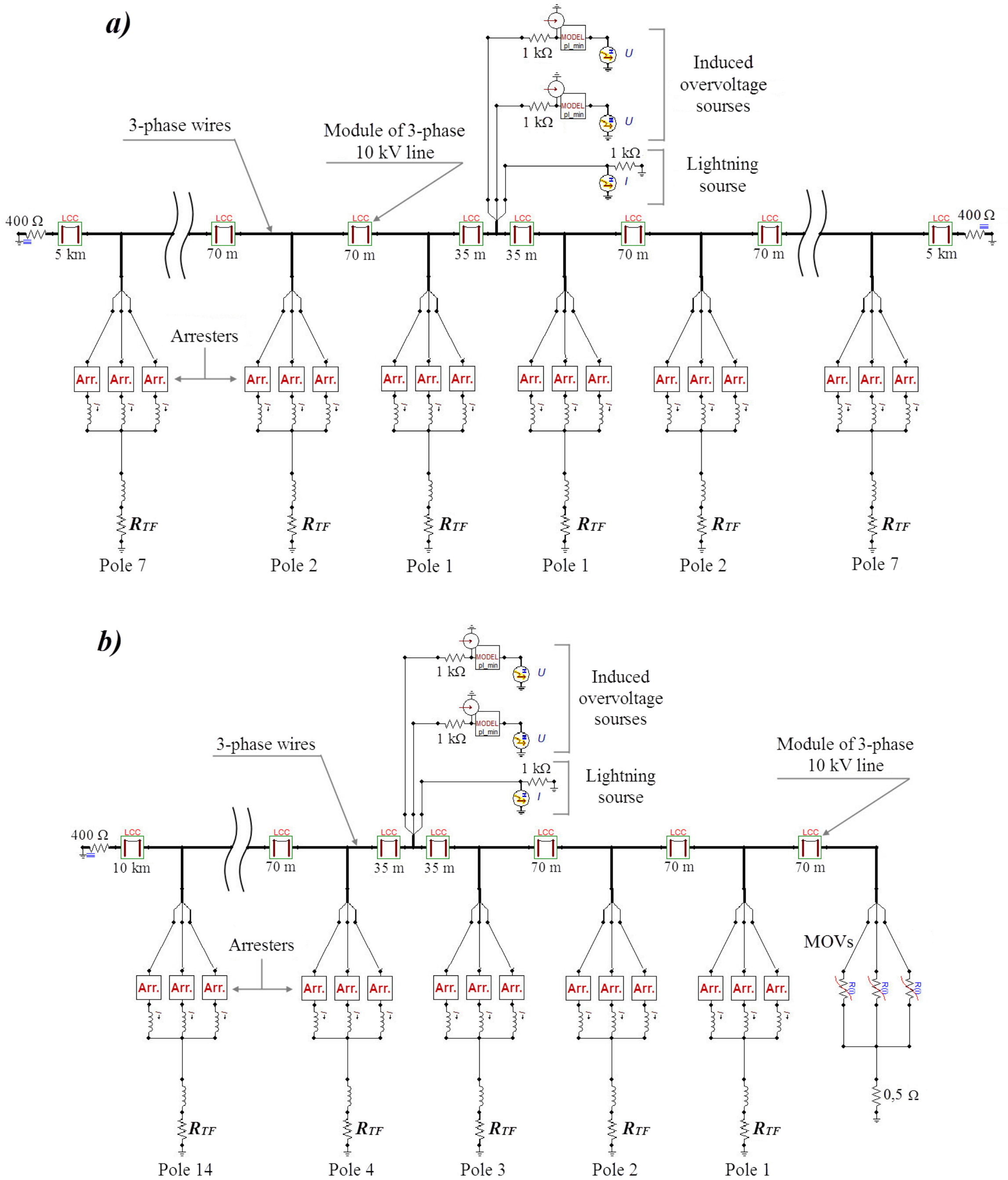

Figure 3. Design model of 10 kV OHL in ATP-EMTP
(a) in case of off-substation lightning strike;
(b) in case of near-substation lightning strike

The study covers two cases of lightning strike into the conductor: in the middle of the span and close to the pole (point of fixation of the conductor to the insulator). Since the height of conductors suspension at 10 kV line is h=9÷10 m and the span length is l=70 m, then the probability of lightning strike close to the pole can be estimated as $P \approx 4 \cdot h/l \approx 0.5$ [5]; therefore, these cases are equally probable and require the same attention.

The design model includes the following elements:

A. 10 kV OHL module

Design module LCC (Line/Cable Component), inserted in ATP-EMTP, represents a model of a long-distance line; the line parameters will be set by means of location of conductors relatively to the ground and to each other. The following values were applied in the study:

- JMarti model type that is the best for transient processes upon impulse actions [6].
- Span length is 70 m.
- Ground resistivity is 100 Ω·m.
- Conductor radius is 0.5 cm.
- Active resistance per conductor length is 0.3 Ω/km.
- Conductors' coordinates as per the pole type.

B. Pole

The study describes the 14 reinforced concrete poles 10 m high, with horizontal conductor s layout. The distance between neighboring conductors is 1.2 m. The pole cross-arms and bodies are represented as concentrated inductances calculated based on the inductance per unit length 1 μH/m [7]. Footing resistance (R_F) of all poles ranged from 10 to 30 Ω.

C. Lightning source

The current supply generates a current impulse with Heidler form [8]:

$$I = I_m \frac{(\frac{t}{t_f})^n}{1+(\frac{t}{t_f})^n} \cdot e^{-\frac{t}{t_{50\%}}} \quad (1)$$

t_f – lightning impulse front time, μs
$t_{50\%}$ – lightning impulse time to half-value, μs
I_m – peak lightning current, A
n=5 – parameter defining current form steepness.

D. Source of induced voltage surges

In case of lightning strike far from the line, the well-known formula $U_{IOV}=28 \cdot I_0 \cdot h_{eff}/y$ [1] is not applied for determination of induced overvoltages (IOV), since it is resulted in implausibly high values of overvoltage, up to 5 MV at a distance of 1 m to the strike point. Had such IOV values existed, that would have caused flashover of the whole insulation of the pole in 110 kV line upon lightning strike into the cable even at minimum lightning currents, but this does not occur in real situation. The model used an assumption that the IOV value should be

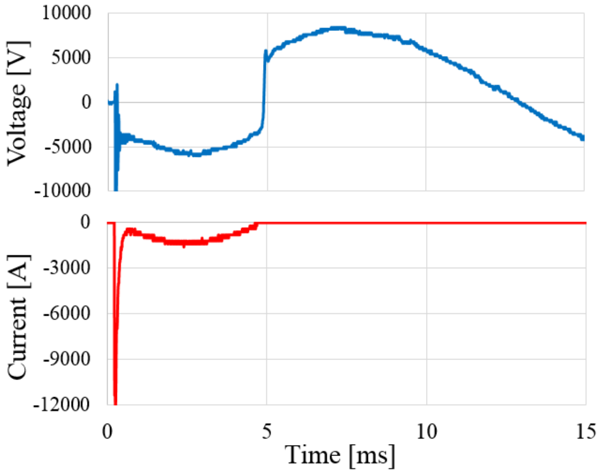

Figure 4. Current and voltage oscillograms when testing a LFA-M for quenching capability

enough for LFA-M discharge, but not too high to bring high current from the supply to the neighboring phases. The selected value was 100 kV with impulse shape of 1.2/4 μs [9]. The voltage supply also represents surge voltage with Heidler form and a block for voltage sign change, because IOV values have the opposite lightning current sign.

E. Arrester module

The model of arrester represents a connection of a switch and a nonlinear element with a control programmable unit. As soon as the difference in potential at the arrester reaches the voltage as per the voltage-time curve (2), the switch will close and a current impulse will run from the conductor to the pole through the arrester. The arrester arc resistance has a nonlinear nature and is set by (3) obtained by means of processing the laboratory testing data from oscilloscope of LFA-M current and voltage as $R=U/I$ (Fig. 4).

$$U = 80 + \frac{60}{t^{1.2}} \text{ kV} \quad (2)$$

t – flashover time, μs

$$R = \frac{1400}{I^{0.8}} \ \Omega \quad (3)$$

I – current through the LFA-M, A.

F. MOV arrester

MOV arrester is defined by nonlinear resistance with VTC [10]. For the study, a MOV arrester with classification voltage of 21 kV at the in-phase current component of 1 mA was chosen.

III. Calculation Results

Let's review a special case of a DLS with the lightning current of 40 kA, front time of 6 μs and time to half-value of 75 μs. The lightnings with parameters not exceeding the above-said ones are registered in 70% of cases [11, 12]. The study has an assumption that the lightning strikes into the outer conductor (phase A).

TABLE I.
PARAMETERS OF SURGES THROUGH THE ARRESTERS IN CASE OF MID-SPAN DLS

R_F (Ω)	Phase	*Im* (kA) t_f / $t_{50\%}$ (μs)					
		Pole 1	*Pole 2*	*Pole 3*	*Pole 4*	*Pole 5*	*Pole 6*
10	A	16.4 5/43	6.3 20/80	—[a]	—	—	—
	B	-0.6 2/10	—	—	—	—	—
	C	-4 25/100	—	4 25/100	—	—	—
20	A	16 5/33	4.7 10/120	—	—	—	—
	B	-2.4 10/50	—	2.4 10/50	—	—	—
	C	-3.6 10/50	1.2 4/13	2.4 10/110	—	—	—
30	A	15.8 5/40	3.8 6/50	—	3.2 15/60	—	1.4 30/140
	B	-2.8 12/60	—	2.8 12/60	—	—	—
	C	-4.2 10/60	2.1 4/12	1.7 6/15	—	2.8 18/70	—

a. The arrester did not operate on the pole of this phase.

A. *Lightning strike far from substation*

Since the calculation is being made for the lightning strike into the middle of the line, then current distributions among the arresters relative to the point of strike are symmetrical.

Therefore, the results from one side of the line only can be reviewed. The poles numbering starts from the point of lightning strike.

Table 1. shows the results of calculations of current distribution in case of a mid-span DLS, i.e.: current peak, front time and time to impulse half-value, non-flashed over arresters are marked with "—".

Traditionally, in lightning protection it is customary to calculate an impulse duration as time until the moment of reaching the current equal to half of maximum value of this impulse. It is reported that the current surge through the arresters mounted on phase A of the poles closest to the point of strike will be shortened in 1.5÷2 times from the impulse shape of 6/75 μs. Moreover, current peak value here is 16 kA. In arresters of phases B and C of this pole, there occur back-flashovers with currents of 2÷4 kA (negative values in Table 1.) with no significant impulse reduction. Surges in other discharged arresters either have similar duration, or "elongate" up to 120 μs with front time of 15÷20 μs, but at the same time having lower current values of 2÷3 kA. In real situation, full impulse duration corresponds to the time of the lightning current passage, but due to flowing of current through the poles and running of its principal part out through the nearest arrester, the surge "top" in distant arresters is cut off, the current drops slower there, thus technically "elongating" the reference lightning current shape. However, within the framework of usual terminology, where an impulse duration is determined as time of reaching a current value equal to 50% of the peak one, its "elongation" is observed here.

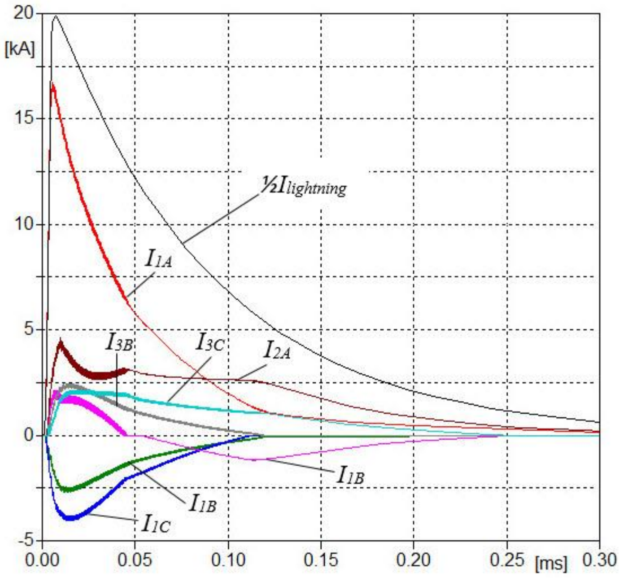

Figure 5. Surge currents through LFA-M upon mid-span DLS for R_F=20 Ω

It should be noted that dangerous cases are those when two or three arresters on one pole flash over; it can lead to two- or three-phase short circuits with high fault currents. Other cases result in current faults through the poles' footing resistances or in phase-to-ground faults.

Additionally, a peculiarity of arresters discharge "next nearest" is observed, when a flashed over arrester on one phase transfers the potential to this pole, thus reducing voltage between the pole and the other phases and preventing flashover of the other arresters.

Oscillograms of currents through operated arresters for the mid-span DLS and R_F=20 Ω are shown in Fig. 5.

Table 2. shows the results of calculations in case of lightning strike into the conductor close to the pole.

In case of strike in close vicinity to the pole, the situation is identical, save that the peak current value ~30 kA is almost twice higher than in the previous case. This means that the closer to the pole the lightning strikes, the larger fraction of current runs out through the nearest arrester. Current electromagnetic surge runs to the neighboring pole twice longer; therefore, less current flows down through it than in the case of a mid-span strike. This impulse is 1.5÷2 times shortened relative to the reference one. Currents in distant arresters also elongate and in general align in values with the ones from the case of the mid-span DLS. Oscillograms of currents through operated arresters for the DLS close to the pole and R_F=10 Ω are shown in Fig. 6.

Upon lightning strike with currents higher than 40 kA, the picture of currents distribution among arresters is generally the same. Due to operation of large amount of arresters far from the strike, currents therein will not exceed 3÷4 kA. For arresters of pole 1, *Im* at lightning currents in the range of 30÷100 kA can be evaluated in proportion by means of changing values in Table 1 and Table 2 relative to 40 kA lightning current.

TABLE II.
PARAMETERS OF SURGES THROUGH THE ARRESTERS IN CASE OF DLS CLOSE TO THE POLE.

R_F (Ω)	Phase	***Im* (kA)** ***t_f / $t_{50\%}$* (μs)**					
		Pole 1	*Pole 2*	*Pole 3*	*Pole 4*	*Pole 5*	*Pole 6*
10	A	31.2 5/40	6.4 15/130	—[a]	—	—	—
	B	-6 18/75	—	2.9 15/70	—	—	—
	C	-8.5 10/55	2.6 5/12	3.2 25/90	—	—	—
20	A	29.7 5/33	4.6 6/150	—	4.2 25/85	—	—
	B	-7.5 8/42	1.2 5/20	2.5 12/35	—	2 30/100	—
	C	-9.5 10/50	2 5/20	2.8 12/80	—	—	—
30	A	29 5/40	4 4/170	—	3.4 14/75	—	—
	B	-8 12/70	1.4 4/12	3.2 12/25	—	—	2.3 25/100
	C	-10.3 8/60	2.2 4/12	2.3 5/60	—	2.6 20/85	—

a. The arrester did not operate on the pole of this phase.

All impacts received due to 40 kA lightning strike with impulse shape of 6/75 µs can be divided into 3 types:

a) Shortened impulse: with current peak value of 16 kA (mid-span strike), 30 kA (strike close to the pole) and current shape of 5/35 µs.

b) Elongated impulse: with peak value of 2÷4 kA current shape of 15/110 µs.

c) Back-flashover impulse: with peak value of 3÷4 kA (mid-span strike), 7÷9 kA (strike close to the pole) and current shape of 10/65 µs.

B. Lightning strike near substation

Design model for this case is distinguished by the presence on one side near the substation of surge arresters grounded via 0.5 Ω low resistance of the substation. A part of lightning current is now flowing out through surge arresters, thus reducing the impact to the arresters from the substation side. The study includes calculations of lightning strike at different distances from the substation. As an example, Table 3 contains the results for the case of DLS into the mid-span between poles 2 and 3. The poles numbering starts from the substation.

In case of a near-substation DLS, current distributions are asymmetric relative to the point of strike. Table 3 shows that the impulse on the side of substation in the arrester nearest to the strike is being shortened more than on the side of the line, since a part of the current runs to the substation. The current impulses' shape on the side of the line is generally preserved, as in the case of the off-substation strike. The same can be said about maximum currents. Poles 4÷7 suffer flashovers by one insulator per pole with phase rotation.

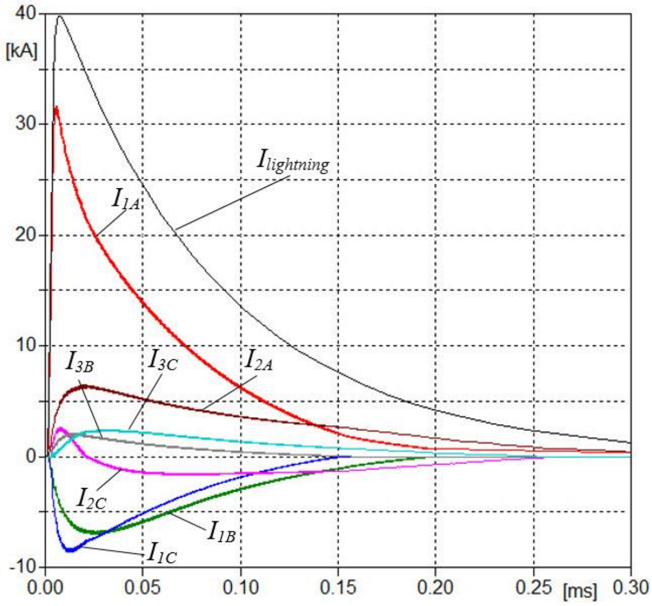

Figure 6. Currents through LFA-M upon 40 kA DLS close to the pole for R_F=10 Ω

Therefore, influence of the substation proximity on the current distribution is felt on one side from the point of lightning strike only. On the opposite side of the line the correlation with results of the off-substation strike is observed. This very case determines more dangerous impact; consequently, it must be determinative.

It shall be noted that the current surge distribution in case of no arresters will have a qualitatively similar picture. Instead of arresters discharge, there will occur flashovers of insulators, which the surge currents of design values and forms are flowing through.

IV. CONCLUSION

(1) The paper presents the results of mathematic simulation of 10 kV OHL upon direct lightning strike into the phase conductor. There have been obtained surge currents' distributions among arresters mounted on the poles depending on the point of lightning strike and the footing resistance.

(2) Thee principal types of impulse actions that can be recommended for running adequate tests and evaluating arresters' operational efficiency have been revealed.

- Shortened impulse with maximum current (it can be named “main”). It has current peak value of ~40% of maximum lightning current upon mid-span DLS and ~75% in case of lightning strike close to the pole. Time to half-value is 1.5÷2 times less than that of lightning current impulse.
- Elongated impulse with current peak value of 3÷4 kA and time to half-value 1.5 times longer than the reference one.

TABLE III.
PARAMETERS OF SURGES THROUGH THE ARRESTERS IN CASE OF MID-SPAN DLS BETWEEN POLES 2 AND 3 NEAR SUBSTATION.

R_F (Ω)	Phase	**Im (kA)** **t_f / $t_{50\%}$ (µs)**							
		MOV	***Pole 1***	***Pole 2***	***Pole 3***	***Pole 4***	***Pole 5***	***Pole 6***	***Pole 7***
10	A	3.2 50/120	4 10/170	16.1 6/29	16.1 6/48	6.5 12/75	—[a]	—	—
	B	1.4 20/60	—	—	-1.5 18/70	—	—	—	—
	C	2.6 20/70	2.2 6/20	-4 18/55	-3.6 25/100	—	4.1 20/100	—	—
20	A	5.5 40/130	5 8/30	14.2 5/33	15.3 5/50	6 8/34	—	—	2.5 25/130
	B	2.5 25/70	—	—	-5.2 20/75	—	—	2.6 18/85	—
	C	4.5 25/70	—	-5.2 16/62	-3 16/7	—	3.6 13/55	—	—
30	A	6.4 35/140	3 8/40	15 5/40	15.2 5/35	5.4 80/200	—	3 16/60	—
	B	4.2 20/80	—	-3.4 18/55	-3.4 20/50	—	2.6 12/45	—	—
	C	5.1 20/80	1.7 8/12	-4.6 18/60	-4.4 15/40	-4.7 60/170	1.8 80/200	—	2.6 17/70

a. The arrester did not operate on the pole of this phase.

- Back-flashover impulse with reference duration and current peak of 3÷10 kA at the lightning current of 40 kA.

(3) The current peak value of "main" impulse depends on distance between the lightning strike point and the pole. It has maximum value when lightning strikes to conductor just near the pole and decreases with the distance increase.

(4) In case of a near-substation DLS, the picture is different on the side of substation only, due to influence of the substation's low grounding resistance. On the opposite side of the lightning strike, the distribution correlates with results of the off-substation strike.

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