A Study of Lightning Surge on Underground Cables in a Cable Connection Station

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Abstract: - This paper is to simulate the transient over-voltage phenomena occurred at 345kV and 161kV underground cables, while the lightning strike on the cable connection station. The feasibility study of changing cable connection methods and related parameters to reduce the damage caused by lightning strike will be thoroughly conducted. The study system including lightning surge, transmission line, transmission tower, arrester, and underground cables are all well modeled. Then, the transient voltage at the cables will be analyzed by different connection methods of grounding wire and length to the arrester. Also, the grounding resistance is considered during the simulation for practical situation. The simulation results show that the length of the grounding wire has more sensitive effects to the transient over-voltage occurred when the common grounding topology is adopted. By contrast, using the independent grounding topology, reduction of the grounding resistance value can more effectively decrease the over-voltage, and avoid exceeding the metallic shield voltage caused by ground potential rise.

Key-Words: - Lightning surge, XLPE Underground Cable, EMTP.

1 Introduction

An overhead line entering earth's surface is connected to the underground cable via a cable connection station. As shown in Fig.1, a surge arrester is mounted on cable terminal to protect the cable and relevant equipments against lightning surge. A 200mm² ground wire of arresters is generally used in 161kV system, and 325mm² used in 345kV system.

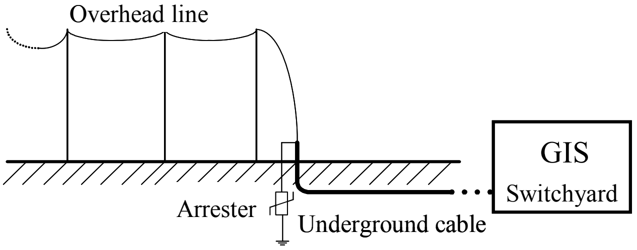


Fig.1 Wiring Diagram

In the event of instantaneous overvoltage arising from lightning surge, the clients and electric utilities may face serious loss due to damage of equipment insulation and subsequent power failures. So, lightning surge is one of major hazards for power transmission lines[1]. The current researches on lightning against underground cable put focus on analyzing the influence of arresters and cable length upon the voltage of lightning surge [2]-[4]. Though the length of arrester lead wire and voltage of conductor were proposed in literature[5], no analysis was once made for common or independent grounding. Therefore, this paper strives to analyze the grounding modes of arresters and the voltage of lightning surge under different grounding conditions.

2 Overview of Lightning and Power Transmission System

The failure of power distribution system is primarily owing to abnormal voltage and over current. The reasons for abnormal voltage include external and internal factors. Of which, external factors are mainly involved with lightning induction of system, lightning stroke and induction caused by nearby power transmission lines, etc. Fig.2 shows accumulative percentage of lightning intensity in 1989～2003. It is observed that, 20kA～30kA accounts for 28% of total number of lightning (831,780).

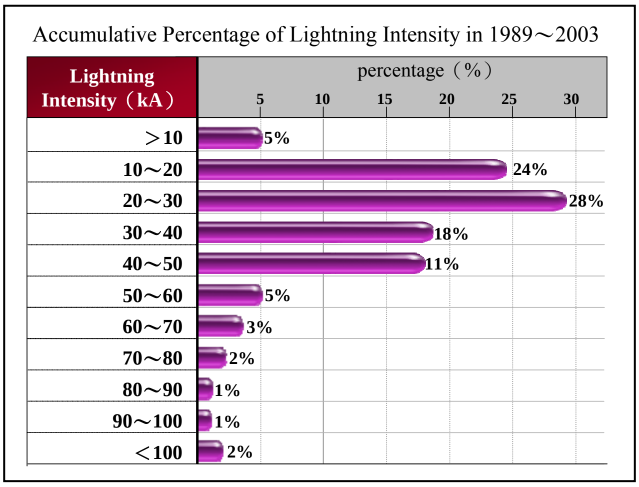


Fig.2 Accumulative Percentage of Lightning Intensity in 1989～2003

The voltage class in this paper covers 345kV and 161kV XLPE cable. Pursuant to Underground Cable Specifications of Chinese National Standard(CNS), the cable is mainly made of such materials with the structure shown in Fig.3.

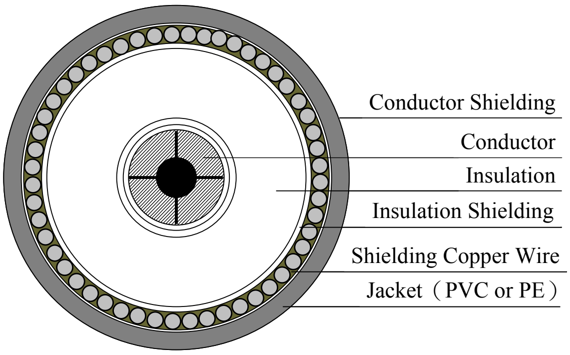


Fig.3 XLPE Cable

3 Description and Analysis of Models

The models of towers and overhead line in this paper follow the approaches and steps in a literature [6]. As for supervoltage tower, the response characteristics of lightning surge were measured separately. These response characteristics include: voltage on cross rods, cross voltage on insulators, induction voltage on power transmission line, etc. The surge voltage was simulated in 120Ω via the help of EMTP, with the results similar to actual measured value. So, the model data was proved to be feasible for evaluating the response characteristics of lightning surge. Eq. (1), (2) and (3) are calculation formulas of the surge resistance. Fig.4 is a size comparison diagram of tower models. Table 1 lists the specifications of towers transmission line.

$$R_i = \frac{-2Z_{t1}\ln\sqrt{\gamma}}{h1+h2+h3}hi \quad (i=1,2,3) \qquad (1)$$

$$L_i = \alpha R_i \frac{2H}{V_t} \quad (i=1,2,3,4) \qquad (2)$$

$$R_4 = -2Z_{t2}\cdot \ln\sqrt{\gamma} \qquad (3)$$

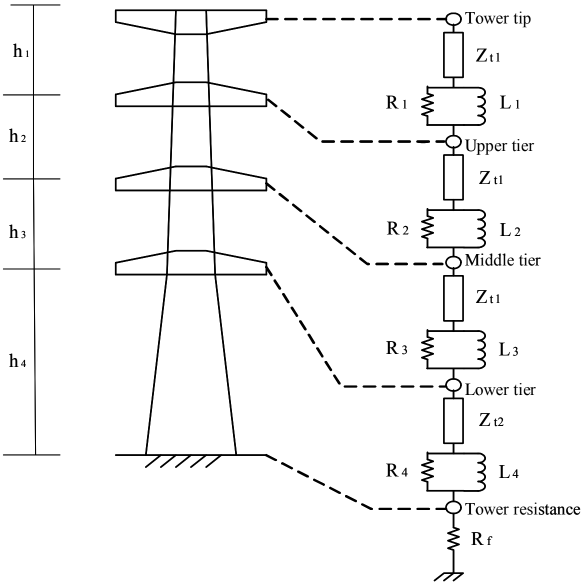


Fig.4 Size comparison diagram of tower models

Table 1 Specifications of towers transmission line

Parameter / System	h1 (m)	h2 (m)	h3 (m)	h4 (m)	Zi	γ	α	
161kV	2.4	4.4	4.4	33	120	0.7	1	
345kV	4.4	8.9	8.95	38.5	120	0.7	1	
Parameter / System	**R1 (Ω)**	**R2 (Ω)**	**R3 (Ω)**	**R4 (Ω)**	**L1 (uH)**	**L2 (uH)**	**L3 (uH)**	**L4 (uH)**
161kV	9.32	16.74	16.74	42.8	3.74	4.93	4.93	12.62
345kV	8.46	17.12	17.12	42.8	1.78	6.93	6.97	17.33

4 EMTP Cable Model

The value obtained from EMTP in literature[8] was compared with actual measured value in literature [9]. The abbreviated drawing and parameters of cable are shown in Fig.5.

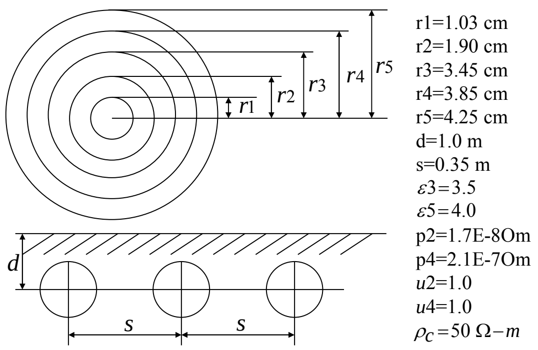


Fig.5 Abbreviated drawing and parameters of cable

To verify this model, let 0×40μs surge of peak voltage 7.3kV enter the cable terminal through 500Ω. The shielded copper wire is grounded through 10Ω, as shown in Fig.6. Then, the sending end voltage of second conductor is observed. Fig.7 depicts an actual waveform, with 0.02ms/per unit on cross axle, and Fig.8 depicts EMTP simulation waveform. The peak voltage is about 1350kV, and occurs at 0.45ms in both cases. According to the literature, it is learnt that BIL(Basic Impulse level) of 345kV and 161kV conductors is 1300kV and 750kV, respectively.

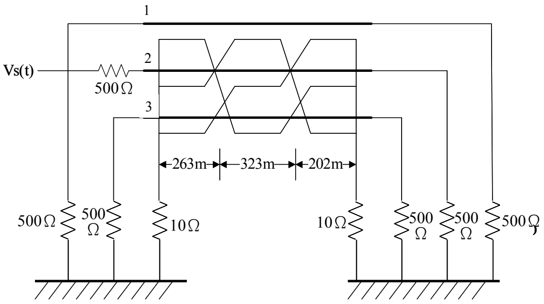


Fig.6 System

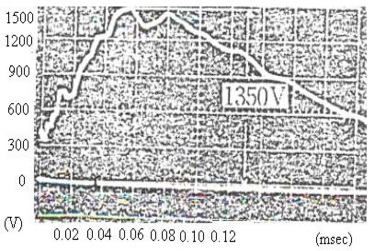


Fig.7 Actual waveform

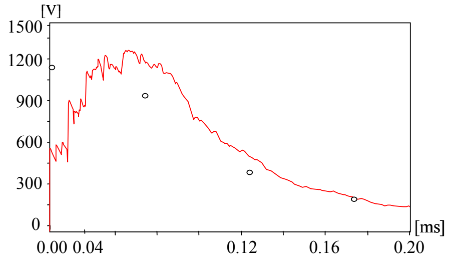


Fig.8 EMTP simulation waveform

The withstand voltage of PVC is 20～40 kV/mm. If 345kV cable uses a conductor of nominal sectional area 2500mm^2, the thickness of PVC is about 8mm. If 161kV cable uses a conductor of nominal sectional area 2000mm^2, the thickness of PVC is about 6mm. Thus, the ground voltage of Concentric Shielding Copper Wire with 345kV is recommend to be less than 320kV, and that with 161kV less than 240kV. Table 2 lists the specifications of 161kV cable. A conductor of nominal sectional area 2000mm^2 is used in this paper, and a conductor of nominal sectional area 2500mm^2 used for 345kV system.

Table 2 161kV cable specification table

Conductor	Nominal sectional area (mm)	1000	1200	1400	1600	1800	2000
	Outside diameter (mm)	38.0	41.7	45.0	48.2	51.0	53.8
Thickness of conductor shielding layer (mm)		2.0	2.0	2.0	2.0	2.0	2.0
Thickness of insulation (mm)		23.0					
Outside diameter of insulation (mm)		88	91.7	95	98.2	101	103.8
Thickness of water-block swelling layer (mm)		1.5					
Diameter of concentric shielding copper wire (mm)		80 wires (2.0)					
Thickness of water impervious layer (mm)		0.4					
PVC Jacket	Thickness (mm)	5.5				6.0	
	Outside diameter (mm)	109.0	111.7	116.0	119.2	123.0	125.8
20℃ maximum DC resistance of jacket (Ω-km)		0.0187	0.0156	0.0133	0.0117	0.0104	0.0093

5 Simulation Analysis and Comparison

The cable connection station is divided into common and independent grounding stations [1]. Fig.11 shows a cable connection station, Fig.9 shows the foundation of cable connection station. It is clearly seen from Fig.9 that, the overhead line is pulled and fastened by insulators onto the foundation. Then, full-aluminum wire is connected to underground cable, and arresters are mounted at cable terminal to remove the surge. A 345kV ground wire of arrester is a 325mm^2 annealed copper wire, and 161kV ground wire is a 200mm^2 annealed copper wire, with a length about 20m～30m. The impedance for 345kV ground resistance is below 10Ω, and for 161kV ground resistance below 20Ω.

Fig.9 shows a cable connection station

Fig.10 shows the foundation of cable connection station

In terms of common grounding, the ground wire of cable terminal arresters and the shielding copper wire share the same grounding system with tower footing resistance, as shown in Fig.11. In terms of independent grounding, the ground wire of cable terminal arresters is grounded independently from the shielding copper wire, and the upper end of ground wire of arrester is interconnected, as shown in Fig.12.

This section analyzed the influence of the length of arrester’s ground wire upon insulation protection, and also observed and compared the cable voltage by changing the length of ground wire with the formula below:

$$L\frac{di}{dt} = L_{LL}\frac{di}{dt} + L_{GL}\frac{di}{dt} \qquad (4)$$

$L\frac{di}{dt}$	total voltage drop of lead wire(kV)
L_{LL}	induction of lead wire from arrester to conducting wire(μH)
L_{GL}	induction of lead wire from arrester to the earth(μH)
$\frac{di}{dt}$	rising rate of surge current(kA/μs)

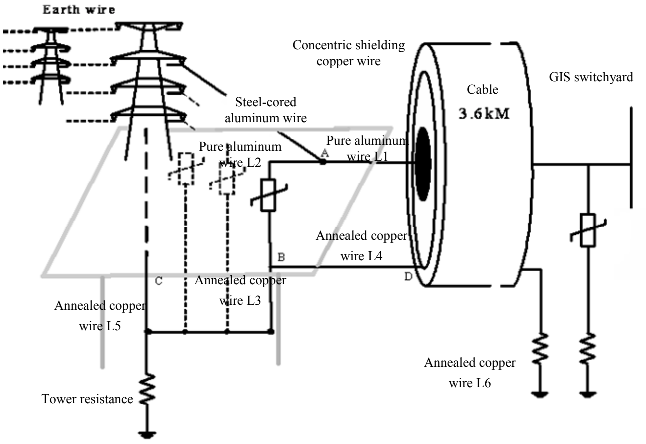


Fig.11 Common grounding of ground wires of arresters in a cable connection station

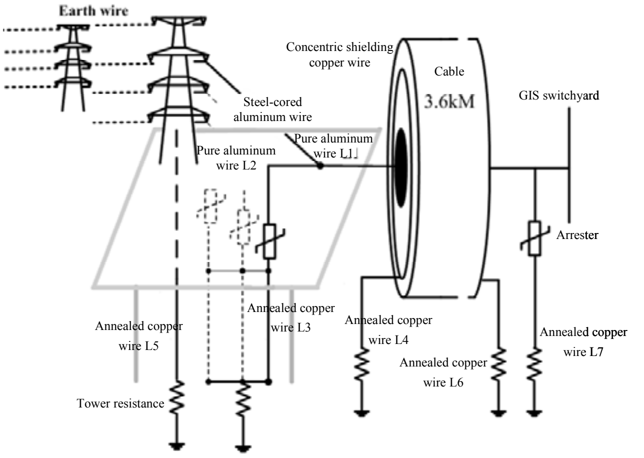


Fig.12 Independent grounding of ground wires of arresters in a cable connection station

To make sure how the change of ground resistance of arresters in the cable connection station has influence upon the simulated results, the standard resistance of 345kV tower reduces from 10Ω to 5Ω, and that of 161kV tower from 20Ω to 10Ω. It is found from simulated results that, ground resistance drop can reduce the voltage of conductors efficiently, especially in 161kV system. It is thus learnt that, when an abnormal voltage intrudes into the cable, prolonging the length of ground wire of arrester will increase the conductor voltage and more probability of insulation damage under common grounding conditions. Meanwhile, the voltage of shielding copper wire will also rise due to surge of earth potential. However, independent grounding has better performance than common ground in terms of reducing conductor voltage, as listed in Table 3. From Table 4 to Table 9, there are lightning striking on the cable near cable connection station, tower top at cable connection station, and overhead ground wire of 345kV and 161kV.

Table 3 Influence of length change upon voltage

	Common ground	Independent ground
While increase length of lead wire the conductor to voltage value of concentric shielding copper wire	The effect is bad	The effect is ordinary
While reduce ground resistance of arrester the conductor to voltage Value of concentric shielding copper wire	The effect is ordinary	The effect is good
Concentric shielding copper wire	The voltage of shielding Copper wire will also rise due to surge of earth potential	There is not this question

Table 4 345kV lightning striking on the cable near cable connection station

345kV lightning striking on the cable near cable connection station	Common ground	Independent ground	Common ground (ground Wire double)	Independent ground (ground Wire double)	Common ground (ground resistance to reduce)	Independent ground (ground resistance to reduce)
20 kA	◎	◎	◎	◎	◎	◎
30 kA	◎	◎	◎	◎	◎	◎
40 kA	◎	◎	◉	◎	◎	◎
50 kA	◉	◎	◉	◎	◉	◎

Table 5 345kV lightning striking on the tower top at cable connection station

345kV lightning striking on the tower top at cable connection station	Common ground	Independent ground	Common ground (ground Wire double)	Independent ground (ground Wire double)	Common ground (ground resistance to reduce)	Independent ground (ground resistance to reduce)
70 kA	◎	◎	◎	◎	◎	◎
80 kA	◎	◎	◎	◎	◎	◎
90 kA	◎	◎	◎	◎	◎	◎
100 kA	◎	◎	◎	◎	◎	◎
110 kA	◎	◎	◎	◎	◎	◎
120 kA	◎	◎	◎	◎	◎	◎
130 kA	◎	◎	◎	◎	◎	◎

Table 6 345kV lightning striking on the overhead ground wire

345kV lightning striking on the overhead ground wire	Common ground	Independent ground	Common ground (ground Wire double)	Independent ground (ground Wire double)	Common ground (ground resistance to reduce)	Independent ground (ground resistance to reduce)
90 kA	◎	◎	◎	◎	◎	◎
100 kA	◎	◎	◎	◎	◎	◎
110 kA	◎	◎	◎	◎	◎	◎
120 kA	◎	◎	◎	◎	◎	◎
130 kA	◎	◎	◎	◎	◎	◎
140 kA	◎	◎	◎	◎	◎	◎

Table 7 161kV lightning striking on the cable near cable connection station

161kV lightning striking on the cable near cable connection station	Common ground	Independent ground	Common ground (ground Wire double)	Independent ground (ground Wire double)	Common ground (ground resistance to reduce)	Independent ground (ground resistance to reduce)
20 kA	◎	◎	◉	◎	◎	◎
30 kA	◉	◉	◉	◉	◉	◎
40 kA	◉	◉	◉	◉	◉	◎
50 kA	◉	◉	◉	◉	◉	◉

Table 8 161kV lightning striking on the tower top at cable connection station

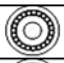
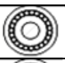
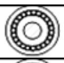
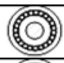
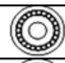
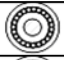
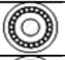
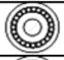
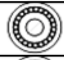
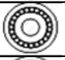
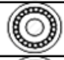
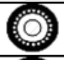
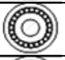
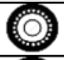
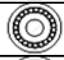
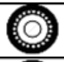
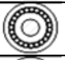
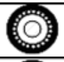
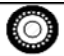
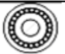
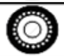
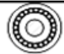
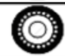
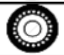
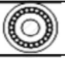
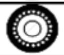
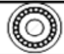
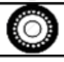
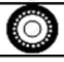
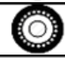
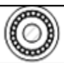
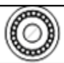
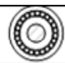
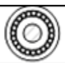
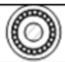
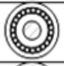
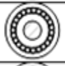
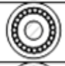
161kV lightning striking on the tower top at cable connection station	Common ground	Independent ground	Common ground (ground Wire double)	Independent ground (ground Wire double)	Common ground (ground resistance to reduce)	Independent ground (ground resistance to reduce)
60 kA						
70 kA						
80 kA						
90 kA						
100 kA						
110 kA						
120 kA						
130 kA						

Table 9 161kV lightning striking on the overhead ground wire

161kV lightning striking on the overhead ground wire	Common ground	Independent ground	Common ground (ground Wire double)	Independent ground (ground Wire double)	Common ground (ground resistance to reduce)	Independent ground (ground resistance to reduce)
90 kA						
100 kA						
120 kA						
130 kA						
140 kA						

6 Conclusions

The major purpose of this paper is to change the length of arrester's ground wire and value of ground resistance, and explore the lightning surge depression effect for underground cables with a view to various grounding modes of arresters in 161kV and 346kV cable connection station. Overhead power transmission lines and towers shall observe existing regulations of Taipower. The cable models and parameters are compared to the case study in references. The simulated results show that, the models currently developed can be used to establish two grounding modes for arresters in existing cable connection stations: common and independent grounding. Simulation is further made for the peak voltage of conductors when lightning surge intrudes into the cables. And, the influence of length of ground wire and ground resistance of arrester upon the system is also observed.

The analytical results demonstrate that, insulation protection effect is often affected by different grounding modes of ground wire of arrester in a cable connection station. When the system is hit by lightning surge, a longer ground wire of arrester will result in more faster voltage rise, especially for common grounding; but reducing the ground resistance of arrester could depress the surge voltage efficiently. With these review results obtained from research efforts, some proper planning could be performed to avoid effectively insulation damage and grounding failure of cables for an improved power supply.

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