The Potential Gradient of Ground Surface according to Shapes of Mesh Grid Grounding Electrode using Reduced Scale Model

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In order to analyze the potential gradient of ground surface of grounding system installed in buildings, the hemispherical grounding simulation system has been designed and fabricated as substantial and economical measures. Ground potential rise (GPR) has been measured and analyzed for shapes of a mesh grid grounding electrode by using the system. The system is apparatus to have a free reduced scale for conductor size and laying depth of a full scale grounding system. When a current flows through a grounding electrode, the system is constructed so that a shape of equipotential surface is nearly identified a free reduced scale model with a real scale model.

The system was composed of a hemispherical water tank, AC power supply, a movable potentiometer, and test grounding electrodes. The water tank was made of stainless steel and its diameter was 2 m. AC power supply produced earth leakage current. GPR was measured by a moving probe of a potentiometer horizontally. The test grounding electrodes were fabricated through reducing grounding electrode installed in real buildings such as a mesh grid type, a combined type and so on. GPR has been measured in real time when a test current has flowed through grounding electrode. GPR was displayed in two-dimensional profile and was analyzed for shapes of a grounding electrode. When a mesh grid type was associated with a rod type and auxiliary mesh electrodes were installed at the four sides of mesh grid grounding electrode, GPR was the lowest of all test grounding electrodes. The proposed results would be applicable to evaluate GPR in the grounding systems, and the analytical data can be used to stabilize the electrical installations and prevent the electrical disasters.

Keywords: ground potential rise, grounding simulation system, auxiliary mesh electrode, earth leakage current, reduced scale

1. Introduction

There are many risk factors caused by inadequate working environments and the deterioration of temporary power installations using equipment with minimum safety devices at construction sites. The temporary power installations are to be used for temporarily supplying power during work at construction sites. As seen the statistical data during recent 5 years in Korea, the electrical shock accidents in temporary power installations were about 110 per year, which showed very high occupation rate of 15%⁽¹⁾⁻⁽⁶⁾.

The grounding is very important among variable safety installations in temporary power installations. When there are produced transient overvoltage, the ground fault, bad insulation in power installation, grounding installation has played an important role in protection of electrical shock as well as stabilization of installation. Therefore, it is desired that a performance of grounding system is evaluated by a touch voltage, a step voltage, a mesh voltage, a transferred voltage, only be not grounding resistance according to

classification of grounding in Korea. The preventive measures are important in protection of electrical shock as well as protection of installation from overvoltage of ground fault and lightning, and the research about this field is lively going on Ref. (5), (7), (8). The analytical techniques used have varied from those using simple hand calculations to those involving scale models to sophisticated digital computer programs. The technique of using scale models in an electrolytic tank determines the surface potential distribution during ground faults.

Therefore, this paper researched ground potential rise (GPR) which was the most important factor for protection of electrical shock by overvoltage of ground fault in power installation. The hemispherical grounding simulation system has been designed and fabricated as substantial and economical measures. Scale model tests are generally employed to determine grounding resistances and potential gradients in the case of complex grounding arrangements where accurate analytical calculations are seldom possible and it can be used to analyze a real grounding system⁽⁹⁾⁽¹⁰⁾. In the future, the analytical data can be used to stabilize installation and to prevent electrical shock accidents.

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2. Experimental Apparatus and Method

2.1 Principles of Reduced Scale Model The hemispherical grounding simulation system is apparatus to have a free reduced scale for conductor size and laying depth of a real scale grounding system. The system constructed so that a shape of equipotential surface is nearly identified a free reduced scale model with a real scale model when current flows through grounding electrode.

When all the physical dimensions of a grounding system are reduced in size by the same scale factor—this includes the conductor diameter and the depth to which the grounding electrode is buried—the pattern of current flow, and the shape of the equipotential surfaces are unaltered. This means that potential profiles measured on a model may be used to determine the corresponding potentials on a full scale grounding electrode. For modeling practical value some further changes are necessary. The full scale grounding electrode is buried in a semi-infinite earth.

A solid medium is inconvenient both from the measurement standpoint and when delicate model must be frequently removed for modification and replaced. The electrolyte presents no particular problem for the homogeneous case; water is a convenient choice. To understand shape and size of a tank, profile of electric field and so on, consider first a hemispherical electrode, at the surface of a semi-infinite earth and of radius r_1 (Fig. 1).

If a voltage is applied to this hemisphere with respect to infinity, all the equipotentials will be hemispheres. A second hemisphere introduced at radius r_2 will not change the equipotentials. The resistance between the two hemispheres can be shown to be

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

where ρ is the resistivity of the medium. Similarly, by letting r_2 go to infinity and replacing r_1 with r_2 it can be shown that

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

where R_2 represents the portion of the resistance external to r_2 , that is between there and infinity. If the replacement of r_1 with r_2 is not done, i.e. Eq. (2) is expressed by r_1 .

If a voltage V_{12} is applied between the two hemispheres, a current I_{12} will flow where

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

If the voltage at some other point, for example at radius r ,

Fig. 1. Equipotential lines around hemispherical electrode in the semi-infinite earth

is measured with respect to the outer hemisphere, the potential of this point with respect to infinity (V_{r2}) may be obtained by simple adding a voltage (V_m)

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

where r_1 is a grounding electrode to simulate and r_2 is a water tank without distorting the field inside it. The ideal model, which a full scale grounding electrode is reduced from infinity to finite space, is a shape to have equipotential line for making identical potential value by a fault current. A shape which is satisfied with a such condition is a hemisphere formed at finite distance that is separated from a full scale grounding electrode such as a rod type electrode, a mesh grid grounding electrode, a linear type electrode, a grounding plate and so on Ref. (11)–(13).

2.2 Configuration of Grounding Simulation System

The grounding simulation system was composed of a hemispherical water tank, AC power supply, a movable potentiometer, and test grounding electrodes. Fig. 2 shows a measuring circuit and a shape of grounding simulation system. A hemispherical water tank was made of stainless and diameter of this was 2 m. The grounding was installed to prevent electrical shock, stabilize a installation, eliminate noise.

As shown in Fig. 2, an isolation transformer was used to consider separation of fault current and safety of measurement. The measuring circuit included an auto-transformer for varying fault current. A variable resistance, which depends on resistivity of water, is 7.64Ω in Fig. 2(a). A voltmeter (V_s) indicates an applied voltage and a voltmeter (V) measures the voltage between a test grounding electrode and a tank. An ammeter (A) measures the current between the test grounding electrode and the tank. A grounding resistance of grounding electrode, which is buried in a semi-infinite earth, is obtained by the ratio of V/I . A probe measures surface

(a) Measuring circuit

(b) Shape

Fig. 2. Measuring circuit and shape of grounding simulation system

Fig. 3. Circuit of AC power supply

Fig. 4. Schematic diagram of potentiometer (unit: mm)

potential or inner potential of water, and is moved by conveyer. GPR is measured by a movable probe and a movable potentiometer outputs a relative position with respect to central point of grounding electrode.

Fig. 3 shows a circuit of AC power supply producing an earth leakage current. An isolation transformer was used for separation of fault current, safety of measurement, protection of circuit damage caused by noise, surge and transient phenomena. A molded case circuit breaker and an earth leakage circuit breaker were installed in order to prevent electrical shock and protect a circuit. Fig. 4 shows a schematic diagram of a movable potentiometer. The variable velocity range of motor is from 0 m/s to 0.01 m/s, and the position and the voltage are measured by moving a probe at the potentiometer. A probe was made of copper and its diameter was 5.1 mm. The probe was completely fixed by supporter so that it wasn't shaken and tilted.

2.3 Test Grounding Electrodes As referred for grounding electrodes at real construction sites, we fabricated the test grounding electrodes. Table 1 shows the full scale grounding electrodes and those fabricated on a scale of one-eighthieth. Water of 48 Ω ·m was used to simulate earth.

The test grounding electrodes were made of stainless because its material was strong in corrosion by water. Those diameter is 1 mm. A thickness of grounding electrode was not applied to a scale of one-eighthieth because it was difficult to fabricate the test grounding electrodes by considering the thickness.

The test grounding electrodes were fabricated for shapes of mesh grid type, and combined type. Fig. 5 shows variable test grounding electrodes such as mesh grid type, combined type A, combined type B. The test grounding electrodes are installed under the surface of the water of a tank. We set up about 9.5 mm in laying depth because the grounding electrode is buried under 0.75 m from ground surface in accordance with Korea Technical Standards. After a test current has flowed through a central part of test grounding electrode, GPR has been measured in real time according as a probe has

Table 1. A full scale model and a reduced scale model of one-eighthieth

Contents	Model	Full scale model	Reduced scale model
Laying depth of grounding electrode		0.76m	9.5mm
Size of mesh grid grounding electrode		24m x 24m	0.3m x 0.3m
Diameter of mesh grid grounding electrode		0.01m	1mm
Length of rod type electrode		8m	0.1m
Diameter of rod type electrode		0.0127m	1mm

Fig. 5. Test grounding electrodes

been moved across the diameter distance horizontally.

3. Results and Discussion

3.1 The Analysis of Mesh Grid Type A potential distribution of ground surface, which is formed by ground fault, generally is displayed with value of ground surface. A potential rise of ground surface in and around a grounding electrode is influenced by a shape of grounding electrode, ground structure, the characteristics of soil, homogeneity of soil, magnitude and continuous time of the earth leakage current and so on Ref. (7), (8), (14), (15). This paper researched GPR which was the most important factor for safety of installation and human body. The test grounding electrodes were fabricated for shapes of mesh grid type, combined type, and the potential gradient was measured and analyzed about each electrode.

The test current is 1 A and constant. The same current is applied to other grounding electrodes, too. The test voltage is variable according to ground resistance of test grounding electrode. The sinusoidal waveforms are sampled and showed in Fig. 6. The waveforms of the applied voltage and GPR are recorded by the digital storage 500 MHz, 5 GS/s sampling rate oscilloscope. The upper part shows an applied voltage and the lower part shows GPR. The measured value

The upper part: applied voltage, 35 [V/div], 20 [ms/div]

The lower part: ground potential rise, 15 [V/div], 20 [ms/div]

Fig. 6. The waveforms of applied voltage and ground potential rise

(a) General view

(b) Enlarged view

Fig. 7. Profile of ground potential for mesh grid type

is a RMS (root-mean-square) value. As shown in Fig. 6, the noise was eliminated by grounding of case, complete fix of probe, shielding of signal wire.

Fig. 7 shows the profile of ground potential for the mesh grid type. Fig. 7(a) shows the general view and Fig. 7(b) shows the enlarged view between 850 mm and 1150 mm. An applied voltage is 43.2 V. As shown in Fig. 7, the potential gradient was displayed with a symmetrical profile at the center of the mesh grid type. The maximum value occurred at central point (1000 mm) and was 40 V per 1 A. The potential gradient was nearly regular from 850 mm to 1150 mm and the grounding electrode was installed at the distance. This proves that the equipotential is formed in the vicinity of a mesh grid type.

When a fault current flows in a grounding electrode by ground fault or lightning, the ground surface potential rises in and around a grounding electrode. The hazard of electrical shock is generally evaluated by a touch voltage, a step

(a) Ground potential rise

(b) Touch voltage

(c) Step voltage

Fig. 8. The analytical result through program on the mesh grid type

voltage during GPR. A touch voltage is a potential difference between facility and ground surface when a human body is touched with the grounded facilities, and a step voltage is a potential difference between the two feet when the potential difference is produced by the test current in the vicinity of a grounding electrode. As a distance between mesh electrodes is narrow, a touch voltage and a step voltage grow lower. In result, the electrical shock accidents can be decreased⁽¹⁶⁾⁻⁽¹⁸⁾.

Fig. 8 shows the analytical results on the mesh grid type by the solution program (CDEGS: Current Distribution, Electromagnetic Interference, Grounding and Soil Structure, Canada). Those results are ground potential rise, touch voltage, step voltage.

When GPR was compared the measuring value of reduced scale model with the computing value of program, a similar profile was showed as Fig. 7(a) and Fig. 8(a). Some difference between the measuring value and the computing value was produced by influence of metallic things in and around the system, effect of supporting thing. Therefore, measuring and computing values have pretty confidence through Fig. 7(a) and Fig. 8(a). When GPR was compared with the touch voltage, the touch voltage showed the contrary distribution against GPR. In the case of the step voltage, the maximum value appeared at the boundaries of grounding electrode, and the minimum value appeared in the vicinity of its center. Because touch and step voltages are decreased by installation of grounding electrode, the electrical shock accidents can be prevented.

3.2 The Analysis of Combined Type A A shape combining mesh grid type with rod type is used much in large buildings. In this paper, the combined type was fabricated and the two kinds were combined type A, combined type B.

Fig. 9. Profile of ground potential for combined type A

The combined type A is shape to install rod types at the four sides of a mesh grid type. Fig. 5(b) shows the combined type A.

Fig. 9 shows the profile of ground potential for combined type A. An applied voltage is 42.3 V and a maximum value is 39.2 V per 1 A. In case of combined type A as well as mesh grid type, the equipotential was nearly formed in the vicinity of the grounding electrodes. As shown in Fig. 7 and Fig. 9, the difference of profiles hardly exists between a mesh grid type and a combined type A in general view, but a combined type A is more smooth than a mesh grid type in potential gradient between 35 V and 40 V in enlarged view. Hence, the combined type A can be more profitable than the mesh grid type with the protection of electrical shock and the stabilization of installation. As shown in Fig. 9(b), a maximum value appears at 1000 mm, and a test current has flowed at the position.

GPR is reduced with a symmetrical appearance at the center of grounding electrode. GPR is increased at the perpendicular part from a mesh conductor and is decreased at the central part between mesh conductors. Fig. 10 shows the analytical results on the combined type A by the solution program. As shown in Fig. 10, profiles according to distance were analyzed against GPR, touch voltage, step voltage. As shown in Fig. 8 and Fig. 10, the combined type A was better than the mesh grid type in prevention of electrical shock.

3.3 The Analysis of Combined Type B Low grounding resistance is very important because it limits hazardous ground potential rise at safe level for equipment and personnel. Recently, variable combined grounding electrodes has been installed in real buildings. The combined type B is shape to install rod types and mesh electrodes at the four sides of a mesh grid type. Fig. 5(c) shows the combined type B such as a photograph, a flat drawing, 3-dimensional drawing. Fig. 11 shows the profile of ground potential for combined type B. An applied voltage is 41.5 V and a maximum value is 38.9 V per 1 A.

Fig. 10. The analytical result through program on the combined type A

Fig. 11. Profile of ground potential for combined type B

When a mesh grid type was associated with a rod type and mesh electrodes were installed at the four sides of mesh grid grounding electrode, GPR was the lowest and the potential gradient was the smoothest of all test grounding electrodes. Fig. 12 shows the analytical results on the combined type B by the solution program. In combined type B, the lowest values were calculated against GPR, touch voltage, step voltage among three types. Fig. 13 shows the comparative profiles

Fig. 12. The analytical result through program on the combined type B

Fig. 13. Profile of ground potential for three types

of ground potential for three types. As shown in Fig. 13, the combined type B is a shape to join three things together, for example, rod type, mesh grid type, mesh electrode.

As a consequence, the combined type B can be most profitable with the protection of electrical shock and the stabilization of installation. In case of combined type B, as a distance between mesh electrodes at the outside is narrow, the potential gradient grows lower.

Electrical shock accidents can be prevented according as a touch voltage and a step voltage grow lower. Especially, the high touch voltage or step voltage is produced because the potential gradient is large at the outside of a mesh grid grounding electrode, and it needs to take care of a grounding design to prevent electrical shock accidents according to the cause stated above.

Therefore, it is effective to make a potential buffer zone that the potential gradient can be reduced according as auxiliary mesh electrodes mediate between grids at a boundary of a mesh grid grounding electrode⁽⁸⁾⁽¹⁷⁾.

4. Conclusions

This paper describes the relationship between electrical shock and ground potential rise, and deals with profiles of ground potential for a mesh grid type, a combined type A, a combined type B. It is effective to use the combined type B that is profitable for protection of electrical shock as well as stabilization of installation. The results are summarized as follows:

(1) In order to analyze the potential gradient of ground surface according to shapes of mesh grid grounding electrode, the hemispherical grounding simulation system has been designed and fabricated as substantial and economical measures.

(2) The grounding simulation system was composed of a hemispherical water tank, AC power supply, a movable potentiometer, test grounding electrodes, and the test grounding electrodes were fabricated for shapes of mesh grid type, combined type A, combined type B. Also, the noise was eliminated by grounding of case, complete fix of probe, shielding of signal line, twisting of power line during measurement.

(3) In case of a mesh grid type, the potential gradient was displayed with a symmetrical profile at 1000 mm, and when we measured GPR of a mesh grid type and a combined type, the equipotential was nearly formed in the vicinity of the grounding electrodes. The potential gradient of combined type A is more smooth than mesh grid type between 35 V and 40 V.

(4) The combined type B shows the lowest GPR, and the smoothest potential gradient at a boundary of a mesh grid grounding electrode. Hence, the combined type B can be extremely suitable the protection of electrical shock as well as the stabilization of installation. As a distance between mesh electrodes is narrow, the potential gradient is reduced. In result, the electrical shock accidents can be decreased.

(5) The risk factors such as ground potential rise, touch voltage, step voltage, were analyzed by solution program. Through a comparison of the measuring value and the computing value, the confidence of measurement was obtained.

(6) In order to prevent electrical shock accidents, it is effective to make a potential buffer zone that the potential gradient can be reduced according as auxiliary mesh electrodes mediate between grids at a boundary of a mesh grid grounding electrode.

(7) With the use of charts given in Figs. 7–10, it is possible to determine suitable grounding system in uniform soils. These charts should be of great help in the design of the grounding systems for buildings.

In the future, we design and fabricate a reduced scale model by referring to the buildings that is already established in Korea, we will compare a full scale model with a reduced scale model and analyze GPR of structural grounding about the buildings.

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