Study of Monitoring Method for Railway Power Equipment



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The Technical Center at the Research and Development Center of JR East Group has studied a monitoring method for railway power equipment based on condition-based maintenance. In those efforts, development of a sensor to monitor the temperature of the compressed connection part of DC-feeder wires has been completed, and the sensor developed has already been put into use on the Joban Line. A prototype high-voltage cable partial discharge monitoring device is now undergoing field tests. At the same time, we have been studying to identify trends in deterioration of lightning arresters and electric switchboards. And, as ambitious research, we are attempting to monitor substations using sound substation equipment emits. This paper will cover summaries of those.

●Keywords: Time-based maintenance, Condition-based maintenance, Wireless sensor, Partial discharge, Lightning arrester

1 Introduction

Power systems for electric railways are composed of a wide variety of wires and equipment, and detecting signs of deterioration and defects is difficult to do with some of that.

Failures of such equipment often result in serious transport disorders. We therefore periodically replace wires and equipment based on standard replacement periods specified for individual items to prevent failures from occurring. This method of maintenance is time-based maintenance (TBM); however, in light of the changes in the management environment of JR East, we cannot continue this type of maintenance because it requires much labor and costs.

Under these circumstances, we have been working on research and development for implementing condition-based maintenance (CBM), a maintenance method where repair and replacement is performed based on the condition of wires and equipment constantly monitored. Among the efforts, equipping trains in commercial operation with a power equipment monitoring system is introduced in another paper of this edition of JR East Technical Review; so, this paper will cover other efforts.

2 Monitoring of Compression Joints of DC Feeders

Feeders for DC electrified sections are important wires for supplying power from substations to trains. As so, they are replaced every 50 to 60 years. Feeders are connected at intervals of a few hundred meters in a method called "linear compression". If the compression joint deteriorates, large current unique to DC electrification occurs and creates a risk of generating heat that could melt the feeder.

In avoiding that risk, temperature control of compression joints is important. The Technical Center has therefore developed a wireless thermal sensor system supplied with power from photovoltaic panels, called an overhead contact line equipment monitoring system (Fig. 1). The system allows us to collect data efficiently by trains from sensors at many joint points using a special reader[1]. It was put into use on part of the Joban Rapid Line between Kita-Senju and Abiko (174 joints) in fiscal 2015. We are further working on data collection and analysis in corporation with the Tokyo Overhead Contact Lines Technology Center and the Abiko Electrification Technology Center with an aim of achieving CBM for feeder compression joints.

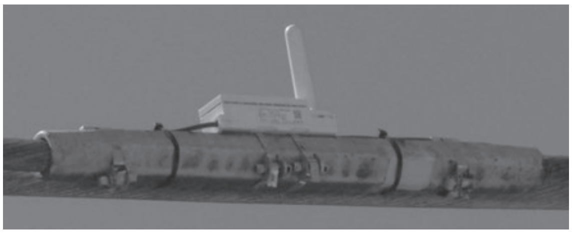

Fig. 1 Wireless Thermal Sensor Attached to Feeder Compression Joint

A key point in this project was what temperature tendencies of feeder compression joints have to be identified to detect deterioration. We came up with a method of deterioration judgment based on the difference in temperature measured between two temperature probes added to the wireless sensor, and we successfully detected and repaired two compression joints showing signs of deterioration with this method (Fig. 2).

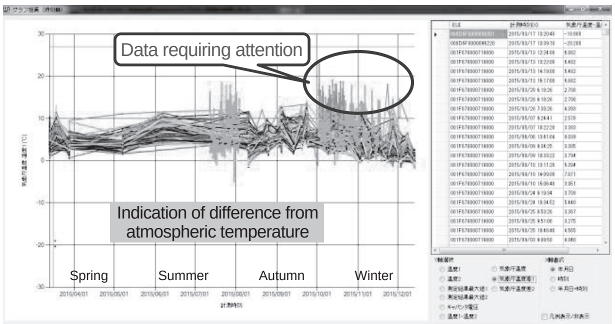

Fig. 2 Temperature Data Indicating Deterioration of Compression Joint

Fig. 3 shows a thermograph image of a compression joint showing signs of deterioration, which indicates heated points are distant from the joint because heat generated by increased

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resistance at the joint is propagated along the twisted wires of the feeder. The fact that such heat generation and propagation is difficult to identify by current periodical inspection using thermography (once every two years in the greater Tokyo area) proves effectiveness of continuous monitoring using thermal sensors.

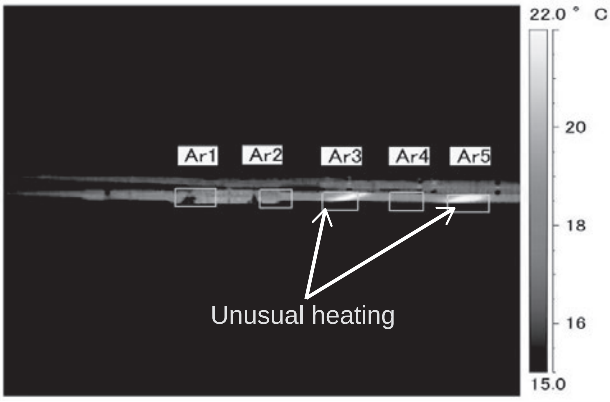

Fig. 3 Thermograph Image of Deteriorated Compression Joint

Taking account of the increase in volume of data due to wider deployment of wireless thermal sensors (the volume of the data for just a half year for 174 points where the system has been preliminarily introduced reached a level the spreadsheet program could not handle), we are working on building a system where data received by the reader is directly transmitted to and processed at the server. By that monitoring of compression joints and transmitting/processing the data, switching feeder maintenance from time-based replacement to CBM can be expected. In that CBM, feeders will be kept in use until signs of deterioration are detected, leading to reduction of both risk and costs thanks to longer use of feeders.

3 Monitoring of High-voltage Cables

High-voltage cables are important equipment for supplying power from substations and power distribution stations to signals and station facilities; however, it is difficult to find an effective inspection method for them because the mechanism by which deterioration progresses is complex and the level of deterioration is difficult to identify by visual observation.

JR East adopted for inspections of 6 kV power distribution high-voltage cables a partial discharge method whereby discharging pulses generated within those cables are detected. This method has an advantage in that inspections can be conducted for live cables within a short period of time using inspection devices on-site as shown in Fig. 4. However, there is an issue with the method in that the inspection results are affected by train noise because high-voltage cables are laid along the tracks.

Fig. 5 shows data that clearly indicates the issue. This is data of how frequent partial discharge is detected with high-voltage cables connected to a power distribution station at Station A in the greater Tokyo area. Partial discharge was continuously measured and the measurement results show a correlation with the number of train runs.[2] In particular, partial discharge was not detected late at night when no trains are operated. Thus, it can be expected that focusing on those late-night hours will allow us to conduct inspections by the partial discharge method with effects of noise avoided.

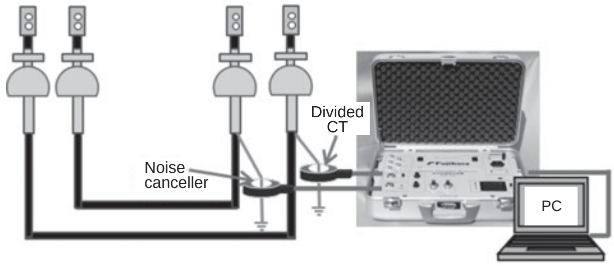

Fig. 4 Inspection of High-voltage Cables by Partial Discharge Method

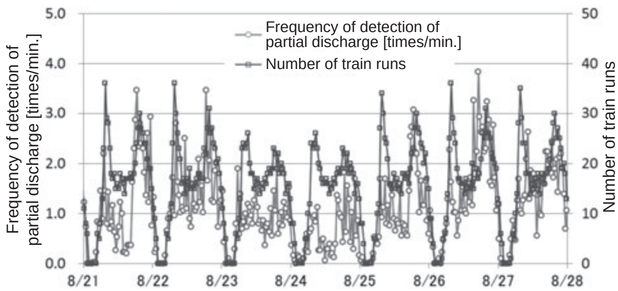

Fig. 5 Correlation between Number of Train Runs and Number of Times Partial Discharge Detected in High-voltage Cables at Power Distribution Station of Station A in the Greater Tokyo Area

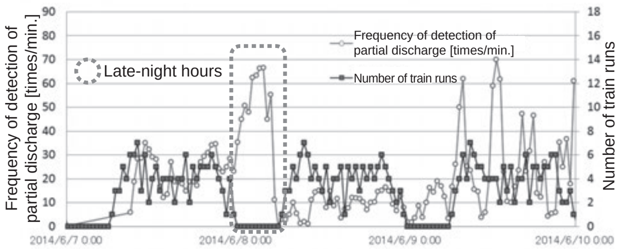

Fig. 6 Correlation between Number of Train Runs and Number of Times Partial Discharge Detected in High-voltage Cables at Power Distribution Station of Station B on Shinkansen Line

Fig. 6 is a plot chart of the number of times partial discharge was detected with high-voltage cables connected to the power distribution station in Station B on a Shinkansen line as an example of such late-night inspection results. As remarkable partial discharge was detected even in the late-night hours, abnormality was suspected in the cables or related equipment. Actual inspection of the cables and equipment revealed traces of discharge at the end of the cables as shown in Fig. 7, proving that continuous measurement of partial discharge is effective as an method of inspection for high-voltage cables.

We have produced a prototype high-voltage cable monitoring device with the cost of the measuring device for the partial discharge method lowered and the specifications improved for a longer monitoring period, and the prototype is now undergoing field tests.

While equipping all high-voltage cables with the monitoring

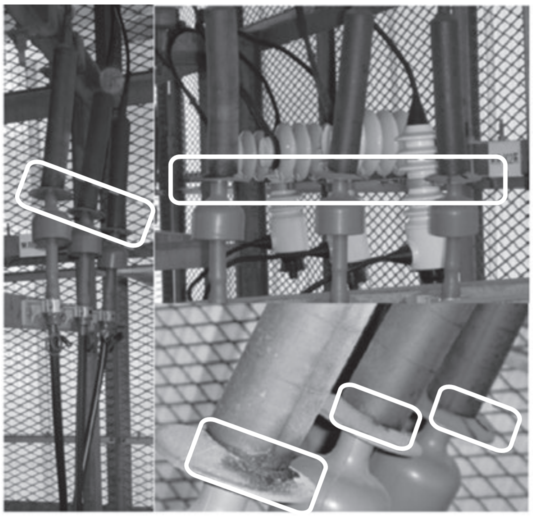

Fig. 7 Traces of Discharge at End of Cables

device is difficult due to cost issues, the device can be equipped to sections with only a single line of high-voltage signal cable and cables for supplying power to important loads to secure reliability.

4 Lightning Arrester Monitoring

A lightning arrester is a device to protect power equipment against lightning. Inspection of lightning arresters is conducted visually and by measuring leakage current once every five years. While presence of faults can be judged at the time of inspection with the current inspections, it is difficult to detect signs of deterioration due to the long inspection interval. In light of that, we are making efforts to establish a continuous leakage current monitoring method with an aim of implementing CBM for lightning arresters.

The lightning arresters to be monitored are those installed at the wayside for which their condition is difficult to check. Since wayside lightning arresters are installed at locations where it is difficult to secure controlling power, continuous recording of leakage current is difficult. Thus, with the aim of obtaining fundamental data for developing a monitoring method and investigating basic composition of the monitoring device, we produced a prototype measuring device that can continuously measure leakage current with no need of external power supply (Fig. 8). The data is recorded in the device and can be wirelessly transmitted to a data reader.

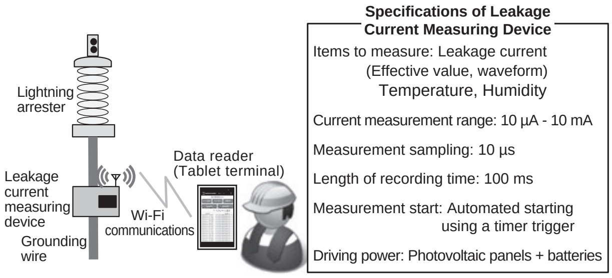

Fig. 8 Overview of Prototype Leak Current Measuring Device for Wayside Lightning Arresters

We set up the prototype in the yard of Station C on a Shinkansen line and measured leakage current. Fig. 9 shows the effective leakage current value and temperature data in the period from February 3 to 12, 2016. The leakage current value stayed at around 300 μA with no remarkable fluctuation.

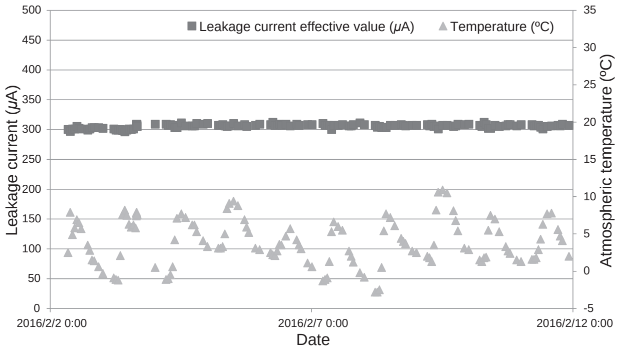

Fig. 9 Leakage Current Effective Value (in Yard of Station C)

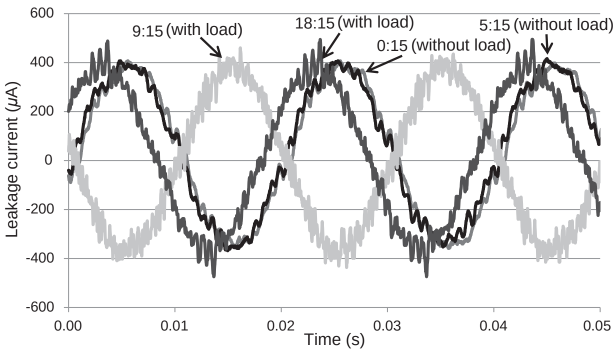

Fig. 10 Arrester Leakage Current Waveform (in Yard of Station C, Feb. 4)

Fig. 10 shows the waveform of the leakage current of a wayside lightning arrester we conducted measurement with. For comparison, the figure shows waveforms measured at different times on the same day. The figure confirms that noise elements are superimposed if load is applied to the wire with the lightning arrester (shown as lines with a load). We did not observe large fluctuation of effective leakage current values in the measurement in Station C on a Shinkansen line because noise elements are relatively smaller there than those at other places even when some load was applied. However, large fluctuation of those values is observed at locations where noise elements are large. We thus conducted frequency analysis (fast Fourier transform, FFT) of waveforms with and without load to find out frequency components included in the current (Fig. 11).

The results confirmed that fluctuation occurs depending on whether or not there is a load with frequency components over 1,500 Hz. This means that even when large fluctuation of leakage current occurs, frequency analysis can identify whether the fluctuation is caused by train load. On the other hand, we found almost no constant fluctuation with frequency components less than 1,500 Hz regardless of presence of load. In light of that, if we can identify leakage current tendencies at deterioration of lightning arresters, we may be able to judge deterioration of lightning arresters by analyzing waveforms monitored.

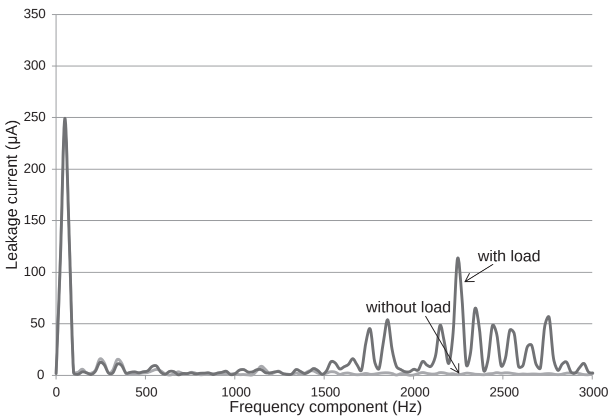

Fig. 11 Comparison of Frequency Analysis of Leakage Current with Load and without Load

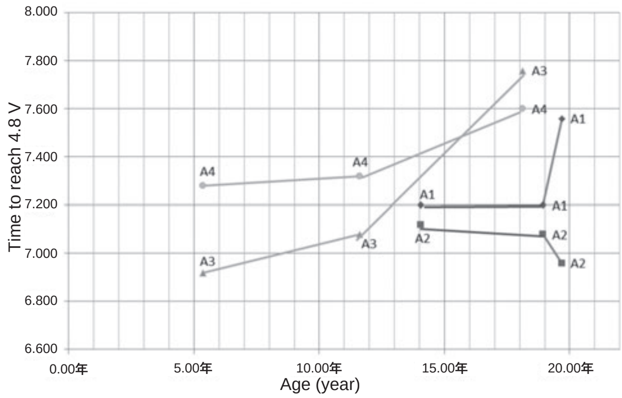

Fig. 12 Relation between Age and Power-up Time

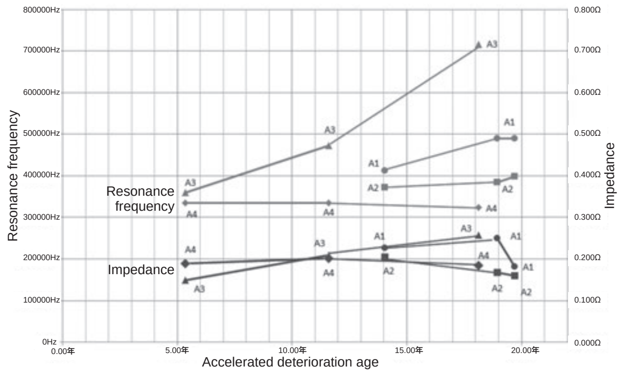

Fig. 13 Relation between Age and Impedance and Resonance Frequency

5 CBM for PCBs of Electric Switchboards

Printed circuit boards (PCBs) of electric switchboards are periodically replaced based on the idea of TBM; however, we currently do not know how the replaced PCBs deteriorate. In order to shift maintenance of PCBs to CBM, we have to identify the change in electric characteristics of PCBs caused by deterioration and establish technology for estimating remaining lifetime of those. For this purpose, we are conducting research by applying accelerated deterioration to PCBs to see whether characteristics are changed.

In accelerated deterioration tests, load current is continuously applied to PCBs using a load device and temperature and humidity stress is applied in a constant temperature and humidity container to accelerate deterioration. As the accelerated deterioration coefficient is determined by multiplying the temperature coefficient and the humidity coefficient,[3] we selected a value 40 times that (nine days to be equivalent to a year) taking into account of the ability of the PCBs to withstand the test conditions.

The sample PCBs were four PCBs produced by the same manufacturer that are used in some JR East substations. The rated values and names of the sample PCBs are as follows.

Rated values: Rated input voltage DC 24V,
Output voltage DC 5V,
Output current capacity 7A
Year of production: 2014
Names of sample PCBs: A1, A2, A3, A4

We decided to conduct measurement of electric characteristics after deterioration progressed to a certain level. Actual measurement was done for pair A1-A2 and pair A3-A4 outside of the constant temperature and humidity container at different times. Measurement was conducted with pair A1-A2 at times equivalent to 14, 19 and 20 years of aging and with pair A3-A4 at times equivalent to 5, 12 and 18 years of aging. Examples of characteristics that showed changes due to aging included power-up time and impedance value and resonance frequency of PCBs.

For power-up time, we measured the time from the moment voltage was applied to PCBs to the time when the voltage reached a specified voltage (operation guarantee voltage 4.8V) to check the change due to aging.

With the PCBs other than A2, time to reach the reach specified voltage became longer as aging progressed. We found the greatest change with A3 where the time was delayed by approx. 0.9 ms. As operation delay was observed with three out of four PCBs, power-up time can be said to be one of the characteristics that change due to aging.

Next, we checked changes due to aging for the impedance value and resonance frequency of the PCBs (Fig. 13). On the input side, a tendency for resonance frequency to increase was observed with PCBs A1, A2, and A3, and a tendency for impedance value to increase was observed with A3. Impedance values with the PCBs other than A3 fluctuated and no constant tendency of change was confirmed. As the inductance of the circuit constant is not considered to change, we think the change of resonance frequency was caused by change of capacitance of the circuit constant.

In the tests, we were able to identify some electric characteristics that change due to aging. However, the PCBs did not reach a condition where they failed—a condition where no voltage is output. In order to establish a method of judging deterioration by monitoring, we will continue accelerated deterioration until PCBs fail in order to identify changes in electric characteristics due to aging and values of characteristics in PCBs that lost functionality.

6 Substation Monitoring by Sound

Abnormalities of substation equipment are checked in patrols relying on human senses of vision, hearing, and smell. Items to be checked differ by device; however, there are many common items such as corrosion damage and appearance abnormalities, abnormal smell, and abnormal sound. Considering that facilities maintenance will be shifted to CBM, we have to identify conditions of devices while keeping down costs. In light of that, we are conducting research on monitoring substations with a focus on sound.

In order to obtain fundamental data to investigate monitoring of substation conditions by sound, we carried out a survey of acoustic conditions in a substation equipment room. The room selected for surveying was an indoor substation where acoustic conditions seemed to be not affected much by external noise. Two types of microphones were used for acoustic measurement: one non-directional and one directional microphone (Fig. 14).

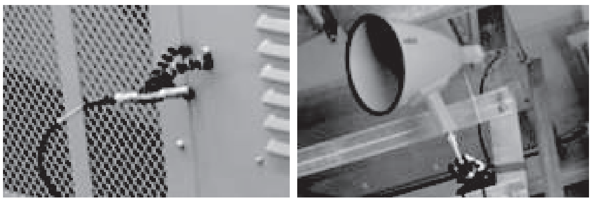

Fig. 14 Microphones (left: non-directional, right: directional)

We set a non-directional microphone near the equipment and a directional microphone distant from it but aimed at the equipment to collect overall sound in the equipment room. Wavelet transformation was applied to the data and analysis conducted with a focus on signal intensity and frequency distribution over time. The items surveyed were sound in the substation equipment room where transformers, rectifiers, and other major devices were installed, sound of transformers, and sound of breakers.

Fig. 15 and 16 are the analysis results for sound in the equipment room and sound of transformers. Sound shown in Fig. 15 was recorded using a directional microphone and that shown in Fig. 16 was using recorded a non-directional microphone. The upper graph in the figure is the waveform of the sound signals and the amplitude indicates sound intensity (AD value). The lower graph is distribution of frequencies included in the sound signals, and gradation corresponds to signal intensity.

Comparing of the two figures tells us that frequency distribution was the same while signal intensity differed, and the frequencies were distributed around an integral multiplication of double the power supply frequency. Theses characteristics of frequency distribution agree with the characteristics of transformer noise,[4] so we can judge that the data in Fig. 15 successfully captures transformer sound. That suggests a possibility that overall sound in the equipment room and sound of distant equipment can be collected at the same time using directional microphones without attaching microphones to each equipment.

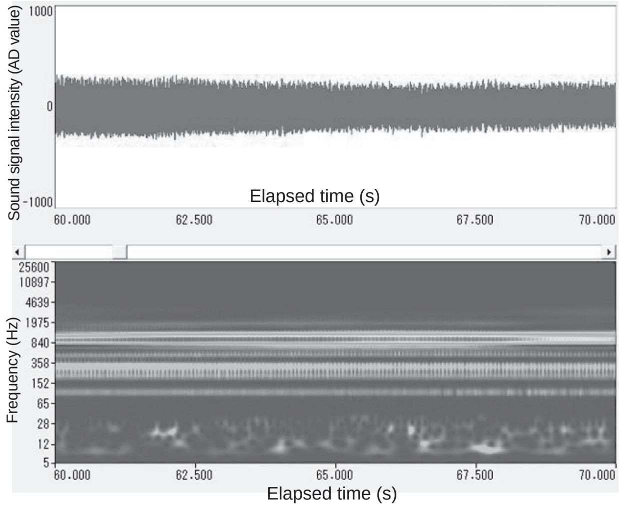

Fig. 15 Sound in Equipment Room of Indoor Substation

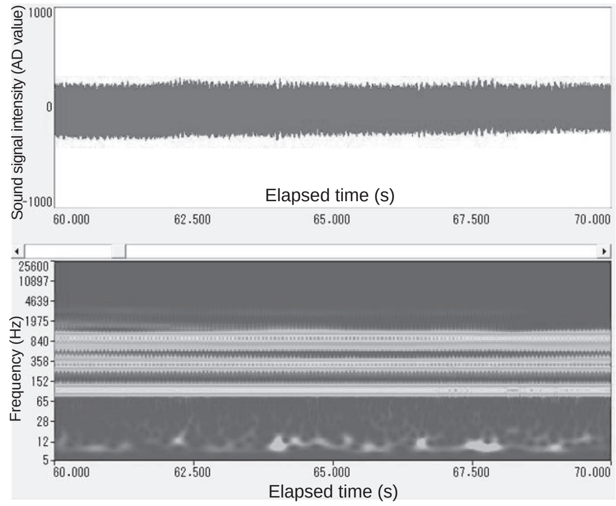

Fig. 16 Sound of Transformer in Indoor Substation

Fig. 17 and 18 show examples of operation sound (turning on and off) analysis results of a 66 kV class gas insulated switchgear (GIS). The data analyzed was obtained from a distant point using a directional microphone.

Comparing the two figures shows characteristic differences in signal intensity and frequency distribution of the sound when turning on and when turning off. We switched the breaker on and off a few times to see correlation in each on and off operation and found a correlation coefficient of 0.8 or greater in both types of operation. Since breakers mechanically operate using motors, rollers, cams, springs and the like, there is a possibility of abnormal noise being generated due to deterioration and changes in acoustic signal intensity and frequency band of the generated sound. We therefore think it will be possible to detect signs of deterioration by comparing sound data with data of normal operation sound based on the similarity of acoustic signals.

The surveys thus far have only gone as far as identifying part of actual sound, so there are many items to check and investigate. Those include frequency bands of the sound of devices other than transformers included in the overall equipment room sound and effect of environmental differences. We will work to further identify actual sound to come up with a monitoring method using sound based on the results of that work.

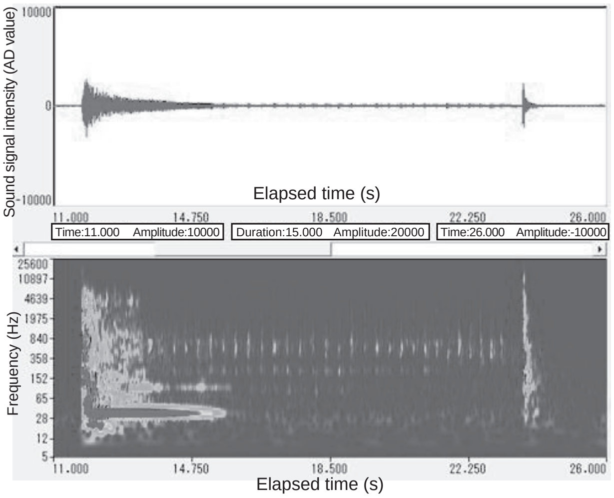

Fig. 17 Sound of Gas Insulated Switchgear (On Operation)

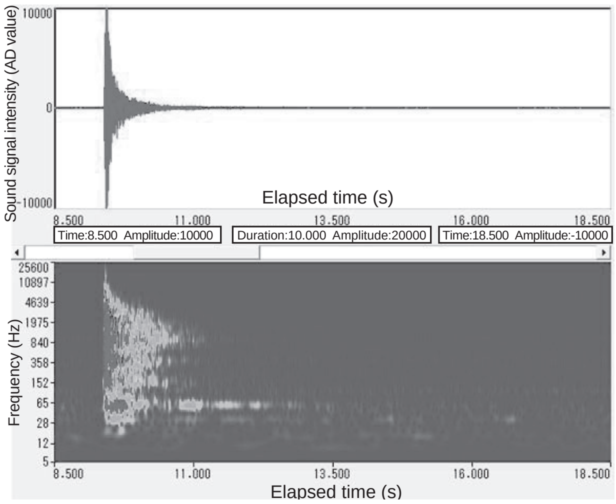

Fig. 18 Sound of Gas Insulated Switchgear (Off Operation)

7 Conclusion

This paper covered monitoring of the temperature of feeder compression joints using wireless sensors, monitoring of partial discharge of high-voltage cables, monitoring of leakage current of lightning arresters, shift to CBM for PCBs of switchboards, and acoustic monitoring of substation equipment operation sound.

We are at different research and development stages for those, with fundamental theories already established for some and selection of items to monitor still underway for others.

A difficulty in monitoring power equipment and implementing CBM as an extension of that is the fact that there are few examples of actual failures due to aging, and we thus do not know what phenomena occur in deterioration with many devices and facilities. The Technical Center is making efforts in finding solutions to this difficult issue by analyzing data and conducting large-scale accelerated deterioration tests. We will report on those efforts in future papers.

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