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Development of switchgear condition monitoring using IoT technology for Condition Based Maintenance

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SUMMARY

Continuous monitoring of substation equipment conditions is becoming easier due to advances in IoT (Internet of Things) technology and reductions in the price of sensors. On the other hand, switchgear (circuit breaker, disconnector, etc.) in substations require maintenance, which involve power outages and on-site inspections once every few years (TBM: Time Based Maintenance). This method requires an enormous amount of labor and time, as it requires operation and on-site inspection for power outages. In addition, even if the switchgear deteriorates during the periodic inspection cycle, it may not be detected, which may lead to a serious failure.

Therefore, we are investigating a new maintenance method that uses IoT technology to monitor the condition of switchgear and inspect it as necessary, such as when a sign of failure is detected (CBM: Condition Based Maintenance). This method will not only reduce the time and labor required for maintenance, but also prevent switchgear failure. In this paper, we examine a monitoring method using "operating/control current" and "operating sound" of switchgear, and evaluate their usefulness for CBM.

To monitor “operating/control current”, we developed a device that automatically collects and transmits the current waveform data generated during the operation of switchgear. Clamp type current sensors are used, and the device can be easily installed without power outage. It allows remote browsing and analysis of the obtained data. Then, we collected data at several substations for more than one year, analyzed the data, and compared it with the cases of switchgear failures. As a result, several peculiar current waveforms (variations in peak height, current carrying time, peak position, etc.) were observed, and the relationship between changes in current waveforms and signs of failure was sorted out.

To monitor “operating sound”, we developed two effective analysis methods: FFT (Fast Fourier Transform) color map and POA (partial overall) time trend in a specific wavelength range. Then, using a switchgear demonstrator, various abnormal operations were simulated and analyzed. As a result, peculiar aspects (waveform shift, disappearance of peak, change in volume, etc.) caused by failures or signs of failure were observed. The relationship between each peculiarity and the operating process of the switchgear was also clarified. And a prototype of a condition monitoring device using these analysis methods was installed in an actual substation on a trial basis, and it was confirmed that the device could correctly diagnose the sound of switchgear operation.

These results suggest that it is possible to diagnose the condition of the switchgear by monitoring the “operating/control current” and "operating sound". In addition, they detect signs of switchgear failure, which can prevent the failure from occurring. Based on these results, we try to analyze more data, improve the accuracy of judging the signs of failure, and automate the process by combining the method with AI technology. We also aim to apply CBM not only to switchgear but also to the entire substation.

KEYWORDS

Switchgear, Circuit - Breaker, Disconnector, IoT, Sensor, CBM, Current - Waveform, Sound

1. Introduction

In recent years, continuous monitoring of substation equipment conditions have become easier due to advances in IoT technology and reductions in the price of sensors. In the future, it is expected that maintenance policies will be fundamentally changed as the IoT (Internet of Things) of substation equipment advances and big data and artificial intelligence are utilized.
The conventional maintenance method for substation equipment involves periodic power outages once every few years and on-site inspection work (TBM: Time Based Maintenance). In the inspection of switchgear, the operating characteristics are directly measured on-site to diagnose the condition of the switchgear. However, the operating characteristics obtained in this process are those obtained immediately after the operation for a power outage. In general, the operating characteristics immediately after such operation tend to show good results, so the operating characteristics obtained during an on-site switchgear inspection may be different from those during daily operation such as network switching. Therefore, this maintenance method for switchgear with a power outage may not diagnose the operating characteristics correctly. In addition, the TBM method requires an enormous amount of time and labor for maintenance because it involves periodic power outages and on-site work.
To address this issue, we are aiming to develop a new maintenance method that uses IoT technology to constantly monitor the condition of switchgear and conduct inspections as needed according to the condition (CBM: Condition Based Maintenance). Fig. 1 shows a conceptual image of the transition from TBM to CBM that we are aiming for.

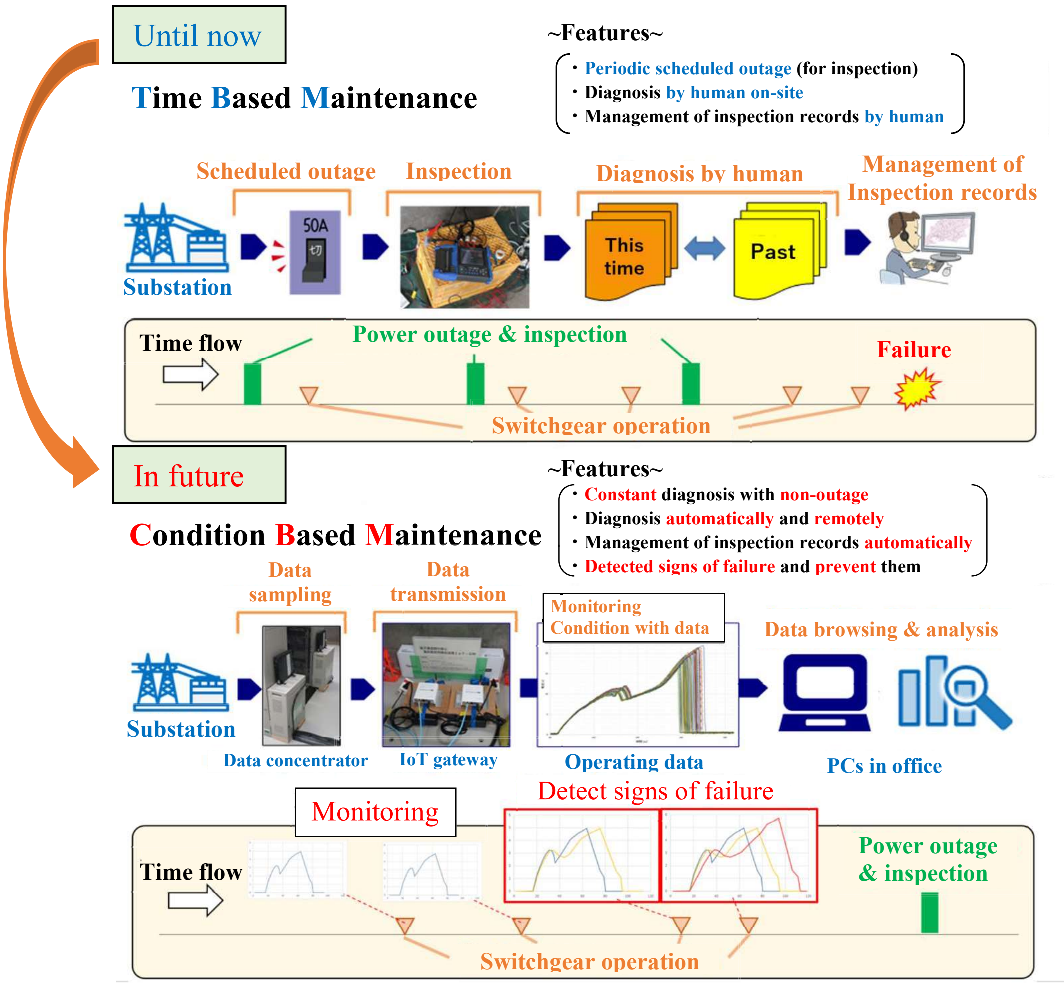


Fig. 1 Conceptual image of transition from TBM to CBM

As a method of CBM for switchgear, sensors are used to constantly monitor operating characteristics from daily operations such as network switching and fault interruption to detect signs of failure. This not only greatly reduces the time and labor required for periodic power outages and on-site work, but also makes it possible to detect the signs of failure with high frequency and high sensitivity, thereby preventing operational failures.
Therefore, we focused on the “operating/control current” and “operating sound” of switchgear as specific monitoring parameters to develop CBM. In this paper, the monitoring of switchgear using current sensors and a microphone is verified, and its usefulness is reported.

2. Monitoring of switchgear condition with operating/control current analysis

2.1 Installation of monitoring devices

In order to efficiently collect and analyze the current waveforms generated during switchgear operations, the monitoring device as shown in Fig. 2 was installed in substations. This device can be easily attached to the operating and control current circuits of the switchgear without power outages by using clamp-type DC current sensors. During a switchgear operation, the current waveforms are detected by the sensors and automatically collected as data and sent to the monitoring device. The data is then automatically transmitted to a system server, where it can be browsed and analyzed remotely. By using this system and analyzing the data obtained over a period of about one year, some peculiar aspects caused by signs of switchgear failure were observed.

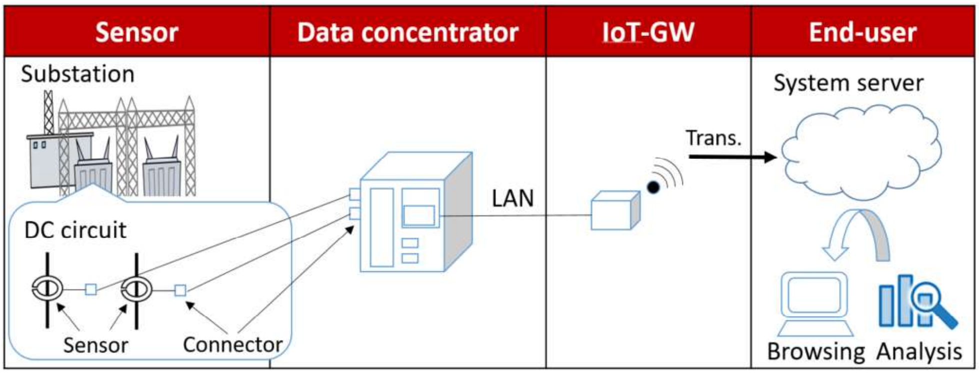


Fig. 2 Configuration of monitoring device (with DC current sensor)

2.2 Example of monitoring with current waveform (disconnector)

Fig. 3 shows the transition in operating current waveform leading up to an operational failure in an 84 kV type-A disconnector. As a sign of failure, magnitude of the current peak gradually changes during the specific operating time period. This is because the load on the motor increases due to a kink caused by dust contamination. Therefore, it is considered possible to detect signs of failure and prevent them by monitoring the current peak in similar cases.

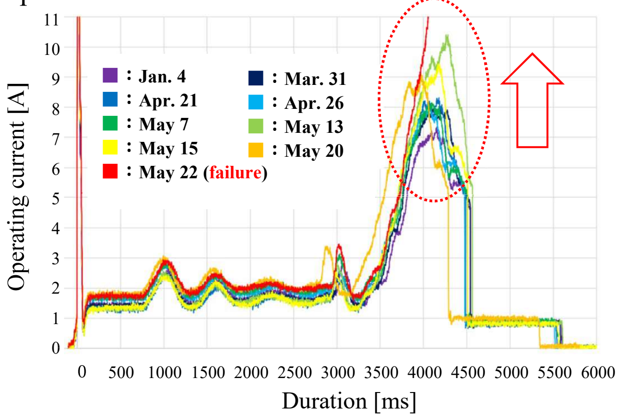


Fig. 3 Transition in operating current waveform leading to failure
(Closing operation of 84 kV type-A disconnector)

Fig. 4 shows a comparison between an abnormal operating current waveform, which is presumed to be a sign of failure, and a normal operating current waveform in an 84 kV type-B disconnector. It should be noted that the type-B disconnector has experienced component damage in the past, leading to operational failure. Comparing both of them, in the abnormal current waveform, the current peak is observed at a time that is not observed in the normal one. This is because the load was applied to the motor at a time that would not occur in the normal operating process due to the sticking of the mechanical part. Therefore, it is considered possible to detect signs of failure and prevent them by monitoring the time to peak of the current waveform in similar cases.

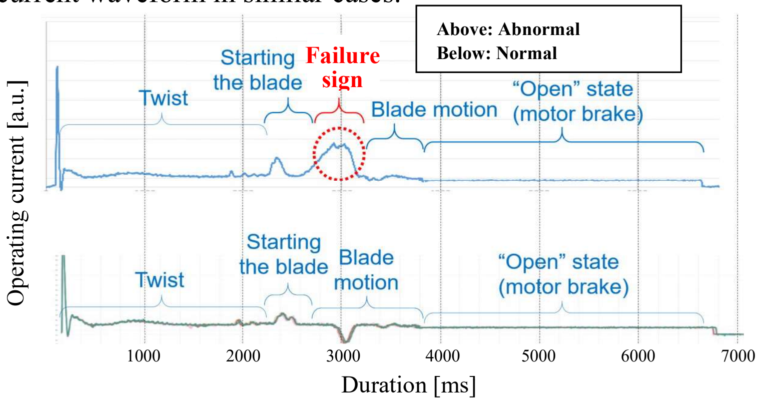


Fig. 4 Comparison of normal and abnormal operating current waveform
(Opening operation of 84 kV type-B disconnector)

2.3 Example of monitoring with current waveform (circuit Breaker) [1], [2]

Fig. 5 (a) shows all current waveforms of 25 84 kV type-C circuit breakers over a period of about one year. It should be noted that type-C circuit breakers have experienced operational failures in the past. There is a large variation in the current carrying time, generally in the range of 34 to 75 ms, but reaching a maximum of 739 ms. Therefore, it is considered possible to detect signs of failure and prevent them by monitoring the current carrying time of the current waveform.

In addition, the data for one of the type-C circuit breakers was extracted and the current carrying time during operation and the ambient air temperature were investigated at that time. As a result, a correlation was observed as shown in Fig. 5 (b). This is due to the fact that lubricating oil that had been applied to the mechanism had deteriorated and the viscosity and frictional force had increased at lower temperatures. This phenomenon returns to its original state (shorter current-carrying time) at higher temperatures, indicating the possibility that it cannot be detected by inspection at high temperatures.

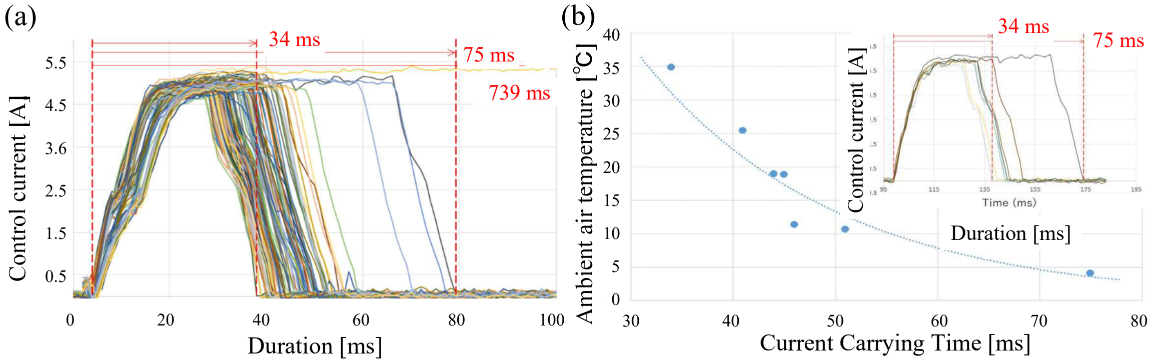


Fig. 5 (a) Variation of control current waveform.
(b) Correlation between current carrying time and ambient air temperature
(Opening operation of 84 kV type-C circuit breaker)

In order to compare and evaluate the results with those of Fig. 5, an 84 kV type-D circuit breaker that has not experienced any operational failures in the past was also investigated in the same way. As a result, the control current waveforms shown in Fig. 6 were observed, and it was found that the variations in current carrying time were very small, 6 ms at the maximum.

From these instances of verification, it was found that there are two types of control current waveform of switchgear, one with a large variation in current carrying time and the other with a small one. By investigating this characteristic, it is thought that an efficient maintenance plan can be implemented for each type.

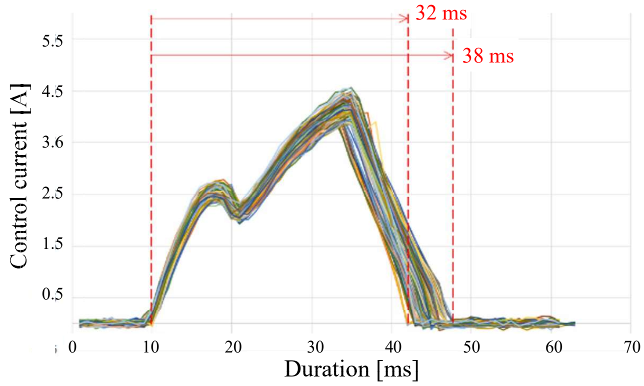


Fig. 6 Variation in current waveforms
(Opening operation of 84 kV type-E circuit breaker)

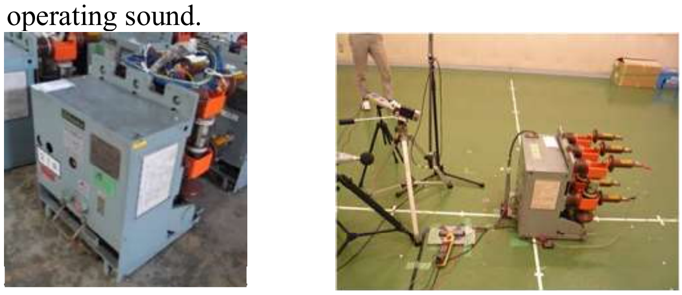
2.4 Toward further development of monitoring with current waveforms

From the above verification results (2-2, 2-3), it is clear that in the operating/control current waveforms of the switchgear, the signs of failure appear as "peak value", "time to peak" and "current carrying time". Detecting them will lead to being able to monitor the condition of the switchgear.
In order to implement monitoring using current waveforms, it is necessary to judge whether or not the various current waveforms are signs of failure. However, the shape and changes in the current waveform differ individually depending on the manufacturer, model, and fault location of the switchgear. Therefore, it is difficult to establish specific criteria for determining the signs of failure in each individual case based on the number of pieces of data obtained so far. So, we believe that by collecting and analyzing larger amounts of data, we will be able to build the database necessary to judge the signs of failure. By analyzing large amounts of data, we can evaluate the shape of the standard current waveform and its variation for each type of switchgear. Additionally, we are considering establishing quantitative criteria for judging signs of failure.

3. Condition monitoring technique for circuit breaker with operating sound analysis

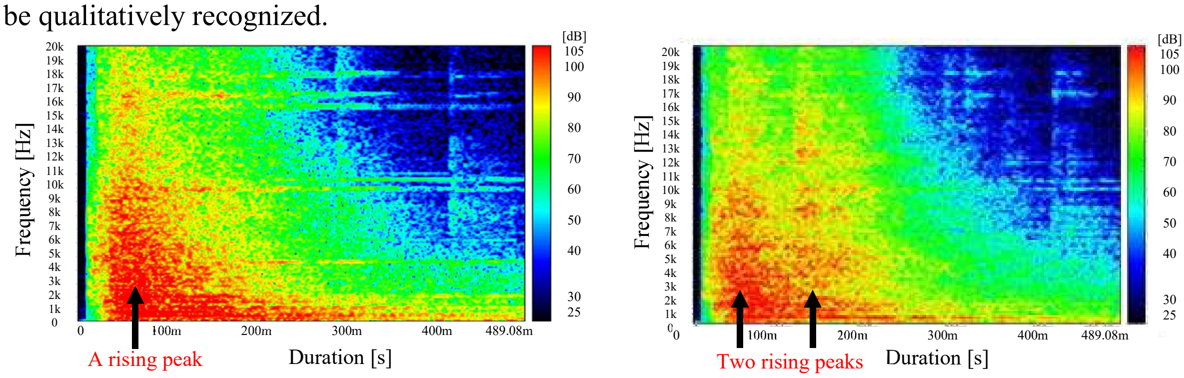
3.1 Development of two analysis methods

As another means of monitoring switchgear, we have focused attention on the sound generated from the operating mechanism of a circuit breaker. And, for the purpose of investigating the possibility of monitoring the condition with the operating sound, a technique was studied to identify the abnormal portion at the time of an operation failure by constantly monitoring the circuit breaker operating sound. Using a sample device with a 7.2 kV circuit breaker, a method for analyzing operating sounds to distinguish between normal and abnormal operation has been studied. As a result, an FFT (Fast Fourier Transform) color map and a POA (partial overall) time trend of 13 kHz to 15 kHz have been found as a new method of operating sound analysis. Fig. 7 shows an example of a 7.2 kV circuit breaker and the state of measuring the operating sound.



(a) Drawing out from cubicle (b) Measuring work
Fig. 7 Example of 7.2 kV Circuit Breaker

First, the FFT color map is an analysis method that evaluates the strength of sound pressure in chronological order for each frequency. When the FFT color map, which is a three-dimensional graph of the frequency spectrum and time with the sound pressure level displayed in color, has been created and the operating sound is analyzed, normal and abnormal can be distinguished by the number of rising peaks as shown in Fig. 8. It has been found that it was possible, and that the difference in pattern could be qualitatively recognized.



(1) Normal open operation (2) Example of abnormal open operation

Fig. 8 FFT color map of operating sound in circuit breaker (open operation)

In addition, the POA time trend of 13 kHz to 15 kHz is an analysis method that numerically evaluates the generated sound pressure in the 13 kHz to 15 kHz band in chronological order, and it has been found that the difference in operating sound can be quantitatively evaluated.
In the FFT color map, it can be seen that the operating sound of the 7.2 kV circuit breaker has continuous noise around 11 kHz, 17 kHz, and 19 kHz in both normal and abnormal conditions. Therefore, we have created and analyzed a two-dimensional waveform of the generated sound pressure level and the time in which the frequency band of 13 kHz to 15 kHz has been selected so as to avoid continuous noise when the circuit breaker is operated. As a result, as shown in Fig. 9, it became possible to estimate the difference between normal and abnormal operations by examining the loudness of the reverberation sound. Using this method, it has been found that it is possible to make a quantitative estimation. The graph based on this two-dimensional waveform is called a POA time trend.

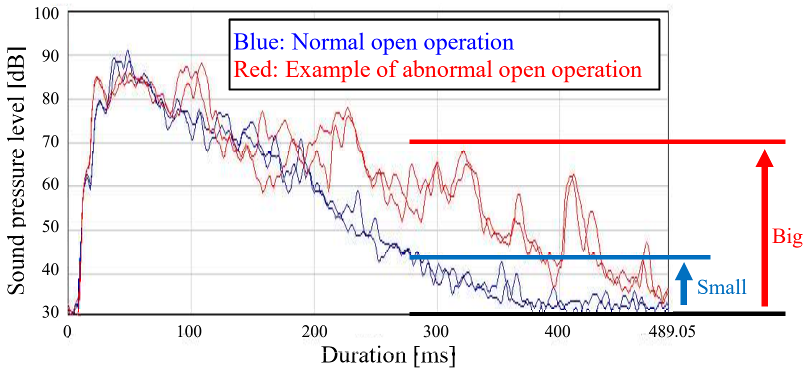
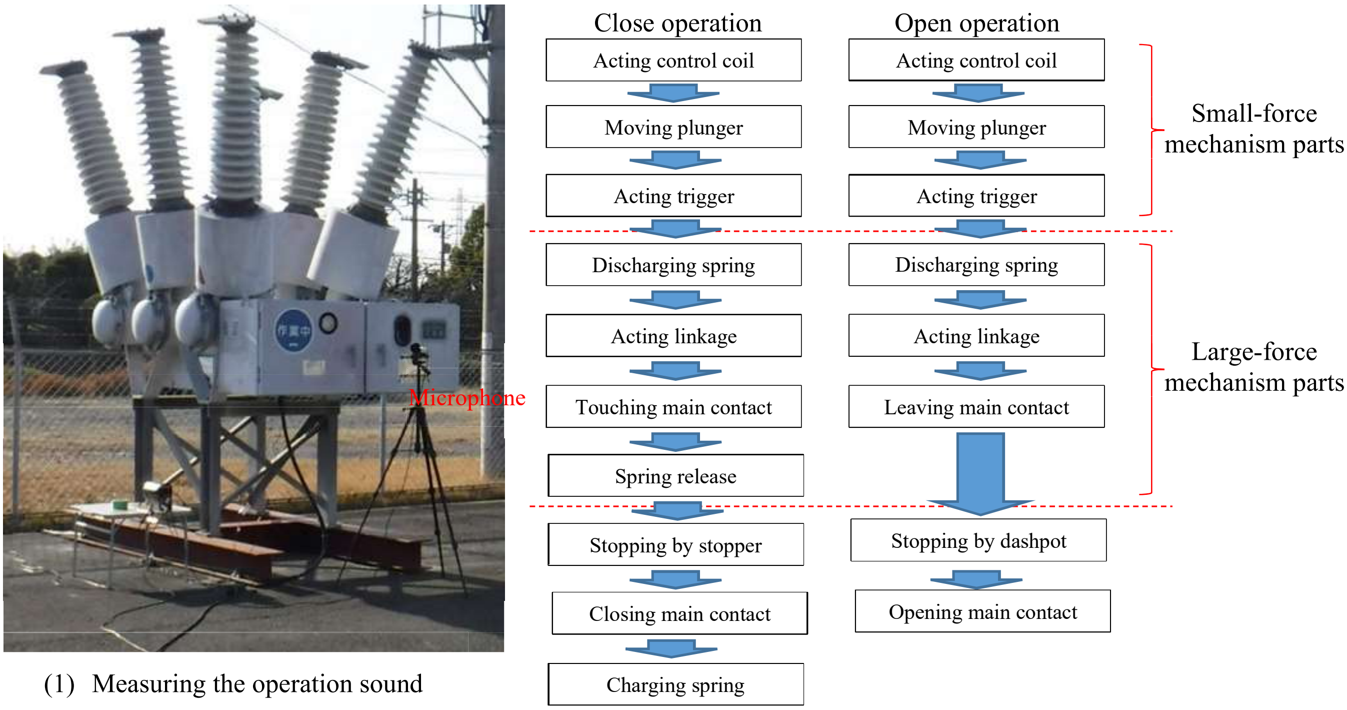


Fig.9 13 kHz - 15 kHz POA. time-trend for open operation

By using the above two analysis methods, it was possible to distinguish the operating sounds with abnormal parts. As a result of the above study, it has been found that operation sound diagnosis of the circuit breaker is an effective condition monitoring technique because the operation sound is generated in time series related to the operation process of the circuit breaker.

3.2 Study of pattern recognition method for condition monitoring

Various abnormal operations have been simulated using a large 84 kV circuit breaker with motor-spring driving-gear as a demonstration machine and a pattern recognition method for abnormal evaluation has been studied. Fig. 10 shows the state of operation sound measurement and the process in the open/close operation of a circuit breaker with the motor-spring driving gear.



(1) Measuring the operation sound

(2) Process in close/open operation in case of motor-spring driving gear

Fig.10 Example of 84 kV Circuit Breaker

The operating mechanism of the circuit breaker is roughly divided into two parts: a small-force mechanism part, such as a control coil, and a large-force mechanism part, such as a linkage mechanism. As a variation of the abnormality for the small-force mechanism part, an electrical failure due to a control voltage drop of the control coil and some mechanical failures as shown in Fig. 11 have been simulated. As a variation of the abnormality for the large-force mechanism, a mechanical failure shown in Fig. 12 has been simulated.

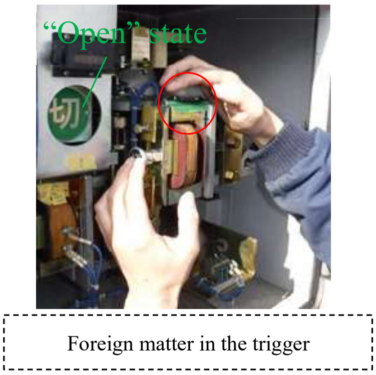


Fig. 11 Abnormal simulation for small-force mechanism parts due to mechanical defect

Fig. 12 Abnormal simulation for large-force mechanism parts due to mechanical defect

It has been found that the operating sound appears as a characteristic change according to the abnormality of each part. As for the abnormality in the small-force mechanism part, as shown in Table 1, the entire waveform starts to be delayed at the sign of the failure to operate, and when the failure to operate occurs, all the subsequent waveforms are lost. As a result, only the peak of the small sound when the first trigger is moved remains.

As shown in Table 2, it can be seen that the following sound starts to be delayed at the sign of failure to close, and only the following sound disappears at failure to operate. This indicates that the operation of the small-force mechanism, which is the first half of the operation process, is normal, but the large-force mechanism, which is the second half, is abnormal.

Table I Results of sound analysis in abnormal simulation of small-force mechanism part

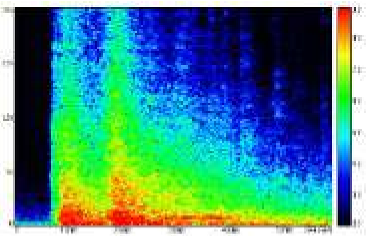
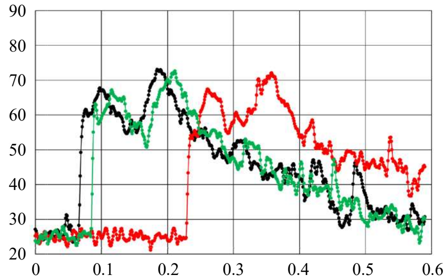
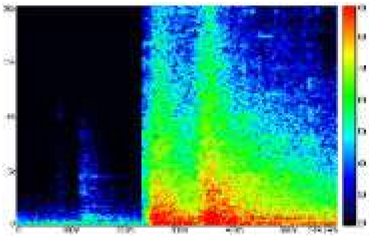
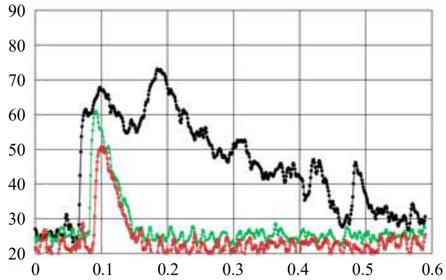
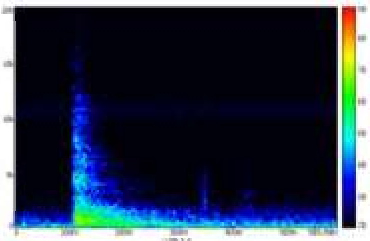
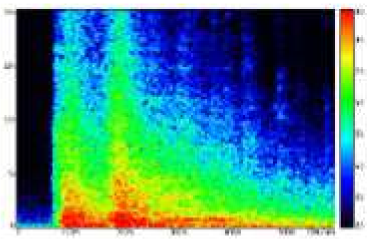
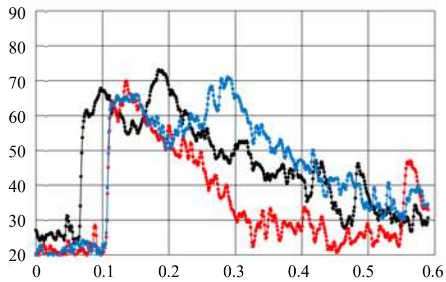
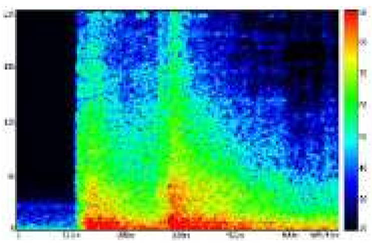
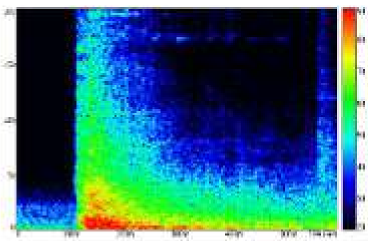
		FFT color map	13 k-15 kHz POA time-trend
Close	Normal	Frequency [Hz]  Duration [s]	Black: Normal Red: Sign due to electrical defect Green: Sign due to mechanical defect 
	Sign	Frequency [Hz]  Duration [s]	Black:Normal Red :Failure to operate due to electrical defect Green:Failure to operate due to mecanical defect 
	Failure to operate	Frequency [Hz]  Duration [s]	Y-axis: Sound-pressure level [dB] X-axis: Duration [s]

Table II Results of sound analysis in abnormal simulation of large-force mechanism part

		FFT color map	13 k-15 kHz POA time-trend
Close	Normal	Frequency [Hz]  Duration [s]	Black: Normal Blue: Sign due to mechanical defect Red: Failure to operate due to mechanical defect 
	Sign	Frequency [Hz]  Duration [s]	
	Failure to operate	Frequency [Hz]  Duration [s]	Y-axis: Sound-pressure level [dB] X-axis: Duration [s]

After doing an abnormal simulation of each part, when the movement of the circuit breaker operation mechanism is superimposed on the 13 kHz to15 kHz POA time trend of the operating sound, as shown in Fig. 13 and Fig. 14, the following four results are obtained. It turned out that the waveform can be roughly divided.

(1) The small-force mechanism moves
(2) The large-force mechanism moves
(3) The mechanism stops at the stopper or shock absorber.
(4) The spring charges (the energy storage mechanism moves)

By arranging the method of recognizing the abnormality pattern based on this idea, it is possible to apply the abnormality judgment using operation sound analysis to the circuit breakers of all manufacturers.

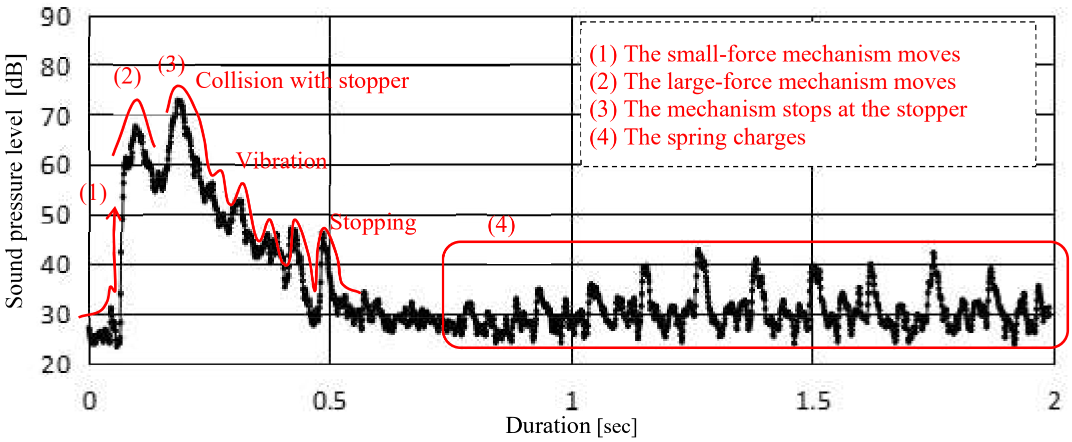


Fig. 13 Key of pattern recognition for close operation

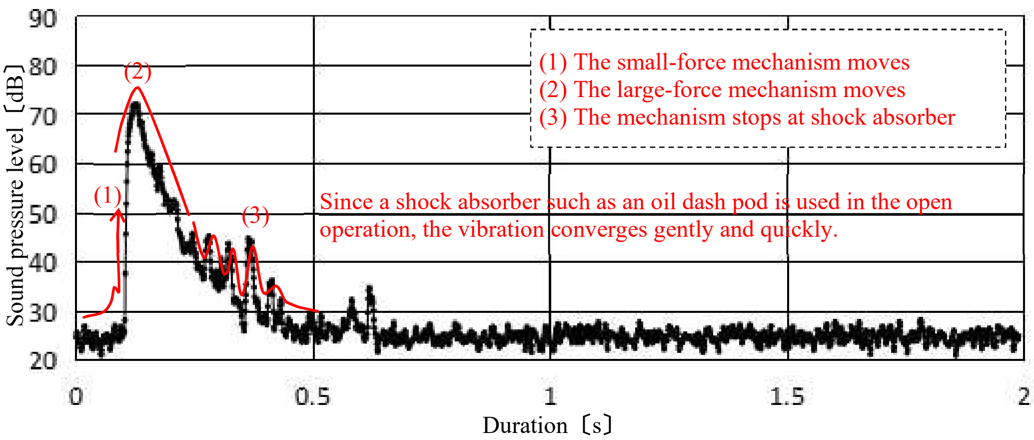
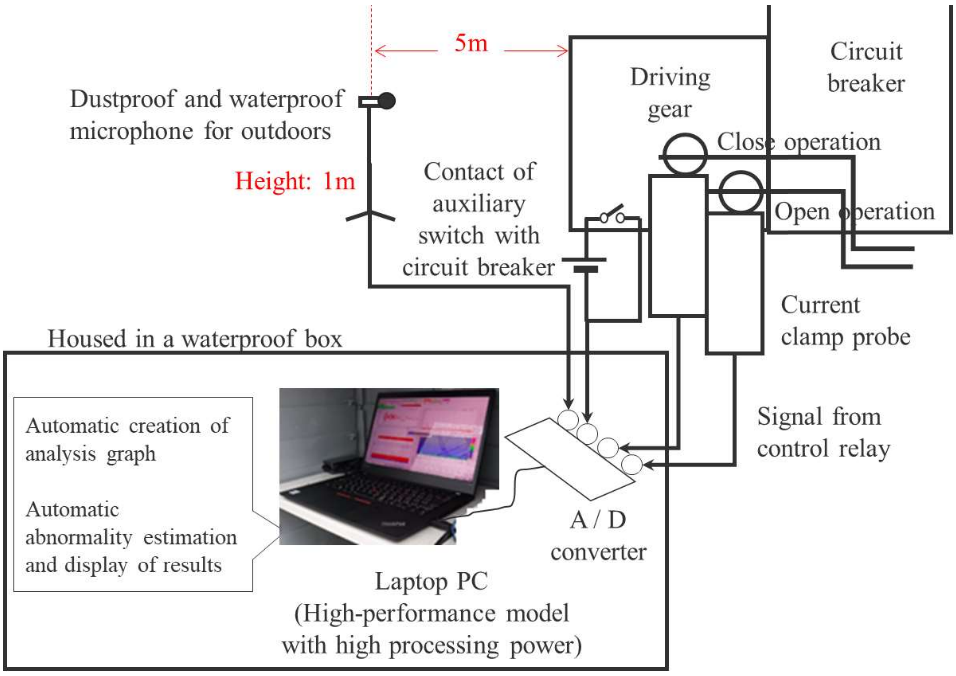


Fig. 14 Key of pattern recognition for open operation

3.3 Trial work of circuit breaker condition monitoring device with operating sound

A condition monitoring device using two operating sound analysis methods have been prototyped and installed on a trial basis in an actual substation. The result showed the monitoring program has been activated according to the open/close operation of the circuit breaker, and the operation of the circuit breaker could be accurately diagnosed. Fig. 15 shows the prototype condition monitoring device and the actual trial situation at the substation.



(1) Prototype condition monitoring device

(2) Trial situation at the actual substation

Fig. 15 Prototype device for trial work

4. Conclusion

In this paper, we focused on monitoring switchgear with "operating/control current" and "operating sound" to implement condition-based maintenance (CBM) of switchgear. As a result, it was found that both methods of monitoring can detect signs of failure that lead to the failure of switchgear. We have also developed devices to monitor both, and such devices can be installed in actual substations. By using these devices, switchgear can be monitored every time it is operated, and by detecting the signs, operational failure can be prevented. This means that the switchgear condition can be diagnosed more sensitively and more frequently than with conventional maintenance (TBM). In addition, since switchgear can be monitored remotely and without power outages, the time and labor required for switchgear maintenance can be greatly reduced.

In the future, we will continue to improve the accuracy of these monitoring techniques and systemize them by combining the method with AI technology. The system will automatically collect and analyze data to detect signs of failure, thereby reducing the time and labor required for daily monitoring of switchgear.

In addition, with the recent advances in IoT technology, it is possible to monitor the condition of equipment at low cost using many other parameters such as “hydraulic pressure” of hydraulic pumps in addition to the “operating/control current” and “operating sound” developed this time. In this way, not only switchgear but also all equipment in the substation, such as winding equipment, can implement CBM as well. By expanding the scope of application of CBM, we aim to automatically monitor the entire substation in the future.

5. BIBLIOGRAPHY

[1] K. Wakaiki “Consideration on operating time of circuit breaker and switchgear” (IEEJ, 2019, No. 325)

[2] T. Kanamori “Consideration on Operating Time of Circuit Breaker” (IEEJ, 2021, No. 268)

[3] T. Sugimoto “Study of Condition Monitoring by Operating Sound for Circuit Breaker” (ASJ, 2018, No. 3-4-16)

[4] T. Sugimoto “Study of Abnormal Pattern Recognition by Operating Sound for Large Size Circuit Breaker in Substation” (ASJ, 2020, 1-10-1)