Technological Trends, Development Tasks and Initiatives for Submarine Power Cable Systems

~ Contribution to the Achievement of SDGs ~

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ABSTRACT In recent years, initiatives for the achievement of the Sustainable Development Goals (SDGs) and efforts toward the carbon neutrality in 2050 have become active, and attention has been focused on reforming the energy structure. Among them, Japanese government has set a target of 30 to 45 GW of offshore wind power generation in 2040, and the demand of the submarine power cable is increasing accordingly.

In addition, since offshore wind power generation is planned to be intensively introduced in Hokkaido, Tohoku and Kyushu areas where the wind conditions are good, a long- distance submarine transmission grid for transmitting electricity to the metropolitan area and Kansai area, which are power load areas. The importance of submarine power cable is increasing more than ever. Furukawa Electric (FEC) is developing technologies from a broad set of perspectives to meet the demands, and this paper describes the recent development status of submarine power cables and future technological trends.

1. INTRODUCTION

Natural disasters caused by global warming will increase in the 21st century worldwide. As a result, initiatives for achievement of SDGs or efforts toward the carbon neutrality in 2050 have become active and an energy structure reform are getting a lot of attention. The recent power supply composition in Japan and the forecast for FY 2030 upheld in the Strategic Energy Plan by the Ministry of Economy, Trade and Industry (METI) is shown in Figure 1. The ratio of power generation using fossil fuels with high CO_2 emission is high and its renewable energy share remains 18% (in the case of discounting hydro power is 10%), however the rate will increase to 37% according to the plan. Since the trend of decarbonization in energy supply is a main stream approach in the world and each country is proceeding with solutions, Japan is required to develop its own rapid solution.

Offshore wind power generation is expected as main power source in Japan which is an island country surrounded by the sea, using its advantageous geographical position, is developing offshore wind power generation as a last resort as the main power source in energy policy[1)]. In April 2019, the “Act on Promoting the Utilization of Sea Areas for the Development of Marine Renewable Energy Power Generation Facilities” was put into a law in force and the legal basis were laid for promoting large scale offshore wind power generation. At the “Public-Private Council on Enhancement of Industrial Competitiveness for Offshore Wind Power Generation” held in December 2020, the introduction target of 10 GW in 2030 and 30 to 45 GW in 2040 was agreed, and the public invitation of four locations in Japan and a total 1.5 GW has already started, and further increase in offshore wind power generation is expected. Furthermore, the regions with high potential for introducing offshore wind power generation are Hokkaido, Tohoku and Kyushu regions, which are far from the areas with high electricity demand. Therefore, a nationwide submarine DC power transmission grid is planned[2)], and the demand of submarine power cable is expected to increase significantly much more than the current level.

We are developing submarine power cables from a broad set of perspectives to respond to the above expectations and to contribute to the achievement of SDGs and the implementation of carbon neutralization by 2050, and this paper describes the current development status and future technological trends.

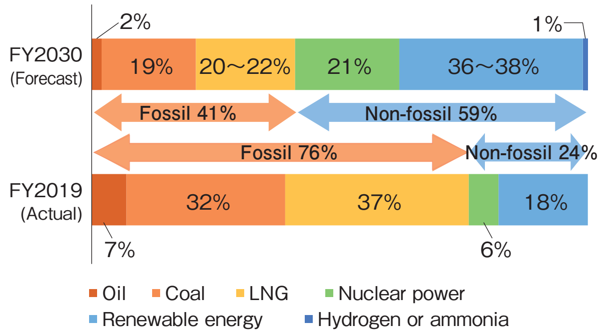

Figure 1 **Comparison of power supply composition between FY2019 (actual) and FY2030 (forecast).[3)]**

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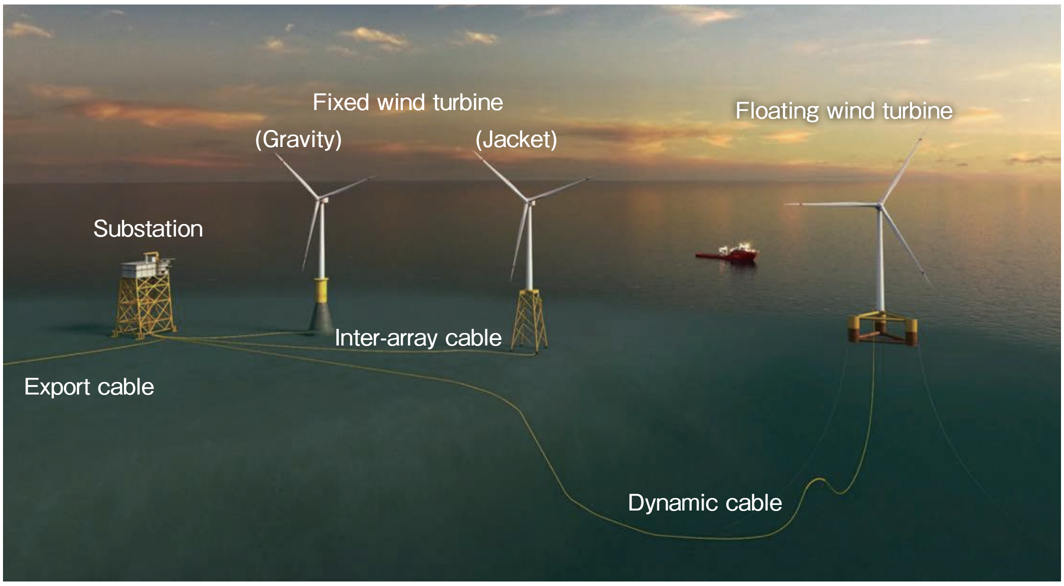

Figure 2 Image of offshore wind power generation.[4)]

2. SUBMARINE POWER CABLE FOR FIXED OFFSHORE WIND POWER GENERATION

Figure 2 shows an image of offshore wind power generation. Currently, most of the offshore wind power generation commercialized worldwide is a system having a foundation built on the seabed that is called fixed offshore wind power. It is being built in a relatively shallow sea area with a water depth of less than 60 m. The cables used are roughly divided into two types, inter-array cables for connecting between wind turbines or between wind turbines and the offshore substation, and an export cable for connecting from the offshore substation to land. And in either cable, in case of the cable for the fixed offshore wind power generation, it does not need to consider fatigue or the like because most part of the cables are laid in a fixed state such as buried laying. However, since the cable is exposed in some part around the foundation, a Cable Protection System (CPS) is used generally for anti-fatigue.

The fixed offshore wind power generation will start in a full-scale introduction around 2023 in Japan. We are steadily proceeding with the development by utilizing the knowhow cultivated in the development of submarine power cables so far according to the above schedule.

2.1 Inter-array Cable

In the early stage of offshore wind power generations, it was about 3 to 5 MW for one port area and the transmission voltage was AC 22/33 kV class. On the other hand, in recent years, due to the expansion of the power generation scale, the study has shifted to the use of wind turbines of over 8 to 12 MW class, and the transmission voltage has typically become AC 66 kV class, and the cable is increasing in size. In addition, as the number of installed wind turbines in wind farms is increasing, the number of inter-array cables installed is increasing, and workability becomes very important. In inter-array cables, development for weight reduction is becoming more important.

The conventional inter-array cable has been the cross-linked polyethylene insulated, lead sheathed, iron wire armored submarine power cable which is used as islands power links. The cable has a lead sheath for preventing the water tree generation, but the use of lead increases the weight of cable.

Therefore, based on the recent technological trends in inter-array cables for fixed offshore power generation facilities, we are studying a low-cost and lighter submarine cables with a semi-dry structure. A cross section of submarine power cable with a semi-dry structure is shown in Figure 3. The cable has two characteristics, the application of tree retardant XLPE (TR-XLPE) and the elimination of lead sheath. The TR-XLPE has a function of water tree prevention and has already been utilized in overseas distribution underground cables with voltages below AC 33 kV.

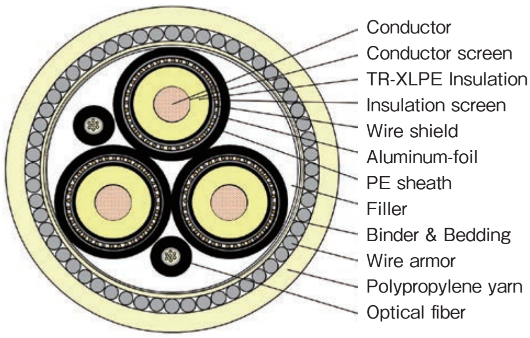

Figure 3 Cross section of semi-dry structured submarine power cable.

By applying of TR-XLPE, it is possible to apply the simple water shielding, such as aluminum laminate film to the water shielding layer instead of the complete water shielding like in the conventional lead sheath, and it can make cable weight lighter. In addition, since lead is designated as an environmentally hazardous substance, it is contributing to the achievement of the SDGs by reducing the amount of used lead.

2.2 Export Cable

Export cable has the same structure as the conventional large submarine power cable which is used for islands power links (Figure 4). As mentioned previously, the power generated by each wind turbine is generally collected at the offshore substation and transmission voltage is increased in order to reduce transmission loss and transferred to the land. The present export cable is mainly AC 154 kV class, but the installation location of the offshore wind power generation is gradually expanding offshore to reach favorable wind conditions, and the amount of power generation is also increasing due to the increase in installed wind turbines, it is expected that higher voltage of AC 220 to 275 kV class cable will be the standard instead of the one of the present cable.

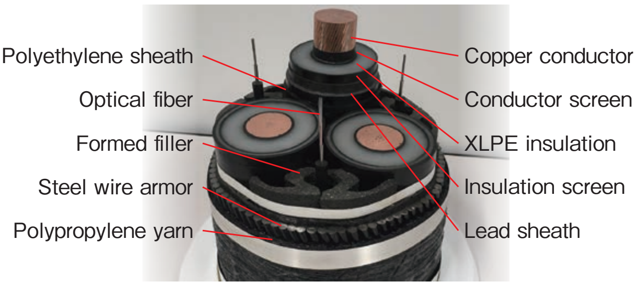

Figure 4 AC 275 kV 1400 mm^2 submarine power cable.

We are approaching the task from both sides of the technical development and the production equipment for higher voltage cable. We are proceeding with the development of a factory joint (FJ) for manufacturing the long submarine cable and a repair joint (RJ) for getting the certification from the technical point of view. From the production equipment point of view, a large stranding machine is applied to strand a larger cable than before.

3. POWER CABLE FOR FLOATING OFFSHORE WIND POWER GENERATION

Floating offshore wind power generation is a power generation system in which a wind turbine is built on a floating body (Figure 2). Since the floating offshore wind power generation generally has a cost advantage in the sea area with more than approximately 60 m of depth comparing with the fixed wind power generation, the floating system is more advantageous in Japan because shallow water area is limited. In addition, since we have a lot of strong wind condition area in Japan shown in Figure 5, potential generation with floating offshore generation is estimated at around 424 GW and the floating system has a tremendous potential (around 128 GW for the fixed system)[5].

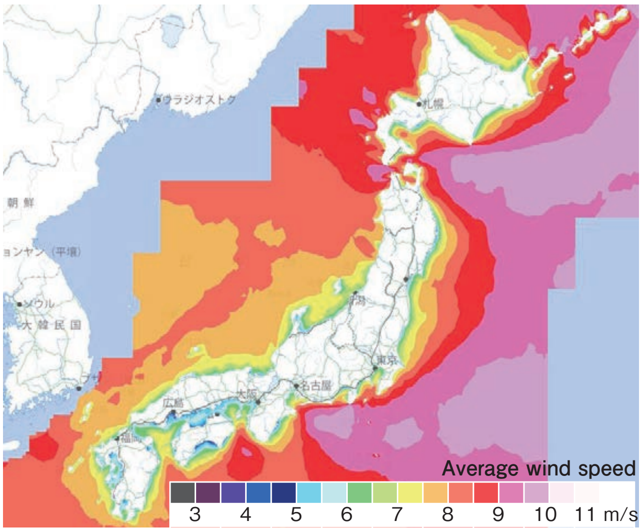

Figure 5 Wind conditions in the sea around Japan.[6]

Currently, floating offshore wind power generation has a little track record, but considering the high potential and the possibility of overcoming issues, it is expected that the number of floating large-scale wind farms will increase from around 2030, we are also developing a power cable for floating offshore wind power generation to contribute to it.

3.1 Dynamic Cable

Figure 6 shows the structure of a dynamic cable. A power cable using for floating wind turbines is called in general a dynamic cable, and since the cable receives a dynamic behavior repeatedly, for instance curvature fluctuation and tension fluctuation due to the wave sway of floating body and fluid force caused by tidal current, durability (fatigue resistance) against tension and bending is required for the cable. Therefore, the design is such as a flexible stranded conductor, a wire strand, a metallic sheath with excellent performance against bending fatigue, a double stranded armor, etc.

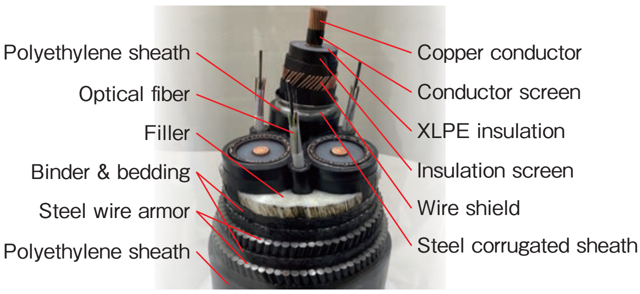

Figure 6 AC 66 kV 100 mm^2 dynamic cable.

FEC participated in the Fukushima Forward Project[7] of METI commissioned project started in 2013. The project aims to create new industries and jobs focusing on renewable energy for recovery from the Great East Japan Earthquake disaster, and three kinds of floating wind turbines of 2 MW, 5 MW and 7 MW were installed and operated off the coast of Fukushima prefecture as a field verification test. FEC provided with AC 22 kV and 66 kV dynamic cables for the floating wind turbines and a floating offshore substation, and 66 kV submarine export cable to landing point. The objective was to realize the world's first floating offshore wind turbine and its safety, as well as reliability and economy.

Furthermore, FEC technology had a great reputation based on the Fukushima Forward Project and got an order of a technical development task for an extra high voltage dynamic cable from Carbon Trust of the United Kingdom[8] and we carried out structural design, installation design, etc. Currently, power cables for offshore wind power generation, led by Carbon Trust, are under consideration to increase the voltage class, and export of dynamic cables is assumed in requirements for higher voltage cables (AC over 66 kV to 275 kV class) in future. We are proceeding world-leading research and development for the above needs.

3.2 Technology Development for Cost Reduction

The example of a floating wind turbine is shown in Figure 7. The mooring method for the present floating offshore wind power generation is in general a catenary laying system, for instance spar-buoy type, semi-submersible type, etc. However, the method has the following problems that the floating body is greatly shaken and the cost of the system is increased by mitigations against fatigue, and that the area occupied by the sea area is large and the influence on fishing and ship operation is important. To solve the problems, a floating and mooring system of Tension Leg Platform (TLP) is being studied now. Since the TLP has a good sway performance, the cable system can be simplified and also occupied sea area by mooring line is significantly reduced. The TLP can contribute to the realization of the floating offshore power generation with highly socially acceptable level and low cost.

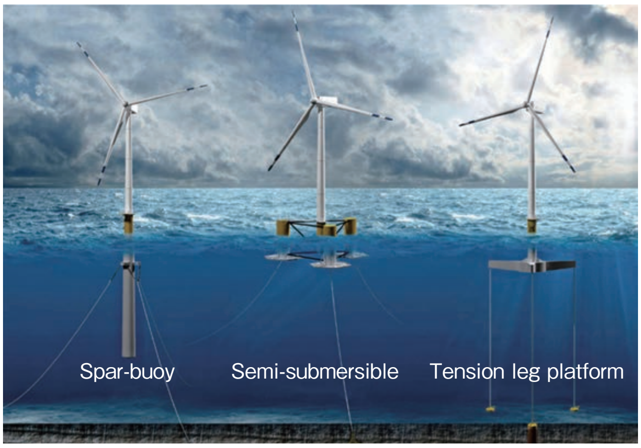

Figure 7 Example of a floating wind turbine.[9]

4. SUBMARINE POWER CABLE FOR WIDE AREA INTERCONNECTION GRID

As mentioned at the beginning, domestic suitable regions for offshore wind power generation are Hokkaido, Tohoku, Kyushu area and the areas are far from high demand area of electricity. Since insufficient free space in the power transmission system becomes a big issue for the transportation of generated power, the development of DC submarine power grid is planned.

Figure 8 shows a conceptual diagram comparing cost between the DC and AC transmission systems. The DC transmission system is suitable for large capacity and long distance where the cross AC/DC break-even point, generally approx. 50 km for submarine power cable, in the case of above construction of transmission power grid, the DC system is more advantageous.

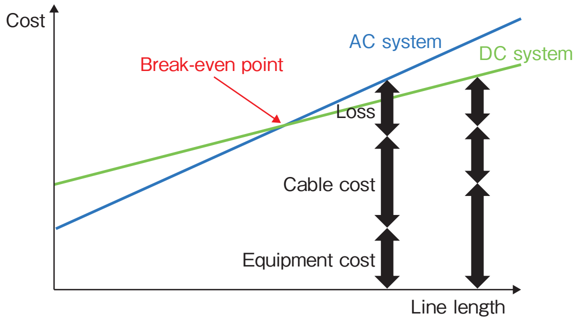

Figure 8 Cost comparison between AC and DC systems.

In addition, power supply between regions becomes possible by a multi-terminal grid between multiple wind farms and land power grid and it leads to stronger resilience.

4.1 Development of Insulation Material for DC System

The conventional crosslinked polyethylene used for AC (AC-XLPE) decreases the insulation property under DC voltage due to the accumulation of the space charge in the insulation[10]. In order to prevent the phenomena, the XLPE developed for DC (DC-XLPE) is applied for extra high voltage DC transmission system.

Figure 9 shows the result of space charge measurements for AC-XLPE and DC-XLPE. The space charge distribution changed significantly by polarity reversal for the AC-XLPE, but the DC-XLPE had very stable space charge distribution[11]. The performance of insulation material for DC cable is important not only for the space charge property but for the volume resistivity and insulation property for long term, and we have been working to develop new insulation material with different property from conventional AC material.

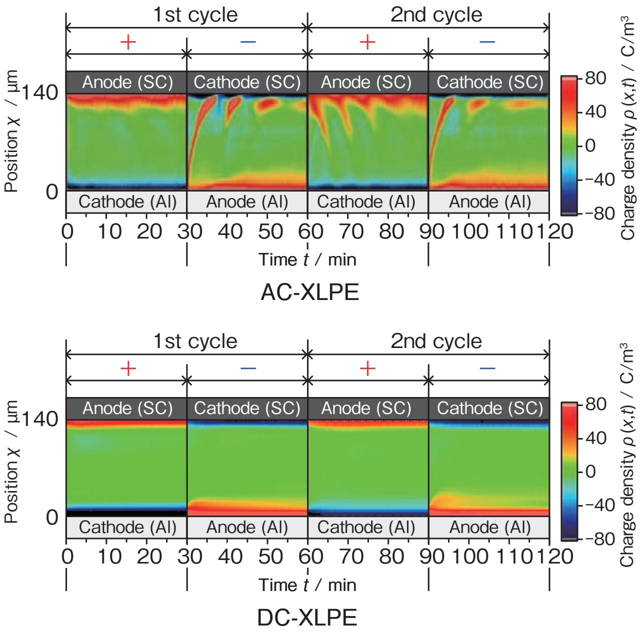

Figure 9 Comparison of space charge characteristics between AC and DC materials.

4.2 Optimization of the DC Cable System

As submarine power cables for wide area interconnection grid will be extra long-distance transmission over several hundred kilometers, the basic temperature varies greatly depending on the surrounding environment. In general, the thermal condition in the land area tends to be stricter than in the under-sea area. Since using of the most thermally severe part as a reference in cable design (selection of conductor size), larger conductor size leads to high cost.

Therefore, the conductor size of the part that is susceptible to thermal restrictions and the part that is not susceptible to thermal restrictions (for instance, under-sea part) are appropriately changed and the cost of the entire system can be reduced. We are developing a DC submarine power cable transmission system that includes cable factory joint with different conductor size (different diameter FJ) and succeeded in developing of a DC 500 kV class[12]. Figure 10 shows the cable used for 525 kV submarine power cable system development, and as a long-term performance test, we conducted a one-year long-term test based on CIGRE TB496 (VSC condition)[13], and we passed all the test listed including the residual performance test and obtained good results.

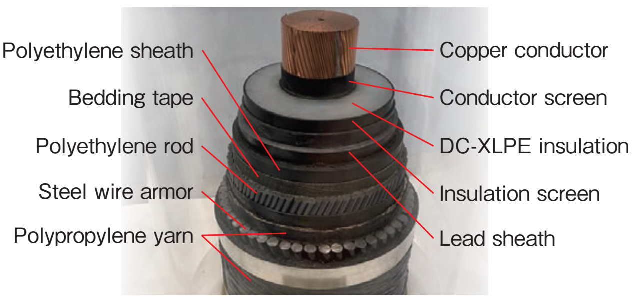

Figure 10 DC 525 kV 1800 mm^2 submarine power cable.

The conventional submarine power cable has a limitation on the water depth at which it can be installed, and is up to about 300 m. Therefore, when installing an extra-long submarine power cable for wide area interconnection grid, it is necessary to detour deep sea area and set a route along the shallow sea area, it leads to high cost and long installation period. Therefore, we are proceeding with the design and manufacturing technology of DC 500 kV class cable that can be installed in the deep sea with a maximum depth of 1500 m, and the development of an installing technology at the same cost level as before.

5. POWER CABLE INSTALLATION TECHNOLOGY FOR OFFSHORE WIND GENERATION

We have more than 100 years of experience in submarine power cables for islands power link and a very large number of deliveries (about 300 cases, 200 km or more). The offshore wind power generation business has also been developing since the dawn of offshore wind power generation, such as installing the first cables in Japan. Table 1 shows the past track record and the state of the cable installation barge of the Fukushima Forward Project shown in Figure 11.

Table 1 Installation results of cables for offshore wind power.

Name	Year	Turbine type	Remarks
Setana	2003	Fixed	The first project in Japan
Hibikinada (NEDO)	2012	Fixed	-
Fukushima	2013	Floating	AC66 kV dynamic cable
Fukushima	2014	Floating	-
Fukushima	2015	Floating	-
Fukushima	2016	Floating	-
Choshi (NEDO)	2015 (Repairing)	Fixed	-

Figure 11 Cable installation barge “KAIYO”.

5.1 Submarine Power Cable Installation Technology for Fixed Offshore Wind Power Generation

An example of the procedure for installing submarine power cable for fixed offshore wind power generation is shown in Figure 12. A protection tube for the hem of the wind turbine called cable protection system (CPS) is attached toward the end of the submarine power cable on the installation barge. The submarine power cable is sent out of the installation barge and is pulled in the wind turbine foundation. After that, the submarine power cable is installed toward the next wind turbine position, and the submarine power cable is cut at the required length at the specified position, and the CPS is attached toward the end of the cable. While hanging the cable with a semi-circular sheave, the submarine power cable is pulled out into the wind turbine, the sheave is pulled out, and the installation is completed.

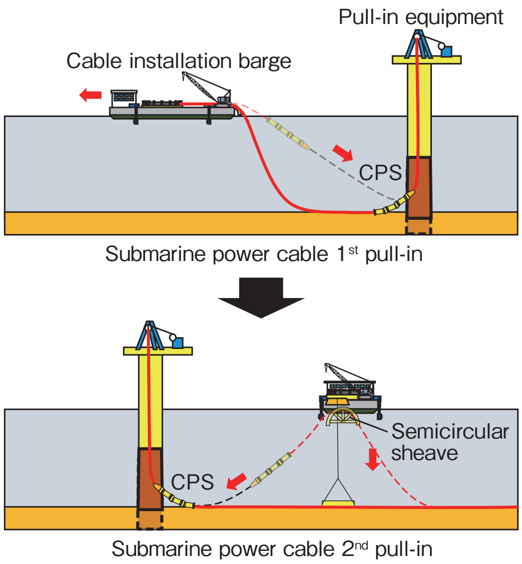

Figure 12 Example of a submarine power cable installation procedure for fixed wind power generation.

5.2 Power Cable Installation Technology for Floating Offshore Wind Power Generation

An installation procedure of the cable for floating offshore wind power generation is shown in Figure 13. A dynamic cable with a bend stiffer, an extreme bend preventing material, attached to the end is sent out from the installation barge and pulled into the offshore substation. The cable is installed while attaching accessories such as distributed buoys and jointed to the submarine power cable at the specified position, and the joint box is immersed and laid down at a specified location.

Next, the submarine power cable is installed toward the wind turbine, and the end of the cable is temporarily placed on the seabed at a specified position. The dynamic cable is pulled into the wind turbine and installed in the same procedure as on the offshore substation side, and the temporarily placed submarine power cable is pulled up on the installation barge for jointing work. After that, the joint box is sunk and the installation is completed.

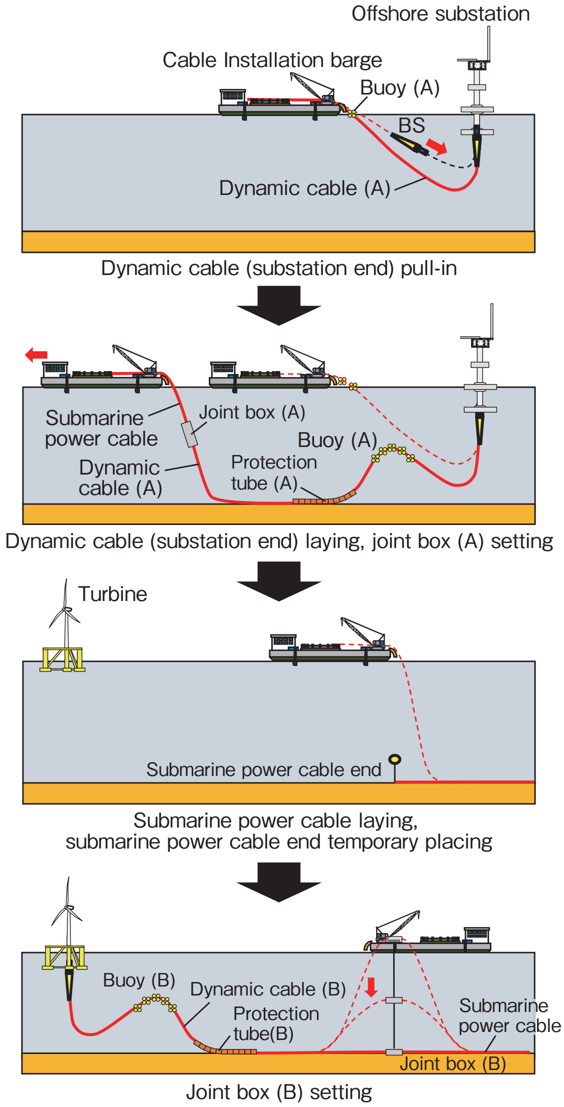

Figure 13 Example of dynamic cable installation procedure.

As mentioned before, the introduction of floating offshore wind generation is expected to increase after 2030. We will keep developing to contribute to the introduction not only from the view point of the cable manufacturing but also from the installation technology perspective.

6. OPERATION AND MAINTENANCE OF SUBMARINE POWER CABLE

Submarine power cables are more difficult to maintain than underground power transmission cables. As mentioned above, the installation environment differs greatly in the track, such as in the sea or in the air, so it is necessary to devise cable design and operation. As shown in the Figure 14, operation and maintenance account for 36.2% of the cost of the offshore wind industry, and how to keep this low is the key to reducing the cost of the offshore wind power generation.

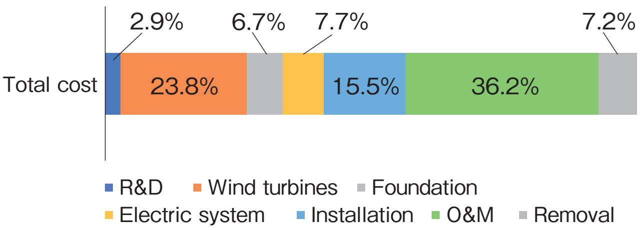

Figure 14 Cost structure of the offshore wind industry (Fixed wind power generation).[14)]

6.1 Dynamic Rating System

When constructing a conventional submarine power cable transmission system, the transmission capacity is determined by the allowable temperature of the conductor, it is designed by selecting a conductor cross-sectional area that enables constant transmission of rated current in the most severe part of the temperature environment over the entire length. However, in the offshore wind power generation, since generated power fluctuates, the size tends to be excessive when applying the conventional conductor cross-sectional area design. Therefore, if the cable conductor temperature is estimated from the amount of power generation and the transmission current is controlled so that the cable can be operated with the optimum conductor size, the transmission system can be constructed efficiently and at low cost. A system that controls the load by estimating the conductor temperature is called a Dynamic Rating System (DRS), and is partially put into practical use in the field of underground power transmission. Cables used for the offshore wind power generation are placed in an installation environment, where the ambient temperature changes drastically, therefore an algorithm that can predict the temperature appropriately according to the environment is required.

The method for estimating the cable conductor temperature is generally to define the thermal resistance and heat capacity of the constituent material and the ambient environment, formulate the heat balance between each layer in a one-dimensional equation, and calculate it by unsteady transient analysis. Then, there is a problem that a strict thermal resistance/heat capacity identification is required and it takes a long time to calculate. Therefore, we obtained the temperature response function of the cable according to the installation environment and developed an algorithm for estimating the conductor temperature. This temperature response function should be obtained ideally from an actual installed cable system, but it can also be obtained by analysis. We think that the analysis is an effective method for offshore power generation cable systems installed in different ambient environments.

Figure 15 shows a model in which a load control experiment of a DC single core submarine power cable was performed using a DRS Server that implemented the estimation algorithm adopted in this development and Figure 16 is an example of the model result. From the Figure 16 (1), the result shows that the current value is controlled below the allowable conductor temperature (90˚C in this experiment). Since the error of the conductor

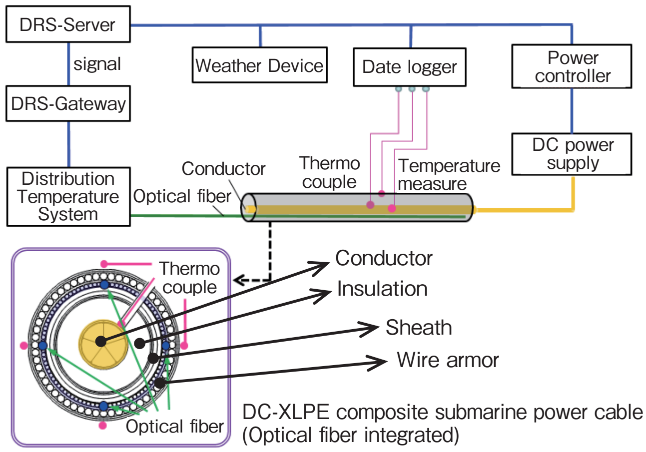

Figure 15 DRS control experiment model.

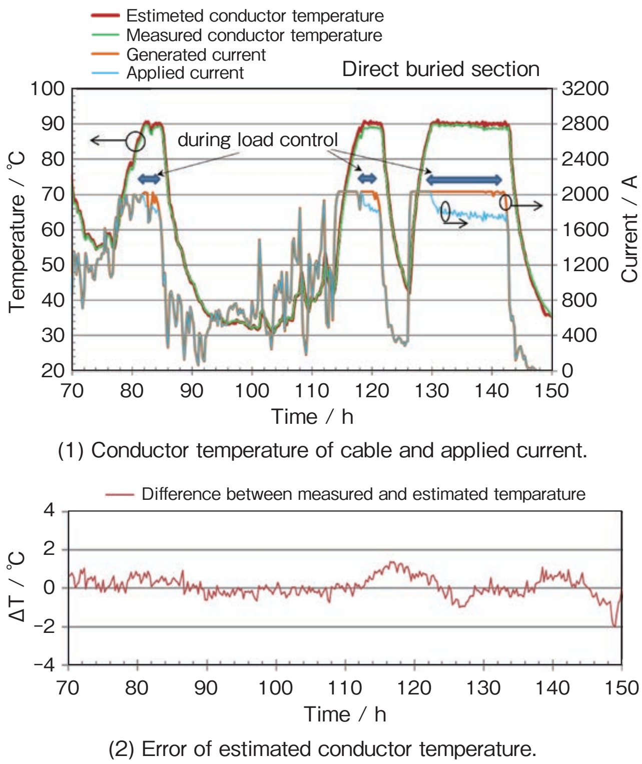

Figure 16 Example of current control experiment results used DRS.

temperature estimated from the figure 16 (2) is within about 2˚C, it is considered to be a practically sufficient accuracy.

We believe that the use of such DRS can contribute to the optimization of the cable system used for the offshore wind power generation.

6.2 Maintenance System

Since submarine power cables are installed and operated on the seabed, it is difficult to carry out regular inspections and maintenance in the same way as underground cables that are directly buried or installed in ducts. In the case of submarine power cables, it is technically possible to check the cable installing and burying status using a remotely operated vehicle, but it is not an easy maintenance method because it is costly. Therefore, as constant maintenance, a system for temperature monitoring using the composite optical fiber and a system for detecting cable damage caused by anchors and fishing gear of ships by combining resistance wires have been put into practical use.

However, the technology for diagnosing the degree of deterioration of the cables has not been established at present. The insulation deterioration diagnosis method used for underground power transmission cables targets water tree deterioration occurring in cable insulation without a moisture barrier and the insulation deterioration mechanism for submarine power cable with moisture barrier has not yet been clarified. Maintenance and operation related to such insulation deterioration is a future development issue.

Therefore, measures for early restoration of submarine power cables and accident prevention measures due to damage are currently under consideration[15]. Repairing a submarine power cable generally requires a lot of time and cost to secure a ship and workers because the cable is generally cut at the seabed, pulled up to a work ship on the sea, and then the cables is repaired. In future, joint ownership of cable maintenance and repair vessels solve these problems. In addition, the development of a management system that utilizes the location information of ships and cables to reduce the risk of accidents on submarine cables and repair methods on the seabed are being considered.

7. CONCLUSION

In this article, we described the technological trends of submarine power cables and results of our efforts. As mentioned earlier, the expansion of the offshore wind power generation is indispensable for achieving the scenario of the Japanese government’s green growth strategy. We will continue to push forward with the development of submarine power cables and contribute to the achievement of SDGs and the realization of carbon neutrality by 2050.

The development related to section 3.2, 4.1 and 6.2 is the result of the New Energy and Industrial Technology Development Organization “Next-generation Offshore DC Power Transmission Systems” and “Research and Development of a Multi-Purpose and Multi-Terminal High Voltage DC Transmission System”.

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