Computer-Assisted Performance Assessment of Outdoor Substation Grounding Systems

Boško Mijatović
Department for Energy and Telecommunications
Civil Engineering Institute "IG"
Banja Luka, Bosnia and Herzegovina
bosko8@gmail.com

Čedomir Zeljković
Faculty of Electrical Engineering
University of Banja Luka
Banja Luka, Bosnia and Herzegovina
cedomir@etfbl.net

Abstract—**The performance of grid grounding system is assessed by using a commercial software package. The most influential input variables are systematically varied and their impact on the system is observed and discussed. The corrective measures are suggested in order to bring the design parameters of the grounding system within their permissible limits.**

Keywords-computer aided design; grounding system; outdoor substation; performance assessment

I. INTRODUCTION

The ultimate purposes of substation grounding systems are to keep the people safe from dangerous electrical shock inside or near the substation and to provide the drainage of fault currents while maintaining the reliable operation [1]. Successful design of a grounding system comes down to bringing a touch voltage and step voltage into limits defined by regulation [2]. In order to meet regulation requirements, the grounding system design may often lead to a complex geometric shapes which stretch over a large area. On the contrary, computation of the ground potential rise in the closed form is possible only for special cases having simple geometry. In realistic complex grounding systems, it is necessary to use some numerical methods, such as finite element method [3], boundary element method [4] or similar, for a precise computation.

In recent years, the developed mathematical methods are incorporated into commercial software packages which distinctly facilitated the process of the system design and visualization of results. Using a software package, it is possible to systematically vary the input variables and to analyze their effect on the grounding system within a reasonable period of time. In this paper we use the program CYMGRD provided by the CYME International T&D company for the design and analysis of a real grounding system for an outdoor high-voltage substation [5].

II. THEORETICAL BACKGROUND

The elements of electrical power system are grounded in order to maintain their potential at approximately the potential of earth. To provide a low-impedance contact, the grounding system inevitably contains a set of metal components buried underground. During the faults or highly unbalanced power system operation the grounding system conducts some current. Since the grounding impedance is never as low as zero, this current always produces some voltage drop. Therefore, the potential rise is occurred on the grounded masses. Due to the current flow through the ground, the potential of the soil surface around the grounding system is also increased in comparison with the potential of remote earth. A typical chart of the soil surface potential above the grounding grid is shown in Fig. 1.

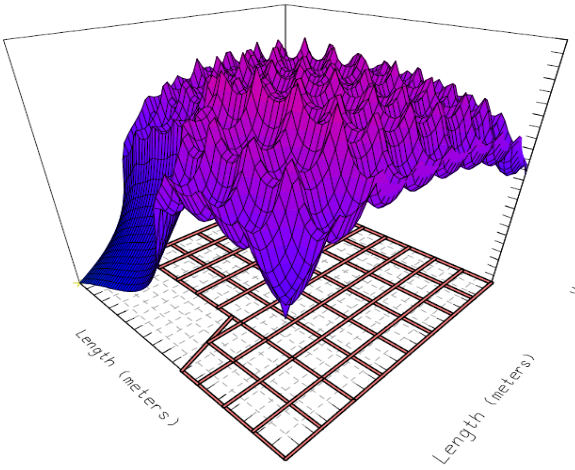

Figure 1. Illustrative chart for the soil voltage above the grounding system

As a result of the potential rise, a plenty of hazardous situations are possible to occur inside or outside of a substation. Basic electrical shock situations are shown in Fig. 2. The following labels are used in the figure: E_{mm} is the metal-to-metal touch voltage, E_k is the step voltage, E_d is the touch voltage, and E_{ip} is the transferred voltage.

Dangerous metal-to-metal touch voltage can be avoided with appropriate equipment positioning. It is not a part of grounding system design. The most common way to avoid transferred voltage endangerment is to isolate cable armoring and electrical protection from main substation grounding. After all, main challenges in grounding system design are to provide compliance of maximum touch and step voltages with their allowable values. Selected grounding grid design should provide safety in substation exploitation but also taking into account a financial aspect of grounding construction and maintenance.

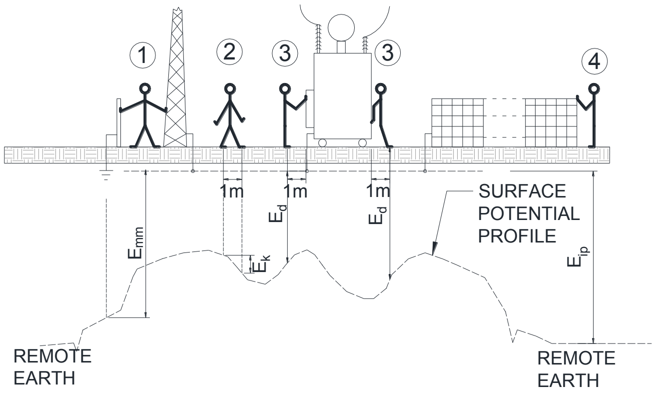

Figure 2. Basic shock situations (modified from [2])

Exposure to touch voltage is illustrated at Fig. 3. U stands for the phase-to-ground potential, Z is the system impedance, I_f is the fault current, I_g is the grounding current, I_b is the body current, R_g is the resistance of grounding and equipment to the point H, R_b is the body resistance, R_{sl} is the surface layer resistance, H is the hand contact point, and F is the foot contact point.

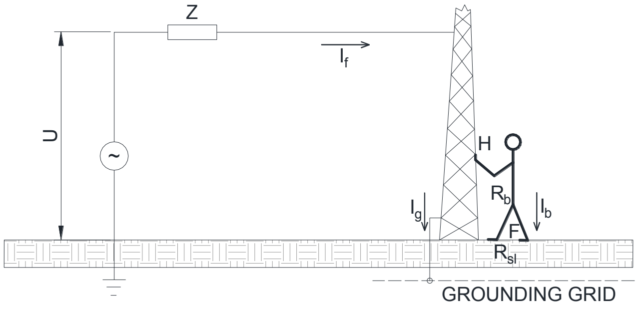

Figure 3. Exposure to touch voltage (modified from [2])

Equivalent touch voltage circuit, corresponding to Fig. 3 is shown in Fig. 4.

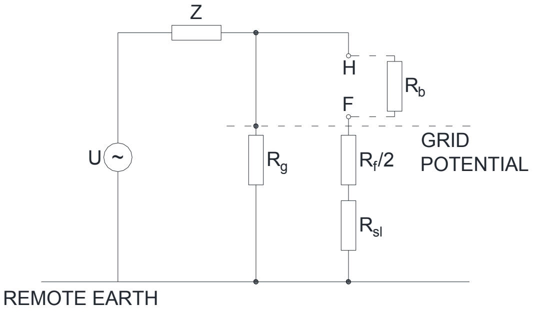

Figure 4. Equivalent touch voltage circuit

The potential of the contact point H corresponds to grounding potential:

$$U_H = I_g \cdot R_g = \frac{U}{Z + R_g} \cdot R_g = \frac{U}{\dfrac{Z}{R_g} + 1} \tag{1}$$

In Eq. 1, Z and U are system defined and they cannot be affected by grounding design. U_H can be controlled by changing grounding resistance R_g. The potential of the contact point F depends on the surface potential distribution. Distribution of potential is a function of grounding system arrangement and grounding potential, which is a key task of grounding system design.

Current through the body I_b after contact between points H and F will be:

$$I_b = \frac{U_H - U_F}{R_{f/2} + R_{sl} + R_b} \tag{2}$$

In Eq. 2, body resistance R_b cannot be affected by grounding design. Body current I_b can be controlled by the foot contact resistance R_f, the surface layer resistance R_{sl} and the touch potential (potential difference U_H-U_F). R_f is a subject of safety at work and can be increased by using protective shoes. The other two variables are subject of grounding system design.

Exposure to touch voltage is represented in Fig. 5, where U_{F1F2} is the potential between point points F_1 and F_2, I_b is the body current on the leg-to-leg path, R'_b is the body resistance leg-to-leg, and F_1, F_2 are the foot contact points.

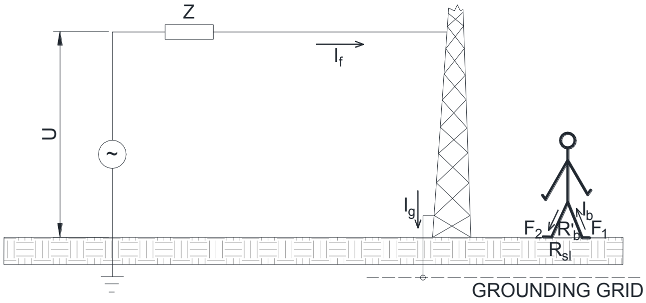

Figure 5. Exposure to step voltage (modified from [2])

Equivalent step voltage circuit, corresponding to Fig. 5 is represented in Fig. 6.

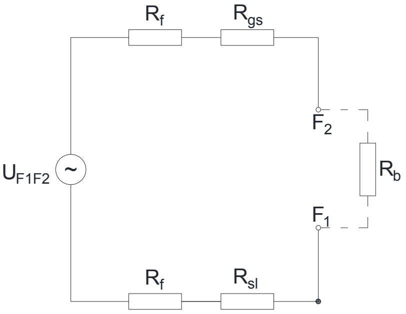

Figure 6. Equivalent step voltage circuit

The body current under potential difference between the foot contact points F_1 and F_2 (step potential) will be:

$$I_b = \frac{U_{F1F2}}{2 \cdot R_f + 2 \cdot R_{sl} + R'_b} \tag{3}$$

Similar as at touch potential calculation, fixed part of Eq. 3 is R'_b, and R_f is a subject of safety at work. Subject of grounding system design are U_{F1F2} and R_{sl}.

Although the body current is only relevant for electrical hazard assessment, touch and step potentials are more favorable for practical use in design, testing and maintenance. Relations between body current and touch (step) potential are fixed for specific grounding system, fault current and body resistance, as it is represented in Eq. 2 and Eq. 3. Maximum allowable body current corresponding to maximum allowable touch and step voltage. Therefore, in the reminder of the paper, the touch and step potentials will be the outputs of the primary importance.

III. TEST CASE

A. *Substation Description*

A test case in this paper is a real outdoor substation for connection of a hydro power plant on a 220kV overhead line. Substation is located on a double layer soil (causeway) with lower layer resistivity of 100Ωm and upper 8m thick layer with approximate resistivity of 800Ωm. Live-to-ground fault current intensity of 9.268kA under -83.2° angle is obtained from a separate study. All calculations are performed for a fault duration of 0.1 seconds, which is a typical time of fault detection and disconnection without automatic reclosing system.

Switchgear disposition within the substation is shown in Fig. 7.

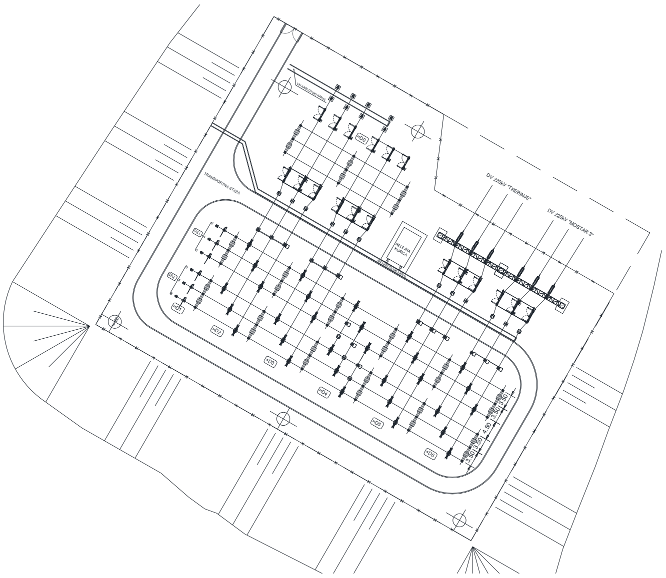

Figure 7. Disposition of the switchgear

B. *Grounding System*

Substation grounding layout is chosen to ensure connection of metal equipment, low grounding resistance, as well as protection from dangerous step and touch voltage. Minimum size of grounding grid is determined by size of area under switchgear equipment, maximum size by substation area (inside the fence).

There are two approaches to substation fence grounding. First and widely used is separation from primary grounding in order to prevent danger voltage transfer outside of protected area. Second approach is metal connection of fence grounding and primary grounding. Both approaches will be considered in simulations presented in this paper.

Configuration of grounding system designed for substation from Fig. 7 is represented in Fig. 8. Grounding grid layout from Fig. 8 is with separated grounding fence widely used for grounding systems ground in low resistivity soil.

In most of the cases, especially in high resistivity soil, use of grounding system from Fig. 8 will not ensure protection from dangerous step and touch potential. In this case it will be necessary to provide additional steps to upgrade the performance of the grounding system.

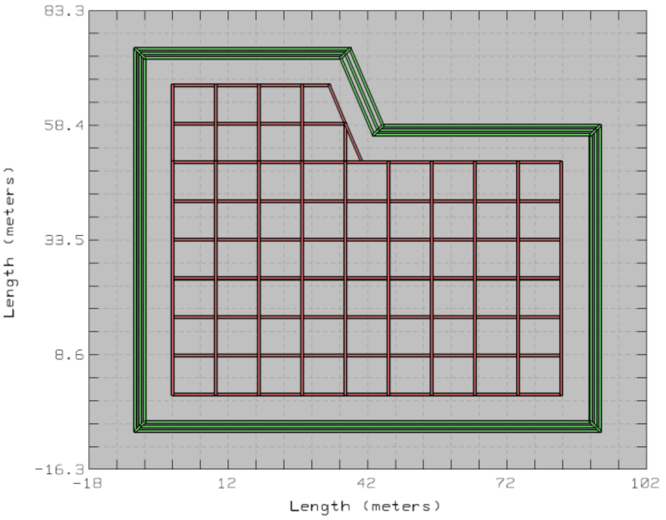

Figure 8. The configuration of the grounding system

The key variables affecting the performance of outdoor substation grounding systems limited to area in a surrounding fence are:

- use of high resistivity soil as surface layer,
- dimension of area used for grounding grid,
- use of grounding rods,
- use of low resistivity soil as laying bed for grounding grid system.

Influence of above listed variables to grounding system will be reviewed in this paper and represented in figures and table below.

IV. SIMULATION RESULTS AND DISCUSSION

A. *Software*

Considering the complexity of electromagnetic processes around grounding electrodes, as well as extensive dimension of substation grid, computer assistance is important factor in modern outdoor substation grounding system design. Simulations presented in this paper were performed using dedicated software CYMGrd, provided by CYME International T&D Company.

B. *Simulation Results*

1) *Reference Case*

Simulations of the grounding system in this paper are provided for low resistivity ground with resistivity of 100Ωm, as well as for double layer soil with high resistivity upper layer, as described for subject substation in section III A. The basic results are shown in Table I (for low resistivity) and Table II (for high resistivity).

TABLE I. GROUNDING SYSTEM GROUNDED IN LOW RESISTIVITY SOIL

Maximum step potential (V)	**Maximum permissible step potential (V)**	**Maximum touch potential (V)**	**Maximum permissible touch potential (V)**
142,51	2879,57	2646	1092,25

TABLE II. GROUNDING SYSTEM GROUNDED IN HIGH RESISTIVITY SOIL

Maximum step potential (V)	**Maximum permissible step potential (V)**	**Maximum touch potential (V)**	**Maximum permissible touch potential (V)**
774,64	2879,57	9567	1092,25

The simulation results for step and touch potential represented in Table 1 and Table 2 exceed their maximum permissible values. It is thus necessary to take further action to get them reduced bellow the maximum permissible thresholds.

2) *Grounding System with High Resistivity Surface Layer*

Adding a thin surface layer of a high resistivity material such as gravel may be a useful corrective measure for bringing the step and touch potentials within the permissible limits. The impact of a surface layer thickness is simulated in CYMGRD software and the results are summarized in Fig. 9 and Fig. 10.

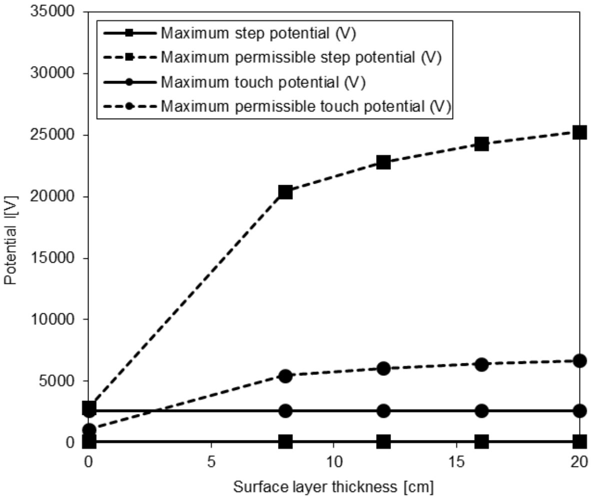

Figure 9. Grounding in low resistivity soil with surface layer

It can be noticed that using of the surface high resistivity layer will affect the touch and step maximum permissible potential, but not the maximum step and touch potential. By using the obtained results, it is possible to assess the effectiveness of this corrective method. For the system grounded in low resistivity soil (Fig. 9), a surface layer of 3 cm is sufficient to set the maximum step and touch potentials within their permissible limits. Nevertheless, a minimum thickness of 10 cm is used in practice, in order to ensure compact layer with proper granulation of material. For grounding system in high resistivity double layer soil (Fig. 10), using of the surface layer will not ensure meeting of maximum permissible touch potential and additional steps should be performed. As the simulations show, the influence of surface layer is limited for layer thickness greater than 10 cm at low resistivity and 15 cm at high resistivity soil.

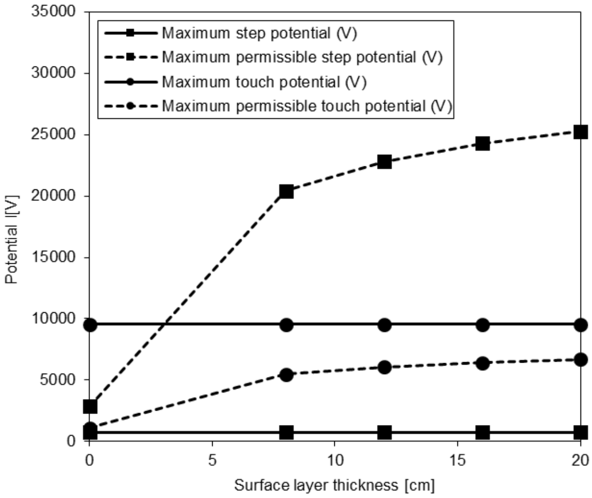

Figure 10. Grounding in high resistivity double layer soil with surface layer

3) *Use of Grounding Rods*

Fig. 11 and Fig. 12 represent simulation results of primary grounding system from Fig. 8, with additional grounding rods. Grounding system is grounded in low resistivity soil and double layer soil with high resistivity upper layer, same as the reference case. Figures are drawn for variable length of the grounding rods.

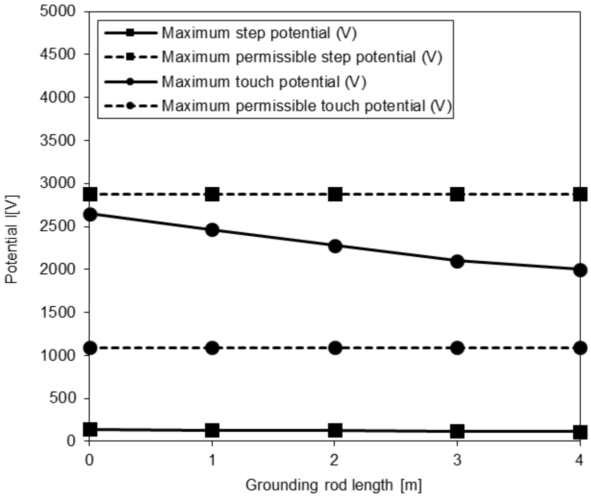

Figure 11. Grounding in low resistivity soil with grounding rods

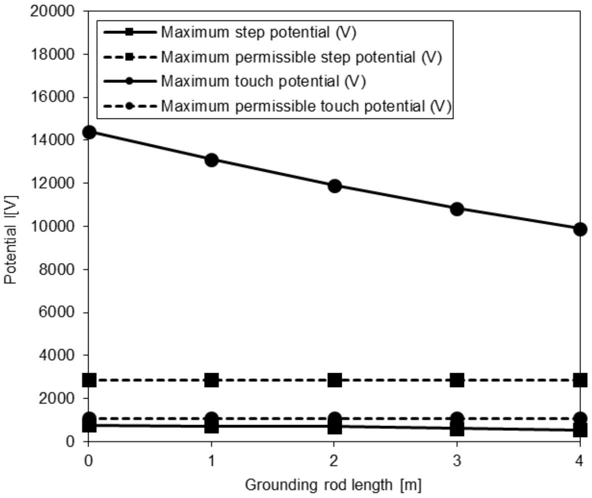

Figure 12. Grounding in high resistivity double layer soil with grounding rods

The simulation results show a greater efficiency of grounding rods in case of grounding system grounded in high resistivity soil. For grounding system in low resistivity soil, the influence of grounding rods on touch and step potential becomes less dominant as the length of the rods increases. Regardless of its positive effects, the use of grounding rods will never decrease the maximum touch potential below the permissible value, for any type of soil and any grounding rod length.

4) Use of Low Resistivity Soil as Encasement for Grounding Rods

Fig. 13 and Fig. 14 illustrate how the grounding rods encased in low resistivity soil layer affect the characteristics of the grounding system. Primary grounding system is grounded in low resistivity soil or double layer soil with high resistivity upper layer, without low resistivity laying bed. Grounding rods used in calculation are 4 m long, with a diameter of 63 mm, embedded in primary grounding grid junction points. Figures are drawn for fixed length of grounding rod and variable thickness of encasement layer.

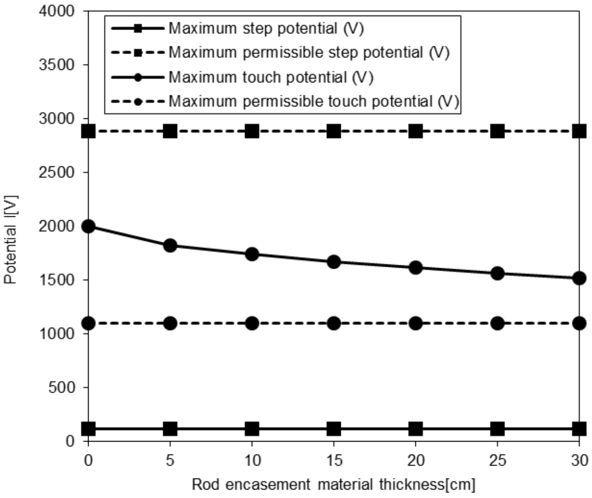

Figure 13. Grounding in low resistivity soil with encased grounding rods

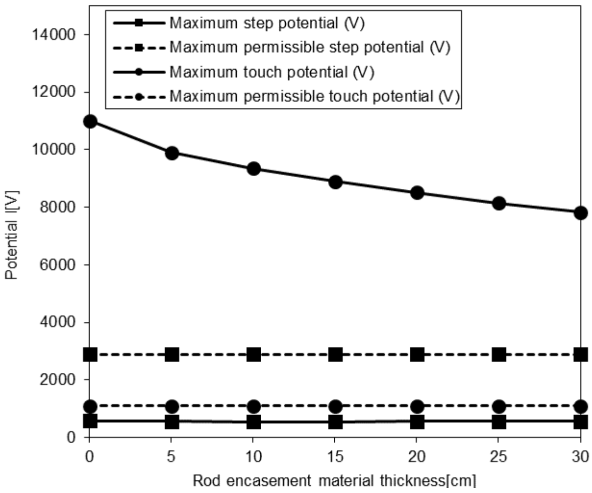

Figure 14. Grounding in high resistivity double layer soil with encased grounding rods

The simulation results show a greater efficiency of grounding rods encasement in case of grounding rods grounded in high resistivity soil. Positive influence to step and touch potential will drop down after encasement material thickness greater than 5 to 10 cm. Influence to step potential will even be negligible because of increasing fault current density at the zone of grounding rods. Increasing of current density will increase gradient of potential at the soil surface, and consequently step potential in the proximity of grounding rod.

5) Widening of Area Used for Grounding Grid

All previous simulations of grounding system grounded in double layer soil with high resistivity upper layer shown significantly greater touch potential from its permissible limits. In order to improve performance of grounding system in high resistivity soil, it is necessary to simultaneously use two or more elaborated additional measures.

The final part of simulation includes a selection of three variant solutions for grounding system grounded in double layer soil with high resistivity upper layer. Each solution involves widening of primary substation grounding grid to total available area, with connection of fence grounding to substation primary grounding system. The characteristics of selected grounding system variant solutions are represented in Table III. Variant solution 1 from Table III includes a wider grounding system with surface high resistivity layer, without grounding rods. Variant solutions 2 and 3 are based on variant 1, modified with grounding rods length of 2 m and 3 m, respectively.

Although all variant solutions presented in Table III fulfill criteria for maximum permissible touch and step potential, they are different from techno-economical aspect. Variant solution 1 is most economically preferred, but solution 2 is less sensitive to drainage conditions, which make it technically preferred. Variant 3 is a variation of variant 2, a bit expensive, but with a greater safety margin in maximum touch potential. Considering benefits of all variant solutions, solution 3 is found as the most favorable for high-resistivity dry soils.

TABLE III. VARIANT SOLUTIONS OF GROUNDING SYSTEM GROUNDED IN HIGH RESISTIVITY SOIL

Description	Variant solution 1	Variant solution 2	Variant solution 3
Grounding resistance (Ω)	1,45	1,42	1,39
Primary grounding conductor length (m)	2222	2222	2222
Grounding rod length (m)	0	2	3
Total length of grounding rods (m)	0	196	294
Rod encasement material thickness (cm)	0	0	0
Surface layer thickness (cm)	15	12	12
Maximum step potential (V)	575	559	611
Maximum permissible step potential (V)	23960	22810	22811
Maximum touch potential (V)	6223	6011	4831
Maximum permissible touch potential (V)	6363	6075	6075

V. CONCLUSIONS

In this paper the application of CYMGRD software to the performance assessment of grid grounding systems is demonstrated. The design process is illustrated on a real outdoor high-voltage substation. The first step was the identification of the most influential input variables. The inputs are then systematically varied and their impact to the performances of the grounding system are computed and discussed. Some useful corrective measures are suggested.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of CYME International T&D company which provided a time limited fully functional version of the CYMGRD software.

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