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A Study on Lightning Overvoltage Characteristics of Grounding Systems in Underground Distribution Power Cables

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Abstract – This paper investigates the transient characteristics of grounding systems used in under-ground distribution power cables. Recently, two kinds of grounding system are used for underground distribution cables in Korea. The first one is conventional multi-point grounding system, the other is newly proposed non-bundled common grounding system. The non-bundled common grounding system has an advantage the decreasing the power loss due to decrease of the shield circulation current. In this paper, the lightning overvoltage induced in neutral wire (in case of non-bundled common grounding system, overvoltage between opened neural wires and grounding in each phase) of these two kinds of grounding systems are estimated and compared by field tests and EMTP simulations. The EMTP simulation methods are firstly verified by comparison of measurement and simulation. Finally, the insulation level against lightning is expected by EMTP simulation results using verified model.

Keywords: Distribution cable system, Lightning overvoltage, Multi-point grounding system, Non-bundled common grounding system

1. Introduction

In general, multiple-point grounding system has been used for 22.9 kV-y underground distribution systems in Korea. The coaxial neutral wire of CNCV cable would be commonly grounded at each straight joint. The circulating current of neutral wire induced by electromagnetic would be flown between both grounding points. This might cause the power loss of underground distribution systems. Therefore, a new technology named as non-bundled common grounding system is proposed for distribution cable systems in Korea. This new system is presently applied in some of actual underground distribution systems. This system has the advantage of increasing the power capacity due to the decrease of the shield circulating current [1-2].

However, the transient overvoltage such as caused by lightning stroke might cause some problems because two phases of coaxial neutral wires are open in non-bundled common grounding system. The defined lightning withstand voltage of neutral wire is 40 kV in insulation standard of Korean utility company. Therefore, the transient overvoltage might exceed the withstand voltage in the case of lightning stroke. Also, there is the possibility of flashover between opened neutral wire and commonly grounded neutral wire in the joint. Those have bad effect on cable insulation. Nevertheless, there is no protection method and equipment against lightning surge.

Therefore, in this paper, lightning overvoltage induced in neutral wire of conventional multiple-point grounding system as well as new non-bundled common grounding system is estimated and compared by field tests and EMTP simulations. EMTP simulation model is also verified by the comparison of measurement and simulation. Finally, system security against lightning surge is evaluated based on insulation standard (ES-6145-0019) of Korean utility company [3].

2. Grounding System in Distribution Cables

Presently, two kinds of grounding systems are used for underground distribution system in Korea. The first one is conventional multi-point grounding system, the other is newly proposed non-bundled common grounding system.

Fig. 1 shows the system diagrams for two kinds of grounding systems used in distribution cables. As shown in this figure, the coaxial neutral wires are commonly grounded at each straight joint for multi-point grounding, while non-bundled common grounding system is not only connected and grounded one phase for fault current return but also kept other two phases open for elimination of circulating current in neutral wire. Fig. 2 shows the characteristics of circulating current in neutral wire for non-bundled common grounding system. In Fig. 2, the arrow means the direction of circulating current in neutral wire. The arrow including ‘X’ means that the induced current is not flowing.

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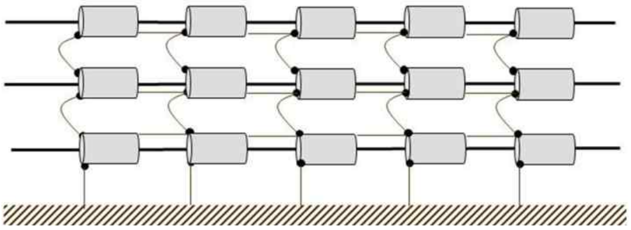
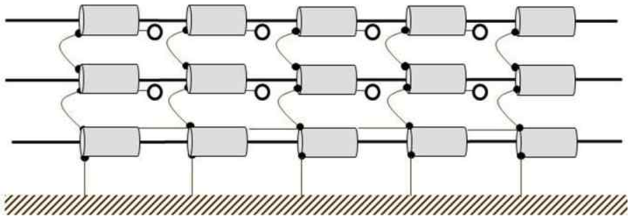


(a) Multi-point grounding system



(b) Non-bundled common grounding system

Fig. 1. Grounding system in distribution cables

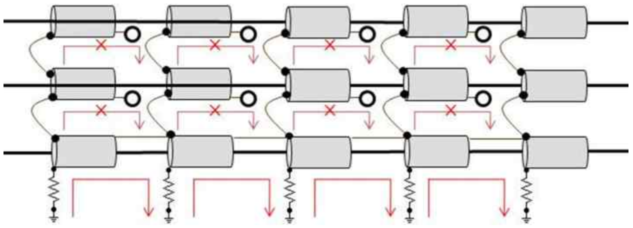


Fig. 2. Circulating current in neutral wire for non-bundled common grounding system

3. Shield Loss

According to IEC 60287 [4] and IEEE Std. 575 [5], the permissible current can be calculated by Eq. (1). The shield current can be also calculated by Eq. (2).

$$I = \sqrt{\frac{\theta - W_d[(\frac{T_1}{2})+n(T_2+T_3+T_4)]}{R[T_1+[n(1+\lambda_1)T_2]+[n(1+\lambda_1+\lambda_2)(T_3+T_4)]]}} \quad (1)$$

where, I is the current flowing in one conductor, θ is the conductor temperature rise above the ambient temperature, R is the alternating current resistance of the conductor at maximum operating temperature, W_d is the dielectric loss for the insulation surrounding the conductor, T_1 is the thermal resistance per unit length between one conductor and sheath, T_2 is the thermal resistance between sheath and armour, T_3 is the thermal resistance of the external serving of the cable, T_4 is the thermal resistance between the cable surface and the surrounding medium, n is the number of load-carrying conductors in the cable, λ_1 is the ratio of losses in the metal sheath to total loss in all conductors in that cable, and λ_2 is the ratio of losses in the armouring to total losses in all conductors in that cable.

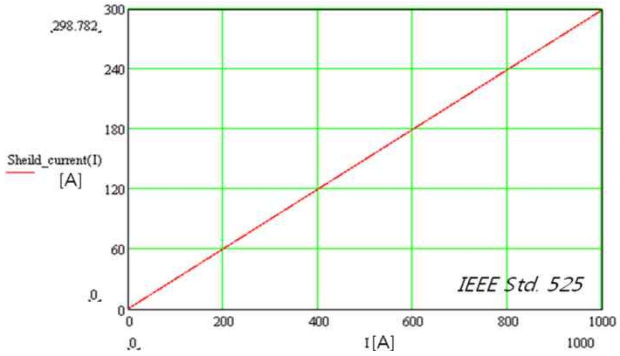


Fig. 3. Relation between shield current and conductor current

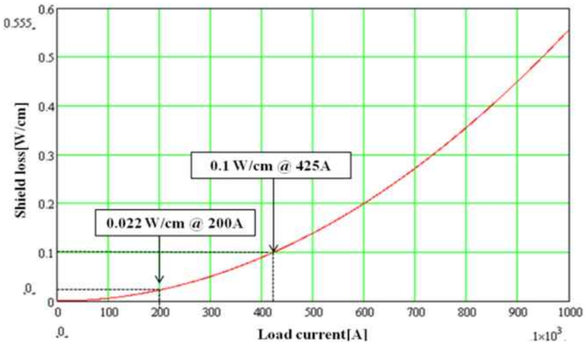


Fig. 4. Shield losses by load current flowing in conductor

$$W_{ST} = 3I^2 R_S \frac{X_M^2}{R_S^2+X_M^2} \quad (4)$$

$$I_s = \sqrt{I^2 \frac{X_M^2}{R_S^2+X_M^2}} \quad (2)$$

$$\lambda_1 = \frac{W_s}{W_c} = \frac{I_s^2 \times R_s}{I_c^2 \times R_c} \quad (3)$$

where, I_s is the shield current, R_s is the resistance of the shield, X_M is the mutual inductance of shield and conductor, W_s is shield loss, and W_c is conductor loss.

Fig. 3 shows the relation between shield current and conductor current at the multiple-point grounding system. As shown in this figure, the shield current is linearly increasing along with conductor current. The shield loss (W_s) and the ratio of losses in the metal shield to total loss (λ_1) is also increasing along with shield current. Finally the permissible current will be decreased with the ratio of losses (λ_1) as shown in Eq. (1)

According to IEEE Std. 575 [5], shield total loss (W_{ST}) can be calculated by Eq. (4). Fig. 4 shows the sheath loss by load current flowing in conductor at multi-point grounding system. As shown in this figure, the shield loss is gradually increasing up to 400 A of load current, and steeply rising above that current. The shield loss is 0.022 W/cm at 200 A of load current which is an average load current in actual distribution underground cable system in Korea. The shield loss shows 0.1 W/cm at 425 A of load current. Therefore, the shield loss is not severe at the normal load condition.

4. Lightning Surge Test for Non-bundled Grounding System

The real test yard is constructed for lightning surge test of non-bundled grounding system in KEPCO Power Testing Center. CNCV 325 mm^2 of 3 phases with 500 m of total length is installed for lightning surge test. The non-bundled grounding system is applied for neutral wire connection. The lightning overvoltage induced in neutral wire is measured at the first joint from surge input point. The length between the first joint and surge input point is 180m. 16 lightning surges with waveform of 8/20 μs strike on the test cable. The magnitude of injected lightning surge is varied from 0.6 kA to 10 kA. The lightning surge is injected using ICG (Impulse Current Generator). The lightning overvoltage in neutral wire is measured using voltage divider of Ross (VD195-15Y). Figs. 5 and Fig. 6 show the diagram and pictures of test cable system.

Fig. 7 shows the V-I characteristic applied in field test.

According to the reference [6], in Korean utility company, the lightning peak current and waveform used for insulation design are 10 kA and 15 kA with waveform of 2/70 μs in underground distribution cable system. However, unfortunately, ICG can just generate the waveform of 8/20 μs and 1/40 μs. Therefore, firstly, the field test is performed based on performance of ICG, then compared with EMTP simulation. From these results, a reliable EMTP simulation model is verified. Finally, the lightning overvoltage induced in neutral wire is estimated by verified EMTP simulation model at the condition of insulation design of Korean utility company with lightning current of 10 kA and 15 kA with waveform of 2/70 μs.

Table 1 shows the withstand voltage of the insulation standard (ES-6145-0019) of Korean utility company for underground distribution system [3]. As shown in this table, the lightning withstand voltage level of jaket is 40 kV. That is, the maximum lightning overvoltage in neutral wire should not exceed 40 kV in the condition of insulation

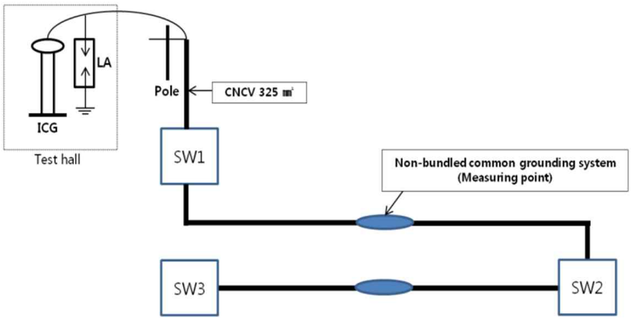


Fig. 5. Diagram of test cable system

(a) Current impulse injection with ICG

(b) First joint measured surge overvoltage

Fig. 6. Pictures of test cable system

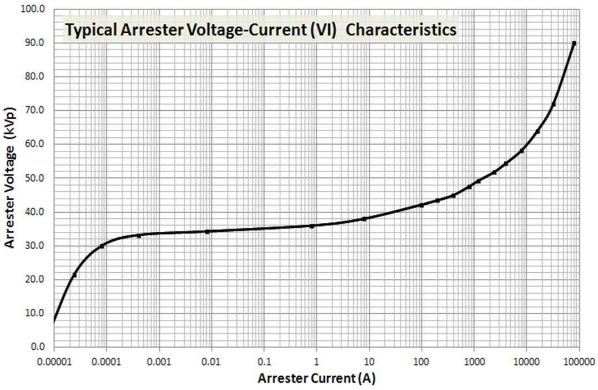


Fig. 7. V-I characteristics of lightning arrester

Table 1. Withstand voltage for underground distribution cable

Voltage rating [kV]	Lightning withstand voltage[kV]		AC withstand voltage[kV]	
	insulation	jacket	insulation	jacket
22.9	150	40	52	4

Table 2. Measurement results by field test

No.	Injected lightning current		Lightning overvoltage induced in neutral wire (kV)
	Waveform (front/tail, μs)	Magnitude (kA)	
1	5/27	0.62	10.6
2	5.1/27	1.0	17.4
3	5/27	1.0	18.5
4	6.3/16.1	1.4	20.2
5	7.1/17.1	1.9	22.2
6	6.9/16.7	1.6	21.0
7	7.5/17.5	2.2	23.2
8	7.7/17.8	2.48	23.5
9	7.9/18.1	3.0	24.5
10	7.9/18	3.0	25.1
11	7.9/18.2	3.7	25.3
12	8/18.5	4.9	27.4
13	8/18.3	5.0	27.6
14	7.9/18.3	5.0	27.5
15	8/18.5	6.9	29.3
16	8/18.5	10.0	35.5

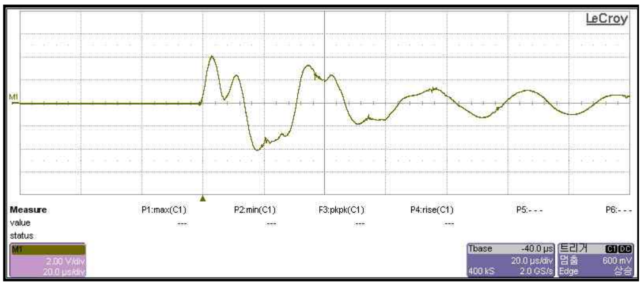
design. However, the lightning withstand voltage level of jacket in Table 1 is different from overvoltage measured in non-bundled common grounding system because measurement is voltage between opened neural wires and grounding in each phase. In general, measured voltage is lower than withstand voltage expressed in Table 1.

Table 2 shows the results measured by lightning surge tests for lightning overvoltage induced in neutral wire. 16 real lightning surge tests are performed with surge magnitude from 0.6 kA to 10 kA. As shown in Table 2, the measured lightning overvoltage induced in neutral wire is increasing along with rising magnitude of injected current. The measured maximum overvoltage during field tests is 35.5 kV at the test condition of waveform of 8/18.5㎲ and injected current of 10 kA. Although tested waveform is not steep comparing with the condition for insulation design of Korean utility company, 2/70 ㎲, the maximum overvoltage is very close to the shield lightning withstand voltage level of 40 kV. Fig. 8 shows the lightning overvoltage measured by oscilloscope at the condition of 7.9/18.1 ㎲ with 3 kA, 8/18.5 ㎲ with 6.9 kA and 10 kA, respectively.

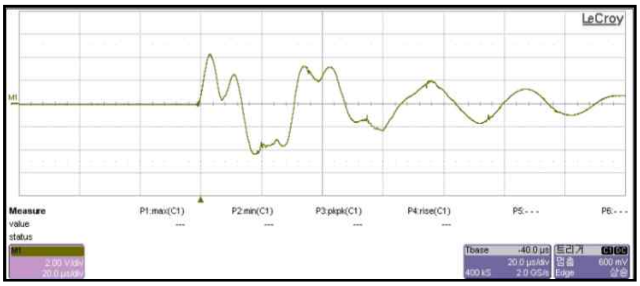
Next, in this paper, the EMTP simulation is also performed for estimation of lightning overvoltage induced in neutral wire at the condition of the lightning peak current and waveform used for insulation design of Korean utility company on the distribution cable system which non-bundled common grounding system is applied

Before estimation of lightning overvoltage by EMTP simulation, in this paper, EMTP modeling is firstly verified by comparison of results of field tests and simulations. The grounding resistance of test cable is also measured applied EMTP simulation. Each measured ground resistance is as follows;

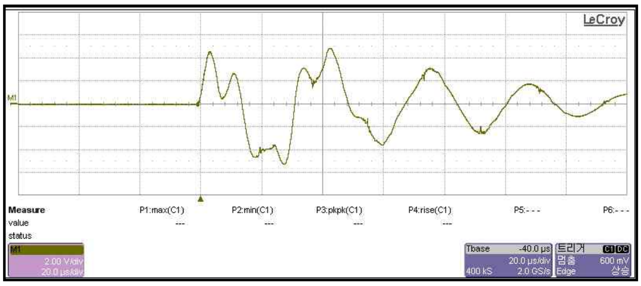
- Grounding resistance of pole : 17 Ω
- Grounding resistance of the first joint : 34 Ω



(a) Oscilloscope measurement(7.9/18.1 ㎲ with 3 kA)



(b) Oscilloscope measurement(8/18.5 ㎲ with 6.9 kA)



(c) Oscilloscope measurement(8/18.5 ㎲ with 10 kA)

Fig. 8. Induced overvoltage waveforms measured for an joint of the neutral wire

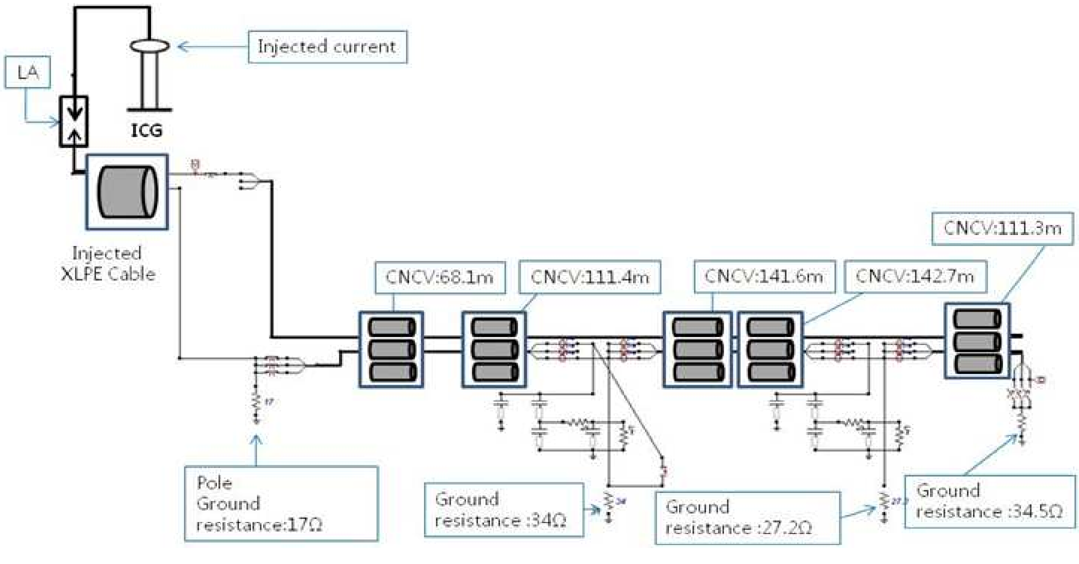


Fig. 9. EMTP simulation diagram

- Grounding resistance of the second joint : 27.2 Ω
- Grounding resistance of the end open point : 34.5 Ω

EMTP simulation is performed considering 16 field test conditions, and the simulation results are compared by measurements. Fig. 9 shows the diagram for EMTP simulation.

The EMTP simulation and measurement results of field tests are compared as shown in Table 3 and Fig. 10. The simulation results are very similar to measurement results. Both the simulation and measurement curves have the same trend along with increasing injected lightning current. The reliability of EMTP simulation method applied in this paper is verified from these results.

The additional EMTP simulation is also performed based on EMTP modeling technique verified in Table 3 and Fig. 10 because of limitation of ICG performance. The additional simulation conditions of the lightning peak current and waveform are 10 kA and 15 kA with 2/70 ㎲ which is the lightning condition for insulation design of Korean utility company.

Table 3. EMTP simulation results

No.	injected lightning current		lightning overvoltage induced in neutral wire (kV)	
	Waveform (front/tail,㎲)	Magnitude (kA)	field test	simulation
1	5/27	0.62	10.6	9.92
2	5.1/27	1.0	17.4	16
3	5/27	1.0	18.5	16
4	6.3/16.1	1.4	20.2	18.8
5	7.1/17.1	1.9	22.2	20.5
6	6.9/16.7	1.6	21.0	19.4
7	7.5/17.5	2.2	23.2	21.4
8	7.7/17.8	2.48	23.5	22
9	7.9/18.1	3.0	24.5	23.2
10	7.9/18	3.0	25.1	23.2
11	7.9/18.2	3.7	25.3	24.7
12	8/18.5	4.9	27.4	26.9
13	8/18.3	5.0	27.6	27.1
14	7.9/18.3	5.0	27.5	27.2
15	8/18.5	6.9	29.3	30.6
16	8/18.5	10.0	35.5	35.8

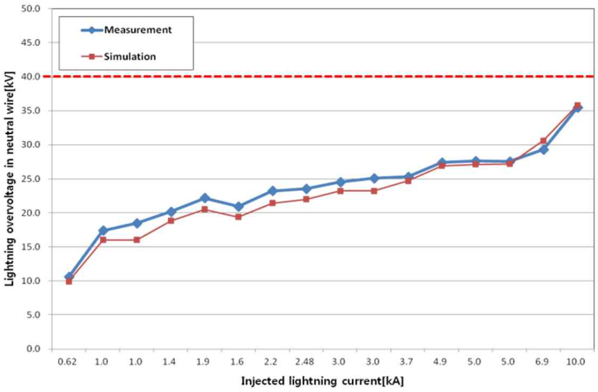


Fig. 10. Comparison of simulation and field test

Table 4 shows the additional EMTP simulation results. As shown in Table 4, the lightning overvoltage induced in neutral wire at the condition of lightning peak of 10 kA with waveform of 2/70㎲ is 42.8 kV. Although calculated lightning overvoltage induced in neutral wire voltage is lower than lightning withstand voltage in same condition, it exceeds the shield lightning withstand voltage level of 40 kV. If the injected lightning current is 15 kA, the result is 52.2 kV. It is far above the withstand voltage level. Therefore, the non-bundled common grounding system may not be stable against lightning stroke on distribution cable systems. The lightning protection is required to stably operate non-bundled common grounding system which is applied to the distribution cable systems. Fig. 11 shows the comparison of field test and simulation including additional simulation results.

Next, the overvoltage in non-bundled common grounding system is compared with the overvoltage in multi-point grounding system as shown in Table 5 and Fig. 12. The

Table 4. Additional EMTP simulation results

injected lightning current		lightning overvoltage induced in neutral wire (kV)
waveform (front/tail, ㎲)	magnitude (kA)	
2/ 70	10	42.8
2/70	15	52.2

Table 5. Comparison of overvoltage between two grounding systems(EMTP simulation)

injected lightning current		lightning overvoltage induced in neutral wire (kV)	
waveform (front/tail, ㎲)	magnitude (kA)	non-bundled common grounding system	multi-point grounding system
5/27	0.62	9.92	1.55
5.1/27	1.0	16	2.5
7.5/17.5	2.2	21.4	4.3
7.9/18.1	3.0	23.2	4.77
8/18.3	5.0	27.1	5.71
8/18.5	6.9	30.6	6.6
8/18.5	10.0	35.8	7.87
2/70	10.0	42.8	8.25
2/70	15.0	52.2	10.27

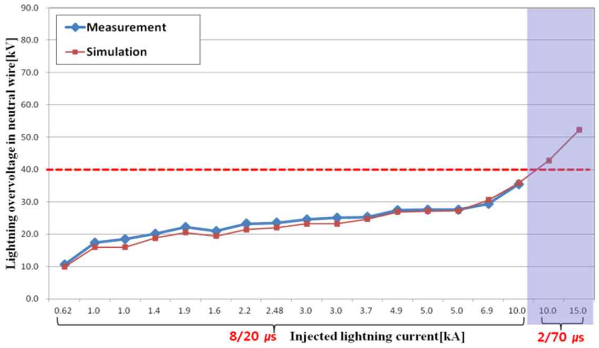


Fig. 11. Comparison of field test and simulation including additional simulation results

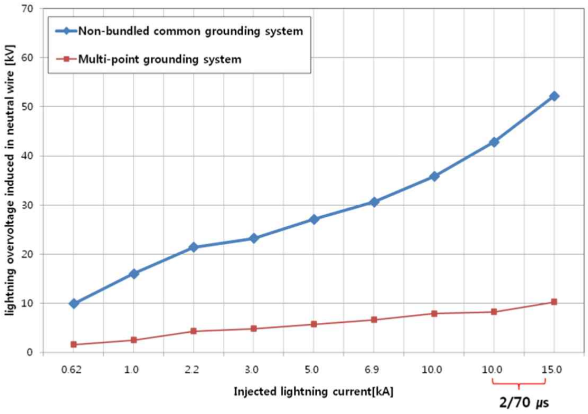


Fig. 12. Comparison of overvoltage between two grounding systems

lightning overvoltage in non-bundled grounding system is much higher than multi-point grounding system, and the overvoltage difference between both grounding systems are steeply growing along with the increase of lightning current peak. Specially, the overvoltage in non-bundled grounding system is increasing along with fast front wave as well as high lightning current peak, while the overvoltage in multi-point grounding system increases slowly regardless of faster front wave and higher lightning current. That is, the multi-point grounding system is much more stable than non-bundled grounding system in respect of overvoltage against lightning stroke. Therefore, reliable lightning protection methods are required for non-bundled grounding system in order to stably supply the power in distribution power cable systems.

5. Conclusions

In this paper, the transient characteristics of two kinds of grounding systems used in Korea were investigated. The results are summarized as follows;

1) Generally, in multi-point grounding system, the shield loss shows 0.022 W/cm at average load current condition of 200 A. That is not severe for power capacity of distribution cable system.
2) The field tests are performed for estimation of lightning withstand voltage level as well as verification of simulation model at the condition of non-bundled common grounding system.
3) Both EMTP simulation and field tests have similar value and trend along with increasing lightning current (Verification of EMTP simulation method)
4) The additional EMTP simulation based on verified model is also performed at the condition of lightning peak current and waveform of 10 kA and 15 kA with 2/70 μs for non-bundled common grounding system.
5) The lightning overvoltage in neutral wire is 42.8 kV and 52.2 kV at the condition of lightning peak current of 10 kA and 15 kA, respectively. Although calculated lightning overvoltage induced in neutral wire voltage is lower than lightning withstand voltage in same condition, it exceeds the shield withstand voltage level of 40 kV against lightning.
6) Therefore, the non-bundled common grounding system is required a special lightning protection to prevent decreasing life expectancy due to damage the cable jacket with lightning surge.
7) The multi-point grounding system is much more stable than non-bundled grounding system in respect of overvoltage against lightning stroke.

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