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FEATURED TOPIC

Technical Development of Cable Installation and Monitoring for the Construction of Japan's High Voltage Direct Current (HVDC) Submarine Transmission Networks

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As global carbon neutrality and large-scale renewable energy development progress, the establishment of long-distance transmission networks to transmit electricity to remote demand areas is rapidly advancing. In Japan, plans for a long-term and large-scale High Voltage Direct Current (HVDC) submarine transmission network from northern Japan to the Tokyo metropolitan area have been outlined. Anticipating this trend, the New Energy and Industrial Technology Development Organization (NEDO) has been continuously engaged in the development of HVDC submarine technology since the fiscal year 2015, and our company has also participated in this effort. Now that the plans for direct current submarine transmission have become more concrete, this paper reviews the development history and considers the prospects for applications in future practical projects and further developments.

Keywords: HVDC submarine cable, protection method, cable-laying vessel, submarine route design

1. Introduction

In line with the recent global trend toward carbon neutrality, large-scale renewable energy development is advancing, and the construction of long-distance transmission networks to deliver this power to demand centers is rapidly progressing. In Japan as well, the future vision for transmission network construction has been outlined in the "Master Plan for Wide-Area Interconnection Systems" by the Organization for Cross-Regional Coordination of Transmission Operators, including long-distance High Voltage Direct Current (HVDC) submarine transmission from northern Japan, which has favorable wind conditions, to the Tokyo metropolitan area.

Considering this global trend and the promotion of DC submarine transmission within Japan, the New Energy and Industrial Technology Development Organization (NEDO) has been conducting technological development related to HVDC submarine transmission since fiscal year 2015, and our company has been participating in this effort. Now that domestic DC submarine transmission plans have materialized, we report on the development history and significance to date, the status of ongoing cable protection methods and self-propelled cable-laying vessel development, and consider future applications in actual projects and future prospects.

2. NEDO HVDC Technology Development

2-1 Development history

Table 1 shows our company's history of HVDC technology development within NEDO over the past approximately 10 years since fiscal year 2015. Although domestic HVDC submarine transmission plans had not yet materialized initially, anticipating near-term domestic application based on global trends, the "NEDO Next-Generation Offshore HVDC Submarine Transmission System Development Project" commenced in fiscal year 2015 as a five-year initiative. Furthermore, in 2020, as a successor project addressing challenges related to deep-sea conditions—a uniquely domestic issue that had come to the forefront—we conducted "Deep-Sea Cable Development" within the "Research and Development of a Multi-Purpose and Multi-Terminal HIGH Voltage Direct Current Transmission System (RIGHT Project)." Furthermore, when the national policy for a HVDC submarine transmission plan between Hokkaido and the Tokyo metropolitan area materialized in 2021, a feasibility study (FS) for HVDC submarine transmission between Hokkaido and the Tokyo metropolitan

Table 1. Trajectory of our DC technology development at NEDO

Item		Next-generation offshore HVDC	Multi-terminal	
			Deep-sea cable	Protection/vessels
		FY2015–FY2019	FY2020–2023	FY2023–2025
Cable		- 525kV cable prototype - Factory Joint Inter-Manufacture connection	- Deep-sea cable development (3-core, 500 m water depth) - Mechanical testing equipment (Tensile bending)	-
Construction method		- High-speed protection pipe laying (model)	- Cable Laying vessel concept design	- Impact resistance testing / selection - High-speed protection pipe laying (actual equipment) - Laying control method - Laying vessel design: (at NYK)
System	Route design	- Seabed database - Optimal route design algorithm (joint research with Professor Baba, the University of Tokyo)	- Submarine database expansion	Submarine database expansion Integrated information system (Route design, construction, and maintenance)
	Long-distance monitoring	-	-	Long-distance optical monitoring

area was conducted as part of the “Survey on the Construction and Operation of HVDC Transmission Systems from Offshore Wind Power, etc.” Subsequently, starting in fiscal year 2023, the “Development of Cable Protection Methods and Foundational Technologies for Advanced Cable-Laying Vessels” (Development of Protection Methods, Cable-Laying Vessels, and Others) was launched. Development is currently progressing systematically and vigorously.

2-2 Need for new development

Through previous investigations and development, it became clear that, unlike the North Sea in Europe, Japan’s deep-water areas feature numerous exposed rock formations on the seabed and that protecting these exposed rock areas requires extremely long periods and high costs. Based on this, there was strong demand from various sectors for the development of methods to perform protection work quickly and at low cost. Furthermore, Japan has never had long-distance submarine power transmission systems that span hundreds of kilometers, and the absence of large self-propelled cable-laying vessels capable of such layings was identified as a major challenge in project planning.

To address these challenges, development of new protection methods and cable-laying vessels commenced in FY2023 as part of the “Research and Development of a Multi-Purpose and Multi-Terminal HIGH Voltage Direct Current Transmission System (RIGHT Project),” a three-year initiative. The plan is to develop methods such as high-speed attachment of protection pipes to cables on cable-laying vessels, aiming for a 20% cost reduction and shorter construction period compared to existing methods. Concurrently, through the basic design of self-propelled cable-laying vessels and other equipment necessary for laying high-capacity, long-distance submarine HVDC transmission cables, the project aims to establish common specifications.

The four companies selected for this development are our company as the lead organization, Furukawa Electric Co., Ltd., Nippon Yusen Kabushiki Kaisha (NYK), and Mitsui O.S.K. Lines, Ltd. (MOL). Development will proceed through cross-industry collaboration and division of work between major cable manufacturers possessing cable installation expertise and major shipping companies possessing vessel design and operation expertise. The development responsibilities of each company are shown in Table 2.

3. Development of Protection Methods, Laying Vessels, and Others

Our company is responsible for developing methods for high-speed laying of cable protection pipes on vessels, conducting marine technology verification, developing self-propelled large cable-laying vessels in collaboration with shipping companies, and developing long-distance cable monitoring and submarine cable information integration systems. This chapter reports on the background, efforts, and outcomes of each development.

3-1 Development of high-speed protection pipe laying method

Seabed surveys revealed that Japan’s seabed geology, particularly in the northern Japan Sea region, has limited sandy areas suitable for burial, with exposed rock formations being predominant. Since burial is impossible on exposed rock, a method exists where crushed stone is placed over the cable for long distances. However, protecting extremely long distances of several hundred kilometers presents significant challenges in terms of cost, construction period, and procurement. Additionally, as a method offering lower cost and shorter delivery times than crushed stone protection, a protection pipe method has been adopted where split protection pipes are continuously attached to the cable onboard the vessel. However, even with this simplified protection pipe method, conventional practices required bolting or securing the split protection pipes with metal bands onboard, necessitating frequent stops in the laying process. This resulted in slow laying speeds, extended project durations, and high costs.

Therefore, to enable high-speed protection pipe laying onboard, we developed a protection pipe with a simple snap-fit mechanism for automatic engagement. We also developed onboard equipment that semi-automatically loads the protection pipe and uses rollers for automatic crimping and assemble. For this development, we first evaluated five types of resin protection pipes from domestic and international sources using a 1/5 scale model (Photo 1). We then conducted verification tests on a full-scale model (Photo 2) on land. The results confirmed that

Table 2. Development theme allocation by company

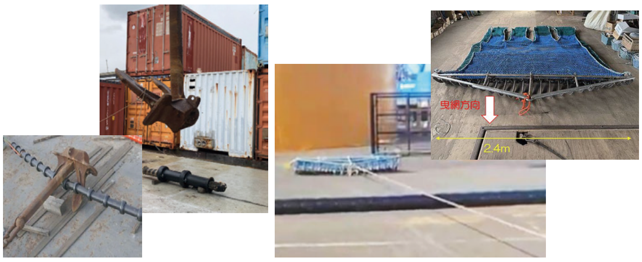
Themes			Responsibility
Development of cable protection pipe laying method	Development of protection methods	Protection pipe construction methods	Sumitomo Electric
		Deep sea rock instration methods	Furukawa Electric
	Development of long-distance cable monitoring technology		Sumitomo Electric
	Marine technology verification		Sumitomo Electric Furukawa Electric
Development of foundational technologies for cable-laying vessels	Cable laying vessels		NYK Sumitomo Electric
	Jointing Vessel / Burial Vessel		MOL Furukawa Electric
Common foundational technology research	Test method review		Furukawa Electric Sumitomo Electric
	Overseas research		Sumitomo Electric

Photo 1. High-speed laying of protection pipe 1/5 scale model

Photo 2. High-speed protection pipe laying, actual model

continuous operation is possible even with the protection pipes installed, and we gained confidence in achieving a laying speed of approximately 10 m/min, comparable to sandy seabed.

Furthermore, submarine cables are anticipated to be subject to damage from ship anchors and fishing tools during fishing activities. Therefore, an anchor drop test was conducted to evaluate the protection pipe's resistance to anchor impact, assessing its damage resistance performance. Regarding fishing tools, we surveyed fishing methods and tools used in various sea areas within Japan and conducted risk assessments. We identified "bottom trawls" and "trawls otter boards "as fishing methods and tools that could pose risks to submarine cables. Using actual samples of each tool type, we conducted onshore tests evaluating cable crossing and the presence or absence of damage. We confirmed that fishing tools generally do not cause significant damage or snagging when crossing over the cable, but further evaluation is under consideration (Photo 3).



Anchor drop test

Dragging anchor test

Fishing Equipment damage test

Photo 3. Cable damage test by anchor / bottom trawl tool

The outcomes of these protection method developments are expected to contribute to determining protection measures for each sea area in actual projects.

3-2 Marine technology verification

Conventional cable laying has been performed using tension management based on information from onboard sensors such as the angle of entry sensor to prevent defects like kinks. However, in recent years, overseas, laying management systems have been put into practical use. These systems consider even the possibility of cables being swept away by tidal currents and ocean currents. They integrate various sensors and ocean information to perform real-time linear calculations, thereby controlling the laying equipment to lay the cable with high precision at the designated location.

Anticipating future demands for precise cable positioning in areas like exposed rock formations, an ocean technology verification was conducted off Awaji Island. This involved using an existing cable-laying barge and the latest laying management system to verify laying accuracy (Fig. 1). Through this verification, it was confirmed that laying position accuracy within a few meters on the seabed surface is achievable. Furthermore, prospects for applying this system to actual projects were established.

Layback 29 m
Vert Top Angle 78.1 deg
Bot Tension 545 258 kg-f
Cable Off Path -7 m

Model Current East 0.97 knot
Model Current North 0.97 knot

Fig. 1. Laying management system for marine technology verification

3-3 Development of self-propelled large cable-laying vessel

The development of a self-propelled large cable-laying vessel, which does not currently exist domestically, is estimated to take 5 to 6 years from design to operational commencement. However, starting design only after securing an actual project order is likely to result in missing the deadline for the actual laying. Furthermore, a dedicated design optimized for Japan's unique water depth, seabed conditions (protection), and port conditions is desirable. However, while our company possesses design and operational experience with conventional barge-type cable laying vessels towed by tugboats, we lack expertise in the complex design, operation, and regulations of self-propelled vessels. Therefore, we established a development framework in collaboration with NYK, which possesses this expertise and track record.

First, in fiscal year 2022, our company established the basic specifications and commissioned NYK to perform the conceptual design. We advanced the conceptual design with the cooperation of a shipyard with proven experience in designing and building the latest self-propelled cable-laying vessels in Europe. Starting in fiscal year 2023, we established a development framework with NYK as the lead and our company providing support. The conceptual design was completed in fiscal year 2024, and we obtained Approval in Principle (AiP) from the Nippon Kaiji Kyokai

(ClassNK). The subsequent basic design is currently underway and is scheduled for completion within fiscal year 2025. This cable-laying vessel will be the maximum size feasible given depth constraints at domestic submarine cable factories. It will be capable of loading and laying a single string of submarine cable weighing 7,000 tons / approximately 80 km, while also featuring a structure capable of carrying the large quantities of protection pipe anticipated for long-distance projects within Japan. It will also feature a dynamic positioning system using various thrusters on the hull bottom and GPS for precise station keeping, along with the latest highly automated laying equipment. Furthermore, it is designed as a multi-purpose vessel capable not only of laying but also of offshore connection / repair and offshore wind power applications. This aims to enhance profitability through improved vessel utilization rates and facilitate its introduction.

Furthermore, for long-distance submarine power transmission, dedicated vessels are expected to share the functions of "laying," "connecting," and "burying" to shorten the construction period. Development of each vessel is proceeding in parallel according to the division of labor among the four companies.


From NYK's public materials

Fig. 2. Conceptual design example of a s large cable-laying vessel

3-4 Development of long-distance monitoring technology and submarine cable integrated information system

Maintenance and monitoring of the long-distance submarine cable, spanning approximately 800 km from Hokkaido to Niigata and totaling 2,400 km in length across positive, negative, and neutral conductors, are critical development items for long-distance submarine power transmission as a core power infrastructure.

Traditionally, optical fibers have been integrated into submarine power cables, enabling not only communication but also monitoring of distributed temperature sensing (DTS) via scattered light from pulsed laser injection and strain caused by external damage, measured by an optical time domain reflectometer (OTDR). Furthermore, distributed acoustic sensing (DAS) using optical fibers has recently become practical, enabling even higher precision and more advanced measurements. However, due to the attenuation of pulsed laser light within the optical fiber, the maximum measurable length was previously limited to approximately 100 km. Yet, for the currently envisioned Sea of Japan route, the longest span between Hokkaido and Akita is about 500 km. This creates an undetectable section of over 300 km near the center, starting from the 100-km limits at both ends.

To overcome this challenge and extend the measurement distance, installing repeaters used in intercontinental optical submarine communication cables is a possible solution. However, repeaters require co-laying separate power cables for electricity supply. If insulation failure occurs in the HVDC cable due to external damage, the resulting high-voltage surge is highly likely to damage the repeater. To address this issue, we developed an optical excitation method that injects optical energy into the repeater via a separate optical fiber distinct from the one used for measurement, thereby supplying the repeater's power.

Through bench tests using dummy optical fibers and marine technology verification using actual cables for some sections, we confirmed that this development enables extension of the measurement length up to 260 km. This provides a clear path toward realizing full-length optical fiber monitoring between Hokkaido and Akita.

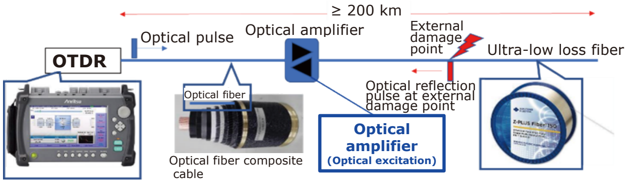


Fig. 3. Optical fiber long-distance monitoring system

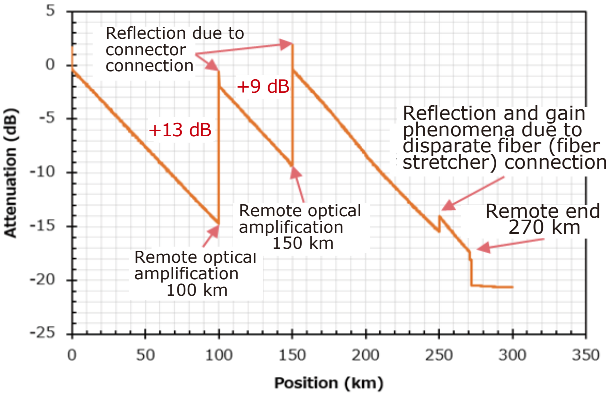


Fig. 4. Example of measurement results (0–270 km)

Furthermore, in 2018, our company collaborated with Professor Baba of the University of Tokyo to jointly develop a submarine cable route optimization calculation system. This system integrates a 10-layer seabed database containing oceanographic information (water depth, seabed geology, and subsea structures) and socio-activity information (fishing data) with an optimization algorithm to rapidly and simply calculate routes essential for initial route FS. However, recent route FS for the Hokkaido-Niigata and marine survey data collected by the Agency for Natural Resources and Energy, along with the detailed route evaluations conducted using this data, revealed a need for additional information and higher mesh resolution. Furthermore, there is also an expectation to integrate not only route design information but also the data required for construction and maintenance monitoring.

Therefore, based on the existing submarine cable route optimization system, we decided to develop an integrated submarine cable information system. This system expands the database to approximately 20 layers by adding hazard information, seabed slope angle data essential for determining cable laying feasibility, and navigation route information needed for external damage risk assessment. Furthermore, it is difficult to interrupt the laying process due to bad weather once it begins, so the system integrates the latest oceanographic and meteorological forecasts up to 10 days ahead, which are necessary for the decision to commence laying, automatic identification system (AIS) information to identify vessels involved in external damage caused by anchor-dragging or other incidents, and the aforementioned optical fiber monitoring information.

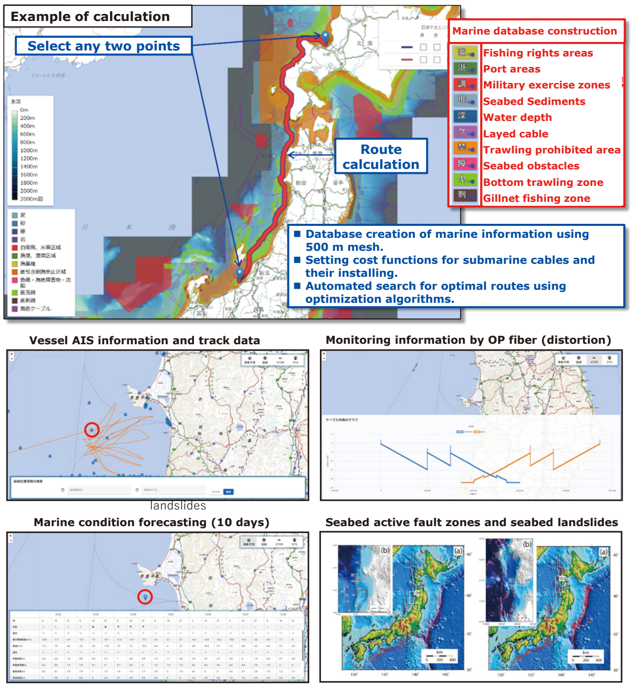


Fig. 5. Submarine cable integrated information system

3-5 Future development outlook

While development has primarily focused on the construction phase thus far, future technological development is anticipated to center on enhancing maintenance and operation after construction. How can we ensure highly reliable maintenance and monitoring for the operation of the 800 km × 3 strands (positive, negative, neutral) submarine cable, totaling 2,400 km?

In recent years, the application of autonomous underwater vehicles (AUVs) to subsea infrastructure has begun. Research and development are underway for an automated subsea cable tracking system aimed at deploying cruising-type AUVs, enabling high-speed, low-cost monitoring of the entire cable length. Furthermore, amid recent reports overseas of repeated incidents where ships with AIS turned off have damaged submarine cables by drugging the anchor, feasibility studies are underway to develop ship monitoring systems using satellite imagery and underwater acoustics, combined with AI for ship identification, from a risk management and deterrence perspective.

Thus, submarine cables are evolving beyond mere power transmission. They are transforming into advanced network systems by integrating various sensing technologies into solutions that enable highly reliable operation and maintenance.

4. Conclusion

Our development of approximately ten years under the NEDO projects has been incorporated into our company’s technology development plan and has yielded the initially anticipated results. Furthermore, we believe these development outcomes have played a designated role in the concrete planning and composition of the ongoing domestic HVDC submarine power transmission project by being incorporated into it in a timely manner. Furthermore, the cross-industry and industry-government-academia collaboration efforts in each NEDO development project are considered to have provided important background for the current formation of the domestic HVDC submarine transmission plan. Going forward, we will advance further technological development to ensure the steady realization of the domestic HVDC submarine transmission plan, while anticipating its expansion globally, including into the Asian region.

(This achievement resulted from work commissioned by NEDO.)

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