Return to Session

# DEVELOPMENT OF DC +/- 250 KV COAXIALLY-INTEGRATED RETURN CONDUCTOR EXTRUDED CABLE

Seishi HIRANO, Electric Power Development Co., Ltd., (Japan), seishi_hirano@jpower.co.jp
Junichi HARAGUCHI, Electric Power Development Co., Ltd., (Japan), junichi_haraguchi@jpower.co.jp
Takehiko MIZUNO, VISCAS Corp., (Japan), ta-mizuno@viscas.com
Yoshihisa NAGOYA, VISCAS Corp., (Japan), y-nagoya@viscas.com

## *ABSTRACT*

*This paper describes the development of +/-250 kV HVDC insulation-extruded cable with coaxially–integrated return conductor (coaxial extruded cable). The features of the HVDC coaxial extruded cable allow both environmental and economic advantages. These advantages lead to the development of the +/- 250kV class HVDC coaxial extruded cables, accompanied with the increasing demand of the HVDC cables with large power transmission capacity. We report the results of designing and manufacturing the +/- 250kV class HVDC coaxial extruded cables and accessories for the two transmission capacities of +/- 250kV/180MW and +/- 250kV/300MW and their electric tests.*

## *KEYWORDS*

HVDC extruded cable, HVDC coaxially-integrated return conductor cable, HVDC transmission

## INTRODUCTION

Recently, the demand of applying the HVDC cables to the long HVDC power transmission lines has been increased. Oil-filled (OF) cables and mass-impregnated (MI) cables are major insulation types of the HVDC cables over insulation-extruded cables such as XLPE cables which are widely applied to the AC power transmission lines. However, OF cables have the limit of transmission length because of the capacity of oil feeding equipment. MI cables have the lower design temperature than OF cables, leading to the increase of the conductor size, although MI cables are suitable for the long HVDC transmission lines. In addition, there is the risk of oil leakage for both OF and MI cables in the event of an accident. On the other hand, extruded cables have the major advantages over OF and MI cables in the above limitations and problems, namely, no limit of transmission length, higher design temperature and no risk of oil leakage, although there is a problem of space charge accumulation in the extruded insulation, resulting in the decrease of the insulation strength under the HVDC application, especially under the operation of HVDC polarity reversal. For that reason, the HVDC extruded cables have been applied to the HVDC transmission lines mainly up to 150kV with no operation of HVDC polarity reversal. Therefore, the HVDC extruded cables for the higher HVDC application with the ability allowable for the operation of HVDC polarity reversal by the suppression of space charge accumulation have been desired to be developed.

In the above background, we have developed the HVDC extruded cables up to 500kV, which was reported previously [1][2]. The problem of space charge accumulation in the cable insulation is solved by using XLPE with an inorganic filler as the cable insulation which suppresses the space charge formation. This solution contributes to the establishment of HVDC extruded cables with excellent electrical and mechanical properties as well as with the ability allowable for the operation of HVDC polarity reversal.

In the following works, we have conducted the development of HVDC insulation-extruded cable with coaxially-integrated return conductor, what is called a coaxial extruded cable, for monopolar transmission, based on the above technology of the HVDC extruded cable [2][3][4]. The HVDC coaxial extruded cable has the structure of a single HVDC cable consisting of a return cable, i.e., return conductor and insulation, arranged coaxially around the main cable core. The features of the cable allow both the reduction of the environmental impact on the surroundings and the economic effect as described below. First, there is no risk of oil leakage because of using the extruded insulations for both the main and return insulation. Moreover, the designed temperature is higher than MI and OF cables, which enables to reduce the size of the conductor and hence the size of the cable, resulting in lowering the cost of both the manufacture and construction. These are the major advantages over MI type HVDC coaxial cable with the IRC (Integrated Return Conductor) which was reported to be applied to the commercial operation on the Northern Ireland-Scotland (Moyle) HVDC interconnection [5]. Second, there is no outer magnetic field theoretically because of canceling the magnetic fields generated by both the main and return currents. This feature mitigates the magnetic deviation (compass error). In addition, the HVDC transmission with return conductor, using the HVDC coaxial extruded cable, avoids the electrolytic corrosion against underground objects and the impact on the creatures by conducting the return current through the return conductor, not through sea and/or earth. Third, the construction cost is less than that of the two separate cables, the main and return cables, especially in the class of small- and medium-power transmission capacity [2][3][4]. In other words, the HVDC coaxial extruded cable is considered to be the ultimate HVDC cable with environmental-friendly features and economic benefits.

We have first developed the +/- 120kV/54MW HVDC coaxial extruded cable and factory joint (FJ) for the power transmission to isolated islands, reported in [2]. We have confirmed the adequate performance of the cable and FJ electrically and mechanically, and have established the fundamental technologies of the HVDC coaxial extruded cable.

Recently, the HVDC coaxial extruded cables with the larger transmission capacity have been demanded. At the following stage, we have developed the +/- 250kV class HVDC coaxial extruded cables and accessories for each of the two medium power transmission capacities. One is the power transmission capacity of +/- 250kV/180MW for the power transmission to isolated islands and the other is the capacity of +/- 250kV/300MW for the interconnection of power system. In this paper, we report the results of designing and manufacturing the above +/- 250kV class HVDC coaxial extruded cables and accessories and their electric tests.

## DEVELOPMENT OF +/- 250KV/180MW HVDC COAXIAL EXTRUDED CABLES AND ACCESSORIES

### Cable design

Firstly, we report the development of +/- 250kV/180MW HVDC coaxial extruded cable for the power transmission between the main land and the isolated island. We designed and manufactured the submarine cable and land cable, based on the design conditions as shown in Table 1. Schematic of HVDC coaxial extruded submarine cable is shown in Figure 1, and the designed dimensions of the submarine cable and land cable are shown in Table 2, respectively.

**Table 1: Design conditions of the +/- 250kV class HVDC coaxial extruded cables**

| Item | | 250kV/180MW | 250kV/300MW |
|---|---|---|---|
| Nominal DC voltage | | +/- 250 kV | +/- 250 kV |
| Transmission power | | 180 MW | 300 MW |
| Transmission length | | 100 km | 50 km |
| Overvoltage | main insulation | 442 kVp Imp. | 460 kVp Imp. |
| | return insulation | 104 kVp Imp.<br>52 kVp AC | 170 kVp Imp.<br>100 kVp AC |
| Allowable temperature | main conductor | 90 deg.C | |
| | return conductor | 75 deg.C | |
| Construction depth of submarine cable | | 400 m | 300 m |

The cross sections of the main and return conductors are designed to be 400mm$^2$ and 215 mm$^2$ for the submarine cable and 500mm$^2$ and 463 mm$^2$ for the land cable, respectively, for the allowable temperatures of each conductor, i.e., 90 deg.C and 75 deg.C for the main and return conductor, respectively. The return conductor consists of copper wires laid around the main insulation core, where the diameter and number of the copper wires are 2.6 mm and 55 wires for the submarine cable and 5.0mm and 30 wires for the land cable, respectively.

The main and return insulations are formed by the extrusion of XLPE with the inorganic filler and polyethylene (PE), respectively, where the main insulation material, XLPE with the inorganic filler, has been developed as the insulating material for the HVDC extruded cables by the authors [1][2]. The thicknesses of the main and return insulations are designed to be 12mm and 6mm for both the submarine and land cables, respectively, based on the design conditions as shown in Table 1.

The lead sheath and PE jacket are laid in order around the return insulation across the semiconductive cushion layer. The submarine cable has the galvanized steel wire armor outside the PE jacket across the bedding. The overview of the manufactured submarine cable is shown in Figure 2.

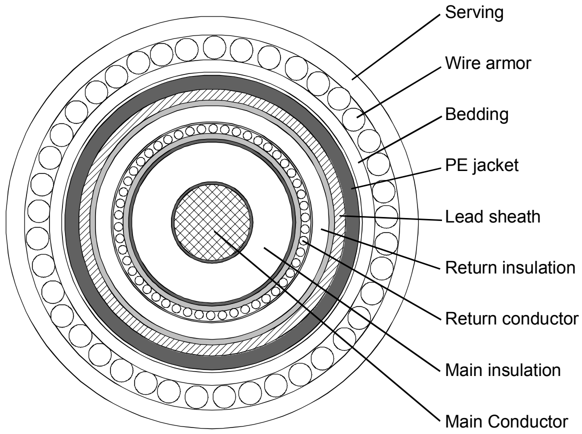



**Figure 1: Schematic of the cross section of HVDC coaxial extruded submarine cable**

**Table 2: Construction of +/- 250kV/180MW HVDC coaxial extruded cable**

| Item | | Unit | Submarine Cable | Land Cable |
|---|---|---|---|---|
| Main conductor cross section | | $mm^2$ | 400 | 500 |
| Main insulation thickness | | mm | 12 | 12 |
| Return conductor | Wire diameter | mm | 2.6 | 5 |
| | No. of wires | wires | 55 | 30 |
| Return insulation thickness | | mm | 6 | 6 |
| Lead sheath thickness | | mm | 3.3 | 3.4 |
| PE jacket thickness | | mm | 4.5 | 4.5 |
| Steel wire armor | Wire diameter | mm | 6 | - |
| | No. of wires | wires | 54 | - |
| Overall diameter | | mm | 124 | 103 |
| Approx. weight | In air | kg/m | 37 | 28 |
| | In water | | 25 | - |


**Figure 2: +/- 250kV/180MW HVDC coaxial extruded submarine cable**

## Accessory design

We designed and manufactured the accessories, i.e., GIS termination, the land-sea transition joint between the land cable and the submarine cable, and the repair joint for the above +/- 250kV/180MW HVDC coaxial extruded cables as follows.

**GIS termination**

Schematic of GIS termination for the +/- 250kV/180MW HVDC coaxial extruded cable is shown in Figure 3. The main insulation of GIS termination is applied with SF6 gas-immersed type insulation, consisting of the condenser type insulation made of silicone oil-immersed papers, epoxy bushing and SF6 gas immersed in the GIS case. This insulation design is based on the design of GIS termination for the usual HVDC extruded cable.

In the case of GIS termination for the HVDC coaxial extruded cable, the return insulation in the termination is needed in both parts of the return cable insulation and the return conductor terminal where the return conductor of the cable and the external lead line for the conduction of return current are connected, because of the DC voltage drops at the return conductor through the return current and the subjected overvoltages. The stress relief cone on the return cable insulation is formed by winding the insulating tape and shielding tape. The return conductor terminal is insulated with the epoxy insulator between the terminal and the GIS case and the porcelain insulator between the terminal and the lower sleeve which is electrically connected to the lead sheath of the cable. The above insulation design in the part of the return conductor terminal is based on the indoor type insulation design.

**Land-sea transition joint**

Schematic of the land-sea transition joint for the +/- 250kV/180MW HVDC coaxial extruded cable is shown in Figure 4. The main conductors of both the land and submarine cables are connected through the conductor sleeve. The reinforcing main insulation at the joint is formed by the method of the tape winding molded joint (TMJ), consisting of the process of winding the HVDC insulating tape whose material is the same as the main cable insulation, and the successive processes of heating, molding and curing the tape-wounded layer. The thickness of the reinforcing main insulation is designed to be 15mm.

The return conductors of both the land and submarine cables are jointed by TIG welding. The reinforcing return insulation at the joint is formed by winding the EPR insulating tape. The thickness of the reinforcing return insulation is designed to be 8mm.

**Repair joint**

Schematic of the rigid type repair joint for the +/- 250kV/180MW HVDC coaxial extruded submarine cable is shown in Figure 5. In this case, the structures and dimensions of the repair joint below the reinforcing return insulation are designed to be the same as the factory joint. The main conductors of the cables are jointed by copper phosphorus brazing. The reinforcing main and return insulations and the joint of the return conductor are formed by the same method as the land-sea transition joint.

The copper tube is used to establish the watertight structure and electrical contact to both sides of the lead sheath of the cables, where both ends of the copper tube are bonded to the lead sheath by lead soldering. The wire armors of the cables are jointed mechanically through the wire armor stop rings and the tension bolts.

## Results of manufacture and electric tests

We manufactured the +/- 250kV/180MW HVDC coaxial extruded cables and the accessories, i.e., GIS termination, land-sea transition joint and repair joint. We confirmed that there was no significant problem of manufacturing and handling the cables and accessories, although the manufacturing time was required to be longer than that for the usual HVDC extruded cables and accessories because of the additional processing of the return conductor and insulation in the cables and accessories.

We carried out the electric tests for the above cables and accessories to estimate the initial electrical characteristics. The electric test items and conditions for +/- 250kV/180MW HVDC coaxial extruded cables and accessories are shown in Table 3, decided by referring to CIGRE WG21-01 Recommendations [6].

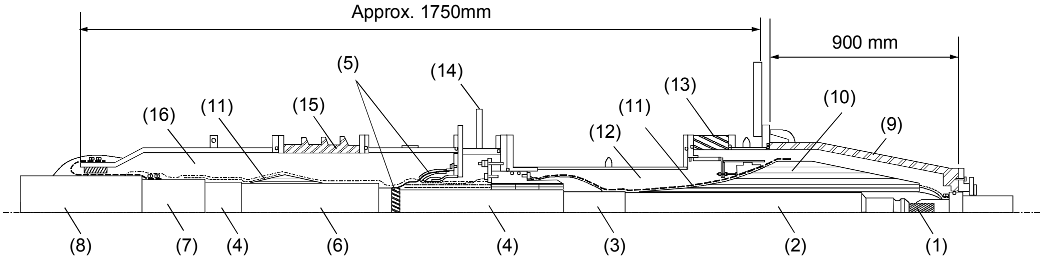
We conducted the electric tests on each part of the return and main insulations for each test sample, according to the electric test conditions as shown in Table 3. For the return insulation tests of the cables, land-sea transition joints and repair joints, the whole of the test sample were heated up to 75 deg.C by external heaters. On the other hand, the return insulation tests of GIS terminations were conducted under the application of AC current of 700A, equivalent to the rated DC current, to both the main and return conductors with the temperature of the GIS termination saturated.

The good results were obtained from the return insulation tests for all test samples of the cables, GIS terminations, land-sea transition joints and repair joints. The impulse breakdown voltages of the return insulation were 430kV to 550kV for the cables, 310kV to 350kV for the land-sea transition joints and repair joints and 210kV for the GIS terminations, respectively. This indicates the sufficient characteristics of the return insulation over the impulse withstand voltage of 130kV.

For the GIS terminations, the flashover occurred along the surface of the epoxy insulator, which lowered the breakdown voltages of the return insulation as compared with the cables and joints.

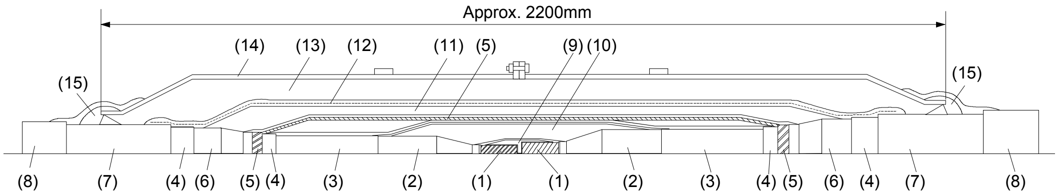
For the main insulation tests of the cables, the temperatures of the main and return conductors were controlled to be 90 deg.C and 75 deg.C, respectively, by applying AC current to the main conductor and by external heaters. On the other hand, the main insulation tests of the land-sea transition joints, repair joints and GIS terminations were conducted under the same heating conditions as those of the return insulation tests, respectively.

Return to Session



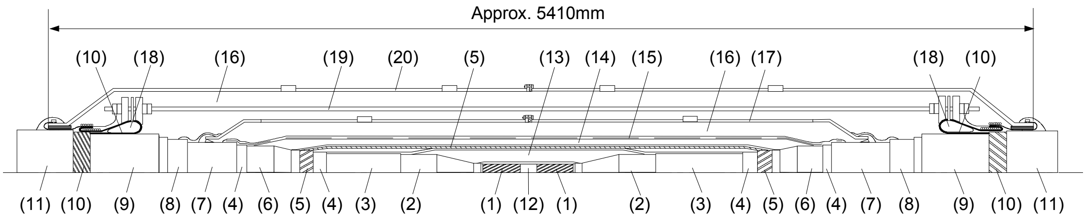

(1) Main conductor
(2) Main cable insulation
(3) Extruded semiconductive layer
(4) Semiconductive cushion layer
(5) Return conductor
(6) Return cable insulation
(7) Lead sheath
(8) PE sheath
(9) Epoxy bushing
(10) Condenser cone
(11) Stress relief cone
(12) Silicone oil
(13) Epoxy insulator
(14) Return conductor terminal
(15) Porcelain insulator
(16) Insulating compound

**Figure 3: Schematic of GIS termination for +/- 250kV/180MW HVDC coaxial extruded cable**




(1) Main conductor
(2) Main cable insulation
(3) Extruded semiconductive layer
(4) Semiconductive cushion layer
(5) Return conductor
(6) Return cable insulation
(7) Lead sheath
(8) PE sheath
(9) Conductor sleeve
(10) Reinforcing main insulation
(11) Reinforcing return insulation
(12) Shielding layer
(13) Waterproof compound
(14) Protective copper tube
(15) Lead soldering

**Figure 4: Schematic of land-sea transition joint for +/- 250kV/180MW HVDC coaxial extruded cable**




(1) Main conductor
(2) Main cable insulation
(3) Extruded semiconductive layer
(4) Semiconductive cushion layer
(5) Return conductor
(6) Return cable insulation
(7) Lead sheath
(8) PE sheath
(9) Bedding
(10) Wire armor
(11) Serving
(12) Conductor welding
(13) Reinforcing main insulation
(14) Reinforcing return insulation
(15) Shielding layer
(16) Waterproof compound
(17) Copper tube
(18) Wire armor stop ring
(19) Tension bolt
(20) Protection box

**Figure 5: Schematic of repair joint for +/- 250kV/180MW HVDC coaxial extruded cable**

The good results were also obtained from the main insulation tests for all test samples of the cables, land-sea transition joints and repair joints. The impulse breakdown voltages of the main insulations were approximately 1100kV for the cables, 1050kV to 1200kV for the land-sea transition joints and repair joints and 900kV to 1050kV for GIS terminations, respectively. The obtained impulse breakdown voltages of all test samples were sufficiently high levels over the impulse withstand voltage of 705kV. The breakdown of the main insulation of the land-sea transition joints and repair joints occurred in the part of reinforcing main insulation (TMJ) or in the part of the cables. Moreover, the breakdown voltages were almost the same as those of the cables. This indicates that the insulating performance of the reinforcing main insulation in the joints is equal to or more than that of the main cable insulation.

As mentioned above, we confirmed the excellent and adequate performance of the +/- 250kV/180MW HVDC coaxial extruded cables and accessories for both the main and return insulations.

**Table 3: Electric test conditions for +/- 250kV/180MW HVDC coaxial extruded cables and accessories**

| Voltage withstand test item | | Test conditions |
|---|---|---|
| Return Insulation | DC | +/- 50kV / 1 hour |
| | AC | 45kVrms / 30 minutes |
| | Impulse | +/- 130kV / 3 times |
| | Impulse breakdown test | Negative voltage step: -20kV / 3 times from -150kV |
| Main Insulation | DC | +/- 625 kV / 3 hours |
| | DC polarity reversal | Voltage: +/- 390kV<br>Polarity retention time: 4 hours<br>No. of polarity reversal: 6 times |
| | DC +Impulse | DC prestress voltage: +/- 260kV / 3 hours<br>Opposite polarity Impulse voltage: -/+ 560kV / 3 times |
| | Impulse | +/- 705kV / 3 times |
| | Impulse breakdown test | Negative voltage step: -50kV / 3 times from -750kV |

## DEVELOPMENT OF +/- 250KV/300MW HVDC COAXIAL EXTRUDED CABLES

### Cable design

In this section, we report the development of +/- 250kV/300MW HVDC coaxial extruded cable for the interconnection of power system. The design conditions of the +/- 250kV/300MW HVDC coaxial extruded cable are shown in Table 1. It is noted that the overvoltage levels of AC and impulse for the return insulation are nearly twice higher than those of +/- 250kV/180MW cable, although the impulse overvoltages for the main insulation are almost the same. Moreover, it is supposed that the increase of power transmission capacity from 180MW to 300MW requires the enlargement of the main and return conductor size. The above problems give rise to the difficulties of designing and manufacturing the cables, especially in the return conductor and insulation, and also of handling the cables.

We designed and manufactured the +/- 250kV/300MW HVDC coaxial extruded submarine cable and land cable, based on the design conditions as shown in Table 1. The designed dimensions of the submarine and land cables are shown in Table 4, respectively.

The cross sections of the main and return conductors are designed to be 1000mm$^2$ and 660mm$^2$ for the submarine cable and 1600mm$^2$ and 865mm$^2$ for the land cable, respectively, where the cross sections of the main and return conductors are required to be more than the twice of +/- 250kV/180MW cables. In particular, we paid attention to the design of return conductor. The increase of the required cross section of the return conductor leads to the increase of the diameter and number of copper wire, which has an influence on the manufacturing process and mechanical properties of the cable, due to the increase of the stiffness of the copper wire. We designed the diameter of copper wire within about 5mm, considering the experiences of manufacturing and handling the +/- 250kV/180MW cables. Consequently, the diameter and number of copper wire are designed to be 5.0mm and 38 wires for the submarine cable and 5.0mm and 47 wires for the land cable, respectively.

**Table 4: Construction of +/- 250kV/300MW HVDC coaxial extruded cable**

| Item | | Unit | Submarine Cable | Land Cable |
|---|---|---|---|---|
| Main conductor cross section | | mm$^2$ | 1000 | 1600 |
| Main insulation thickness | | mm | 12 | 12 |
| Return conductor | Wire diameter | mm | 5 | 5 |
| | No. of wires | wires | 38 | 47 |
| Return insulation thickness | | mm | 6 | 6 |
| Lead sheath thickness | | mm | 4.2 | 4.4 |
| PE jacket thickness | | mm | 4.5 | 4.5 |
| Steel wire armor | Wire diameter | mm | 8 | - |
| | No. of wires | wires | 53 | - |
| Overall diameter | | mm | 162 | 132 |
| Approx. weight | In air | kg/m | 71 | 50 |
| | In water | | 55 | - |

The thickness of the main insulation, using XLPE with the inorganic filler, is designed to be 12mm, the same as the +/- 250kV/180MW cables. In the design of the return insulation, it is important to suppress the increase of the return insulation thickness for the higher performance required for the return insulation. We attempted to improve the performance and reliability of the return insulation by the improvement in the manufacturing process, and then the thickness of the return insulation is designed to be 6mm, the same as the +/- 250kV/180MW cables.

From the above discussions, the reasonable designs of the +/- 250kV/300MW cables are achieved as shown in Table 4.

### Results of manufacture and electric tests

We manufactured the +/- 250kV/300MW HVDC coaxial extruded submarine and land cables, where the manufactured submarine cable had no wire armor because the our first purpose was to estimate the electrical characteristics. There was no significant problem of manufacturing and handling the cables.

We conducted the electric tests for the above cables to estimate the initial electrical characteristics. The electric test items and conditions for +/- 250kV/300MW HVDC coaxial extruded cables are shown in Table 5, decided by referring to CIGRE WG21-01 Recommendations [6].

Before the electric tests, the bending tests were conducted for both the submarine cable without wire armor and the land cable, and no damages were observed after the bending tests.

The procedures of the electric tests for both the return and main insulations of the cables were the same as the +/- 250kV/180MW cables. For the return insulation tests of the cables, the test samples were heated up to 75 deg.C by external heaters. On the other hand, for the main insulation tests, the temperatures of the main and return conductors were controlled to be 90 deg.C and 75 deg.C, respectively, by applying AC current to the main conductor and by external heaters.

**Table 5: Electric test conditions for +/- 250kV/300MW HVDC coaxial extruded cables**

| Voltage withstand test item | | Test conditions |
|---|---|---|
| Return Insulation | DC | +/- 30kV / 1 hour |
| | AC | 82kVrms / 5 minutes |
| | Impulse | +/- 225kV / 10 times |
| | Impulse breakdown test | Negative voltage step: -50kV / 3 times from -250kV |
| Main Insulation | DC | +/- 600 kV / 3 hours |
| | DC polarity reversal | Voltage: +/- 375kV<br>Polarity retention time: 4 hours<br>No. of polarity reversal: 6 times |
| | DC +Impulse | DC prestress voltage: +/- 250kV / 3 hours<br>Opposite polarity Impulse voltage: -/+ 585kV / 10 times |
| | Impulse | +/- 720kV / 10 times |
| | Impulse breakdown test | Negative voltage step: -50kV / 3 times from -750kV |

The satisfactory results were obtained from the return and main insulation tests for the submarine and land cables. The impulse breakdown voltages of the return insulation were 500kV to 650kV, the average of about 20% higher than those of the +/- 250kV/180MW cables. This indicates the effect of the improvement in the manufacturing process of the return insulation, that is, the improvement in the performance and reliability of the return insulation with the sufficient impulse breakdown voltage levels over the impulse withstand voltage of 225kV. Besides, the impulse breakdown voltages of the main insulation were 1200kV to 1350kV, which were approximately equal to those of the +/- 250kV/180MW cables and sufficient levels over the impulse withstand voltage of 720kV.

The above electric test results, including those of the +/- 250kV/180MW cables, demonstrate the high and stable performance in both the main and return insulation of the +/- 250kV class HVDC coaxial extruded cables. Therefore, we confirmed that the designs of the cables, especially in the insulations and conductors, were suitable for the required performance.

## CONCLUSIONS

In this work, we designed and manufactured the +/- 250kV class HVDC coaxial extruded cables and accessories for each of the two medium power transmission capacities, and conducted the electric tests on the above cables and accessories in order to estimate the initial electrical characteristics.

One is the +/- 250kV/180MW for the power transmission to isolated islands, and we dealt with the submarine and land cables and accessories, i.e., GIS termination, land-sea transition joint and repair joint. We confirmed that there was no significant problem of manufacturing and handling the cables and accessories and they had an adequate performance.

The other is the +/- 250kV/300MW for the interconnection of power system, and we were involved in the submarine and land cables. We confirmed that the +/- 250kV class HVDC coaxial extruded cables, including the +/- 250kV/180MW cables, had a high and stable performance in both the main and return insulations, indicating the suitable design of the cables for the requirements.

In the further work, we are planning to develop the accessories for the +/- 250kV/300MW HVDC coaxial extruded cables.

## REFERENCES


[1] T. Yamanaka, T. Kimura, Y. Murata, H. Hirota, I. Shigetoshi and S. Maruyama, 2003, "Development of DC extruded cables and factory joints in Japan", JICABLE 2003, A.7.3, 211-216.

[2] Y. Maekawa, K. Watanabe, S. Maruyama, Y. Murata and H. Hirota, 2002, "Research and Development of DC +/- 500kV Extruded Cables", CIGRE 2002 Session Paper 21-203.

[3] T. Yamanaka, M. Yoshida, S. Maruyama and Y. Murata, 2001, "The Development of the Coaxial Integrated Return Conductor DC XLPE Cable and the Factory joint", CIGRE Regional meeting 2001, New Delhi, India.

[4] T. Yamanaka, T. Kimura, K. Watanabe and I. Shigetoshi, 2002, "Development of Coaxial Type DC Extruded Insulation Cable and Factory Joint", IEEE/PES T&D Conference 2002: Asia Pacific, Yokohama, Japan.

[5] Georg E. Balog and Gunnar Evenset, 2002, "Integrated Return Conductor Cable", CIGRE 2002 Session Paper 21-301.

[6] "Recommendations for Testing DC Extruded Cable Systems for Power Transmission", CIGRE WG21-01, December 12, 2002.