

Dynamic Cable System for Floating Offshore Wind Power Generation

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Floating offshore wind power generation has attracted increasing attention because of the deep water levels around Japan. We have developed a dynamic cable system that stably transmits electric power from floating offshore wind turbines to a substation on land, and tested it in a demonstration project led by the Japanese Ministry of the Environment. During the demonstration, no problems occurred with the cable system, and a subsequent investigation found no remarkable deterioration. These results confirmed that the cable system withstands mechanical stress caused by the large excursion of hybrid spar-type floaters. We have also developed a method to analyze the behavior of the cable in the sea to optimize the cable installation design and ensure long-term reliability.

Keywords: offshore wind power generation, submarine cable, dynamic cable

1. Introduction

In recent years, offshore wind power generation*¹ has attracted increased public attention owing to the necessity of using renewable energy as a solution to cope with global warming.

Floating offshore wind power generation (i.e., wind turbines floating on the sea) has attracted significant public attention in Japan, a country that is surrounded by deep water. The first demonstration of floating offshore wind power generation in Japan was performed under the auspices of the Japanese Ministry of the Environment.

We developed a dynamic cable system that achieves stable power transmission from floating offshore wind power generation facilities (that are subject to significant movement) to the shore and applied it to this demonstration project.

This paper reports on the development of the dynamic cable system for a 100-kW floating off-shore wind turbine (half-scale model) and 2-MW floating off-shore wind turbines (full-scale model).

2. Overview of Floating Offshore Wind Power Generation

Offshore wind power generation has two variations in installation configuration (see Fig. 1). In Japan, floating offshore wind power generation (in which the wind power generation equipment is designed to float on the sea) has been the focus of research and development efforts. This is because the sites suitable for bottom-mounted offshore wind power generation (in which the wind power generation equipment is designed to be secured to the seabed) are limited due to the deep water around the coast of Japan.

Floating offshore wind power generation is in the demonstration phase around the world, and reviews are underway for its commercialization. In Japan, the first demonstration project to test floating offshore wind power generation started in FY2010 using 100-kW and 2-MW

floating off-shore wind turbines off the Goto Islands, Nagasaki Prefecture, implemented under the auspices of the Japanese Ministry of the Environment.

The location of the demonstration site is shown in Fig. 2.

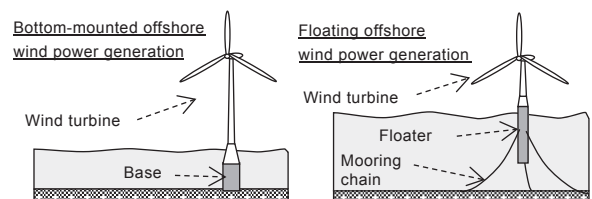


Fig. 1. Overview of offshore wind power generation

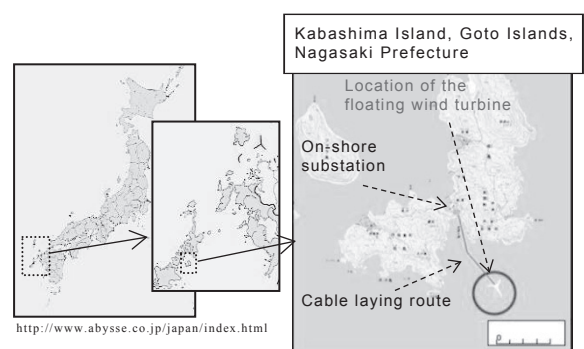


Fig. 2. Location of the demonstration project Implemented under the auspices of the Japanese Ministry of the Environment

3. Development of a Dynamic Cable System

3-1 What is a dynamic cable?

While conventional submarine cables are installed or secured on the seabed, the cables for floating offshore wind

power generation facilities have floating components to enable them to move with the floater (see Fig. 3). The cables are continuously subjected to bending and twisting forces, etc., caused by the tidal current and floater behavior; therefore, they are likely to suffer mechanical damage in various sections.⁽¹⁾

Stable power transmission from offshore wind turbines to the shore requires dynamic cables that are characterized by excellent mechanical strength.

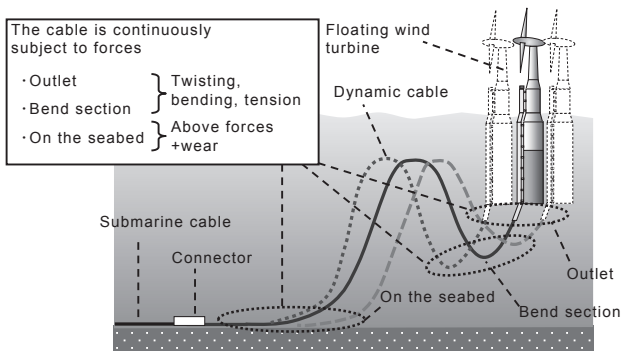


Fig. 3. Example of cable connection to a floating offshore wind power generation facility

3-2 Development of the cable for the 100-kW floating off-shore wind turbine

(1) Structure of the cable for the 100-kW wind turbine

We selected a 6.6 kV-class three-core XLPE cable by taking into account the generator capacity and on-shore grid voltage for connection.

The cable is likely to be subjected to twisting forces in the lateral direction (due to the movement with the floater behavior), suffer from external damage to primary insulation caused by objects floating in the sea, and experience continuous repetitive wear due to contact with the seabed. To cope with the twisting and external damage, we employed a cable armor manufactured with the double wire alternating coiling technique.^{*2}

In addition, a wire shield^{*3} was employed to cope with fatigue on the cable caused by the repetitive behavior of the floater. Figure 4 shows the structure of the three-core XLPE cable equipped with double wire armor.

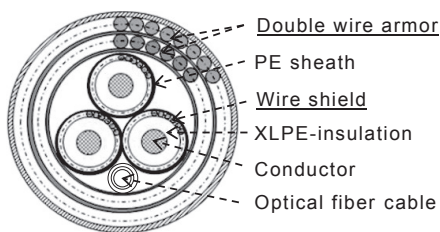


Fig. 4. Three-core XLPE cable structure equipped with double wire armor

(2) Cable-laying design for the 100-kW wind turbine

The floater moving distance at the 100-kW wind turbine under stormy conditions (e.g., a typhoon) was expected to be ± 25 m. We employed a cable offset design^{*4} that could absorb the floater moving distance. Figure 5 shows the offset profile for the 100-kW wind turbine.

To maintain the offset profile, buoys were used on the intermediate part of the cable. In order to prevent the cable from becoming kinked near the seabed, the buoy position was secured using a wire and sinker to restrict the moving range of the buoy and minimize change in the profile from the buoy to the seabed.

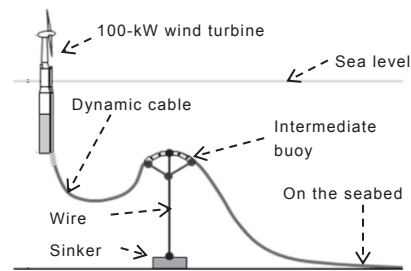


Fig. 5. Offset profile for the 100-kW wind turbine

(3) Test simulating the behavior of the cable on the seabed

We conducted a forced oscillation test with the actual cable on the seabed as a model in order to determine the mechanical forces that act on the cable. Figure 6 shows an overview of the behavior simulation test conducted with the cable on the seabed, and Table 1 lists the test conditions. We used the Middle Towing Tank of the National Maritime Research Institute to conduct the test.

We used a forced oscillation test unit to oscillate the top end of the cable with the predetermined force and measured the strain applied to the wire armor. We confirmed that the strain undergone by the wire armor of the cable did not pose any problem for practical use.⁽⁴⁾

We also compared the measured values of the cable profile change with the results of the cable behavior simulation obtained using the analysis software. In order to determine the cable profile change, we measured the changes in the angle between the cable and the seabed using an accelerometer. The profile change results for the

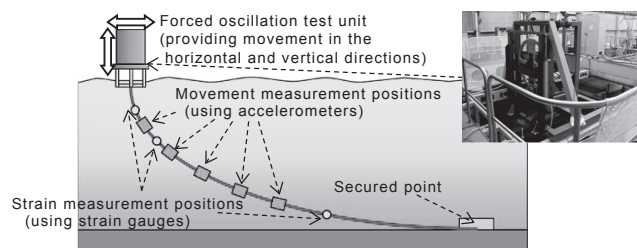


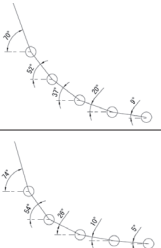
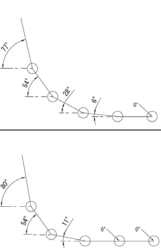


Fig. 6. Overview of the behavior simulation test with the cable on the seabed

Table 1. Simulation test conditions for the cable on the seabed

Movement condition	Direction	-	Vertical	Horizontal
	Duration of cycle	sec	3 - 20	3 - 20
	Distance of oscillation	mm	10 - 248	30 - 130
Strain measurement position*		mm		1000
		mm		3000
		mm		8500
Movement measurement position*		mm		1500
		mm		2500
		mm		3500
		mm		4500
		mm		5500

*The outlet of the test unit (the top end of the cable) is used as the reference (0 mm)

cable on the seabed are shown in Fig. 7. The cable was not subjected to any extreme bending, and the difference in the angle change between the measured and simulation values was a maximum of 6°, indicating that the simulation provided a good prediction of the cable profile change. We were able to confirm the validity of the analysis.

	Accelerometer measurement results		Profile of the cable on the seabed	
	Position* (mm)	Angle change (deg)	Initial (Movement 0 mm)	Maximum movement (movement 248 mm)
Simulation results	1500	7		
	2500	2		
	3500	9		
	4500	14		
	5500	9		
Measurement results	1500	6		
	2500	0		
	3500	15		
	4500	10		
	5500	5		

*The outlet of the test unit (the top end of the cable) is used as the reference (0 mm).

Fig. 7. Profile change measurement results for the cable on the seabed

(4) Demonstration results for the 100-kW floating off-shore wind turbine

We laid a cable of approximately 2 km between the 100-kW wind turbine (off Kabashima Island in the Goto Islands in Nagasaki Prefecture) and substation on Kabashima Island. Photo 1 shows the cable laying work. Connection with the grid commenced on July 26, 2012.



Photo 1. Cable laying to the 100-kW wind turbine

The demonstration continued for approximately one year until May 2013.

During this period, the area was affected by Typhoons No. 15 and No. 16 (both of which were very strong typhoons), causing the floater to move by up to 21 m.⁽²⁾ The dynamic cable withstood the significant repetitive movements produced, and remained in operation without any problems arising. The demonstration was completed safely.⁽³⁾ We confirmed that the cable could be laid properly for a hybrid-spar type floater structure.

3-3 Development of the cable for the 2-MW floating off-shore wind turbine

(1) Structure of the cable for the 2-MW wind turbine

In the future, 66-kV cables will be the mainstream cable for wind farms. They need to have a waterproof layer to prevent the ingress of moisture and guarantee long-term insulation performance under submerged conditions. For the 2-MW demonstration plant, a 6.6-kV cable was used with waterproof layers provided around its XLPE insulation to simulate a 66-kV cable.

The waterproof layer was designed to have excellent corrosion and fatigue resistance characteristics. Figure 8 shows the structure of the dynamic cable equipped with a waterproof layer.

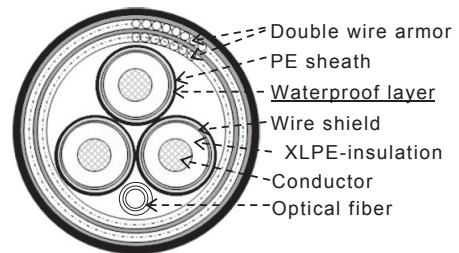


Fig. 8. Structure of the dynamic cable equipped with a waterproof layer

(2) Cable laying design for the 2-MW wind turbine

In line with the replacement of the 100-kW wind turbine with the 2-MW one, we reviewed the possibility of removing part of the existing cable and replacing it with the dynamic cable equipped with a waterproof layer. Figure 9 shows a conceptual diagram of the cable-laying configuration for the 2-MW wind turbine. Based on the

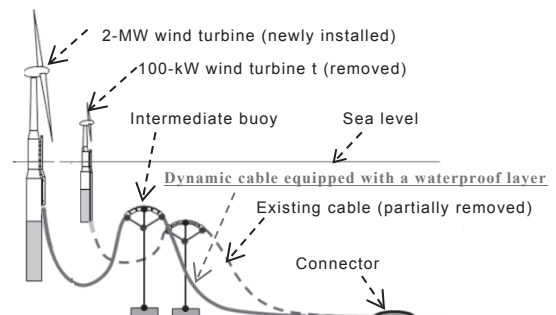


Fig. 9. Conceptual diagram of cable-laying configuration for the 2-MW wind turbine

simulation results of the floater design, the maximum moving distance of the 2-MW wind turbine was calculated to be ± 40 m. The cable profile was designed to absorb this distance.

(3) Demonstration results for the 2-MW wind turbine

In line with the removal of the 10-kW wind turbine, part of the existing cable near the turbine was removed and connected to the dynamic cable. The cable was laid to the moored wind turbine while forming the predetermined profile. Photo 2 shows the cable laying work to the 2-MW wind turbine.

The cable laying work (including offshore connection with the existing cable) was completed safely, and power generation commenced in October 2013. The demonstration continued for approximately two years until the end of 2015. The dynamic cable performed properly during the demonstration period and the demonstration was completed safely.

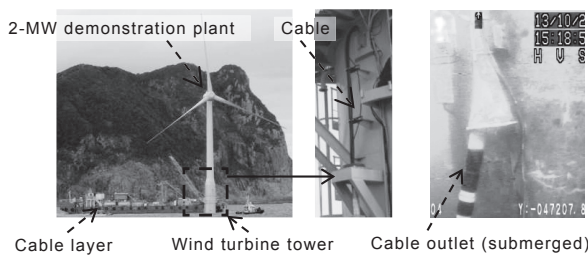


Photo 2. Cable laying to the 2-MW wind turbine

(4) Results of the cable dismantling investigation

To verify the validity of the dynamic cable structure and laying configuration, we dismantled and investigated the dynamic cable that was removed after the demonstration. Specifically, we dismantled and investigated the cable outlet whose curvature was subject to significant change due to the floater behavior. The results of the dismantling investigation are shown in Photo 3.

Although there was concern about the potential damage to the cable caused by the repetitive curvature change, the cable core and waterproof layer remained intact. No moisture ingress was found inside the waterproof layer.

The above results showed that our dynamic cable is suitable for floating offshore wind power generation both

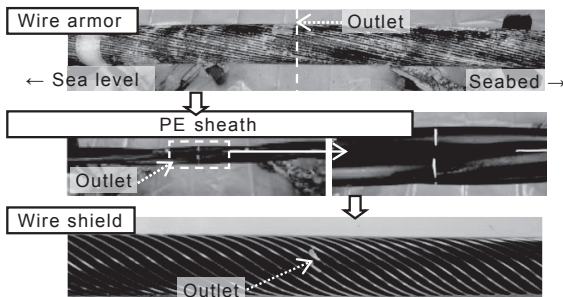


Photo 3. Cable dismantling and investigation results

in performance (to sufficiently endure the mechanical stress that applies to the cable) and structure (to absorb the mechanical stress with the offset profile employed for the cable laying configuration).

4. Development of a Cable Behavior Analysis Technique

4-1 Issues in evaluating the long-term reliability of the cable

To evaluate the long-term reliability of a dynamic cable system for floating offshore wind power generation, the mechanical force that applies to the cable must be determined. It is effective to perform an analysis of cable behavior in waters of different oceanographic conditions. We developed an analysis technique focusing on the cable behavior.

4-2 Review of the analysis technique

(1) Behavior analysis model

We selected a dynamic cable equipped with a waterproof layer for analysis. For the cable-laying configuration, we selected an offset profile and analyzed sections of the cable that were likely to suffer particularly from mechanical damage (e.g., the sections near the cable outlet from the floater and near the seabed). The analysis model is shown in Fig. 10.

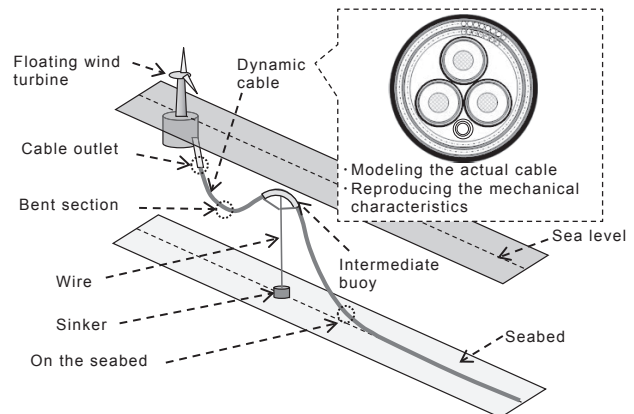


Fig. 10. Cable behavior analysis model

(2) Analysis procedure

After designing the cable structure and the cable-laying configuration, we performed analysis in accordance with the procedure shown in Fig. 11.

4-3 Results of the cable behavior analysis

(1) Results of the initial profile balance analysis of the cable

We entered the external force conditions (e.g., cable weight, buoyancy, and ocean current) and the mechanical constant of the cable into the analysis software to determine whether an appropriate offset profile could be formed under the initial conditions. Figure 12 shows the results of the analysis of the balancing of the initial cable-laying

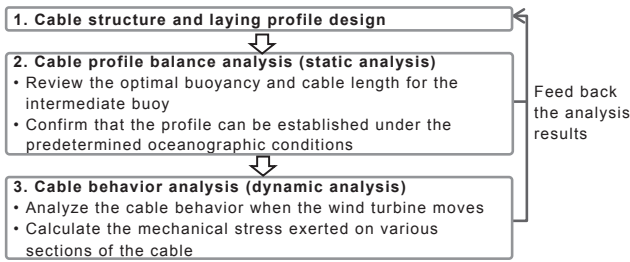


Fig. 11. Cable behavior analysis procedure

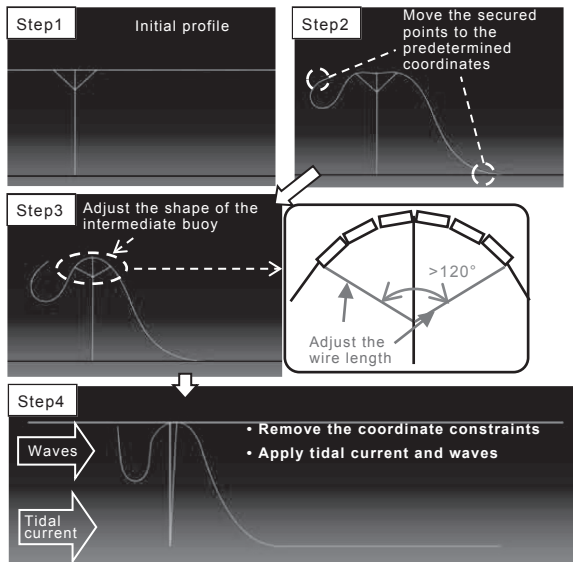


Fig. 12. Balance of the initial cable-laying configuration

configuration.

We confirmed that the predetermined offset profile could be realized after balancing of the external forces, such as gravity, tidal current, and waves.

(2) Results of the cable behavior analysis

We analyzed the cable profile change by taking into account the behavior of the floating offshore wind power generation facility and the balancing of the initial cable laying configuration. We confirmed that the cable profile could absorb the floater behavior. Figure 13 shows the analysis procedure of the cable behavior.

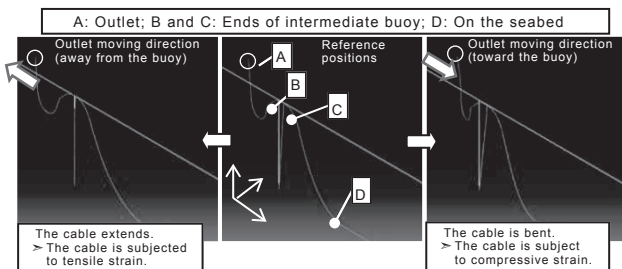


Fig. 13. Cable behavior analysis result

We also calculated the strain applied to the cable (see Fig. 14). We confirmed that the change in strain reaches a maximum at the suspended section of the cable (Section A–B in Fig. 13), resulting in a significant change in the cable profile.

Meanwhile, we confirmed that the change in strain between the intermediate buoy and the seabed (Section C–D in Fig. 13) is small and that the cable profile change near the seabed can be minimized by mooring the intermediate buoy to the seabed.⁽⁵⁾

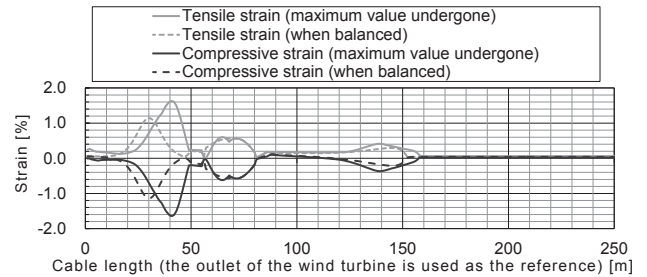


Fig. 14. Strain calculation results (for cable surface)

5. Conclusion

We will review the reliability of the cable structure and cable-laying design by using various behavior data derived from the demonstration project and model verification of the 2-MW wind turbine. Furthermore, we will optimize the cable-laying configuration using the analysis technique for cable behavior that has been developed.

We will feed back the results of this review in designing the dynamic cable system and propose a stable power transmission system to help expand the use of wind power as one option for renewable energy.

6. Acknowledgements

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Technical Terms

- *1 Offshore wind power generation: In wind power generation, the force of the wind drives a wind turbine, causing the generator to turn and generate electricity. Offshore wind power generation can produce more electricity than on-shore wind power generation because the offshore wind is more consistent and stronger than the on-shore wind.
- *2 Double wire alternating coiling cable armor: Wire armor is peculiar to a submarine cable. It is designed to ensure tension resistance when laying the cable and protect the cable from external damage caused by anchors and fishing implements. In double wire alternating coiling, inside and outside wire layers are coiled around the cable in opposite directions. This structure helps to equalize the torsional rigidity of the cable in the lateral direction.
- *3 Wire shield: A shielding layer prevents the electrical field produced by the conductor from radiating outside the cable. A wire shield consists of copper wire coiled spirally around the cable core. This structure helps to absorb expansion and contraction of the cable when the cable is bent.
- *4 Offset design: A cable is laid loose in an S-shape to absorb the movement of a floating wind turbine with the margin (loose part) of the cable.

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