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IMPACT OF THE CHARACTERISTICS OF OVERHEAD GROUND WIRES ON THE CURRENT REDUCTION FACTOR, AND THEIR EFFECT ON THE CHANGE OF GROUNDING SYSTEM POTENTIAL

VPLIV LASTNOSTI NADZEMNEGA ŽIČNEGA OZEMLJILA NA KOEFICIENT ZNIŽANJA TOKA IN POSLEDIČNO NA SPREMEMBO POTENCIALA OZEMLJITVENEGA SISTEMA

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Keywords: surface potential, current reduction factor, grounding, touch voltage, step voltage

Abstract

This paper shows the impact of the characteristics of overhead ground wires on the change of grounding system potential in a power system substation during a single line to ground fault. The touch and step voltages can be affected by changing the overhead ground wire radius. The calculation of the current reduction factor depending on the size of the overhead ground wire is also presented. Furthermore, simulations of the grounding system potential, the surface potential as well as the touch and step voltages of a study case have been made using CYMGRD simulation software, which has implemented the IEEE 80-2000 standard (IEEE Guide for Safety in AC Substation Grounding). The power system substation observed in the simulation includes two incoming 110 kV transmission lines with two 110 kV bus bars as well as 35 kV and 10 kV bus bars. The entire grounding system of the substation is comprised of a conducting net aligned horizontally, and mutually interconnected by vertically placed conducting rods. The simulations

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performed show the change of the observed potential values for a given size of the overhead ground wire. In order to determine the maximum fault current that can occur in the observed substation (which is needed for calculation of the substation ground potential), a single-phase short circuit is simulated on the 110 kV bus bars, using the simulation software DIgSILENT Power Factory.

Povzetek

V tem članku je predstavljen vpliv lastnosti nadzemnega žičnega ozemljila na spremembo potenciala ozemljitvenega sistema v razdelilni transformatorski postaji v primeru enofaznega kratkega stika z zemljo. Sprememba polmera nadzemnega žičnega ozemljila lahko povzroči spremembo napetosti dotika in napetosti koraka. Prav tako je predstavljen tudi izračun koeficienta znižanja toka, ki je odvisen od dolžine nadzemnega žičnega ozemljila. Predstavljene pa so tudi simulacije potenciala ozemljitvenega sistema, površinskega potenciala, napetosti dotika in napetosti koraka dotičnega primera obravnave, ob uporabi CYMGRD simulacijskega programskega orodja, zasnovanega na standardu IEEE 80-2000 (IEEE Navodila za varnost pri ozemljevanju izmeničnih razdelilnih postaj). Obravnavana razdelilna transformatorska postaja vključuje dva 110 kV dovodna daljnovoda z dvema 110 kV zbiralkama ter 35 kV in 10 kV zbiralkama. Pri tem je celotni ozemljitveni sistem razdelilne postaje sestavljen iz horizontalno položene prevodne ozemljitvene mreže, ki je medsebojno povezana z navpičnimi prevodnimi ozemljitvenimi palicami. Izvedene simulacije so pokazale spremembo opazovanih vrednosti potenciala pri določeni dolžini nadzemnega žičnega ozemljila. Z namenom določitve maksimalne vrednosti kratkostičnega toka, ki lahko steče v obravnavani razdelilni postaji in je potreben za izračun ozemljitvenega potenciala, je z uporabo simulacijskega programskega orodja DIgSILENT Power Factory izvedena simulacija enofaznega kratkega stika na 110 kV zbiralkah.

1 INTRODUCTION

When a ground fault occurs in a substation, the flow of the fault current to the earth produces potential gradients within and around the grounding system. In such cases, the ‘step voltage’ is defined as the difference between the surface voltage experienced by a person whose stride is 1 m long, [1]. The surface voltage where individuals stand while their hands are in contact with a grounded structure is called a ‘touch voltage’, [1]. Good design of a substation grounding system should have low grounding system resistance with considerable touch and step voltages that are tolerable to a person, [2]. For the grounding system resistance of large power substations, in the majority of cases, their resistance is about 1 Ω or even lower, while the grounding system resistance of smaller power substations is usually between 1 and 5 Ω, [3]. It is challenging to estimate the resistance of a grounding system based on the length of its conductors, especially if conducting rods are used. The effort for calculation is greatly eased by using specialized simulation software tools, mostly available commercially, based on numerical methods for the calculation of the desired variables.

CYMGRD is simulation software specialized for grounding systems that have implemented the IEEE 80-2000 standard, [4]. Based on a plotted grounding system, CYMGRD calculates the allowed touch and step voltages for a given single-phase short circuit current. In this paper, the impact of the overhead ground wire (OHGW) characteristics on the change of a power system substation ground potential is presented. Simulation cases are based on a real power system substation of 110/35/10 kV with its corresponding grounding system. Determination of single-

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phase short circuit current, needed for grounding system analysis, is performed using DIgSILENT Power Factory software, [5].

2 DETERMINATION OF THE CURRENT RESPONSIBLE FOR THE INCREASE OF GROUNDING SYSTEM POTENTIAL

The total amount of the single-phase short circuit current I_f can be presented as the sum of the transformer neutral currents I_{TR} and the sum of the short circuit currents of each transmission line $3I_0$, [6]. The equivalent circuit diagram of a single-phase short circuit current distribution in case of the fault in power system substation with two incoming transmission lines is shown in Figure 1.

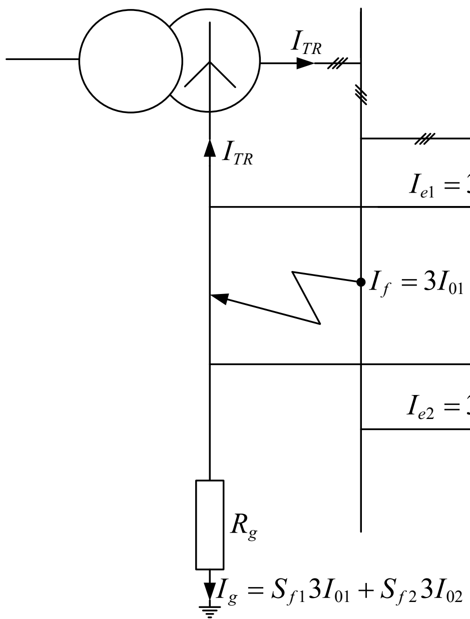

Figure 1: *The short circuit current distribution of a power system substation with two incoming transmission lines (A - phase, B - neutral)*

In order to determine the current responsible for the increase of the grounding system potential, the amount of the current that flows through the grounding system needs to be known. In case of a short circuit inside the power system substation, the fault current is divided between the local ground grid and several metallic return paths associated with the incoming and outgoing lines, i.e. overhead ground wires, cable sheaths and feeder neutrals, [7].

The IEEE 80-2000 standard's Guide for Safety in AC Substation Grounding describes a way of calculating the reduction factor based on the information of incoming transmission lines and power system substation bus bars, [8]. It describes the procedure for the calculation of the current that goes through the grounding system into the ground, and gives the data needed for the calculation of the root mean square value of the asymmetrical failure current for the grid value of X/R in respect to the transient state time.

The quotient of the current which goes through the grounding system I_g and the short circuit current $3I_0$ gives the reduction factor S_f given in the form of Equation (2.1):

$$S_f = \frac{I_g}{3I_0} \quad (2.1)$$

where:

S_f is the current reduction factor;

I_g is the value of the current which flows through the grounding system;

$3I_0$ is the short circuit current through the neutral conductor.

The current that flows through the grounding system needs to be corrected by the factor D_f as shown by Equation (2.2):

$$I_G = D_f I_g \quad (2.2)$$

where:

I_G is the maximum current which can appear in the grounding system;

D_f is the transient state factor.

Expressing the symmetrical value of the grounding network current I_g by rearranging the Equation (2.1); substituting it into Equation (2.2) yields Equation (2.3) for the maximum grounding system current:

$$I_G = D_f S_f 3I_0 \quad (2.3)$$

The D_f factor takes into account the network value of X/R during the transient state. In case of a failure time larger than 30 periods for the nominal current harmonic of 50 Hz, the value of the factor D_f is approximately equal to 1, as presented in Figure 2.

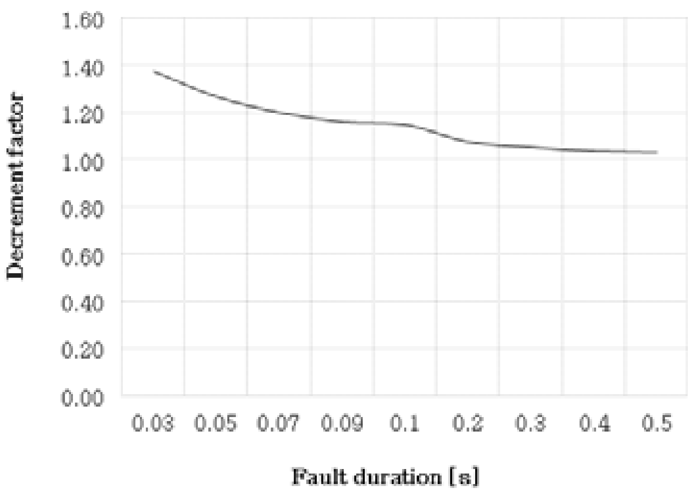

Figure 2: *Decrement factor in relation to transient state time*

The current reduction factor S_f depends on the overhead protection wire resistance; it can be calculated using Equation (2.1), giving Equation (2.4), [9]:

$$S_f = \frac{I_g}{3I_0} = 1 - \frac{Z_{LE}}{Z_E} \tag{2.4}$$

where:

$\underline{Z}_{LE}$ is the mutual impedance of the loop overhead ground wire and the line conductor with common earth return;

$\underline{Z}_E$ is the loop impedance of the overhead ground wire and the earth return.

In order to determine previously mention variables following equations will be used, [9]:

$$\underline{Z}_E^{'} = R^{'} + \frac{\mu_0\omega}{8} + j\left[\frac{\mu_0\omega}{2\pi}\left(\ln\left(\frac{\delta}{r}\right) + \frac{\mu_r}{4}\right)\right] \tag{2.5}$$

$$\underline{Z}_{LE}^{'} = \frac{\mu_0\omega}{8} + j\left[\frac{\mu_0\omega}{2\pi}\ln\left(\frac{\delta}{d_{LE}}\right)\right] \tag{2.6}$$

$$\delta = \frac{1.85}{\sqrt{\dfrac{\mu_0\omega}{\rho_E}}} \tag{2.7}$$

where:

$\underline{Z}_{LE}^{'}$ is the mutual impedance per unit length of the loop overhead ground wire and the line conductor with common earth return;

$\underline{Z}_E^{'}$ is the loop impedance per unit length of the overhead ground wire and the earth return;

d_{LE} is the distance between the conductors and the overhead protection wire;

δ is the depth of the earth path;

ρ_E is the soil resistivity;

$R^{'}$ is the resistance per unit length of the overhead protection wire.

3 INFLUENCE OF THE FAULT PROTECTION SYSTEM SPEED ON THE ALLOWED CURRENT VALUE THROUGH A HUMAN BODY

The current value that a person can feel when in contact with overvoltage is relatively low: about 1 mA. The amount of current from 1 mA to 6 mA is called the 'releasing current'; by definition, it represents the current value that does not cause muscle contraction. For women, its maximum value is taken to be 6 mA, while for men its maximum value is taken to be 9 mA. The values between 60 mA to 100 mA represent a danger of ventricular fibrillation and the halting of heartbeat.

Non-fibrillation current of amplitude I_B with the duration time between 0.03 s and 3 s is related to absorbed energy that the body receives; it is described by Equation (3.1):

$$S_B = I_B^2 t_s \tag{3.1}$$

where:

I_B is the root mean square value of the current which flows through the body;

t_s is duration time of failure;

S_B is the empirical constant related to allowed absorbed energy of the body.

The amplitude and the duration time of the current that flows through the human body needs to be lower than the one that causes ventricular fibrillation.

The duration of the current flow through the human body that can be tolerated in the majority of people is directly related to the current amplitude, [8]. It is assumed that 99.5% of people weighing about 50 kg can withstand the current with amplitude I_S and duration time t_s represented with the equation (3.2):

$$I_B = \frac{0.116}{\sqrt{t_s}} \tag{3.2}$$

For people with weight from about 70 kg upwards, Equation (3.3) is usually used:

$$I_B = \frac{0.157}{\sqrt{t_s}} \tag{3.3}$$

Equations (2.6) and (2.7) are both valid if the duration time of failure is between 0.03 s and 3 s; it is not suitable for very short or a very long duration failure time. In Figure 3, the allowed current values in respect to the shock duration time with values from 0.03 s to 3 s are presented.

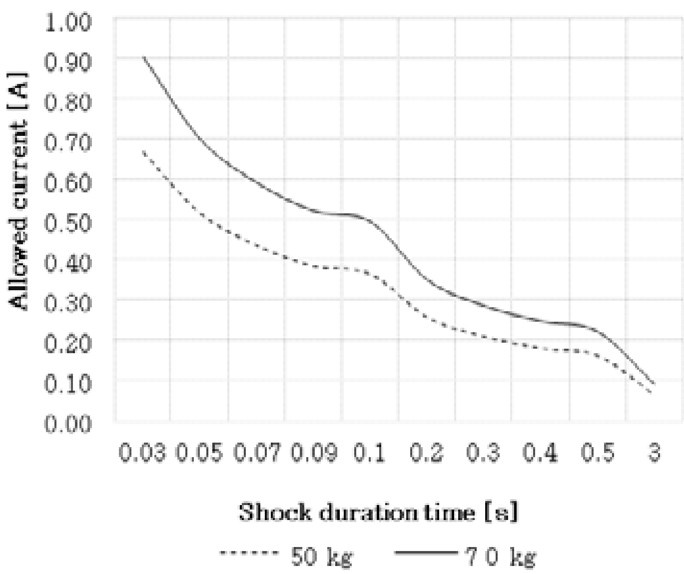

Figure 3: *The value of the allowed current through the body*

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4 GROUNDING SYSTEM SIMULATION

The power system substation observed in the simulation is the Valpovo transformer station, which includes two incoming 110 kV transmission lines with two 110 kV bus bars as well as 35 kV and 10 kV bus bars. The grounding grid is placed 0.8 m underground and made up of 12 transverse and 9 longitudinal conductors mutually interconnected creating the grid of 110 m × 80 m with a total conductor length of 1950 m. In order to lower the grounding system resistance, 25 grounding 3 m long conducting rods are connected to the grounding grid. The grounding system is presented in Figure 4.

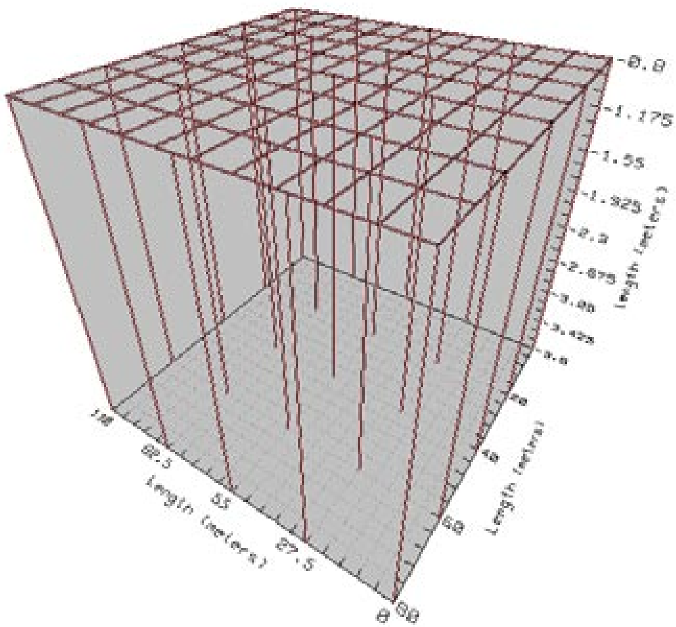

Figure 4: *The Grounding system layout*

4.1 Soil Analysis

For simulation of the grounding system, it is necessary to have the soil resistivity data, which in this case has been obtained by measuring using Wenner method. The measured values were imported into the CYMGRD simulation software. The two-layer soil model simulation has been performed. The results of the soil analysis are presented in Table 1.

Table 1: *Results of the soil analysis*

Upper Layer Thickness (m)	9.02
Upper Layer Resistivity (Ωm)	72.34
Lower Layer Resistivity (Ωm)	11.96

4.2 Safety Parameter Analysis

The allowed touch and step voltages depend on different parameters, such as shock duration, body weight, surface layer thickness and material. With a surface layer thickness of 0.1 m and resistivity of 500 Ωm for a body weight of 70 kg, the allowed touch and step voltages are calculated depending on the shock duration. The simulation results obtained using CYMGRD software according to IEEE 80-2000 standard are presented in Figure 5.

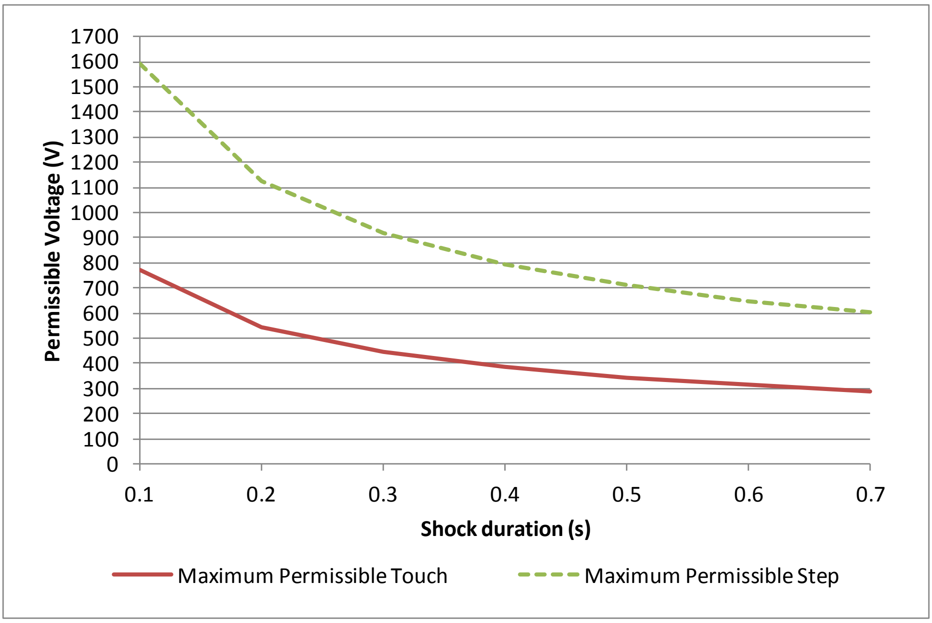

Figure 5: *Maximum permissible values of touch and step voltages in respect to shock duration time*

4.3 Single-phase short circuit current determination

In order to determine the increase in the grounding system potential, it is necessary to determine the single-phase short circuit current; in this case, it has been done using DIgSILENT Power Factory simulation software. The simulation model covers the entire Croatian transmission system. The results are shown in Figure 6.

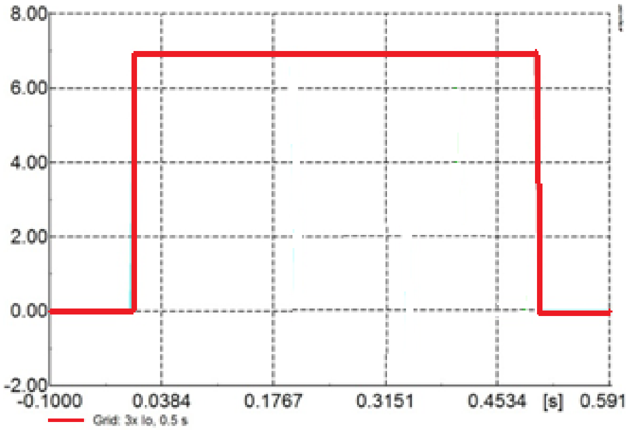

Figure 6: *Single-phase failure duration time*

Disconnection time of the short circuit protection system is set to 0.5 s. The value of the single-phase short circuit current equals 7480 A.

4.4 Grounding System Analysis

The current reduction factor is calculated using Equations (4–7) considering two incoming transmission lines for different radii of OHGW, which are some of the standard sizes of zinc-coated steel OWHG that could be used in the observed transmission lines. The geometric mean distance between the line conductors and OWHG is 5.76 m, while the soil resistivity is assumed to be 72.34 Ωm. The results are presented in Fig. 7.

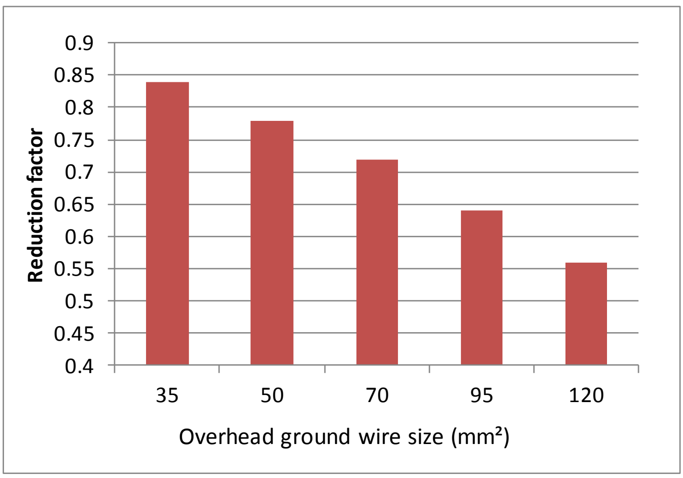

Figure 7: *Current reduction factor in respect to some standard sizes of overhead ground wires*

For the several standard sizes of OWHG, the grounding system potential, the maximum surface potential, the minimum surface potential and the maximum touch voltage are calculated using

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CYMGRD. The fault duration is set to 0.5 s. The transient state factor D_f is assumed to be 1. The value of the single-phase short circuit current is 7480 A. The results are presented in Table 2.

Table 2: *Results of the grounding analysis for different sizes of the overhead protection wire*

OHGW size (mm²)	Current reduction factor	Grounding system potential (V)	Max. surface potential (V)	Min. surface potential (V)	Max. touch voltage (V)
35	0.84	876.4	784.6	515.6	360.8
50	0.78	813.7	728.5	478.7	335
70	0.72	751.1	672.5	441.9	309.2
95	0.64	667.7	597.8	392.8	274.9
120	0.56	584.2	523.1	343.7	240.5

As it can be seen in Table 2, the grounding system potential and the surface potential decrease with the increase of OHGW size.

Due to the results of the safety parameter analysis presented in Chapter 4.2, for the fault duration of 0.5 s and the body weight of 70 kg, the maximum permissible touch voltage is 344.34 V. In the case in which 35 mm² OHGW is used, the maximum touch voltage that occurred exceeds the maximum permissible touch voltage. The distributions of the touch voltage and the surface potential around the grounding grid for the case of 35 mm² OHGW are presented in Figure 8 and Figure 9, respectively.

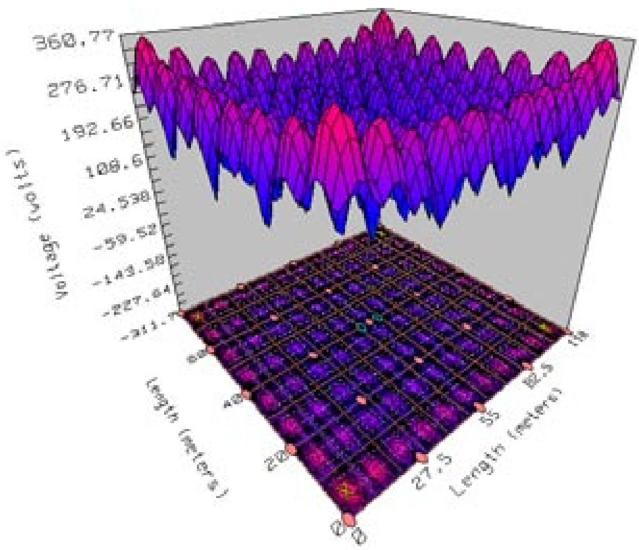

Figure 8: *The distribution of the touch voltage around the grounding grid for the case with OHGW size of 35 mm²*

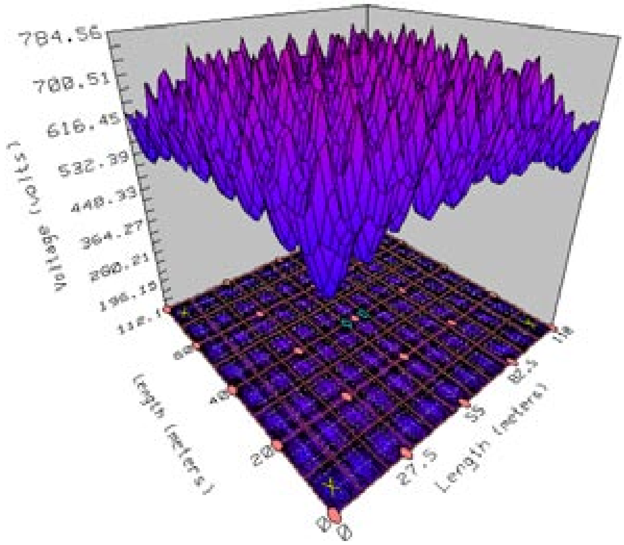

Figure 9: *The distribution of the surface potential around the grounding grid for the case with OHGW size of 35 mm²*

A profile plot along the main diagonal of the grid using a stride of 1 m is presented in Figure 10. The maximum step voltage that occurred equals 49.1 V, which is less than the maximum permissible step voltage.

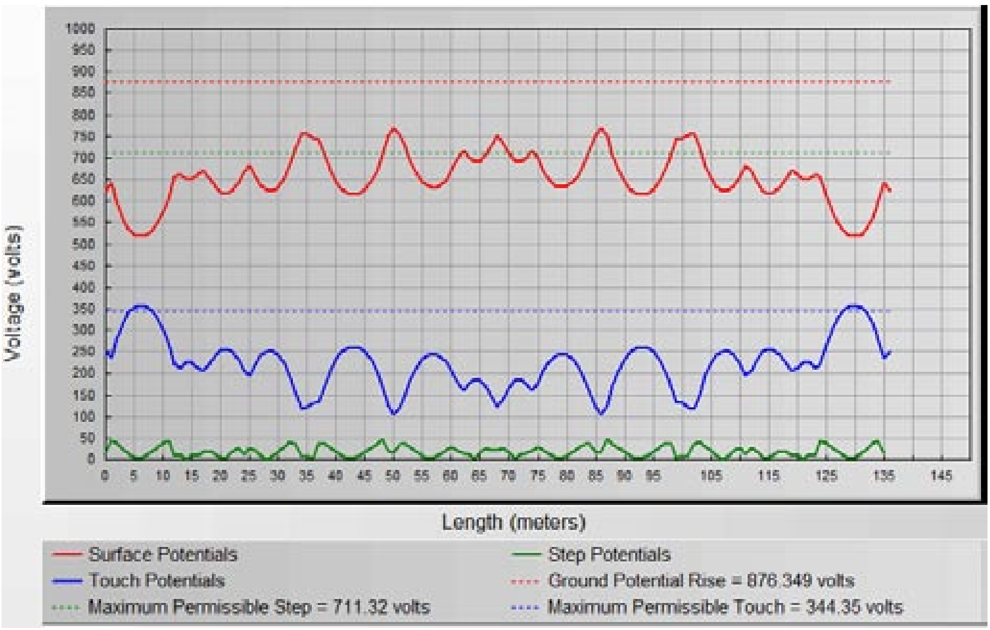

Figure 10: *Profile plot along the main diagonal of the grid using a step of 1 m for the case with OHGW size of 35 mm²*

The size of OHGW that is actually used on 110 kV transmission lines that are connected to the observed transformer station is 70 mm². In this case, the maximum permissible touch and step voltages are not exceeded. Distributions of the touch voltage and the surface potential around the grounding grid for the case with 70 mm² OHGW are presented in Fig. 11. and Fig. 12.

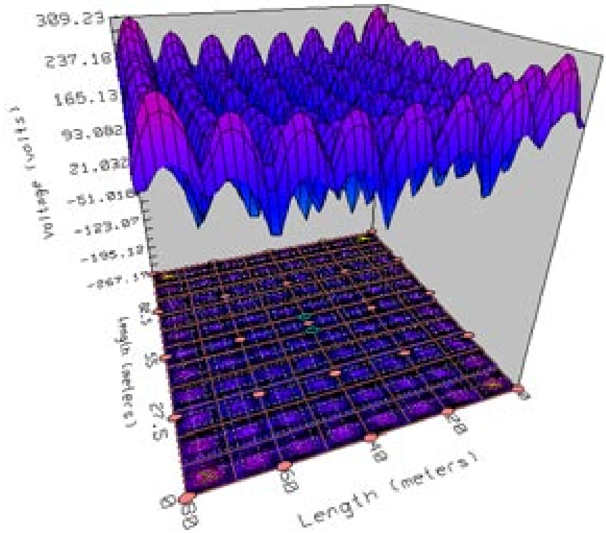

Figure 11: *The distribution of the touch voltage around the grounding grid for the case with OHGW size of 70 mm²*

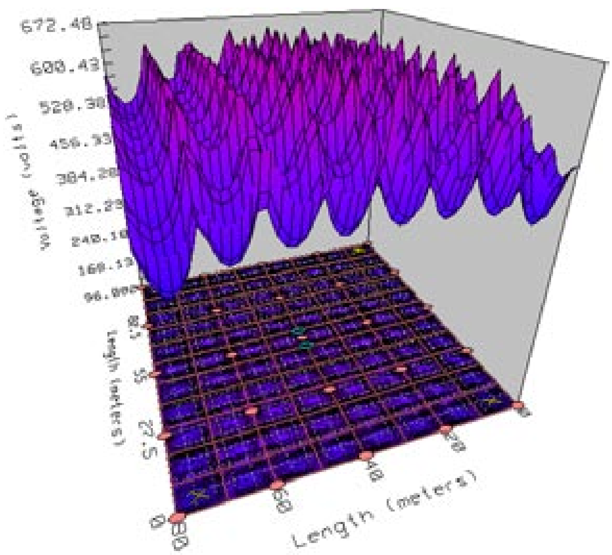

Figure 12: *The distribution of the surface potential around the grounding grid for the case with OHGW size of 70 mm^2*

A profile plot along the main diagonal of the grid using a stride of 1 m for the case with OHGW size of 70 mm² is presented in Fig. 13. Maximum occurred step voltage equals 39.5 V.

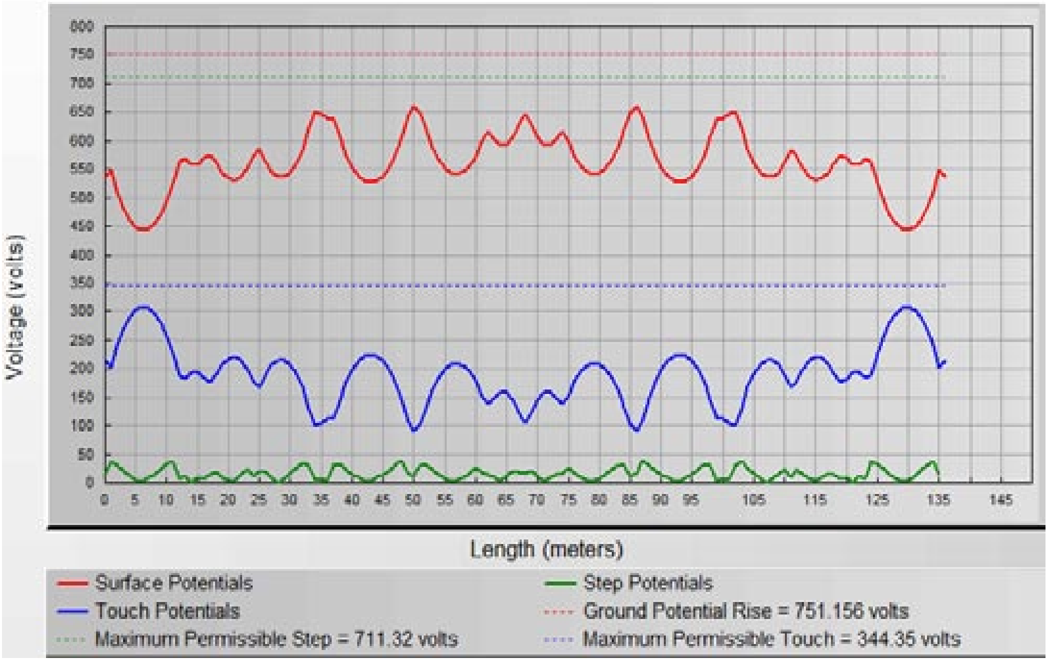

Figure 13: *Profile plot along the main diagonal of the grid using a step of 1 m for the case with OHGW size of 70 mm²*

4 CONCLUSION

This paper shows the impact of the characteristics of overhead ground wires on the change of the grounding system potential in the observed power system substation during a single line-to-ground fault. Calculation of the current reduction factor depending on the size of the overhead ground wire is presented. Simulations of the grounding system potential, the surface potential, and the touch and step voltages have been made using CYMGRD simulation software for a particular study case. The simulation results show that the touch and step voltages, as well as the surface potential decrease with the increase of the overhead protection wire radius. Permissible touch and step voltages are exceeded if 35 mm² overhead ground wire is used in the observed substation. The simulation results for the case of the mm² overhead ground wire, which is actually used on the transmission lines connected in the observed transformer station, show that permissible touch and step voltages are not exceeded.

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Nomenclature

(Symbols)	(Symbol meaning)
D_f	transient state factor
S_f	current reduction factor
I_g	the value of the current which flows in grounding system
$3I_0$	short circuit current through the neutral conductor
I_G	maximum current that can appear in the grounding system
I_B	root mean square value of current that flows through the body
t_s	fault duration time
S_B	empirical constant related to allowed absorbed energy of the body
$\underline{Z}_{LE}$	mutual impedance of the loop overhead ground wire and line conductor with common earth return
$\underline{Z}_E$	loop impedance of overhead ground wire and earth return
$\underline{Z}'_{LE}$	mutual impedance per unit length of the loop overhead ground wire and line conductor with common earth return
$\underline{Z}'_E$	loop impedance per unit length of overhead ground wire and earth return
d_{LE}	distance between conductors and overhead protection wire
δ	depth of the earth path
ρ_E	soil resistivity
R'	resistance per unit length of the overhead protection wire