Experimental Investigation of Surge Propagation Characteristics on a Substation Grounding System

V V Kolobov¹, M B Barannik¹, V V Ivonin¹

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

E-mail: m.barannik@ksc.ru

Abstract. With the correct choice of the arrester by voltage class and compliance with the calculated protective distance without taking into account the propagation velocity of the current wave on the grounding grid, overvoltages exceeding discharge or residual voltage may occur on the protected equipment, in particular the transformer. Thus, when calculating the installation of the arrester that protects the substation from incoming lightning surges from a transmission line, it is necessary to take into account the propagation of the current wave on the grounding grid. The propagation velocity of electromagnetic waves in a 150 kV substations grounding grid was measured. The measured wave propagation velocities are in the range of 50–100·10⁶ m/s. Thus, the obtained velocity of wave propagation on the grounding grid used in service is several times less than the speed of light. The measured value correlates well with similar experiments conducted for buried conductors located in soils with similar parameters and the results of mathematical modeling for a grounding grid having similar dimensions and mesh size.

1. Introduction

The primary purpose of an grounding system is to protect and safeguard personnel and equipment against the hazards and devastation that may be caused by the flow of high-frequency lightning- and arrester discharge currents or severe 60-Hz ground-fault currents in electrical power systems [1]. Nevertheless, the grounding grids are usually designed considering only low-frequency occurrences (60-Hz ground-fault currents) [2].

In order to comply with legal and regulatory requirements, substation grounding systems must be tested after installation and repeated during maintenance every few years. Tests are necessary to make sure that during the ground fault, personnel are not exposed to any dangers and telecommunications equipment will not be damaged. The amount of ground potential rise (GPR) and the associated voltage hazards are directly related to the short-circuit currents and impedance of the entire grounding system.

For monitoring, the total resistance of the grounding grid and the ground fault potentials on protective fences, high-voltage installations are determined. They also conduct studies of the integrity of the conductors of the grounding grid, which can be corroded over time [3, 4].

When the grounding grid is dissipating the lightning current into the earth, the area that discharges the current is initially small around the lightning current injection point and grows at a speed that depends on the propagation of the electromagnetic field in the earth [5]. During this period, the distribution of the transient ground potential rise (TGPR) at the grid conductors is uneven and can
attain high values near the current injection point [6 - 9]. This phenomenon can cause overvoltage in the primary equipment and secondary circuits, which disrupts the security and reliability of the system. Special mitigation measures are suggested to reduce TGPR related disturbances [10]. One such measure is to increase the density of the grounding grid mesh at points where high transient currents are expected, and the use of this approach has been reported in many published studies, e.g. [11, 12].

One of the reasons for this study was the accident of a transformer at one of the substations caused by the arrival of a lightning overvoltage along the line. At the same time, the arresters of all three phases protecting the transformer were serviceable and the grounding grid resistance was tested.

2. Experiment

The experiment was conducted on the switchgear of a 150 kV distribution substation. The scheme of the experimental setup for studying the wave propagation velocity in the grounding grid is shown in Figure 1. The generator part of the setup includes a current pulse generator connected to the ground grid at a stationary point, an oscilloscope for monitoring the current shape and measuring the grounding potential rise (GPR) at the point of current injection, as well as a device for generating a zero-time pulse (ZTP), the front of which coincides with the front of the input current. GPR at the point of current injection is measured by the known the fall-of-potential method relative to the remote earth [13]. A current pulse generator based on an inductive energy storage device was used in the experiment. The generator was developed to study the transient impedance \( Z(t) \) [14] of local (small area) grounding of power transmission lines and lightning rods. The scheme and operation of the generator are considered in detail in [15, 16].

![Figure 1. Experimental setup for measuring the surge propagation characteristics of substation grounding grid.](image)

The generator with an inductive energy storage forms a current pulse (Figure 2) with a very short front (no more than 100 ns). This current form contains a wide range of frequencies, which coincides with the frequency components of the overvoltage wave on the power line from secondary lightning strikes [17] and components of the overvoltage wave during insulation breakdown [18].

The measuring part of the experimental setup is designed to measure the potential of the grounding grid relative to the remote earth at the selected measuring points. The measurement of the potential of the grounding grid at the observation point was also performed using the fall-of-potential method. The measuring part includes a second two-channel oscilloscope, a voltage divider, a potential led conductor, and a remote potential electrode. As can be seen from the figure, one common remote potential electrode was used in the generator part and measuring part of the setup, installed outside the
substation switchgear at a distance of 100 m from the current pulse generator. The voltage from the voltage divider was applied to the first input of the oscilloscope. A ZTP voltage was applied to the second input of the oscilloscope, corresponding to the pulse front of the input current (Figure 3). The measurement of the wave propagation delay along the grounding grid was determined relative to the ZTP front. The ZTP came from an input current generator via a 100 m long coaxial cable.

To provide galvanic isolation between the coaxial cable connected to the oscilloscope of the measuring part of the experimental setup and the output current flow circuits of the pulse generator, the galvanic isolation unit was developed. The functional diagram of the unit is shown in Figure 4. ZTP is formed from the voltage drop on the resistive shunt $R_s$, which is also used as a current sensor to control the shape and amplitude of the input current (Figure 1). The voltage removed from the shunt $V_{R_s}(t)$, which repeats the shape of the input current $I_{inj}(t)$, is applied to one of the channels of the oscilloscope 1 and simultaneously to the measuring input of the comparator of the galvanic isolation unit. During the time interval, while the voltage amplitude $V_{R_s}(t)$ exceeds the voltage of 2 V at the reference input of the comparator, a rectangular pulse with an amplitude of 3.3 V is formed at the output of the comparator. The value of 2 V of reference voltage is determined by the values of resistors $R_1$ and $R_2$, which form a voltage divider. The pulse from the comparator output is fed to the input of the digital isolator chip, made on the basis of a pulse transformer. Maximum permissible voltage of isolation barrier of the chip is 5 kV and a propagation delay does not exceed 20 ns.

The primary circuits of the galvanic isolation unit are powered by a 3.3 V Li-ion rechargeable battery. An isolated dc-dc converter is used to power the secondary galvanically isolated circuits of the digital insulator. Due to application of a high-speed comparator and a digital isolator, the total input-output propagation delay of the galvanic isolation unit does not exceed 25 ns. The zero-time pulse rise time is 100-150 ns.

Before conducting the experiment, the propagation delay zero-time pulse $\Delta t_p$ was determined by the coaxial cable (see Figure 3). For this purpose, the end of the cable was connected to the second input of the oscilloscope 1 of the experimental setup. As can be seen from Figure 3, the propagation delay was 0.55 $\mu$s, which corresponds to the velocity of wave propagation on a coaxial cable lying on the ground, $\sim 180 \cdot 10^6$ m/s. Figure 3 also shows that the shape of the pulse does not coincide with the meander. This effect is explained by the fact that some time after the start of the zero-time pulse, the voltage drop on the resistive shunt $R_s$ exceeded the voltage $+3.3$V power supply of the primary circuits of the unit and reached $+5$V, respectively, the pulse shape at the output of the digital isolator...
chip was distorted. But this effect did not matter, since the shape of the zero-time pulse front, which is important for relative measurements of the time delay, remained undistorted and allowed the experiment to be carried out and did not reduce the accuracy of the results.

Figure 4. Functional block diagram of the galvanic isolation unit.

Figure 5 shows the location of the measurement points at the substation. Point 1 is the place where the pulse current generator is connected to the grounding grid or current injection point. The output of the current pulse generator and the voltage probe of measuring system were connected to the grounding buses on the portal towers and to the wires connecting the substation grounding grid with the corpus of electrical devices (equipment) as close to the surface of the earth as possible. To ensure reliable electrical contact with the grounding conductors, specially designed C-clamps were used.

Figure 5. The location of the measuring points at the substation. Point 1 is the current injection point also. The dotted line shows the estimated position of the grounding grid conductors.

At each measurement point, the shape of the voltage drop pulse relative to the remote earth and the zero-time pulse were recorded using a digital oscilloscope 2. The resulting waveforms were stored in
the oscilloscope's memory for subsequent processing. The processing of the measurement data consisted in bringing the zero of the time axis of the voltage pulse obtained at measurement points 2-5 to the zero of the time axis of the current pulse by the time shift method, taking into account the propagation delay of zero-time pulse. As already noted, the GPR form at the current input point was recorded by the second channel of the oscilloscope 1 simultaneously with the recording of the input current form by the first channel of the oscilloscope and the oscillogram did not require additional processing. Figure 6 shows the initial sections of the voltage pulses for all measurement points. The zero of the time axis corresponds to the time when injected current to start. The wave propagation velocities measured for points 2-5 are in the range of 50–100·10^6 m/s. Thus, the obtained velocity of wave propagation on the grounding grid used in service is several times less than the speed of light.

The pulse received at the farthest point 5 is of the greatest interest, since the distance from the place where the current is injected into the grounding grid to this point is precisely known, and, in addition, it can be assumed that there is a direct conductor of the grounding grid between points 1 and 5. It can be seen from Figure 6 that the velocity of the wave propagation from point 1 to point 5 is 65 m/μs or 65·10^6 m/s. The obtained experimental value correlates well with similar experiments conducted for buried conductors [19] located in soils with similar parameters and the results of mathematical modeling [20] for a grounding grid having similar dimensions and mesh size and located in soils with a resistivity of 1000-2000 Ω·m.

![Figure 6. Voltage waveforms obtained at measuring points 1–5. The waveforms are normalized to the injected current pulse rise.](image)

3. Conclusions
With the correct choice of the arrester by voltage class and compliance with the calculated protective distance without taking into account the propagation velocity of the current wave on the grounding grid, overvoltages exceeding discharge or residual voltage may occur on the protected equipment, in particular the transformer.

The results obtained during the experiment coincide with the calculated results of the wave velocity for soils of similar resistivity. In our opinion, it is necessary to reduce the local impulse resistance at the point of connection of the arrester to the grounding grid, for which it is necessary to reduce the mesh size of the grounding grid, that is, to increase the number of vertical grounding rods exactly in location of the arrester.

When calculating the installation of the arrester that protects the substation from incoming lightning surges from a transmission lines, it is necessary to take into account the propagation velocity of the current wave on the grounding grid.
4. References

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