10690 Session 2022
B1
PS1: LEARNING FROM EXPERIENCES

# Investigation of Cause of Breakdown and Replacement of 275 kV SCOF Cable by XLPE Cable in Japan

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## SUMMARY

In recent years, self-contained oil-filled (SCOF) cables have deteriorated with age, and there is a need to establish methods for their diagnosis. In this paper, we report on the root cause of dielectric breakdown, measures to prevent dielectric breakdown and replacement in an aged 275 kV SCOF cable. In the 275 kV SCOF cable line, the cable section near the joint suffered from dielectric breakdown. The breakdown occurred immediately after the restart operation. Therefore, we considered that one factor responsible for this breakdown was the switching surge at the point of degradation.

When we conducted a removal survey at the breakdown point, colored deposits were found on the cable insulation paper near the joint. Then, these deposits were found to be copper and sulfur compounds, and the copper compounds reduced the electric strength of the cable.

Through model tests, our research was the first to confirm that the formation of copper compounds is accelerated by the components of vulcanization accelerators used in rubber products for joints.

Based on our findings, we expected that the root cause of the breakdown was as follows.

The components of the rubber product promoted the formation of copper compounds, which accumulated on a part of the cable. The accumulation of copper compounds led to the deterioration of insulation performance. Finally, the overvoltage due to the switching surges at the accumulation point led to the dielectric breakdown.

However, prior to failure, the dissolved gas analysis (DGA) did not indicate the need for emergency repairs. Therefore, we further reviewed the current diagnostic method.

We applied a diagnostic method of DGA that was useful for detecting the deterioration of joints where acetylene, a deterioration indicator, was generated. However, DGA and other diagnostic methods did not focus on the amount of copper in insulating oil. Therefore, we developed a new diagnostic method (ICP-imposed deterioration diagnosis method) that focuses on the relationship between the amount of copper and the progress of deterioration.

We also overcome the following issues to install the partial discharge monitoring system of the existing SCOF lines. It is difficult to secure a power supply and to communicate partial discharge signals in manholes. To solve this problem, we introduced partial discharge (PD) monitoring system with a power harvester using an inductive coil and Power Line Communication (PLC). We applied it to some of the SCOF lines installed in the duct and manhole.

In addition, we applied the proposed diagnostic method (ICP imposed deterioration diagnosis method) and identified several degradation points on the line. Thus, we replaced the SCOF cable with a cross-linked polyethylene (XLPE) cable and transition joints (TJs).

**KEYWORDS:** SCOF - Degradation - Diagnosis - Gas Analysis - ICP - PD - TJ - PLC

## 1. INTRODUCTION

In Japan, approximately 3,000 km of self-contained oil-filled (SCOF) cables are currently in operation. Most of these were installed before the 1980s, and over 60% of them are more than 30 years old, the oldest being over 50 years old as shown in Fig.1. However, though the age of these cables is increasing, until now, the number of breakdowns involving SCOF cables has been relatively lower than that of cross-linked polyethylene (XLPE) cables, and they have maintained a high level of reliability. One reason for this is that we have been managing the deterioration of joints using dissolved gas analysis (DGA).

In addition, cables with a lead sheath that caused considerable oil leakage have been replaced. Therefore, the present SCOF cables are mainly aluminum sheathed, and the frequency of oil leakage has been decreasing in recent years.

However, in recent years, there have been several instances of breakdowns owing to the deterioration of joints. Therefore, we plan to replace all SCOF cables with XLPE cables by 2045. Reliability maintenance for long periods until replacement is completed is a major issue.

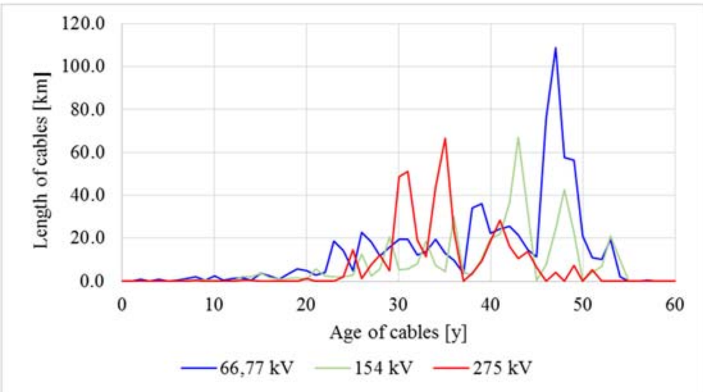


Fig. 1 Length of SCOF cables installed by major TSO (Transmission System Operator) in Japan

## 2. MAINTENANCE METHODS FOR SCOF CABLES (ADVANCEMENT OF DGA AND APPLICATION OF SUPPORT VECTOR MACHINES)

Japanese Transmission System Operator (TSO) have attempted to improve the maintenance of their facilities through DGA and dismantling surveys of SCOF cables. We collected oil from the joint before removal and measured the dissolved amount of flammable gases, such as acetylene, ethane, methane, and carbon monoxide using DGA. Subsequently, a dismantling survey was conducted to check the insulating layer for traces of carbonization and other discharges, as well as other abnormalities caused by deterioration. We then investigated the correlation between the abnormalities in the insulating paper and the concentration of each gas in the DGA. In addition, a new pattern analysis method was introduced (support vector machine; SVM [1]) to reflect this correlation. Thereafter, we used two forms of DGA and combined them to evaluate degradation.

For SVM, the accuracy of degradation estimation with the results of the dismantling survey was improved by approximately 80%. Based on these results, SVM has been widely used by Japanese TSO.

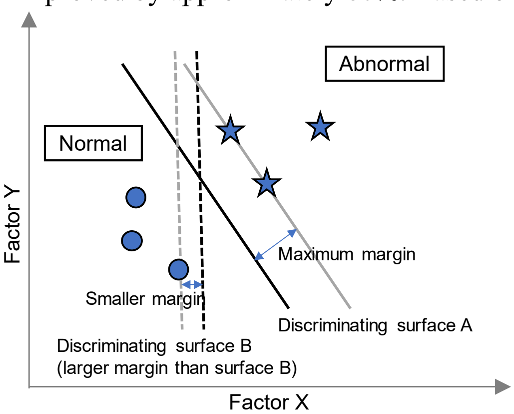


Fig. 2 Principle of SVM

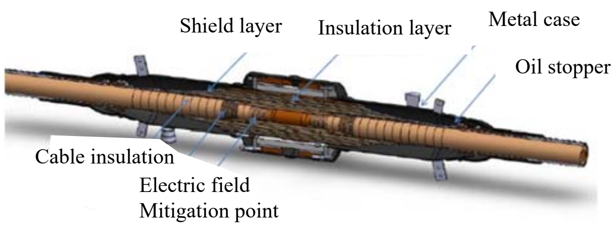


Fig. 3 SCOF joint structure

## 3. INSULATIION BREAKDOWN OF 275kV SCOF CABLE FACILITIES AND DISMANTLING INVESTIGATION RESULTS

In 2019, a 34-year-old 275 kV SCOF line (copper 2000 $mm^2$ with aluminum sheath) broke down. The breakdown point was the cable section near the joint as shown in Fig.4. The insulation breakdown occurred immediately after the restart operation.

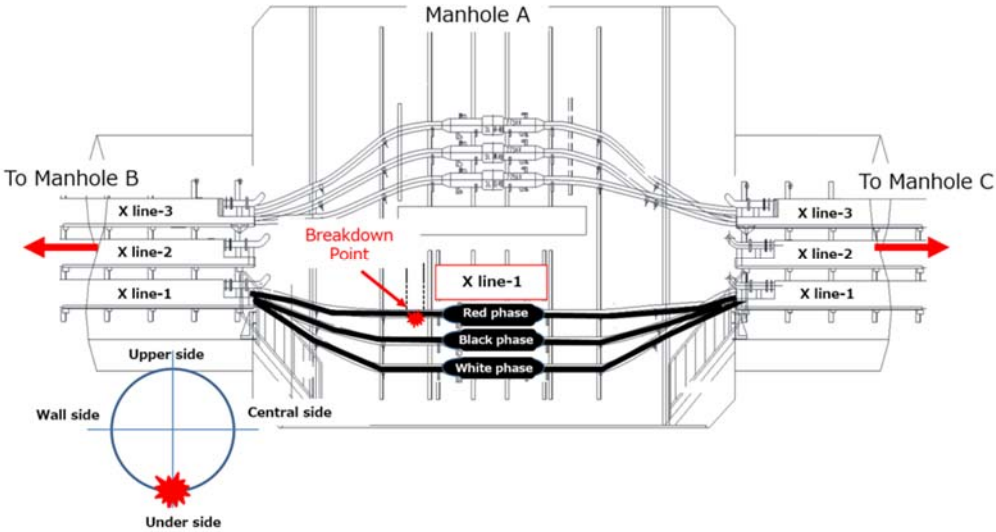


Fig. 4 Location of insulation breakdown

### *3-1. Document review and operational investigation*

We conducted document reviews such as manufacturing and installation record, and operational investigations to determine the cause of insulation breakdown.

(1) No abnormalities were found in the cable manufacturing record and cable installation record surveys.

(2) From the DGA data of the joint, the abnormal rank of the SVM was relatively high, but not at a level that showed any signs of imminent dielectric breakdown.

(3) The three-phase lumped section near the breakdown point became hot because of the temperature analysis at the operational current. However, it was below the allowable temperature. No abnormal heat generation was observed.

(4) No partial discharge alarm was set off before the breakdown, even with the partial discharge measurement that had been conducted since March 2018.

(5) We checked the cumulative number of switching surge inputs on the lines. As a result, we confirmed that among the three lines, breakdown line was the only one to occur over 1,000 times (Fig. 4) .

### *3-2. Dismantling survey*

We removed the breakdown area and conducted a dismantling survey as shown in Fig. 5 and Fig. 6. Yellow deposits were found on the surface layer of the cable insulation paper, black deposits on the middle layer up to the area near the conductor, and minute red deposits near the conductor. Elemental analysis confirmed the presence of copper, carbon, and sulfur.

We confirmed that there was no abnormality in the mechanical strength (tensile strength, elongation rate) and polymerization of the insulating paper near the breakdown point. We also conducted an impulse voltage test for the removed cable, which was near the breakdown point. The results showed that the cable was a breakdown at −1500 to −1600 kV, which is higher than the specified value (−1200 kV), confirming its high voltage resistance performance.

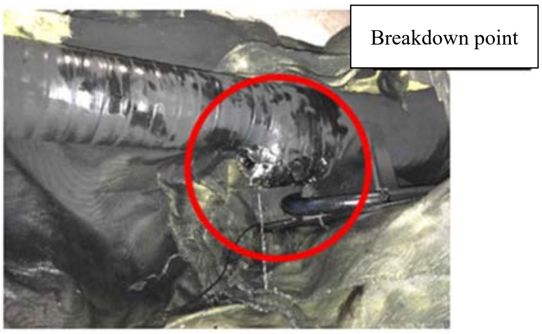

Fig. 5 Status of insulation breakdown (general)

Fig. 6 Status of insulation breakdown (magnified)

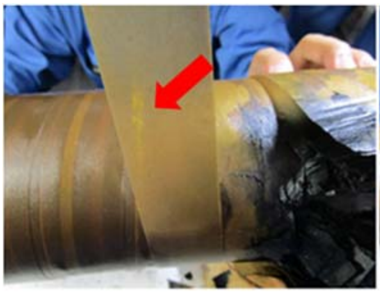
Fig. 7 Yellow deposits

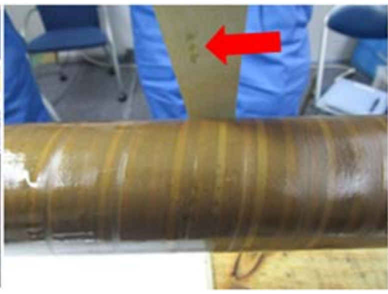
Fig. 8 Black deposits


Fig. 9 Red deposits

## 4. DEGADATION PROCESS

Copper and sulfur compounds were detected in the cable insulation paper from the dismantling survey [2]. These compounds were found in the cable sections near the termination where insulation breakdown occurred in the past. In addition, we have confirmed that the insulation performance deteriorates (discharge start voltage in areas without deposits: 40 to 50 kV/mm, discharge start voltage in areas with deposits: 27 to 40 kV/mm) in areas where these compounds are detected.

This suggests that the copper–sulfur compounds identified in this study are key factors responsible for the deterioration of the insulation performance. In a detailed investigation of the insulating oil collected from the actual cables, we confirmed that the occurrence of copper elution and sulfur components was higher than that in the fresh oil. In addition, it was confirmed that sulfur components were used as vulcanizing agents in the rubber materials of the joints.

Therefore, model tests were performed and the following observations were noted.

In the electrophoresis model test with dissolved copper and sulfur, the electrophoresis phenomenon occurred. In addition, higher sulfur content led to higher deposition of the compounds. (Fig. 10)

In other words, it was confirmed for the first time that deposition of copper compounds is promoted by the components of vulcanization accelerators used in rubber products for joints.

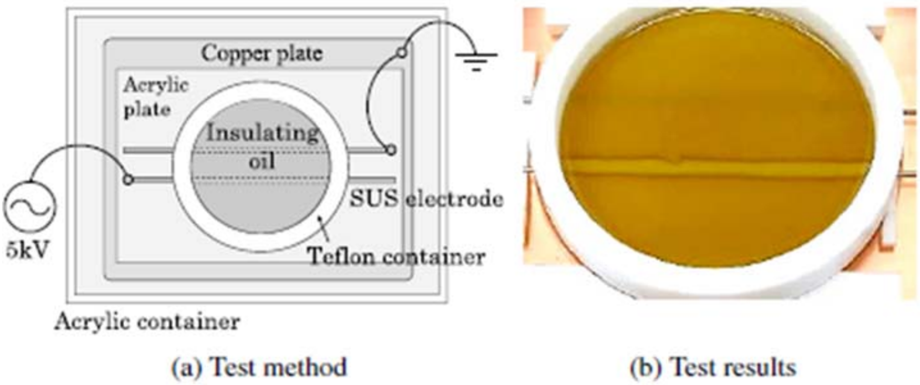

Fig. 10 Dielectrophoresis test results

It was observed that the number of switching surges on the line that broke down was higher than that of the other lines.
Therefore, it was assumed that the degradation process occurred as follows:

- Step 1: The vulcanization accelerator of the rubber material inside the joint promotes the elution of deterioration-causing substances (copper and sulfur components).
- Step 2: Copper compounds are agglomerated and deposited at specific locations owing to electrophoresis, etc.
- Step 3: Partial discharge occurs sporadically by a switching surge at the point of agglomeration and accumulation.
- Step 4: Waxing occurs because of partial discharge
- Step 5: Repeated agglomeration and partial discharge results in loss of insulation strength.
- Step 6: A surge caused by the system switching operation causes a dielectric breakdown in the area where the insulation strength is reduced.

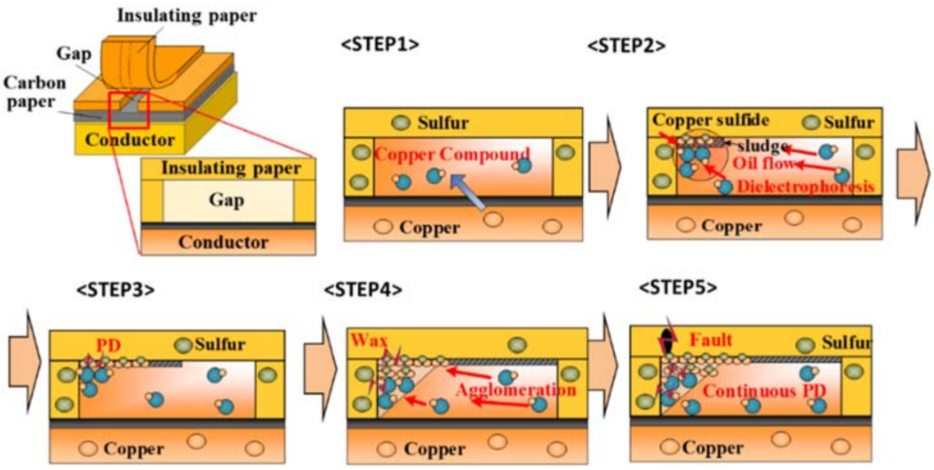

Fig. 11 SCOF cable charging degradation mechanism [3]

To confirm this process, we created the model shown in Fig. 12, which simulates the electric field gradient of a real cable and conducted an electrical charge test. As a result, it was confirmed that partial discharges were repeatedly generated, followed by dielectric breakdown. In addition, we observed copper–sulfur compound deposits in the breakdown holes.
From these results, we have confirmed the validity of the assumed process.

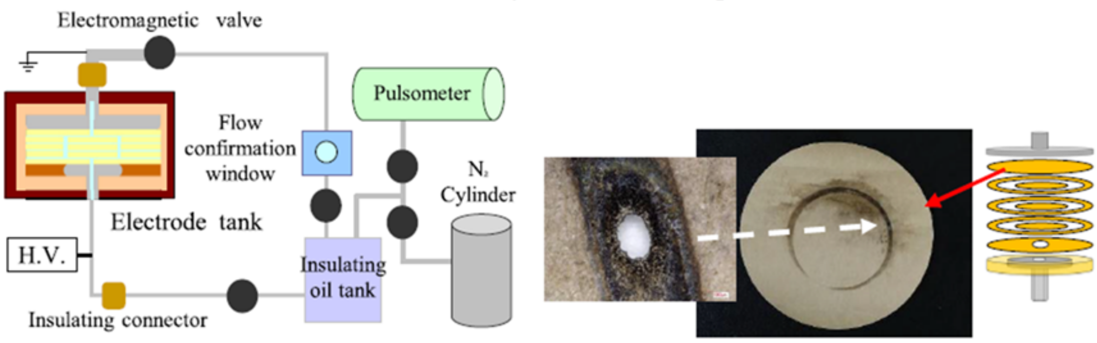

Fig. 12: Simulated cable electric field gradient model and insulation breakdown

## 5. MEASURES TO PREVENT RECURRENCE

### *5-1. Upgrading of DGA (ICP imposed deterioration diagnosis method)*

As a future preventive measure, we applied a new diagnostic method (ICP imposed deterioration degradation diagnosis) that can detect the above degradation process (copper dissolution is a crucial factor).
ICP diagnosis is a diagnostic method for determining the progress of imposed deterioration based on the amount of dissolved copper and the amount of gas generated. The diagnosis results were compared with the results of dismantling surveys and were reported to be approximately 96% consistent. [4]

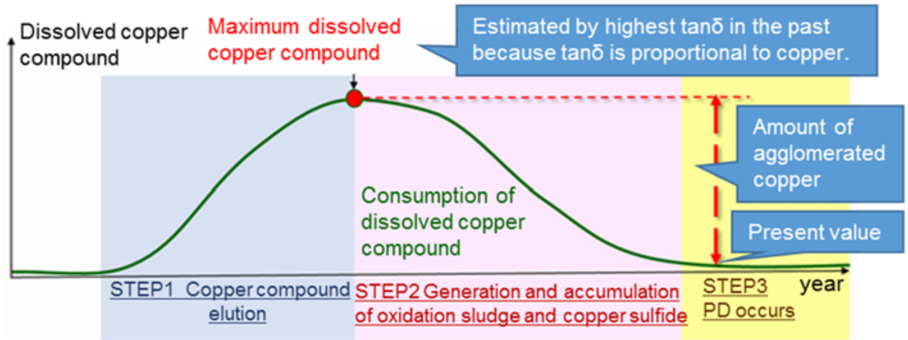


Fig. 13 Concept of diagnostic method using ICP measurement

We applied the ICP diagnosis method to the other joints on the same line. The result of ICP diagnostic method showed a joint that had the worst abnormal rank.
Thereafter, we carried out a removal and dismantling survey of this joint, and found similar deposits, discoloration, and layering in the cable section near the joint. These results demonstrated the validity of the ICP diagnosis results. Based on the results of the insulation breakdown and dismantling survey, we decided to apply this method on a full scale.

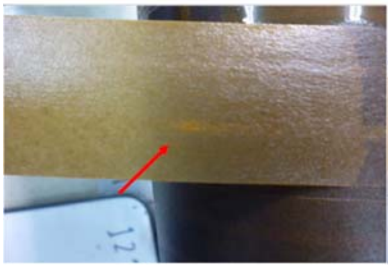

Fig. 14: Yellow deposits

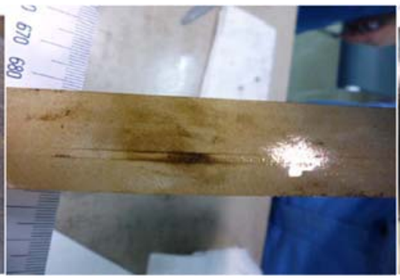

Fig. 15: Black deposits

Fig. 16: Red deposits

### *5-2. Increasing the accuracy of partial discharge measurement*

In order to detect abnormalities at an early stage prior to ICP diagnosis, we implemented constant monitoring of the 275 kV SCOF cable facilities through partial discharge measurements. For signal detection, we adopted a clamp-type high-frequency CT, which does not require line outage and is easy to install. We set the partial discharge measurement device to detect a certain amount of partial discharges for monitoring the deterioration. This was in view of the discharge characteristics of the existing SCOF cables and the results of on-site measurements of background noise and signal attenuation for each line.
The device automatically sends out an alarm when the three parameters of discharge quantity Q (pC), discharge pulse frequency N (pps), and duration (s) exceed the predetermined threshold values. In this insulation breakdown investigation, we investigated the PD measurement data and found that a signal with phase characteristics specific to partial discharges was observed six days before the occurrence of insulation breakdown, as shown in Fig. 17 and Fig. 18. However, because the discharges were sporadic, the duration did not reach the set threshold value, and the partial discharge alarm did not go off. In the future, we will consider the improvement of the system to detect sporadic discharges to set off the alarm.
There are some SCOF cables in ducts and joints in manholes. In partial discharge measurements for such locations, it is sometimes difficult to apply communication methods, such as optical cables or wireless, to transmit signal data or to secure a power supply for the equipment. Therefore, we developed an online partial discharge monitoring system that uses PLC (Power Line Communication) as the communication channel and obtains the induced power from other cable lines. [5] Fig. 19 shows the configuration of PLC.
The frequency band used for PLC is lower (150–400 kHz) than the band used for partial discharge measurement (1 MHz or higher); thus, there is no effect on the partial discharge measurement. Fig. 20 shows results of simulated signal detection test in actual facility.

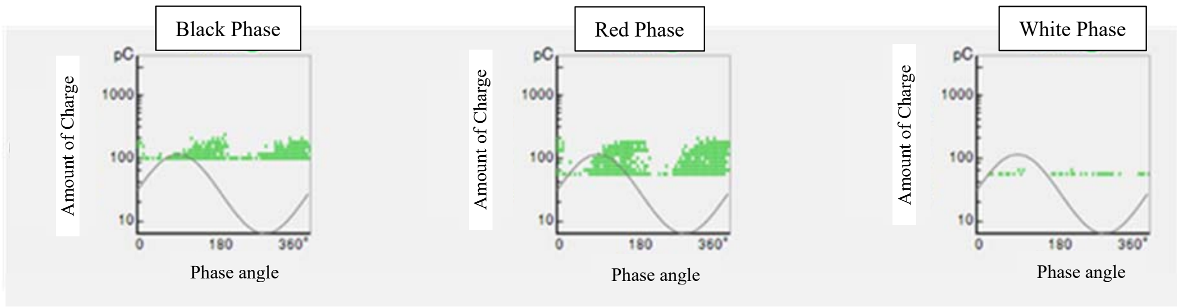


Fig. 17 Phase characteristics (PQN) measurement data of adjacent joints
(13:36:40, 6 d before dielectric breakdown)

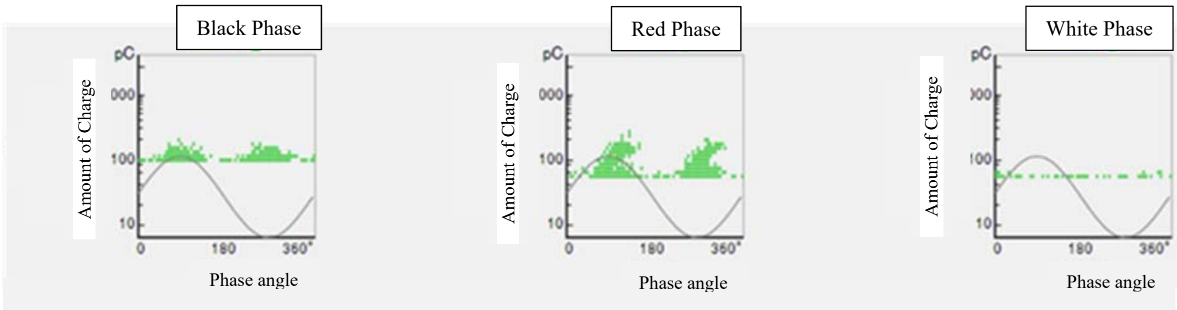


Fig. 18 Phase characteristics (PQN) measurement data of adjacent joints
(14:12:10, 6 d before dielectric breakdown)

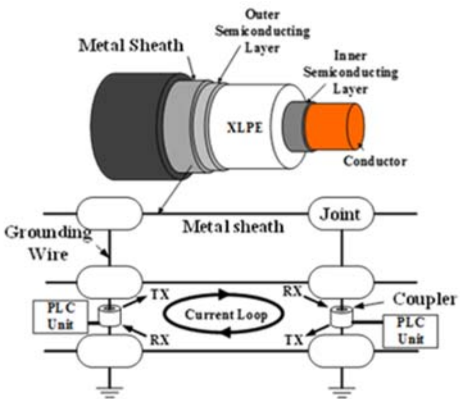


Fig. 19 Signal transmission by cable sheath

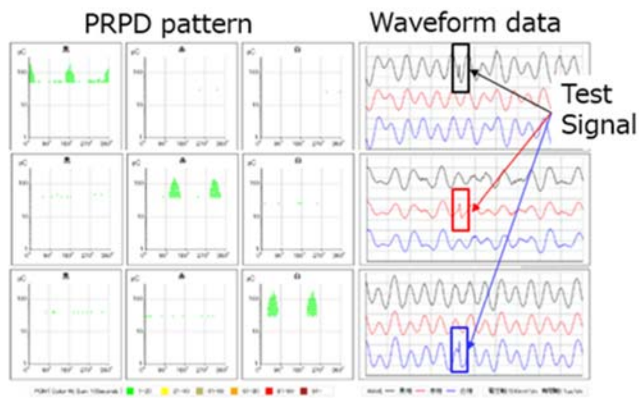


Fig. 20 Results of simulated signal detection test in actual facility

## 6. OUTLIN OF THE REPLACEMENT WORK

As the results of the ICP diagnosis were abnormal, replacement work had to be performed at the earliest to prevent insulation breakdown. We then confirmed that the deteriorated joints were made by the same manufacturer. However, as the line could not tolerate power outages for a long period, we replaced the section of the line that includes the same type of joint (approximately 3.8 km) by the XLPE cable and TJ (transient joints).

The replacement work for the deteriorated line with TJ was completed in June 2020 in a short time and the second line was replaced on June 2021. The remaining lines will be replaced at the earliest.

Fig. 21 shows the outline of the TJ, which is a combination of PMJ (Pre-fabricated Mold Joint) and the joint of SCOF cable. We applied the TJ after confirming the required characteristics, such as electrical and mechanical properties of both sides, and quality control methods, such as manufacturing and installation procedures. The assembly space was small, and the installation was difficult. However, we completed the assembly of the TJ without any problems via work verification meetings and construction management following the procedures.

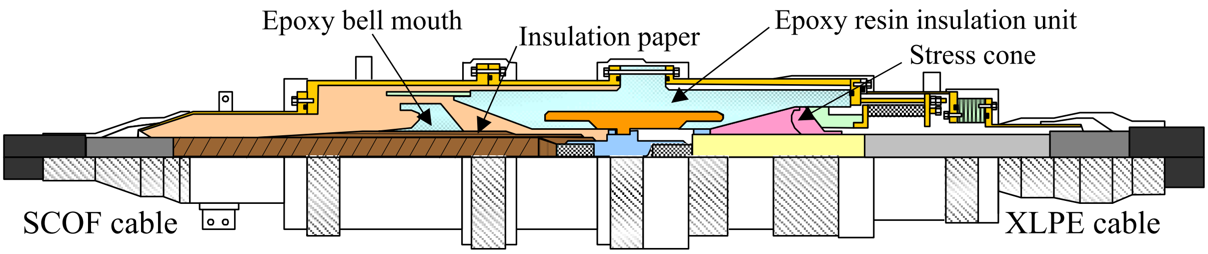


Fig. 21 TJ structure

SCOF cable fires have also occurred in the past and we recognized the importance of disaster prevention equipment.Therefore, we introduced an automatic fire extinguishing system without a power supply for the first time as a disaster prevention system for TJs. The outline of the system is as shown in Fig 22.

- Fire can be detected by the melting of the sensor tube owing to the heat generated by the fire.
- The pressure drop in the tube owing to melting causes the valve to be opened, and the firefighting foam is released from the nozzle.

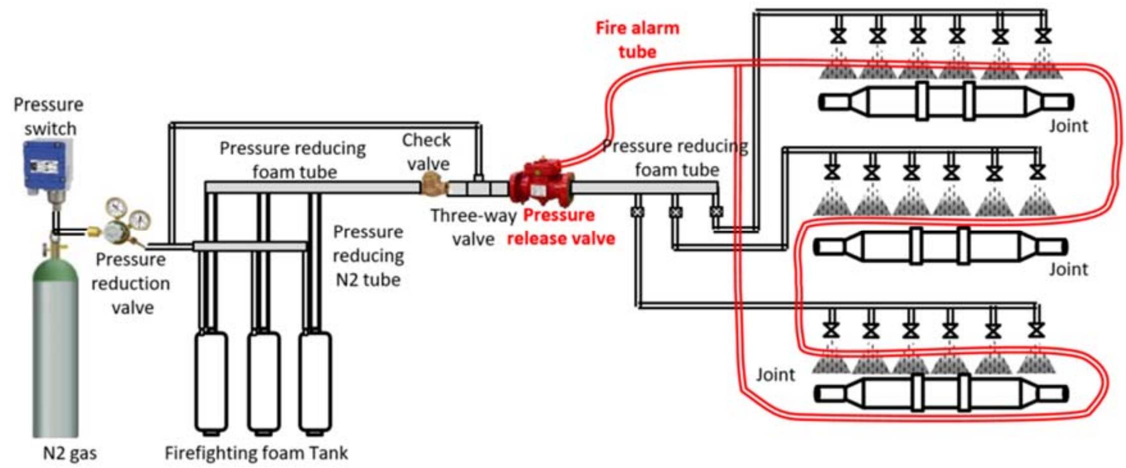


Fig. 22 Overall view of an powerless fire extinguishing system

Fig. 23 Overview of TJ

Fig. 24 Disaster prevention equipment for TJ (fire extinguishing system)

## 7. CONCLUSION

An insulation breakdown occurred in a highly aged SCOF cable line. We confirmed the cause of the breakdown from the dismantling investigation and model test results. Our findings are as follows: Sulfur in the rubber material of the joints speeds up the elution of copper that leads to the accumulation of these materials. When a switching surge is applied to the deposited area, partial discharge occurs. This process is repeated and causes the formation of wax. The wax reduces the strength of the insulator, and thus the switching surge causes a breakdown in the insulation.

Therefore, we developed and applied a new diagnostic method (ICP imposed deterioration diagnosis method) focusing on the relationship between the amount of copper and the progress of deterioration.
As a result, we confirmed the deterioration in other parts of the line. Owing to the dismantling investigation of the relevant parts, we confirmed the presence of the copper compounds. This validates of our diagnostic method.
In addition, we replaced the deteriorated section in line with XLPE cables. In this case, we applied a TJ to achieve quick replacement.
Based on this experience, we will continue to improve the accuracy of the diagnostic method and prevent breakdowns until all aged SCOF cable replacements are performed.

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