ANALYSIS OF WIND TURBINE GROUNDING SYSTEMS IN TERMS OF TOUCH AND STEP VOLTAGES

Çağrı KÖKSAL[1], Ömer GÜL[1]

[1]Istanbul Technical University, Electrical-Electronics Faculty, 34469 Maslak, Turkey
cagrikoksal@live.com,gulomer@itu.edu.tr,

Abstract:*Power generation from renewable resources is increasingly growing. The numbers of wind turbines and wind farms are increasing as well. Wind turbines and wind farms require grounding systems in order to protect the living creatures and turbine components from fault current and lightning current. This study uses grounding systems consisting of conductors and electrodes with different and asymmetric depths of embedment as well as a non-homogenous two-layer soil model. By employing this model, it examines the effect of the reinforcement of the grounding system of a wind turbine on the step and touch voltages. Then, it examines the grounding system of a wind farm consisting of several wind turbines.*

Keywords:*Touch voltage, step voltage, wind turbine, grounding***.**

1. Introduction

Wind turbines are generally constructed on high areas where the wind potential is high. Thus, the risk of lightning is significant for wind turbines, which are, by their nature, high structures. Lightning current flows through blades, rotor and tower. Therefore, grounding systems should be designed for wind turbines in order to prevent damage on turbine components and living creatures by hazardous voltages from lightning currents and fault currents.

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].

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 are 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.

By employing a two-layer soil model 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.

Studies relating to wind turbine grounding systems [3-5,9] design wind turbine grounding systems in various geometric shapes. However, such studies neglect the effects of the reinforcements bar in the foundation concrete of the wind turbine connected to grounding electrodes [3-5].

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 connects the wind turbines to each other to examine the effects on the step voltages and touch voltages.

2. Measurement Of Soil Resistivity

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.

CYMGRD software supports Wenner four-pin soil resistivity measurement technique. The measurement diagram concerning Wenner four-pin soil resistivity measurement technique is given in Figure 1. According to this method, while the outer electrodes provide current I,

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measured by an ammeter, 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.

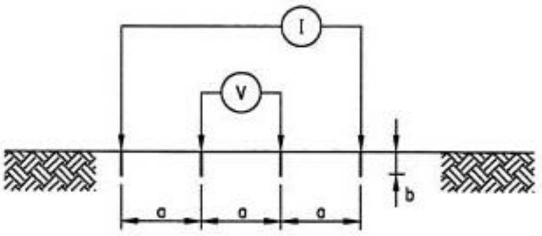

Figure 1. Wenner method [1].

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):

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

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

$$\rho = 2\pi a\ \ V / I \quad (2)$$

In the two-layersoil 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 of the resistivity values measured by Wenner method in equation 4. and calculated by equation 3., thereby determining the optimum soil layer resistivities (ρ1, ρ2) and thickness (h).

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

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]

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

ρ_{mi}: soil resistivity measured based on pin distances [Ω.m]
$\rho(i)$: soil resistivity calculated based on pin distances [Ω.m]

3. Safety Analysis

The maximum permissible step and touch voltages for different body weights according to IEEE Std. 80-2000’e 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 2:

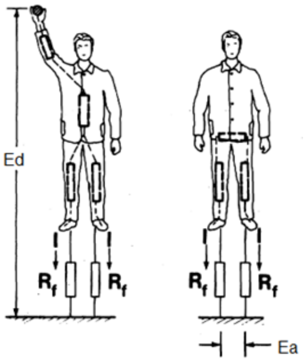

Figure 2. Touch and step voltages [6].

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

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

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 RB 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.

$$R_F = \frac{\rho}{4 \cdot b} \quad (7)$$

Whereρ is soil resistivity and b is the radius of the foot contact surface. By taking b as approximately 0.08 m [7];

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

The maximum permissible body current according to IEEE Std. 80-2000 [8]:For a body weight of 50 kg:

$$I_B = \frac{0.116}{\sqrt{t_s}} \quad (9)$$

For a body weight of 70 kg:

$$I_B = \frac{0.157}{\sqrt{t_s}} \qquad (10)$$

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 Cs surface layer reduction coefficient.

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

p_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).

$$R_F = \frac{\rho}{4 \cdot b} \cdot C_s \qquad (12)$$

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:

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

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

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

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

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

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

4. Three – Dimension Design of the Grounding System of Wind Turbines

This section examines the foundation grounding of wind turbines, taking into account the Foundation reinforcement bars 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 [9]. First, the grounding is performed merely with the Foundation reinforcement bars. 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.

For the two-layer soil model, a soil analysis is conducted using the data in Table 1. Using equation (3), the upper layer resistivity is found to be 202.84 Ω.m, the upper layer thickness 2.15 m and the lower layer resistivity 22.25 Ω.m. The resistivity of the concrete surrounding the electrodes and conductors is accepted to be equal to the soil resistivity.

Table 1. 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 / 3000 Ω.m			

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 534.17 V and the maximum permissible touch voltage 1050.07 V.
Grounding system data are given in Table II.

Table 2. Geometric parameter.

Grounding electrode diameter	16 mm
Grounding conductor diameter	16 mm
Grounding electrode length	3 m
Foundation dimensions (width x length x depth)	7 m x 7 m x 2.5 m
Reinforcement spacing	20 m

Case 1. Figure 3 shows the wind turbine grounding by Foundation reinforcement bars.

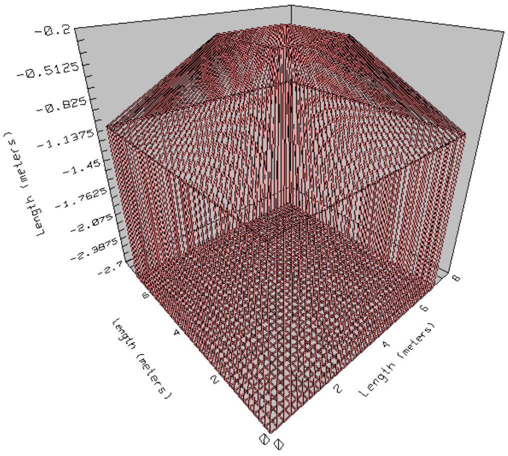

Figure 3. Three-dimensional view of the grounding system in Case 1.

As seen in Figure 4, since the maximum touch voltage (3217.02 V) is higher than the maximum permissible touch voltage (1050.07 V) in this grounding system, it fails to meet the necessary safety criteria.

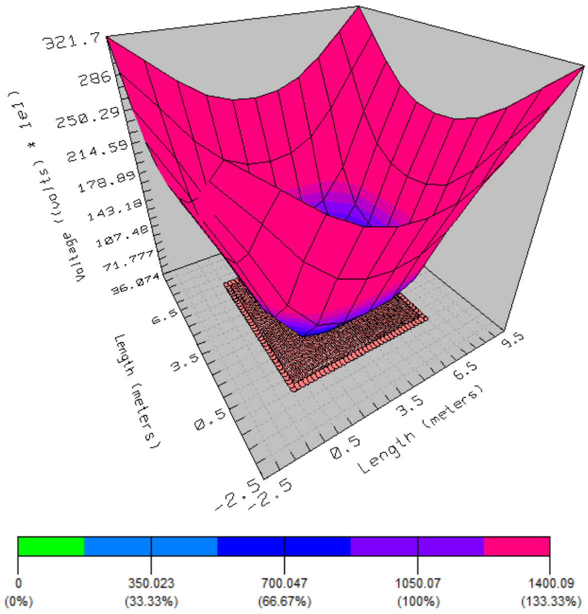

Figure 4. Touch voltages for the grounding system designed for Case 1.

Case 2. The design in Case 1 should be revised to ensure the safety of living creatures by additional electrodes and conductors. To that end, a grounding system is designed, which includes a square conductor with a perimeter of 48 m and 3 m long electrodes on the corners, as seen in Figure 5.

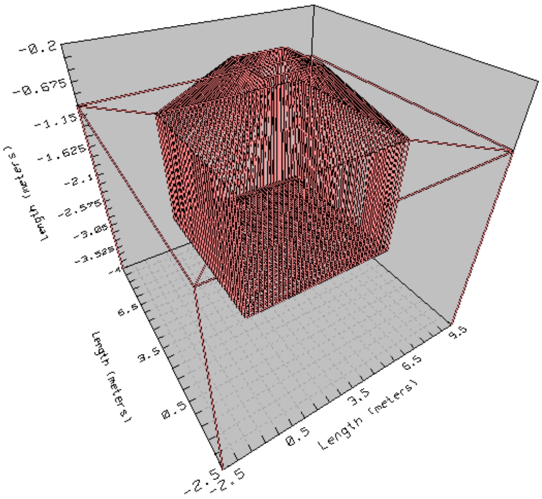

Figure 5. Three-dimensional view of the grounding system in Case 2.

As seen in Figure 6, since the maximum touch voltage (1571.5 V) is higher than the maximum permissible touch voltage (1050.07 V) in this grounding system, it fails to meet the necessary safety criteria.

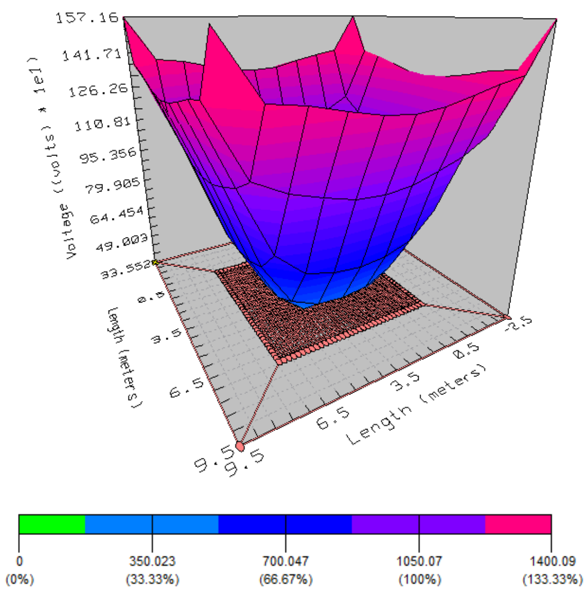

Figure 6. Touch voltages for the grounding system designed for Case 2.

Case 3. The designs in Case 1 and Case 2 should be revised to ensure the safety of living creatures by additional electrodes and conductors. To that end, a grounding system is designed with a total electrode and conductor length of 630 m, as seen in Figure 7.

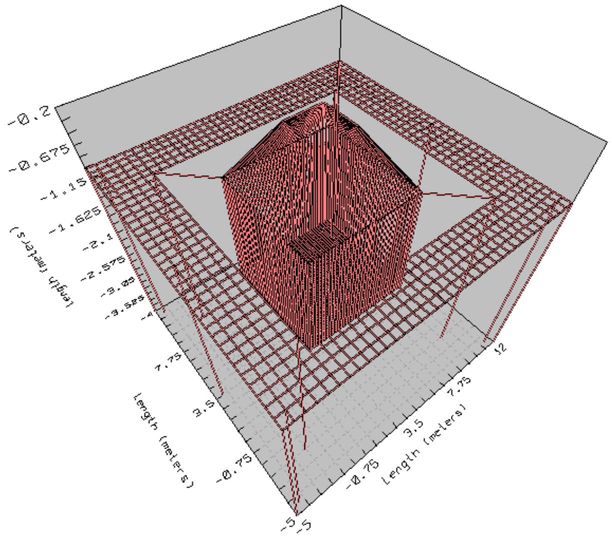

Figure 7. Three-dimensional view of the grounding system in Case 3.

As seen in Figure 8, the maximum touch voltage (1039.82 V) is lower than the maximum permissible touch voltage (1050.07 V). The maximum step voltage generated (363.51 V) is lower than the maximum permissible step voltage (468.94 V). This design meets the necessary safety criteria.

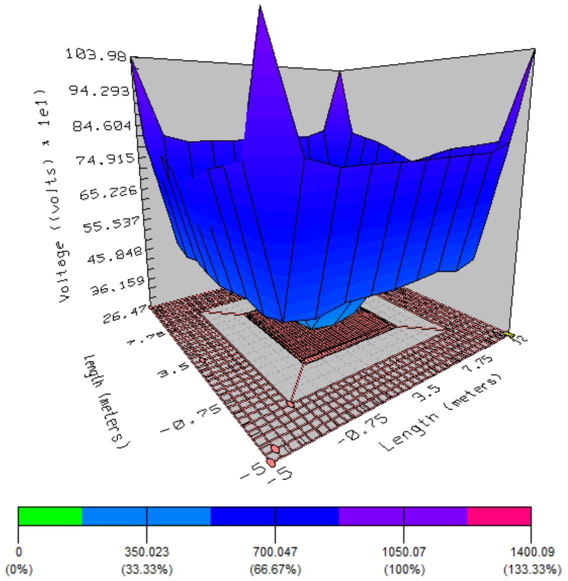

Figure 8. Touch voltages for the grounding system designed for Case 3.

4. Wind Farm Grounding System Analysis

Another way of reducing the touch and step voltages of the wind turbines examined above and making them safer for living creatures is to connect the grounding system of each wind turbine to each other. Wind turbines are connected to each other by 150 m, 2/0 awg copper conductors.

Wind turbine grounding systems given under Case 1, Case 2 and Case 3 are connected to each other by 7 turbine grounding systems as seen in Figure 9. The touch and step voltages generated are given in Table 3.

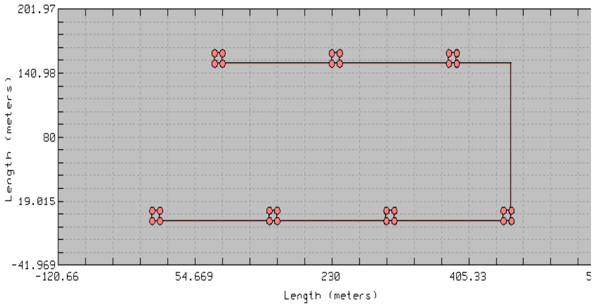

Figure 9. Layout plan of the wind farm grounding system.

It is found that the connection of turbine Foundation reinforcement bars to each other is sufficient in terms of step and touch voltages in a wind farm consisting of 7 wind turbines.

Table 3. Wind farm grounding system examination

Wind farm	Touch Voltage (V)	Step Voltage (V)
Case 1	393.7	44.14
Case 2	378.74	32.27
Case 3	348.26	26.86

A grounding system, in compliance with IEEE Std. 80-2000 in terms of step and touch voltages, is designed without using additional grounding electrodes on the turbines.

5. Conclusions

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This study examines the grounding systems of a single wind turbine and a wind farm by employing a non-homogenous two-layersoil model. The effect of the Foundation reinforcement bars is included in the grounding design of the single wind turbine.The step and touch voltages of the grounding system of the single wind turbine fails to meet the necessary safety criteria by first using merely reinforcements. The step and touch voltages of the grounding system of the single wind turbine are altered to meet IEEE Std. 80-2000 by including some electrodes and conductors

Then, a wind farm is created by using merely the reinforcements as turbine grounding system instead of neglecting them as in the turbine grounding literature [3-5]. This wind farm, consisting of 7 wind turbines connected to each other, allows to design a grounding system conforming to IEEE Std. 80-2000 in terms of step and touch voltages.

The use of merely foundation reinforcements in turbine grounding and the non-use of additional grounding electrodes reduce the cost of the grounding system.

It should be noted that in the case that the grounding conductor connecting the turbines in the wind farm to each other breaks off, the grounding of the single turbine will pose a risk in terms of step and touch voltages.

6. References

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Çağrı Köksal was born in 1987 in Kadirli,Turkey. He received B.Sc.degree electrical and electronics engineering from Istanbul University and M.Sc degree electrical engineering from Istanbul Technical University, Istanbul, Turkey in 2010 and 2013,respectively. His current research interests intelligent transport system and distribution system. He is currently control engineer in Turkish State Railways.

Ömer Gül was born in 1970 in Adana, Turkey. He received the M.S and Ph.D. degrees in electrical engineering from Istanbul Technical University, Istanbul, Turkey, in 1995 and 2001, respectively. He was at UMIST, Manchester, U.K., as a visiting researcher for six months during 1999–2000. He is a recipient of the Siemens Excellence Award 2001. His research areas include distribution system, power quality and load modelling. He is presently an associate professor at Istanbul Technical University.