Experimental modeling of lightning strike in soil

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Abstract. The results of full-scale experiments of lightning current flow through soil are presented. With the pulse high voltage generator the current of several tens of kiloamperes amplitude was created in soil on the length up to 70 m. The measured current and voltage profiles, the calculation of resistance and its profile between electrodes in soil are presented. The investigation of resistance value behavior was performed in case of several electrical breakdowns.

1. Introduction

Extent of electrification of the country reflects its industrial development therefore lightning protection and systems of protective grounding of power lines and substations is an actual problem as capacities of generation of the electric power constantly grow, and it need to be transformed and transferred with high degree of reliability. Especially the problem is particularly acute in those countries that have rather big territory and a big variety of soils with various size of specific conductivity is noted: Russia, China, United States of America, Australia and others. Influence of specific conductivity of soil is obvious: at low conductivity the value of resistance of grounding is high therefore at a lightning stroke with amplitude of current in several tens kiloamperes through grounding in system an overvoltage in hundreds of kilovolts can occur. Emergence of such overvoltage can lead to breakdown of a surface of insulators, isolation destruction, short circuit, destruction of conducting elements of the transmitting or transforming system. Strike of a lightning in an overhead ground wire of a power line or in the lightning rod near substation can be an example. Recently also actual is a question of impact of current of a lightning discharge on electronics that is used even more often at construction of so called smart grids.

Investigations of lightning influence on grounding systems began from the first half of the twentieth century [1–5] when there was an intensive electrification of the countries, and operating experience of systems of power networks has been collected. Early researches [1, 2] have shown essential distinction between stationary and non-stationary behavior of electric parameters on an electrode in soil. The further pilot study [5] has confirmed the observed effect at various configurations of the electrodes placed in soil and for various types of soil. Later several researchers have developed models that take into account this behavior [3, 6–9]. It should be noted that the majority of tests is carried out in laboratory conditions which results, obviously, can't be transferred to soil of the concrete region of country where it is planned to build an object of electrical system. It is connected with the fact that too many parameters have influence on the value of grounding resistance: structure, dispersion, type and amount of inclusions, humidity, temperature and many others. Nevertheless, qualitative results reflect a tendency of change of soil resistance during electrical discharge:

(i) with increase in current the resistance of grounding decreases,

(ii) with current of amplitude in several-kiloamper breakdown with formation of plasma channels of the reduced resistance is possible,

(iii) there is delay time between the beginning of increase of potential on the grounding electrode and the beginning of breakdown that depends on many parameters, for example, humidity [10, 11],

(iv) in experiments the effect of memory for the soil at the subsequent breakdowns [12] is not observed.

Ensuring reliable grounding at the concrete region of construction of object (power line or substation, for example) requires carrying out the full-scale tests considering the characteristic size (volume) of the soil involved in a lightning discharge, structure of the soil (including, humidity), temperature, etc. Usually building of new objects happens far from the city, so it is necessary to create laboratory in the place or to create mobile laboratory that can move from place to place and make necessary tests. One of types of such mobile laboratories are laboratories with artificially induced lightning (rocket-and-wire technique) [13]. In this work the mobile test system based on the generator of pulse voltage, which is capable to work independently in field conditions and to create a discharge current with amplitude up to 100 kA, is used. This is further work in the Moscow region on research of spreading of current of a lightning in soil [14].

2. Mobile test system

For research of electrophysical properties of soil with assistance of Joint-Stock Company "Federal Grid Company of Unified Energy System" and Stock Company "G M Krzhizhanovsky Power Engineering Institute" in 2010–2013 the mobile test system on the basis of the generator of pulse voltage (GPV) has been developed and made. The system is capable to conduct autonomous field researches within 10 days. GPV is made according to the scheme of the high-voltage generator of Arkadiev–Marx in which high-voltage capacitors (N is the number of capacitors) with a capacity of C each are charged in parallel connection up to U_c voltage (U_c is the charge voltage), and release of the saved-up electrical energy happens at their series connection by means of high-speed switchers (dischargers, their quantity makes $N - 1$). At the same time the output amplitude of voltage U_0 can be estimated by the value NU_c, and generator capacity—by $C_0 = C/N$. The design is chosen in such a way that N can be varied, and $N = 60$ is the maximum value with corresponding value $C_0 = 1.4$ μF. Independently the value U_c can be varied up to maximum value of 40 kV so the maximum value U_0 can be 2.4 MV, and GPV stores electrical energy of 4 MJ. The generator is designed to operate with a load resistance R from 10 Ω to 100 Ω and with inductance of the discharge circuit 200 μH. In these ranges of electrical parameters the current does not change its sign and the current profile corresponds to the lightning current discharge. With these parameters it is possible to obtain amplitude-time characteristics of a discharge close to the parameters of the lightning current discharge.

During electrical breakdown of soil the current and voltage oscillograms in the discharge circuit are registered. For these measurements voltage dividers, shunts, Rogowski, digital oscilloscopes with a bandwidth of 100 MHz and a sampling rate of 1 GS/s are used. The discharge circuit is formed by two copper plating metal rods with a diameter of 16 mm and a length of 1.5 m, placed in the ground. The distance between the rods was of the 50 m and 70 m (length change associated with the study of soil memory effect). Tests were conducted in the summer (July) in the Moscow region in Troitsk. Before beginning the tests addition investigations have been conducted, which showed the absence of underground cables or other conductive objects in the soil.

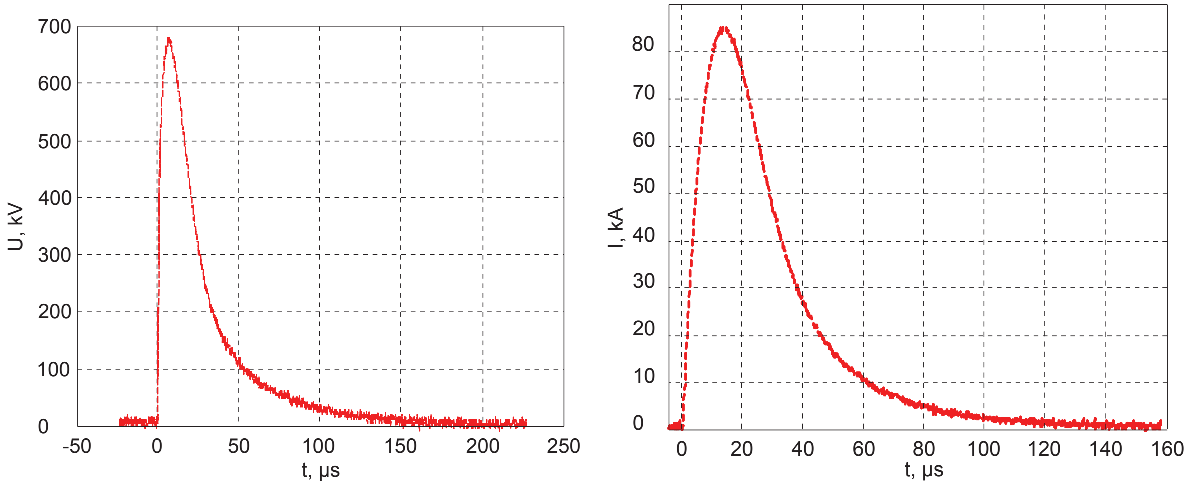

Figure 1. Voltage (from the left) and current (from the right) between grounding electrodes at experiment No. 1128.

Tests were carried out in two stages. In the first stage the tests with relatively high amplitude of current (80 kA) have been carried out in order to estimate a range of resistance changing during the discharge time. Due to the limited autonomous operational time in the second stage the study had several goals. In the second stage the research was carried out with a reduced current amplitude value (less than 10 kA) in order to determine how the minimum value of the resistance of soil changes in such conditions. Furthermore, in the second step in the experiments the amplitude of the current was varied with increasing and decreasing. This was necessary for the investigation of the memory effect. Furthermore, the distance between the ground electrodes was different in the first (50 m) and second (70 m) stages. Increase the distance was made in order to determine how it affects the resistance of the soil between the grounding electrodes.

Figure 1 shows the typical current waveform and the voltage in the discharge circuit, formed by the high voltage generator and the ground, in which the electrodes are placed. These waveforms were recorded in all the experiments, but in different cases have changed the value of the charging voltage U_c of, the number of stages N of the generator (and, accordingly, the C_0, the inductance of the discharge circuit). This led to the fact that the voltage was applied to the electrodes with different amplitude and current was flowing in the ground of varying amplitude. This was necessary in order to obtain the dependence of the resistance (minimum value) on the amplitude of the discharge current.

To calculate the soil resistance, a simple model of an equivalent circuit of the discharge circuit was built. The circuit can be represented as connected in series inductance, resistance (varistor) and a capacitor, which in the initial moment of time is charged to U_0 voltage. Since during the discharge process current and voltage waveforms were recorded, it can be written:

$$I(t)R(t) = U(t) - L\frac{\mathrm{d}I}{\mathrm{d}t}, \tag{1}$$

where $I(t)$ is the current through the soil of resistance $R(t)$, L is the inductance of the circuit between the electrodes, $U(t)$ is the voltage applied to electrodes. The inductance of the circuit can be measured by low-voltage devices (LRC-meter AKIP-6102, that measures inductance L, resistance R and capacitance C). In this case measured value $L = 20$ μH. Since the current and voltage profiles and inductance value are known, it is possible to get the time profile of the

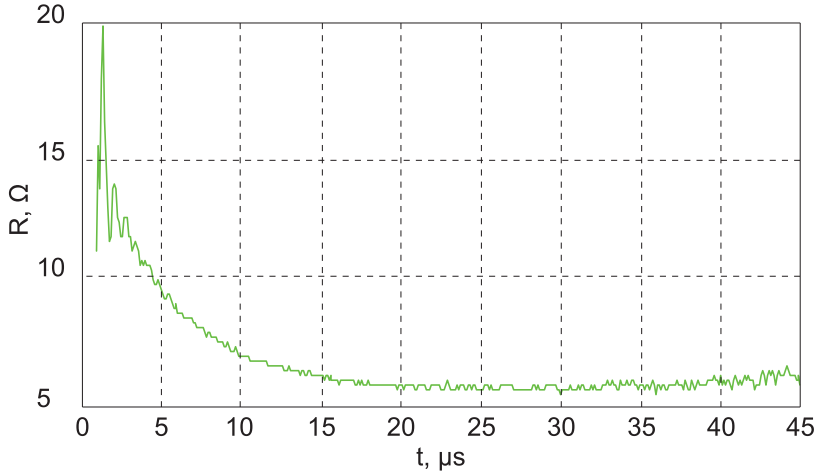

Figure 2. Soil resistance evolution during discharge in experiment No. 1128.

Table 1. Parameters and results of first stage experiments.

No.	U_c (kV)	C_0 (μF)	$U_{\max}$ (kV)	$I_{\max}$ (kA)	$R_{\min}$ (Ω)	τ (μs)	$\tau_{0.1/0.9}$ (μs)	$\tau_{0.5}$ (μs)
1120	27	8	190	9.5	18	85	30	120
1124	27	3	200	21	8	80	30	110
1125	33	3	230	26	7	70	28	105
1126	28	3	360	41	6	50	13	65
1128	33	1.4	660	85	6	30	7	28

resistance change (figure 2). At the beginning of discharge the rate of current rise is high, and the noise on the waveform has significant amplitude, so the calculation of soil resistance in the first microseconds is difficult. However, we can not expect that this resistance is higher than 30 Ω (this value is obtained by means of low-voltage measurements with LRC-meter AKIP-6102).

During the study several experiments were conducted, and obtained waveforms have similar shapes. Time profiles of soil resistance change also have similar shapes. The results are summarized in table 1. The table shows the basic values that reflect the shape of waveforms: U_c is the generator charge voltage, C_0 is the generator capacity during discharge, $U_{\max}$ is the registered amplitude of the voltage between the electrodes in the soil, $I_{\max}$ is the amplitude of the current through the soil, $R_{\min}$ is the minimum value of resistance during the discharge, τ is the time to reach the minimum resistance, $\tau_{0.1/0.9}$ is the current rise time at the level of 0.1/0.9, $\tau_{0.5}$ is the current fall time to the value of half the amplitude.

The second series the tests (experiments No. 1131–1143) were carried out in order to determine whether the memory effect in the soil exists, as well as to determine the ground resistance value in different discharge conditions. For the experiments GPV has been moved a few tens of meters from previous testing place, where, as expected, discharges into the soil did not occur. The distance was increased between the ground electrodes 70 m. With this configuration, equipment tests were conducted at reduced current amplitudes less than 8 kA. At a distance of 70 m low-voltage measurement of resistance between the electrodes has given a value of 35 Ω. The principal difference from the first series of tests is experimenting first at low amplitudes of current

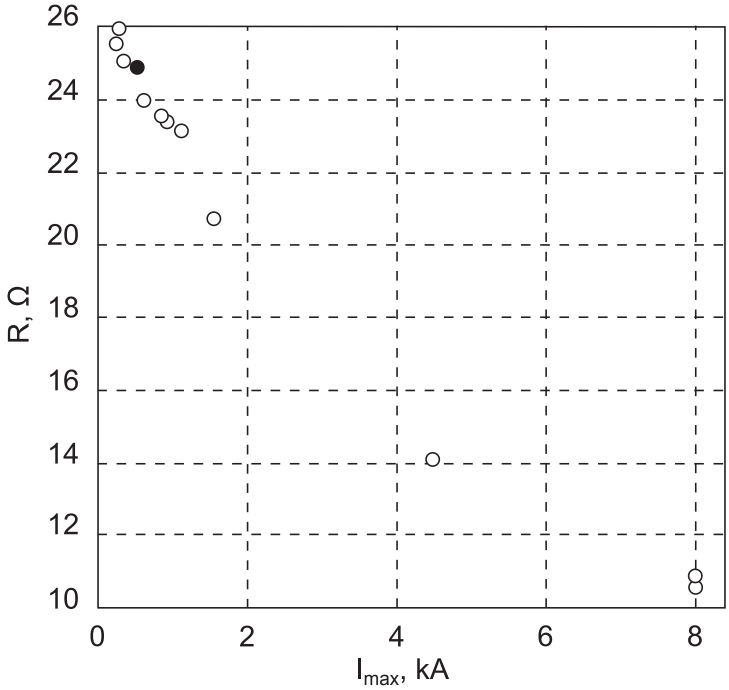

Figure 3. Soil resistance versus amplitude of discharge: ● —experiment No. 1143.

(hundreds of amperes), then at high amplitudes (8 kA), and then again at low amplitudes. The results of soil resistivity measurements during the discharge current is shown in figure 3. It can be seen that the values of minimum ground resistance (see filled point that corresponds to the experiment No. 1143 with a current amplitude of 500 A) are returned to the values measured before to the breakdown of soil discharge with a current amplitude 8 kA.

3. Conclusions

The resistance of soil has been measured with a relatively high conductivity between the grounding electrodes in a lightning current discharge conditions and with the distance between electrodes up to 70 m. It was shown that the soil resistance decreases with increasing discharge current amplitude. In this case some time after the beginning of the current decreasing resistance begins to increase (to recover). Experimentally obtained data points that in the range of values of the lightning current (up to 100 kA) there is a minimum value of resistance between the ground electrodes, so with increasing of the current amplitude the resistance value tends to this value. For current values that corresponding weak lightning (up to 10 kA) the minimum value of the ground resistance depends on the amplitude of the current almost linearly. In this range of current amplitudes a memory effect (change the behavior of the soil resistance value during series of discharges) were not observed. In contrast to the experimental works with low conductivity soils (mainly sandy soil) [10–12] time delay between beginning of discharge and current rise was not observed.

Acknowledgments

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