Insulation Design and Reliability Evaluation of ± 80 kV HVDC XLPE Cables

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Abstract – This paper describes insulation design and its reliability evaluation of ± 80 kV HVDC XLPE cable. Recently, the construction of HVDC transmission system, which is combined overhead line with underground cable, has been completed. This system is installed with existing 154 kV AC transmission line on the same tower. In this paper, the lightning transient analysis is firstly reviewed for selection of basic impulse insulation level and nominal insulation thickness. Then the electrical performance tests including load cycle test and superimposed impulse test based on CIGRE TB 496 are performed to evaluate the reliability of newly designed HVDC cable. There is no breakdown for ± 80 kV HVDC XLPE cable during electrical performance test. Finally, this system is installed in Jeju island based on successful electrical performance test (Type test). After installation tests are also successfully completed.

Keywords: Basic impulse insulation level, HVDC XLPE cable, Lightning, Insulation design, Performance test

1. Introduction

HVDC is a preferred technology for transmitting large amount of power across long distance. HVDC results in overall higher efficiency and reliability than AC system transmitting the same amount of power. One of the biggest advantages of HVDC transmission is efficiency. HVDC transmission can supply more electricity with less power losses than AC system.

In Korea, the construction of hybrid transmission system has been completed. This system consists of existing 154 kV AC transmission line and newly installed ± 80 kV HVDC transmission line on the same tower. HVDC transmission line is combined overhead line and underground cable.

In previous papers [1-3], the lightning analysis and basic impulse insulation level were investigated including surge arrester type and capacity for ± 80 kV HVDC transmission line. Specially, the new DC cable with nano-composite XLPE insulation was developed to improve improve the insulation efficiency as well as to decrease the impact on the space charge.

In this paper, firstly, the basic impulse level and insulation thickness are reviewed in detail based on the transient analysis results for ± 80 kV HVDC cables. Then, the performance tests including load cycle test and superimposed impulse test were performed based on CIGRE TB 496 [4] for evaluating the reliability of newly designed HVDC cable. Finally, the qualified cable was

installed in HVDC test area in Jeju. The test after installation was also successfully completed in 2012. The final commissioning test of converter station is now in progress.

2. ± 80 kV HVDC Transmission Line

± 80 kV HVDC transmission line in the hybrid transmission system is connected from Hanlim converter station to Geumak converter station in Jeju island. The length of overhead DC line section with ACCC 160 mm² is 4 km, underground cable section with nano-composite XLPE insulation is 0.5 km. Fig. 1 shows the diagram of power system in Jeju island. In this figure, the red line means ± 80 kV HVDC transmission line.

Fig. 2 shows the picture and diagram of ± 80 kV HVDC XLPE cable. This cable consists of conductor (①), inner semiconducting layer (②), nano-composite XLPE insulation (③), outer semiconducting layer (④), metal sheath (⑤)

Fig. 1. Power system diagram of Jeju island

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Fig. 2. ± 80 kV HVDC XLPE cable

and oversheath (⑥)

Fig. 3 shows the detailed configuration of the system. As shown in this figure, the system consists of a 154 kV AC transmission line and a ± 80 kV HVDC transmission line on the same tower. In addition, the HVDC transmission line is connected to underground cables.

3. Basic Impulse Insulation Level

In previous papers [2-3], the surge arrester for ± 80 kV HVDC transmission line has been already selected by various lightning overvoltage analysis. The required maximum continuous operation voltage (MCOV) is 59.4 kV_{rms}. Therefore, the surge arrester with the rated voltage of 78 kV_{rms} and MCOV of 63.1 kV_{rms} is selected for ± 80 kV HVDC transmission line. The nominal discharge current is also selected by 10 kA based on IEC 60099-4 [5]. These kinds of surge arrester have been installed at cable head (joint between overhead lines and underground cables) and converter station inlet.

In this paper, EMTP simulation is used for lightning analysis and insulation design of ± 80 kV HVDC cables. The EMTP model is illustrated in Fig. 4. Four story tower model and back flashover model are used for lightning analysis. The arching horns modeled by TACS and MODELS are also applied in this simulation model. The applied lightning current and waveform are 80 kA and 2/70 μ s. This lightning surge strikes on grounding wire of

Fig. 4. Captured EMTP Simulation

Table 1. Lightning overvoltage according to arrester installation

	Cable head		Converter station inlet	
	Pos. pole	Neg. pole	Pos. pole	Neg. pole
Without arrester	647.6 kV	610.9 kV	664.5 kV	663.7 kV
With arrester	182 kV (8.99 kA)	179 kV (6.82 kA)	171.3 kV (3.88 kA)	172.3 kV (4.2 kA)

() : discharge current of surge arrester

HVDC overhead transmission line section at 1 km from cable head.

The lightning overvoltages according to surge arrester installation are compared in Table 1. The lightning overvoltage with surge arrester is significantly decreased from 647 kV to 182 kV. At this moment, the surge arrester does not exceed the nominal discharge current of 10 kA. The discharge current measured at the positive pole of cable head is 8.99 kA. Fig. 5 shows the lightning overvoltage with surge arrester in cable head as well as converter station inlet.

The basic impulse insulation level is calculated based on EMTP simulation result and several standards of IEC 60071-1 [6], IEC 60071-5 [7] and CIGRE TB 496 [4].

In this paper, DC voltage source is not considered for

Fig. 3. Detailed system configuration

(a) Cable head

(b) Converter station inlet

Fig. 5. Lightning overvoltage with surge arrester

EMTP simulation because the calculation error is occurred by complicated impedance matrix. Therefore, for superimposed DC source, the Bahder's coefficient is applied as expressed in Eq. (1) [6-8].

$$K = (U_p - U_i) / U_0 \quad (1)$$

where, K is Bahder's coefficient. It generally has a coefficient $0 < K < 1$. $K=0.5$ is applied based on Electra 86 recommendation in this paper [8]. U_o is the rated DC voltage, U_i means the maximum lightning impulse voltage to grounding acting alone and U_p is the maximum transient voltage to ground with lightning superimposed on U_o . Table 2 shows the lightning overvoltage considering DC source superimposition. The overvoltage superimposed DC rated voltage can be calculated by Eq. (2). It is critical when the polarity is opposite to U_o .

$$U_K = U_c + K \times U_0 \quad (2)$$

where, U_c is calculated lightning overvoltage when the DC rated voltage is not considered for simulation. U_k is the overvoltage considering DC source superimposition. As shown in Table 2, the overvoltages considering superimposition of opposite DC rated voltage are 222 kV and 219 kV, respectively. They are 40 kV higher than

Table 2. Lightning overvoltage considering DC superimposition

Lightning overvoltage	EMTP simulation	Pos. pole	182 kV
		Neg. pole	179 kV
	Considering DC superimposition	Pos. pole	222 kV
		Neg. pole	219 kV

the overvoltage without DC superimposition. Therefore, the maximum overvoltage by DC source superimposition of 222 kV can be selected to coordinately withstand overvoltage for the basic impulse insulation level of ± 80 kV nano-composite HVDC XLPE cable.

Then, the safety margin of 20 % considering accuracy of EMTP model and other uncertain factors based on IEC 60071-5 [7] is applied for the calculation of the basic impulse insulation level. Finally, the standard basic impulse insulation level for ± 80 kV nano-composite HVDC XLPE cable can be selected by IEC 60071-1 [6].

The maximum lightning overvoltage considering safety margin of 20% is 266.4 kV. From this result, the standard basic impulse insulation level of 325 kV for ± 80 kV nano-composite HVDC XLPE cable can be finally selected.

4. Insulation thickness

The insulation thickness for ± 80 kV nano-composite HVDC XLPE cable is calculated considering impulse withstand voltage (U_{imp}) based on the standard basic impulse protection level (U_{bil}) of 325 kV and design stress for impulse voltage (EL_{imp}). Eq. (3) shows the calculation for impulse withstand voltage and the minimum insulation thickness can be calculated by Eq. (4).

$$U_{imp} = (A \cdot U_{bil} + K \cdot U_0) \cdot k_1 \cdot k_2 \cdot k_3 \quad (3)$$

where U_{imp} is calculated impulse withstand voltage (kV), U_{bil} is standard basic impulse protection level, A is the tolerance of arrester protection level (recommended by CIGRE TB 189), K is Bahder's coefficient, U_0 is the DC rated voltage, K_1 is the repetition deterioration coefficient, K_2 is the temperature coefficient, and K_3 is the overall safety factor for uncertainties.

$$t = U_{imp} / EL_{imp} \quad (4)$$

where t is minimum insulation thickness (mm) and EL_{imp} is the design stress for impulse voltage.

The calculated impulse withstand voltage (U_{imp}) of 411.13 kV can be calculated by Eq. (3). Finally, the minimum insulation thickness of 10.8 mm is also calculated by Eq. (4). Therefore, the nominal insulation thickness of 12 mm is selected in this paper for ± 80 kV nano-composite HVDC XLPE cable.

5. Electrical Performance Test

The electrical performance test (Type test) should be performed on test cable based on CIGRE TB 496 for evaluating the reliability of newly designed ± 80 kV HVDC XLPE cable [4]. Electrical performance tests are made before supplying on a general commercial basis of cable system in order to demonstrate satisfactory performance to meet the intended application. Once accessory with respect to materials, manufacturing process, design electrical stress levels, which might adversely change the performance characteristics [9].

Fig. 6 shows the flow chart for electrical performance test of ± 80 kV HVDC XLPE cable. The order of electrical performance test is 1st load cycle test, polarity reversal test, 2nd load cycle test, superimposed impulse voltage test including switching and lightning impulse, and DC test. Fig. 7 shows the system diagram for electrical performance test. The test is performed in Underground Test Lab in KEPCO Power Testing Center. Fig. 8 shows the real picture of installed test cable for performance test.

The conditions for load cycle tests including 1st 24-hour load cycles, polarity reversal cycles and 2nd 48-hour load cycles are as follows:

Fig. 6. Flow chart for electrical type test

Fig. 7. System diagram for electrical type test

Fig. 8. Real picture of installed test cable for type test

- Eight 24-hour load cycles at negative polarity at $1.85 \cdot U_0$ (148 kV)
- Eight 24-hour load cycles at positive polarity at $1.85 \cdot U_0$ (148 kV)
- Eight 24-hour load cycles with polarity reversal cycles at $1.45 \cdot U_0$ (116 kV)
- Three 48-hour load cycles at positive polarity at $1.85 \cdot U_0$ (148 kV)

24-hour load cycles consist of an 8 hours heating period and a 16 hours cooling period. During the last 2 hours of heating, the conductor temperature shall be at 70°C which is suggested by manufacturer. 48-hour load cycles consist of a 24 hours heating period and a 24 hours cooling period. During the last 18 hours of heating period the conductor temperature should be more than 70°C . 48-hour load cycles are only required as part of the test procedure to ensure that electrical stress inversion is well advanced within the cycle. For a polarity reversal, starting with positive voltage, the voltage polarity shall be reversed three times every “24 hours” load cycle (evenly distributed) and one reversal shall coincide with the cessation of loading current in every “24 hours” load cycle. The recommended time duration for a polarity reversal is within 2 minutes.

During all load cycle tests, there are no breakdown of ± 80 kV HVDC XLPE cable and interruption of testing. The load cycle test is successfully completed. Figs. 9 and Fig. 10 show the results of polarity reversal cycle test and 2nd 48 hour heat cycle test.

Then, the superimposed impulse voltage tests are performed. The switching surge withstand test and lightning impulse withstand test are performed on ± 80 kV HVDC XLPE cable. During the impulse tests, conductor temperature of more than 70°C shall be reached for a minimum of 10 hours before the voltage impulses are applied and shall be maintained throughout the duration of the test. Fig. 11 shows the test circuit diagram for superimposed impulse test. The voltage and temperature maintained for superimposed impulse test are shown in Fig. 12. Also, the conditions for switching and lightning impulse test are as follows:

Fig. 9. Polarity reversal cycle test results

Fig. 10. 2nd 48 hour heat cycle test results

Fig. 11. Circuit diagram for superimposed impulse test

- Switching impulse test (10 times each)
 - Test objective at U_o , 10 consecutive impulses to $-144\text{ kV} \pm 3\%$
 - Test objective at $-U_o$, 10 consecutive impulses to $144\text{ kV} \pm 3\%$
 - Waveform (front/tail) : $200\text{--}300\mu\text{s}$ / $1000\text{--}4000\mu\text{s}$
- Lightning impulse test (10 times each)

Fig. 12. Maintaining voltage and temperature for superimposed impulse test

(a) The first waveform(peak : -142 kV , $222.9\mu\text{s}/2259\mu\text{s}$)

(b) The last waveform(peak : -144.5 kV , $223.94\mu\text{s}/2252\mu\text{s}$)

Fig. 13. The first and last negative superimposed switching impulse waveform

- Test objective at U_o , 10 consecutive impulses to $-325\text{ kV} \pm 3\%$
- Test objective at $-U_o$, 10 consecutive impulses to $325\text{ kV} \pm 3\%$
- Waveform (front/tail) : $1\text{--}5\mu\text{s}$ / $40\text{--}60\mu\text{s}$

(a) The first waveform(peak : 333.8kV, 3.488 μ s/44.653 μ s)

(b) The last waveform(peak : 322.6kV, 3.461 μ s/44.5 μ s)

Fig. 14. The first and last positive superimposed lightning impulse waveform

During superimposed impulse tests, there are no breakdown of ± 80 kV HVDC XLPE cable and interruption of testing. The superimposed impulse test is successfully completed. Figs. 13 and Fig. 14 show the waveforms of the first and last negative switching impulse test and positive lightning impulse, respectively.

± 80 kV HVDC XLPE cable is installed in Jeju island based on successful electrical performance test including load cycle tests and superimposed impulse voltage test. The construction has been already completed. After installation tests including DC withstand voltage test, non-destructive test and TDR (Time Domain Reflectometer) test are also successfully completed. Fig. 15 shows a DC withstand voltage test of real HVDC cables in Jeju. Fig. 16 shows the TDR test results during after installation test. As shown in this figure, the inserted signal from cable head is reflected back from termination of converter station inlet. There is no abnormal signal between the first and the second reflections. The time difference between these two reflections is 5.37 μ s. Therefore, the propagation velocity of real HVDC cables can be calculated as 186.2 m/ μ s. This velocity can be applied for fault location when the fault

Fig. 15. DC withstand voltage test in real HVDC cable system

Fig. 16. TDR test result during after installation test

occurs on this HVDC cable.

6. Conclusions

In this paper, the insulation design and its reliability evaluation of newly developed nano-composite ± 80 kV HVDC XLPE cable is reviewed. The results are summarized as follows;

- 1) The maximum overvoltage including safety margin and DC superimposition is 266.4kV. The basic impulse insulation level of 325 kV can be finally selected based on IEC 60071-1.
- 2) The calculated minimum insulation thickness is 10.8 mm. The nominal insulation thickness of 12 mm is selected for ± 80 kV nano-composite HVDC XLPE cable.
- 3) The electrical performance test is performed based on CIGRE TB 496 for evaluating the reliability of newly designed ± 80 kV HVDC XLPE cable.
- 4) During all load cycle tests including 1st and 2nd load cycle and polarity reversal, there are no breakdown of ± 80 kV HVDC XLPE cable and interruption of testing.
- 5) During all superimposed impulse tests including

switching and lightning impulse tests, there are no breakdown of ± 80 kV HVDC XLPE cable and interruption of testing.

- 6) ± 80 kV HVDC XLPE cable is installed in Jeju island based on successful electrical performance test. The construction and after installation tests including DC withstand voltage test, non-destructive test and TDR are also successfully completed.

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