Effects of Ground Resistance on Overvoltage caused by Line to Neutral faults in a 22.9 kV Underground systems

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Abstract: In this paper we propose grounding design method which was considered of touch voltage when a person is contacting the housing of pad-mounted equipment in a 22.9kV overhead-underground system during line to neutral faults. Specially, In order to confirm the actual overvoltage magnitude which occurs on neutral line, we considered some screening(shielding) effects; CNCV cable and down town screening effects. The screening coefficients were deducted from field test results in a distribution line which is identical with an actual power line. The purpose of this paper is to attempt to suggest the guidance for grounding system design which is based on a real field faults situation in distribution lines.

1 INTRODUCTION

Korea Electric Power Corporation(KEPCO) which operates power distribution system had established and revised many proper ground design standards for adapting to its operating distribution system through various studies on grounding related methods. An optimized grounding design method of outer cover of pad-mounted equipment of KEPCO's underground distribution system is suggested on this study using field test and revised analysis program which had not been easily approached before. Also economical design way by revising old method which designs and manages with independent grounding resistance values is presented. This study describes technical basis review, system interpretation in a ground point of view, hazardous voltage setting up method, and ground design method verification which is presented by proof test about enclosures grounding value for pad-mounted equipment in grounding standard of underground distribution system.

2 GROUNDING STANDARDS OF PAD-MOUNTED EQUIPMENT IN KEPCO

Grounding standards of pad-mounted equipment is set down that 'The enclosure of extra high voltage equipment which is installed inside of building or on the ground should apply the 1st class ground construction'. Clause 1, article 33 of electric equipment technology standard criteria states that metal beam or metal outer cover for ground installation implements ground construction depends on the operating voltage. The 3rd class ground for below 400[V], special 3rd class ground for above 400[V] and the 1st class ground for extra high voltage are regulated. And DS-5400, which is design standard for KEPCO, states that each circuit of transformer, enclosure of circuit breaker and neutral line of cable connects to common earth panel. The common earth panel should be constructed to 10[ohm] which is the 1st class ground construction.

Figure 1 is the example of grounding construction for pad-mounted equipment.

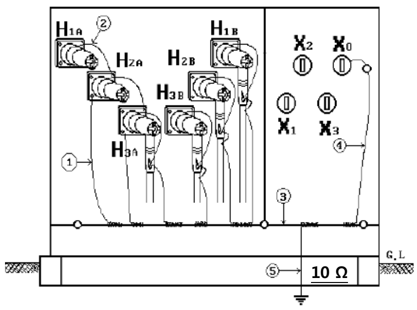


Figure 1: Drawing of pad-mounted transformer with cable neutral connection wire (1), elbow earth wire (2), earth connection wire (3), LV terminal earth wire (4) and grounding wire (5)

Even though no regulation for measuring method of ground resistance exists, according to authentic interpretation parallel resistance value measurements are recommended.

3 PARAMETER CALCULATION FOR HUMAN SAFETY REVIEW

Touch voltage limit and theoretical calculation method of fault point voltage by using equivalent circuit are presented according to international standard. Also compares the dangerous voltage through EMTP simulation when ground fault happens in real distribution system.

3.1 Calculation result of voltage limit for international standard

3.1.1. Calculation result of Touch voltage

Touch voltage limitation for international standard is not presented in distribution system standard, but is presented in detail about the whole overview for review in IEEE standard 80 which is substation ground design guide. Only table is presented in IEC 60749-1 without detail description about the calculation. Consistency is maintained by adapting IEEE which has clear calculation base and procedure.
In IEEE std 80, The limit value of 0.5% death probability for 57[kg] animal is applied and converted to electric shock current for 50[kg] human. By using this, allowable current for human (I_{50kg}) and Touch voltage (V_{touch}) presents at formula (1) and (2) [1].

$$I_{50kg} = \frac{116}{\sqrt{T}} \text{ [mA]} \qquad (1)$$

Operation time of relay of circuit breaker in transformer substation and GIS were applied to the duration of current exposure time(T) to consider the protection property of ground system and safety factor were considered in calculation as well. Calculation result shows at table 1.

Table 1: Exposure time calculation result

Relay operation time	GIS cut-off time	Safety factor	Exposure time[T]
3 [cycle]	5 [cycle]	1.5	(3+5)x1.5 = 12 cycle(0.2 s)

Recommendation of IEEE is applied for body resistance(R_{body}) and contact resistance of feet(R_{feet}) to calculate the Touch voltage. But contact resistance of hand to enclosure(R_{hand}) is not considered.

$$V_{touch} = I_{50kg} \times (R_{body} + \frac{R_{feet}}{2} + R_{hand}) \text{ [V]} \qquad (2)$$

Where: Body Resistance(R_{body}) = 1,000 [Ω]
Foot Resistance (R_{foot}) = 3 × ρ_s = 300 [Ω]
Earth Resistivity (ρ_s) : 100 [Ω·m]
Hand Resistance(R_{hand}) = 0 [Ω]

By using formula 1 and 2, Human allowable current and Touch voltage are calculated after calculate constant value. The result is in table 2. Touch voltage limit is calculated to 298V in table, this means that the limitation of voltage increase of outer cover when ground fault happens at ground equipment which human contacts.

Table 2: Calculation Result of Human Allowable Current and Touch Voltage

Section	Formula	Result
Allowable body current (mA)	$I_{50kg} = \frac{116}{\sqrt{T}}$	259
Touch voltage (V)	$V_{touch} = I_{50kg} \times (R_{body} + \frac{R_{feet}}{2})$	298

3.1.2. Fault point voltage calculation by using equivalent circuit

In this chapter, equivalent circuit analysis is explained to predict voltage increase of outer cover of ground equipment when ground fault happens in ground distribution system.
Through equivalent circuit basic concept and separated phenomenon of fault current are explained to predict limit value of individual resistance value within limit range of touch voltage which is presented at section 3.1.1.
Figure 2 is the equivalent circuit of under ground distribution system when ground fault happens.
In real system, inside of pad-mounted equipment or fault point voltage by fault current when adjacent cable fault becomes the same as the enclosure voltage, because enclosure of pad-mounted equipment and cable sheath(neutral line) are grounded.
This becomes the worst condition considering the human danger because the voltage of fault point is the maximum.

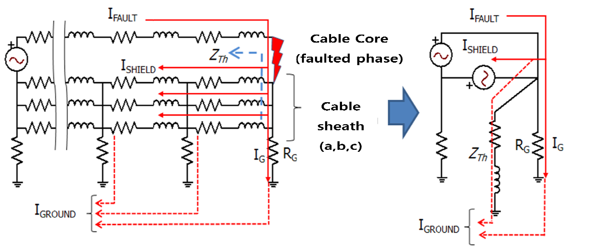


Figure 2: Fault current classification in line to ground fault situation and equivalent circuit

Fault current (I_{FAULT}) when ground fault happens is the same as formula (3). As stated on the formula, cable sheath current(I_{SHIELD}) and ground return current (I_{GROUND}) and shielding coefficient($K = 1 - \frac{Z_m}{Z_n}$) caused by self impedance of neutral line(Z_n) and mutual impedance(Z_m) are considered.

$$I_{FAULT} = I_{SHIELD} + I_{GROUND} = (1-K) \times I_{FAULT} + K \times I_{FAULT} \qquad (3)$$

Also, ground return current, (I_G), of enclosures grounding line by Thevenin Equivalent Circuit on ground fault is shown in formula (4).

$$I_G = \frac{Z_{th}}{R_G + Z_{th}} \times I_{GROUND} = \frac{Z_{th} \times K}{R_G + Z_{th}} \times I_{FAULT} = S_f \times I_{FAULT} \qquad (4)$$

Here, the formula (4) is defined as below.

Z_{th} : Thevenin Equivalent Impedance [$Z_n + (\frac{Z_{th} \times R_{ave}}{Z_{th} + R_{ave}})$]

Z_n: Neutral line impedance between points

R_{ave}: Average resistance of cable connectors

S_f: Split factor of enclosures grounding [$\frac{I_G}{I_{FAULT}}$]

R_G: Enclosure grounding resistance of apparatus in fault point

Apparatus external potential voltage(V_G) is calculated shown in the formula (5) on ground fault of underground distribution system in order to review dangerous voltage to human.

$$V_G = I_G \times R_G = S_f \times R_G \times I_{FAULT}\ [v] \qquad (5)$$

Table 3 shows the impedance and coefficients for enclosures grounding impedance 10 [Ω] of ground apparatus, ground impedance of manhole touch point 16 [Ω/250m], ground cable for distribution TR CNCV-W 325 [㎟, 3 phase 1 line].

Table 3: Cable Impedance and Coefficients

Z_n	0.0783+j0.7439 [Ω/km]
Z_m	0.0585+j0.7437 [Ω/km]
K	0.0265
R_{ave}	16 [Ω]
Z_{th}	1.2938+j1.2523 [Ω]
S_f	0.00419
R_G	10 [Ω]

Therefore, voltage at faulty point in Table 3 is obtained by calculation of formula (4) and (5). The size of fault current is obtained from 227 Bank substations bus impedance data in Seoul, 2006.

Table 4: Touch Voltage at fault location by formula

Fault location	Fault Current	Touch Voltage
4.0 [km]	4.76 [kA]	200 [V]

3.2 Voltage Calculation at Fault Point by EMTP

In order to calculate the voltage at faulty point by EMTP, Source impedance, main transformer at 1st stage, and bus impedance are modeled to equivalent impedance at power at 2nd stage. Equivalent impedance at power is calculated by comparison based on the fault current at each faulty position mentioned in 3.1.2 and EMTP simulation.

Table 5 shows the calculation result when supply impedance is not considered in EMTP model. The error between theoretical value and EMTP fault current becomes bigger as the more fault location from the source.

Table 5: Calculation result when supply impedance is not considered in EMTP model.

Fault location	0km	1km	3km	5km	7km	9km	10km
Theory (A)	6,046	5,693	5,048	4,494	4,026	3,634	3,462
EMTP (A)	6,046	5,817	5,385	4,991	4,635	4,316	4,169
Error (%)	0.0	2.2	6.7	11.1	15.1	18.8	20.4

To minimize the error, reactance is inserted at the front of EMTP supply and simulated result is presented in table 6 after reflect 2.2364[ohm] by using trial and error method.

Fault current error is decreased remarkably depends on the distance, so modeling is applied by making the real investigated information and amount of fault current.

Table 6: Fault current comparison when applies equivalent supply impedance

Fault location	0km	1km	3km	5km	7km	9km	10km
Theory (A)	6,046	5,693	5,048	4,494	4,026	3,634	3,462
EMTP (A)	6,046	5,686	5,040	4,488	4,020	3,628	3,456
Error (%)	0.0	0.1	0.2	0.1	0.1	0.2	0.2

EMTP simulation in figure 3 assumes that single phase to ground fault at distance 4 [km] from source and the fault point resistance is 0 [ohm] which is bolted fault. Simulation result is at table 7.

Table 7: Touch Voltage by EMTP simulation

Fault point / Fault current	Fault current	Touch voltage	Comment
4.0 [km]	4.76 [kA]	202 [V]	Similar with table 4

3.3 Comparison analysis of fault point voltage

After review the validity of EMTP by comparing theoretical calculation result and EMTP simulation results, fault point voltage calculation method by EMTP simulation is valid for considering ground resistance of the enclosure of pad-mounted equipment. Table 8 shows the error range of EMTP simulation result compare to theoretical calculation results.

Table 8: Touch voltage in calculation result vs. EMTP simulation.

Calculation result	EMTP result	Error percentage
200 [V]	202 [V]	1 [%]

In this chapter related theory calculation method to review human safety by fault point voltage when single line to ground fault occurs in underground system is discussed, several parameter choices are discussed and validity of EMTP simulation is verified. Because multi-grounded underground distribution system consists of multiple loop, theoretical analysis is complicated. So it is recommended to use EMTP simulation which is accurate and easy to recalculate.

4 ANALYSIS FOR SHIELD EFFECT IN URBAN AREA

Downtown shield effect is phenomena that Touch voltage drops when ground fault happens because of the affect of metal pipe buried or other cables aside from the shield effect by line impedance.
Calculation of downtown shield coefficient is difficult because of ground resistivity changes, adjacency of metal pipe of city gas or etc. So shielding coefficient in urban areas should be drawn from field test [2][3].
Because EMTP model can't reflect the affect of ground potential rise near fault point when ground fault occurs, downtown shield effect should be reflected to decide the Touch voltage which can be practically hazardous to human body.
Downtown shield coefficient (K') is drawn in this chapter by comparing the test result of fault point voltage to EMTP simulation result through experimental test.

4.1 Experimental test summary and condition

For experimental test, EMTP simulation about the voltage variance of fault points is first implemented with the same condition as experimental test ground has. And comparison analysis for EMTP simulation result is implemented after measure the fault point voltage of phase and neutral line when ground fault occurs. Overhead line in field test yard is total 17[km] length (2[km] for underground, 14.5[km] for overhead line, 0.74[km] for underground), kind of line is CNCV 325[mm^2] for underground cable and ACSR/AW-OC 160 or AL 95 [mm^2] for overhead lines. Fault current is 160 ~ 800 [A] and ground fault is generated between single phase of pad-mounted equipment and cable sheath by Artificial Fault Generator. Figure 3 shows field test yard and measurement

Figure 3: KEPCO's field test yard and Artificial Fault Generator (1)

4.2 EMTP Simulation on Ground Fault with respect to field test

EMTP simulation is implemented based on the test system to compare the field test measurement result and simulation result for verifying the voltage variance trend of fault point when ground fault occurs. For the simulation, ATP-Draw's LCC model is used. Line length and kinds which were mentioned in chapter 4.1 are applied. For neutral line grounding and ground rod resistance value of enclosures of pad mounted equipment, measured value are used for modeling similar to the real line.
The magnitude of fault current and grounding resistance value is chosen to random value and pre-simulation is performed. And fault point voltage is predicted after reflect the measured value during experimental test. Fault current (I_{FAULT}) and Ground resistance value of outer cover (R_G) are measured value during experimental test and Ground side current (I_G) and Voltage of fault point (V_G) are EMTP simulation results at table 9.

Table 9: Fault point voltage by EMTP simulation

Item	I_{FAULT} [A]	R_G [Ω]	I_G [A]	V_G [V]
CASE_1	800	30	7.157	214.7
		115	1.889	217.3
		420	0.519	217.9
		530	0.411	218.0
CASE_2	445	29	4.111	119.2
		101	1.194	120.6
		410	0.295	121.1
		510	0.237	121.1

4.3 Fault point voltage of experimental result

Fault point voltage measurement result shows on table 10. No significant voltage variance of equipment enclosure is observed when ground rod resistance changes from 30 to 500[ohm].
Because of ground voltage increase by fault current and GPR of adjacent ground rod affect, voltage of fault point is measured very lower than EMTP simulation result estimates. As mentioned on the introduction, EMTP simulation can't reflect ground potential rise and adjacent ground rod affect, downtown shield coefficient is drawn and applied to minimize the error between simulation and environmental test result.

Table 10: Fault point voltage in field test result

Item	I_{FAULT} [A]	R_G [Ω]	I_G [A]
CASE_1	800	30	42.5
	805	115	42.7
	800	420	42.7
	800	530	42.8
CASE_2	440	29	23.7
	440	101	23.8
	450	410	23.8
	450	510	23.8

4.4 Comparison of the result by applying downtown shield coefficient

Table 11 shows the result of the fault point voltage (Touch voltage) by applying downtown shield coefficient. Compare to EMTP simulation result, experimental test was calculated has 80 [%] ratio of EMTP simulation result. If downtown shield coefficient (K'=0.2) is applied, both voltage of fault

point and EMTP simulation result are coincided. EMTP simulation results by this ground potential rise and potential interference reflect the improved reliability of the simulation results.
Since field test is performed in limited area, downtown shield coefficient could be different depends on the region in real world. But fault point voltage can be predicted precisely when only the shield effect which this study presents is considered. The result is at table 11.

Table 11: Touch voltage which applied to downtown shield effect

Item	Voltage at faulty point (V_G)		Shielding Coefficient(K')		Touch Voltage(V_{touch})		
	EMTP	Test	EMTP	K'	EMTP	Test	Error(%)
CASE_1	214.7	42.5	214.7	0.2	42.9	42.5	1%
	217.3	42.7	217.3		43.5	42.7	2%
	217.9	42.8	217.9		43.6	42.8	2%
	218.0	42.8	218.0		43.6	42.8	2%
CASE_2	119.2	23.7	119.2		23.8	23.7	1%
	120.6	23.8	120.6		24.1	23.8	2%
	121.1	23.8	121.1		24.2	23.8	2%
	121.1	23.8	121.1		24.2	23.8	2%
CASE_3	77.6	15.4	77.6		15.5	15.4	1%
	78.5	15.5	78.5		15.7	15.5	1%
	78.8	15.5	78.8		15.8	15.5	2%
	78.8	15.5	78.8		15.8	15.5	2%
CASE_4	42.4	8.5	42.4		8.5	8.5	0%
	43.2	8.5	43.2		8.6	8.5	1%
	43.3	8.5	43.3		8.7	8.5	1%
	43.4	8.6	43.4		8.7	8.6	2%

5 TOUCH VOLTAGE BY EMTP SIMULATION

5.1 Review criteria

In this chapter, review the limit value which remains within dangerous voltage when grounding resistance of enclosure of pad-mounted equipment changes by using EMTP simulation. The voltage of enclosure of pad-mounted equipment is reviewed at the middle of distribution line and the end of it when single phase to neutral fault occurs for this. The voltage of enclosure of pad-mounted equipment means Touch voltage and assumes that it is the same as the voltage of fault point. And downtown shield coefficient is applied to EMTP simulation results. Simulation system assumes that TR CNCV-W 325 [mm^2] at underground system, 3 phases 1 circuit and sheath grounding with 16 [ohm] every 250m for manhole connection point. Ground rod resistance of the enclosure of equipment is simulated with 10[ohm] and 100[ohm], the limit of Touch voltage is 298[V]. And 100[ohm] of grounding resistance value for every concrete pole is applied.

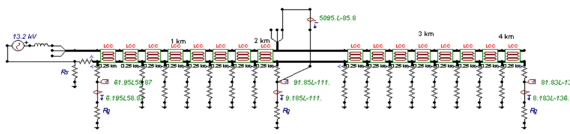
5.2 Touch voltage of underground system

In case the system is configured with only under ground system, Touch voltage is reviewed as 298[V], regardless of grounding resistance value changes from 10[ohm] to 100[ohm], line length and fault locations. Calculation result is at table 12.

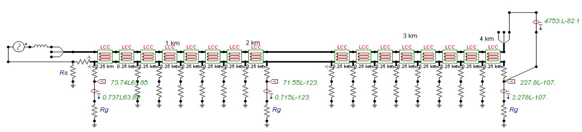
Table 12: Touch voltage of underground line configuration system

Fault location [km]	Ground fault in the middle [V]		Ground fault in the end [V]	
	10 [Ω]	100 [Ω]	10 [Ω]	100 [Ω]
1	8.9	10.3	18.7	20.9
2	14.6	15.7	31.9	34.1
3	17.6	18.8	38.7	42.6
4	18.4	20.4	40.4	45.6
5	18.6	20.4	40.1	45.3
6	18.6	20.0	38.2	43.3
7	18.5	19.7	35.9	40.6
8	19.0	20.1	33.7	38.0
9	18.0	19.0	31.6	35.5
10	17.7	18.6	29.8	33.4

Simulation results show that Touch voltage is twice bigger when the ground fault happens at the end of line than the middle of line. Voltage difference of fault point depends on the fault point can be analyzed by referring the EMTP simulation system in figure 4. EMTP model for analysis is assumed that has 4 [km] of line length and is 100% underground system.



(a) Line model for middle point fault



(b) Line mode for edge point fault

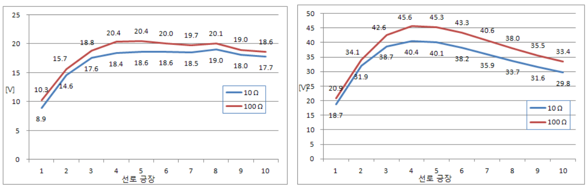
Figure 4: Model depends on the fault location

Looking at the calculation step of voltage of fault point, neutral composite impedance of (a) can be expressed as formula (6), and (b) can be expressed as formula (7).

$$Z_N = \frac{(R_G \times \frac{Z_{th}}{2})}{(R_G + \frac{Z_{th}}{2})} \ [\Omega] \quad (6)$$

$$Z_N = \frac{(R_G \times Z_{th})}{(R_G + Z_{th})} \ [\Omega] \quad (7)$$

If we compare the formula (6) and (7) intuitively, they have 2 times of difference in neutral composite impedance. When considering the magnitude of fault current and classification rate, it is verified that EMTP simulation is valid.



(a) fault at middle point (b) fault at end point

Figure 5: Touch voltage according to ground fault location

Figure 5 is the simulation results of Touch voltage depends on the ground fault position from the supply in total 10[km] of ground line. As we can check in figure 5, the position of most increasing Touch voltage is near 4[km] and give variance of ground resistance of equipment cover from 10 to 500[ohm] during EMTP simulation. When the resistance value of enclosure is increased, touch voltage increases was saturated within limit value like as table 13. In conclusion, 100% underground system can be safer for human safety if sheath is grounded in multi-grounded neutral regardless the line length or fault location.

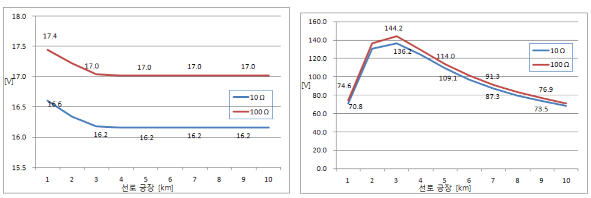
Table 13: Touch voltage variance due to ground rod resistance increase

Enclosures grounding [Ω]	10	100 (10 times)	500 (50 times)	note
EMTP [V]	40.4	45.6 (Increase 13%)	46.1 (Increase 14%)	46.2[V] (saturation) in case exceeds 500[ohm]

5.3 Underground and Overhead line mixed system

By changing the length of underground line from 1 to 10[km] and the length of overhead line from 1 to 10 [km], simulation results by EMTP is analyzed. Overall fault point voltage measured high when the underground line is 3[km] condition.

Figure 6 shows the simulation result with condition that overhead line configured as from 1 to 10 [km] and underground line configured as 3 [km]. Regardless the line length or equipment position, limit voltage is maintained within 298[V].



(a) In underground line (b) In overhead line

Figure 6: Touch voltage according to ground fault location

It was reviewed that draw from substation to underground line is considered. When fault occurs at the end of overhead line, the highest fault point voltage is observed with the underground line 2[km] and overhead line 3[km]. The voltage rise is maintained within the limit. In conclusion, even if draw side is underground line, safety is confirmed regardless of overhead line length.

6 CONCLUSION

Regarding the pad-mounted equipment of underground distribution system of KEPCO, to draw ground resistance value of enclosure of pad-mounted equipment, limit of Touch voltage for human safety is confirmed. By using the constant of underground distribution line, theoretical review and verification of validity is performed through EMTP line simulation. In addition, actual ground fault by using verification test line is produced. So about the downtown shield effect of near underground distribution line area by underground utilities is quantified. EMTP simulation results reflect this result, so prediction of voltage increase when the ground fault happens in underground line could precise. Technical contribution of this paper is as follows.

- Safety condition of human body and downtown shield effect is reviewed when ground design of ground equipment for distribution line which switch from non-grounded system to multiple ground system.
- Verification test for the qualification of downtown shielding effect and the evidence is prepared.
- Review the voltage increase when the ground fault happens in various line configuration system in multiple ground system, and analyzed the effectiveness according to the variance of ground resistance value.

To increase the accuracy of ground design, review of excessive voltage is needed. To do this additional review is expected to proceed about lightning arrester installation standard and the changes in cable diameter.

7 REFERENCES

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[2] IEEE std 367, " IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage From a Power Fault", 1996

[3] Rajotte, Y., "Touch Voltages on Underground Distribution Systems During Fault Conditions", IEEE Trans. Vol.5, No.2, 1990