Development Status of HVDC XLPE Cable System in Korea

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ABSTRACT

In this paper, our development results have been described in detail for HVDC XLPE cable system for various voltage ratings. In the anticipation of the global market growth in near future, it has been inspired to provide the diversity of our products. For this purpose, we started with developing ±80kV cable system in 2010 and LCC/VSC type full scaled cables have been developed for those four operating voltages such as ±80kV ±150kV, ±250kV and ±320kV.Furthermore, the development of ±525kV for both types has been now undergoing and would require a couple of years more.

KEYWORDS

HVDC transmission lines, HVDC XLPE cable, LCC type, VSC type

INTRODUCTION

Ascribed to the technical advantages confirmed since last couple of decades, HVDC transmission systems have been employed all over the world for long-distance power transmission lines to interconnect power grids between the continents and for short distance between neighbor countries. Besides, the global market requires a HVDC power cable system with large power transmission capacity bringing about the economic benefits.

It has been conceived to develop new insulation materials suitable to meet the commercial goals. In this regards, HVDC material technology has been developed depending on the type of the converter station and cable system, for which related material researches have been carried out diversely. In order to avoid any unexpected service failure of HVDC power cable system, many a research have been conducted to find a solution enabling to decrease the space charge accumulation inside the cable system. And thus, the development of XLPE material has been mostly focused to obtain long term stability and relatively high transmission efficiency.

In this paper, our development plan has been described in detail for HVDC XLPE cable system for various voltage ratings; insulation material at laboratory, miniature cable for the evaluation of characteristics and finally the design of full scaled power cable system including necessary joints. We started with developing ±80kV cable system in 2010 and then the necessary efforts will be continued for ± 525kV for several years more. For this purpose, various materials have been employed for the cable insulation depending on the type of converters; Nano composite compound by adding Nano inorganic filler for LCC type and commercially available compound for VSC. It could be pointed out that our efforts have also extended to develop exclusively an optimized manufacturing process by which Nano composite XLPE could be obtained for the cable insulation by use of our own surface treated Nanoparticles. In this way, model cable has been fabricated using our compound before being put into the fundamental investigation: DC and impulse breakdown, Analysis of DC field distribution as a function of temperature up to 90 degree.

Regarding LCC cable, our first ±80kV cable system has been developed and then related type test has been conducted according to CIGRE test recommendations (CIGRE TB 219). Afterwards, in order to verify the required long term reliability and stability, well-equipped test-bed has been built in Jeju Island for the first time in Korea. Our successful results based on the deep investigation pushed its first commercial service in 2013. In connection with VSC cable, our cable systems have been designed and manufactured for three operating voltages such as ±150kV, ±250kV and ±320kV; they have been all put under type test in accordance with CIGRE TB 496. In particular, ±250kV LCC cable system shows also satisfied results. Furthermore, the development of ±525kV for both types has been now undergoing and would require a couple of years more.

HVDC XLPE CABLE SYSTEM FOR LCC TYPE

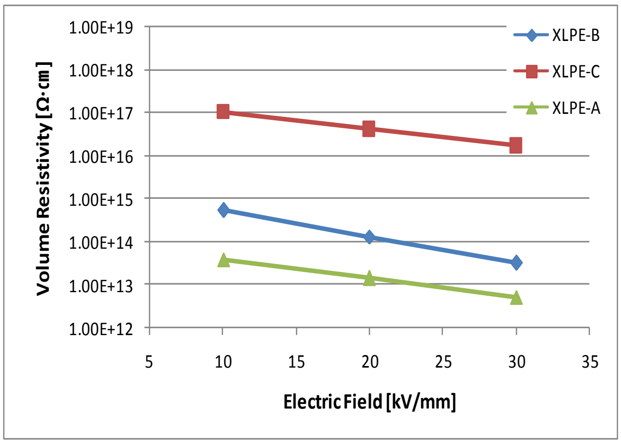
Development of the HVDC XLPE material

The ±80kV and ±250kV HVDC XLPE cables for LCC type were developed based on the material research mentioned earlier. We have been studied various materials such as conventional AC XLPE, conventional DC XLPE, and newly developed DC XLPE with nano-particles for HVDC XLPE cable application. The surface of nanoparticles was modified by various surface treatment materials in order to have a compatibility with polyethylene and improve distribution and dispersion of particles in XLPE matrix. Many researchers have studied how to improve the dispersion of nano-particles in nano-composites and develop an effective analytical tool to quantify the degree of dispersion. We have also struggled to solve these problems in this research. Since the distribution and the dispersion of nano-particles in nanocomposites is critical for the performance and properties of materials, it was very important to ensure the reasonable dispersion by analytical methods.

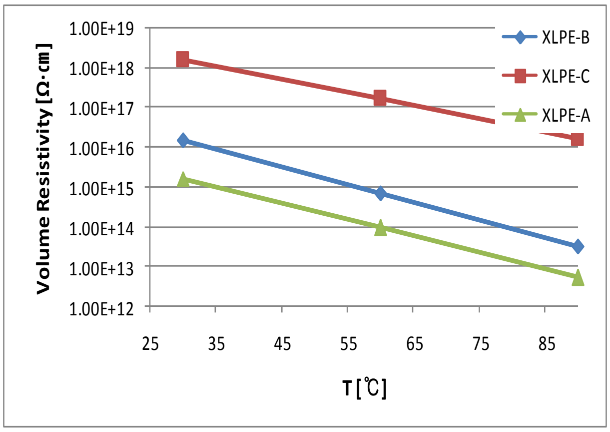
The electrical stress distribution under DC steady state conditions, is determined by the resistivity(or conductivity) of insulation materials. The resistivity of materials are characterised by using equations below,

$$\rho = \rho_0 \exp(-\alpha T - \beta E) \qquad [1]$$

Where ρ_0 is the resistivity at reference temperature and electric field, α and β are temperature and electric field coefficient, respectively. For calculation of the electric field distribution, knowledge of temperature and electric field dependence of resistivity are essential.



a) Volume resistivity depending on electric stress(at 90 ℃)



b) Volume resistivity depending on temperature(at 30kV/mm)

Fig. 1: Volume resistivity characteristics of AC and DC XLPE compounds

Figure 1 shows the volume resistivity as a function of the applied electric field and measuring temperature for three different insulation materials: (a) conventional AC XLPE (XLPE-A), (b) conventional DC XLPE (XLPE-B) and (c) developed nano-DC XLPE (XLPE-C).

It can be clearly seen that the volume resistivity was gradually decreased with increasing applied electric field in all case, and the volume resistivity of XLPE-C is higher than those of XLPE-B and A.

Development of HVDC ±80kV XLPE cable system

HVDC ±80kV and ±250kV XLPE cables were developed based on the material research mentioned earlier. As an insulation material, we used nano-composite XLPE. We prepared a 50m long HVDC ±80kV XLPE cable as the specimen and conducted the mechanical pre-conditioning and electrical tests sequentially. The test items and conditions for HVDC ±80kV XLPE cable are shown in Table 1, as specified in Electra TB 219. Before the electrical tests, cable was subjected to bending test.

Table.1: Test condition and items

Test item		Test condition	Result
Mechanical test	Bending Test	Diameter : 2.3m	Good
Electrical Test	Loading Cycle test	-148kV : 8 Cycles +148kV : 10 Cycles	No B.D
	Polarity reversal test	±116kV : 10 Cycles	No B.D
	Super-imposed impulse test	Lightning impulse :(±) 80kV+L.I(±-)325kV 10 times Switching impulse :(±) 80kV +S.I(±)114kV 10 times	No B.D
	Subsequent DC Test	-148kV / 2hrs	No B.D

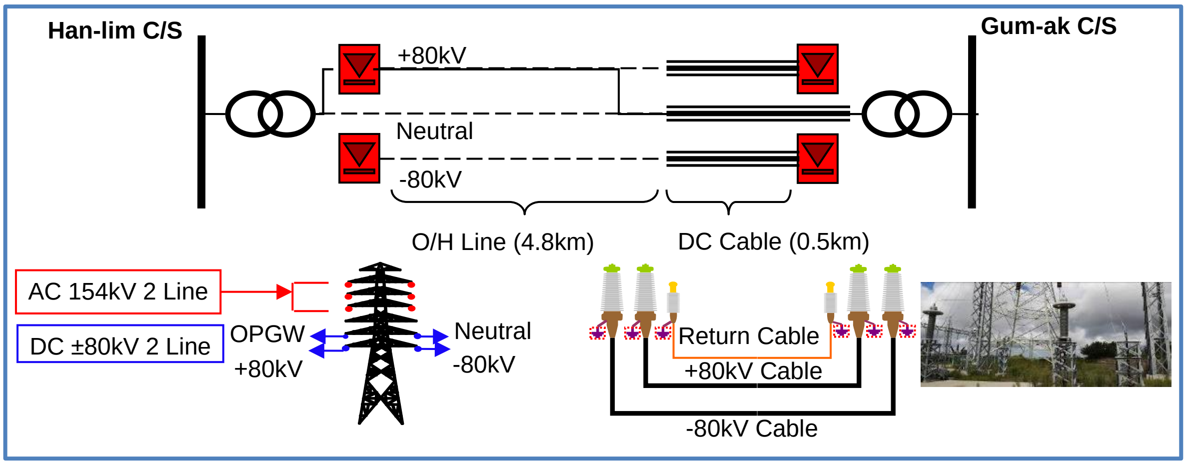


Fig. 2: HVDC cable system diagram

During all of electrical tests, the temperature of the conductor was controlled to be more than 70 ºC by applying AC current to the conductor. The cable system specimen has passed the type test successfully, no breakdown occurred during load cycle test, polarity reversal test and superimposed impulse test

The Jeju Island HVDC test-bed shows a HVDC 80kV transmission system, which is designed to transmit 60MW power from the Han-Lim converter station to the Gum-ak converter station through an approximately 4.8 km long overhead line and an approximately 0.5km long DC XLPE cable. This test-bed has been operated since June, 2013. The system configuration of Jeju Island HVDC test-bed is shown in Figure 2.

Development of HVDC ±250kV XLPE cable system

At first the development tests such as DC voltage withstand test and polarity reversal test were carried out to check the DC operating performance. The overview of test circuit for 250kV HVDC cable system is shown in Figure 3. The development and type tests were conducted in KEPRI Gochang Power Testing Center (Korea Laboratory Accreditation Scheme (KOLAS) accredited testing laboratory). The cable system consists of the approximately 50m long 500 ㎟ copper XLPE cable and two terminations.

a) Load cycle test

b) Superimposed impulse voltage test

Fig. 3: Overview of test circuit for HVDC ±250kV XLPE cable system

The development tests were carried out with no load cycle, load cycle and polarity reversal tests. Table 2 shows the development test conditions. DC voltage withstand test with no load cycle was conducted at each polarity of a DC 463kV for 24 hours. The load cycle consists of two 24hour load cycles at negative polarity of DC 463kV. Additional performance tests focusing on polarity reversal withstand tests on a 363kV voltage were carried out on the same cable system loop, where voltage polarity was reversed every eight hours during the heat cycles. The heating may be achieved by AC current, and a conductor temperature was controlled to be at 90 ºC during at least the last 2 hours of the heating period. The cable system successfully passed under the test programme above of the development test.

Table.2: Condition and items of development test

Test item		Test condition
No load cycle test	DC voltage test	±463kV/24hours
	Lightening impulse test	±730kV/10times
Load cycle and polarity reversal tests	DC voltage test	-463kV/2cycles
	Polarity reversal test	±363kV/2cycles

The type test was carried out on the same cable system loop after the development test. The cable and outdoor termination were submitted to the complete qualification according to LCC protocol of CIGRE TB 496. The type test was performed with load cycle and also with polarity reversal test and superimposed impulse voltage tests. In case of the superimposed switching and lightning impulse tests, a blocking capacitor and a protection resistor were used for the protection of testing facilities.

The electrical type tests were performed in the following manner:

Load cycle and polarity reversal test for LCC type

- 8 cycles at (-)463kV, “24hours” load cycle(8hrs heating/16hrs cooling)

- 8 cycles at (+)463kV, “24hours” load cycle(8hrs heating/ 16hrs cooling)

- 8 cycles with polarity reversal at 363kV, “24hours” load cycle(8hrs heating/16hrs cooling, Polarity reversals every 8hrs)

- 3 cycles at (+)463kV, “48hours” load cycle(24hrs heating/ 24hrs cooling)

The superimposed impulse voltage test was performed on test objects that have successfully passed the load cycle test, in the following manner:

Superimposed switching impulse test for LCC

- Udc = (+)250kV, $U_{P2,O}$ = (-)489kV, 10 times

- Udc = (-)250kV, $U_{P2,O}$ = (+)489kV, 10 times

Superimposed lightning impulse test for LCC

- Udc = (+)250kV, U_{P1} = (-)604kV, 10 times

- Udc = (-)250kV, U_{P1} = (+)604kV, 10 times

After the successful completion of the superimposed impulse test, the subsequent DC test was carried out for 2 hours at negative DC voltage of 463kV with no heating. The cable system passed successfully and is qualified for LCC. After the completion of the type test for LCC, the additional switching impulse withstand tests were carried out at $\pm U_{P2,S}$ voltage levels to be qualified for VSC type. Additional superimposed lightning impulse test for VSC type

- Udc = (+)250kV, $U_{P2,S}$ = (+)489kV, 10 times

- Udc = (-)250kV, $U_{P2,S}$ = (-)489kV, 10 times

All of the tests were successfully completed without any problem.

HVDC XLPE CABLE SYSTEM FOR VSC TYPE

Designs of HVDC cable and accessories

Specific environmental and installation conditions led to design a copper conductor size of 2500 ㎟, conducted from annealed profiled copper and filled with water blocking compound to limit water propagation in case of cable severance. The conductor of the cable was applied to keystone shaped for the compactification of cable and the minimization of insulation compound. The insulation part consists of an inner semi-conducting screen layer, the insulation compound and an outer semi-conducting insulation screen, extruded simultaneously. A semi-conducting water swelling tape is then applied between the outer semi-conducting screen and the metallic sheath in order to limit water propagation along the cable core in case of cable damage. The metallic sheath is made of lead alloy, over which it is extruded a layer of polyethylene compound. The armour includes bending, Armour and outer covering, applied in one common process. Armour is made of one layer of galvanized copper wires. Outer covering is made of polypropylene strings that provide a degree of abrasion protection and reduce cable friction during laying. The weight of the cable is about 68 kg/m in air and the outer diameter is approx. 157 mm. Figure 4 shows the construction of HVDC submarine power cable.

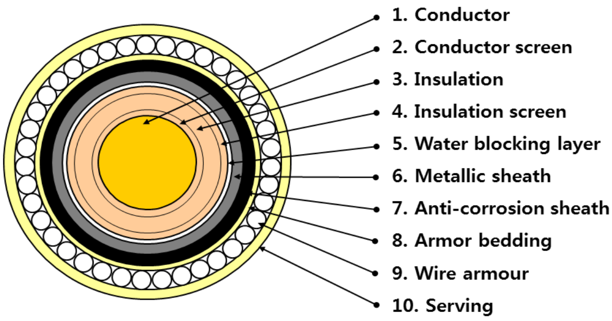


Fig. 4: Construction of HVDC submarine power cable

Factory joint is a tape-molded type that has advantage of controlling the cable diameter and the same structure. Figure 5 shows design of factory joint. The conductor in the XLPE factory joint is welded and abraded to flush the cable conductor. The insulation system is made up of cross bonded PE (XLPE). Conductor, insulation and insulation screens are cured each curing processes. Over the insulation system a lead tube is swaged down on the insulation system and soldered to the lead sheath of the cable. The lead plumbs are reinforcement before a heath shrink sleeve is applied over the joint area.

Fig. 5: Designe of factory joint

Repair joint is a pre-molded type that has advantage of jointing convenience. Figure 6 shows design of repair joint. The conductor joint on the repair joins is made with compression ferrules. Pre-molded joint body is used to form the electrical insulation system. A stainless steel joint box is used for mechanical protection of the joints and as an axial tension member during installation. Stainless steel is chosen in order to prevent corrosion problems. The armor wires are connected to each other with the brass joint lug to ensure continuity of the wires. Bend Restrictors are used on the ends of the joint box in order to control the bending radius of the cable close to the joint.

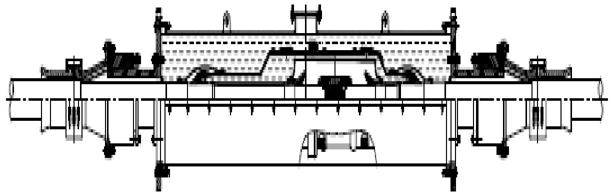


Fig. 6: Designe of repair joint

Development of HVDC ±150kV XLPE cable system

The research on the HVDC XLPE ±150kV underground power cable system has been carried out last 2 years. For development of HVDC ±150kV and ±320kV cable, various materials have been employed commercially available compound for VSC. The electrical tests for type test were performed with load cycle voltage test, super-imposed impulse test and subsequent DC tests according to VSC protocol of CIGRE TB 496. Approximately 50 m sample of cable included land joint for underground cable systems was assembled termination at both ends. The object passed the test, no breakdown occurred during load cycle test and superimposed impulse test. Table 3 shows results of type test.

Table.3: Results of type test

Electrical test	Test condition	Result
24hours Load Cycle test	DC(±)278kV : 12 Cycles	No B.D
48hours Load Cycle test	DC(+)278kV : 3 Cycles	No B.D
Super-imposed impulse test	Lightning impulse DC(±)150kV+L.I(±)370kV : 10 times Switching impulse DC(±)320kV+S.I(±)320kV :10 times	No B.D
Subsequent DC Test	DC(-)278kV / 2hrs	No B.D

Close and Return

Development of HVDC ±320kV XLPE cable system

For the successful complete of type test, development tests of joint were performed at same test condition and level of type test. The research on the HVDC XLPE ±320kV submarine and underground power cable systems has been carried out for last 6 years. In early stage of the research, the validity of the design and the excellent performance of the cable, termination, factory, repair and land joints are confirmed by the development tests recommended by CIGRE. In case of electrical test, the development tests of factory and land joints were carried out with load cycle (Heating cycle voltage and lightning impulse tests) and no load cycle (DC voltage and lightning impulse tests) tests. All development tests were completed successfully and figure 7 shows the photo graphics of development test.

Fig. 7: Development test

The mechanical tests were carried out with coiling test, tensile bending test and straight tensile test. In case of mechanical tests, shall not give rise to permanent deformation of the conductor or armouring. Figure 8 shows the photo graphics of mechanical test for type test.

a) Coiling b) Tensile bending c) Straight tensile

Fig. 8: Mechnical tests for type test

Coiling test was carried out on a cable of suitable length which forms at 8 complete turns of the coil. The coiling diameter was 7m and the direction of coiling was clockwise rotation. The coiling a line parallel to the cable axis was marked on the cable in order to check the uniformity of twist in the cable during coiling operations. Tensile bending test was performed approximately 50 m sample taken from the cable length after coiling test. The cable sample was wound and unwound on the drum for 3 times consecutively without changing the direction of bending. Tensile test was performed approximately 54 m sample that is installed repair joint. The suitable tension in the cable was increased to make the cable in a straight line. After 15min, the length between two suitable index lines be measured; let this length be L_o. The tension in the cable was increased to up to T_{max} and maintained for 15 min. Then the length Lmax between the index lines was measured and revolution of the free head recorded. The tension was decreased to T_o and the length $L_{o'}$ was measured as above. The whole cycle was performed three times. For each cycle the following relative elongations is calculated:

$$(L_{max} - L_o) / L_o \text{ and } (L_{o'} - L_o) / L_o \qquad [2]$$

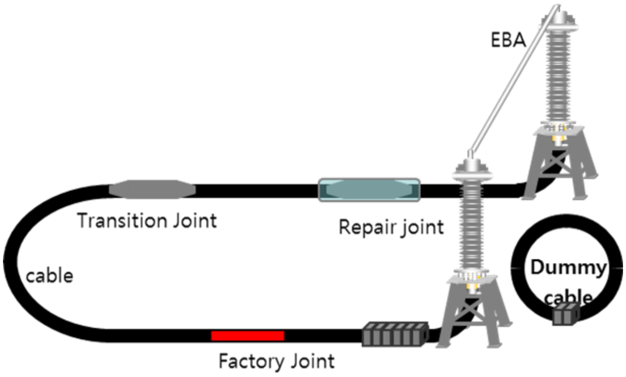


Fig. 9: Test circuit of type test

After straight tensile, approximately 50 m sample of cable included factory joint, transition joint and repair joint for submarine and underground cable systems was assembled termination at both ends. Figure 9 shows test circuit for type test. The electrical tests for type test were performed with load cycle voltage test, super-imposed impulse test and subsequent DC tests according to VSC protocol of CIGRE TB 496. During all of electrical test, the temperature of the conductor was controlled to be more than 70 ºC by applying AC current to the conductor. The cable system specimen has passed the type test successfully, no breakdown occurred during load cycle test and superimposed impulse test. Table 4 shows results of type test.

Table.4: Results of type test

Electrical test	Test condition	Result
24hours Load Cycle test	DC(±)592kV : 12 Cycles	No B.D
48hours Load Cycle test	DC(+)592kV : 3 Cycles	No B.D
Super-imposed impulse test	Lightning impulse DC(-)320kV+L.I(+)780kV DC(+)320kV+L.I(-)780kV : 10 times Switching impulse DC(+)320kV+S.I(+)670kV DC(+)320kV+S.I(-)670kV DC(-)320kV+S.I(-)670kV DC(-)320kV+S.I(+)670kV :10 times	No B.D
Subsequent DC Test	DC(-)592kV / 2hrs	No B.D

Prequalification test was conducted in KEMA HVDC Laboratory of Holland. The cable system consists of the approximately 120m long cable included factory joint, repair joint, land joint, transition joint and two terminations. Figure 10 shows test loop for prequalification test. Prequalification test is progressing according to CIGRE TB 496 and will be completed in August 2018.

Fig. 10: Test loop for prequalification test

Conclusion

In this paper, our development results have been described in detail for HVDC XLPE cable system for various voltage ratings; insulation material at laboratory, miniature cable for the evaluation of characteristics and finally the design of full scaled power cable system including necessary joints.

Regarding LCC cable, our first ±80kV cable system has been developed and then related type test has been conducted according to CIGRE test recommendations (CIGRE TB 219). Afterwards, in order to verify the required long term reliability and stability, well-equipped test-bed has been built in Jeju Island for the first time in Korea. Our successful results based on the deep investigation pushed its first commercial service in 2013. In connection with VSC cable, our cable systems have been designed and manufactured for three operating voltages such as ±150kV, ±250kV and ±320kV; they have been all put under type test in accordance with CIGRE TB 496. In particular, ±250kV LCC cable system shows also satisfied results.

In the anticipation of the global market growth in near future, it has been inspired to provide the diversity of our products. For this purpose, LCC and VSC type full scaled cables have been developed for those four operating voltages such as ±80kV ±150kV, ±250kV and ±320kV. Furthermore, the development of ±525kV for both types has been now undergoing and would require a couple of years more.

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