LIGHTNING PROTECTION OF MEDIUM VOLTAGE OVERHEAD LINES WITH COVERED CONDUCTORS BY ANTENNA-TYPE LONG FLASHOVER ARRESTERS

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INTRODUCTION

A new, so called, antenna type of long flashover arrester (ALFA) is presented in this report. With the use of ALFA it is possible to protect MV lines with covered conductors in a very simple way using the covered conductor with its insulation as long flashover arrester. An antenna is connected to an electrode installed over the surface of the covered conductor. When lightning channel approaches to the overhead line high value potential is induced at the antenna. Under this induced voltage creeping discharge develops into both directions from the electrode thus bridging the gap between cut-through clamp and the insulator.

LONG FLASHOVER ARRESTER PRINCIPLE

Unless special lightning protection steps are taken to safeguard medium voltage overhead power lines with covered conductors, a lightning overvoltage leads first to a flashover of a line insulator and next to a breakdown of the solid conductor insulation. With a high probability such a lightning flashover brings about a power frequency arc which keeps burning at the insulation breakdown point until the line is disconnected. The arc can easily burn the insulating covering and, with heavy fault currents, melt the conductor.

MV lines can be effectively protected against both lightning overvoltages and conductor fusion by long flashover arresters (LFA) whose length is much greater than that of the insulator which it protects [1-3]. Due to a special inner structure of the LFA, its impulse flashover voltage is less than that of the insulator which it protects ; so when subjected to lightning overvoltage the LFA gets flashed over while the insulator withstands. Advantages of the LFA are a simple construction and thus a low cost and a good reliability because lightning discharges develop along the LFA without causing a power arc follow (PAF).

It appears highly promising to make the covered conductor itself perform functions of a long flashover arrester (Fig. 1) [1, 2, 4]. To this end, a cut-through clamp is to be mounted at a definite distance from the end of the conductor's binding; this clamp maintains contact with the core of the conductor.

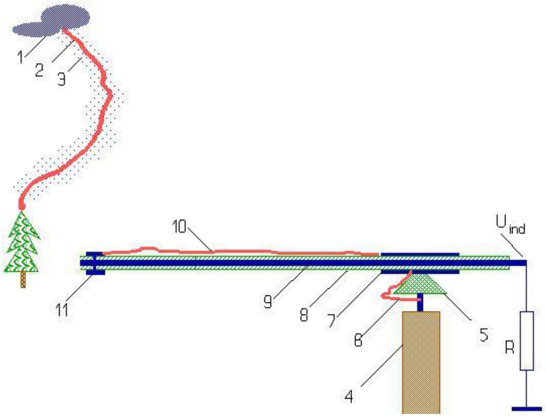


Fig. 1. Lightning protection diagram of overhead line with covered conductors

1 – thunderstorm cloud; 2 – lightning channel; 3 – space charge; 4 – pole; 5 – insulator; 6 – insulator flashover channel; 7 –binding; 8 – insulating cover; 9 – conductor's core; 10 – surface flashover channel; 11 – cut-through clamp.

A lightning overvoltage between the conductor and the pole first flashes over the line insulator and next causes a creeping discharge, which develops on the surface of the covered conductor starting from the end of its binding. On reaching the cut-through clamp, the creeping discharge connects the overhead line conductor to the line pole via a fairly long discharge channel formed by the conductor and the insulator flashover paths. Because of a large total length of the discharge channel thus formed, the lightning flashover does not give rise to an AC power arc, which assures uninterrupted operation of the overhead line. However, the breakdown strength of a covered conductor's insulation is relatively low, ranging from 150 to 200 kV according to the thickness and material of the insulation and the insulator and binding construction [5]. Besides, as an insulator gets flashed over voltage is applied to the insulation of a covered conductor abruptly, with a high rate of rise. This prevents the creeping discharge from reaching the cut-through clamp and shunting the conductor insulation, which leads to a breakdown of the insulation. Because induced overvoltages can be as heavy as 300 kV the insulation of covered conductors can be broken down, particularly with direct lightning strokes on line conductors resulting in much heavier overvoltages.

ANTENNA-TYPE LFA PRINCIPLE

A covered conductor with a relatively weak insulation can be used to build a lightning protection system provided the voltage applied to the insulation rises smoothly, permitting the creeping discharge to reach the cut-through clamp and to shunt the conductor insulation before the voltage rises to the breakdown level. The idea of the antenna-type long flashover arrester (ALFA) is to use an antenna connected to an arrester for causing its flashover even before the lightning leader comes in direct contact with the power line (see Fig. 2). While the lightning leader still moves from the thunderstorm cloud to the overhead line a high potential is induced on the arrester's antenna. The antenna is connected to an electrode on the surface of the covered conductor. A difference of potentials between the electrode and the grounded core of the conductor causes formation of a creeping discharge developing both ways from the electrode. Even before the lightning leader strikes the line such a creeping discharge flashes over the surface of the covered conductor, shunting the covered conductor's insulation by the creeping discharge channel and thereby protecting it from breakdown.

A lightning stroke on a line conductor or close to the line causes a overvoltage both on the conductor and the binding, which gets connected to the conductor via the discharge channel. As the overvoltage reaches the insulator flashover level the insulator gets flashed over making the lightning overvoltage current flow from the conductor via the cut-through clamp down a lightning flashover channel along the conductor, as well as down a lightning flashover channel over the insulator (not shown in Fig. 2, see Fig. 1) and on to the ground down the body of the conducting pole. The lightning overvoltage current is followed by the AC follow current flowing down the flashover channel. The arc gets extinguished when the follow current crosses the zero, and the power line continues it uninterrupted operation without an outage.

EMBODIMENT OF LIGHTNING PROTECTION SYSTEM

Shown in Fig. 3 is an alternative embodiment of such a lightning protection system for a medium voltage (MV) overhead line with covered conductors. The line pole is fitted with a steel stand, such as a piece of pipe. Cut-through clamps are mounted on each phase conductor of the line at a distance from certain the ends of the metal binding of the conductor. In the middle of the conductor sections between the cut-through clamp and the end of the close-by binding, the electrodes are mounted on the surface of the conductor insulation. Antennas are stretched between each electrode and the tip of the stand and secured to the stand via composite tension insulators.

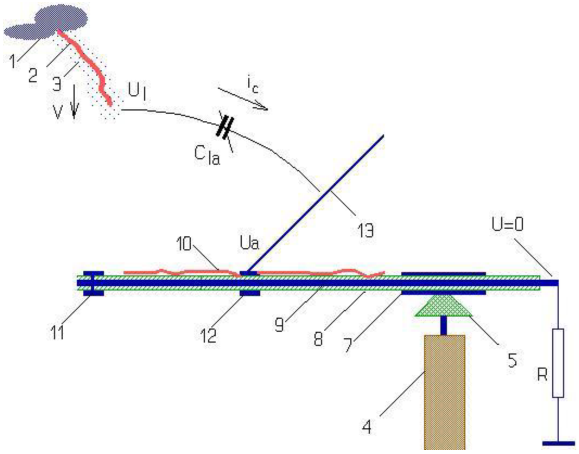
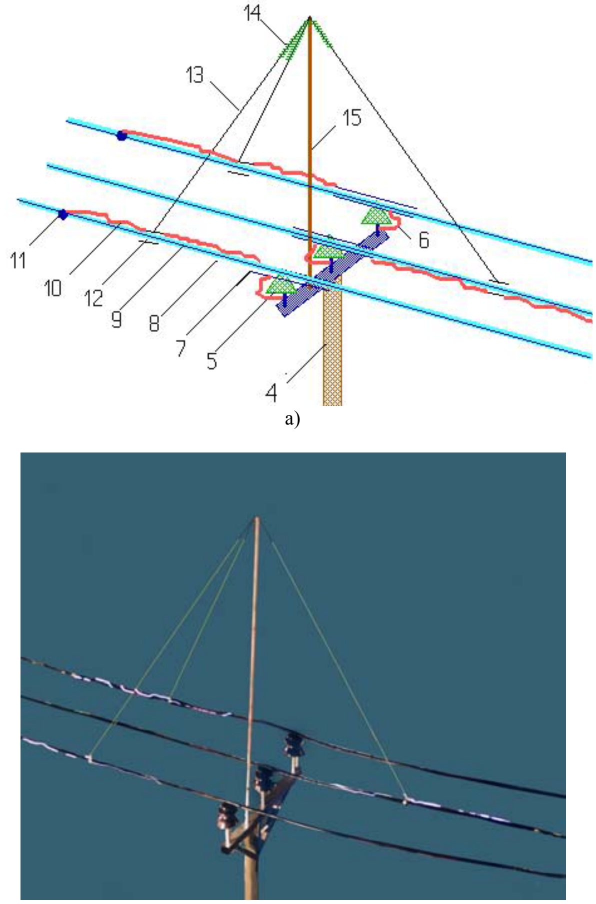


Fig. 2. Illustration of the operating principle of ALFA: For items 1 to 11, see Fig. 1; 12 – electrode; 13 – antenna.

As the lightning channel approaches the line a high potential gets induced on an antenna and thus on its phase conductor electrode. A high voltage taking rise between the electrode and the conductor core causes a flashover of the covered conductor by a creeping discharge. A final lightning stroke on the pole body or on one of the conductors results in a flashover of all the three line insulators (Fig. 3a) and thus in a three-phase short circuit with fairly long flashover channels. The total length *L* of a flashover channel between two phases is found from the formula:

$$L = l+h+h+l \qquad (1)$$

where:



a)

b)

Fig. 3. Protection of MV overhead line by ALFA.
a) Electric schematic; b) Line mock -up testing

For items 1 to 13 see Figs. 1 and 2; 14 – composite insulator; 15 – steel pipe.

$l = l_1 + l_2$, the flashover length over the covered conductor's surface; l_1, the flashover length from the antenna electrode to the binding; l_2, the flashover length from the antenna electrode to the cut-through clamp; *h*, the flashover length over the insulator surface.

The follow current is a two-phase short circuit current. It can be as heavy as 10 kA. For such current a critical electric field strength, which prevents formation of a power arc is E_{cr}= 4 kV/m [3]. The total flashover length necessary to rule out a power arc is found from the equation

$$L = U / E_{cr} \,. \tag{2}$$

E.g., the flashover length for 12 kV lines is $L = 12/4 = 3$ m and for 6.6 kV ones, $L = 6.6/4 = 1.65$ m.

The flashover length over the surface of a covered conductor *l* is found from (1) as follows:

$$l=(L-2h)/2, \tag{3}$$

making $l = 1.3$ m for 12 kV lines (at $h = 0.18$ m) and $l = 0.7$ m for 6.6 kV lines (at $h = 0.15$ m). With the antenna electrode installed about midway between the binding end and the cut-through clamp, $l_1 \approx l_2 \approx 0.75$ m and $l_1 \approx l_2 \approx 0.35$ m for 12 and 6.6 kV lines, respectively.

To start development of creeping discharges on the surface of a 0.35 to 0.75 m long covered conductor, an impulse voltage of a 60 to 80 kV crest value is sufficient [2,6].

CALCULATION OF ANTENNA VOLTAGE INDUCED BY APPROACHING LIGHTNING LEADER

The calculation was performed for the embodiment alternative shown in Fig. 3. The induced voltage is directly proportional to the linear charge along the approaching lightning channel. In its turn, the linear charge can be approximately related to the lightning current with the help of relationship [7] as follows:

$$\tau = \sqrt{\frac{I_l}{1.56}} \times 100 \,, \tag{4}$$

where I_l is lightning current, kA; τ, linear charge, μC/m. It is thus clear that the heavier is the lightning current, the higher is the induced voltage, i. e. the higher is a lightning above the line, the earlier will the ALFA be triggered. By contrast, the less heavy is the lightning current, the lower is the induced voltage.

According to CIGRE (K. Berger), 95% of lightnings feature a current in excess of 5 kA [8]. A lightning stroke with a current of this magnitude on a conductor causes an overvoltage of about 800-900 kV, which exceeds considerably the insulation level of a medium voltage (MV) power line. Thus a direct lightning stroke on such a line inevitably results in an insulation failure even at a minimum magnitude of current.

This is why the efficiency of ALFA should be checked at minimum lightning current magnitudes. If the arrester performs well at a minimum lightning current, it will be even more efficient at any heavier lightning current. With all this taken into account, calculations were made for the minimum magnitude of lightning current $I_l = 5$ kA. Using the equivalent charge method, the lightning channel was presented as a 5000 m long vertical cylindrical conductor. In accordance with (4), the linear charge was taken to be 180 μC/m, i. e. the total charge of the channel-simulating cylinder was 0.9 C. The radius of the channel-simulating cylinder was found from the formula

$$r_l = \frac{\tau}{2\pi\varepsilon_0 E_{str}} = \frac{180\cdot10^{-6}}{2\cdot3.14\cdot8.85\cdot10^{-12}\cdot0.8\cdot10^{6}} \approx 4m \,, \tag{5}$$

where E_{str} = 0.8 MV/m is the electric field strength in the streamer zone of the negative-polarity lightning channel. The tip of the lightning channel was simulated by an 8 m long cylinder of a 4 m radius. The total charge of the tip was assumed to be, according to the recommendation of [7],

$$q_t = 9\tau r_l = 9\cdot180\cdot4 = 6480\mu C \tag{6}$$

The charge of the thunderstorm cloud was not taken into account. The cylinder was assumed to go down at a constant speed $v_l = 3\cdot10^5$ m/s= 0.3 m/μs, the elevation of its lower end above the ground, further referred to as the lightning height, varying from 300 m to 15 m. The calculation showed the channel potential to vary inconsiderably, from 20.3 MV to 19.7 MV, in other words, to stay within around $U_l \approx 20$ MV.

As the lightning channel approaches the ground, partial capacitance C_{la} between the channel and the antenna increases (see Fig. 4). Capacitance to the ground of the antenna and its electrode on the conductor surface includes also capacitance of the electrode about the earthed conductor core. As a creeping discharge takes rise and develops the discharge channel together with streamers gets coupled to the antenna-electrode system forming an antenna-electrode-streamers system with an even larger capacitance; this joint antenna-ground capacitance C_{ag} grows with the progress and development of the creeping discharge channels. Connected in parallel with C_{ag} is a ground leakage resistance *R* whose value is function of the resistance of two wet polluted parts of the conductor l_1 and l_2 and that of the line insulators and the antenna (Fig. 2). The equivalent circuit diagram used to calculate the antenna potential vs. time is shown in Fig. 4. The inputs for calculation with the help of the circuit diagram shown in Fig. 4 are the values of its components C_{la}, C_{ag} and R. The equivalent EMF can be assumed to be equal to the potential of the lightning channel $U_l \approx 20$ MV.

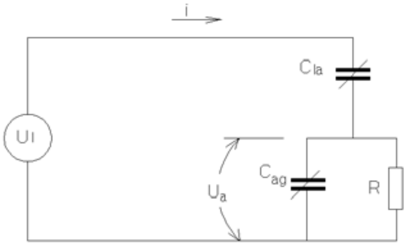


Fig. 4. Equivalent circuit diagram used to calculate the antenna potential vs. time

The values of partial capacitance between the lightning channel and the antenna C_{la} and between the antenna and the ground C_{ag} (with allowance for the electrode and creeping discharge streamers) are calculated using the equivalent charge procedure.

The calculation was made for two cases: 1) lightning stroke on the pole, with the lightning channel assumed to descend vertically in line with the pole; 2) lightning stroke on the conductor in the mid-span, with the lightning channel assumed to be removed 35 m from the pole.

Partial capacitance between the lightning channel and the antenna C_{la} was found for a standard 10 m high 12 kV pole at lightning heights H_l varying from 300 to 15 m and streamer lengths l_{str} varying from 0 to 1.0 m.

Capacitance C_{la} was shown by the calculation to range from 0.4 to 2.5 pF for Case 1 and from 0.25 to 0.5 pF for Case 2. Capacitance C_{la} increases rapidly as the lightning height H_l decreases but shows a slight variation only with a changing streamer length l_{str}. Calculated values of capacitance C_{la} are well approximated by power functions of the form

$$C_{la} = \frac{a}{H_l^n}, \qquad (7)$$

where a, n are parameters; H_l, lightning height, m.

Partial capacitance C_{la} between the channel and the antenna is approximated by (7) with values of the parameters a = 862 pF and n = 1.95 for Case 1 and a = 2.37 pF and n=0.53 for Case 2.

With a count-down approach, i. e. with the zero time taken to be the instant of the lightning striking the ground and τ assumed to be the lightning channel propagation time from the lightning lower end to the ground, the lightning height can be expressed as

$$H_l = v_l \tau \approx 3 \cdot 10^5 \tau \cdot \qquad (8)$$

By substituting (8) in (7), the channel-antenna partial capacitance vs. time relationship is as follows:

$$C_{la} \approx \frac{a}{H_l^n} \approx \frac{a}{(3 \cdot 10^5 \cdot \tau)^n} \qquad (9)$$

It was also shown by calculation for several fixed creeping discharge streamer lengths that partial capacitance C_{ag} between the antenna (with allowance for the electrode and creeping discharge streamers) and the ground depends heavily on the streamer length. Therefore the antenna potential vs. time relationship was calculated using the circuit diagram in Fig. 4 with allowance for variation of capacitance between lightning and antenna according to (9) several fixed creeping discharge streamer lengths.

Computation was carried out with the help of the "Microcup" program. Leakage resistance R (Fig. 4) was varied from 10 kOhm to 100 MOhm. Shown in Table 1 are calculated values of the antenna potential at leakage resistance R=1 MOhm. It can be seen from Table 1 that the antenna potential depends heavily on the streamer length l_{str}. The larger is l_{str}, the larger is capacitance C_{ag} of the antenna- ground system and, in accordance with the Fig. 4 diagram, the lower is the antenna potential. For example, with the lightning channel aligned with the pole 30 m above the ground, the antenna potential would be 280 kV without streamers and 190 kV with 0.5 m long streamers, i. e. one third less. Thus, as streamers increase, the antenna potential and, accordingly, the voltage on the LFA cable insulation go down.

Table 1 shows also that in Study Case 2 (with the lightning

TABLE 1. Antenna potential U_a, kV vs. lightning height and location at various streamer lengths l_{str}

H_l,	τ,	Streamer length l_{str}, m				
m	µs	0	0.25	0.5	0.75	1.0
300	1000	0 0	0 0	0 0	0 0	0 0
200	667	1.5 2.2	1.4 2.1	1.3 2.0	1.2 1.9	1.1 1.9
100	333	11 6.0	9.7 5.7	8.6 5.3	7.9 5.0	7.1 4.8
50	170	71 16	62 15	52 13	45 12	40 11
30	100	280 32	230 29	190 25	160 22	130 20
20	67	760 54	620 47	480 40	400 35	330 31

15	50	$\frac{1450}{76}$	$\frac{1180}{67}$	$\frac{900}{54}$	$\frac{750}{47}$	$\frac{600}{40}$

Note: Numerator and denominator show antenna potential for Case 1 and 2 lightning channel locations, respectively.

channel shifted 35 m from the pole) the antenna potential is a few times lower than in Study Case 1. The difference is particularly marked at small lightning heights (H_l= 75-15 m): when the lightning channel is aligned with the pole the distance to the antenna is function of the lightning height only, while with a mid-span position of the the lightning it depends on the distance to the pole as well (here 35 m). Still, even with the lightning channel 35 m away from the pole and at a 15 m lightning height (Table 1), the antenna potential is about 80 kV with no streamers, which exceeds the creeping discharge breakdown voltage on a 0.75 m long cable [2]. This assures a flashover on the surface of a covered conductor of a 12 kV line (see Section 2).

The antenna potential depends on the leakage resistance as well. Fig. 5 quotes calculated antenna potential vs. time for 0.25 m long streamers and for various leakage resistance values.

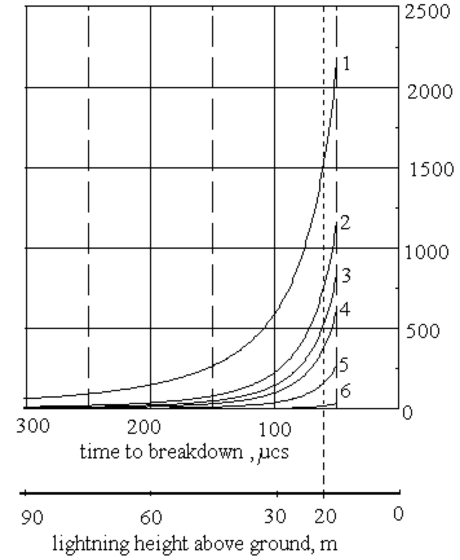


Fig. 5. Antenna potential vs. time to breakdown of the lightning-ground gap τ at different values of leakage resistance *R* (streamer length, 0.25 m; lightning channel aligned with the pole):
1. *R* = 100 MOhm; 2. *R* = 1 MOhm; 3. *R*=500 kOhm;
4. *R* = 300 kOhm; 5. *R* = 100 kOhm; 6. *R* = 10kOhm.

It can be seen from Fig. 5 that, as the lightning channel approaches the overhead line, the potential of the antenna increases sharply, the rate of increase growing with time. The antenna potential depends heavily on the leakage resistance: the lower is resistance, the lower is potential. Theoretically, the antenna potential could be as high as 2000 kV. However, it cannot happen in real life because, at a 60 to 80 kV voltage between the electrode and the core, a flashover occurs in the gap l_2 on the surface of the covered conductor between the electrode and the cut-through clamp (see Fig. 3 a); this makes the antenna connect to a line conductor via the flashover channel, and the antenna potential drops considerably.

At surface conductivity γ of 10 µS, characteristic of wet polluted surface of conductors and line and antenna insulators, leakage resistance is about 1 MOhm. With the lightning descending more or less in line with the pole, the conductor surface is flashed over at an 80 kV antenna potential when the lightning is about 45 m above the ground (see Fig. 5, curve 2); with the lightning channel located in the middle of a 70 m span, i. e. 35 m away from the pole, a covered conductor is flashed over when the lightning is some 15 m above the ground (see Table 1).

It has thus been shown that the surface of a covered conductor is flashed over well before the lightning channel comes in contact with a power line, both with the lightning channel above the pole and the lightning striking the pole, and with the lightning channel above a span of the line and the lightning striking a mid-span point.

PRELIMINARY EXPERIMENTAL CHECK

Shown in Fig. 6 is a test arrangement permitting to simulate operating conditions of an antenna-type lightning protection system according to Fig. 2. Capacitance between the lightning channel and the antenna was simulated by an air capacitor consisting of a high voltage doughnut electrode (1.2 m external diameter and 0.3 m diameter of the tube) and a 6 m square plane of 0.5 m wire mesh, with a 2 m insulating gap between the electrode and the wire mesh. An impulse generator was used to apply positive and negative polarity 1.2/50 µs impulses. Voltage was raised in 20 kV steps. At either polarity, incomplete discharges were observed near the electrode at a 600 kV output voltage; at about 640 kV output voltage the cable surface was completely flashed over (Fig. 6, a), i. e. the cut-through clamp got connected to the binding via creeping discharge channels and the electrode on the conductor surface. The procedure simulated the stage of a lightning approaching a power line.

Application of a 900 kV positive or a 1150 kV negative impulse led to a breakdown of the air gap between the doughnut and the plane of the air capacitor, all the output voltage from the impulse generator coming abruptly to the electrode on the surface of a covered conductor (Fig. 6 b). While the line insulator was flashed over the insulation of the covered conductor was not damaged.

With the air capacitor shunted by a piece of wire the test voltage was applied directly to the conductor core (Fig. 1) without involving the antenna; this resulted in an insulator flashover and a conductor insulation breakdown. The tests have thus amply demonstrated and proved efficiency of the antenna which assures a creeping discharge flashover over the surface of the conductor insulation well before a lightning stroke on the line. Such a preventive flashover protects the conductor insulation against a breakdown by a lightning stroke, at the same time creating a fairly long lightning flashover path which rules out a power arc.

An important feature of the suggested lightning protection system is its simplicity; as seen from Fig. 3, it comprises a metal stand (one per three phases on a pole), three wire rope antennas, three light-weight composite tension insulators, three electrodes, and three cut-through clamps. Again, this system protects the line against both induced overvoltages and direct lightning strokes.

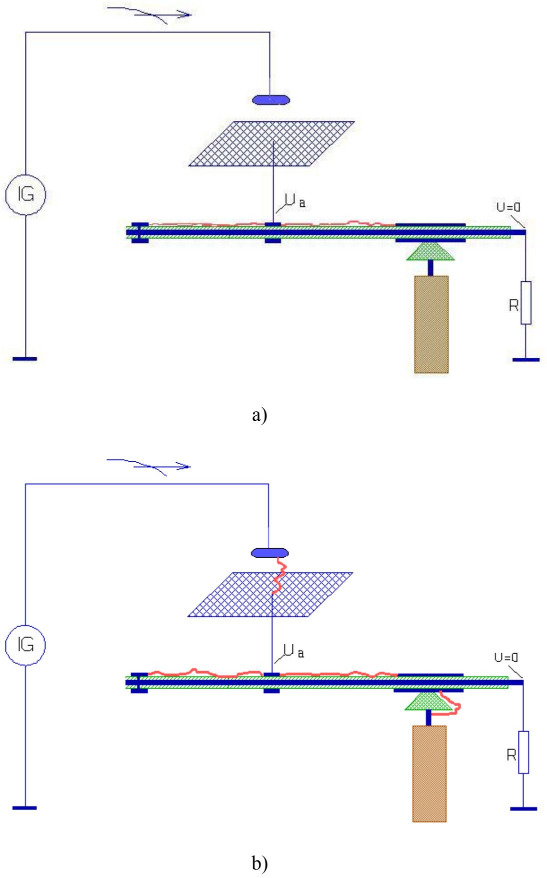


Fig. 6 Simplified test outline
a) simulation of lightning leader approaching a line;
b) simulation of lightning final strike.

Reported here is only one of many possible configurations of an antenna-type long-flashover arrester. In the authors' opinion, the above lightning protection system can be also developed for higher voltages.

CONCLUSIONS

1. An antenna connected to a long-flashover arrester on a covered conductor assures its flashover as the lightning channel is approaching the power line, well before a direct contact of the channel with a conductor or pole of the line.
2. Such a flashover prepares a fairly long path for a flashover occurring during a lightning stroke on the line, and thus prevents a breakdown of the conductor insulation.
3. A long-flashover arrester fitted with an antenna protects the line against both induced overvoltages and direct lightning strokes.
4. A simple design makes long-flashover arresters considerably less expensive than conventional metal oxide arresters.
5. The suggested lightning protection system appears highly promising and encouraging further research and development studies covering, among other things, its higher voltage applications.

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