SUPPRESSION OF THE ATMOSPHERIC OVER-VOLTAGES IN GROUNDING NEUTRAL CONDUCTOR LOW VOLTAGE GRIDS

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ABSTRACT

This paper reports the issues related to over-voltages in low-voltage distribution networks characterized by high specific soil resistance. Detailed description of real case observed on GSM Transmitter Glavica – Vrgorac is reported. Transmitter is supplied via distribution cable from SS 10/0,4 kV/kV Podprolog. Since specific soil resistance and corresponding transmitter grounding resistance are quite high, over-voltages were flowing towards substation grounding system via cable neutral conductor, instead through transmitter grounding system. In this case, authors applied innovative approach. The solution is based on the theory considering the impulse grounding behavior rather than the classical static response. Instead of modelling horizontal grounding electrode as Ohmic resistance, electrode capacitance and inductance are incorporated (adopted Telegrapher's equation). Following solution arisen: approximately in the middle, 100 m long part of the existing over-head cable was replaced by buried cable. Instead of neutral conductor from the cable (which was disconnected), non-insulated Cu wires (2x 50 mm²) were applied. The novelty is in the application of non-insulated neutral conductor as the lightning grounding. Validity of solution is verified via extensive in-situ measurements.

INTRODUCTION

The introduction section will describe basic terms used in text. Lightning is usually defined as atmospheric electricity discharge visible using naked eye. The aforementioned discharge is created if portion of atmosphere becomes electrically charged or if potential difference exceeding the breakdown voltage appears. The common source of lightning are specific clouds, so called cumulonimbus. [1] Even though the terms lightning and thunder are related, they are not equal, since term thunder refers to acoustic effect generated by lightning passing through the air. Grounding system may be defined as grid connection point to earth. It is established using grounding electrode. The current passing through the grounding electrode results in voltages generated across the surface of the earth, meaning, between two points on the earth potential difference may appear. [2] The previously described phenomenon is highly undesirable in context of safety. Namely, the humans or the animals may bypass such two points with their bodies and consequently be exposed to the potential difference. The imaginary lines connecting the points of equal potential will be defined as equipotential lines. [3] The shape and mutual distance of the equipotential lines depends on the grounding electrode geometry, current passing through the electrode and soil resistivity. [1] According to theory [2], the electric field lines are perpendicular to equipotential surfaces. In case of spherical or semi-spherical grounding electrode geometry, equipotential lines are circles. However, if grounding system includes radial grounding, or the cables with the grounding effect (screen), equipotential lines may be irregular. Depending on grounding system purpose, one distinguishes operation grounding, protection grounding, lightning grounding and combined grounding. [1] Since this paper deals with the lightning grounding exclusively, we will limit ourselves to that type of grounding. According to DIN VDE terminology, lightning grounding is grounding systems responsible for taking lightning current to earth. Due to specific lightning current waveform and amplitude, stipulated requirements for lightning grounding differs from requirements for other types of grounding. [3] Even though in comparison to the metals earth is for few order of magnitude worse conductor, it makes sense to introduce the concept of specific soil resistance, analogous to specific resistance of the metal. The specific soil resistance of the soil is defined as resistance between two sides of the cube with the edges of 1m in length made of that soil. [1] This value may vary from few tens to few thousands of Ωm, depending on the soil type, structure and the stratification. Current passing from the metal grounding electrode to the earth passes through the increasing surfaces of the soil, and consequently, reduced resistance. Its is because of this why voltage drop in the immediate vicinity of the grounding electrode is particularly important in terms of safety, specially in case of high soil resistivity.

Due to aforementioned reasons, prior to the grounding system design, specific soil resistance measurements are often performed. Once grounding systems is constructed according to the design, grounding resistance is measured and its agreement with legislation verified. [1]

Various grounding electrode geometries may be applied, ranging from horizontal/vertical electrode, spheres, grids, etc. [4] The most common solution for LV overhead power lines are parallel grounding electrodes mounted on the pillars carrying the cable. [4]

In case of the problem described in this paper, differences in soil resistivity resulted in distribution of the lightning current through neutral conductor. Namely, instead of passing to earth through the grounding system of the GSM transmitter Gomila, lighting current flowed through the neutral conductor of the overhead power cable to the grounding system of the local substation supplying the transmitter. The surge arresters are installed on 3 locations along the power cable, but they have never been activated by the lightning. Classical parallel grounding electrodes operated as voltage dividers resulting in almost all lightning current flowing to the substation grounding, leading to serious damages on substation equipment and appliances in the nearby houses. Our innovative solution, based on serial grounding electrode rather the parallel grounding electrodes significantly improved the situation. In the rest of the paper, we will describe the solution and methods used to verify its validity.

PROBLEMS WITH THE GSM TRANSMITTER GOMILA AND SUBSTATION PODPROLOG 1

GSM transmitter Gomila is fed from SS 10/0,4 kV/kV Podprolog 1 via self-supporting overhead cable SKS (3x35+70) mm^2, with the length of 1145 m. Since grounding system is based on TN-C-S scheme, neutral conductor is grounded within SS 10/0,4 kV/kV Podprolog 1 via joint grounding. Additionally, it is grounded at the first pillar, in the middle of the cable and at the transmitter Gomila. Grounding electrodes of the pillars are made of horizontal galvanized iron stripes with the rectangular cross-section of 25 mm x 4 mm. Grounding system of the transmitter is made of 3 rings and 6 radial horizontal electrodes while substation grounding consists of 2 rings and 4 radial horizontal electrodes. Geographical location of the transmitter supply with list of measurements is given in Figure 1.

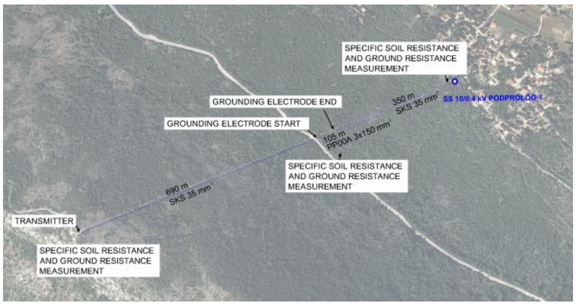

Figure 1.Geographical location of the transmitter Gomila supply with list of measurements

As it is usually made [1], grounding electrodes are mutually parallel. Atmospheric voltages at the transmitter Gomila are occurring around 10 times per year. Instead of flowing through transmitter grounding, lighting current flowed to SS 10/0,4 kV/kV Podprolog 1 and from there via cables to the objects in the vicinity of the substation. Aforementioned currents resulted in significant damages within the substation (fuses, energy meters) as well as on the various electronic devices on customers side (TV sets, etc). It is worth of mentioning that surge arresters never activated, even though they are installed in the begin, middle and end of the overhead power cable.

MEASUREMENT METHODOLOGY AND POST PROCESSING FOR THE SOIL RESISTIVITY AND GROUNDING RESISTANCE

This chapter outlines the description of the applied measurement and processing techniques. The location of certain measurements is depicted in Figue 1. Due to already mentioned assumption of the significant differences of the soil resistivity, which was somewhat confirmed by previously performed partial measurements, systematic geoelectrical vertical soil probing has been performed. This approach is based on the assumption that soil can be dived on arbitrarily selected number of horizontal layers. Each layer is described by its thickness and resistivity. Layers are mutually differing, but soil within layer is homogeneous. Vertical geoelectrical probing was executed with an aim to obtain soil resistance at the location of the GSM transmitter, location of the pillar were overhead cables converts to the buried cable and the location of SS Podprolog 1.

Measurements are used using Schlumber method [5]. Rest of the chapter briefly describes the measurement methodology, while more details can be found in [4]. The measurements are done using 4 probes/electrodes, injecting low frequency current through outer electrodes A and B, while voltage drop is measured across inner electrodes M and N (Figure 2).

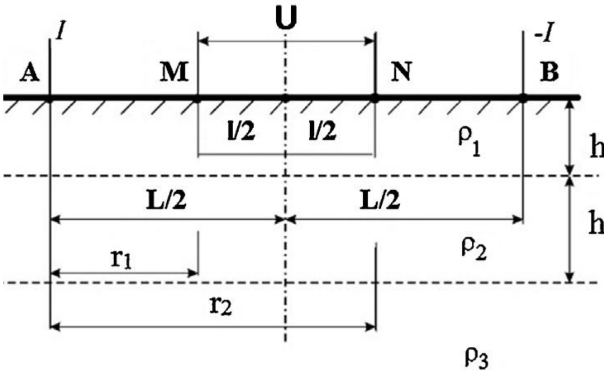

Figure 2. Geoelectrical soil probing according to Schlumberger method

Theoretical curve for multi-layer soil model is given by:

$$\rho_T = \frac{r_1 r_2}{r_1 - r_2}\, \rho_1 \int_0^\infty k(\lambda, \bar{x})[J_0(\lambda r_1) - J_0(\lambda r_2)]\mathrm{d}\lambda \quad (1)$$

were symbols stand for following:

ρ_T – theoretical curve for specific resistance of the multilayered soil model, Ωm

ρ_1 – specific resistance of the first layer, Ωm

r_1, r_2, λ – Bessel function parameters (Fig. 2)

J_0 – zero order Bessel function

x – auxiliary function parameters

Detailed comments for equation (1) can be be found in [4]. On the other side, measured value for specific soil resistance (soil resistivity) can be obtained from relation (2):

$$\bar{\rho} = \frac{\pi R}{l}\left[\left(\frac{L}{2}\right)^2 - \left(\frac{l}{2}\right)^2\right] \qquad (2)$$

were symbols stand for following:
R – soil resistance obtained from measurements according to Schlumberger method, **Ω**
L – distance between current probes in Schlumberger method, m (Fig. 2)
l – distance between voltage probes in Schlumberger method, m (Fig. 2)

Interpretation of the results and formation of the vertical layers is done applying the version of the Newton algorithm for minimum number of layers, i.e. Tikhonov algorithm. [5] Applying previously described, specific soil resistance data are obtained as displayed in Table I. Ground resistance is measured applying usual 3p-method, as described in Figure 3. [5]

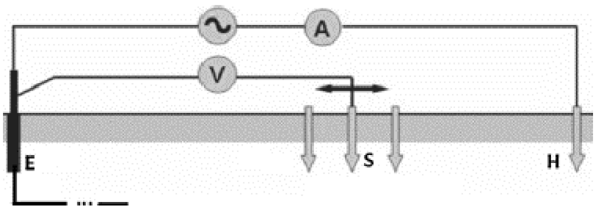

Figure 3. Schematic description of the 3p-method for measurement of the ground resistance

In this case we will also mention only most important settings of the 3p-method. 127 Hz square wave current of the magnitude of 11.1 mA is injected through auxiliary current probe H, earth and tested grounding system. The voltage drop is measured between the tested grounding and the auxiliary voltage probe S. The resistance is obtained as ratio of the voltage and the current, assuming frequency of 127 Hz is low enough to treated voltage/current ratio as resistance rather than impedance. In order to ensure that auxiliary voltage probe S is away from the voltage funnel of the tested grounding E, S-probe is shifted 2-3 m towards and away from E.
Results of the specific soil resistance measured at the location of the transmitter, the middle of the power cable (where the overhead cable converts to buried cable) and at the substation, show there are significant differences.

Table I. Results of the geoelectric soil probing

Measurement location	Soil layer No.	Layer thickness h_i/m	Specific layer resistance ρ_i/Ω_m
Transmitter	1	0,4	1018
	2	21,3	13746
	3	rest	30127
Transition from overhead to buried cable	1	1	787
	2	0,9	10932
	3	rest	953
SS 10/0.4 kV Podprolog 1	1	1,6	298
	2	1,4	1406
	3	rest	417

Table II. Results for the ground resistance measurements

	SS 10/0.4 kV Podprolog 1	Middle of the line; transition from overhead to buried cable	GSM transmitter Gomila
Ground resistance (all lines in parallel)/*Ω*	0,87	1,54	2,09
Ground resistance (only one line)/*Ω*	0,91	5,29	9,62

Since the soil resistivity measured near the substation exhibits value few times lower than values measured at the location of the transmitter (see Table I), neutral conductor of the power cable supplying the transmitter was behaving as the lightning conductor distributing the atmospheric surges from GSM transmitter Gomila to SS 10/0,4 kV/kV Podprolog 1, and from there to objects in the vicinity of the substation. Classical parallel grounding electrodes were behaving as voltage dividers. As result of this, the atmospheric charge was discharged at the location of the lowest grounding resistance (SS Podprolog), see Table II. This was the initial situation which obviously required the solution differing from classical parallel grounding systems. The novel solution proposed by authors was designed and after installation tested in-situ, as described in the following chapter.

SOLUTION DESCRIPTION AND VALIDATION

After defining the problem, different solutions were analysed. Following approach arose as optimal solution: section of the neutral conductor is converted to lightning grounding, see Figures 4 and 5. This chapter describes short description of the lightning phenomena strike and related concepts as well as description of the proposed innovative solution. The solution arises from the Telegrapher's equation treating the resistive, inductive, capacitive and conductive contribution of the grounding system via the concept of the effective length. [1], [6] At the end of chapter, results of the field measurements executed in order to validate the proposed solution are presented.

While flowed by the high lightning currents, grounding systems exhibit high voltages and formation of the electric fields, particularly for the soils characterized by low conductivity. Aforementioned electric field may exhibit values higher than soil break-down voltage, leading to break-down in the soil surrounding the grounding electrode. As a result of this, soil surrounding the electrode becomes more conductive. This phenomenon may be understood as expansion of the grounding electrode effective cross-section, resulting in reduced grounding resistance R_Z. [7] However, the inductivity of the grounding electrode, originating from the magnetic flux around the conductor, disables homogeneous current flow along entire length of the conductor. Consequently, current scatters to the soil along first few meters of the grounding conductor only. [7] This second phenomenon, preventing the activation of the entire grounding conductor length, may be understand as growth of the grounding resistance R_Z. Resulting resistance, so called impulse resistance R_I, will depend on fact which of previously described two phenomena will overcome. The difference between impulse grounding resistance R_I and grounding resistance R_Z depends on not only the lightning current magnitude, but also its waveform. The steeper current waveform, meaning shorter front time T_F, results in expended current penetration along the electrode. The front time exhibits values in interval 1,8μs to 4,5μs. Considering the specificity of the lightning current waveform, it makes sense to define grounding effective length. This unit provides the information regarding useful length of the grounding electrode in terms of the lightning strike. In other words, the grounding electrode longer than its effective length will exhibit grounding resistance lower than its impulse resistance. On the other side, grounding electrode shorter than its effective length will apply its entire length to scatter the lighting current, meaning, impulse resistance will be equal to grounding resistance. Effective length of the rounding electrode is obtained from following expression:

$$l_E = 1{,}1\sqrt{\frac{T_F}{G_1 L_1}} \qquad (3)$$

were symbols stand for following:

l_E – effective length of the grounding electrode, m

G_1 – electrode conductance-per-length, S/m

L_1 – electrode inductivity-per-length, mH/m, for horizontal electrode usually 1,5 mH/m

T_F – current waveform fron time, μs, according to [1], chosen value is 4,5 μs

For the horizontal cylinder-shaped grounding electrode, electrode conductance-per-length is obtained from following equation:

$$G_1 = \frac{3{,}1}{\rho_z} \cdot \frac{1}{\ln\frac{l}{r}} \qquad (4)$$

were symbols stand for following:
ρ_Z – soil resistivity, Ωm
l - grounding electrode length, m
r – grounding electrode radius, m

Applying the aforementioned relations, effective length of the electrode is calculated in order to obtain the optimal length of the Cu conductor in the soil. From the Table I, one realizes that location were overhead cable converts to buried cable and were additional horizontal grounding electrode starts, soil resistivity foir the first meter of the soil depth exhibits value of 787 Ωm. Due to reasons of safety and considering soil resistance of the next layer (Table I), conservative value of 1000 Ωm is chosen. Assuming current waveform front time of 4,5 μs [1], effective value of 106,51 m is obtained. Based on this value, additional horizontal grounding electrode is realized using 2 Cu conductors with the cross-section of 50 mm^2 and length of exactly 100 m, meaning, physical length of the grounding electrode is few meters shorter than effective length, see Figures 4 and 5. Using this approach, the optimal ratio between the impulse resistance and the grounding resistance is achieved, particularly for the soil characterized by relatively high soil resistivity [5], as one described in this paper. Schematic representation of the LV grid section (substation-transmitter) is shown in Figure 4. Figure 5 displays the cross-section of the cable trench, with 3 phase conductors active and neutral conductor disconnected. Parallel to the cable, 2 Cu conductors are sited, acting as the neutral conductor and the grounding electrode at the same time.

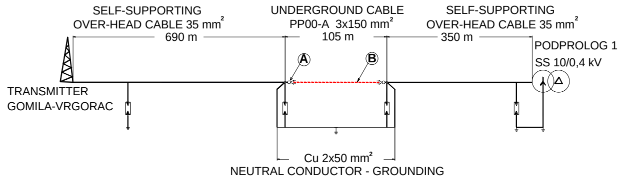

Figure 4: Schematic representation of the proposed solution

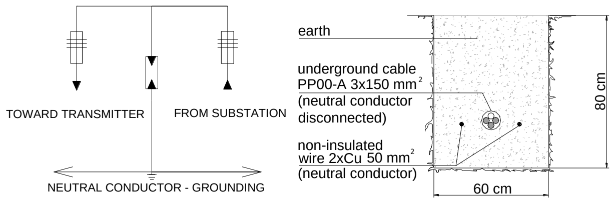

Figure 5. Connection scheme (Detail A from Figure 4) and b) Cable trench (Detail B from Figure 4)

Using this approach, neutral conductor behaves as grounding electrode, loop resistance is reduced and the overall protection level increased. The advantages of this solution in comparison to classical parallel grounding electrodes are visible from the in-situ measurements. The verification of the solution is performed, as already told, using field measurements, simulating, within limitation of the available equipment, actual lighting strike conditions. Using the surge generator 15 kV voltage pulse is injected in the ground in the vicinity of the new grounding electrode and induced voltage value are measured in the begin and at the end of the grounding electrode, as well as at the substation. Obtained values are shown on the oscillograms (Figures 6 a to 6 d).

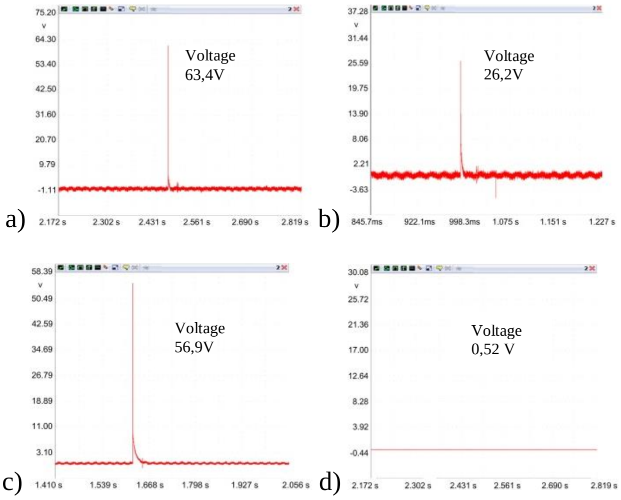

Figure 6. Oscilloscope-based measurements of the pulses in the grounding begin (a), grounding end with original neutral conductor from the cable being disconnected (b), grounding end with neutral conductor from the cable being connected (c), substation (d)

In order to validate the proposed solution, installed grounding is bypassed with neutral conductor from the cable on both sides. For same test condition, in this grounding electrode configuration we obtained results as shown in Figure 6 c).

Analyzing peak values on the oscillograms (Figures 6 a) to 6 d)), following is concluded:

1) Discharging the 15 kV pulse in the vicinity of the “our” grounding electrode 63,4 V pulse is obtained.

2) For same conditions, at the grounding electrode end pulse of 26,2 V is measured. According to the expectations, significant portion of the potential from the grounding begin is scattered to earth, i.e., voltage at the grounding end is lower than same value at grounding begin for factor of 2,4.

3) If grounding electrode is bypassed by neutral conductor from the cable, voltage pulse of 56,9 V is measured at the grounding end. This result clearly shows that efficiency of the grounding system from 2,4 reduced to 1,1. In other words, there is an obvious discrepancy between efficiency of the grounding system based on parallel grounding electrodes and proposed innovative solution, where neutral conductor is “pulled-out” from cable and sited directly in the ground.

4) For same measurements geometry as described in 2), voltage measured at the location of the substation is negligible (equal to noise level – 0,52 V), proving the excellent response of the novel grounding geometry.

Finding 3) may be confusing at the first thought, but it arises from the fact that there is the significant difference in the soil resistivity along the cable path (Table I). In case neutral conductor from the cable is connected on both sides, lightning current will not scatter to the earth on the location of the nearest grounding electrode, but on the location with the lowest ground resistance – substation Podprolog 1 (Table II).

CONCLUSION

This paper reports the solution for the atmospheric over voltages suppression being distributed from the GSM transmitter Gomila to area of SS 10/0,4 kV/kV Podprlog 1. The novelty of the proposed solution is in using the external neutral conductor as the grounding electrode and neutral conductor. The validity of the solution is verified via extensive in-situ measurements using surge generator simulating the waveform similar to actual lightning waveform. Measurements are performed with and without neutral conductor from the cable, verifying the proposed solution against classical parallel grounding electrodes. Furthermore, it is realized that since such grounding system is operational (May 2015.) no reports on lightning-induced damages were submitted, even though the multiple lighting storms occurred.

Same solution may be applied for all low voltage grids with grounded neutral conductor, where, due to high differences in soli resistivity, atmospheric surges are distributed along the neutral conductor.

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