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GROUNDING SYSTEMS DESIGN WITH 3D-SOFTWARE FOR SOLAR CHIMNEY POWER PLANT

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Abstract

Solar chimney power plants require grounding systems in order to prevent turbine components and living creatures from lightning and fault current. The main objective of this paper is to develop an effective solar chimney power plant grounding systems model to levels ensure that step and touch potentials are within the acceptable levels using effective design implementation steps based on the IEEE Std. 80-2000. The grounding systems consisting of conductors and electrodes with different and asymmetric depths of embedment as well as a non-homogenous two-layer soil model are analysed. A novel approach for grounding systems of solar chimney power plant is performed with 3D software. Three different types of grounding models are proposed and simulated for solar chimney power plant. The singular vertically turbine configuration of solar power plant is used in the first and second models. The first model which has new grounding configuration is suitable for touch voltage than second model. Finally, it examines the grounding system of a solar chimney consisting of horizontally 32 turbines in the third model. The touch voltages below the maximum permissible values are achieved in the first and third models.

Key words: *Grounding, Solar Power Generation, Power System Protection, Fault Currents, Electrical Safety*

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1. Introduction

In modern societies, one of the most important indicators of the economic growth is energy. Energy demand increases continuously due to the rapid population growth and industrialization. This demand cannot be satisfied with the available limited resources. Thus, it is gaining much more importance to benefit from the renewable energy resources in a more effective manner.

Solar chimney power plant is one of the generation stages of electricity energy based on solar energy. As a result of the increase in investments in developing technologies and renewable energy resources, the numbers of solar chimneys is also increasing day by day. As solar chimneys is an electric power system operating with the rise of air due to heat increase, installation is foreseen for regions with high solar energy potential and medium-scale altitude as a result of feasibility studies in installation.

Together with the rising of heated air, as solar chimneys contain energy generation units of a long chimney system, the risk of exposure to lightning and possibility of fault current stemming from generation components are significantly high. Suitable grounding systems should be designed in order to prevent the harm of these undesired over currents on turbine generators other generation system components and also on living creatures.

Grounding system analysis is based on minimum ground potential rise during the fault. Among the requirements to be met in grounding system design as per IEEE Std. 80-2000, it is specified that the step and touch voltages to be generated during a fault should be less than the maximum permissible step and touch voltages. Step and touch voltages depend on the structure of the grounding system, soil structure and fault current [1].

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Grounding system designs often use formulas based on experiences. These formulas are given for a single-layer soil model and a certain type of electrode. They do not provide sufficiently accurate results as there is more than one grounding electrode and the soil layer virtually consists of more than one layer. In order to eliminate such insufficiency, there is a need for computer software that computes with realistic models. This study carries out grounding design through the use of CYMGRD (CYMe's GRounDing) grounding design software that conducts analysis through finite elements method [2].

By employing a two-layer soil model used in this paper in CYMGRD for the earth consisting of one or more non-homogenous and horizontal or vertical layers, it is possible to determine the resistivity and thickness of layers [2].

With the formulas specified in the standards, the grounding resistances and the touch and step voltages can be accurately calculated for the grounding systems, which are made of horizontally-placed conductors and vertically-placed electrodes, and have fixed depth of embedment [1]. CYMGRD software is used to perform more accurate calculations of the grounding resistances and the step and touch voltages of the grounding systems, which consist of asymmetric electrodes and conductors, and have varying depths of embedment.

In the literature, studies on solar chimneys are generally about static and dynamic problems as well as thermodynamic modeling. Pasumarthi and Sherif examined the performance characteristics of solar chimneys by conducting both theoretical and experimental studies [3,4]. Padki and Sherif analyzed the power and efficiency of chimney systems with different geometries [5].

This paper, realistic solutions including grounding conditions for solar chimney systems have been performed with 3D analysis instead of a system design by using experienced-based empirical formulations. This study carries out an appropriate design for the maximum permissible step and touch voltages by including the reinforcements into the grounding system. Then, it examines model of the grounding system of a solar chimney consisting of horizontally 32 turbines.

2. Solar Chimney Power Plant

Solar chimney is a system based on the rising of hot air, which converts the thermal energy into kinetic energy and then kinetic energy into electric power. In this chapter, general structure of the solar chimney is explained over a vertical solar chimney model. In this system the air under the collector is heated through solar radiation on the collector surface. Because of the density difference between the hot air and the cold air outdoors, the air is conveyed horizontally towards the center of the collector. By turning the rotor in the middle of the chimney in the center of the collector, kinetic energy in the air is converted into mechanical energy. Through increasing the number of revolutions of the rotor shaft, mechanical energy is transferred to the generator and converted into electric power. In Fig. 1, schematic diagram of power generation in solar chimneys is shown and in Fig. 2, power plant in Manzares which is the first study on solar chimneys is displayed [6].

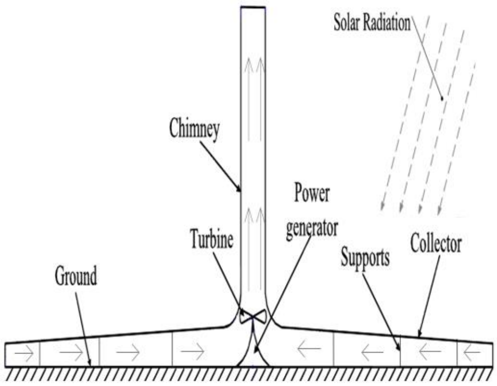

Fig. 1. Schematic diagram of solar chimney power plant.

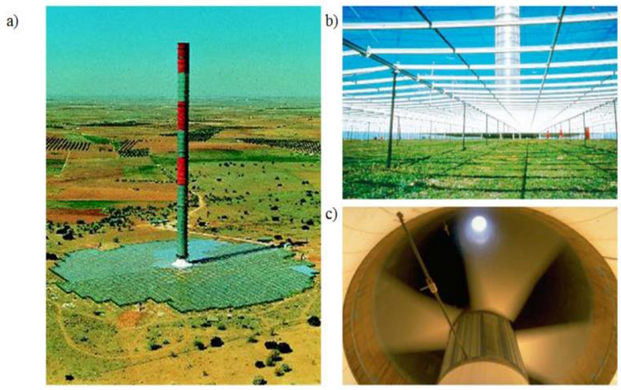

Fig. 2. Pictures of Manzanares solar chimney plant prototype: (a) whole plant; (b) collector; (c) turbine [6].

In the table I is presented lots of solar chimney power plant including collector diameter (Rcol), chimney height (Hchi) and chimney diameter (Rchi) values.

Table 1. Some of the solar chimney models

Location	Solar Chimney Power Plant				Ref
Region	R_{col} (m)	H_{chi} (m)	R_{chi} (m)	Power	
Manzares, Spain	122	194.6	5.08	48 kW (designed) 36-41 kW (measured)	Haaf [7] and Haaf et al.[8]
Yinchuan, China	250	200	5	110–190 kW	Dai et al. [9]
Mediterranean region	625	550	41	2.8–6.2MW	Nizetic et al. [10]
Arabian Gulf region	1000	500	50	>8 MW	Hamdan [11]
Adrar, Algeria	250	200	5	140–200 kW	Larbi et al. [12]
Qinghai-Tibet Plateau	2825	1000	40	372 TJ/year-829TJ/year	Zhou et al. [13]
Kerman, Iran	40	60	1.5	4.035 kW	Najmi et al. [14]
5 cities in Iran	122	194.6	5.08	175–265 MWh year	Asnaghi et all.[15]

In order to align short-circuit faults and undesirable over currents that may occur in solar chimney power plants containing turbine and generator components with allowed maximum to touching and step voltages evaluated in IEEE 80-2000 standard, the most suitable grounding model is required. For this reason, calculation of a 3D computer aided grounding model in accordance with IEEE 80-2000 standard is found suitable for the protection of system components and living creatures.

3. Measurements of Soil Resistivity for Two-Layer Soil Model

As the earth structure is composed of multi-layered strata that have different resistivities, it would be a more appropriate approach to measure the grounding resistance based on the multi-layered earth model.

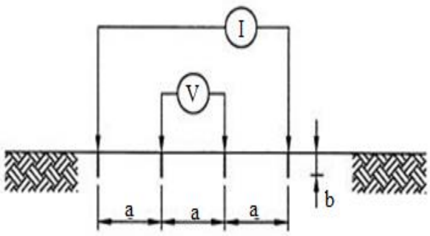

Fig. 3. Wenner method [1].

CYMGRD software supports Wenner four-pin soil resistivity measurement technique. The measurement diagram concerning Wenner four-pin soil resistivity measurement technique is given in Fig. 3.

According to this method, while the outer electrodes provide current I, measured by an ampermeter, the voltage V generated among the inner electrodes for the soil resistance by the current is measured by a voltmeter, and Ohm's law is applied to find the voltage [2]. To be able to model the multi-layer soil structure in this software, it is possible to use a two-layer soil consisting of an upper layer with a finite depth and a lower layer with an infinite depth, which have different resistivities.

Soil resistivity (ρ) is calculated using the formula below, based on the measured values of V and I, depth of electrodes (b) and electrode spacing (a):

$$\rho = \frac{4\pi a(\mathrm{V}/\mathrm{I})}{\left[1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}\right]} \tag{1}$$

If *a* is very large compared to be, the equation (1) can be reduced to equation (2), neglecting *b*.

$$\rho = 2\pi a\left(V / I\right) \tag{2}$$

In the two-layer soil model, the thickness of the lower layer is accepted to be infinite, and the thickness of the upper layer is used to calculate the soil resistivities of the upper and lower layers.

The software employs the finite elements method and minimizes the error function (4) of the resistivity values measured by Wenner method and calculated by equation (3), thereby determining the optimum soil layer resistivities (ρ_1, ρ_2) and thickness (h).

$$\rho_a = \rho_1 (1 + 4 \cdot \sum_{n=1}^{\infty} \left[\frac{(\frac{(\rho_2 - \rho_1)}{(\rho_2 + \rho_1)})^n}{\sqrt{1 + \left(\frac{2 \cdot n \cdot h}{a}\right)^2}} - \frac{(\frac{(\rho_2 - \rho_1)}{(\rho_2 + \rho_1)})^n}{\sqrt{4 + \left(\frac{2 \cdot n \cdot h}{a}\right)^2}} \right]) \tag{3}$$

ρ_1: upper layer soil resistivity [Ω.m] ρ_2: lower layer soil resistivity [Ω.m]

h: upper layer thickness [m] n: an integer from 1 to ∞ a: electrode spacing [m]

$$f(\mathrm{x}) = \sum_{n=1}^{N} \left[(\rho_{mi} - \rho(\mathrm{i}))^2 / {\rho_{mi}}^2 \right] \tag{4}$$

ρ_{mi}: soil resistivity measured based on pin distances [Ω.m]

ρ(i): soil resistivity calculated based on pin distances [Ω.m]

4. Safety Analysis for Grounding Systems

The maximum permissible step and touch voltages for different body weights according to IEEE Std. 80-2000's are given in equations (13), (14), (15) and (16).
If we express the maximum permissible touch and step voltages, using equations (5) and (6) as seen in Figure 4:

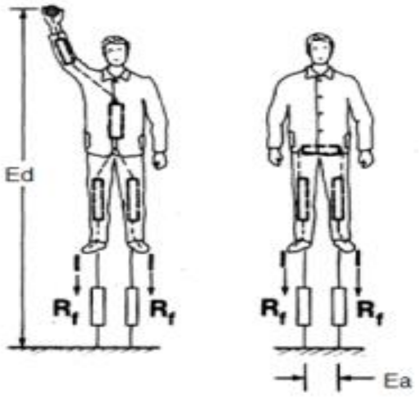

Fig. 4. Touch and step voltages [17].

$$E_{touch} = (R_B + R_f / 2) \cdot I_B \tag{5}$$

$$E_{step} = (R_B + 2 \cdot R_f) \cdot I_B \tag{6}$$

R_B: human body resistance [Ω]
R_F: the ground resistance of one foot [Ω]
I_B: the maximum permissible body current [A]
Human body resistance R_B is accepted to be 1000 **Ω** for 50 kg and 70 kg body weight.
The ground resistance of one foot is calculated by equation (7).

$$R_F = \frac{\rho}{4 \cdot b} \tag{7}$$

Where ρ is soil resistivity and b is the radius of the foot contact surface. By taking b as approximately 0.08 m [17];

$$R_F = \frac{\rho}{(4)\cdot(0.08)} = 3 \cdot \rho \tag{8}$$

The maximum permissible body current according to IEEE Std. 80-2000 [18]:
For a body weight of 50 kg:

$$I_B = \frac{0.116}{\sqrt{t_s}} \tag{9}$$

For a body weight of 70 kg:

$$I_B = \frac{0.157}{\sqrt{t_s}} \tag{10}$$

t_s: fault elimination time [s].
Surface layer with a high resistivity may be added in order to keep the permissible touch and step voltages high. In such a case, the effect on the foot resistance is found by C_s surface layer reduction coefficient.

$$C_S = 1 - \frac{0.09 \cdot (1 - \rho / \rho_S)}{2h_s + 0.09} \tag{11}$$

ρ_s: resistivity of the surface part of soil [Ω.m]
h_s: thickness of the surface material with high resistance [m]
The effect of surface layer reduction coefficient is multiplied by foot resistance (R_F) to obtain equation (12).

$$R_F = \frac{\rho}{4 \cdot b} \cdot C_s \tag{12}$$

If the calculated values of R_F, R_B, I_B and C_s are added into equations (5) and (6):
Touch and step voltages in the case that the body weight is 50 kg:

$$E_{touch} = (1000 + 1{,}5 \cdot C_s \cdot \rho_s) \cdot 0{,}116 / \sqrt{t_s} \tag{13}$$

$$E_{step} = (1000 + 6{,}0 \cdot C_s \cdot \rho_s) \cdot 0{,}116 / \sqrt{t_s} \tag{14}$$

Touch and step voltages in the case that the body weight is 70 kg:

$$E_{touch} = (1000 + 1{,}5 \cdot C_s \cdot \rho_s) \cdot 0{,}157 / \sqrt{t_s} \tag{15}$$

$$E_{step} = (1000 + 6{,}0 \cdot C_s \cdot \rho_s) \cdot 0{,}157 / \sqrt{t_s} \tag{16}$$

Grounding systems are designed to keep the step and touch voltages below such values for the safety of living creatures.

5. 3D Design of the Grounding System for Solar Chimney Power Plant

This section examines the foundation grounding of solar chimneys, taking into account the foundation reinforcements through the use of CYMGRD software. The study of M. S. Naderi et al. is taken as reference to verify the results obtained by the soil model, geometric model and simulations [18]. First, the grounding is performed merely with the foundation reinforcements. Then, the grounding systems are included, and a grounding system is designed, which does not exceed the maximum permissible touch and step voltages according to IEEE Std. 80-2000.

Table 2. Soil data.

Electrode spacing (m)	1	2	4	8
Resistivity (Ω.m)	200	150	80	30
Thickness and resistivity of the surface layer	20 cm / 10000 Ω.m			

Table 3. Geometric parameters.

Grounding electrode diameter	16 mm
Grounding conductor diameter	16 mm
Grounding electrode length	7 m
Foundation dimensions (width x length x depth)	120 m x 2 m x 3 m
Reinforcement spacing	20 cm
Arc conductor depth	1.5 m

For the two-layer soil model, a soil analysis is conducted using the data in Table 2. Using equation (3), the upper layer resistivity, the upper layer thickness and the lower layer resistivity were referenced values of the option of two-layer (from soil measurement) determined by the program as soil model. The resistivity of the concrete surrounding the electrodes and conductors is accepted to be equal to the soil resistivity.
Using the equations (15) and (16) for a body weight of 70 kg according to IEEE Std. 80-2000, the maximum permissible step voltage is found to be 11419.1 V and the maximum permissible touch voltage 3021.3 V. Grounding system data are given in Table 3.

A. Case 1

Based on the studies on wind turbines in the literature, suitability of the grounding network designed as the first model to the grounding system in solar chimneys has been analysed by software. Fig. 5 shows the solar chimney grounding by foundation reinforcements.
As seen in Fig. 6, since the maximum touch voltage (2492.6 V) is lower than the maximum permissible touch voltage (3021.3 V) in this grounding system, it is achieved to meet the necessary safety criteria.
In the model designed for the first case, it is seen that the surface voltage, step voltage and touch voltage are within the limit values specified in the standard.

A. Case 2

For the case in which the area where solar chimney is installed is designed round, in the grounding model the number of conductors is decreased as distinct from the first model and instead, the number of electrodes is increased and a different approach has been aimed (Fig. 7).
As seen in Fig. 8, since the maximum touch voltage (4272.7 V) is higher than the maximum permissible touch voltage (3021.3 V) in this grounding system, it fails to meet the necessary safety criteria.

In the second case, touch voltage - one of the voltage components - is not within the allowed values as specified in Fig. 9.

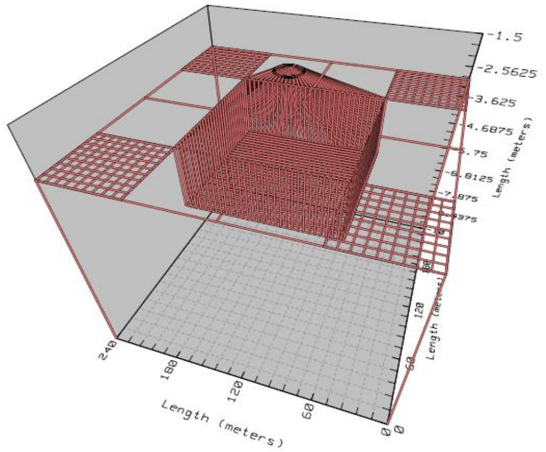

Fig. 5. Solar chimney grounding model 1.

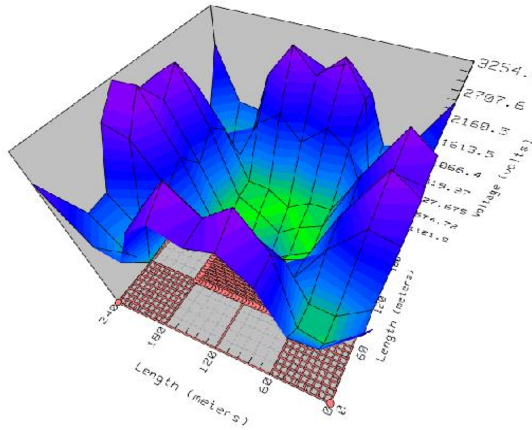

Fig. 6. Touch voltages to the grounding system designed for case 1.

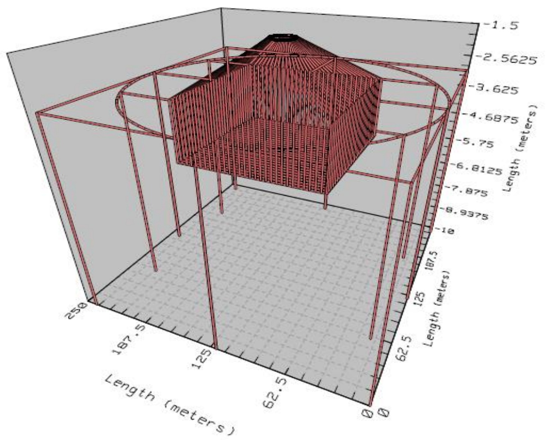

Fig. 7. Solar chimney grounding model 2.

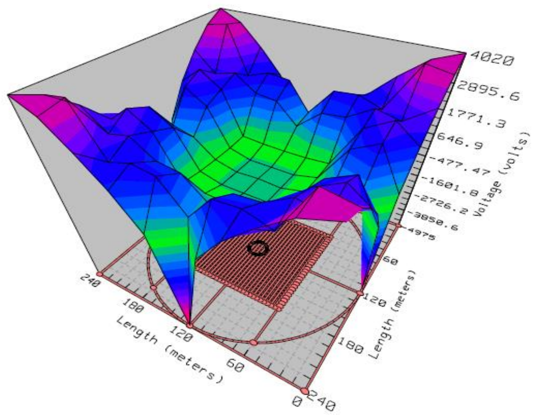

Fig. 8. Touch voltages to the grounding system designed for case 2.

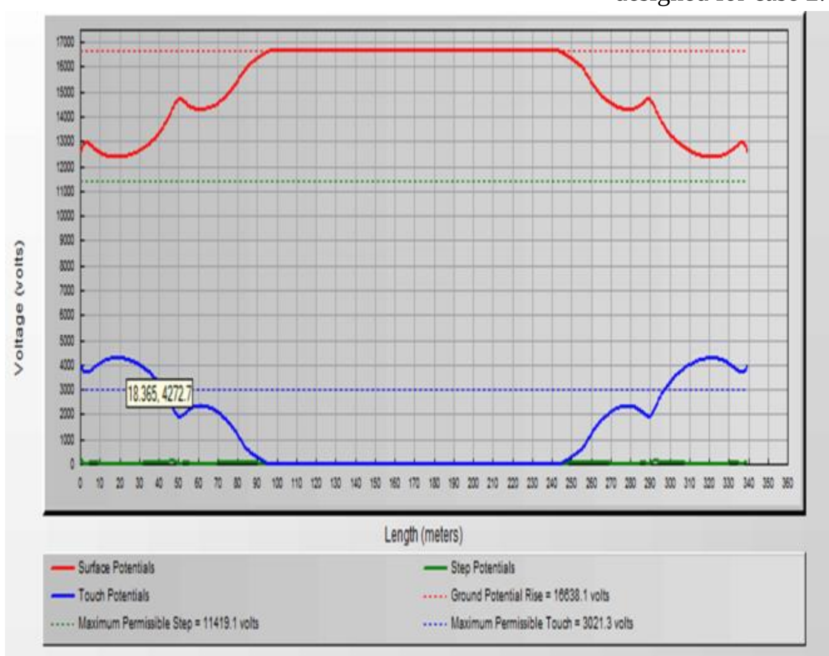

Fig. 9. Potentials profile for case 2.

C. Case 3

In solar chimney system, a new grounding system model approach has been designed for systems with 32 turbines in horizontal direction. Here, by placing a grounding electrode at every corner of 32-turbine structure, reaching of grounding to suitable voltage values allowed has been aimed (Fig. 10).
As seen in Fig. 11, since the maximum touch voltage (2865.9 V) is lower than the maximum permissible touch voltage (3021.3 V) in this grounding system, it doesn't fail to meet the necessary safety criteria. It is seen in Fig. 12 that voltage components are within the allowed limit values.

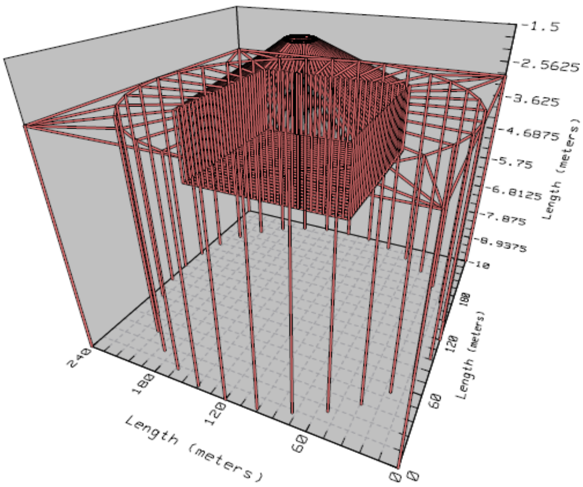

Fig. 10. Solar chimney grounding model 3.

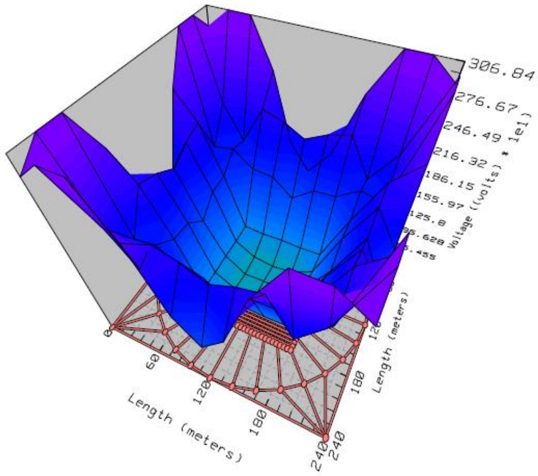

Fig. 11. Touch voltages to the grounding system designed for case 3.

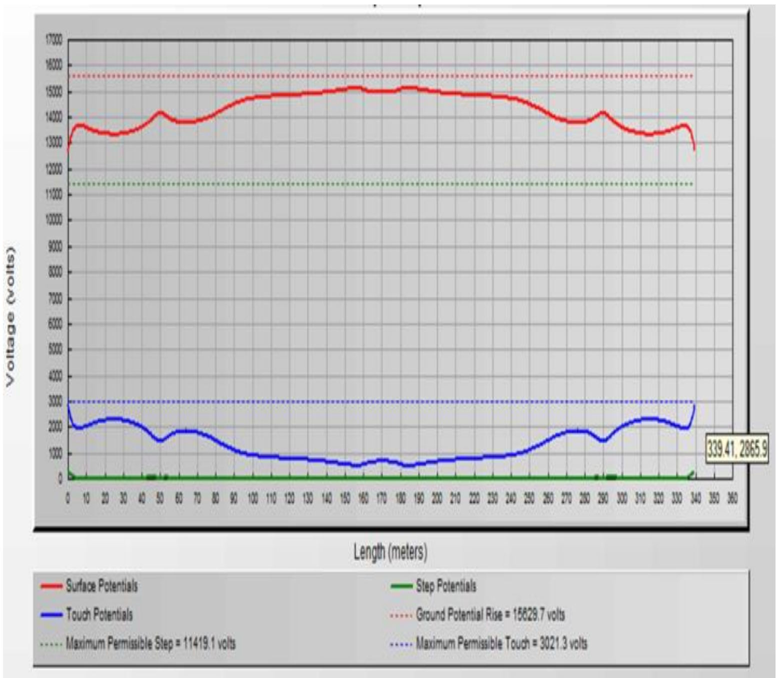

Fig. 12. Potentials profile for case 3.

6. Conclusion

As solar chimneys are renewable energy resources with high and wide area, it is important to build grounding system in parallel with the values specified in the standard in order to protect solar chimney components and living creatures from lightning and fault currents.

This study examines the grounding systems of a single solar chimney and comprising 32 turbines with a solar chimney by employing a non-homogenous two-layer soil model. The effect of the foundation reinforcements is included in the grounding design of the solar chimney. The step and touch voltages of the grounding system of the solar chimney are altered to meet IEEE Std. 80-2000 by first using merely reinforcements and then including some electrodes and conductors. The use of merely foundation reinforcements in solar chimney grounding and the non-use of additional grounding electrodes reduce the cost of the grounding system.

Grounding system designs often use empirical formulas based on experiences. Therefore, the aim of the study is to contribute to a reliable grounding model with such new approach as well as the generation performance of solar chimney power plants in the literature

Different grounding models for both vertical-axis and 32-turbine horizontal-axis solar chimney power plants are designed in this paper. The same configurations of solar power plant are applied in the first and second models. Touch voltage is reduced in first model than second model by new grounding configuration. Finally, it examines the grounding system of a solar chimney consisting of horizontally 32 turbines in the third model. Touch voltage of the third model is achieved to find below the maximum permissible touch voltage.

Step voltages are also provided permissible values. Table 4 shows touch voltages of all models.

Table 4. Touch voltages values of all cases

Models	Touch Voltage (V)	Permissible Touch Voltage (V)
1	2492.6	3021.3
2	4272.7	
3	2865.9	

While touch voltage of the second model is found 4272.7 V, this value is reduced in the first model to 2492.6V. Touch voltage of the third model which has 2865.9V is found. The touch voltages below the maximum permissible values are achieved in the first and third models. So the first and third models are appropriate to use in the grounding systems design for solar chimney power plants.

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