Contribution to the achievement of SDGs
by Furukawa Electric Group

Initiatives of the Power Cable Division Toward Carbon Neutrality by 2050

– Development of Dynamic Power Cable Systems for TLP Floating Offshore Wind Power Generations and Deepwater Submarine Cables –

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ABSTRACT Efforts to achieve carbon neutrality by 2050 are gaining momentum, and the transformation of the energy structure is attracting attention. In particular, the government has set a future goal of significantly increasing the amount of power generated by offshore wind power generation, which is driving demand for submarine power cables. In addition, in order to make renewable energy the main power source and strengthen the power network, a master plan for a wide-area interconnection system using DC submarine cables has been presented, and the importance of submarine power cables is increasing more than ever. We are developing technologies to meet these demands, and in this paper we describe the development of a dynamic power cable system for TLP (Tension Leg Platform) floating offshore wind power generation and the development of a deepwater submarine cable.

1. INTRODUCTION

In October 2020, Japan declared that it would aim to achieve carbon neutrality by 2050, reducing greenhouse gas emissions to zero overall. To achieve this, it is necessary to significantly accelerate efforts such as structural transformation of the energy and industrial sectors and the creation of innovation through bold investments. The Ministry of Economy, Trade and Industry has taken the lead in formulating the "Green Growth Strategy for Carbon Neutrality by 2050"[1)] in cooperation with related ministries and agencies, and the entire country is working on this. To achieve carbon neutrality by 2050, it is essential to introduce a large amount of renewable energy. Among these, offshore wind power generation has a great potential and is expected to play an important role in Japan, which is surrounded by sea on all sides and has the sixth largest exclusive economic zone (EEZ) in the world. Figure 1 shows future introduction targets and a picture of introduction by region. The introduction target

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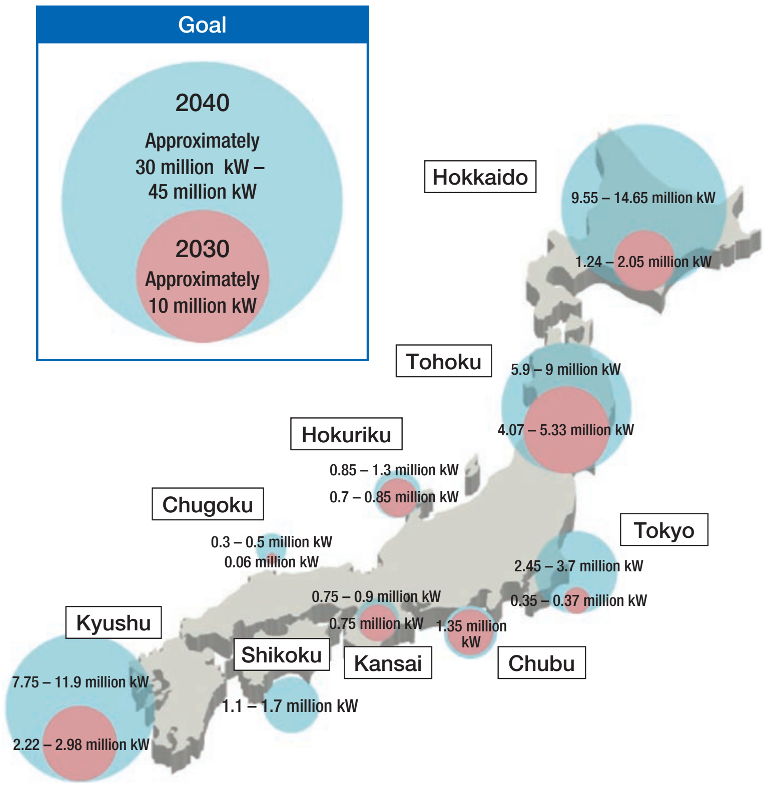

Figure 1 Picture of a regional offshore wind power generation deployment[3)].
Referred and translated the figure on page 4 of the Material from "the 2nd Public-Private Council for Strengthening Industrial Competitiveness of Offshore Wind Power" (December 15, 2020) by the author.

is 10 million kW in 2030 and 30 to 45 million kW in 2040, and further increase in offshore wind power generation is expected. In addition, the areas with high potential for introduction of offshore wind power generation are Hokkaido, Tohoku, and Kyushu, which are far from the large electricity demand areas such as the Tokyo metropolitan area. Therefore, it is expected that the demand for submarine power cables will increase significantly from the current level, as a plan for the development of a direct current transmission network (Master Plan for Wide-area Interconnection Grid[2]) that connects power generation areas and demand areas is being formulated.

We are developing submarine power cables from various angles to meet these expectations and contribute to the realization of carbon neutrality by 2050. In this paper, we will discuss the development of a dynamic power cable system for TLP floating offshore wind power generation and the development of a deepwater submarine cable.

2. DEVELOPMENT OF A DYNAMIC POWER CABLE SYSTEM FOR TLP FLOATING OFFSHORE WIND POWER GENERATION

2.1 Characteristics of TLP Floaters

The Tension Leg Platform (TLP) is one of the floating structures for the offshore wind power generation, and is firmly anchored to the seabed by tension moorings. Compared to other floating structures (semi-submersible, spar type), it is characterized by less oscillation due to waves and tides, a smaller exclusive area of the sea area, and a minimal impact on the fishing industry (Figure 2).

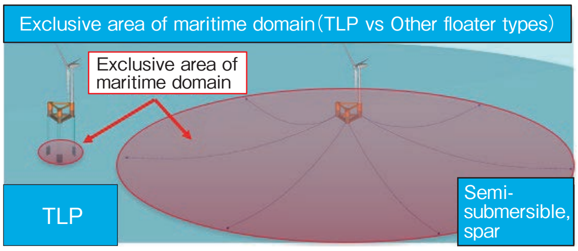

Figure 2 Comparison of floating structures for the offshore wind power generation.

Under the Green Innovation Fund, a project aimed at achieving carbon neutrality by 2050, from fiscal 2022 to 2023, four companies, including Furukawa Electric, conducted preliminary technology studies[4)-6)] of the TLP floater with the goal of reducing the cost of floating offshore wind power generation. Specifically, the TLP floater, a mooring, a mooring foundation, and a dynamic power cable were developed for use off the coast of Ishikari Bay. This paper describes the key points of the development of the dynamic power cable system, which was undertaken by Furukawa Electric.

2.2 Cable System Design Optimization

Taking advantage of the TLP's characteristic that the floating motion is smaller than other floating forms, the dynamic power cable system was optimized from the viewpoint of "cable structure" and "linear design" with the goal of reducing costs.

(1) Optimization of cable structure

Conventionally, when a power cable using solid insulating materials such as cross-linked polyethylene (XLPE) is charged with a voltage and when moisture penetrates the cable insulation, a water tree occurs in the insulation, causing the insulation performance to deteriorate. As a countermeasure, a metallic water barrier is installed to prevent water from entering. In the case of a dynamic power cable, since it constantly oscillates underwater, a metal sheath is used as a water shielding layer for fatigue resistance. A corrugated shape of the metal sheath is sometimes used to easily relieve the distortion.

Since TLP has the potential to satisfy fatigue and mechanical properties even with a simpler structure because of its small floating motion, we adopted a cable design in which an aluminum laminate film is applied to the water impermeable layer, called a Semi-dry[7)], as shown in Figure 3, instead of a corrugated stainless steel.

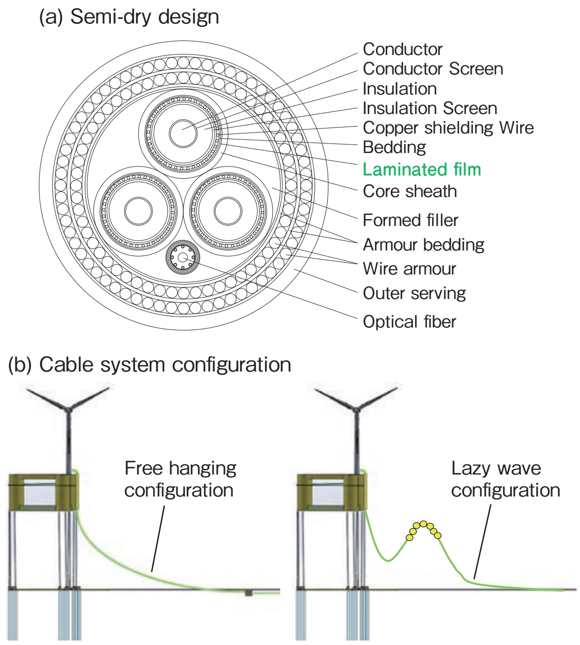

Figure 3 (a) Semi-dry design. (b) Cable system configuration.

(2) Adoption of free-hanging linearity

When laying dynamic power cables in a floating structure, it is necessary to take into account the oceanographic conditions and the design conditions of the floating structure, and to make the cable shaped to withstand dynamic behavior. In general, in other floating structures, a lazy-wave type linearity is adopted, in which a buoy is installed in the middle of the dynamic power cable to alleviate the distortion of the cable caused by the floating structure's behavior. On the other hand, since the floating structure motion of the TLP is small, it is possible that the cable can withstand dynamic behavior without distortion absorption, so a free-hanging linearity without a buoy is adopted.

By optimizing (1) and (2), it is expected that the cost reduction effect will be achieved compared to the linear shape design using the water impermeable layer and the buoy.

2.3 Behavior Analysis

We verified whether the semi-dry design and the free-hanging linear dynamic power cable could withstand the underwater behavior based on the oceanographic conditions and floater motion in the target sea area by performing behavior analysis using the OrcaFlex, a software widely used for behavior analysis of marine systems. The cable specifications are shown in Table 1.

Table 1 Specifications of cable and design criteria.

Property	Unit	Value
Outer diameter	m	0.142
Weight of 1 m cable in air	kg/m	40.6
Submerged weight of 1 m cable	kg/m	24.3
Allowable tension	kN	160
Allowable axial compression force	kN	16
Allowable minimum bending radius	m	2.85

(1) Ultimate Limit State (ULS) analysis

The ULS analysis confirmed the feasibility of the cable system when extremely severe marine conditions were assumed. Specifically, assuming conditions that occur once every 50 years, the analysis narrowed down the cable extension direction so that the tension, axial compression force, and curvature applied to the cable would fall within the allowable values shown in Table 1.

Based on the constraints of the floater and its mooring, fourteen directions in which the cable can be extended were selected, and an analysis was carried out for five directions of predominant waves[8], which resulted in a narrowing down to seven directions (NorthEast (NE), East-NorthEast (ENE), East-SouthEast (ESE), SouthEast (SE), South-SouthEast (SSE), South (S), and South-SouthWest (SSW)) as shown in Figure 4.

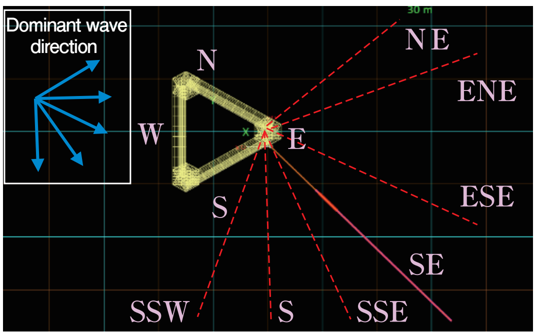

Figure 4 Narrowing down cable laying direction options with ULS analysis.

(2) Fatigue Limit State (FLS) analysis

In the FLS analysis, the long-term reliability of the system was confirmed for the seven extension directions narrowed down by the ULS analysis, assuming actual wave conditions. Specifically, based on the occurrence frequency data of the peak period and significant wave height for each wave direction[8] off the coast of Ishikari Bay, Hokkaido, the fatigue life of the water shielding layer and the steel wire armour was estimated by performing a behavior analysis under all wave conditions (all load cases).

The results of the FLS analysis are shown in Table 2. The fatigue life of the water shielding layer was the longest in the southeast direction at 41 years, which was more than twice the expected service life of 20 years.

Table 2 FLS analysis results.

Cable laying direction	SE	S	SSW
Fatigue life of the water barrier layer	41 years	26 years	24 years
Fatigue life of the armuor layer	>1000 years		

From the results of the ULS analysis and the FLS analysis, it was confirmed that the semi-dry design and the free-hanging linear dynamic power cable system design could withstand the behavior under the target marine conditions.

2.4 Axial Compression Test

The presence or absence of cable abnormalities when the expected axial compression force is actually applied to the cable was confirmed by axial compression tests. A 400-cycle repeated axial compression test was performed on each of the partially bent cable sample and the straight cable sample under the test conditions shown in Table 3.

Table 3 Test conditions.

Sample Length	2 m
Sample	(1) Bending samlpe (R = 10 m) (2) Straight sample
Axial compressive force	(1) 30 kN, 50 kN (2) 75 kN
Cycle	400 cycles

Even after 400 cycles, no abnormal data was confirmed in the strain-axial compression force characteristics, and no abnormalities were observed in the appearance of the cable armour as shown in Figure 5. The above results

(a) Outer layer (b) Inner layer

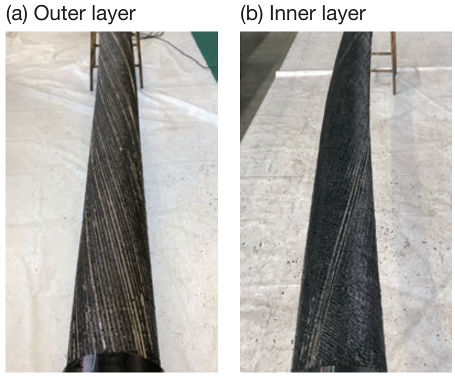

Figure 5 Armour layer of sample (1) after completing the test. (a) Outer layer, (b) Inner layer

show that the expected axial compression characteristics can be satisfied even in the actual cable.

2.5 Summary

In the elemental technology study of the TLP floater, which aims to reduce the cost of floating offshore wind power generation, the adoption of a semi-dry design and a free-hanging design for the dynamic power cable contributed to cost reduction. Furthermore, behavior analysis and mechanical tests confirmed that the cost-optimized cable structure and linearity are applicable to the TLP floater.

3. DEVELOPMENT OF DEEPWATER SUBMARINE CABLES

3.1 Background of the Development of Deepwater Submarine Cables

Many areas in Japan's exclusive economic zone (EEZ) are deep, and developing a submarine power cable that can be used at great depths can contribute to optimizing the laying route (shortening the route).

Figure 6 shows an example of a possible submarine cable route for a DC interconnection[9]. The project involves bringing electricity generated off the coast of Fukushima and Chiba prefectures onto land in Kanagawa prefecture and connecting it to the grid. When the installation route from off the coast of Chiba Prefecture to Kanagawa Prefecture is assumed, the route would be about 90 km if it were to be 300 m deep, but if a route with a depth of 1500 m could be selected, the distance could be shortened to about 65 km. In this case, an increase in deepwater routes is expected as a wide-area submarine cable DC interconnection. On the other hand, the current situation in Japan is that only a depth of about 300 m has been applied[10]. Therefore, by developing a cable that can be applied to deepwater, it is possible to shorten the route, reduce transmission loss, and shorten the construction period.

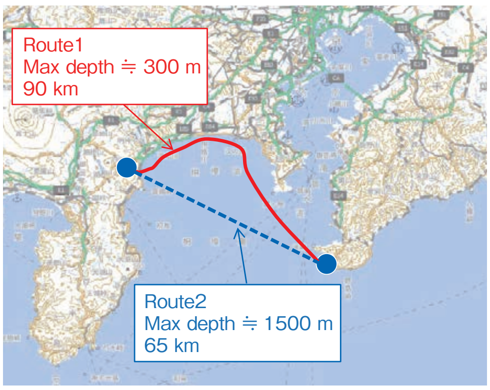

Figure 6 Assumed route of DC interconnection line.

There are several examples overseas of deepwater DC cables that have been installed at depths of 1000 m or more, but all of them are Mass Impregnated (MI) cables. The MI cable means that cables with insulation in which a high-viscosity insulating compound is impregnated into the insulating paper. Compared to the Crosslinked polyethylene (XLPE) cables, MI cables have a lower conductor allowable temperature during operation, making it difficult to secure transmission capacity, and since they are filled with insulating compound, there is a possibility of marine pollution in the event of an accident. Therefore, as a commissioned project of the New Energy and Industrial Technology Development Organization (NEDO), the authors have been developing a single-core DC 500 kV submarine cable with a transmission capacity of 1 GW and a deepwater depth of 1500 m using XLPE cables, which have a high conductor allowable temperature and are solid insulated without concerns about marine pollution. In this study, we fabricated a prototype cable suitable for deep water installation, evaluated its mechanical and electrical properties, and are reporting the results.

3.2 Cable Structure

3.2.1 Selection of cable structure

To determine the cable structure, first consider the voltage class, conductor size, and number of installed lines based on the transmission capacity, and then estimate the cable length and cable laying tension based on the water depth and route survey of the laying area. In addition, since the cable structure may also depend on the specifications of cable laying vessel, the selection of cable laying vessel, and outfitting are also considered in parallel with the consideration of the cable laying tension and shipping length.

In this study, we omitted some processes, such as the implementation of route surveys and the selection of the cable laying vessel, and assumed that there were no constraints due to the specifications of the cable laying vessel, and considered the cable structure based on the power transmission capacity, voltage class, and water depth conditions.

3.2.2 Conductor structure

When laying a cable at a depth of 1500 m, the cable's own weight for 1500 m is always applied as tension to the cable on the cable laying vessel (Figure 7). Therefore, it is essential to reduce the weight of the cable in the development of a deepwater cable. In general, copper, which has high conductivity, is used for the conductor of a power cable for power transmission, whether on land or

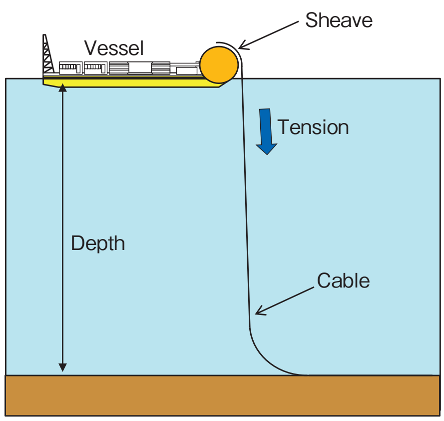

Figure 7 Cable installation model.

on the seabed, in order to reduce the cross-sectional area. On the other hand, aluminum, which has a low specific gravity, is suitable for reducing the cable weight, and we investigated to use it as a conductor. Since aluminum has a lower conductivity than copper, the conductor cross-sectional area tends to be larger, i.e., the outer diameter tends to be larger. Therefore, the weight of the cable armour tends to increase, but since a larger cable volume is more subject to buoyancy in water, we applied an aluminum conductor, which is advantageous for the weight underwater, in this study.

In AC transmission, the skin effect occurs, which causes the current to flow only on the surface of the conductor, so in order to transmit a large current, it is necessary to use split conductors or insulate the wires. On the other hand, DC does not have the skin effect, so the wire diameter can be made thicker and improving the space factor is effective. In the case of round wires, air gaps are created even when twisted, so we considered a keystone conductor in which segmented-shaped wires are twisted together to improve the space factor. By improving the space factor, it is possible to reduce the conductor diameter, and the overall weight of the cable, including the armour, can be reduced.

3.2.3 Armour structure

The tension applied to the cable during installation is mainly shared by the armour. When laying at a depth of 1500 m, it is important that the cable can withstand the static tension due to the cable's own weight as well as the dynamic tension due to waves, etc., so a two-layer structure with alternating twisting that takes torque balance into consideration is suitable for the armour. We used iron-based materials for the armour, taking into consideration their mechanical properties and cost. In order to increase the cable transport volume and reduce the cable tension during installation, it is desirable to have a small cable weight including the armour. As candidates for the armour structure, we targeted a round wire structure and a rectangular structure to improve the space factor, and we examined the shape, number, configuration, etc., similar to the conductor.

We compared the ϕ8 round wire structure (Case 1) used in general submarine cables with three types of armouring structures (Case 2, Case 3, and Case 4) that can improve the space factor (Table 4). The cable structure inside the armouring was the same for all three.

Table 4 Comparison of cable weight for various armour structures.

No.	Unit	Case1	Case2	Case3	Case4
Armour (Height x Width)	mm	Round wire ϕ8	Flat wire H6.1 x W10	Flat wire H4 x W16	Flat wire H3 x W10
Outer diameter	mm	169	162	153	149
Weight of 1 m cable in air	N/m	721	709	573	503
Submarged weight of 1 m cable	N/m	495	503	388	328

When comparing only the cable weight, Case 4, which has a smaller cross-sectional area of the armouring, is the lightest, but in this study, we considered the versatility of manufacturing and selected armouring structure Case 1, which can use ϕ8 steel wire that can be purchased according to JIS standards, and collected basic data through mechanical and electrical evaluations.

3.3 Cable Characteristic Evaluation

3.3.1 Prototype cable

A prototype DC500 kV cable with aluminum keystone conductor 1200 mm^2 and double steel wire armour was fabricated (Figure 8, Table 4-Case 1). Specifications are shown in Table 5. The mechanical stresses that should be confirmed for deepwater applications were evaluated using the prototype cable. In addition, electrical tests (long term loading cycle voltage test and impulse voltage test) were performed on the samples after tensile bending tests.

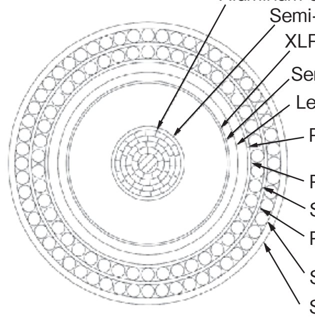

Figure 8 Prototype DC500kV submarine cable for deepwater.

Table 5 Specification of a prototype cable.

Conductor	Aluminum keystone 1200 mm^2
Insulation	XLPE
Water barrier	Lead alloy
Sheath	Polyethylene
Armour	ϕ 8 mm double steel wire
Outer diameter	ϕ 169 mm
Weight of 1m cable in air	721 N/m
Submarged weight of 1 m cable	495 N/m

3.3.2 Tensile properties

When laying the cable, the static tension due to its own weight and the dynamic tension due to waves, etc. are applied to the cable. When laying the cable at a depth of 1500 m, the tension applied to the cable becomes very large. A tensile test was performed using a prototype cable to evaluate whether abnormalities (such as breakage or deformation) occur in the cable when tension is applied. The formula for calculating the tension was based on CIGRE TB 623[11]. When the water depth exceeds 500 m, the tension must be calculated based on the static tension calculated from the cable weight (Table 4) and the water depth (1500 m), as well as the dynamic tension based on the movement of the cable laying vessel. Since the information on the installation area and the cable laying vessel is required, so here we applied the values for the Sardinia Island – Italian Peninsula (SAPEI) DC interconnection line shown in CIGRE TB 623 (Sieve vertical oscillation bh = 3 m, Period Tp = 8 sec), and performed the test at approximately 1000 kN obtained by the test tension calculation formula in CIGRE TB 623. Two cable samples were prepared for the test, and the tension of the entire cable and the tension applied to the conductor were measured.

Figure 9 shows the tensile test. Figure 10 shows the axial stiffness against the tension applied to the entire cable. The experimental value was smaller than the value calculated by the stress analysis program LAYCAL[12]. The possible causes are the gaps between the layers inside the cable, the crushing of the cushioning layers such as Poly Propylene (PP) yarn and tape, and the slack of the cable due to horizontal pulling. Figure 11 shows the change of sharing ratio of conductor. The conductor share changed between 8 and 12% against the tension applied to the entire cable. The conductor share calculated by LAYCAL was 8%, and the graph shows that the test result was greater than the calculated value. It is suspected that the calculation did not take into account the radial movement of the armour due to the gaps between the layers inside the cable or the crushing of the cushioning layers such as PP yarn and tape. There were no abnormalities in the appearance of the sample after the test, and no deformation or damage was observed in the Polyethylene (PE) sheath or lead sheath inside the armour.

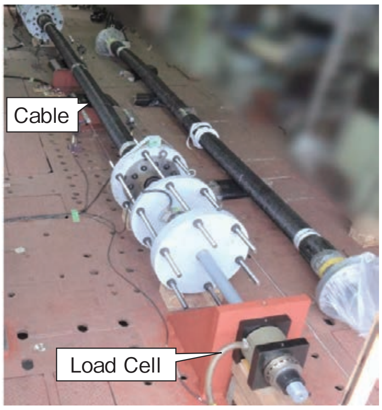

Figure 9 Picture of tensile test.

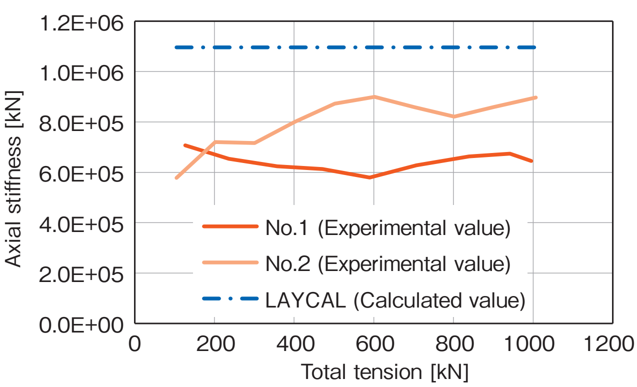

Figure 10 Relationship between an axial stiffness and a cable tension.

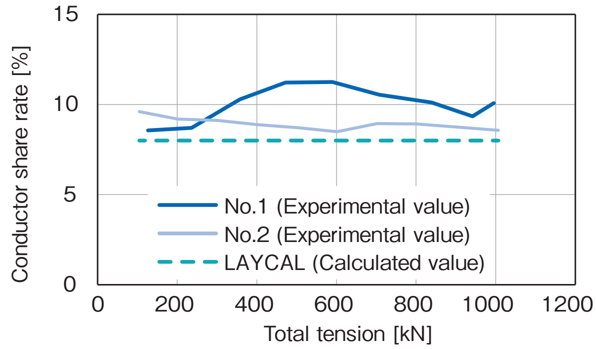

Figure 11 Relationship between a load sharing ratio of conductor and a cable tension.

3.3.3 Tensile bending test

A tensile bending test was conducted to simulate the tension due to the cable's own weight when laying the cable on the seabed and the lateral pressure applied by the sheaves of the cable laying vessel. The test method was based on CIGRE TB 623[11], and the cable sample was made to make 1.5 round trips (a total of 3 passes through the drum) while applying a test tension to the cable sample. Table 6 shows the test conditions. The tensile properties equivalent to a water depth of 1500 m were confirmed in the tensile test described above, and the purpose of this test was to evaluate the effects of the lateral pressure. The sheave diameter of the expected cable laying vessel is 10 m, but two conditions (ϕ8 m, ϕ5 m) were used to perform a strict evaluation and to evaluate the effects of the lateral pressure.

Table 6 Conditions of a tensile bending test.

Item	Unit	Test conditions	Requirements
Test tension	kN	732	989
Sheave diameter	m	ϕ8 / ϕ5	ϕ10
Sidewall pressure	kN/m	183 / 293	198

Figure 12 shows the test conditions. Table 7 shows the results. The tension was maintained at or above the test tension while the sheave was moving. After the test, cables No. 1 to No. 3 showed no abnormalities in appearance, and no flattening or deformation was observed in the steel wire, PE sheath, or lead sheath. After the test,

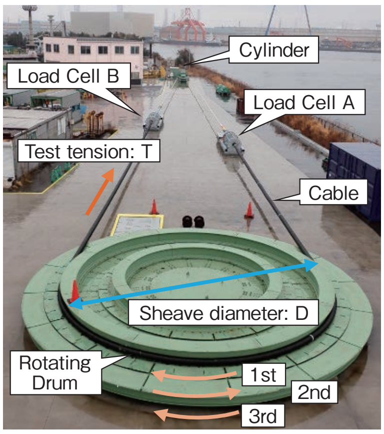

Figure 12 Picture of a tensile bending test.

Table 7 Test results of tensile bending test.

No.	Condition	Result
1	ϕ 8 m sheave	good
2	ϕ 5 m sheave	good
3	ϕ 5 m sheave (for electrical test)	good

cable No. 3 was used for a long term loading cycle voltage test.

3.3.4 Electrical test

After the tensile bending test, the steel wire armour was removed from the cable and a long term loading cycle voltage test was conducted. The test conditions were based on CIGRE TB 496[13] (Table 8). Figure 13 shows the test conditions. Under the test conditions shown in Table 8, a current load was applied for a total of 30 days, and the test was completed successfully.

Table 8 Conditions of a long term loading cycle voltage test.

(U_T=1.85U_0, U_0=500 kV, T_{cond}=90℃)

DC Voltage [kV]	Cycle	Condition	Result
−925	12cy	90℃×24 hr/cycle	good
0 (Earthing)	−	Rest period (24 hr<)	good
＋925	12cy	90℃×24 hr/cycle	good
＋925	3cy	90℃×48 hr/cycle	good

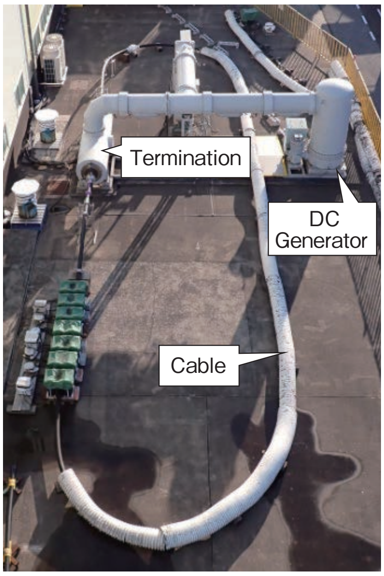

Figure 13 Picture of a long term loading cycle voltage test.

In order to evaluate the remaining performance after the long term loading cycle voltage test, the test line was reassembled and an impulse voltage test was performed. The withstand voltage level was set by assuming a DC superimposed opposite polarity lightning impulse test, which causes the highest stress, and taking into account the Bahder's coefficient. The Bahder's coefficient is the contribution rate of DC voltage to the breakdown voltage when a reverse polarity impulse voltage is superimposed on a DC voltage applied to the cable[14]. The Bahder's coefficient is related to the accumulation of space charge in the cable insulation, and although the degree of the coefficient varies depending on the material, it was set to K=1 as a sufficiently conservative value. The impulse voltage test was performed under the test conditions shown in Table 9 and was completed successfully. After the test, the parts that had been subjected to the lateral pressure in the tensile bending test were disassembled and inspected, and no deformation or damage was found in the PE sheath, the lead sheath, or the outer semi-conductor screen.

Table 9 Conditions of the impulse voltage test.

U_T=K*U_0+U_{P1} (U_0=500 kV, U_{P1}=2.1 U_0)

Voltage [kV] U_T	Times	Condition	Result
−1550	10	T_{cond} = 90℃	good
+1550	10	T_{cond} = 90℃	good

3.4 Summary

In order to shorten the laying route of deepwater DC cables, a prototype cable was fabricated and evaluated, assuming a single-core cable with a depth of 1500 m, with an aluminum keystone conductor and a ϕ8 double steel wire armour.

It was confirmed that the prototype cable has sufficient mechanical performance for installation at depths of 1,500 m and electrical performance for 500 kV DC transmission.

4. CONCLUSION

This paper describes the development of a dynamic power cable system for TLP floating offshore wind power generation and the development of a deepwater submarine cable.

As the power cable division, we are focusing on the development of submarine cables, including those for offshore wind power generation, for which demand is expected to continue to grow, and are working to improve the production capacity and construction capabilities of our factories to meet this demand. As part of capital investment in our factories, we are working to increase our manufacturing capacity for long submarine cables, such as by operating a large turntable (7,000 ton) for submarine cables, and to improve our processes. As for construction capabilities, we are working to expand our partnerships with partner companies, to improve our laying methods, and to develop new cable laying vessels[15].

In order to achieve carbon neutrality in 2050, it is essential to expand offshore wind power generation, and all divisions are working together to meet this demand.

This result was obtained as a result of a commissioned project (JPNP20001) by the New Energy and Industrial Technology Development Organization (NEDO) for "Development of basic technology for multi-purpose multi-terminal DC power transmission systems/Development of DC deepwater cables (single-core depth 1500 m class)" and a grant project (JPNP21015) for "Green Innovation

Fund Project/Reducing the cost of offshore wind power generation/Development of low-cost floating foundation manufacturing and installation technology/Development of floating offshore power generation equipment using the TLP method to achieve low cost and excellent social acceptance”.

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