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Design Methods of Power Cable Transmission Systems for Large-Scale Installation of Renewable Energy

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With the expansion of the use of renewable energy, it is necessary to construct not only AC distribution systems that connect renewable energy power plants to the existing grid but also long-distance large-capacity DC transmission lines. The AC cable systems are prone to various problems such as AC harmonic resonance and current zero missing, which require designs based on power system simulation. The large-scale DC transmission lines are expected to play an important role as multi-terminal transmission systems in the future, and their electrical system design and submarine route design require advanced cable technology. This paper reports on our new cable system design methods for AC distribution lines and DC transmission lines that contribute to the increasing use of renewable energy.

Keywords: renewable energy, long-distance AC cable, harmonic resonance, transmission system design, DC submarine cable

1. Introduction

The use of renewable energy for decarbonization has been increasing rapidly in recent years. However, in order to deliver the electricity generated by unevenly distributed renewable energy power plants to the consuming areas, it is indispensable to expand the independent transmission lines that connect the plants to an existing grid. Expansion of the core power grid is also required to compensate for the transmission capacity that cannot be fulfilled by the existing grid. This paper describes the problems peculiar to long-distance AC cables that are frequently used for the grid interconnection of renewable energy sources, such as wind power, and solutions to these problems, as well as the system design technology for DC submarine transmission cables that deliver large amounts of power to the consuming areas.

2. Transmission System for Wind Power Generation

Recently, 100 MW class onshore wind power generation has been planned in locations with good wind conditions, and in many cases, the distances to the point of interconnection with general power transmission/ distribution companies has increased. Wind power generation companies usually plan to interconnect the power they generate by constructing their own underground power transmission lines using long-distance AC cables. Although underground transmission has less site constraint than overhead transmission and shortens the construction period, technological problems specific to long-distance AC cables have become apparent.

These problems will also occur in offshore wind power generation, which is expected to expand in the future. Jointly with Nisshin Electric Co., Ltd, a Sumitomo Electric Group company, we propose a solution that integrally solves the problems concerning the electrical characteristics of cables and the design of substation equipment.

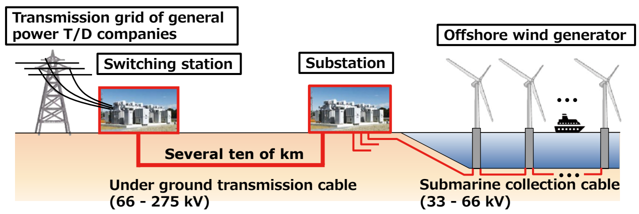

Fig. 1. An example of a transmission system for wind power generation

2-1 Technological problems concerning long-distance AC cables

It is well known that AC cables have capacitance like capacitors and increase the charging current and reduce the effective power transmission capacity as their length increases. (The details are described in Section 3 "Strengthening Grids Using DC Submarine Transmission Cables.") In recent years, as AC cable installation distance has increased, problems with electrical systems, including substation equipment, have often been raised. In this section, the major electrical phenomena attributable to capacitance and the measures against them are described.

(1) Increase of current during ground fault

There is a concern that a ground fault may lead to the accidental shutdown of operation. The electricity accumulated in the cable flows into the equipment together with the fault current, causing the accident current to increase. As a countermeasure, a compensation reactor is located at the neutral point of the transformer to cancel out the current flowing into the equipment from the cable with a reverse current.

(2) Consideration of harmonic resonance (low-order harmonic resonance)

As the capacitance of the cable (C) increases, the frequency of resonance with the inductance (L) of the power system decreases. As a result, resonance phenomena occur at specific frequencies (fifth and seventh), increasing the possibility of voltage distortion of the power system. When a harmonic resonance phenomenon occurs, the harmonics expand and possibly overheat the equipment. Installation of a harmonic filter is effective countermeasure equipment (Fig. 2).

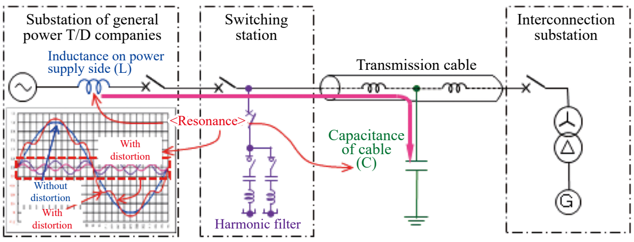

Fig. 2. Schematic illustration of harmonic resonance

(3) Measures against residual charge

When a circuit breaker installed in a long-distance AC cable system is turned off, a peak voltage (electric charge) remains in the capacitance C of the cable. If the circuit breaker is turned on in this state, the residual voltage is superimposed on the commercial voltage, causing an over-voltage, which may damage the equipment and cable. In addition, if the residual charge is discharged by a grounding switch, the sudden movement of the charge may induce a voltage in the cable shielding layer, resulting in dielectric breakdown.

As a preventive measure, a grounded voltage transformer is installed to confirm that it can discharge the residual voltage without any trouble.

(4) Voltage fluctuation and increase in voltage

When a general power transmission and distribution company uses a circuit breaker to charge a long-distance AC cable system of a renewable energy business operator, the system may fluctuate the voltage exceeding the range specified by the general power transmission and distribution company, depending on the charging capacity of the cable. As a preventive measure, section switching stations are established to divide the long-distance cable and shunt reactors are installed to offset the charging capacity of the cable. In addition, the Ferranti effect by capacitance increases the voltage at the power plant in excess of the voltage at the interconnection point (power system). This means that voltage must be taken into account when a long-distance cable is used.

(5) Current zero missing

When neutral point compensation reactors or shunt reactors are installed to solve the problems with long-distance cables, a current zero missing may occur. This is a phenomenon in which the accident current does not pass through the zero point as in the case of DC, differently from a normal AC waveform, when an electrical accident occurs. If this phenomenon occurs, the accident current cannot be shut off and the circuit breaker will be damaged. As a preventive measure, the resistance of the neutral point compensation reactor is increased or the shunt reactor is turned off in advance (Fig. 3).

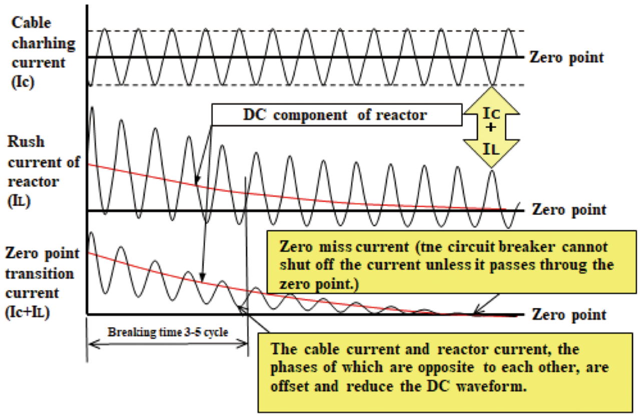

Fig. 3. Schematic illustration of current zero missing phenomenon

2-2 Case study of troubles that occurred in Europe

It is well known that Europe, which is well ahead of the rest of the world in the expanded use of renewable energy, is renovating existing grids, including optimization, capacity increase, and new construction, in parallel with the introduction of renewable energy. However, only a few papers have reported what kind of problems occurred and how they were solved. In this section, we discuss the power transmission problems that have occurred in Europe and have been reported in several papers published.

(1) Troubles that occurred in AC grids

The Anholt offshore wind farm (WF) in Denmark, which started operation in 2013, is a large-scale WF that generates 400 MW of electricity using a 33 kV, 152-km-long current collection cable. The electricity is transmitted through a 220 kV AC cable to an onshore substation 85 km (25 km on the seabed and 60 km on land) distant from the WF, boosted to 400 kV at this substation, and interconnected to a power system. There are papers that take the Anholt offshore WF as a model for inquiring into harmonic resonance phenomena and evaluating long-distance AC cable systems.[1] It has been reported that the budget for grid reinforcement in Europe is several times larger for local systems (DSOs) than for trunk systems (TSOs) and that there have been many cases of reinforcement by converting overhead transmission systems to underground transmission systems during the past dozen years. Many of the papers recently published in Europe describe a current zero missing phenomenon, suggesting that some sorts of troubles attributable to AC cables have occurred.

The Institute of Electrical Engineers of Japan organized a special working committee valid for three years from July 2020 to June 2023 in order to investigate the current status of offshore wind power generation and the electrical power technology that is the key to the wide-spread use of offshore wind power generation. The committee will inquire into the actual state of offshore wind power generation under the consideration that this type of power generation, which is positioned as a key power source in Europe, is the result of the accumulation of know-how acquired from various troubles that occurred during more than 20 years of operation history, such as cable breakage, dielectric breakdown at offshore substations, and burnout of harmonic filters. We look forward to the investigation results of the committee.

(2) An example of trouble in HVDC power transmission and offshore wind power generation

The BorWin1 offshore WF in Germany, which started operation in December 2010, transmits 400 MW of wind-power generated electricity using a 200-km-long DC cable (125 km on the seabed and 75 km on land) and interconnects the cable with an onshore grid through a two-level PWM converter. According to a report, BorWin1 had a technological problem with harmonic resonance.[2]

The cause of this phenomenon is different from that of harmonic resonance phenomena observed in conventional AC power systems. Since the offshore wind turbine is electrically isolated from the onshore grid by an HVDC system, the above phenomenon is considered to have been attributable to the electrical characteristics between the offshore converter and wind turbine generator, which are connected through a 154 kV cable, transformer, and 33 kV cable.

2-3 Power system analysis technologies

We use PSCAD and CPAT as power system analysis tools. They are outlined below.

(1) PSCAD

PSCAD is power system simulation software developed by Manitoba Hydro International Ltd. in Canada, and it is used by more than 1,000 companies and research institutes around the world. Standardly equipped with various components, this software is a visual design tool having an advantage in the analysis of transient phenomena. We use this tool mainly to analyze harmonic resonance.

(2) CPAT

CPAT is an integrated power system analysis tool uniquely developed by the Central Research Institute of the Electric Power Industry. Using CPAT as a base, this research institute also developed CPATFree, which provides limited analysis functions (an analysis tool) and the scale of the grids that can be analyzed. We use CPATFree mainly to analyze voltage rise in long-distance AC cables and reactive power that is created during grid interconnection.

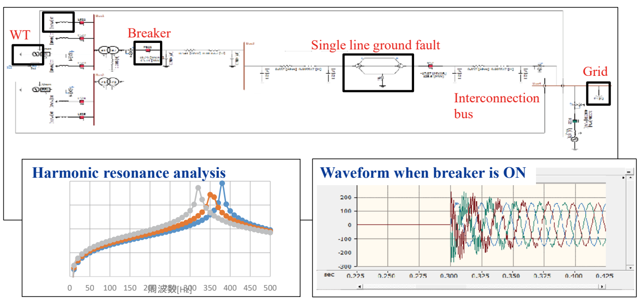

Fig. 4. An example of analysis using PSCAD

2-4 Optimal design of current collection cable layout for wind turbine

In Japan, which is surrounded by the sea, offshore wind power generation is expected to expand in the future. In offshore wind power generation, multiple wind turbines are connected by AC submarine cables to collect the generated power on shore. These AC cables are required to be laid according to a cost-effective design after taking into account the loss due to the reactive current generated in the cables. However, the more the number of wind turbines increases, the more difficult it becomes to design an optimal cable layout. We have developed a current collection cable layout design system that uses an optimization method in order to determine a cable layout that quantitatively minimizes the cost.

In this system, a 33 kV or 66 kV triplex AC submarine cable is used as the current collection cable, and the cable layout is designed after selecting the optimal size from among the conductor sizes of 80 to 1,000 mm^2. The cost of each cable is set according to the conductor size. The objective of the optimization is to minimize the total cost of the current collection cable in the WF. In addition, the transmission capacity of each cable is restricted by reactive current according to the size of the conductor and the length of the cable.

The following is an example of current collection cable layout design for a WF consisting of 25 wind turbines with a rated capacity of 10 MW. The voltage was set at 66 kV. In this example, two types of conductor sizes, 80 and 150 mm^2, were selected. The locations and capacities of the wind turbines can be set for each project. The new design system makes it possible to quantitatively and economically determine the current collection cable layout in a very short time (Fig. 5).

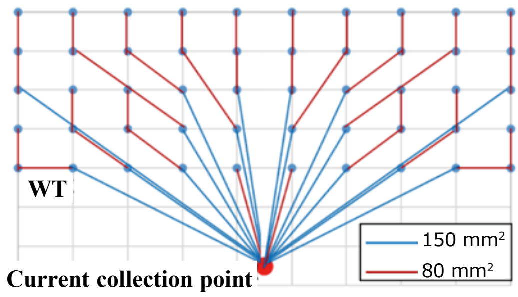

Fig. 5. An example of current collection cable layout design

3. Strengthening Grids Using DC Submarine Transmission Cables

The renewable energy potential of Japan is said to be several tens of gigawatts. About 80% of the above potential is unevenly distributed in Hokkaido, Tohoku, and Kyushu, which are far from large consumption areas, making the power system fragile. Studies have recently begun to solve this problem by directly interconnecting renewable energy generation sites and large consumption areas through DC submarine power transmission cables. In addition, various policy-formulation activities and studies are accelerating in order to achieve carbon neutrality by 2050. In these circumstances, there are high expectations in various quarters for our DC submarine power transmission system design technologies.

In general, the study of cable technology is required at each stage of a submarine power transmission project until the start of construction as shown in Fig. 6. First, a rough system is designed by evaluating the break-even point of DC versus AC based on the transmission capacity and distance, and at the same time, the basic specifications of the project are formulated by planning the submarine cable installation route. The study of basic specifications is an important step to grasp the scale of the submarine cable project, and the study must be evaluated quantitatively and within a short period of time. We assume the role of the technological study of cables at each design stage. This section describes each of the techniques we have developed to evaluate the break-even point in basic specification studies and to optimally design submarine cable routes.

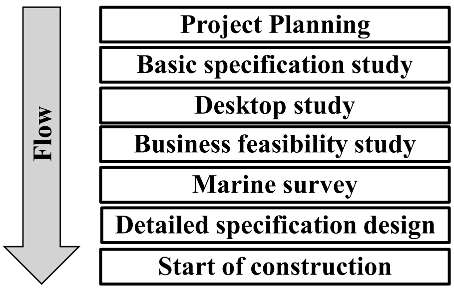

Fig. 6. Work flow until the groundbreaking of a submarine cable project

3-1 Evaluation of the break-even point of DC system versus AC system

There are two options for transmission systems, DC and AC. It is necessary to select either one of the two systems according to the transmission distance, capacity, and other factors. Since DC transmission requires expensive AC-DC converters as shown in Fig. 7, AC transmission is economically advantageous for short transmission distances. However, the loss due to reactive current in the AC cable increases as the transmission distance increases, resulting in the need for installing large-scale phase modifying equipment. Therefore, DC transmission, which does not generate reactive current, becomes advantageous for long-distance transmission. The transmission distance at which the economic advantages of DC and AC are reversed is called the AC-DC break-even point. We have developed a method for quantitatively evaluating the break-even point using an optimization technique.

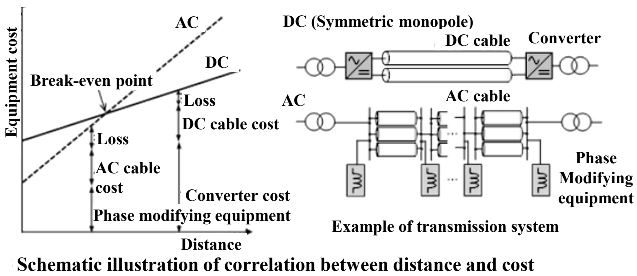

Fig. 7. System comparison between DC and AC transmission

In this study, we designed the lowest cost transmission system for each of WFs having transmission distances of 10, 50, 100, and 150 km by using the optimization technique, and we evaluated the break-even point of each transmission system. The cost to be evaluated was defined as the sum of the yearly equipment installation cost for each transmission system and the transmission loss caused by the cable in a year. The equipment installation cost was determined by adding up the total cost of materials and equipment consisting of a combination of the cables and substation equipment shown in Table 1. For the transmission loss evaluation, the loss caused by the cable was determined after consideration of the WF operation rate and then converted into the amount of electricity sales loss (9 JPY/kWh).

Table 1. Equipment required for each transmission system

Transmission	DC	AC
Transmission voltage	525 kV, 320 kV, 250 kV	275 kV, 154 kV
Conductor size	800, 1200, 1600, 2000, 2500 mm^2	
Transforming equipment	Voltage Source Converter	Phase modifying equipment

Figure 8 shows the results of the break-even point evaluation for a WF whose rated capacity was assumed to be 1,000 MW, and the average yearly operating rate would be 20%. The break-even point for this WF was evaluated to be 50 km. Thus, our quantitative evaluation method makes it possible to evaluate the optimal design of transmission systems after taking into account the operation rate unique to renewable energy fluctuating power sources.[3]

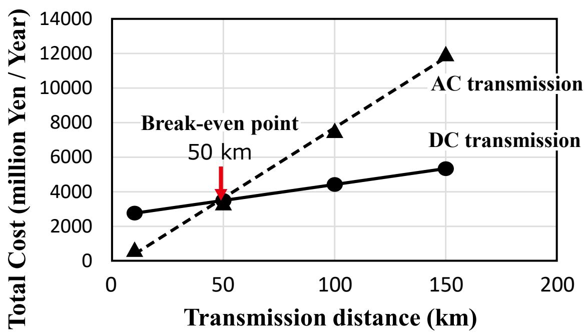

Fig. 8. Relationship between cost and transmission distance

3-2 Optimal design system for submarine cable routes

The construction cost of a submarine transmission line is significantly affected by the marine environmental conditions on the route, and a high level of know-how and a complicated and long-term study are required for the optimal design of the transmission line. We quantitatively evaluated the effects of various marine conditions on the route design and have developed a method for designing submarine transmission routes that minimize the cost.

(1) Construction of marine information database

We constructed a database of major marine environmental information that affects submarine cable route design. Water depth[4] and seabed geology[5] were selected as technological conditions that affect the specifications of the cable and its installation method, while fishery information,[6] harbor district,[7] and military exercise area[8] were selected as restricted area information. These five types of marine information within the Japanese exclusive economic zone were compiled as a visible five-tier architecture database. Each data type was divided into meshes with certain latitude and longitude widths so that each mesh has a square of about 500 m in width. This makes it possible for the database to assure the accuracy of cable route design required in the initial planning stage of a long-distance submarine transmission line construction project.

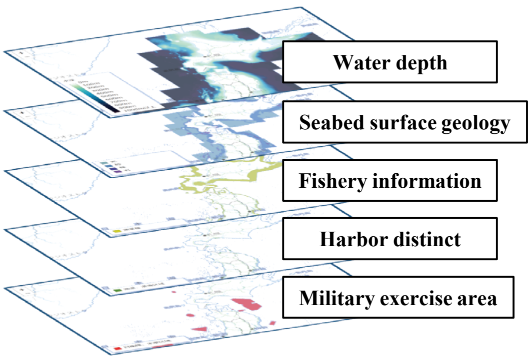

Fig. 9. Marine information database

(2) Cable route design method using optimization technique

We applied a shortest path search method to the submarine cable route design algorithm. In this method, the route capable of minimizing its weight is selected from among multiple routes connecting the start and end points.

The submarine transmission route with the minimum cost is searched by defining the cost of the submarine transmission line as its weight. In particular, the cable material cost, cable installation cost, and ship outfitting cost are weighted based on the data stored in the marine data mesh.

(3) Correlation between marine environmental conditions and submarine line construction cost

The construction cost of a submarine transmission line is calculated by adding up three major costs: cable material cost, installation cost, and outfitting cost. The unit cost of cable materials was set according to the specifications of 500 kV DC cables, the latest technology, based on the maximum amount of renewable energy that would be introduced by the WF. The cable materials were assumed to be armored with a single- or double-layer steel wire depending on the cable tension that increases as the water depth increases. It was assumed that, in a shallow water area, the cable would be protected from external damage caused by fishing gear and anchorage. Specifically, the unit cost of burying the cable was set when the sea bed is sandy, while the unit cost for installing protective pipes was set when the sea bed is rocky. In the case of a deep-sea area, the unit cost of cable installation was set on the assumption that it would be submerged without protection. The outfitting cost refers to the cost of the cable gripping brake unit that produces a gripping force in response to the cable tension that is produced in a deep-sea area, and the cost was calculated to increase in steps according to the cable tension that is produced at the maximum water depth along the cable route.

(4) Development of optimal design system for submarine cable route

We have developed a highly practical submarine cable route design system by uploading the above database, route design algorithm, and cost indicators on a cloud. When the display of each of the five types of data is provided with an ON/OFF function and transparency setting function, the database of the marine environment makes it possible to check the marine environment on the cable route as needed. When two arbitrary points are selected on a map or latitude-longitude coordinates are input, this design system determines the optimal cable route that minimizes the cost of the cable installation between the two points in a few seconds and displays the optimal route on the map. At the same time, the design system calculates the cable length, maximum water depth, and cost. This design system makes it

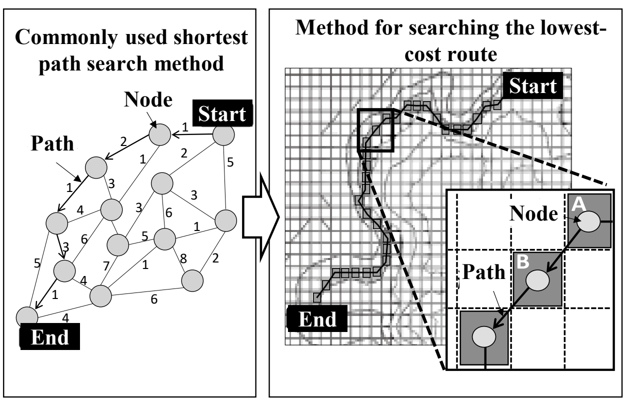

Fig. 10. Transmission route design method that uses optimal path search method

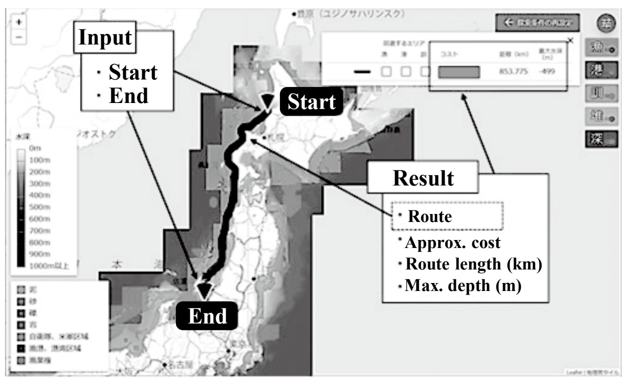

Fig. 11. Optimal design system for submarine cable route

possible to quantitatively design the most economical submarine cable route in a very short time and at low cost, thereby greatly contributing to the business feasibility evaluation of a submarine cable line in the initial stage of the project.[9] In addition, we are considering to upgrade this design system so that it can take into account transmission loss.

3-3 Survey of submarine transmission cable route

In order to determine the actual cable installation route based on the route outlined by the optimum design system, a desktop study and a marine survey on a research vessel are conducted. The objectives of the desktop study are to determine the marine survey route and to improve the accuracy of submarine transmission line construction cost, both of which require a high level of know-how on the design and installation of submarine cables. In the desktop study, a large amount of marine information, such as detailed seafloor topography, water depth, and fishing activities issued by various organizations, is collected and analyzed in order to obtain a feasible and economical submarine route, the cable installation method, and material specifications. Through the desktop study, the cost and construction period of the submarine transmission line are concretized, making it possible to concretely envisage the project plan and feasibility.

The marine survey is the final survey conducted before the construction of the submarine transmission line. Based on the results of the desktop study, a survey vessel cruises the entire cable route to investigate in detail the actual distribution of the seabed structure, the unevenness of the seabed, and so on, thereby making it possible to determine the route of the submarine cable and its construction and material specifications after taking into account the economic efficiency, feasibility, and risk of the project. Based on the results of this survey, the cost and construction period of the submarine transmission line are clarified, allowing the construction to start.

These surveys require a high level of know-how and experience in the entire process, from design to manufacturing and installation of submarine cables. We are a world's leading cable manufacturer having a proven track record in designing, manufacturing, and installing submarine transmission cables in Japan and overseas.

3-4 Multi-terminal DC submarine transmission system

In Japan, a long and narrow island country surrounded by deep sea, many large-scale offshore WFs are expected to be constructed in a row along the coast, unlike those constructed in the shallow and wide area of the North Sea in Europe. In the present situation where the interconnection of WFs to existing trunk power transmission lines is restricted, it is considered reasonable to c ollect the electricity from WFs and convert it to DC at multiple substations and transmit it to demand areas.

Such a DC transmission system connecting three or more points is called a multi-terminal offshore DC transmission system (Fig. 12), as opposed to the conventional DC transmission system connecting two points.

In Japan, the New Energy and Industrial Technology Development Organization (NEDO) launched in 2015 a five-year project titled "Development of a Next-Generation Offshore DC Transmission System" in preparation of upcoming large-scale introduction of offshore wind power. In this project, R&D activities were promoted under an industry-academia collaboration. The University of Tokyo, Tokyo Electric Power Company Holdings, Inc., and TEPCO Power Grid, Inc. played a central role. We participated in this project to establish cable design technology best suited for wind power, to fabricate and evaluate a prototype of cable, and to develop an intercompany joint and cable installation method (Photo 1 and Fig. 13).

When constructing a large-scale DC transmission line with multiple terminals, it is important from the viewpoint of minimizing the construction cost and period to introduce a multi-vendor system which combines converters and submarine cables of multiple manufacturers. However, since the design concept of DC cable insulation material differs from manufacturer to manufacturer, jointing cables

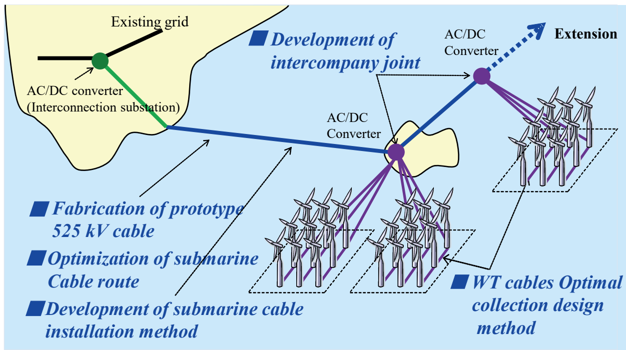

Fig. 12. Schematic illustration of a multi-terminal DC submarine transmission system


Photo 1. A prototype of 525 kV DC submarine cable

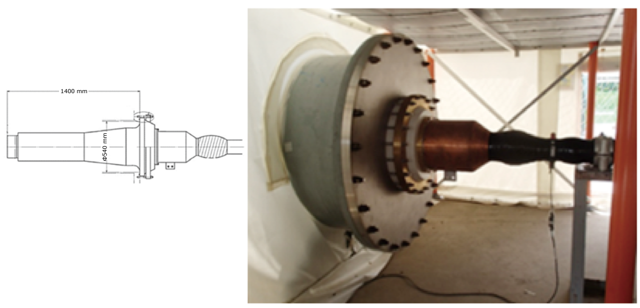
Fig. 13. Testing of 525 kV DC cable and intercompany joint

of different companies is generally unacceptable, and this has restricted multiple companies from jointly constructing a transmission line. To remove this restriction, we have developed a technology that can joint cables of different companies by combining gas immersed termination (EB-G).(10),(11) In addition, through this development project, we have been promoting the evaluation of a prototype of the world's most advanced 525 kV DC submarine cable and the development of high-speed cable installation technology necessary to minimize long-distance cable installation costs. We will utilize the results of the above activities to realize DC submarine grids, which are expected to expand in the near future.

4. Conclusion

Power transmission systems will significantly change in the future as the use of renewable energy further expands worldwide. In such a situation, it is necessary to establish and institutionalize an efficient design concept for all grids, instead of optimizing the grid interconnection of individual renewable energy sites. In addition, in order to deliver unevenly distributed renewable energy potential to distant demand areas, DC submarine transmission lines are expected to play an important role in the grid master plan that is currently under discussion. We are prepared to contribute to the popularization and expansion of renewable energy by using our advanced technologies and products.

The development results described in Section 2-4 and subsequent sections were mainly obtained from the research study commissioned by NEDO. We advanced this commissioned study under the guidance of Messrs. Yokoyama and Baba, both of whom are professors at the University of Tokyo. We would like to take this opportunity to express our gratitude to all individuals concerned.

- PSCAD is a trademark or registered trademark of Manitoba Hydro International Ltd., in Canada.
- CPAT and CPATFree are trademarks or registered trademarks of the Central Research Institute of the Electric Power Industry.

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