Development of Long Flashover and Multi-Chamber Arresters and Insulator-Arresters for Lightning Protection of Overhead Distribution and Transmission Lines

Podporkin G. V.

Streamer Electric Company, 195220 Saint-Petersburg, Russia, georgij.podporkin@streamer.ru

Long Flashover Arresters (LFAs) were suggested and developed for lightning protection of Medium voltage lines 3-35 kV against induced overvoltages and direct lightning strokes. Main feature of LFAs is increased length of lightning flashover path. The LFA's length may be several times greater than that of an insulator (string, etc.). Due to a special inner structure the LFA impulse flashover voltage is lower than that of the insulator and when subjected to lightning overvoltage the LFA flashovers before the insulator. Increased length of flashover insures quenching of power arc follow when current crosses zero. This phenomena can be called "zero quenching". Main advantage of LFAs is that current and energy pass outside the arresters. Reported also are results of research and development of multi-chamber arresters (MCA) and insulators (MCIA) that combine characteristics of insulators and arresters. The base of multi-chamber arresters (MCA), including MCIA, is the multi – chamber system MCS. MCS of first generation comprises a large number of electrodes mounted in a silicon rubber length. Holes drilled between the electrodes and going through the length act as miniature gas discharge chambers. MCS of this type insures power arc quenching when follow current crosses zero ("zero quenching"). MCS of second generation has more complicated chamber design but it quenches impulse arcs without a follow power arc ("impulse quenching"). The devices permit protection of overhead power lines rated at 10 to 220 kV and above against induced overvoltages and direct lightning strokes without using a shield wire.

Keywords: lightning protection, overhead lines, flashover, arc, quenching, multi chamber arresters

1 INTRODUCTION

Overhead power transmission lines (OHL) are tall and rather extended objects. For instance, total length of 6-10kV OHLs in Russia is approximately 2 million km and in China – 10 mln. km. That is why overhead lines are exposed to frequent lightning strikes that are able to cause the line short circuits, cut-offs and, in some cases, insulators breakdown, cable burnouts, wood poles splitting and similar faults. So, OHLs should be protected from lightning surges.

OHLs of 110kV and higher are traditionally protected by means of a shielding wire. However, in case of high soil resistivity (rocks, sand, permafrost), the required low tower footing resistance is failed to be ensured. At high values of tower footing resistance the shielding wire will not protect OHL from direct lightning strike (DLS) to the line, since so called back flashover occurs.

In regions with strong ice-forming the use of a shielding wire is very inconvenient either, since the ice formed on the wire will cause a large slack of the wire and frequently – its breakage and fall down the OHL cables, i.e. a serious accident. Melting of ice is an expensive and labor-consuming procedure. Attempts to discard the use of shielding wire have led to very frequent lightning outages.

In principle, in order to ensure the required lightning-surge proofness, the use of metal – oxide surge arresters (MOA) is possible, but the cost of such technical solution is rather high.

For 6-35kV OHLs shielding wires are not used, as a rule, since there occurs a back flashover upon lightning strike to the wire. In fact, up to the late 1990-s OHLs of 6-35kV in Russia were constructed with no lightning protection at all.

During 1995-2003, 'Streamer Electric Company' developed a lightning protection system for 10kV OHLs by means of long flashover arresters (LFA) [1,2]. The LFA operating principle is that a rather long flashover path on the LFA surface is ensured with the use of creeping discharge effect. Due to this long flashover path, a transfer of surge discharge to power arc follow (PAF) of commercial frequency is ruled out. A distinctive feature of LFAs is that the discharge occurs outside the device and is not of serious hazard thereto. Since 1999, LFAs have been applied at a series of 12 kV OHLs. As of 2015, there is over a million LFAs successfully operating in various utilities.

Since 2004 and up to present time, 'Streamer', has carried out intensive research work on arresters with multi-chamber system (MCS), as a result of which arresters for voltage classes 6 to 35kV have been successfully developed [3]. Then a new type MCS ensuring lightning overvoltage arc blowout with no PAF has been created [4,5]. Arresters on the base of such MCS may be used in networks with high sort-circuit currents (around 30kA and higher). Also, offered was a principally new device: multi-chamber insulator arrester (MCIA) combining properties of insulator and arrester at the same time. When using MCIA, it is possible to provide protection for OHLs of any voltage class, i.e. the higher the voltage class, the higher the number of insulators in the string and, accordingly, the higher the rated voltage and the arc blowout capacity of the MCIA string.

There are different designs of insulators with arrester characteristics possible. MCIAs are based on standard commercially manufactured insulators (glass, porcelain or polymer ones) with MCS installed in a special way. At that, installation of MCS will not cause deterioration of insulating properties of the insulator, but will add properties of arrester thereto. That is why, in case of MCIA use on the OHL, it is possible to discontinue applying a shielding wire. This will help to lower the height, weight and cost of towers, as well as cost of the whole OHL system, and ensure a reliable lightning protection of the lines, i.e. curtail drastically a number of the line cut-offs and decrease losses from undersupply of energy and operating expenses.

LFA and MCA are Russian products and according to their design parameters, technical specifications and functional capabilities represent a special class of lightning protection devices that have no world analogues. LFA and MCA are patented, apart from Russia, in USA, EC and other countries.

2 LONG FLASHOVER ARRESTERS

2.1 LFA OF LOOP TYPE

Fig. 1 presents an LFA of Loop type (LFA-L) installed on a metal structure which models distribution line pole [1]. A piece of cable with steel cord is bent in a loop and connected to the pole with a clamp. A metal tube is placed over the insulated loop in its middle part forming, together with the line conductor, a sparkover air gap *S*. At one arm of the loop, intermediate ring electrodes are installed. The loop is at the same potential as the structure.

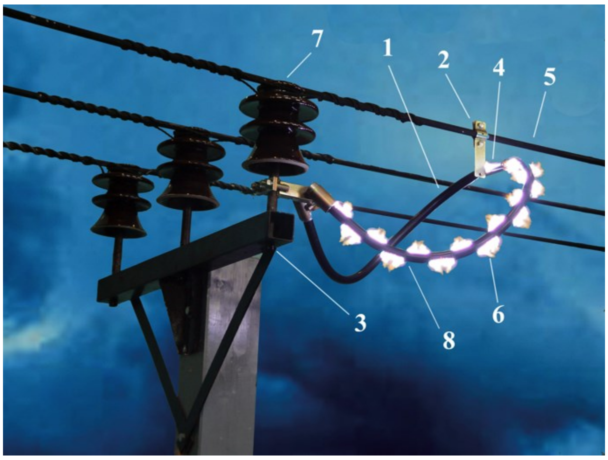


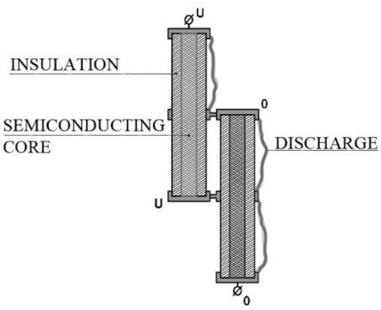
Fig.1: Loop-shaped LFA
1 – cable loop; 2 – clamp; 3- steel structure; 4 – metal tube; 5 – power line conductor; 6 – flashover channel; 7 – insulator; 8 - intermediate ring electrodes

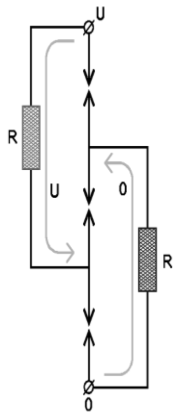
Due to a relatively big capacitance between the metal tube and the steel cord inside the cable, the tube is practically at the same potential as the pole. Therefore an overvoltage taking rise between the line conductor and the pole will be also applied between the metal tube and the line conductor. If the overvoltage is large enough, the sparkover gap *S* will break down and the overvoltage will be applied between the metal tube and the steel cord inside the cable to its insulation. Due to the overvoltage, a creeping flashover develops from the metal tube to a clamp of the insulated loop passing intermediate ring electrodes and next to the structure, thus completing the discharge circuit. The intermediate electrodes have protrusions at opposite sides.

Therefore flashover channel is broken into serially connected pieces of channels and due to this reason arc quenching is facilitated (see photo in Fig. 1).

2.2 LFA-M (MODULAR)

An LFA-M arrester consists of two cable-like pieces with a resistive core [2]. There are also intermediate ring electrodes on its surface for the same purpose as for LFA-L (see above). The cable pieces are arranged so as to form three flashover modules 1, 2, 3 as shown in Fig. 2-2. The resistive core of the upper piece, whose resistance is *R*, applies the high potential *U* to the surface of the lower piece at its middle. Similarly, the resistive core of the lower piece of the same resistance *R* applies the low potential 0 to the surface of the upper piece, also at its center. In this way the total voltage *U* is applied to each flashover module at the same moment, and all three modules are assured conditions for simultaneous initiation of creeping discharges developing into a single long flashover channel.





a) *b)*

Fig. 2: LFA-M arrester for protection of 12 kV overhead lines
a) block diagram; b) electric schematic

2.3 APPLICATION GUIDELINES

Protection against induced overvoltages

To eliminate high short circuit currents associated with two-or three-phase lightning flashovers to ground, LFA-Ls are recommended to be installed one arrester per pole with phase interlacing (Fig.3) With such an arrangement, a flashover to ground results in a circuit comprising two phases, two arresters and two grounding resistors that limit the fault current and ease arc quenching. The higher are the values of the grounding resistance, the more effective is LFA-L operation.

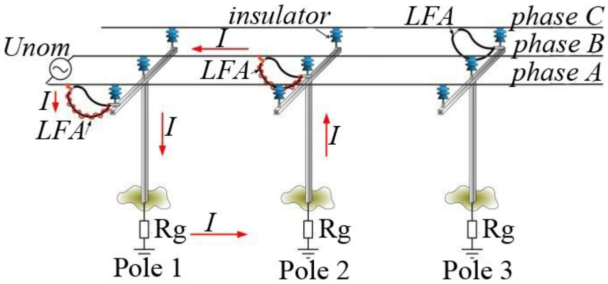


Fig. 3: Schematic of LFA-L installation on a distribution line

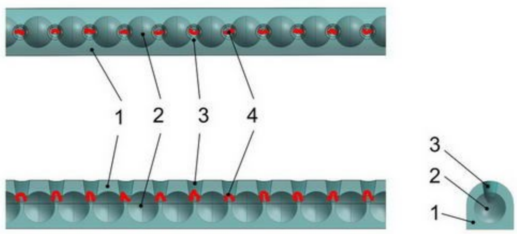
Protection against direct lightning strokes

A direct lightning stroke causes flashover of all the insulators on the affected pole. Therefore, in order to protect the line against a direct lightning stroke, LFA-Ms should be mounted on the pole in parallel with each line insulator (Fig. 4). Phase-to-phase faults on a pole can give rise to follow-up current on the order of 10 kA. In order to quench such currents, flashover length of the LFA-M 12 kV should be 1.5 m, i.e. much higher than that of LFA-L (0.8 m) which intended to protect overhead lines against induced overvoltages.

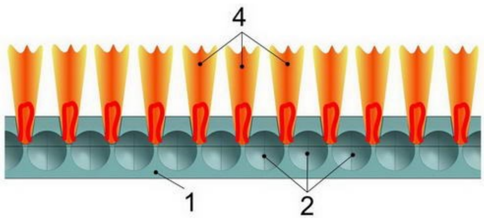
Fig. 4: Protection of 12 kV overhead lines against direct lightning strokes by LFA-M arresters

3 MULTI– CHAMBER SYSTEMS, MCS, "ZERO QUENCHING"

The base of multi-chamber arresters (MCA), including MCIA, is the MCS shown in Fig. 5. It comprises a large number of electrodes mounted in a length of silicon rubber. Holes drilled between the electrodes and going through the length act as miniature gas discharge chambers. When a lightning overvoltage impulse is applied to the arrester, it breaks down gaps between electrodes. Discharges between electrodes take place inside chambers of a very small volume; the resulting high pressure drives spark discharge channels between electrodes to the surface of the insulating body and hence outside, into the air around the arrester. A blow-out action and an elongation of inter-electrode channels lead to an increase of total resistance of all channels, i. e. that of the arrester, which limits the current.



a)



b)

Fig. 5: Multi-chamber system (MCS)
a) diagram showing the discharge onset instant;
b) diagram showing the discharge end instant;
1 – silicon rubber length; 2 -electrodes; 3 – arc quenching chamber; 4 – discharge channel

Multi-Chamber Arresters 24 kV

The principal components of a 24 kV MCA (see Fig. 6) are an MCS, a fiberglass bearing rod and an assembly for securing arresters to insulator pins. Arresters are mounted on insulator pins with air gaps of 3 to 6 cm between top ends of arresters and the conductor. A lightning overvoltage first breaks down the air spark gap and next the arrester's MCS, which assures extinction of follow current.

Shown in Fig. 6 is an arrester with 40 gas discharge chambers intended for protection of 24 kV overhead lines against induced overvoltages. One piece of this model is installed on each phase-interlacing pole as for LFA (see Fig. 3). In this case, the path of AC follow currents that are associated with lightning overvoltage-induced multi-phase includes the tower-grounding resistance circuits. Thanks to an extra resistance of the pole grounding circuit, follow currents are made lower, which raises the quenching efficiency of the arrester.

Fig. 6: 24 kV multi-chamber arrester MCA-24 for protection against induced overvoltages

4 MULTI– CHAMBER SYSTEMS, MCS, "IMPULSE QUENCHING"

To increase the follow current quenching efficiency of an MCS, it is offered to have a four- to twenty-fold longer elementary gap of a discharge chamber, compared to the MCS described in section 3 [4,5]. A low discharge voltage of such an advanced MCS can be attained through use of creeping discharge and cascading operation of MCS circuit chambers (see Fig. 7).

Creeping discharge flashover voltage is known to depend little on the electrode spacing, i. e. a fairly large gap can be flashed over even at a relatively low voltage (see, for instance, [1]).

Cascading is caused by effect of an additional electrode set up along the entire MCS (Fig. 7). It is connected to the last electrode of the last chamber and isolated from all the other electrodes.

The additional electrode is connected to the ground and thus has a zero potential. As the MCS gets actuated the high potential U is applied to the first electrode. The voltage gets distributed among chambers' spark gaps most unevenly. The cascade operation of discharge gaps assures needed low flashover voltages for actuation of an MCS as a whole.

Shown in Fig. 7 is an MCS design with electrodes as pieces of stainless steel tube and additional electrode passing through these electrodes. Length of breakdown gaps is additionally increased by using diagonal discharge slots. Due to such design MCS becomes more compact. Besides capacitance between tube electrodes and additional electrode of a discharge chamber C_0 is much higher than between adjacent electrodes of the chamber C_1. This insures very non uniform distribution of voltage among discharge chambers and consequently decreases discharge voltage.

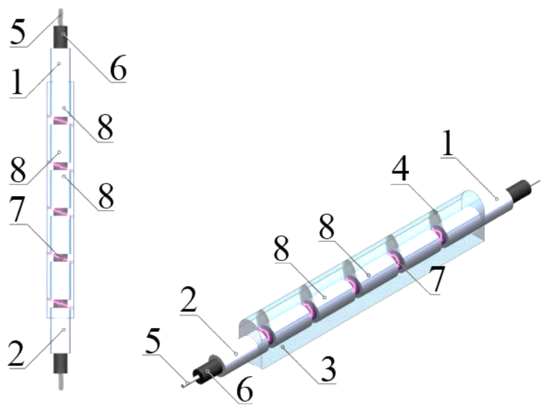


Fig. 7: MCS with additional electrode passing via metallic tube electrodes
1 - main high potential electrode; 2- main low potential electrode; 3- silicone rubber;
4 – discharge slot; 5- additional electrode (cable conductor); 6 – cable insulation; 7 – discharge channel; 8 – intermediate electrodes

Shown in Fig. 8 is a sketch of a gas discharge chamber intended for use in arresters protecting overhead lines against direct lightning strokes. The discharge chamber is strengthened mechanically by a glass- fiber plastic sleeve.

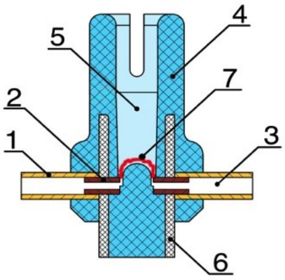


Fig.8: Cross-section of discharge chamber of multi-chamber arrester
1- outer tube; 2 – inner tube; 3 – cavity;
4 – silicone rubber; 5 – discharge slot;
6- fiber-glass plastic sleeve;
7 – discharge channel

Multi-Chamber Arresters and Insulator-Arresters

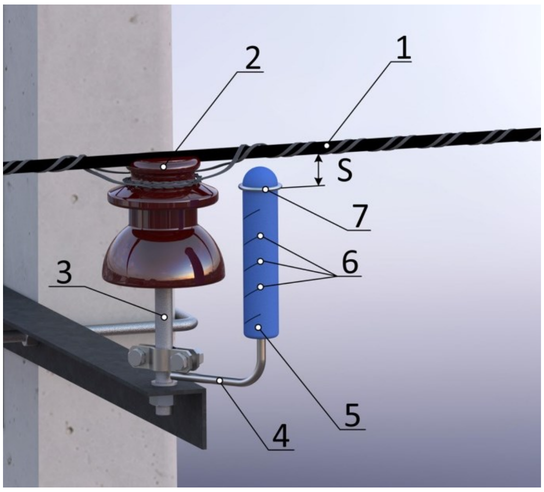
Fig. 9 presents MCA for protection 12 kV line against induced overvoltages (MCA12-I). MCS of the arrester consists of 10 chambers made in accordance with Fig. 7. For avoiding of connection between plasma clouds outgoing from discharge chambers at their operation the chambers alternately directed in opposite sides: five odd chambers directed in one side and 5 even – in opposite side.

MCA12-I should be installed at overhead lines in the same manner as Long Flashover Arresters of Loop type (LFA-L), i. e. one arrester per pole with phase interlacing (see Fig. 3).

MCA12-I quenches discharge impulse arc of induced overvoltages without power follow current. Conductor erosion caused by impulse current with amplitude of about 1 kA and duration 5 mcs is insignificant. This enables to use the arrester without additional clamps on conductors (bared and covered as well).

At Fig. 10 a prototype of MCA for protection 12 kV lines against direct lightning strikes (MCA12-D) is presented. MCS of the arrester consists of 10 chambers made in accordance with Fig. 8. Due to lightning overvoltage at the line conductor sparkover gap S between the conductor and arrester electrode breaks down and the MCS operates.

For protection against direct lightning strikes the arresters should be installed at all three phases at a pole (as at Fig. 4).



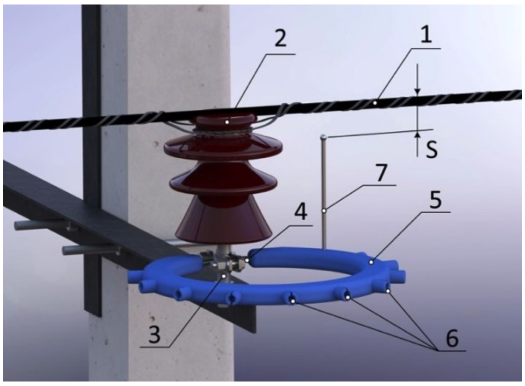
a)

b)

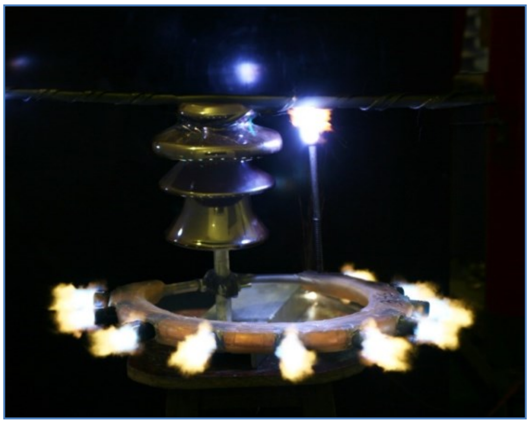
Fig. 9: MCA for protection 10 kV line against induced overvoltages (MCA10-I)
a) general view; b) test photo
1 – conductor; 2 – insulator; 3 – rod; 4 – clamp; 5 – silicon rubber body; 6 – discharge splits; 7 – electrode; S – sparkover gap

Fig. 11 shows a string of two MCIA based on a U120AD insulator. Strings of multi-chamber insulators-arresters (MCIAS) are intended for protecting 35 to 220 kV and above overhead lines against direct lightning strokes.

The MCS of an insulator-arrester comprises 14 chambers made in accordance with Fig. 8.



a)



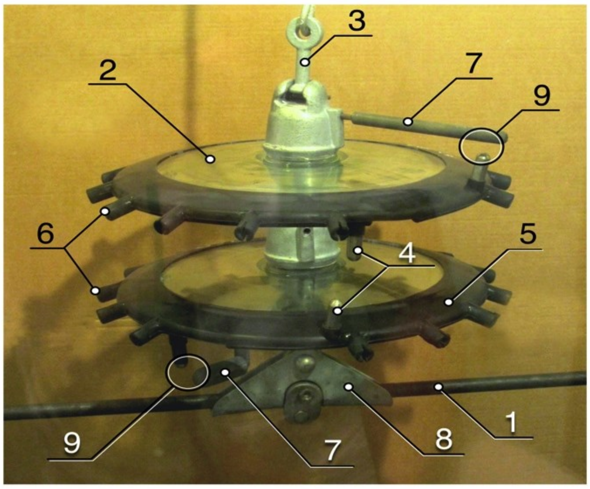
b)

Fig. 10: MCA for protection 10 kV line against direct lightning strikes (MCA10-D)
a) general view; b) test photo
1 – conductor; 2 – insulator; 3 – rod; 4 – ring of steel rod; 5 – silicon rubber body; 6 – discharge splits; 7 – electrode; S – sparkover gap

As a line conductor gets exposed to lightning overvoltage air gaps between electrodes and respective taps, as well as gaps between taps of adjacent insulators, are sparked over actuating the MCS as a whole.

Discharges between electrodes take place inside chambers of a very small volume; the resulting high pressure drives spark discharge channels between electrodes to the surface of the insulating body and hence outside, into the air around the MCS.

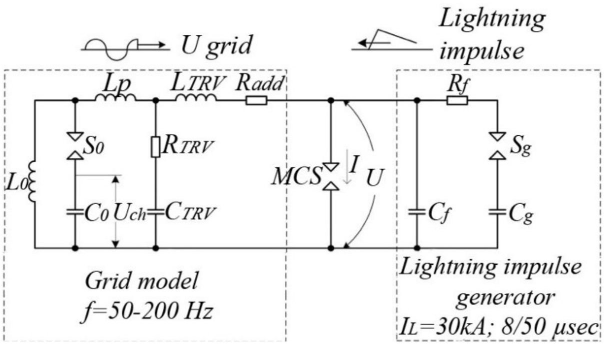
A blow-out action and an elongation of inter-electrode channels lead to an increase of total resistance of all channels, i. e. that of the MCS, which limits the lightning overvoltage impulse current and quenches impulse arc.



a)

b)

Fig. 11: String of two MCIA prototypes based on U120AD insulator:
a) general view; b) during tests:
1 – conductor; 2 –U120AD insulator; 3 – ball eye; 4 – taps; 5 – arrester's body; 6 – discharge chambers; 7 – electrodes; 8 – suspension clamp; 9 –upper and lower coordination spark gaps



Grid simulator:
C_o = 350 μF – capacitance of oscillatory circuit;
L_o = 22 mH - inductance of oscillatory circuit;
L_p = 11 mH– inductance,
L_{TRV} = 1 mH– Transient Return Voltage (TRV)-governing inductance;
R_{TRV} = 50 Ohm – TRV-governing resistance;
C_{TRV}=0,125-3,375μF - TRV-governing capacitance;
R_{add} = 0- 10 Ohm – additional resistance;
S_o– spark discharge gap of grid simulator;

Lightning voltage and current impulse generator:
C_g = 0,02-6,5 μF – capacitance of impulse generator;
R_f = 5-100 Ohm – front resistance;
C_f = 4500 pF – front capacitance;
S_g – total spark discharge gap of impulse generator;
MCS –test MCS;

Fig. 12: Circuit diagram of test setup

5 ARC QUENCHING TESTS

Test procedure

The circuit diagram of the tests is shown inFig. 12. Follow current quenching tests were carried out according to the procedure described in [4] for three modes:

1. Induced overvoltages (surge capacitance of voltage and current impulse generator C_g= 0,02 μF; impulse current I_{max} ≈ 2,5kA; 1/4 μs);

2. Back flashover overvoltages (C_g =0,5 μF; I_{max} ≈ 2,5 kA; 1,2/50 μs);

3. Direct lightning stroke overvoltages (C_g =6,5 μF; I_{max} ≈ 30 kA; 8/50 μs).

Negative polarity lightnings account for some 90% of the total number. For this reason impulses simulating the lightning overvoltage impulse were taken to be negative. A lightning can strike at any instantaneous value of the grid voltage.

The worst possible case is a negative direct lightning stroke on a line conductor at negative instantaneous grid voltage. Here the total current across the arrester, made up by the overvoltage impulse current and the follow current of the grid, tends to reach the fault current level of the grid without crossing zero. That is why most of the tests concentrated on this particular ratio of overvoltage impulse and grid polarities (-/-). However in some cases (-/+) ratio was used.

The test procedure was as follows: first, the capacitor bank C_o and the impulse generator were charged; operation of the impulse generator led to breakdown of the test MCS and the auxiliary arrester S_o. Thus both a lightning overvoltage impulse and the AC voltage were applied to the test MCS simultaneously. As the lightning overvoltage impulse ends, only power frequency voltage remains applied to the arrester.

Voltage and current oscillograms were recorded during the tests (see Fig. 13). Fig. 13,b also presents additional computer oscilloscope patterns of arc dynamic resistance R_{dyn} obtained by dividing the digital oscilloscope pattern of voltage U by the oscilloscope pattern of current I.

Studies have shown that spark discharge quenching can take place in two instances: 1) when the instantaneous value of lightning overvoltage impulse drops to a level equal to or larger than the instantaneous value of power frequency voltage, i. e. lightning overvoltage current gets extinguished with no follow current in the grid (this type of discharge quenching is further referred to as impulse quenching, see Fig. 13 a); 2) when 50 Hz follow current crosses zero (this type of discharge quenching is further referred to as zero quenching, see Fig. 13 b).

Principal test results

***LFA and LFA-M** (see section 2)*

LFA and LFA-M arresters quench the follow current arc upon its zero crossing, i. e. zero quenching (see Fig. 13 b).

Of the practical interest here is so-called critical gradient, i.e. operating voltage gradient of the flash over path at which the impulse sparkover transition to arc does not occur: $E_{cr} = U/l$ (where U – current value of applied voltage; l – lightning sparkover length).

Principal results of completed experimental research, as well as the most representative data of other authors are shown in Fig. 14. Generally, the research was carried out with active pattern of the follow current within the range of current variation from 20A to 10kA.

As it is seen on Fig. 14, the critical gradient is highly dependable on the line short-circuit current.

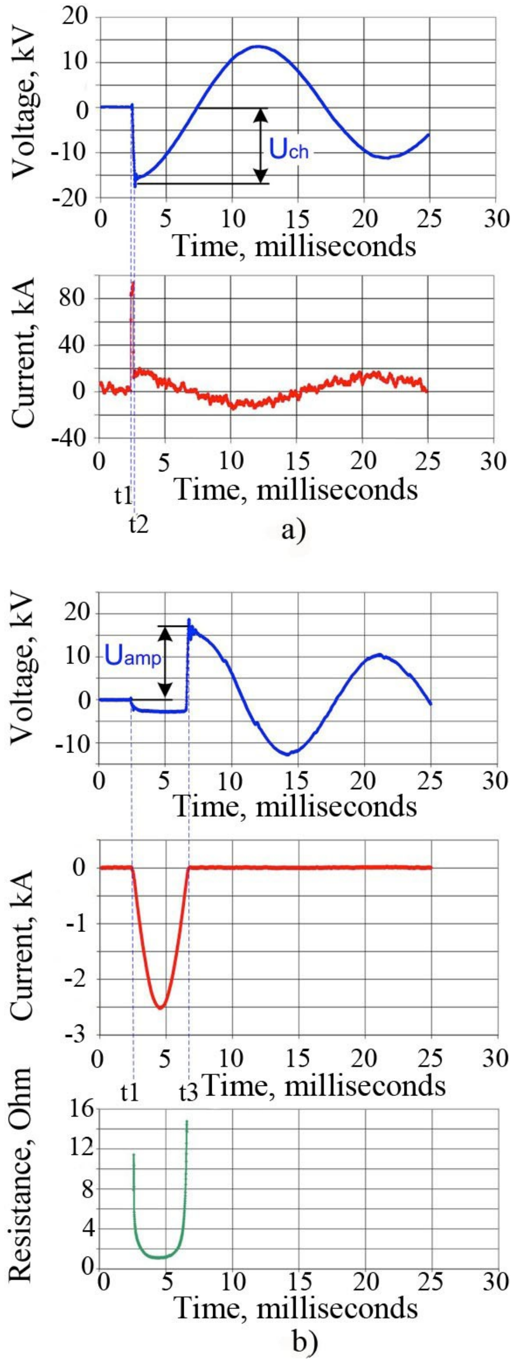


Fig. 13: Typical voltage, current and resistance oscillograms in power follow current quenching tests

a) impulse quenching; b) zero quenching;

t_1-application of AC and lightning impulse;

t_2- quenching of lightning impulse;

t_3- quenching of power follow current

The higher the short circuit current within the range from 20A to 300A, the lower the critical gradient.

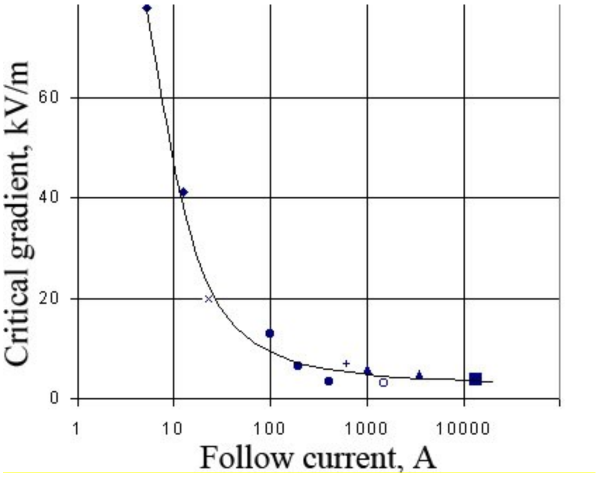


Fig. 14: Relationship between critical gradient of impulse sparkover transition to arc and effective value of follow current x – *lab. [6];*● - *lab.[1,2];* ○ - *OHL [7];* + - *OHL [8];*▲ - *OHL [9];* ■ - *OHL [10];* ◆*-lab. [7], capacitive current*

In order to exclude the impulse sparkover transition to power arc, the sparkover length L of LFA can be determined as $L = U/E_{cr}$.

MCA zero quenching *(see section 3)*

It was shown by the tests that quenching occurs 'in impulse' at low values of U_{ch} but 'in zero' as U_{ch} increases.

Of interest is the fact that both at impulse quenching (Fig. 13 a) and at zero quenching (Fig. 13 b), voltage does not get chopped to zero, as it happens in standard rod-plane and rod-rod gaps, and a considerable residual voltage exists.

Shown in Fig. 15 are oscilloscope patterns obtained for various numbers of MCA chambers. Fig. 16 shows experimental values of grid voltage at which follow current is quenched versus the number of MCS chambers.

The data of Fig. 6 make it possible to estimate the needed number of MCS chambers for arresters of different voltage classes.

MCA impulse quenching *(see section 4)*

Given below are some test results (see Table 1). The grid simulator had to imitate the operating environment of e crest value of fault current is $I^*_{f.}$=30·V2=42.4 kA (ampl.). Earlier studies demonstrated that the issue of impulse or zero follow current quenching pattern is settled close to the instant t=100 µs. With a sine form of 50 Hz current, its instantaneous value at this moment equals $i= I^*_{f.}\sin(\omega t)$= $42.4\sin(314\cdot100\cdot10^{-6})\approx1.3$ kA. That was why the grid simulation was set up so as to assure a near-linear build-up of current from zero to 1.3 kA in 100 µs.

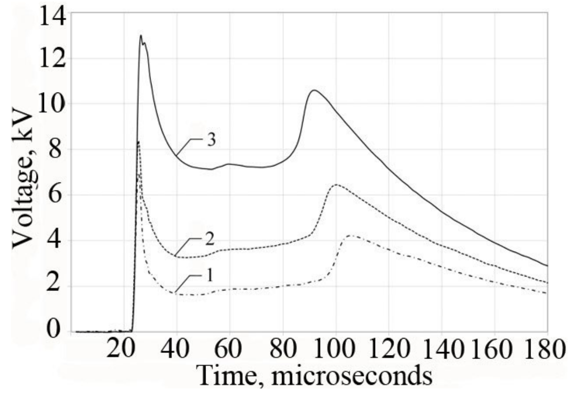


Fig. 15: Oscilloscope patterns for MCS with different chamber numbers m 1 – 50; 2 – 100; 3 – 200

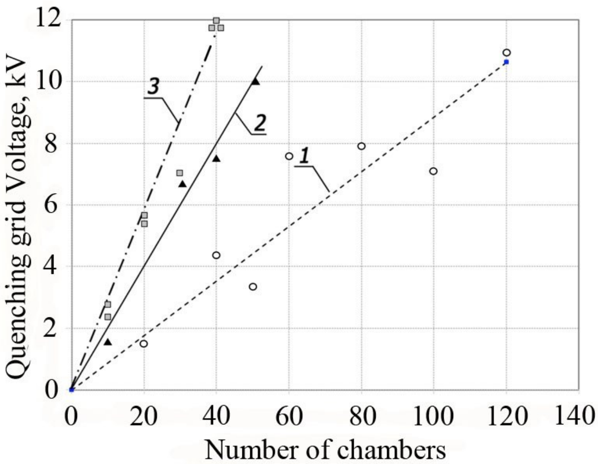


Fig. 16:Follow current-quenching grid voltage vs. number of MCS chambers

1 - impulse quenching (instantaneous value) ○*;*

2 - zero quenching at R_g=0 (effective value) ▲*;*

3 - zero quenching at R_g=10 Ohm (effective value) □

This condition is met with frequency of the grid's oscillatory circuit being f = 200 Hz.

Table 1 shows principal test findings for MCIAS comprising two insulators-arresters (see Fig. 11). The crest voltage capacity of the grid simulator is within U_{ch} =30 kV. This determined the number of MCIA in a string during the tests.

The maximum permissible phase voltage $U_{max.}$ of a 220 kV line is 146 kV. As seen from Table 1, a two-insulator MCIAS assures arc quenching at $U_{2\ MCIA.}$ of 21 kV. At 14 units per string an MCIAS can be believed to assure quenching at $U_{14MCIA.}$ of 7·21 = 147 kV. Thus a fourteen-unit insulator MCIAS can assure quenching of lightning overvoltage impulse arc without generating follow current.

Table 1.

Test object / Fig. No.	Current impulse			Over-voltage	U_{ch} / U_{quench}, kV
	I_{max}, kA	Time, µs			
MCA12-I / 9	2,5	1/4		in-duced	12 / 8,5
MCA12-D / 10	30	8/50		direct strike	12 / 8,5
2x MCIA / 11	30	8/50		direct strike	30 / 21

Note: U_{ch} – charging voltage of grid unit capacitors; $U_{quench}=U_{ch}/\sqrt{2}$– respective effective phase voltage of grid

6 CONCLUSIONS

1. Effective method for lightning protection of overhead distribution lines by Long Flashover Arresters (LFA) is presented. The LFA, which is based on the principle of surface discharge along a piece of insulated conductor, increases the lightning flashover length significantly and by this manner eliminates Power Arc Follow.
2. Multi-chamber systems have been designed that assure quenching of lightning overvoltage impulse arc without follow current in the grid, which permits application of MCS-based insulators-arresters in grids with fault currents as heavy as 30 kA.
3. New type arresters for protection 12 kV lines against induced overvoltages and direct lightning strikes are suggested.
4. A novel insulator-arrester design has been developed, based on a cap-and-pin insulator.
5. Strings of 14 insulators-arresters are capable of assuring lightning protection of 220 kV overhead power lines with no shielding wire.
6. New type arresters and insulators-arresters can be relatively easily adapted for application on power lines of other voltage classes.

REFERENCES

[1] Podporkin G V, Sivaev A D, IEEE Transactions on Power Delivery 13 (1998) 814-823.

[2] Podporkin G V, Pilshikov V E, Sivaev A D, IEEE Transactions on Power Delivery 18 (2003) 781-787.

[3] Podporkin G V, Enkin E Yu, Kalakutsky E S, Pilshikov V E, Sivaev A D, IEEE Transactions on Power Delivery 26 (2011) 214-221.

[4] Podporkin G V, Enkin E Yu, Pilshikov V E, Lightning Protection of Overhead Distribution and Transmission Lines by multi–chamber insulators-arresters of a novel design, CIGRE SC C4 2012 HAKODATE Colloqium, Japan.

[5] Podporkin G V, Enkin E Yu, Pilshikov V E, Zhitenev V V, Lightning Protection of Overhead Distribution and Transmission Lines by Multi–Chamber Arresters and Insulators – Arresters of a Novel Design, CIGRE SC C4 2014, 10-14 May, Lyon, France.

[6] Bellaschi P L, Lightning and 60-Cycle Power Tests on Wood Pole Line Insulation, A.I.E.E. Trans. 66 (1947) 838-50.

[7] Podporkin G V, Lightning protection of 6-10 kV overhead power linesby long flashover arresters, S. Petersburg University 2001 (in Russian).

[8] Burgsdorf V V, Lightning Protection of Overhead Transmission Lines and Operating Experience in the U.S.S.R., CIGRE Paper, No. 326, Paris, 29pp., 1958.

[9] Armstrong H R, Stoelting H O, Veverka E F, IEEE Trans. on PAS, PAS-86 (1967) 206 - 214.

[10] Morooka Y et al., Insulation Cover Thickness Required For Line Breakage Prevention Capitalizing on Creeping Discharge Characteristics of Insulated Wires, In: Proc. 24th ICLP, 984-988.