

A Simulator for Potential Distribution Analysis

Gyung-Suk Kil[†], Hyong-Jun Gil* and Dae-Won Park**

Abstract – This paper proposes a reduced-scale simulator that can replace numerical analytic methods for the estimation of potential distribution caused by ground faults in various grounding systems. The simulator consists of a hemispherical electrolytic tank, a three-dimensional potential probe, a grounding electrode, and a data acquisition module. The potential distribution is measured using a potentiometer with a position-tracing function when a test current flows to the grounding electrode. Using the simulator, we could clearly analyze the potential distribution for a reduced-scale model by one-eightieth of the buried depth and length of the grounding rod and grounding grid. Once both the shape of the grounding electrode and the fault current are known, the actual potential distribution can be estimated.

Keywords: Reduced-scale simulator, Potential distribution, Grounding system, Hemispherical electrolytic tank

1. Introduction

Grounding systems play an important role in the prevention of electric shocks as well as in the stabilization of power facilities by dissipating fault currents caused by lightning, ground faults, and insulation breakdown into the ground [1-3]. There has recently been a strong interest in electrical grounding systems owing to the increasing use of power facilities. Grounding resistance is important to dissipate fault current, but it is essential to evaluate the performance of grounding systems by measuring the touch and step voltage to prevent electric shocks.

In this study, therefore, we examined a simulator that can estimate the ground potential rise—the most important parameter considered in the prevention of electric shocks. It is very difficult to achieve an optimum arrangement of the grounding electrodes to minimize the grounding resistance and potential rise, owing to various structural parameters such as the buried depth, the spacing between electrodes, and the size of electrodes in a grounding system.

The simulator for potential rise analysis proposed in this paper is a reduced-scale model that can replace numerical analytic methods for analyzing the grounding resistance and potential distribution in a complicated arrangement of grounding electrodes [4-6].

2. Design and Fabrication

2.1 Electrolytic tank modeling

[†] Corresponding Author: Division of Electrical and Electronics Engineering, Korea Maritime University, Korea. (kilgs@hhu.ac.kr)

* Electrical Safety Research Institute, Korea Electrical Safety Corporation. (fa523@paran.com)

** Division of Electrical and Electronics Engineering, Korea Maritime University. (dwpark77@hhu.ac.kr)

Most grounding systems for large-scale power systems and signal networks are mesh-type systems, composed of many horizontal buried wires and vertical grounding rods. A simulator of an electrolytic tank is a system that reduces the conductor's size and the buried depth of an actual grounding system to appropriate dimensions, and that can keep the equipotential surface fixed when a current flows into the grounding electrodes in the same manner as that of an actual grounding system. The equipotential surface around a finite electrode, which is buried under uniform ground, is distributed hemispherically as the distance from the electrode increases. Even if this ground equipotential surface is replaced by a conductive material, the shape of the potential distribution appears the same. The potential distribution inside the tank, therefore, becomes constant when a voltage maintaining the original potential is applied to the next side.

Assuming a hemisphere with radius r_1 on the surface of an infinite plane as given in Fig. 1, the equipotential surface becomes a hemisphere when a voltage is applied from a point at infinity [7-9].

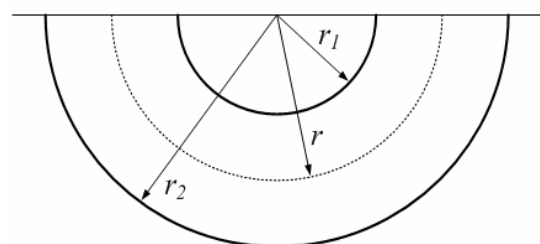


Fig. 1. Equipotential line around hemispherical grounding electrode in semi-infinite earth

The equipotential surface does not change even when a

hemisphere with radius r_2 is set up, and the resistance between these two hemispheres is as follows.

$$R_{12} = \frac{\rho}{2\pi} \left(\frac{1}{r_1} - \frac{1}{r_2} \right) \quad (1)$$

Similarly, if r_2 is ∞ and r_1 is replaced with r_2 , the resistance R_2 at an infinite point is as follows.

$$R_2 = \frac{\rho}{2\pi r_2} \quad (2)$$

In addition, when voltage V_{12} is applied between these two hemispheres, the current is as follows.

$$I_{12} = \frac{V_{12}}{R_{12}} = \frac{2\pi V_{12}}{\rho} \frac{r_1 r_2}{r_2 - r_1} \quad (3)$$

Therefore, the potential V_r at distance r from an infinite point is the sum of the potential at point r from the external wall of the tank, i.e., the measured voltage V_m , and potential V_{r2} on the tank at the infinite point, as given in Eq. (4).

$$V_r = V_{r2} + V_m = \frac{I\rho}{2\pi r_2} + V_m \quad (4)$$

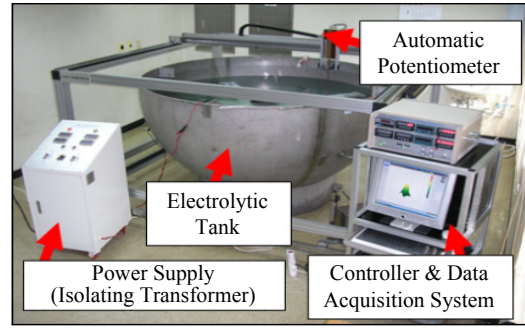
In the above example, r_1 is the radius when the simulated electrode is converted to a hemispherical one, and r_2 is the radius of the water tank. Since r_2 is greater than r_1 , the electric field is not distorted inside the tank.

An ideal model to reduce an infinite practical grounding system to a finite space is the shape of an equipotential surface formed by the fault current. A reduced-scale model that meets this requirement is a hemispherical shape formed at a distance from the grounding electrodes, such as buried wires, rods, plates, and grids.

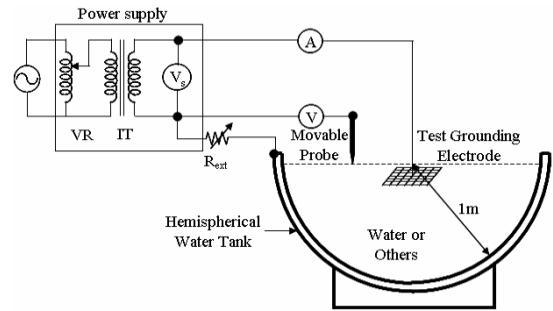
2.2 Simulator

The simulator, which is shown in Fig. 2, consists of an electrolytic tank with a diameter of 2 m, a potential probe with a three-dimensional (3D) potentiometer, a data acquisition module, and a reduced-scale grounding electrode placed at the bottom of the tank toward the center. The electrolytic water tank is made of SUS 304 stainless steel; its thickness is 6 mm, and its diameter and depth are 2 m and 1.2 m, respectively.

The variable resistance R_{ext} depending on the current and resistance of the water is set to 6.04Ω in the experiment; the resistivity of the water is $40 \Omega \cdot m$.



(a) Outline



(b) Measurement principle diagram

Fig. 2. Outline and measurement principle diagram of an experimental water tank

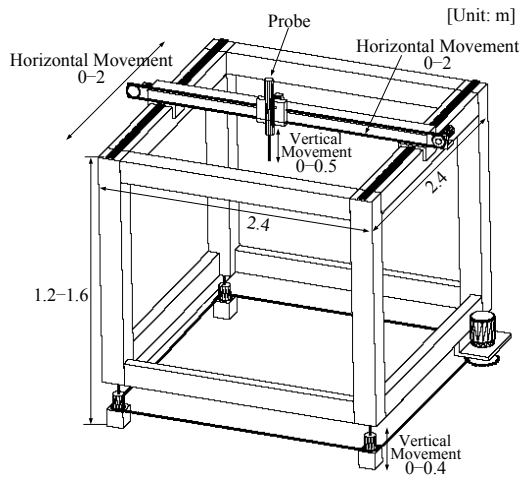
The voltmeter and ammeter indicate the voltage between the electrode and the point at infinity and the current flowing to the electrode, respectively. The ground resistance of a grounding system buried in a semi-infinite earth is obtained by the ratio V/I . A probe—a copper rod 5.1 mm in diameter—measures the potential at the surface or under the water, and the position of the probe is traced using a 3D potentiometer.

The probe's movements are controlled using a variable speed motor, and its maximum speed is 0.01 m/s. Fig. 3 shows the potential measurement system. The grounding electrode has a diameter of 1 mm and is made of stainless steel. A current is applied between the grounding electrode and the tank, and the surface potential rise is measured by moving the probe from the center of the tank to the tank wall along the water surface. The grounding electrode placed beneath the water surface is supported, as shown in Fig. 3(b), and it can be moved in steps of 1 mm vertically in the range of 0.3-1 m and horizontally in the range of 0-1 m.

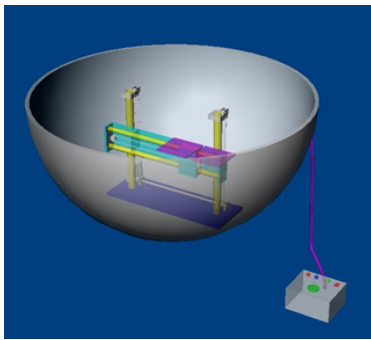
The simulator is designed on a PC, and the potential rise is automatically analyzed on the basis of the test current and measurement area.

Fig. 4 shows the operation display of the simulator in which the measurement area, data format, etc., are set up. The measurement data are displayed in two- (2D) or three-dimensional plan.

In order to evaluate the accuracy of the simulator, an available current was applied to the simulator, and the



(a) 3 D potentiometer



(b) 3 D layout

Fig. 3. Potential measurement system

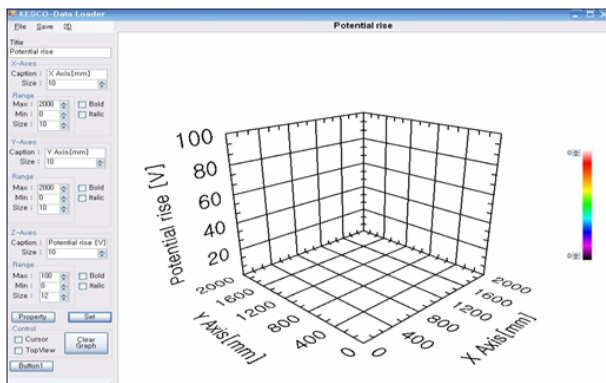


Fig. 4. Operation display of simulator

potential rise at the grounding electrode installed at the center of the tank 0.5 m away from the electrode was measured five times at 30-min intervals.

Table 1 shows the potential rise values measured using an oscilloscope and the simulator. The maximum deviations between the measurements obtained using the two instruments were 0.28% at the electrode and 0.45% at a point 0.5 m away from the electrode.

Table 1. Comparison of potential rise measured using two instruments

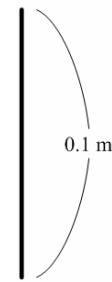
Instrument	Potential at the electrode [V]	Potential at a distance of 0.5 m from the electrode [V]
Oscilloscope	107.2–107.5	8.62–8.83
Simulator	107.0–107.8	8.61–8.79

3. Experiment and Results

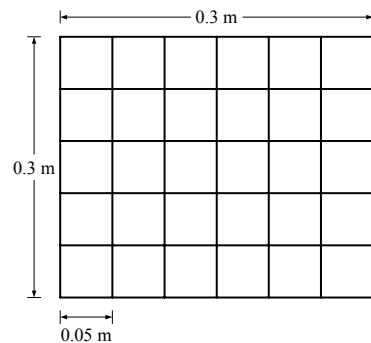
A simulation was carried out for a vertical grounding rod and a horizontal grounding grid. The dimensions of an actual grounding system and those of a reduced-scale model are given in Table 2; their sizes are shown in Fig. 5. The buried depth and length of the ground rod are reduced by one-eighth; the diameter is not considered in the reduced value because it does not affect the resistivity and potential rise.

Table 2. Comparison of actual grounding systems and their reduced-scale model

Type	Item	Model	
		Actual-scale	Reduced-scale
Grounding rod	Buried depth[mm]	750	9.5
	Length of the ground rod[m]	8	0.1
	Diameter of the ground rod[mm]	12.7	1.0
Grounding grid	Buried depth[mm]	750	9.5
	Size of grid[m]	24 × 24	0.3 × 0.3
	Diameter of the grid[mm]	10	1.0



(a) Grounding rod

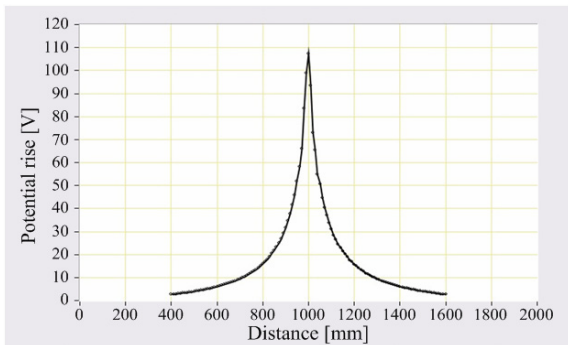


(b) Grounding grid

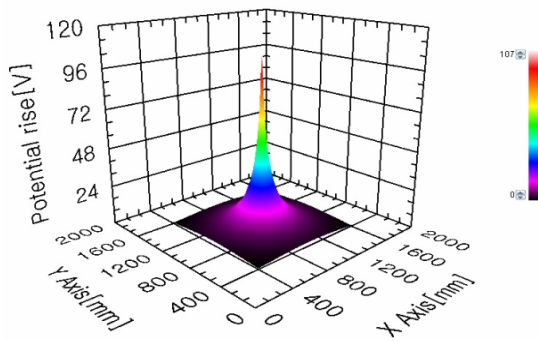
Fig. 5. Size of reduced-scale grounding electrode

A current was applied between the grounding electrode and tank, and the surface potential rise was measured by moving the probe from the center of the tank to the tank wall along the X and Y axes. Fig. 6 shows the 2D and 3D potential distribution measured along a radius of 600 mm from the center of the grounding rod. The applied voltage that can generate a current flow of 1 A in the electrode was 222 V, and the maximum potential of 107 V appeared at the center of the tank, where the grounding rod was placed.

The potential rise distribution appeared very steep around the grounding electrode and resembled a circular cone, as shown in Fig. 6(b).



(a) 2 D distribution diagram



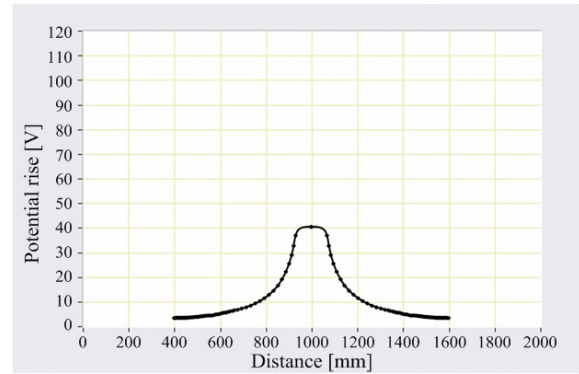
(b) 3 D cubic distribution diagram

Fig. 6. Potential distribution of grounding rod

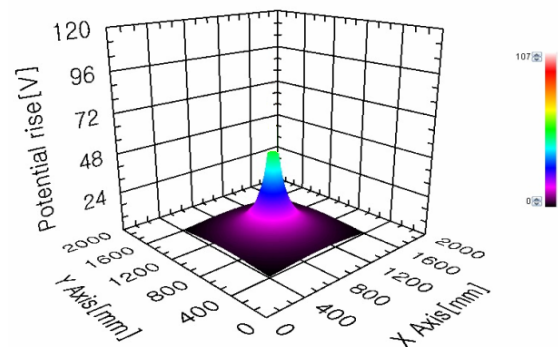
Fig. 7 shows the potential distribution measured on the grounding grid. The measurement area is the same as the one on the grounding rod.

The applied voltage that generates a flow of 1 A in the grounding grid was 42 V, and the maximum potential of 40 V appeared at the center of the grounding rod. The potential distribution, unlike that on the grounding rod, showed an equipotential surface of the grounding grid. This proves that an equipotential surface is formed in the vicinity of the grounding grid.

The 3D potential distribution was bell shaped, as shown in Fig. 7(b). The potential on the grounding rod decreased abruptly, but the one on the grounding grid decreased gradually with increasing distance from the center of the electrode.



(a) 2 D distribution



(b) 3 D distribution

Fig. 7. Potential distribution of grounding grid

5. Conclusion

This paper deals with the design and fabrication of a simulator using an electrolytic tank for potential distribution analysis. A hemispherical simulator that considers an equipotential surface as the ideal reduced-scale model for large grounding systems has been proposed.

The accuracy of the measurement system of the simulator was evaluated using a grounding electrode; the maximum deviation was within 0.45%. We could clearly analyze the potential distribution for a reduced-scale model by one-eightieth of the buried depth and length of the grounding rod and grounding grid. Once both the shape of the grounding electrode and the fault current are known, the actual potential distribution can be estimated.

Acknowledgements

This research was financially supported by the Ministry of Education, Science Technology (MEST) and National Research Foundation of Korea (NRF) through the Human Resource Training Project for Regional Innovation

References

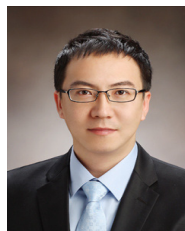
- [1] Sung-Wook Kim, Byung-Doo Moon, Hwang-Kuk Kim, Dae-Won Park, Gyung-Suk Kil, Chang-Hwan Ahn, "A Study on the Frequency Dependence of Impedance and Risk Voltages in a Grounding System", in *Proceedings of International Conference on Electrical Engineering 2009*, Shenyang, China, July 2009.
- [2] A. Geri, "Behaviour of grounding systems excited by high impulse currents: the model and its validation", *IEEE Transactions on Power Delivery*, vol. 14, No. 3, pp. 1008-1017, July 1999.
- [3] Jaeseok Choi, Hongsik Kim, Junmin Cha and Roy Billinton, "Nodal Probabilistic Congestion and Reliability Evaluation of a Transmission System under the Deregulated Electricity Market," in *Proceedings of IEEE PES SM2001 Conference*, Vancouver, Canada, July 2001.
- [4] N. M. Nor, A. Haddad, and H. Griffiths, "Characterization of ionization phenomena in soils under fast impulses", *IEEE Transactions on Power Delivery*, Vol. 21, pp. 353-361, 2006.
- [5] R. Zeng, J. He and Z. Guan, "Novel Measurement System for Grounding Impedance of Substation", *Power Delivery, IEEE Transactions on*, vol. 21 no. 2, pp.719-725, Apr. 2006.
- [6] IEEE Std. 80-2000, "IEEE Guide for Safety in AC Substation Grounding", pp.8-29, 2000.
- [7] IEEE Std. 81.2-1991, "IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems", pp. 20-64, 1991.
- [8] R. Cadecott, D. G. Kasten, "Scale Model Studies of Station Grounding Grids," *Power Apparatus and Systems, IEEE Transactions on.*, vol. PAS-102, no. 3, pp. 558-566, Mar. 1983.
- [9] P. Lipavsky, R. E. Nienaber, "Measurement of Ground Potential Difference at Power Substation", *IEEE Trans. on Power Delivery*, vol. 6, no. 1, pp. 62-69, Jan. 1991.



Gyung-Suk Kil He received the B. S., M. S. and Ph. D. degrees from Inha University, Korea in 1984, 1987 and 1996, respectively. Since 1996, he has been a Professor at Division of Electrical and Electronics Engineering, Korea Maritime University. He was with the Cardiff University as a Visiting Professor in 2003. His research interests are in the area of high voltage engineering, grounding technique, lightning protection, illumination engineering, and LED applications.



Hyong-Jun Gil He received his B.S. degree in Electrical Engineering from Inha University in 1997 and his master's degree in Electrical Engineering from Inha University in 1999 and his Ph.D. degree in Electrical Engineering from Inha University in 2006, respectively. He is currently working as a senior researcher in Electrical Safety Research Institute attached to Korea Electrical Safety Corporation. His research interests are in the area of electrical safety, electrical grounding, lightning protection and high voltage engineering.



Dae-Won Park He received the B. S., M. S., and Ph. D. degrees in electrical and Electronics Engineering from Korea Maritime University, Korea in 2003, 2005, 2011, respectively. From 2005 to 2007, he has been researcher of Korea Railroad Research Institute. He is currently a Post-Doctor at Division of Electrical and Electronics Engineering, Korea Maritime University. His research interests are in the area of high voltage engineering, lightning protection, and illumination engineering.