Influence of Nonlinear Processes in Soils on the Impulse Resistance of Grounding Electrodes

V V Ivonin

1Northern Energetics Research Centre, Branch of the Federal Research Centre “Kola Science Centre of the Russian Academy of Sciences, Apatity, Russia

E-mail: v.ivonin@ksc.ru

Abstract. The article presents the results of laboratory studies of nonlinear processes during the flow of pulsed currents into moistened soil from electrodes modelling grounding devices of electric power facilities. A methodology for studying the pulse parameters of grounding devices has been developed and a laboratory stand and a generator measuring system have been developed on which these investigations were performed. The experiments were carried out on three types of electrodes at voltages of 20 - 50 kV and pulse durations from units to hundreds of microseconds. The article presents the combined results of optical and oscillographic studies. It is shown that the cause of the formation of spark channels during the nonlinear spreading of the pulsed current in the soil, when there is a sharp decrease in the grounding resistance, is the ionization-overheating instability that occurs when the current density on the electrode is greater than the critical one. The development of instability leads to an inhomogeneous current distribution and the appearance of spark channels. On the basis of experimental data, the current-voltage characteristics of the electrodes are obtained.

1. Introduction

The values of overvoltages at electric power facilities caused by incoming lightning surges from a transmission lines or direct lightning strikes into an object is determined, among other things, by the values of the pulse resistances of the grounding. It is known that the resistance of grounding grid depends on their design and the resistivity of the surrounding soil. The soil is a combination of substances, including water, air, gravel, sand, clay, mineral and organic compounds. The properties of these substances affect the electrical characteristics of the soil. And although the breakdown characteristics of liquid, solid and gaseous dielectrics are well studied [1], a physical model that would be universal with respect to the characteristics of the breakdown of composite soils has not yet been developed. Therefore, much attention is paid to the study of electro-magnetic processes occurring in grounding grid and adjacent soils [2, 3], especially in areas with high soil resistivity, to which the Kola peninsula belongs.

It is generally assumed that the electric field created by large currents leads to the appearance of spark channels in the aqueous medium and through gas inclusions in the soil surrounding the electrode [4]. Since the resistivity of the plasma in these channels is lower than the resistivity of the surrounding soil, there is a significant decrease in the resistance of the grounding electrode. This phenomenon is usually called soil ionization or spark formation in the soil [5, 6].
Many articles are devoted to the processes of ionization and spark formation in the soil. The first of them, written by Towne [7], is dated 1929. In it, the author explains for the first time the difference between the stationary and pulse resistance of grounding devices.

Subsequent experiments conducted by Bellaschi [8] confirmed these observations for different types of soil and electrode configuration. Since then, many scientists have developed models describing these processes in grounding devices (Chisholm and Janischewsky [9], Geri [10], Korsun'tcev [11], Liew and Darveniza [12], Oettle [4], Nixon [13], Ryabkova [14], Wang [15], Cooray [16]).

This problem remains relevant due to the introduction of electronic equipment in the energy system that is sensitive to transients caused by lightning discharges.

2. Experimental setup
The scheme of the experimental setup is shown in Figure 1. Spark formation studies were carried out in a cylindrical glass vessel with a diameter of 30 cm and a height of 45 cm, filled with moistened quartz sand. The inside of the vessel was covered with a copper foil to create a grounded shield. For optical studies, a hole of 20×13 cm was made in the copper screen, through which, with the help of a digital camera, spark channels were recorded. The studies were carried out on electrodes of various shapes (disk, ball and corner), which were located inside the container in the thickness of the sand and leaned against a transparent wall in the window of the grounded screen. The registration was carried out using a digital camera with an open shutter, which was installed opposite the window at a distance of 20 cm. Voltage pulses with an amplitude of up to 50 kV and a front duration of no more than 1 microsecond were formed by a pulse voltage generator (PVG). The pulse duration was regulated by changing the parameters of the RC chain in the range from several microseconds to hundreds of microseconds. The voltage and current pulses were recorded using a resistive voltage divider and a current shunt, the signals from which were fed to a digital oscilloscope.

According to the oscillograms of pulse processes, namely, the dynamics of changes in currents, voltages and calculated values of resistances, it is possible to judge the processes of spark formation and the influence of soil characteristics, the type of electrode system and the parameters of the pulse action on these processes.
3. Experimental results

Figure 2 shows the waveforms of voltage $U(t)$, current $I(t)$ and the pulse resistance curve $R(t)=U(t)/I(t)$ for an electrode in the form of a disk with a diameter of 21.5 mm and a thickness of 1 mm. The experiments were carried out in soil with a resistivity of 1300 $\Omega\cdot m$ and a moisture of 10%. As can be seen from the figure, with a voltage pulse with an amplitude of 36 kV, a front duration of 1 microsecond and a pulse duration up to a half-life of 28 microseconds, a sharp drop in the resistance of the grounding electrode occurs almost immediately, due to the appearance of spark channels in the soil. The minimum resistance value always lags behind the maximum current value. This delay increases with increasing soil moisture. The spark formation process begins at the nonlinear stage of the pulse current spreading near its maximum, when $dU/dI < 0$, and the resistance of the electrode in the soil decreases almost to a minimum.

Experiments with various types of electrodes have shown that in the case of a disk electrode and a corner electrode, the sparking processes begin at lower voltage values relative to the spherical electrode. This is due to the fact that even with small values of the voltage at the edges of the disk and the corner, the electric field strength will be much greater than the voltage on the surface of the sphere and will exceed the critical value of the $E_c$ [17]. At the same time, the pulse resistance of the electrodes drops almost 2 times.

The delay of the spark formation process from the start of the voltage pulse is determined by the time of the development of ionization-overheating instability in wet sand [18, 19], which is longer than the time of the development of ionization-overheating instability in atmospheric air. Longer delay times are probably due to the fact that the current in the soil spreads over conducting wet areas, so significant energy consumption is required to warm up the water, which has a large heat capacity, and for its evaporation.

With an increase in both the voltage amplitude and the current duration, the value of the pulse resistance decreases (Figure 3). The length of the spark channels and the brightness of the spark glow,
which is flare-like, also increases, which is associated with an increase in the energy input into the resulting plasma channel (Figure 4). With an increase in the duration of voltage pulses of more than 70 microseconds, the pulse resistance reaches a minimum value, which remains constant with a further increase in the pulse duration [20].

![Figure 3](image1.png)

**Figure 3.** Dependence of the pulse resistance of the electrode on the duration of the applied pulse.

1 - 30 kV, 2 - 36 kV, 3 - 42 kV

![Figure 4](image2.png)

**Figure 4.** Obtained pictures of plasma channels around the corner electrode at a voltage amplitude $U=42$ kV and different durations of the applied current pulse.

$\text{a} - 2 \mu s, \text{b} - 30 \mu s, \text{c} - 70 \mu s$

The processes of spark formation are optically more pronounced on the electrodes in the form of corners with a size of $35 \times 35$ mm and a thickness of 5 mm with a sharply unequal electric field at the edges. The process of sparking occurs on the electrodes in places with the highest current density. At a sand moisten of 10%, the formation of plasma channels is flare-like, but at a sand moisten of 20%, counteracted spark channels are formed. The formation of plasma channels on the disk electrode also has a flare character, however, plasma channels are fixed at a higher voltage amplitude and a longer pulse duration.
All processes at the beginning of spark formation in the soil, and especially in an inhomogeneous field, as already indicated – are nonlinear. This is well illustrated by the current-voltage curves, which are constructed from the oscillograms of currents and voltages obtained during experiments. Figure 5 shows the results of experiments on a spherical electrode half-buried in the soil. The amplitude of the voltage pulses was in the interval from 25 to 50 kV. At low voltages, the pulse resistance was linear and equivalent to a stationary resistance. At high voltages, when the current density exceeds the critical value, the current-voltage characteristic has a loop-like shape associated with soil ionization.

![Current-voltage curves of moistened quartz sand at different amplitudes of the voltage.](image)

**Figure 5.** Current-voltage curves of moistened quartz sand at different amplitudes of the voltage.

1 – 28 kV, 2 – 37 kV, 3 – 42 kV, 4 – 45 kV, 5 – 48 kV

4. Conclusions
A sharp decrease in the pulse resistance of grounding devices during the flow of large-amplitude currents is associated with the processes of ionization and sparking occurring in the surrounding soils. These processes are nonlinear, which is confirmed by the current-voltage characteristics obtained during experimental studies.

The nature of the development of spark processes depends on the parameters of the applied pulses and the parameters of the soil, as well as the electrode design. The conducted optical studies show that spark channels are formed in places where the electric field strength exceeds a critical value. With an increase in the amplitude and duration of the pulses, the number of spark channels, their length and brightness increase. The reason for the formation of spark channels during the nonlinear spreading of the pulsed current in the soil is ionization-overheating instability, which leads to an inhomogeneous current distribution over the cross section and the appearance of spark channels.
5. References

[1] Kostenko M V 1973 High Voltage Technique (M.: Higher. school) p 528
[2] Nor M 2006 Review: soil electrical characteristics under high impulse currents IEEE transactions on electromagnetic compatibility Vol 48 № 4 p 826
[3] Takeuchi M, Yasuda Y and Fukuzono H 1998 Impulse characteristics of a 500 kV transmission tower footing base with various grounding electrodes Proc. 24th Int. Conf. Lightning Protection Birmingham, U.K., Sep. 14–18 p 513
[4] Oetyle E E 1988 A new general estimation curve for predicting the impulse impedance of concentrated earth electrodes IEEE Transactions Power Delivery vol 3 pp 2020 – 2029
[5] Vasilyak L M, Vetchinin S P, Panov V A, Pecherkin V J and Son E E 2014 Nonlinear impulse current spreading and electrical breakdown in soil High Temp 52 pp 797–802
[6] Yasuda Y, Kondo S, Hara T, Sonoi Y and Furoka Y 2003 Measurement of soil ionization characteristics of grounding and its analysis using dynamic grounding model IEEJ Transactions on Power and Energy V 123B № 6 p 718
[7] Towne H M 1929 Impulse characteristics of driven grounds General Electric Review pp 605 – 609.
[8] Bellaschi P L, Armittington R E and Snowden A E 1942 Impulse and 60-cycle characteristics of driven grounds – part II AIEE Transactions vol 61 pp 349 – 363
[9] Chisholm W A and Janisichewskyj W 1989 Lightning surge response of ground electrodes IEEE Transactions Power Delivery vol 4, 2 pp 1329 – 1337
[10] Geri A 1999 Behaviour of grounding systems excited by high impulse currents: the model and its validation IEEE Transactions Power Delivery vol 14, 3 pp 1008 – 1017
[11] Korsuncev A V 1958 Application on the theory of similarity to calculation of impulse characteristics of concentrated electrodes Elektrichestvo 5 pp 31-35
[12] Liew A C and Darveniza M 1974 Dynamic model of impulse characteristics of concentrated grounds Proceedings of the IEE vol 121, 2 pp 123–135
[13] Nixon K J 2006 The lightning transient behaviour of a driven rod earth electrode in multi-layer soil PhD dissertation, University of Witwatersand, South Africa
[14] Ryabkova E Ya 1978 Grounding in high voltage installations (M.: Energy) p 224
[15] Wang J and Liew A C 2005 Extension of dynamic model of impulse behavior of concentrated grounds at high currents IEEE Transactions on Power Delivery vol 20, 3 pp 2160 – 2165
[16] Cooray V, Zitnik M, Manyahi M, Montano R, Rahman M and Liu Y 1993 Physical model of surge-current characteristics of buried vertical rods in the presence of soil ionization Journal of electrostatics 30 pp 17 – 28
[17] Ivonin V V, Danilin A N, Efimov B V, Kolobov V V, Selivanov V N, Vasilyak L M, Vetchinin S P, Pecherkin V Ya and Son E E 2016 Optical images of spark channels under a spreading pulse current in soil Advances in Applied Physics, vol 4, 4 355–361
[18] Vasilyak L M, Pecherkin V Ya, Vetchinin S P, Panov V A, Son E E, Efimov B V, Danilin A N, Kolobov V V, Selivanov V N and Ivonin V V 2015 Electrical breakdown of soil under nonlinear pulsed current spreading J. Phys. D: Appl. Phys. Vol 48 285201
[19] Ivonin V V, Danilin A N, Efimov B V, Kolobov V V, Selivanov V N, Vasilyak L M, Vetchinin S P, Pecherkin V J and Son E E 2015 Optical investigations of spark channels in soil under spreading of pulse current Applied Physics 4 pp 50-53
[20] Pecherkin V Ya, Vasilyak L M, Vetchinin S P, Panov V A, Son E E, Danilin A N, Ivonin V V, Kolobov V V, Kuklin D V and Selivanov V N 2015 Optical investigations of pulsed sparks in soil near electrode J. Phys.: Conf. Ser. 653 012151