Characteristics of Water Tree in Submarine Cables (Wet-Design) for Offshore Wind Power Generation -Consideration of long-term water tree testing method-

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As wind turbines grow in size and output capacity, submarine cables transmitting the generated electric power face challenges related to manufacturability, cost, and workability. To overcome these challenges, we have been developing submarine cables without the impervious structure. However, it is difficult to estimate cable life due to the progression of water tree deterioration in flooded cable insulation. To evaluate the cable life of non-impermeable structure, we examined a long-term water tree test method capable of simulating 30 years of operation. By analyzing the time variation of supersaturated moisture content in cable insulation, realistic test periods can be achieved. Future endeavors involve the development of water-tree-resistant cables to withstand long-term operation and high pressures on actual lines, utilizing the test method.

Keywords: water-tree resistance, cohesive moisture, saturated moisture content, long-term service life, submerged voltage endurance test method

1. Introduction

Countries around the world are making efforts to reduce greenhouse gas emissions. The European Commission has set a goal of reducing greenhouse gas emissions by 55% from the 1990 level by 2030. Meanwhile, Japan aims to reduce greenhouse gas emissions by 46% from the FY2013 level by FY2030, and it has also declared “2050 Carbon Neutrality” to reduce the country’s overall greenhouse gas emissions to zero by 2050.(1) The Green Growth Strategy towards this declaration relies mainly on decarbonization in the electricity sector through maximizing the introduction of renewable energy, especially offshore wind power. Thus, offshore wind power will certainly increase its importance in the future.

Sumitomo Electric Industries, Ltd. believes that, with the future trend of offshore wind power generation in mind, the importance of power cables for transmitting generated electricity will increase inevitably. Therefore, we have promoted a new power cable that can overcome the problems relating to the manufacturability, cost, and ease of installation of conventional submarine cables for offshore wind power generation. This cable is constructed of a water-tree-resistant insulator and eliminates the need for an impermeable structure.(2)

On the other hand, there are many unsolved problems regarding the service life of cables having no impermeable structure since they accelerate degradation called water-tree degradation, which will be described later, when submerged in water. However, in the development of a new power cable that will undertake a key role in the electricity infrastructure, estimating its service life is essential. In this study, we have established a test method for evaluating the service life of submarine cables of a non-impermeable structure that are expected to be operated for a long period in actual transmission lines. This paper discusses the results of the establishment.

2. Growth of Water Trees in Submarine Cables of Non-impermeable Structure

The insulator of non-impermeable submarine cables is continually infiltrated with water, and degradation called water-tree degradation progresses inside the insulator (Fig. 1). Accordingly, it is important to evaluate the long-term water-tree resistance of these cables.

There are various views on the generation and growth mechanisms of water trees. In general, when a cable is continually exposed to a certain voltage in a humid atmosphere, water trees grow from small foreign particles, voids, protrusions, and other parts in the insulator.(2) If water trees grow in the insulator, they will become local defects and cause the cable to dielectrically break down at

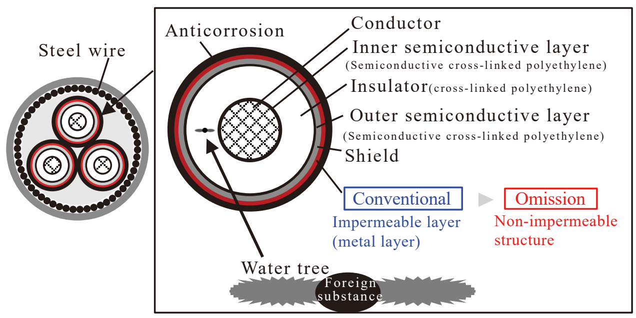

Fig. 1. Non-impermeable submarine cable and water tree

the operating voltage.[3] We have been studying to create a water-tree-resistant insulator that enables the development of a non-impermeable submarine cable.

3. Study of Long-term Water-tree Test Method

In our study of water-tree-resistant insulators, we have evaluated their water-tree characteristics by subjecting prototype cables to various submerged voltage endurance tests. For example, in the past, we carried out submerged voltage endurance tests in accordance with the CIGRE TB722 RegimeB test condition and our original "stress test" condition, both of which are shown in Table 1. Figure 2 shows the relationship between the maximum water-tree length and test time obtained by testing cables composed of the same type of insulator under each of the test conditions shown in Table 1. It has already been confirmed that the trend of water-tree growth differs depending on the test condition as shown in Fig. 2.[2]

Table 1. Submerged voltage endurance test conditions

Item		CIGRE TB722 RegimeB	Stress test
Electric field		6.4 kV/mm (500 Hz)	4 kV/mm (50 Hz)
Water quality		Seawater	Tap water
Submerging condition	Submerging method	Submerging in seawater introduced from outside	Conductor/ submerging in tap water introduced from outside
	Temperature application method	External heating	External heating
		40°C constant after pretreatment at 55°C/500 h	Heat cycle of RT ⇋ 60°C per day
Voltage application time		125 days	180 days

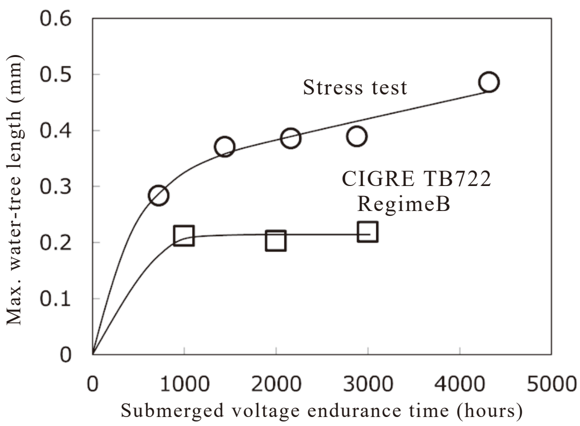

Fig. 2. Relationship between submerged voltage endurance test condition and maximum growth length of water tree

Various test conditions are used to evaluate the submerged voltage endurance of cables. The test condition most suitable for evaluating the long-term water-tree resistance of cables is the one capable of simulating the condition of the actual transmission line in which the cables are operated. Meanwhile, the long-term growth behavior of water trees in actual transmission lines has not yet been clarified, and, including the tests shown in Table 1, the test method capable of evaluating the long-term operability of cables in the actual transmission lines has not been established until today.

For the above-described stress test, increased water supply to the test insulator has been specified to make the growth of water trees severe to the insulator, on the basis of the past test results that the growth of water trees an insulator is generally correlated with the insulator's moisture content. As a result, it has been confirmed that the water trees tend to grow longer under the stress test condition than under the CIGRE TB722 RegimeB condition, as expected. Moisture in an insulator is considered to be composed of water vapor attributable to the humidity in the insulator and condensed moisture (hereafter referred to as "supersaturated moisture") that is generated when water vapor is supersaturated due to a heat cycle or other cause. There is a paper reporting that the presence of supersaturated moisture accelerates the growth of water trees.[4] Although it is unlikely that supersaturated moisture in a liquid state is generated in minute areas of a crystal size in the insulating resin, it is easy to estimate that supersaturated moisture is generated in the voids in the insulator. For example, when a void was created in a cross-linked polyethylene sheet, which is used as the insulator for a general-purpose power cable, and a heat cycle was applied to the sheet under a submerged condition, the generation of supersaturated moisture in the void was observed as shown in Photo 1.

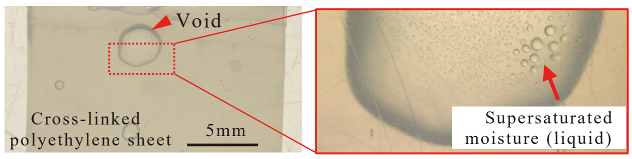

Photo 1. Supersaturated moisture generated in a void in a cross-linked polyethylene sheet

This result suggests that supersaturated moisture is generated and accumulates in water trees that are considered to be the aggregates of micro-voids, and it is consistent with the correlation between the growth of water trees and moisture content. Further, this result is also consistent with the significant growth of water trees that was observed when the stress test was conducted under a heat cycle condition, as shown in Fig. 2. Therefore, the difference in the growth characteristics of water trees is considered to be dominantly affected by the difference in the supersaturated moisture content of the insulator.

Based on the above, we focused on the supersaturated moisture content of the insulator to establish a long-term water-tree test method that can simulate the long-term operation of power cables in actual transmission lines.

3-1 Analysis of the moisture content of insulator: under actual transmission line condition

We considered that if it is possible to realize a test cable containing the same amount of supersaturated moisture as that in a cable that is degraded due to long-term operation in an actual transmission line, this test cable can be deemed as one that simulates the degradation of actual transmission lines at an accelerated pace.

In this study, we first conducted a CAE analysis of the change with time of the supersaturated moisture content of an insulator under a possible actual transmission line condition. In particular, a 66 kV class cable of a non-impermeable structure was analyzed with CAE analysis software (COMSOL Multiphysics) on the assumption that this cable was submersed in water. The conditions shown in Table 2 were used as an example of possible actual transmission line conditions. In addition, the analysis was conducted using a diffusion equation and considering the cross-sectional shape of the cable. Further, the inner layer of the insulator was chosen for the analysis since this layer maximizes the electric field when the cable is in operation and increases the severity of the analysis condition to the water-tree resistance of the cable.

Table 2. An example of actual transmission line condition for array cables

Temperature of the cable conductor	Ambient temperature of the cable	Other
The heat cycle conditions were established based on the assumption that the temperature of the cable conductor varied between 60°C and 90°C due to the load fluctuation attributed to wind conditions with wind power generation, and that the temperature fluctuated alternately in one week.	The temperature of the sea water, which was away from the array cable, was considered to be constant (base temperature: 25°C), but the temperature of the sea water near the cable was considered to change due to the load fluctuation.	The shutdown period due to inspection of the wind turbine and other factors was considered to be the no-load condition (with the conductor temperature dropping to the base temperature).

The analysis results are shown in Fig. 3. This figure shows the saturated water vapor content of the insulator (the maximum amount of water vapor that can be contained in the insulator), which changes in response to the conductor temperature heat cycle, and the change with time of the amount of water vapor that permeates the inner layer of the insulator. It can be seen from this figure that, depending on the operating condition of the cable, the water vapor content of the inner layer exceeds the saturated water vapor content, and this results in the production of supersaturated moisture.

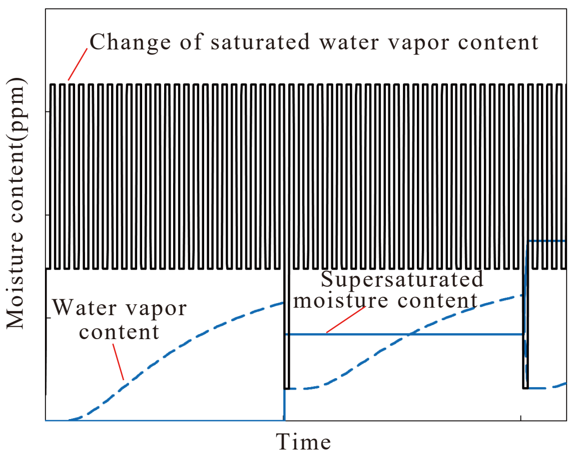

Fig. 3. Supersaturated moisture content of insulator's inner layer: actual transmission line condition

When only the change in supersaturated moisture content during 30 years was analyzed on the basis of the results shown in Fig. 3, the results showed that, under the actual transmission line condition assumed in Table 2, the generation of water trees ranged from several tens to 100 ppm per year. However, the number of water trees generated in actual transmission line cables during their long-term aging tends to saturate even after they were maintained under a severe installation condition. Therefore, it is considered that the amount of supersaturated moisture that can accumulate in a water tree is limited.

3-2 Analysis of the moisture content of insulator: each test condition

For the tests shown in Table 1, the change with time of supersaturated moisture content during each test was analyzed for cables of different structures (CIGRE TB722 RegimeB: 11 kV class; stress test: 6.6 kV class) on the assumption that they were submerged under each condition shown in the table. The analysis results for the CIGRE TB722 RegimeB test cable are shown in Fig. 4. This figure shows that the water vapor content increased during the test, but supersaturated moisture was not generated. The reason is that a heat cycle is not defined in the test condition.

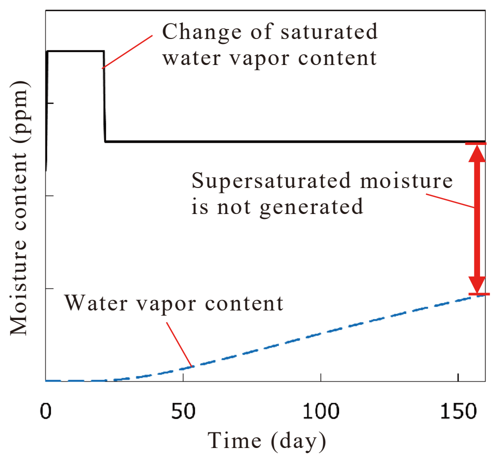

Fig. 4. Supersaturated moisture content of insulator's inner layer: CIGRE TB722 RegimeB

Subsequently, the results of analysis under the stress test condition are shown in Fig. 5. Since the stress test condition requires the application of a heat cycle as shown in Table 1, supersaturated moisture was generated (approximately 40 ppm at the end of the test). The total amount of the supersaturated moisture was nearly equal to the minimum amount that was expected to reach in one year under the actual transmission line condition that had been assumed, indicating that the analysis did not appropriately simulate an actual transmission line condition. This would be probably because that the heat cycle condition was not suitable for the generation of supersaturated moisture and the high-temperature retention time was insufficient.

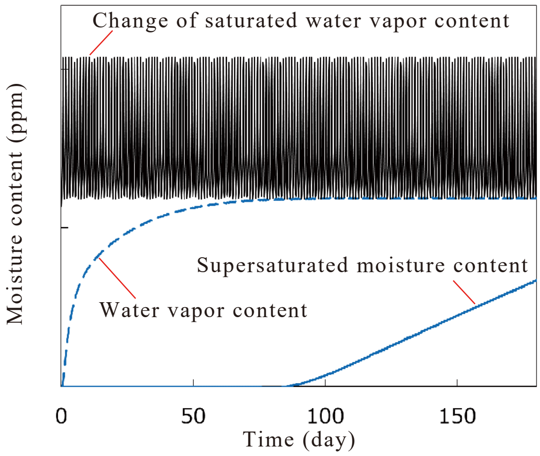

Fig. 5. Supersaturated moisture content of insulator's middle and inner layers (stress test)

The above analysis results suggest that the accumulation of saturated moisture is greater under the actual transmission line condition than under each of the test conditions and that the former condition is severe for testing the growth of water trees due to the effect of supersaturated moisture.

3-3 Condition for long-term water-tree test

As described above, each of the test conditions shown in Table 1 may not be suitable for simulating the growth of water trees in actual transmission lines. To address this problem, we worked to establish a test method that can simulate the growth of water trees during 30-year long-term operation of actual transmission lines. The test condition for the new test method must enable the measurement of supersaturated moisture content nearly equal to that of actual transmission lines.

The volume of the insulator of the cables used in actual transmission lines is limited. Cross-linked polystyrene contains molecular chains composed of carbon, hydrogen, and other substances, and these molecular chains can only exist in the free volume of the insulator as water molecules. Since supersaturated moisture is in a liquid state, the place where it can exist in the insulator is further limited. Therefore, it is considered that the amount of supersaturated moisture that can accumulate is limited. Since supersaturated moisture accumulates in the microvoids in water trees, as has already been described, the amount of supersaturated moisture ranges from 200 to 600 ppm when estimated from the density of water trees grown in the insulator of a cable during its 30-year long-term operation in a submerged actual transmission line (our actual measurement values). Therefore, the upper limit of the amount of supersaturated moisture a cable can contain during its operation for 30 years is considered to be approximately 600 ppm. In the study for establishment of the new test condition, the upper limit of the accumulation of supersaturated moisture was determined to be 900 ppm after considering a surplus ratio (1.5) to approximately 600 ppm, the content that was estimated above on the assumption that the transmission line was operated for 30 years. Then, an analysis was conducted to determine a heat cycle condition that makes it possible to achieve a supersaturated moisture content of 900 ppm within a reasonable test time.

Figure 6 shows a graph of the time until the limit content of 900 ppm is reached under the test condition studied, the actual transmission line condition, and the test conditions shown in Table 1. In the case of the test conditions shown in Table 1, supersaturated moisture was not generated under the CIGRE TB722 RegimeB condition, as has already been described. The limit content was not reached under the stress test condition. It was also found that, under the actual transmission line condition, the limit content is reached after approximately 11 years. In contrast, under the test condition examined in this study, the limit content was reached in approximately 90 days. These results suggest that, when supersaturated moisture content is considered to dominantly affect the growth of water trees, evaluation of the water-tree resistance of cables under a simulated actual transmission line condition can be performed within a relatively short time by setting an appropriate heat cycle condition.

Accordingly, this long-term water-tree test method makes it possible to evaluate the water-tree resistance of cables by simulating their operation for 30 years in actual transmission lines within a reasonable test time.

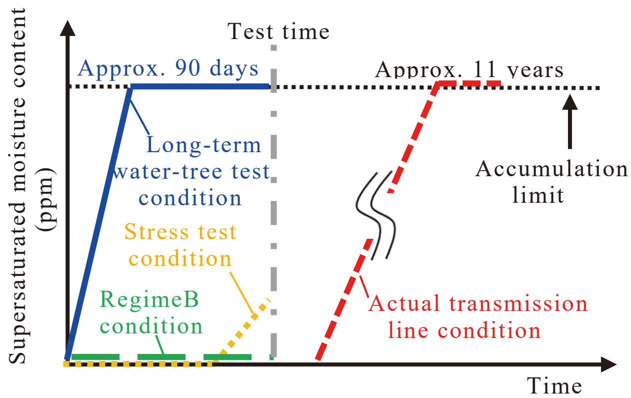

Fig. 6. Time for supersaturated moisture to reach the accumulation limit

4. Conclusion

For offshore wind power generation, which is attracting worldwide attention, we have been working to develop a non-impermeable submarine cable that can improve manufacturability, cost, and ease of installation. In the development of a new power cable that plays a key role in electricity infrastructure, estimating the service life of the cable is important. In this study, we inquired into the method for testing non-impermeable cables that will be operated for a long period in actual transmission lines. In particular, we analyzed the change with time of supersaturated water content of cable insulators and established a long-term water-tree test method that can simulate 30-year long-term operation of actual transmission lines within a reasonable test time. In the future, we will evaluate this test method using actual test equipment to develop a higher-voltage, water-tree-resistant cable that can be operated for a long period in actual transmission lines.

References

(1) Cabinet Secretariat, “Growth Strategy Conference (6th) Handout 1: Green Growth Strategy for 2050 Carbon Neutral,” pp.1-19 https://www.cas.go.jp/jp/seisaku/seicho/seichosenryakukaigi/dai6/index.html

(2) Y. ida, S. Yamasaki, Y. Sakaguchi, H. Hirota, and T. Uozumi, “Characteristics of water trees in Submarine Cables (Wet-Design) for Offshore Wind Power Generation,” SUMITOMO ELECTRIC TECHNICAL REVIEW No.94 (2022)

(3) S. Katakai, S. Hiwatashi, H. Suzuki, “Study of Inception Mechanism of Electrical Trees from Bow-tie Trees,” IEEJ Transactions on Fundamentals and Materials, Vol.139, No5, pp.264-276 (2018)

(4) S. Kuma, K. Aoma, H. Sakaguchi, “Generation Mechanism of Bow-tie Trees and Development of their Suppression Method,” IEEJ Transactions on Fundamentals and Materials, Vol.103, No.10, pp.569-576 (1983)

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