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A Study on Lightning Surges in Underground Distribution Systems

Chae-Kyun Jung†, Sang-Kuk Kim* and Jong-Beom Lee**

Abstract - The effects of surge arresters for the protection of transmission systems against direct lightning strokes have already been reviewed by many researchers. However, their studies have not encompassed underground cable systems. Therefore, in this paper we investigate the 22.9kV combined distribution systems that have arresters and ground wires. In addition, we analyze the overvoltages on underground distribution cable sections when direct lightning strokes contact the overhead ground wire using EMTP. Finally, we discuss the effect of lightning strokes according to the change of cable length and installation of arresters. This study provides insulation coordination methods for reasonable system design in 22.9kV underground distribution cable systems.

Keywords: Arresters, Insulation coordination, Lightning surge, Underground distribution systems

1. Introduction

Distribution systems are equipped with a tremendous amount of protective equipment including arresters and earth wires in order to prevent transient overvoltage against switching surge or lightning surge. The typical lightning surge generated in distribution systems normally has the time-to-crest of 0.1 ~ several[μs] and the overvoltages can be changed by time-to-crest. This presents particular danger in the event of a back flashover[1, 2].

In systems that contain distribution overhead line and underground cable, this surge can severely affect the cable system section. The insulation of underground distribution cable is not self-restoring and high overvoltage of the cable section by lightning surge has a negative effect on the aging of the cable insulation. Therefore, in order to protect the cable, it is essential to maintain the protective level[4-5]. Consequently, underground distribution cables need new standards for more reasonable insulation design and the various surge phenomena have to be studied on a continual basis.

Most arresters used in underground distribution systems have been installed according to special domestic and international design standards. In order to check the various international standards, we refer to many references[1, 4, 5, 7]. In this paper, the authors describe the lightning overvoltage when the direct lightning surge contacts with the 22.9kV distribution system. Then we analyze the overvoltage according to the various surge conditions including back flashover, reflection wave and change of cable length. The protective methods based on the application of the lightning arrester are also discussed using several cases.

2. Lightning Surge Current

2.1 Characteristic of Lightning Surge Current

The characteristic of lightning current and the surge impedance of distribution lines depend on the rate of rise of surge voltage on the lines. The lightning current travels along both sides of the line at the stroke point. The overvoltage can be expressed by equation (1).

$$e_f = \frac{I_{stroke} \cdot Z_{line}}{2} \tag{1}$$

Where

e_f : Voltage between line and earth

I_{stroke} : Lightning surge current

Z_{line} : Surge impedance of overhead line

The lightning surge current of more than 10kA can occur at the stroke point. If protective devices like arresters are not installed near the lightning strike point, the magnitude of this current can be even higher. Fig. 1 shows the reflected and transmitted surge impedance in the combined distribution system. In this system, the overvoltage transmitted in the cable section can be expressed as in equation (2) [3].

$$e_{cable} = \frac{2 \cdot Z_{cable}}{Z_{line} + Z_{cable}} \times e_f \tag{2}$$

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Where, Z_{cable} means the surge impedance of the cable.

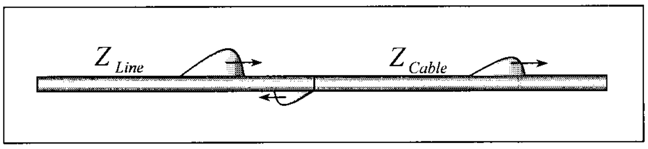


Fig. 1 Surge impedance on overhead line and cable

2.2 Time-to-crest and Time-to-half

Fig. 2 indicates the triangular lightning current waveform of 2/70μs. Its peak current is 20kA and the applied surge impedance is 400Ω[7,10].

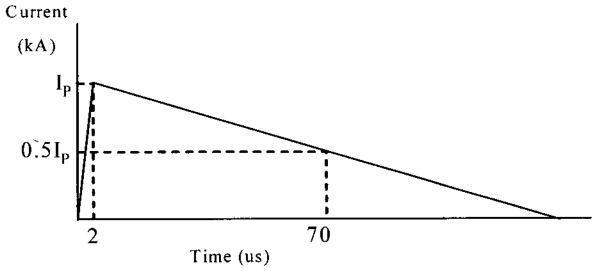
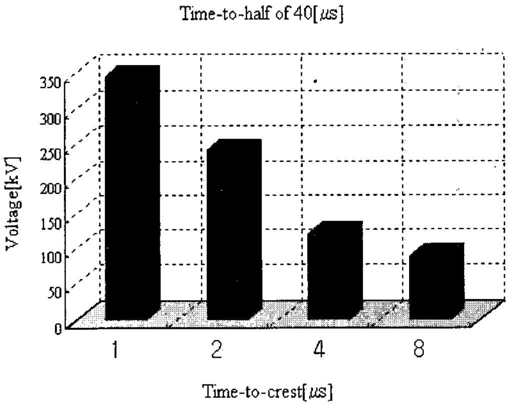
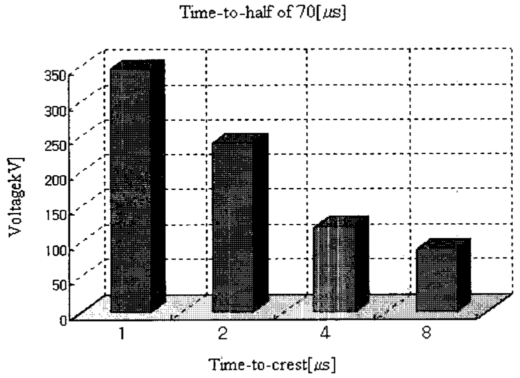


Fig. 2 Waveform of lightning current



(a) Time-to-half of 40μs



(b) Time-to-half of 70μs

Fig. 3 Voltage according to time-to-half

Fig. 3 shows the magnitude of voltage according to time-to-crest and the time-to-half of the lightning current in a cable system. As shown in this figure, time-to-half has no effect on the increase in voltage, while we can see that voltage is increased as time-to-crest rises.

3. Combined Distribution System Modeling

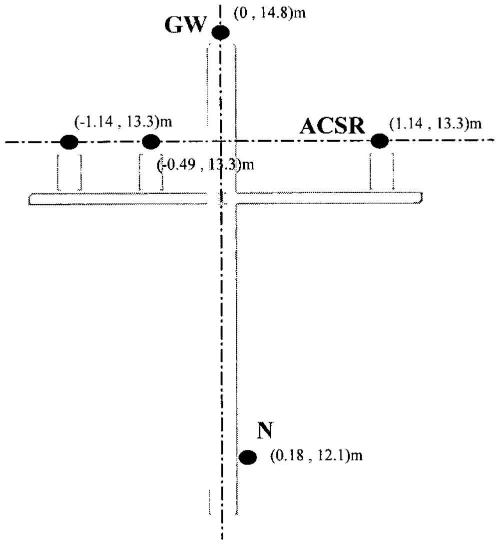
3.1 Overhead Line and Underground Cable Modeling

A) Overhead Line Section

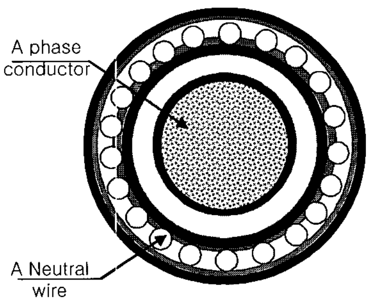
* Overhead line type and conductor size: ACSR 160㎟
* Grounding wire type and conductor size: ACSR 95㎟
* Neutral wire type and conductor size: ACSR 32㎟
* Total length of overhead line section: 1km
* Applied distance between poles: 50m

B) Underground Cable Section

* Cable type and conductor size: CNCV 325㎟
* Cable end is grounded by matching resistance



(a) Overhead line section



(b) Underground cable section

Fig. 4 Configurations of applied combined distribution system

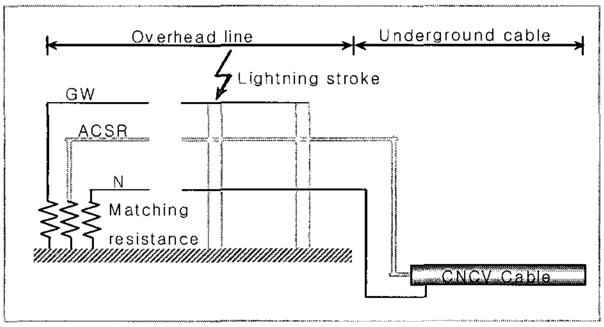


Fig. 5 Combined distribution system diagram

Fig. 4 presents the configuration of the overhead line and the structure of the pole and underground cable, respectively. The line constant of each section is calculated by the distributed parameter circuit with the frequency of 500kHz using EMTP simulation. Fig. 5 shows the diagram of the combined distribution system simulated in this paper.

3.2 Earth Resistance of Grounding Wire and Lightning Arrester

Equation (3) expresses the earth resistance of grounding wire and neutral wire set by Design Standard-3500 (ES-3500) and Design Standard-3800 (ES-3800) of domestic standard [12-13].

$$1.2\left(\frac{1}{\left(\frac{1}{R_1}+\frac{1}{R_2}+\cdots\frac{1}{R_n}\right)}\right)=5[\Omega/km] \qquad (3)$$

The earth resistance of lightning arresters set by domestic standard is 25Ω, a grounding wire does not accommodate earth at a pole with arresters.

3.3 Characteristic of Lightning Arrester

The arresters used in Korea are classed into 3 kinds according to the rated voltage of 18kV, 21kV and 24kV. The rated voltage of most arresters installed in distribution systems is 18kV of ZnO type and the earth resistance is 25Ω.

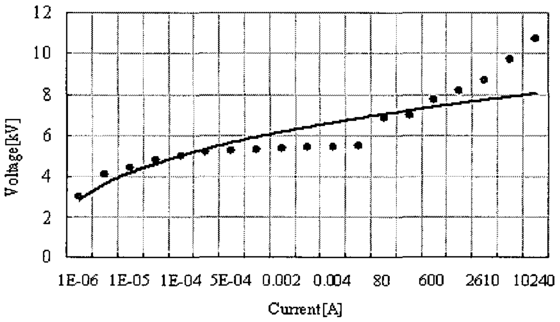


Fig. 6 V-I characteristic curve

Fig. 6 indicates the V-I characteristic curve of the lightning arrester that was used for this paper.

4. Case Study

4.1 Effect of Back Flashover and Reflection Surge

The overvoltage occurred at the distribution line, insulator and neutral wire by back flashover is shown in Fig. 7. The LP (Line Post) type insulator exceeds a critical flashover voltage of 180kV. Then overvoltage of line and neutral also become much higher.

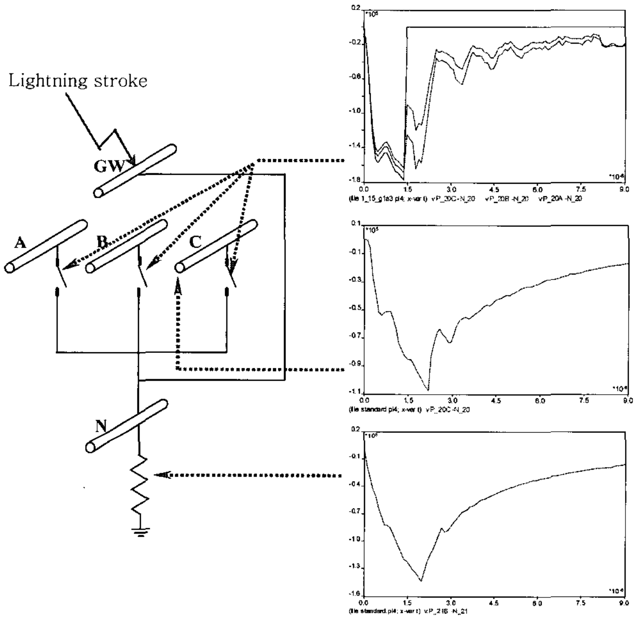


Fig. 7 Overvoltage by back flashover

Fig. 8 compares overvoltage when reflection surge is considered and when it is not. As shown in Fig. 8, the reflection surge has significant effect on underground distribution cable systems.

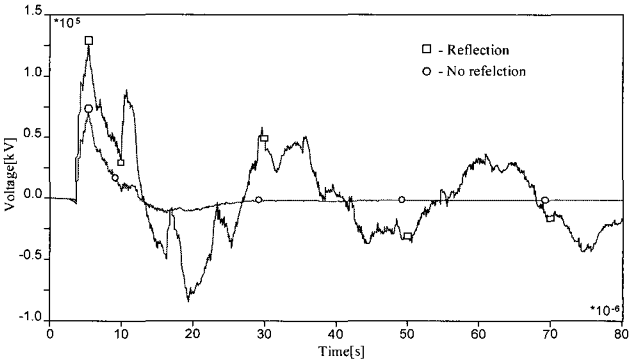


Fig. 8 Effect of the reflection surge on underground distribution cable systems

The surge impedances of overhead line and underground cable are different from each other. Generally, the surge impedance of the overhead line is much higher than that of the underground cable. Therefore, the positive and negative reflection surge generated on the underground cable systems can be changed by the difference of both impedances. If the lightning surge occurs on the combined distribution system, it travels along both directions of the line. Then the transmission and the reflection occur on both ends of the connection point between overhead line and underground cable and the installation point of devices such as transformer and disconnecting switch. Cable length is shorter and overvoltage is higher because the superposition by reflection of the traveling wave appears several times in the underground cable systems. Finally, the overvoltage on the cable system can be steeply increased by fast time-to-crest of lighting surge.

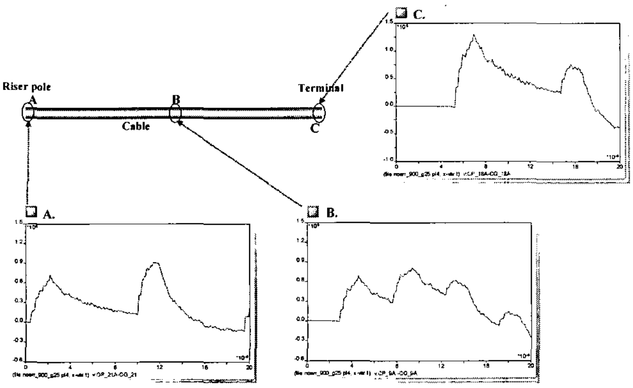


Fig. 9 Overvoltage on underground distribution cable systems

At point A of Fig. 9, the first peak voltage appears by the surge that traveled from the stroke point of the overhead line and the second peak point occurs by the effect of the reflection surge reflected from the cable end. The reflected surge can generate higher lightning overvoltage than the surge that traveled into the cable systems when the cable end is opened. At point B, there are several peak points by the superposition of the incident and reflected surge. In point C, the overvoltage by the lighting surge that traveled into the cable is higher than the one by lighting surge transmitted from the overhead line.

4.2 Effect of Cable Length

The overvoltage of cable section by the change of cable length is shown in Fig. 10. In the case of considering the effects of reflection wave, the magnitude of lighting overvoltage depends on cable length. Especially, at the rising point of cable, if the cable length is shorter, the overvoltage by lightning surge is higher. The overvoltage that exceeds the BIL (Basic Lightning Impulse Insulation Level) can be checked along entire cable sections and then the critical length of that cable can be selected. From these results, we can prove that the appropriate protective equipment has to be installed at the cable systems in order to maintain the safety level at the system below critical length. The critical length studied in this paper is about 900m.

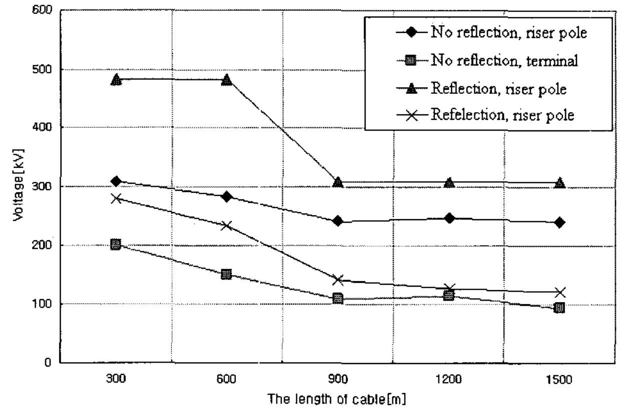
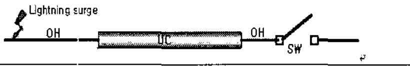
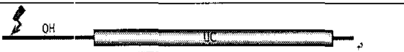
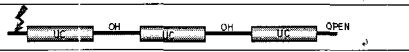
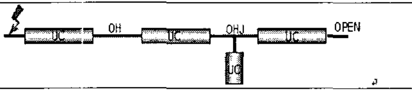


Fig. 10. The effect of reflection wave on underground cable systems

Table 1 Cases for analysis of the combined distribution systems

Case	Model
Case 1	
Case 2	
Case 3	
Case 4	

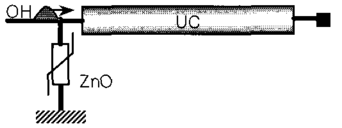
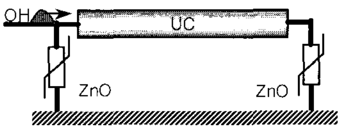
※ Where, UC=Underground Cable, OH=Overhead lines, OHJ=Overhead junction, SW=Switch.

The several cases of the combined distribution systems are expressed in Table 1. Four cases are set by the location and number of the cable section in combined distribution systems. All cases consider direct lightning surge strokes on the grounding wire. Specially, if the back flashover generates between the grounding wire and conductor, the system becomes more dangerous. That is, in Table 1, if there is load or disconnecting switch at a cable end, the overvoltage can be approximately two times greater because of the surge transmitted from overhead lines. Therefore, it's important to install protective equipment according to the various characteristics of the systems.

4.3 Protection Methods

Case 7 is superior to case 6 because reflection wave return from the cable end is the only lightning overvoltage before the operation of arresters. The highest lightning overvoltages generally appear at the cable end. Therefore, when equipment such as the transformer, disconnecting switch or circuit breaker is installed at the end of the cable without the use of arresters, the fault rate of the equipment can amplify. The insulation breakdown rate in an insulator also increases. These are the main causes of age acceleration in cable.

Table 2 Protection methods by arrester installation

Case	Model
Case 5	
Case 6	
Case 7	

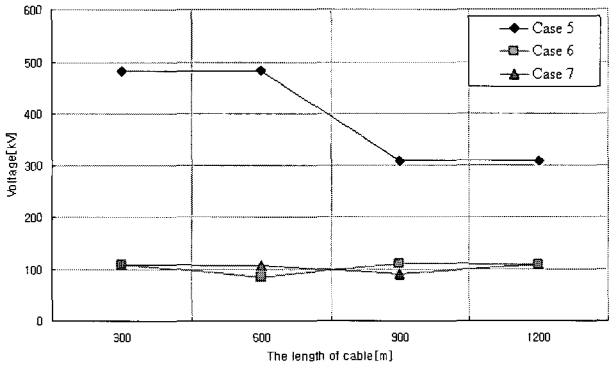


Fig. 11 Voltage at the rising cable

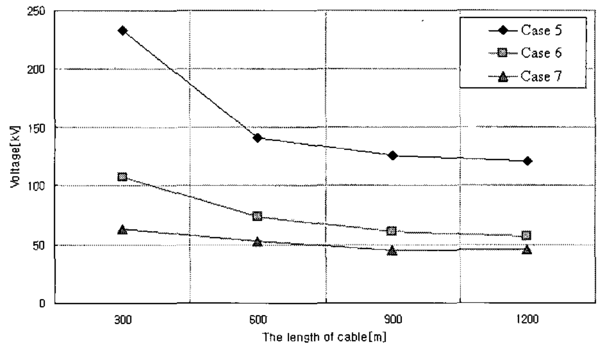


Fig. 12 Voltage at the cable end

Voltage at the rising cable according to installation of arresters is shown in Fig. 11. Fig. 12 indicates voltage at the cable end. As shown in Fig. 11, there is no difference between case 6 and case 7. However, in Fig. 12, Case 7 is higher than Case 6. In Case 6, the overvoltage by lightning surge can be decreased by the only arrester installed at the riser pole. But the reflection at the cable end causes an increase in the overvoltage.

5. Conclusions

This paper has studied the effect of lightning surge in the 22.9kV underground distribution cable system. It has also analyzed the lightning overvoltage according to the change of cable length and the effect of surge reflected from a cable section. Finally, we have discussed the system protection by the application of arresters.

1) The overvoltage by lightning surge traveling into the cable section depends on the cable length and time-to-crest.
2) The appropriate protective equipment must be installed at the cable systems in order to maintain safety level at the system below critical length. The critical length studied in this paper is about 900m.
3) When cable length is shorter, the overvoltage is higher because the superposition caused by reflection of the traveling wave appears several times in underground cable systems.

Acknowledgements

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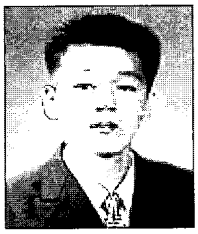

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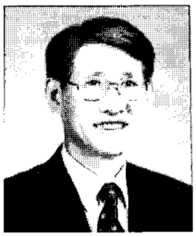

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