Improvement of lightning protection by application of a breakable micro-discharger

Yu.K. Bobrov, I.V. Zhuravkov, E.I. Ostapenko and V.V. Starikov
All-Russian Electrotechnical Institute
12, Krasnokazarmennaya St., Moscow, 111250, Russia

Yu.V. Yurgelenas
General Physics Institute, Russian Academy of Science
38, Vavilova St., Moscow, 119991, Russia

***Abstract*—An essential increase of lightning protection efficiency can be achieved by means of insertion of a disconnecting device (breakable micro-discharger) into the circuit between the lightning diverter and grounding. Such upgraded lightning protectors are subject to the most frequent lightning strokes. Activity of these lightning protectors becomes apparent when breaking the circuit with the micro-discharger. At that instant, there occurs an intensive electrodynamic process of formation of a leader in the lightning protector circuit being disconnected. The leader propagates to a thundercloud, and triggers its discharge, being similar to a missile carrying a grounded wire to the cloud. Results of evaluative calculations of reactive parameters for a discharge *LC*-circuit of a lightning and lightning protector are given in the paper, and the process of discharge in a circuit of a lightning protector with a micro-discharger is also considered. The effect of breakdown of long air gaps having a micro-discharger in a circuit of a lightning protector is explained by occurrence of an autoresonance condition in the corresponding *LC*-circuit. Laboratory simulation of this effect has been realized on a 'rod-plane' air gap in the All-Russian Electrotechnical Institute. For the method applied, the US Patent 6,545,480 of April 8, 2003 has been taken out by Mr. Zhuravkov.**

I. General and equivalent electric circuit for initial state of a system 'lightning protector – thundercloud'

In a general case, the electric circuit of a lightning leader can be simulated by a long line having the variable length dependent on time. However, for the time present, theoretical footings for long lines do not contain a theory of long lines having the variable length. Therefore, we employ the other possibility of analysis of a discharge circuit of a lightning by means of a circuit with lumped parameters.

Fig. 1 shows a circuit of a lightning rod with grounding device in the system 'thundercloud – ground'.

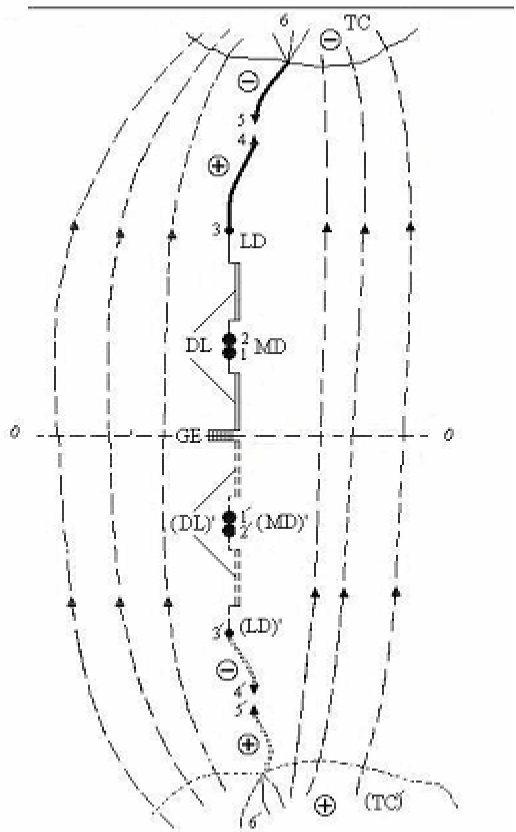


Fig. 1. The circuit of a lightning rod with a grounding device and a thundercloud.
0 – 0 is the level of zero potential of earthen ground;
TC is a thundercloud;
DL is a current-carrying downlead from a lightning diverter (LD) to a grounding electrode (GE);
MD is a breakable micro-discharger.
All the structural components of the circuit, denoted with accents signify their mirror reflections in an assumed ground of ideal electric conductivity.

An earthen ground is considered to be of good electric conductivity which makes it possible to apply the method of mirror reflection both of the thundercloud (*TC*) over the ground, and of the devices of the lightning protector. In case of a permafrost soil, its surface can be considered as an opaque one, and mirror reflection of ground-based apparatuses leads to a different approach when calculating capacity of components of these apparatuses and a thundercloud. Main electrical parameters of the circuit current for discharge of a lightning into a lightning rod are given in Fig. 2 in the form of an equivalent electric circuit.

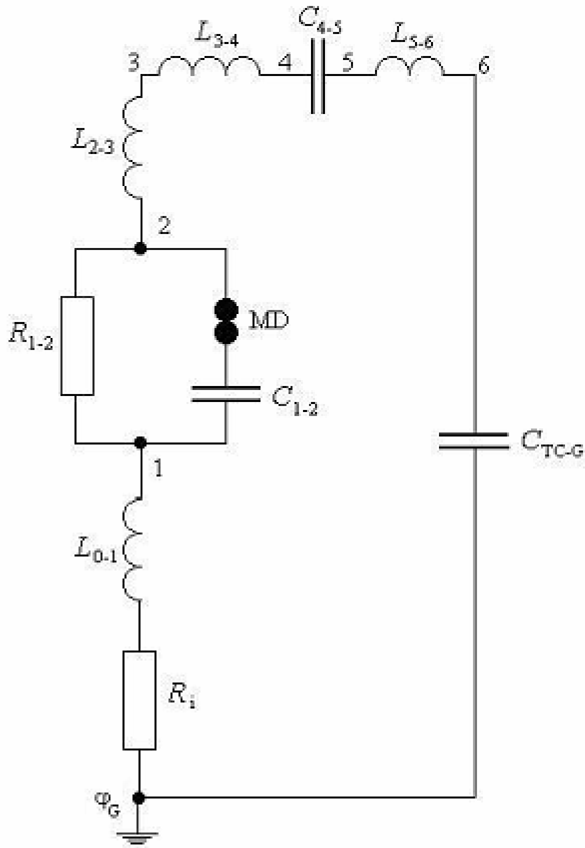


Fig. 2. The equivalent electric circuit with lumped parameters in accordance with the drawing of Fig. 1.
R_i is the impulse resistance of the grounding;
$L_{0\text{-}1}$ is the inductance of the section of the grounding downlead from the breakable micro-discharger (electrode 1) to the level of zero potential;
$R_{1\text{-}2}$ is the resistance of the plasma;
$C_{1\text{-}2}$ is the capacitance between electrodes 1 and 2 of the breakable micro-discharger;
$L_{2\text{-}3}$ is the inductance of the section of the grounding downlead from the breakable micro-discharger (electrode 2) to the lightning diverter (3) of the lightning protector;
$L_{3\text{-}4}$ is the inductance of the rising counter-leader of the lightning;
$C_{4\text{-}5}$ is the capacitance between the channels of the rising and descending leaders;
$L_{5\text{-}6}$ is the inductance of the descending leader of the lightning;
$C_{TC\text{-}G}$ is the capacitance of the thundercloud with respect to the earthen ground.

One of possible versions of arrangement of a breakable micro-discharger (MD) is presented in Fig. 3. Our practice shows it advisable that frequency of opening and closing of the micro-discharger electrodes should be about 0.01–0.1 Hz.

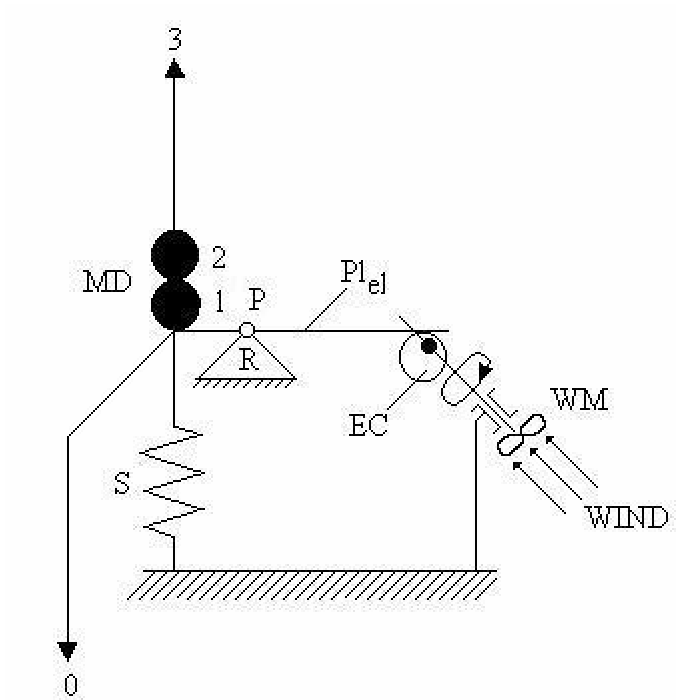


Fig. 3. A possible version of arrangement of a breakable micro-discharger (MD) with a drive mechanism powered by natural permanent energy sources.
1 and 2 are the lower and upper spherical electrodes correspondingly, of the breakable micro-discharger (MD);
EC is the eccentric which is set in rotary motion by the wind motor (WM), and acting on the flat elastic plate (P_{el}), swinging in the pivot (P) mounted on the rest (R).
Return of the electrodes into starting position is realized by the cylindrical spring (CS).

For evaluation of possible oscillation conditions in a discharge current circuit of a lightning and lightning protector, the electric circuit of Fig. 2 can be simplified by presentation of the main capacitive and inductive components with their equivalent values:

$$L_{dcc}^{eq} = L_{0-1} + L_{2-3} + L_{3-4} + L_{5-6} \quad (1)$$

$$\frac{1}{C_{dcc}^{eq}} = \frac{1}{C_{1-2}} + \frac{1}{C_{4-5}} + \frac{1}{C_{TC-G}} \quad (2)$$

where L_{dcc}^{eq} and C_{dcc}^{eq} are the equivalent inductance and capacitance of the discharged current circuit.

II. EVALUATION OF REACTIVE PARAMETERS OF THE DISCHARGE CURRENT CIRCUIT OF A LIGHTNING

In general, leader channels of a lightning discharge should be presented in the form of long lines with distributed parameters [1 – 4]. However at the first evaluative stage, calculations can be carried out on the base of an equivalent electric circuit with lumped parameters, see Fig. 2.

A. Inductive parameters [5]

1) Inductance of the steel ferromagnetic grounding downlead

The two approaches are of interest:

1. Evaluation of all the inductive parameters of the circuit depicted in Fig. 2, presence of a formed leader stage of the lightning discharge is supposed here; and
2. Evaluation of only those inductive parameters of the system which exist before the beginning of the leader discharge process.

The first choice takes into account not only stationary components of construction of the lightning protector such as the steel ferromagnetic grounding downlead with the lightning diverter, the grounding having the impulse resistance R_i , and the breakable micro-discharger 1 - 2, but also the inductive parameters of the leader channels of the lightning, including those parameters for a wide region of a displacement current at a discharge of capacitance of the thundercloud $C_{TC\text{-}G}$ to the ground.

At the second choice, it is necessary to determine only the inductive parameters of the particular construction of the lightning protector without leader channels of a lightning, for prediction of possible occurrence of oscillatory processes in an expected circuit of a discharge current of a lightning, in the presence of a breakable micro-discharger as a cause of initiation of a high-frequency resonant condition in the circuit. In case of occurrence of a voltage resonance, large overvoltages can appear on the lightning diverter, and initiate a streamer-leader stage of the rising counter-leader. It can be sufficient for explanation of the considered effect of an essential increase of distance of breakdown when inserting a breakable micro-discharger.

It is also possible to consider the third version of the circuit having a developed descending lightning leader with the height of its orientation to the lightning protector h_l . In this case, the inductance of the lightning leader having the length $H_{TC} - h_l$ where H_{TC} is the height of the thundercloud, shall be included into a system of determinative inductive parameters for the problem.

Of all the components of the inductance L_{dcc}^{eq} (see Equation 1), only components $L_{0\text{-}1}$ and $L_{2\text{-}3}$ are determined by time-constant values of inductance of the grounding downlead of the lightning protector. The downlead usually is a steel ferromagnetic conductor made of rolled wire having diameter 8 mm to 10 mm, length $l_{0\text{-}3}$ about 15 m, and relative permeability μ in the range from 700 to 900. Because of large values of μ, the internal inductance L_i of the grounding downlead can do an essential or even determinative share for its total inductance, taking into account its external component L_e [5], that is

$$L_{0-3} = L_{0-3}^{i} + L_{0-3}^{e} \qquad (3)$$

where

$$L^i_{0-3} = \frac{\mu_0 \mu\, l_{0-3}}{8\pi}\xi \quad (4)$$

At absolute permeability $\mu_0 = 4\pi \cdot 10^{-7}\ g/m$ and the parameters of the steel downlead given above, $L^i_{0-3} = 525 \cdot \xi\ \mu\text{H}$. The factor ξ depends on frequency of the current ω, radius of cross-section of the conductor r, and its specific conductance γ.

As $\xi = \xi(kr)$, where

$$k = \sqrt{\omega \mu_0 \mu \gamma}\ , \quad (5)$$

according to [5], $kr = 4.48 \rightarrow \xi = 0.61$. It results in the internal inductance $L^i_{0-3} \approx 320$ μH. External inductance

$$L^e_{0-3} = \frac{\mu_0 l_{0-3}}{2\pi}\left(\ln\frac{2l_{0-3}}{r} - 1\right) = 12.045\,\mu\text{H}\ , \quad (6)$$

being added to the internal inductance results in the total inductance of the downlead $L_{0-3} = 332.3\,\mu\text{H}$; at that, the external inductance component does not exceed 4% of the total inductance value.

2) Inductance of leader channels of a lightning

Assuming a mean radius of channels of lightning leaders equal to $r_l \approx 2 \cdot 10^{-2}$ m, and their length equal to l_l, inductances of plasma channels of lightning leaders are calculated by the equation:

$$L_l = \frac{\mu_0 l_l}{2\pi}\left(\ln\frac{2l_l}{r_l} - 1\right) \quad (7)$$

For example, if $l_l = l_{3-4} = 50\,\text{m}$ and $l_l = l_{5-6} = 900\,\text{m}$, then $L_{3-4} = 72.5\,\mu\text{H}$ and $L_{5-6} = 1873.4\,\mu\text{H}$.

Hence according to Fig. 1 and 2, the sum of inductances of the leader channel elements of the lightning discharge current circuit, and inductance of the ferromagnetic grounding downlead of lightning protector, is equal to the value of inductance of the lightning discharge current circuit:

$$L_{dcc} = L^i_{0-3} + L^e_{0-3} + L_{3-4} + L_{5-6} = 2280.94\,\mu\text{H} \quad (8)$$

The obtained result (8), contains uncertainties for values of lengths of the leader channels $l_{3\text{-}4}$ and $l_{5\text{-}6}$ which have been adopted when evaluating these values. Calculation of characteristics of a discharge circuit when ignoring contribution of leader channels to a total inductance, can be one of methods to estimate this share, that is $l_{3\text{-}4} = 0$, $l_{5\text{-}6} = 0$ and

$$L_{dcc} = L^i_{0-3} + L^e_{0-3} \tag{9}$$

Inductance of the capacitor $C_{TC\text{-}G}$ can be neglected due to lack of a channel form of the displacement current.

B. Capacitive parameters [6].

In the equivalent electric circuit of a discharge of a lightning into the lightning conductor (see Fig. 1 and 2), there are three capacitance:

$C_{TC\text{-}G}$ is capacitance of a thundercloud with respect to the Earth surface. Probably it is one of the most in the circuit. As a source of a current of a lightning, it is charged to very high negative electric potentials which are equal, as a rule, to several megavolts. For flat countries, probability of lightning discharges with negative polarity is equal to 90 % approximately. In these cases, counter-leaders of lightning protectors have positive polarity, physical processes of their initiation and propagation are described in [7] on the base of so-called 'DD-analogy', that is on analogy of propagation of plasma at electrical breakdown in gases in its any different initial and final stages, and on analogy of physical and chemical processes of propagation of flame fronts (deflagration) and detonation in combustible gaseous mixtures.

1) Capacitance of the micro-discharger gap

Capacitance $C_{1\text{-}2}$ between electrodes of the breakable micro-discharger can be very large in principle because when breaking the electrodes, the distance between them increases from atomic values $d = (5–10)\cdot 10^{-10}$ m (nanometers) up to micro-distances of a fraction of a millimeter. It is clear that, in this case, the capacitance between electrodes will be very large if their surface area s do not depend on a distance between electrodes $s \neq f(d)$. In any case, it does not seem to be practically possible to calculate the capacitance between electrodes at such small distances between them [6]. Therefore in case of micro-gaps, one also has to turn to evaluations, for example at the mentioned distances between electrodes, some 'macroscopic' value of their area, participating in formation of the corresponding capacitance $C_{1\text{-}2}$, is to be assumed. For example at the area $s = \pi r^2$, $r = 3\cdot 10^{-3}$ m and $d = 10^{-9}$ m , the capacitance will be equal to

$$C_{1-2} = \frac{\varepsilon_0 s}{d} = \frac{\pi \cdot 9 \cdot 10^{-6}}{4\pi \cdot 9 \cdot 10^{9} \cdot 10^{-9}} = 0.25\,\mu\text{F} \tag{10}$$

and at $d = 0.5 \cdot 10^{-9}$ m, the value of capacitance will be twice as much, that is $C_{1-2} = 0.5\,\mu\text{F}$.

One can compare the value of capacitance C_{1-2} with that of capacitance of a thundercloud having dimensions $d \approx 10^3$ m and $r \approx 10^3$ m that is

$$C_{TC-G} = \frac{\pi \cdot 10^6}{4\pi \cdot 9 \cdot 10^9 \cdot 10^3} = 0.025\,\mu\text{F} \qquad (11)$$

The comparison shows that the capacitances are in ratio $C_{1\text{-}2} \approx (10\text{–}20)C_{TC\text{-}G}$ that is, at the adopted very tentative evaluation of dimensions of a thundercloud with its height H_{TC}, these capacitances are very great, and comparable in their values. The least capacitance of the circuit is C_{4-5}, it results in the following inequality:

$$\frac{1}{C_{4-5}} >> \frac{1}{C_{TC-G}} \geq \frac{1}{C_{1-2}} \qquad (12)$$

it follows from this that the capacitance between leader channels being the least one of the circuit, shall be adopted as the equivalent capacitance of the discharge circuit.

2) *About physical processes in the gap between electrodes of the breakable micro-discharger*

At above-mentioned small distances (some nanometers) between electrodes of the breakable micro-discharger, even small potential difference in the gap created the extremely strong electric field having intensity comparable with that of atomic field $E_a = 5.14 \cdot 10^{11}$ V/m . There can occur no electric discharges in the gap because there is no gaseous medium in it because the value of the gap is far less than mean distances between molecules of ambient atmospheric air. In such small gaps, conditions of density of a gaseous medium are similar to those of a deep vacuum.

Autoelectronic emission from the electrode - cathode 2 with transport and absorption of the emission electron flux by the electrode - anode 1 (see Fig. 2) will be the first of possible physical processes at the given value of electric field strength in the gap. However, the electron flux only is not sufficient for formation of a current-conducting plasma medium in the gap; for this, it is necessary also to provide a flux of positive ions of the anode into it. A physical cause of such a possible, and probably existing, ion flux can be 'field evaporation of metal' [8], or, in other terms, its 'Coulomb burst' [9]. These mechanisms have the same physical base in essence. Specifically, in a strong electric field about several volts per Angstrom unit, superficial electrons of the anode metal are being drawn deep into the heart, baring the superficial ions of the metal, and causing their mutual Coulomb repulsion, decay and evaporation from the surface as well as further propagation of the front of the ion evaporation wave into the heart of the metal; or, at some way of a sufficiently fast release of superficial electrons of metal, causing forced emission of electrons outwards from it, and as a result, also baring the ion frame of the metal lattice, when within the surface layer, only forces of Coulomb repulsion remain – it is 'Coulomb burst'. For this purpose, they act on a metal surface either by powerful laser radiation of the UV band enabling penetration of radiation into an appreciable depth of a metal, or by means of an electric burst of small wires under such a fast condition when the heating to high temperatures, of metal electrons only is provided but a previous low temperature of ions is retained.

In future, it will have to find out which mechanism of emission of anode metal ions is realized in fact. Probably it is caused by a powerful flux of auto-electrons from the cathode followed by 'Coulomb burst' of the anode, or, probably a thin layer of the anode metal having an extremely strong electric field near the anode at emission of ions due to 'field evaporation of metal' of the anode. Simultaneous occurrence of the mentioned phenomena which is similar to thermal autoelectronic emission, and resulting in formation of an electron-ion plasma in the gap of the micro-discharger, is also probable.

At a sufficiently sharp drop of voltage across the micro-gap, a current through the plasma tends to zero value, and processes of cooling of the plasma, and of its decay due to different physical mechanisms of loss of charged particles (diffusion of electrons, their recombination with metal ions and transit onto the anode, adhesion to negative ions), and of loss of energy (thermal conductivity: electronic, ionic and radiant). One should take into consideration possibility of presence of a high-frequency mode of the mostly reactive *LC*-circuit of a lightning discharge current when the voltage across the gap with the plasma changes its polarity, and the current passes through zero causing decay of the plasma and its subsequent periodic formation. Taking into account this sufficiently evident fact, one can also consider a mode of periodic extinction of the plasma at every instant of a passage of the current through zero value. In other words, it is sufficient to create a micro-gap once, and then, in the circuit of the ferromagnetic grounding downlead of the lightning protector, there spontaneously appear periodic ignitions and extinctions of the plasma in the gap which are coordinated with high-frequency voltage oscillations in the discharge circuit of the lightning, even if the stage of appearance of its leader channels has not commenced yet. Even at their absence, there exist inductive-capacitive parameters of the grounding downlead, its capacitance with regard to the thundercloud, taking into account the mirror reflection of all the structural components of the circuit, see Fig. 1. Such a mode imposed by high-frequency voltage oscillations in the lightning current circuit, of periodic appearance and disappearance of a plasma in the gap of the breakable micro-discharger, can be designated by auto-resonant state of a discharged circuit of lightning current because of presence of a breakable micro-discharger in it.

3) Capacitance with respect to the Earth, and to a thundercloud

To prove possibility of a high-frequency mode of the circuit of the lightning discharge current, it is necessary, in addition to inductance data, to determine the corresponding capacitance parameter C_{4-5} between the descending and rising leaders of the lightning (see Fig. 4).

According to [6], capacitance of a wire of finite length l, diameter $2a$ and height h of the wire extremity over the plane 0 – 0 (see Fig. 5) is calculated by equation

$$C' \approx \frac{2\pi\varepsilon_0 l}{\ln\frac{l}{a} - D_2} \qquad (13)$$

where parameter D_2 depends on the ratio (h/l).

At that, within the broad limits of change of this ratio $0.332 < h/l < 0.475$, the mean value of the parameter is equal to $D_2 \approx 0.4$ though the total range of values of the ratio is very great $0.02 < h/l < \infty$, at this, the parameter varies within the limits

$0.928 > D_2 > 0$ accordingly.

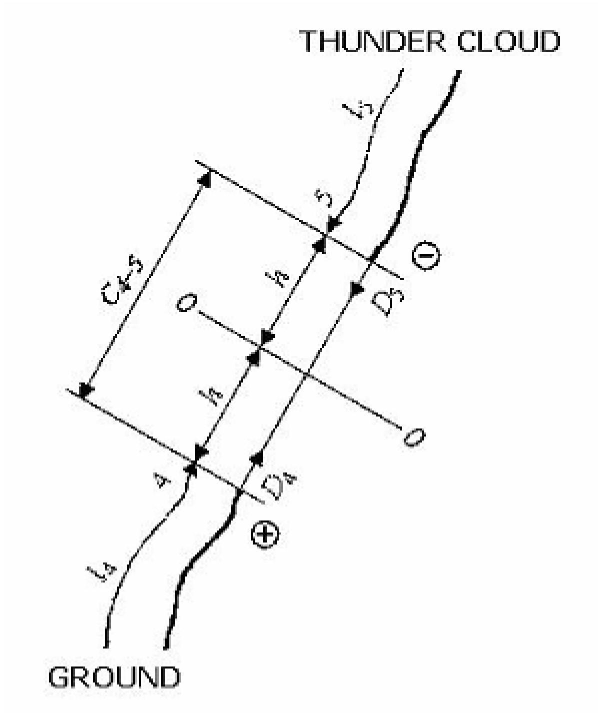


Fig. 4. The simplified structure diagram of counter-leaders with capacitance between them C_{4-5} being calculated accordingly [6] with respect to the neutral mutual-reflecting plane 0 – 0. The capacitance is calculated at given instant values of lengths of leaders l_4, l_5, and distances between them $2h$.

At the instant of initiation of descending lightning leader, $l(t = t_0) = 0$ and $h(t = t_0) = H_{TC}$, so that $h(t_0)/l(t_0) \to \infty$ and $D_2 = 0$. On the contrary, at $l(t) >> h(t)$, $h(t)/l(t)$ is very small value, and $D_2 \to 1$.

1. The capacitance value with respect to the Earth, of a leader channel of a lightning having the length $l = 100$ m , radius $a \approx 5\cdot10^{-3}$ m and the height of the thundercloud $H_{TC} = 10^3$ m, so that $h/l = 9 \to D_2 = 0.34$, is evaluated to be $C' \approx 435\,\text{pF}$ according to (13). Capacitance between the leader channels (see Fig. 4) will be half as much because it is equivalent to the two capacitances C' series-connected [6], that is $C_{4-5} = (1/2)C' = 217.5\,\text{pF}$

2. The value of capacitance of the downlead with respect to the thundercloud at $l = 15$ m, $a = 4\cdot10^{-3}$ m, $h = 935$ m , is evaluated by the same equation (13) at $(h/l) = 65.7 \to D_2 = 0.2$, that is $C_{3-6} = 52\,\text{pF}$.

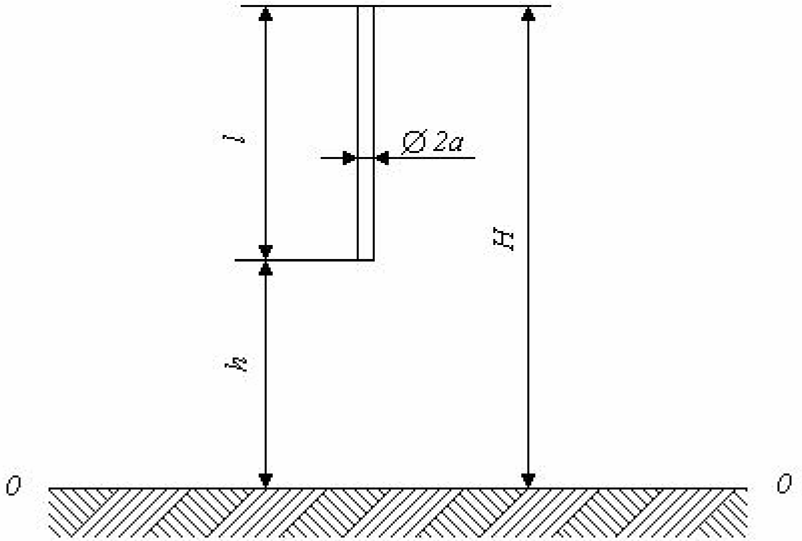


Fig. 5. The idealized diagram for calculation of capacitance of a rod having a circular cross section, over the plane 0 – 0, similar to that plane on Fig. 4.

4) Some characteristics of parameters against time

The relationship $C' \approx C'(l, l/a)$ is found to be mainly determinative, at that, for a given height of a thundercloud H_{TC} , the equation

$$l(t) + h(t) = H_{TC} \tag{14}$$

is true. This equation is valid for any instant of time t . If, as it follows from an experiment, the speed of a leader front is practically constant against time $D_l(t) = const$, then, at the values $l(t) = D_l t$ and $h(t) = H_{TC} - l(t) = H_{TC} - D_l t$, for the ratio (h/l), it can be written

$$\frac{h(t)}{l(t)} = \frac{H_{TC} - D_l t}{D_l t} = \frac{H_{TC}}{D_l t} - 1 = \frac{M}{t} - 1 \tag{15}$$

where $M = H_{TC} / D_l$ is a new constant against time. The rate of change of the ratio, in contrast to the speed of a leader front, is not constant against time but varies in inverse proportion to the time squared

$$\frac{d}{dt}\left[\frac{h(t)}{l(t)}\right] = -\frac{M}{t^2} \tag{16}$$

For example if the height of a thundercloud $H_{TC} \approx 10^3$ m and speed of the lightning leader $D_l \approx 2 \cdot 10^4$ m/s then $M = 5 \cdot 10^{-2}$ s . The constant M has the sense of the time which is needed for the leader front to travel the distance between the thundercloud and the earth surface, that is the distance H_{TC} . It is quite possible that the mentioned parameter functions against time, which are of major importance during processes of propagation of lightning leader channels, are of less importance to determine initial conditions for the supposed discharge circuit of a lightning when its leader stage has not started yet.

III. Parameters of an Oscillatory Circuit of a Lightning Discharge, and Its Resonant Condition

Having the evaluative values of reactive parameters of the circuit of a lightning discharge current at $C_{dcc}^{eq} = C_{4-4} = 217.5\,\text{pF}$ and $C_{dcc}^{eq} = C_{3-6} = 52\,\text{pF}$ as well as $L_{dcc}^{eq} = 2280\,\mu\text{H}$ and $L_{dcc}^{eq} = 32.3\,\mu\text{H}$, the main characteristics of the oscillatory circuit are determined as follows:

A. *Characteristic impedance of the circuit* $\rho = \sqrt{L/C}$:

a) Taking into account only the inductance and capacitance of the current-carrying grounding downlead $\left(L_{dcc}^{eq} = 332.3\,\mu\text{H}, \quad C_{dcc}^{eq} = 52\,\text{pF}\right)$, $\rho_{1-3} = 2.52\,\text{k}\Omega$;

b) Taking into account the inductances and capacitances of the lightning leader channels $\left(L_{dcc}^{eq} = 2280.94\,\mu\text{H}, \quad C_{dcc}^{eq} = 217.5\,\text{pF}\right)$, $\rho_l = 3.24\,\text{k}\Omega$

B. *Natural frequency of the circuit* $f = \left(2\pi\sqrt{LC}\right)^{-1}$ *is accordingly equal to:*

a) $f_{dcc}^{1-3} = 1.23\,\text{MHz}$; b) $f_{dcc}^{l} = 0.23\,\text{MHz}$.

The circular frequencies are equal accordingly to $\omega_{dcc}^{1-3} = 7.73 \cdot 10^6$ rad/s and $\omega_{dcc}^{l} = 1.45 \cdot 10^6$ rad/s .

Thus, in the plasma of the gap of the breakable micro-discharger, the current circuit is being opened and closed 1.23–0.23 millions times per second, and therefore the capacitance between electrodes 1 - 2 is automatically controlled (created and bridged by the plasma) with the frequency of the lightning discharge circuit, opening at zero current, and charging at the plasma decay. Such a condition of the micro-discharger can be named 'autoresonant condition', since, at that, the switching is realized automatically with a frequency of the lightning discharge circuit. That is why, at presence of a breakable micro-discharger in the circuit of the grounding downlead of the lightning protector, the voltage across the lightning diverter, and that across the front of a formed descending leader, will rise according to a pattern of voltage resonance in series-connected reactive elements of a lightning discharge circuit.

Condition for resonance in the circuit, as it is known, can be written as equation of its reactance:

$$x_L = \omega L_{dcc} = x_C = \frac{1}{\omega C_{dcc}} \tag{17}$$

For a circuit without leader channels, at values $\left(L_{dcc}^{eq} = 332.3 \cdot 10^{-6}\ \text{H},\quad C_{dcc}^{eq} = 52 \cdot 10^{-12}\ \text{F}\right)$, the resonance conditions, accordingly (17), are determined by resonant frequency of the circuit $\omega_0 = \omega_{dcc}^{(1-3)}$ that is by the value $\omega_{dcc}^{(1-3)} = 7.73 \cdot 10^6\ \text{rad/s}$ evaluated above.

It is known that, at a voltage resonance, the values of voltages across the inductance and capacitance can significantly exceed the voltage across the circuit terminals that is between electrodes 1 and 2 of the micro-discharger. The latter voltage can be assumed to be equal to the voltage drop across the impulse resistance of the grounding R_i. The circuit impedance z, at $x = x_L - x_C = 0$, is minimal and equal to $z = \sqrt{R_i^2 + r^2} = R_i$, and the current i, at a given voltage $\Delta\varphi_{TC-G}$, reaches the maximum value $i = \Delta\varphi_{TC-G} / R_i$. In ideal theoretical case, at $R_i = 0$, the circuit impedance is also equal to zero under a resonant condition, and the current is infinitely great at any finite value of voltage $\Delta\varphi$. So exactly the voltage across the inductance and capacitance are infinitely great.

It follows from the equation (17) that a resonance can be reached varying either the frequency of voltage of the source (frequency of the lightning current circuit) or the parameters of the circuit – inductance and capacitance. Attention shall be paid once more to a determinative role of a breakable micro-discharger for assurance of such a frequency of switching which is always equal to resonance (natural) one of the circuit of the lightning discharge current, even at a subsequent essential change of reactive parameters of the circuit in the course of propagation of a plasma formed at a breakdown of the air by a lightning. Such an auto-coordinated resonant condition is explained by an instant conformity of natural frequency of the circuit to switching in the micro-discharger.

The resonant condition in the circuit is assured, first of all, in that case, if the characteristic duration of changes of circuit parameters considerably exceeds characteristic time needed for achievement of resonant condition. For example if the leader speed is assumed to be equal to D_l, and the length of its propagation to 100 diameters of the leader channel $l_l \approx 100 d_l$, the inductance and capacitance of the leader are supposed to be of small variance, then the value d_l / D_l can be assumed as the characteristic time of change of the leader parameters. This time must exceed the characteristic time of development of resonance $\sim 1/\omega_c^l$. For example, at the experimental values $D_l \approx 2 \cdot 10^4\ \text{m/s},\quad d_l \approx 8 \cdot 10^{-3}\ \text{m}$ and $\omega_{dcc}^l = 1.45 \cdot 10^6$, one can obtain:

$$\frac{l_l}{D_l}=\frac{100d_l}{D_l}=\frac{8\cdot 10^{-1}}{2\cdot 10^4}=4\cdot 10^{-5}\ \mathrm{s}\geq\frac{1}{\omega_{dcc}^l}=0.69\cdot 10^{-6}\ \mathrm{s} \tag{18}$$

The even greater assurance of initiation and development of a resonance will be in the lightning current circuit at absence of leader process of propagation of a lightning discharge when there are no reactive components of this circuit which are mobile and variable in space and time. In this case, 'time of awaiting' of a resonant condition of a discharge process tends to infinity, and always exceeds the time needed for development of resonance phenomena.

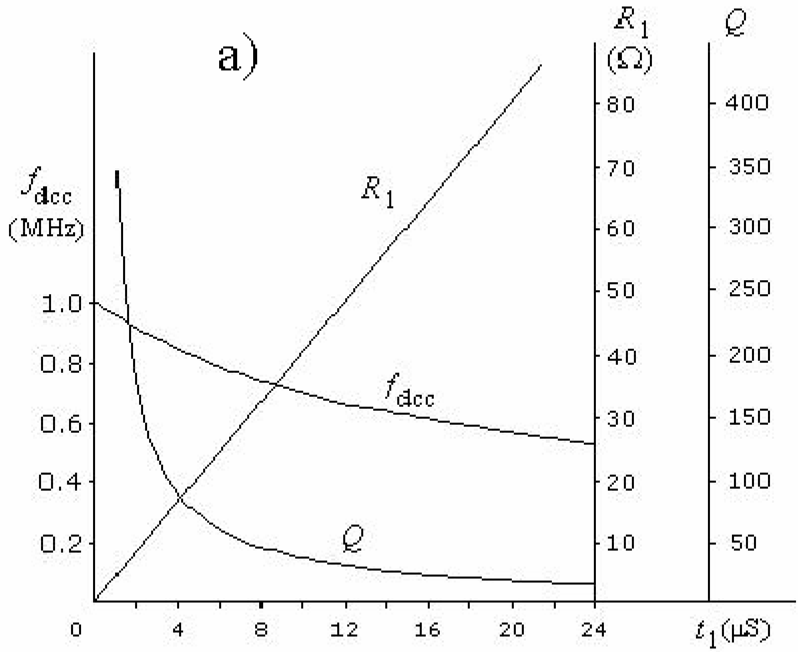
Considering clauses for development of a voltage resonance to be realized in the time, it is necessary to evaluate their qualitative characteristics which is associated with a quality factor of an oscillating circuit. A quality factor Q is determined as a ratio of the voltage across the equivalent inductance L_{dcc}^{eq} and capacitance C_{dcc}^{eq} to the voltage φ_{1-2} arising across the capacitance C_{1-2} at switching when there is a voltage resonance.

$$Q=\frac{\varphi\left(L_{dcc}^{eq}\right)}{\varphi_{1-2}}=\frac{\varphi\left(C_{dcc}^{eq}\right)}{\varphi_{1-2}}=\frac{\rho i}{R_i}=\frac{\rho}{R_i} \tag{19}$$

As it is known, Q is named not only 'quality factor' of a circuit but also its 'resonance factor'. Besides reactive components of a circuit, its quality factor essentially depends on an active parameter – impulse resistance of the grounding R_i .

For example, in case of a permafrost soil, $R_i \rightarrow \infty$ and the circuit quality factor (19) is almost equal to zero, and no voltage resonance has to be expected in the lightning current circuit (probably this effect of absence of resonance is observed in the high-voltage networks of JSC 'Tyumenenergo' where low level of lightning proofness of overhead lines, and low reliability of power supply of the oil and gas company 'Oktyabrskneftegas' take a place). If normal soil conditions with the specified value $R_i = 10\,\Omega$ are assumed then the quality factor, at $\rho_{1-3} = 2.52\,\mathrm{k\Omega}$, is equal to very great value $Q = 2.52\cdot 10^2$, and the voltage across the inductance (lightning diverter) increases at the resonance by a factor of 252, at the frequency $f_{dcc}^{1-3} = 1.23\,\mathrm{MHz}$ created by the breakable micro-discharger. In this connection, the breakable micro-discharger can be named 'high-frequency generator in a lightning discharge current circuit' exiting a voltage resonance in it.

Fig. 6 shows dependence of quality factor of an oscillatory circuit of a lightning discharge current on time taking into account the increase of resistance of leader channels at their development. It follows from the figure that at initiation of leader channels when their resistances are close to the initial zero values, voltage resonance is guaranteed more surely. Just at the given initial instant of origin of leader channels, their orientation to a lightning diverter is determined with necessary selectivity of the path at this voltage autoresonance in the oscillatory circuit of a lightning discharge current.



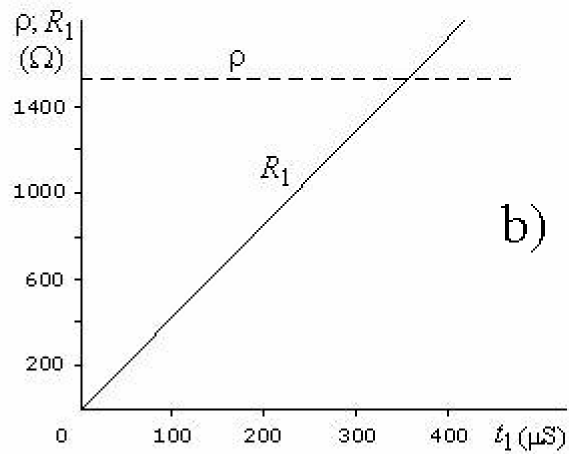


Fig. 6. Dependence of quality factor $Q(t)$ of a lightning discharge current on time duration t of forming and propagation of a lightning discharge in its leader stage reflected by the increase of the resistive parameter $R_l(l(t))$ of the leaders at their lengthening in propagation process.

For evaluation of absolute values of overvoltages at the resonance, it is necessary to evaluate the initial voltage φ_{1-2}. This voltage can approximately be adopted assuming the distance between electrodes 1 - 2 to be $d_{1-2} \approx 10^{-4}\,\mathrm{m}$, and the electric field strength to be $E_{1-2} \approx 100\,\mathrm{kV/cm} = 10^{7}\,\mathrm{V/m}$. Then the sought voltage will be equal to $\varphi_{1-2} = E_{1-2} d_{1-2} = 10^{3}\,\mathrm{V}$, and the resonant overvoltage across the lightning diverter to

$$\varphi_{L_{dcc}^{eq}} = Q\varphi_{1-2} = 252 \cdot 1\,\mathrm{kV} = 252\,\mathrm{kV}\,. \tag{20}$$

Such a value of the resonant overvoltage will unconditionally affect both the initial start of the counter-leader of the lightning diverter, and the descending leader of the lightning, that is across the very capacitance $C_{dcc}^{eq} \approx C_{4-5}$, there will also occur an overvoltage resonance with the same value of 252 kV.

IV. Effect of an Essential Increase of Disruptive Distance, Observed on a Model of a 'Rod-Plane' Gap with an In-Series Breakable Micro-Discharger

Fig. 7 shows the diagram of the model for demonstration of the effect being investigated, of electrical breakdown of an air gap at insertion of the breakable micro-discharger into a cleavage of the circuit. The effect of essential increase (by a factor of 2–3) of the disruptive distance between the positive rod electrode and the plane one, should be explained by the above considered resonant conditions of the discharge circuit.

Capacitance of the rod with regard to the plane is also being evaluated by equation (13) at the known values $l = 0.1\,\mathrm{m}$, $a = 5 \cdot 10^{-3}\,\mathrm{m}$; at the ratio $h/l = 4 \cdot 10^{-2}/10^{-1} = 0.4 \rightarrow D_2 = 0.604$, it results in

$$C' = \frac{2\pi\varepsilon_0 l}{\ln\frac{l}{a} - D_2} = 2.32\,\mathrm{pF} \tag{21}$$

Taking into account the mirror reflection in an ideal conducting plane, the capacitance will have the value $C_{r-p} = (1/2)C' = 1.16\,\mathrm{pF}$. The inductances of the parts of the circuit, according to equation (6)

$$L_e = \frac{\mu_0 l}{2\pi}\left(\ln\frac{2l}{a} - 1\right) \qquad (22),$$

have the following values: for the rod $\left(l_{2-3}=0.1\,\text{m},\quad a=5\cdot10^{-3}\,\text{m}\right)$ $L^{e}_{2-3}=0.054\,\mu\text{H}$; for $l_{1-6}+l_{4-5}=0.14\,\text{m},\quad l_{5-6}=0.15\,\text{m},$ at the mean value $a=2\cdot10^{-3}\,\text{m}$, $L^{e}_{1-6}+L^{e}_{4-5}=0.448\,\mu\text{H}$. And $L^{e}_{5-6}+L^{e}_{1-4}=0.12\,\mu\text{H}$.

Then the total inductance will be equal to

$\Sigma L^{e}=0.054+0.448+0.12=0.622\,\mu\text{H}$.

The natural frequency of the discharge circuit of the model will be equal to

$$f_{dcc}=\left[2\pi\sqrt{C_{r-p}\left(\Sigma L^{e}\right)}\right]^{-1}=187\,\text{MHz}$$

where C_{r-p} is the capacitance between the rod and plane. The circular frequency $\omega_{dcc}=2\pi f_{dcc}=1.175\cdot10^{9}\,\text{rad/s}=\omega_{0}$. The condition of the voltage resonance in the circuit, according to (17), is realized at the resonant natural frequency ω_{0}.

The characteristic impedance of the circuit is equal to

$$\rho=\sqrt{\frac{\Sigma L^{e}}{C_{r-p}}}=732\,\Omega$$

The active parameter of the circuit is absent in an explicit form. However its value can be evaluated taking into account the resistance of the connecting conductors. If these copper conductors have the mean diameter of the cross-section $d_{cc}=10^{-3}\,\text{m}$ and the length $l_{cc}\approx3\cdot10^{-1}\,\text{m}$, then, at specific resistance of copper $\rho_{cop}=0.017\,\mu\Omega\cdot\text{m}$, the resistance of the connecting conductors will be equal to

$$R_{cc}=\frac{\rho_{cop}l_{cc}}{\pi\left(2d_{cc}\right)^{2}}=0.00648\,\Omega\,.$$

If R_{cc} is the only active parameter of the discharge circuit, and the radiation resistance can be neglected, though at high frequencies, it can be the significant component of active losses of the circuit, the quality factor of the circuit will be very great

$$Q=\frac{\rho}{R_{cc}}=\frac{732}{648\cdot10^{-5}}=1.13\cdot10^{5}\,,$$

and it proves the quality of resonance in the circuit to be high.

For evaluation of overvoltages across the rod, it is necessary to determine the voltage φ_{1-2} across the electrodes of the breakable micro-discharger. This voltage can be evaluated assuming the distance between the electrodes $d_{1-2}\approx10^{-3}\,\text{m}$, and the electric field strength in the gap about $E_{1-2}\approx30\,\text{kV/cm}=3\cdot10^{5}\,\text{V/m}$, that is

$$\varphi_{1-2} \approx 3 \cdot 10^5 \cdot 10^{-3} = 3 \cdot 10^2 \text{ V} .$$

Then the resonant overvoltage, as an 'expected' quantity will have the value

$$\varphi_L = Q \cdot \varphi_{1-2} = 1.13 \cdot 10^5 \cdot 3 \cdot 10^2 = 3.39 \cdot 10^7 = 33.9 \text{MV}$$

that exceeds all the possible limits of dielectric strength of the gap l_{3-4}. It is also clear that such a great value of the overvoltage, exceeding even the potential level of the lightning itself, undoubtedly will result in so called 'repetitive ignitions' of the discharge plasma, and the level of the resonant overvoltage will be limited by a remaining potential of chopping a voltage on the electrically weakest point of whole system of the insulating construction. The great value of the resonant overvoltage on the model having the gap 'rod – plane' with the breakable micro-discharger in series, entirely explains the essence of action of this discharger, and creates possibilities for design solutions to matters of improvement of lightning protection with separately standing rod lightning protectors.

It can be deemed that the experiment on model gives a satisfactory explanation for the effect of increase of disruptive distance at insertion of a breakable micro-discharger into a discharge circuit. Disappearance of this effect at change of the positive polarity of the rod to the negative one, is explained by the known 'polarity effect' when dielectric strength of the air increases by a factor of 2–2,5 in abruptly non-uniform electric field; a physical essence of the latter effect is considered in [7]. The polarity effect is mainly caused by the significantly more losses of free electrons from the ionization region as a result of their diffusion, and especially of their drift in the external electric field. The latter kind of the losses is direct losses of electrons due to their drift movement in an electric field of negative polarity at all the streamer and leader stages of a breakdown, because such a negative polarity field bring out electrons from the region of their ionization formation, in contrast to a positive field which holds them in the ionization region at the significantly surer formation of plasma of breakdown of gases [7]. Such intensive drift losses of free ionization electrons lead to elimination of possibility of breakdown even under great resonant overvoltages.

V. The Experimental Data on Disruptive Voltages in the Air Gap

In the test station of the All-Russian Electrotechnical Institute, on the installation having the rectified high voltage up to 300 kV, experiments on a breakable micro-discharger were carried out in conformity with the diagram, see Fig. 7.

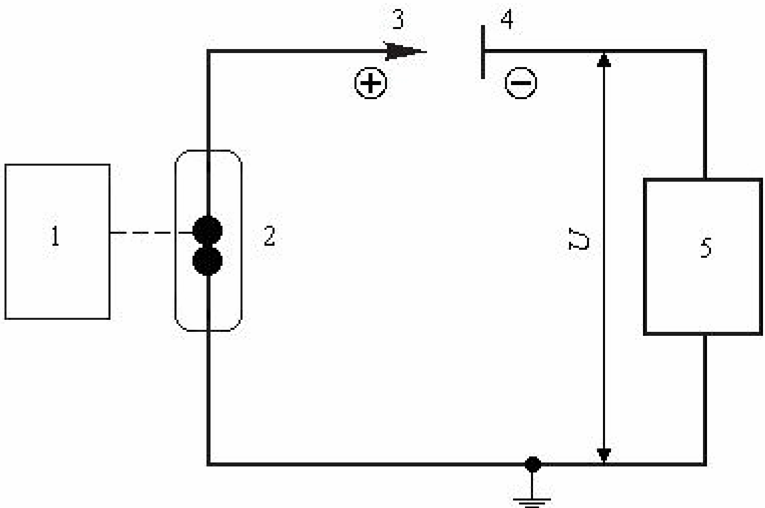
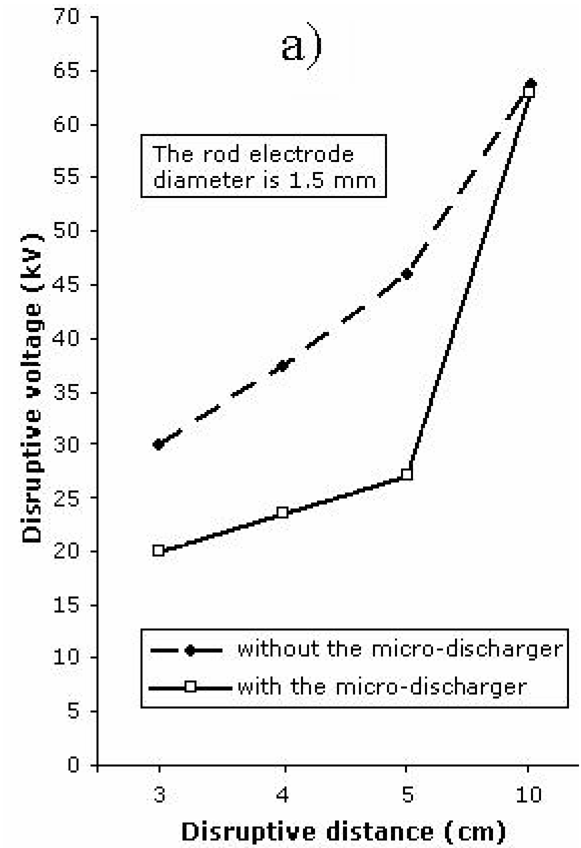
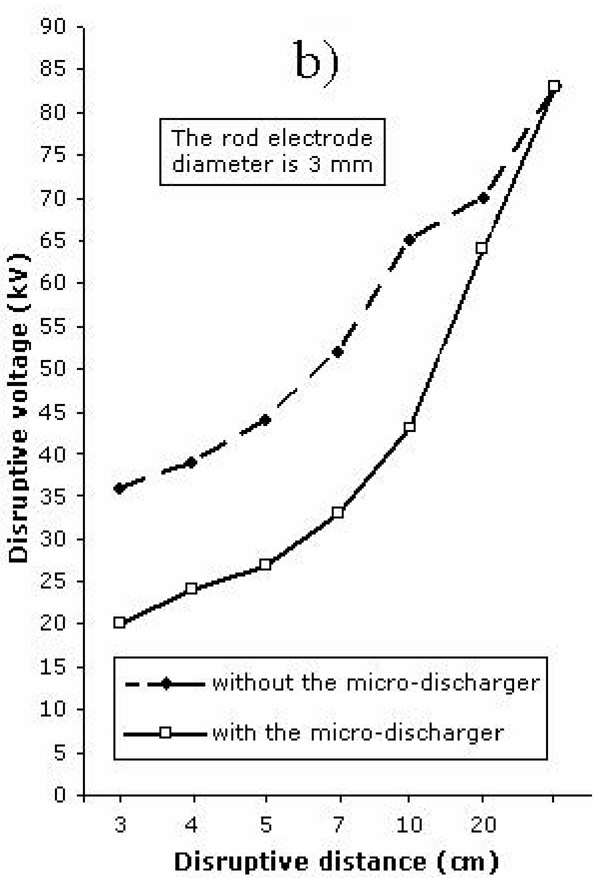


Fig. 7. The electric circuit of the system 'rod – plane – micro-discharger'
1 is the drive of the micro-discharger
2 is the micro-discharger
3 is the rod
4 is the plane
5 is the voltage source
U is the potential difference

The main experimental data on disruptive voltages obtained by us in the gap 'rod – plane' are shown in Fig. 8. It follows from this that disruptive voltages generated by the method of auto-resonance excitation of the discharge circuit are essentially less than 50 % disruptive voltages. From Fig. 9, it follows that the above evaluated frequency of auto-resonance condition is close to the measured auto-resonance frequency.


a)
The rod electrode diameter is 1.5 mm
Disruptive voltage (kV)
Disruptive distance (cm)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
3
4
5
10
without the micro-discharger
with the micro-discharger


b)
The rod electrode diameter is 3 mm
Disruptive voltage (kV)
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
3
4
5
7
10
20
Disruptive distance (cm)
without the micro-discharger
with the micro-discharger

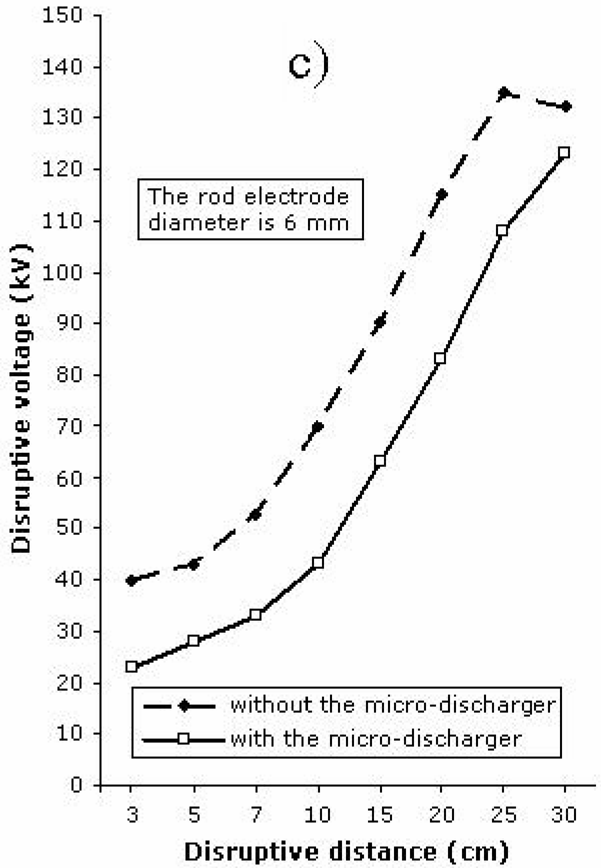


Fig. 8. The comparison characteristics of disruptive voltages for typical gaps 'rod-plane' having different sizes of the rod electrode. The voltages were evaluated as $U_d = U_{50\%} - 3\sigma$, where

$U_{50\%}$ is a value of the disruptive voltage corresponding to probability of 50%;

σ is the mean square deviation of the disruptive voltage, from a 50% value.

These disruptive voltages were obtained accordingly the above described method with excitation of auto-resonance conditions in the discharge circuit by means of the micro-discharger.

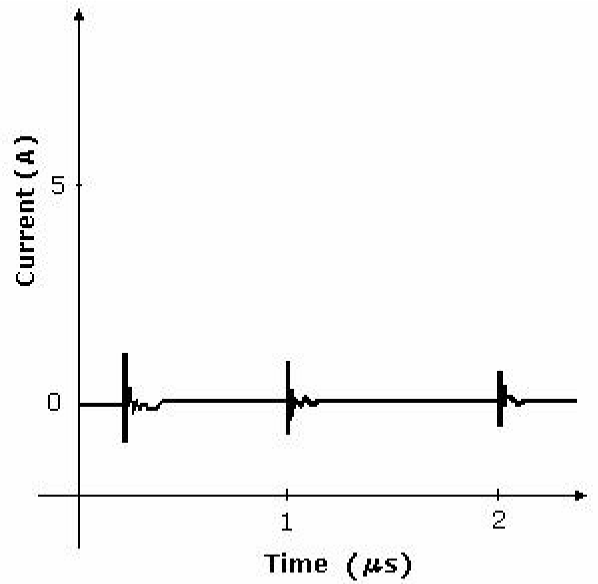


Fig. 9. Oscillogram of current in the discharge circuit before occurrence of a breakdown

VI. Conclusion

On the base of the results obtained and adopted methods of investigation, the following deductions can be done:

1. A breakable micro-discharger in a cleavage of a grounding downlead of a lightning rod is an essential structural factor for active control of orientation of a lightning towards a lightning protector.

2. The effect of orientation of a lightning, and the increase of disruptive distances can be explained by occurrence of a voltage resonance mode in the circuit of the lightning discharge current.

3. The increase of the disruptive distance between the electrodes 'positive rod – plane' by a factor of 2–3, is explained by a voltage resonance in the series *LC*-circuit of the model of a discharge gap, occurring when having inserted a breakable micro-discharger into the discharge circuit of the gap.

4. It has been established that there exist the effect of auto-resonance condition in a discharge circuit of a lightning, and of a model of a discharge gap. This condition arises due to switching properties of the micro-discharger, and occurs even when changing reactive parameters of discharge circuits of a lightning and of a model.

5. Disappearance of the effect of increase of a disruptive distance at negative polarity is explained by the known 'effect of polarity' [10], of which physical nature is considered in [7].

6. There is a need for a practical use of the effect of increase of disruptive distances by means of application of breakable micro-dischargers in structures of separately standing lightning rods.

7. Theoretical evaluative analysis, simulation, and the experimental data have proved the efficiency of this new active method of improvement of lightning protection to be high.

REFERENCES

[1] Стекольников И.С. Природа длинной искры. М.: Изд-во АН СССР 1960. -271 с., ил.

[2] Бобров Ю.К., Шостак В.А. Электродинамика лидерного разряда молнии // Тез. докл. I Всесоюзн. Научн-техн. Конф.: Безопасность полета в условиях опасных внешних воздействий. Киев, 1981. С.16-17.

[3] Бобров Ю.К. Электродинамика лидерного канала разряда // Техн. электродинамика. 1991. №3. С. 29-32.

[4] Бобров Ю.К., Сорокин А.В. Моделирование переходного процесса в лидерном канале электрического разряда // Техн. электродинамика. 1986. №5. С.12-18.

[5] Калантаров П.Л., Цейтлин Л.А. Расчет индуктивностей: Справочная книга. – 3-е изд., перераб. и доп. Л.: Энергоатомиздат. Ленингр. отд-ние, 1986. – 488 с., ил.

[6] Иоссель Ю.Я., Кочанов Э.С., Струнский М.Г. Расчет электрической емкости. – 2-е изд. перераб. и доп. – Л.: Энергоиздат. Ленингр. отд-ние, 1981. – 288 с., ил.

[7] Дьяков А.Ф., Бобров Ю.К., Сорокин А.В., Юргеленас Ю.В. Физические основы электрического пробоя газов / Под ред. А.Ф. Дьякова. – М.: Издательство МЭИ, 1998. – 400 с., ил.

[8] Бобров Ю.К., Сорокин А.В. Испарение металла и поверхностные процессы в сильных полях. В кн. Физико-технические проблемы передачи электрической энергии. Сб. научн. статей, Выпуск 1, под редакцией А.Ф. Дьякова. – М.: Издательство МЭИ, 1998 г., 325 с., ил. (С. 254 – 317).

[9] Рухадзе А.А., Юсупалиев У. О возможности кулоновского взрыва металла, ЖТФ, т.74, в.7, 2004, С.127 -128.

[10] Дмохоская Л.Ф., Ларионов В.П., Пинталь Ю. С., Разевиг Д.В., Рябкова Е.А. Техника высоких напряжений. Учебник для студентов электротехнических и электроэнергетических специальностей вузов. Под общей ред. Д.В. Разевига. Изд. 2-е, перераб. и доп. М., «Энергия», 1976. 488 с., с ил.