論 文
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낙뢰로부터 전력설비 보호를 위한 한전의 절연설계 기준

Insulation Design Standards for Protection of Power System against Lightning in Korea Electric Power Corporation

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Abstract - As it has been reported that more than 60% of transmission line faults occurs due to lightning strokes, lighting is one of concerned issues in electric power utility company. Most of transmission line is double circuit in Korea. Double circuit outages account for 33.7 percent of total lightning faults from 1996 to 2004. Even though transmission fault might be cleared shortly by protective system, it could deteriorate the power quality accompanied with sag or flicker. Moreover, double circuit fault may lead to more aggravated situation, for instance, blackout. To protect transmission lines from lightning stroke, reduction of tower footing resistance, multiple ground wires and unbalanced insulation in double circuit lines have been adopted. In this paper, we would like to introduce insulation design standards for lightning protection of Korea Electric Power Corporation.

Key Words : Insulation Coordination, Standard Design, Lightning, Flashover, Lighting Performance, Transmission Line

1. Introduction

According to the records of KEPCO(i.e. Korea Electric Power Corporation, a grid company in Korea), as shown in Fig. 1, more than 66 percent of power failure has been caused by lightning. Most of transmission line is double circuit in Korea. Double circuit outages account for 33.7 percent of total lightning faults from 1996 to 2004. Even though transmission fault might be cleared shortly by protective system, it could deteriorate the power quality accompanied with sag or flicker. Moreover, double circuit fault may lead to more aggravated situation, for instance, blackout.

Conventionally, reduction of tower footing resistance has been a basic approach to avoid back flashover failure. Because the resistivity of soil is often high in mountain area, the effectiveness of this method often could be deteriorated. Increased insulation length and overhead ground wire on top of the tower have been also adopted to avoid lightning failure. Unbalanced insulation of the double circuit line was proposed as another method, especially for suppression of double circuit fault. Since development of zinc oxide arrester, transmission line arresters have been thought as more effective alternative of conventional countermeasures[1][2][3][4].

Recently, we had studied about lightning protection and revised the design standards for lightning protection from research results[5][6][7]. In this paper, we would like to introduce the revised insulation design standards of insulation coordination for lightning protection in Korea Electric Power Corporation.

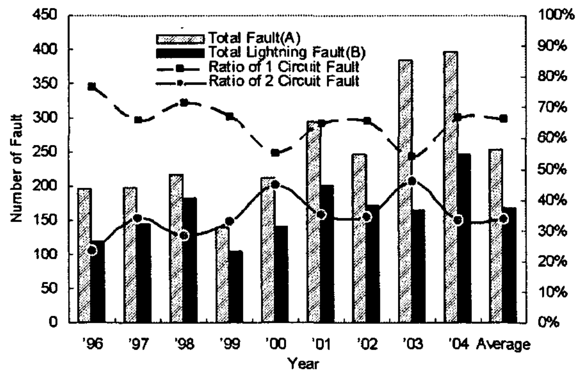

Fig. 1 Lightning faults in KEPCO transmission lines

2. Power System and Lightning in KOREA

Table 1 shows transmission system of KEPCO. KEPCO has installed 28,758 circuit kilometers of transmission facilities. The 154 kV transmission line represents for 66.5 % of them as the 66 kV line, the 345 kV and 765 kV line occupies 2.9 %, 27.5 % and 2.3 %, respectively. As

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shown in Fig. 2, 75 % of lightning failure have been taken place in 154 kV transmission lines.

Table 1 Transmission system of KEPCO

Voltage [kV]	Circuit. Length [C-km]		
	Overhead	Underground	Total
765	662	0	662
345	7,697	220	7,917
154	17,111	2,009	19,120
66	826	2	828
HVDC	30	202	232
Total	26,326	2,433	28,758

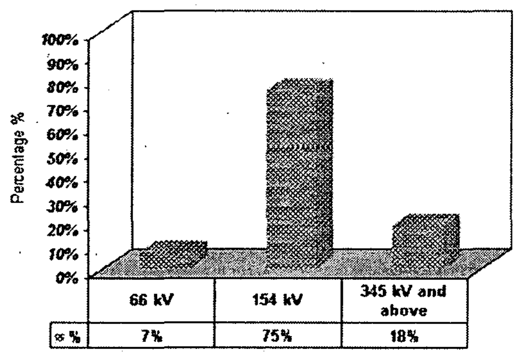

Fig. 2 Lightning faults versus transmission voltage

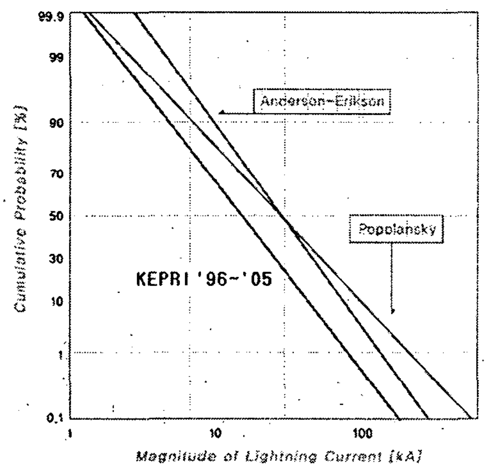

Fig. 3 Cumulative Probability Distribution of Current

$$\text{KEPRI 1996} - 2005 \quad : P = \frac{1}{1+(I/17.51)^{2.86}} \qquad (1)$$

The restructuring of electric power industry over last years have introduced competition into the power market in Korea. It has enforced for electric companies to find more effective solution for lightning than ever.

For the optimal operation of the power system and the basic research of the lightning parameters, LPATS (Lightning Positioning & Tracking System) has been operated from 1995 in KEPCO. For the optimal insulation design, we had accumulated the lightning parameters. Among the lightning parameters, Fig. 3 and equation (1) show the accumulated probability of lightning current in Korea with comparison to Anderson-Erikson's and Poplansky's curve. These curves will be used for lightning protection design in power utilities. According to these curves, the amplitude of lightning current measured in Korean peninsula seems to be smaller than other countries.

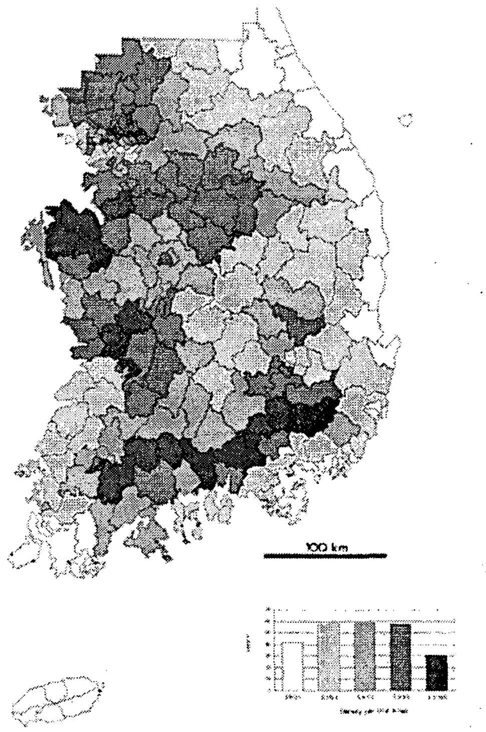

Fig. 4 Lightning density per km^2 by LPATS

Fig. 4 shows the lightning density per km^2 in Korea. Lightning was concentrated Chung-Nam and Jeon-Nam province areas. In these regions, we had experienced many lightning failures in transmission lines.

3. Design Standards for Transmission Line

3.1 Basic conceptions for design

The basics for designing insulation coordination for 154 kV and 345 kV solid grounded system is as follows.

- The design must ensure no flashover due to internal abnormal overvoltages and designed reliability to external abnormal overvoltages including lightning.

The maximum operating voltage of 154 kV system is 170 kV and that of 345 kV is 362 kV. Types of insulators string are suspension, tension and jumper support. Tower is basically vertical type. 345 kV systems use 4-bundled conductor. With considering efficiency of maintenance, arcing horn is used to protect insulator from abnormal conditions. Type of substation is gas insulation or air insulation.

According to previous standards, switching overvoltage of phase-to-ground was 2.8 [p.u.] for 154 kV system. In case of 345 kV system, that was 2.5 [p.u.]. 345 kV case was suggested by Common Wealth Engineering of USA[8]. But, because we could not find the calculation evidences of 154 kV system and power system conditions were changed as compared with the past, we had decided and confirmed the overvoltage targets based on the latest research reports and EMTP (Electro-Magnetic Transient Program) calculation results. At EMTP calculation, we had considered overhead transmission lines and under ground cable lines.

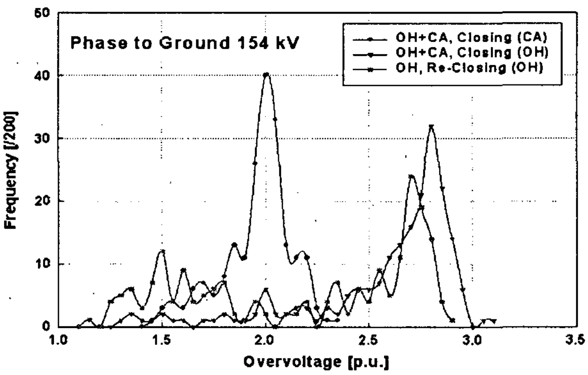

Fig. 5 Incidence of switching overvoltage by EMTP (Phase-to-ground, 154 kV system, total 200 cases)

Table 2 Calculated results for switching overvoltage (Phase-to-ground)

Voltage	T/L	Measuring point	Mean(M) [p.u.]	Standard Deviation(σ)	M+2σ [p.u.]
154 kV	OH+ CA	CA[1]	1.932	0.171	2.274
		OH[2]	2.552	0.373	3.298
	OH	OH	2.161	0.544	3.249
345 kV	OH+ CA	CA	1.9815	0.2220	2.4255

[1] CA : under ground cable lines
[2] OH : overhead transmission lines

Fig. 5 shows the incidence of phase-to-ground switching overvoltage by EMTP calculation at 154 kV system. From calculation results, we had decided switching overvoltage as 97.5 % confidence interval(M+2σ). The maximum overvoltage of 154 kV system was 3.3 [p.u]. That was bigger than the previous standards's value 2.8 [p.u.]. In case of 345 kV, the calculated value was nearly same as the previous value 2.5 [p.u.]. Table 3 shows the calculated results for switching overvoltage of phase-to-ground. As same idea, we had calculated switching overvoltages of phase-to phase and power frequency overvoltages at each voltage level. From these results, we had decided overvoltage targets for insulation design. Table 3 shows the revised overvoltage targets per unit for insulation design.

Table 3 Overvoltage targets per unit for insulation design

Voltage	Type of overvoltage		Over voltage [p.u.]	Base voltage
154 kV	Power Frequency temporary	Phase-to-ground	1.35	$\frac{170\ kV}{\sqrt{3}}$
		Neutral-to-ground	0.68	
	Switching	Phase-to-ground	3.3	$\sqrt{2} \times \frac{170\ kV}{\sqrt{3}}$
		Neutral-to-ground	4.6	
345 kV	Power Frequency temporary	Phase-to-ground	1.35	$\frac{362\ kV}{\sqrt{3}}$
		Neutral-to-ground	0.68	
	Switching	Phase-to-ground	2.5	$\sqrt{2} \times \frac{362\ kV}{\sqrt{3}}$
		Neutral-to-ground	4.0	

3.2 Insulation targets withstand voltage and critical flashover voltage

The selection of insulation strength consistent with expected overvoltages to obtain an acceptable risk of failure.(IEEE Std C62.22) Insulation coordination comprises the selection of the electrical strength of equipment and its application, in relation to the voltages which can appear on the system for which the equipment is intended and taking into account the characteristics of available protective devices, so as to reduce to an economically and operationally acceptable level the probability that the resulting voltage stresses imposed on the equipment will cause damage to the equipment insulation affect continuity of service.(IEC 71-1) Insulation coordination is the process of correlating electrical equipment insulation strength with protective device characteristics so that the equipment insulation strength and the protected voltage level provided by protection devices depends on engineering judgment and cost.

Target withstand voltage(V_W) for insulation design will be calculated as equation (2) at each voltage level. If we know target withstand voltage, critical flashover voltage ($V_{50\%}$) will be calculated as equation (3).

$$V_W = V_B \times n \times k_1 \quad [kV] \tag{2}$$

$$V_{50\%} = \frac{V_W}{1 - m \cdot \sigma_s} \quad [kV] \tag{3}$$

Where,

V_B : Base voltage for 1 p.u.

n : Overvoltage targets per unit

k_1 : Compensation coefficient for weather conditions
for switching overvoltage : 1.082
for power frequency overvoltage : 1.165

σ_s : Standard deviation as Table 4.

m : multiplier as Table 4.

Table 4 m and σ_s

Item	Applied Value
m	3
σ_s [%]	Power frequency overvoltage : 3
	Switching overvoltage : 5

3.3 Calculation of lightning outage rate

As a tool for calculation of lightning outage rate, 'FLASH' program was used, which was developed by EPRI of USA. For the system with three ground wires, EMTP and KEPRI developed algorithm were used for calculation.

Table 5 Lightning outage rate for two circuits (by FLASH) [event/100km·year]

Voltage		154 kV			345 kV		
A type tower	A[1] [m]	3.8	4.1	5.3	6.7	7.3	8.3
	B.F.R[2]	1.703	1.663	1.667	0.815	0.810	0.817
	S.F.R[3]	0.001	0.001	0.000	0.026	0.020	0.012
	total	1.705	1.664	1.667	0.840	0.830	0.829
B type tower	A [m]	3.2	3.6	5.0	6.9	7.5	8.5
	B.F.R	1.710	1.681	1.663	0.771	0.766	0.762
	S.F.R	0.011	0.010	0.009	0.063	0.051	0.043
	total	1.721	1.691	1.672	0.833	0.817	0.805

[1] Arm length of ground wire
[2] B.F.R : Back Flashover Failure Rate
[3] S.F.R : Shielding Failure Rate
[4] IKL = 20

Table 6 Lightning outage rate versus number of ground wire [event/100km·year]

Item		FLASH	KEPRI_LFOR	
		Two ground wires	Two ground wires	Three ground wires
154 kV 4-circuits	B.F.R	4.4945	4.6950	3.3020
	S.F.R	0.1600	0.4695	0.1510
	total	4.6545	5.1645	3.4530
345 kV 4-circuits	B.F.R	2.9580	1.1620	0.8800
	S.F.R	0.6475	0.5430	0.5430
	total	3.6055	1.7050	1.4230

[1] IKL = 20

First, we had calculated lightning outage rate for two circuits line. For calculation, standard A-type tower and B-type transmission tower were selected as representative and IKL was used as 20. Table 5 summarizes results of the calculation. Also, we had calculated lightning outage rate for four circuits line. In this simulation, we considered ground wire numbers as parameters. Table 6 shows lightning outage rate versus number of ground wire.

As calculation of lightning failure rate of transmission system requires complex processing and lots of assumptions, it is difficult to simply estimate the failure rate of four circuits line from two circuits results. Because the height of four circuits tower is generally taller than that of two circuits tower, the failure rate tends to be high. As the surge impedance of tower is proportional to $\sqrt{H}$, where H is tower height, even small lightning current may raise the possibility of back flashover at the tower. As the tower height goes high, lower part conductors of the tower begin to be exposed to shielding failure. Table 6 shows calculation result of lightning failure rate for system with two ground wires and three ground wires.

Table 7 Designed target of lightning failure rate [event/100km·year]

Voltage	Designer target		Predictive calculations	Real outage rate
	previous	changed		
154 kV	1.0	1.0	1.0	0.52
345 kV	1.0	2.0	2.0	1.28

From calculation results, we had obtained design targets of lightning outage rate of transmission line. Predictive calculation using KEPRI-developed algorithm gives that the lightning failure rate is 2.0 [event/100km·year] for 154 kV system and 1.1 [event/100km·year] for 345 kV system, respectively.

According to last ten years of operation records, the lightning failure rate of 154 kV system is 1.3 [event/100 km·year] and the lightning failure rate of 154 kV system 0.52 [event/100km·year]. These records are lower failure rate than that of predictive calculations. The designed targets are determined as 2.0 for 154 kV and 1.0 for 345 kV on the basis of result of predictive calculation result and operation records.

For insulation design against lightning, we had expressed four preconditions at design standards as follows;

- IKL : The degree of lightning activity is measured by the iso keraunic level which is defined as the number of days per year on which thunder is heard at particular location. In designing, IKL is assumed as 20 over the country.
- Ground wire : Two ground wires are in principal on the top of tower for the two circuits line and three ground wires are for the four circuits line.
- Arm length for ground wire location : Arm length for ground wire is same as the longest arm in tower.
- Tower footing resistance : Generally, tower footing resistance should be 15 ohms for 154 kV and 10 ohms for 345 kV.

4. Design Standards for Substation

Table 8 Main specification of surge arrester

Voltage [kV]	Item		For phase conductor	For Transformer Neutral point
154	MCOV [kV_{rms}]		115	57
	Rated voltage [kV_{rms}]		144	72
	Rated discharging current [kV_{rms}]		10	10
	Discharging class		3	3
	Protective level [kV_{rms}]	urgent	413	187
		lightning	375	170
		switching	315	155
	Pressure relief		40 kA, 50 kA	
345	MCOV [kV_{rms}]		230	115
	Rated voltage [kV_{rms}]		288	144
	Rated discharging current [kV_{rms}]		10	10
	Discharging class		3	3
	Protective level [kV_{rms}]	urgent	825	374
		lightning	750	340
		switching	630	310
	Pressure relief		40 kA, 50 kA and 63 kA	

Table 9 Install locations of arrester

Voltage [kV]	Insulation type	outlet of line	Install location
154	Air insulation	overhead line	· within 25 m from inlet of line · within 50 m from inlet of transformer
		under ground cable	· cable connection point at the tower into underground · within 50 m from inlet of transformer
	Gas insulation	overhead line	· inlet of line into substation
		under ground cable	· cable connection point at the tower into underground · at transformer
345	Air insulation	overhead line	· within 10 m from inlet of line · at end of bus · within 17 m from inlet of transformer
		under ground cable	· cable connection point at the tower into underground · at end of cable towards substation · within 10 m from inlet of transformer
	Gas insulation	overhead line	· inlet of line · at transformer
		under ground cable	· cable connection point at the tower into underground · at transformer

Table 8 shows main specifications of surge arrester required to protect power apparatus at 154 kV and 345 kV system. For locations of surge arrester in substation, we had estimated surge amplitudes by EMTP[9]. We had assumed lightning current which comes to the substation as two cases ; one is direct lightning stroke from the power line and the other is back flashover of transmission tower by the lightning stroke on the top of the tower. The commercial transmission line has ground wires to prevent direct lightning stroke, so we consider only back flashover case here. And the lightning surges would travel to the substation if the back flashover occurs in the tower. The assumed lightning current is 1 microsecond wave front and 70 microsecond wave tails. We examined the variation of overvoltage at the substation according to the arresters location.

The location of surge arrester depends on the insulation type of substation and the connecting method between substation and transmission line as listed in Table 9. First, for optimal insulation design, we will install the surge arrester at the incoming point of the line.

Main protective characteristic of arrester is divided into two at the protection object. One is for the phase conductor at substations and power plants. The other is for neutral point of star connected transformer.

The required insulation strength is determined to ensure enough margins against internal and external abnormal overvoltages as shown in Fig. 6. The basic insulation level for 154 kV insulator string is decided on the basis of horn gap of 1,120 mm and the formula (4) representing positive lightning flashover characteristic.

$$V_{50\%} = 0.55d + 80 \quad [kV] \tag{4}$$

From the formula (4) and horn gap of 2,340 mm, the basic insulation level for 345 kV insulator string can be calculated as 1,367 kV.

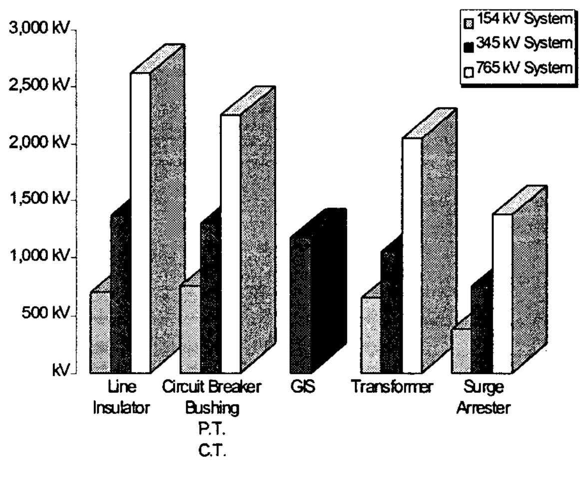

Fig. 6 Insulation coordination level of KEPCO system

5. Conclusion

After the restructuring of electric power industry over last in Korea, protective technology for power system from natural disaster such as lighting or typhoon is getting more interests. In the more competitive power industry and more sensitive atmosphere to serious electric power damage or blackout, the utility company, KEPCO, is forced to search more effective solution for. Besides conventional effort, alternative attempts such as transmission line arrester or multiple ground wire are under test, experiment or research to continuously upgrade the reliability of electric energy supply.

We had revised the design standards for lightning protection from research results. In this paper, we had introduced the revised design standards of insulation coordination for transmission system and substation as follows ;

- For the optimal insulation design, we had accumulated the lightning parameters by LPATS. We had estimated the accumulated probability of lightning current in Korea with comparison to Anderson-Erikson's and Poplansky's curve.

$$\text{KEPRI 1996} - 2005 \quad : P = \frac{1}{1+(I/17.51)^{2.86}}$$

- For the design standards of transmission line, we had defined and estimated the basic conceptions for design, the insulation targets withstand voltage/critical flashover voltage and the calculation of lightning outage rate.
- For insulation design against lightning, we had expressed four preconditions at design standards(IKL, ground wire, arm length for ground wire location and tower footing resistance)
- For the design Standards of substation, we had expressed specifications of surge arrester and locations of surge arrester in substation.

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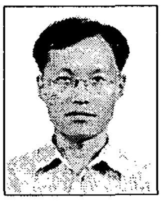

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