Evaluation of Grounding Performance of Energized Substation by Ground Current Measurement

J.K. Choi, Y.H. Ahn, J.W. Woo, G.J. Jung, B.S. Han, K.C. Kim

Abstract— Substation grounding systems typically build up a large network of various grounding electrodes, which consists of a substation grounding grid, multi-grounded transmission line skywires and distribution line neutral wires. Although the Fall-of-potential (FOP) method has been widely used for ground resistance measurement, it is difficult to use the method in case of such a substation grounding system because of the difficulty of interpretation of the measured FOP profile. In this paper, we have presented a practical example of ground resistance measurement in a 154 kV substation under commercial operating condition. Conventional FOP tests and the measurement of ground current splits to each part of the grounding system were conducted simultaneously. A simple interpretation method of FOP profiles, with the measured ground current splits, has been suggested.

Keywords: ground resistance, grounding system, substation, Fall of potential method.

I. Introduction

The fall-of-potential (FOP) method has been widely used for the measurement of ground resistance [1]. In FOP method, the potential probe is located on the straight line between the ground electrode and the current probe. The apparent resistance R is obtained with the current I circulating between the ground electrode and the current probe, and with the voltage difference V between the ground electrode and the earth surface at which the potential probe is located. Once the FOP test is completed, the rule of 61.8% is commonly applied to determine the proper position of the potential probe which reads the true ground resistance.

In general, substation grounding systems build up a large grounding electrodes network which consists of a substation grounding grid, multi-grounded transmission line skywires and distribution line neutral wires. In such a grounding system, it is difficult to use FOP method since the rule of 61.8% is no longer valid. The main difficulty in the interpretation of FOP profile measured in a substation comes from the fact that the current injected into the substation grounding system diverts into many ways: transmission line skywires and distribution line neutral wires as well as the substation grounding grid

In this paper, we have presented a practical example of ground resistance measurement in a 154 kV substation under commercial operating condition. Usual FOP test and the measurement of ground current splits to each part of the grounding system were conducted simultaneously. A simple interpretation method of FOP profiles, with the measured ground current splits, has been suggested.

.

II. Measurement of Ground Current Splits

Figure 1 shows the measurement circuit in a substation grounding system. Brief descriptions of the circuit are the followings :

(1) Test current injection system:
- Generator (1.6 KVA, AC 100V output, 50 Hz)
- Voltage controlling Tr. (input:100V, output:0~130V)
- Step-up Tr. (2 KVA, 100/440 V)

(2) Data acquisition system:
- DAQ (8 channel, 16 bit A/DC, 1 Ms/s)
  (Ch#1~7 for current & Ch#8 for voltage measurement)
- clamp-on type current & differential voltage probes
- Portable computer with LabVIEW

And other accessories.

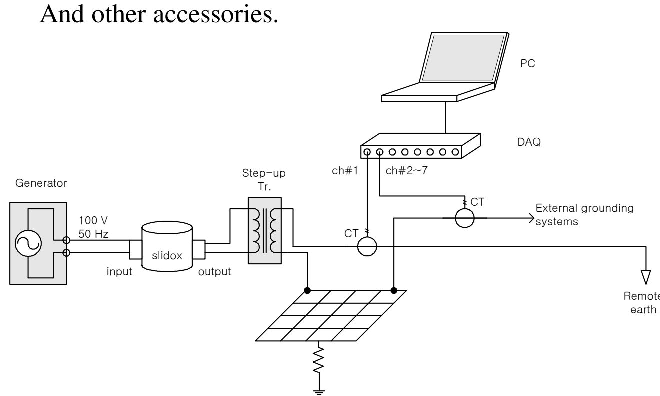


Fig. 1. Configuration of the current splits measuring circuit

Configuration of the test site is shown in Figure 2. The overall substation grounding system consists of three parts: the substation grounding grid, one skywire which is multi-grounded through tower footings, and four neutral wires which are also multi-grounded through pole grounds. The size of the grounding grid is 70 m x 50 m with 5 m of conductor spacing and 150 mm^2 of conductor cross sectional area. And the grid is enclosed with an outer fence (100 m x 72 m), which is grounded and connected to the grid.

Jong-kee Choi, Yong-ho Ahn, Jung-wook Woo and Gil-jo Jung are with Korea Electric Power Research Institute, Daejeon, KOREA (e-mail: jkchoi@kepri.re.kr).
Byung-sung Han is with the Department of Electrical Engineering, Chonbuk University, Kwangjoo, KOREA (e-mail: rhbs@moak.chonbuk.ac.kr).
Kyung-Chul Kim is with the Department of Electrical Engineering, Hongik University, Chochiwon, KOREA (e-mail: yangjier@hongik.ac.kr).

Presented at the International Conference on Power Systems Transients (IPST'05) in Montreal, Canada on June 19-23, 2005
Paper No. IPST05 - 128

There are one 154 kV transmission line and four 22.9 kV distribution lines in the substation being investigated. To measure the current distributions in each part of substation grounding systems, 50 Hz test current was injected between the grid and the current probe located far from the substation. At the same time, outgoing currents in four distribution line neutral wires and one transmission line skywire are measured and 50 Hz signals are extracted through spectrum analysis. By this way, all residual noise signals in the frequency spectrum of 60 Hz and its harmonics, which are inevitable in the substations under operating condition, could be eliminated.

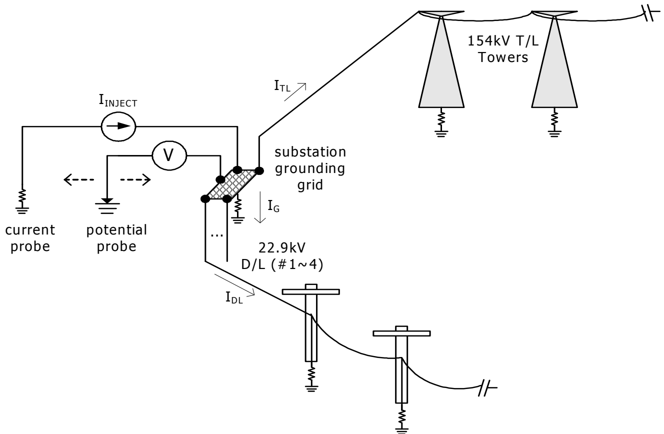


Fig. 2. Overall grounding system of 154 kV substation under study

The current probe was installed in two directions taking into account the given physical conditions near the substation. One current probe was located 185 m apart from the substation and coursed to an opposite direction of both transmission and distribution lines (CASE-0). The other current probe was 169 m distant from the substation and directed to near distribution lines (CASE-1). With these two current probes, the current splits measuring tests were conducted and the test results were summarized in Table 1. Since the ground current which was leaked into earth through the grid only, I_G, could be obtained by algebraic summation of the currents flowing into the grid, I_{INJECT} - I_{TL} - I_{DL}. The current split factor of the grid, which is denoted by S_f and defined by $|I_G / I_{INJECT}|$, can be calculated.

TABLE I
SUMMARY OF THE CURRENT SPLITS IN THE GROUNDING SYSTEM UNDER STUDY

		CASE 0	CASE 1
I_{INJECT} [A_{rms}]		3.34∠0°	3.87∠0°
I_{TL} [A_{rms}]		0.230∠19°	0.684∠7°
I_{DL} [A_{rms}]	*#1 D/L*	*0.596∠-8°*	*0.365∠-7°*
	#2 D/L	*0.439∠-7°*	*0.989∠-8°*
	#3 D/L	*0.397∠-13°*	*0.801∠-9°*
	#4 D/L	*0.696∠-8°*	*0.343∠-10°*
	SUM	2.128∠-9°	2.499∠-9°
S_f [p.u]		0.315	0.202

III. INTERPRETATION OF FALL-OF-POTENTIAL PROFILE

Figure 3 shows the FOP test circuit with an external impedance $Z_{external}$. The bigger hemispherical electrode represents a substation grounding grid and the smaller one is a current probe. $Z_{external}$ stands for multi-grounded skywires and neutral wires which are connected to the grounding grid. The rule of 61.8% is that the apparent resistance measured at 61.8% point on the straight line between the ground electrode and the current probe (i.e. x=0.618D in Fig. 3) come to be same with the true resistance of the ground electrod on condition that S_f=1.0.

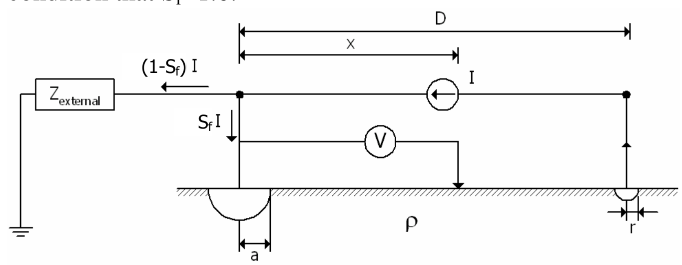


Fig. 3. FOP test circuit and hemispheric model

With external grounding system or in case of multi-grounded system, such as a substation grounding system, S_f is always smaller than 1.0 and the rule of 61.8% is no longer valid. It is needed, therefore, to take into account the effect of S_f. Ground resistance of a hemispherical electrode in a uniform soil with radius "a" and resistivity "ρ" is expressed by (1). Earth surface potential at point "x" is expressed by (2) and equation (3) is an apparent resistance at point "x". Let us suppose a correction factor k(x) by (4), then we can get R_{TRUE} in regardless of "x" by multiplying R(x) by k(x).

$$R_{TRUE} = \frac{\rho}{2\pi a} \tag{1}$$

$$V(x) = \rho\frac{S_f I}{2\pi x} - \rho\frac{I}{2\pi(D-x)} \tag{2}$$

$$R(x) = \frac{V(a)-V(x)}{I} \tag{3}$$

$$k(x) = \frac{R_{TRUE}}{R(x)} \tag{4}$$

$$= \frac{(a-D)(x^2-Dx)}{(aS_f - S_f D + a)x^2 + (S_f D^2 - a^2 S_f - a^2)x + aS_f D(a+D)}$$

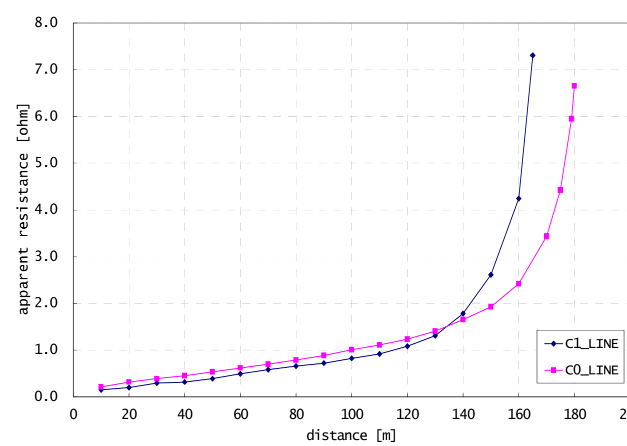


Fig. 4. Measured Fall-of-potential profiles

Fig. 4 shows the measured FOP profile in two cases (Case-0, Case-1) and Fig. 5 shows the resistance profile after multiplying by k(x) to produce R_{TRUE}. (1.1 ~ 1.2 Ω). In an ideal condition (shown in Fig. 3), the compensated resistance curve should be entirely flat by (3) (R_{TRUE} = k(x) R(x)), which is not the case in Fig. 5. This can be explained. Since the substation grounding grid is simplified as a hemispherical electrode, the accuracy of the model shown in Fig. 3 will be poorer when the region of interest is closer to the grounding grid or the current probe, which have not the shape of hemisphere in real situations. It means that the compensated data (=k(x) R(x) closer to left (the grounding grid) or right part (the current probe) on x-axis of Fig. 5 would not be accurate. This explains the non-flat part of the graph to left and right side. In the central part of the graph, however, the curve becomes almost flat.

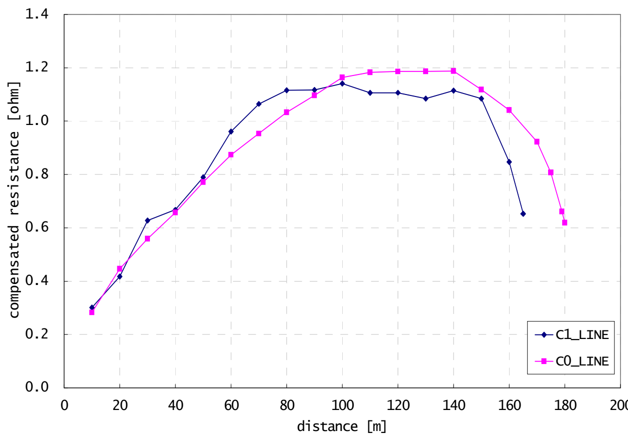


Fig. 5. Fall-of-potential profiles after multiplied by correction factor k(x) to produce R_{TRUE} graph (i.e Flat section in the graph, R_{TRUE}=1.1~1.2 Ω)

Since the substation was in commercial operating condition, it was practically impossible to remove electrical connections between the substation grounding grid and skywires/neutral wires for direct measurements of ground resistance of the grid. As an alternative, the ground resistance of the substation grounding grid was calculated using a sophisticated computer program CDEGS [5]. For the calculation, earth resistivity survey near the substation was carefully conducted to identify horizontally multi-layered equivalent soil model. The computed apparent resistivities agree well with the measured values to show the simulated earth model represents the electrical characteristics of the real earth in good manner (Fig. 6).

TABLE II
PARAMETERS OF HORIZONTALLY 3-LAYERED EARTH MODEL

	Resistivity [Ωm]	Thickness [m]
Top Layer	112	3.64
Central Layer	47.2	2.64
Bottom Layer	399.3	∞

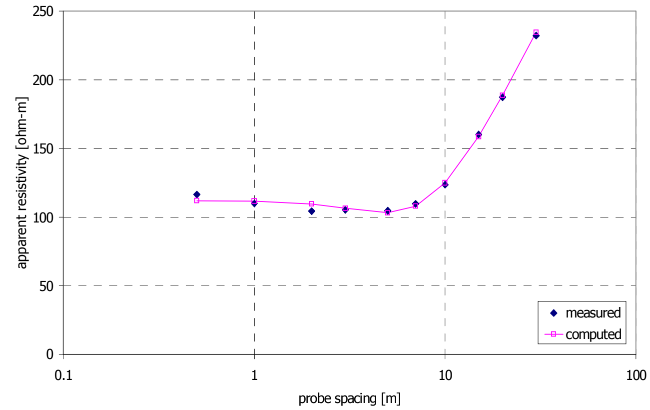


Fig. 6. Measured and computed apparent resistivities

With the multilayered soil model described in Table II and the grounding grid model, CDEGS produced 1.39 Ω of ground resistance.

IV. Conclusions

In this paper, we have presented an example of ground resistance measurement in an energized 154 kV substation. First, the currents diverting into each part of the substation grounding system were measured with the current flowing between the substation grounding system and the current probe. By algebraic sum of the measured currents, the current leaking into earth through the grounding grid, I_G, could be obtained. Second, Fall-of-potential test was conducted. A correction factor k(x) was proposed to obtain true ground resistance from the measured FOP profile. With multiplying the measured FOP profile by k(x), we could obtain the ground resistance of the grounding grid, 1.1~1.2 Ω, without removal of any skywires or neutral wires from the grid. The obtained value was similar with the calculated value of 1.39 Ω, which was calculated by a sophisticated computer program CDEGS with multi-layered earth model.

V. References

[1] M. Bouchard, F. P. Dawalibi, and D. Mukhedkar, "Survey on Ground Resistance and Earth Resistivity Measurements," in IEEE Winter Power Meeting, January 30 - February 4, 1977.

[2] H.Sarmiento, J.Fortin, D.Mukedkar, "Substation ground impedance: comparative field measurement with high and low current injection methods," in IEEE Trans. On PAS, vol. PAS-103, no.7, July 1984, pp. 1677-1683

[3] J.Fortin, H.Sarmiento, D.Mukedkar, "Field measurement of ground fault current distribution and substation ground impedance at LG-2, Quebec," in IEEE Trans. On PD, vol. PWRD-1, no.3, July 1986, pp.48-60

[4] Shashi G.Patel, "A complete field analysis of substation ground grid by applying continuous low voltage fault," in IEEE Trans. On PAS, vol.PAS-104, no.8, Aug. 1985, pp.2238-2243

[5] F. P. Dawalibi and F. Donoso, "Integrated Analysis Software for Grounding, EMF, and EMI," in IEEE Computer Applications in Power, Vol. 6, No. 2, April 1993, pp. 19-24.

[6] *IEEE Guide for Measurement of impedance and safety characteristics of large, extended or interconnected grounding systems,* IEEE Standard 81.2-1991

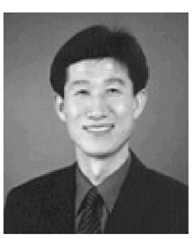
VI. Biographies

Jong-kee Choi received his B.S. degrees in electrical engineering from Dongguk University and M.S. in electrical engineering from Hongik University in 1992 and 1995, respectively. He has been working as a senior member of technical staff at Korea Electric Power Research Institute since 1995. His interests cover the transient behavior of grounding system of substations and power systems. He may be reached at jkchoi@kepri.re.kr.

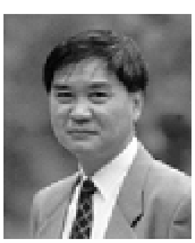
Yongho Ahn received his B.S. degrees in electrical engineering from Inchon University and M.S. in electrical engineering from Chonbuk University in 1984 and 2000, respectively. He has been working as a senior member of technical staff at Korea Electric Power Research Institute since 1995. His interests cover the transient behavior of grounding system of substations. He may be reached at yhan@kepri.re.kr.

Giljo Jung received his M.S. degrees in electrical engineering from Yonsei University and his Ph.D degree in electrical engineering from Soong-sil University in 1995 and 2001, respectively. He has been a leader of Transmission and Substation Tech. Group of Korea Electric Power Research Institute since 1996. His interests cover substation grounding system and HVDC transmission system.

Jung Wook Woo was born in Daegu, Korea, on Sept.19, 1968. He received his B.S and M.S. degree in the Department of Electrical Engineering from Kyungpook National University, Korea. He has been worked for Korea Electric Power Research Institute (KEPRI) he is in charge of the Power System Laboratory. His research interests include the analysis of overvoltage characteristics of power system and the analysis of lightning characteristics in Korea.



ByungSung Han received his Ph.D degrees in electrical engineering from Louis Pasteur University, France. He is currently a professor in the Department of Electrical Engineering in Chonbuk University. He may be reached at rhbs@moak.chonbuk.ac.kr.r



KyungChul Kim gradurated from electrical engineering department, Hongik University in 1977. He received his M.S. and Ph. D. in electrical engineering from New Mexico State University and the University of Texas at Arlington in 1984 and 1988, respectively. He has been a professor in the Department of Electrical Engineering at Hong-ik University since 1991. His present interests cover the harmonics and grounding analysis of power systems.