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Transition to Digital Smart Maintenance in Steel Plant Power Equipment

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Abstract:

Improving equipment maintenance is an urgent issue in the steel industry. In particular, the power supply network, a critical plant infrastructure, is required to improve equipment maintenance. Because failures in the network can affect multiple production lines and there are concerns that the recovery period will be prolonged, maintaining network reliability is essential. However, conventional maintenance methods are limited to long-term diagnoses that involve power outages, making condition-based maintenance difficult and costly. We are currently transitioning to Smart Maintenance by introducing an online-based digital diagnostics system that utilizes location and analysis of partial discharge and dissolved gas monitoring technology to perform condition-based predictive maintenance.

1. Introduction

At JFE Steel's West Japan Works (Kurashiki), a large number of plants, beginning with the blast furnace, and the power receiving and transforming equipment that provides the power supply for these plants, exist at a large site with an area of more than 10 million m^2. Many of these facilities were built between 1966 and 1976, during Japan's period of high economic growth, and many have already been in operation for more than 50 years and have reached the period for equipment renovation. However, it would be difficult to replace this vast amount of equipment simultaneously since the power network includes more than 2 000 transformers and more than 7 000 distribution panels. Furthermore, the blast furnace cannot be shut down, and steel production cannot be interrupted. Therefore, arranging a time to shut off an electrical system for repair/renovation is difficult and can be costly. For this reason, we have established a method to prioritize repair and renovation of aged electrical assets based on testing and assessment of the level of deterioration and the criticality of repair needs. The priority list established by testing and diagnosis helps us to make a sequential repair and renovation schedule, which helps us to use a given budget more effectively to improve electrical network reliability.

We call this method of testing, assessing, and prioritizing repair/renovation of electrical assets "Smart Maintenance."

In a sizeable power-consuming facility, the Smart Maintenance method becomes essential because it is imperative to ensure the reliability of the power supply system in an environment where a mixture of new and old equipment operates. Smart Maintenance aims to detect the early signs of equipment deterioration that may lead to failure. JFE Steel has developed and actively introduced various technologies related to the development of Smart Maintenance to date. This paper introduces examples that have demonstrated the effectiveness of Smart Maintenance remarkably well.

2. Examples of Smart Maintenance

2.1 Smart Maintenance System

The conventional method to protect power transformers is the "protection relay system." When the system detects excessive currents and leakage currents, the relay trips and cuts off the flow of electricity to the failure point. The primary purpose of the protection relay system is to prevent the propagation of failures, thereby protecting the rest of the power network and its assets. It is a reactive method, which means the protection system reacts when a failure occurs somewhere in the network, and it is not a predictive or preventive means of protecting the network from the initial failure. In fact, machinery and other equipment at the site have already been damaged in many cases before the protection system is activated, and considerable time is required for recovery.

In contrast to the protective relay system, the Smart Maintenance concept is based on continuous monitor-

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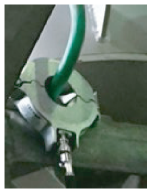
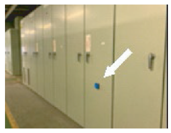
ing and detection of signs of incipient equipment failure and issuance of alerts to the maintenance personnel. In the Smart Maintenance system introduced by JFE Steel, the following three items are monitored continuously to detect and identify equipment deterioration and incipient failure in power transformers: (1) partial discharge, (2) dissolved gas in insulating oil, and (3) local overheating.

Partial discharge (PD) refers to a localized breakdown of the space between two conductors in a small portion of solid or fluid electrical insulation under high voltage stress. However, the breakdown does not entirely bridge the gap between the two electrodes. Types of partial discharge include Corona Discharge, Surface Discharge, and Void or Internal Discharge. Corona discharge occurs directly into the air and emanates from a sharp surface of the conductor. Surface discharge, also called tracking discharge, propagates along the surface of insulation. Contamination and moisture along the insulation surface are the two most common causes of surface discharge. Void or internal discharge is most often caused by a defect in the solid insulation of cables, bushings, GIS junction insulation, and other components. Void discharge is highly destructive to insulation and typically worsens until it causes ultimate failure. If PD is left uncorrected for an extended period, the insulating material will deteriorate, resulting in dielectric breakdown and a fault. Furthermore, in some cases, airborne PD generates ozone and/or nitric acid, which causes corrosion of metallic parts, leading to mechanical failure. Thus, it is crucial to monitor the occurrence of PD, and in case PD is detected, promptly identify the location and cause of occurrence and eliminate the cause. In the Smart Maintenance system, PD is monitored and detected by using HFCT (High Frequency Current Transformer) sensors, FMC (Flexible Magnetic Coupler) sensors, and TEV (Transient Earth Voltage) sensors. **Photo 1** shows a case of incipient tracking creepage discharge, and **Table 1** shows the specifications of the various types of sensors.

Photo 1 Case of creepage discharge[1)]

Table 1 Partial discharge sensor[2)]

	HFCT	FMC	TEV
Application	Cable transformer GIS	Extra-high-voltage cable	Enclosed witchboard
Principle	Electromagnetic coupling	Electromagnetic coupling	Electromagnetic coupling
Sensitivity	1 MHz ~ 80 MHz	500 kHz ~ 50 MHz	100 kHz ~ 300 MHz
Appearance			 

In the case of dissolved gas in insulating oil, if local overheating or partial discharge occurs in a transformer, the decomposition of the insulating oil generates combustible gas, which is then dissolved in the oil. For example, ethylene (C_2H_4) is typically generated by low-temperature overheating, and acetylene (C_2H_2) is generated by high-temperature overheating due to PD and arcing of metal parts. It is then possible to analyze and identify the signs of deterioration by collecting oil samples and investigating the type and concentration of the dissolved gas. Conventionally, this analysis of dissolved gas in transformer oil was carried out by a batch method with a 6-month to 1-year cycle. However, given the declining number of skilled electrical engineers/technicians and the subsequent heavy workload, it is becoming more and more difficult to do manual batch testing of a vast number of power transformers, even at an interval of once a year. At JFE Steel, we implemented an automated, continuous monitoring system. **Photo 2** shows the appearance of a continuous monitoring device for analysis of dissolved gas in transformer oil.

Photo 2 Appearance of continuous monitoring device for dissolved gas in insulating oil[2)]

External local overheating is a phenomenon in which the temperature rises due to the Joule heat generated by a flowing current and contact resistance when

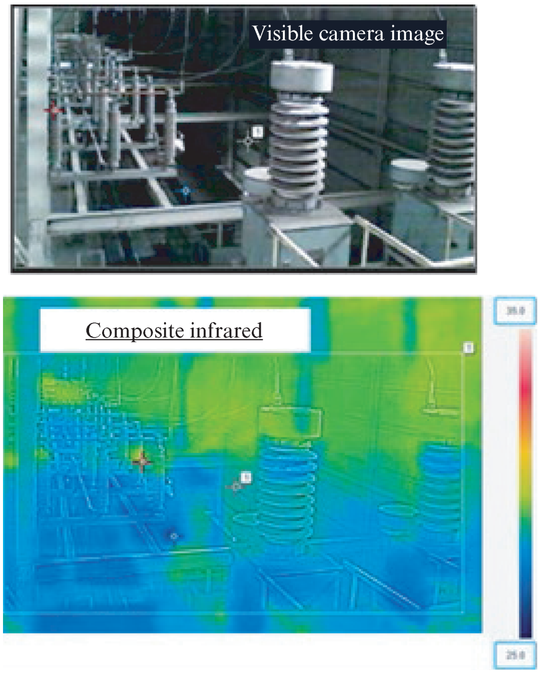


Fig. 1　Image examples of infrared camera[2)]

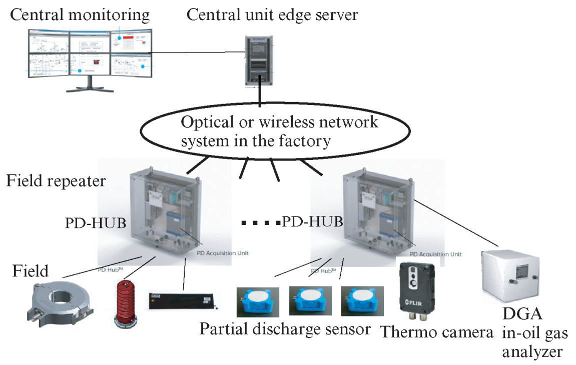


Fig. 2　Substation monitoring system configuration diagram[2)]

poor contact occurs in a junction in the circuit of electrical equipment, such as a termination, bus bar connection, external bushings, and others, and may lead to a fault if left uncorrected. In JFE Steel's Smart Maintenance system, external local overheating is monitored using infrared cameras. These infrared cameras can display visible-light camera images and infrared thermographs separately or as a composite image, as shown in **Fig. 1**, and can give an alarm if a hot spot exceeds a set temperature.

The Smart Maintenance system links multiple substations and the Energy Center (Central Control Room) via an optical fiber network, as shown in **Fig. 2**, and continuously monitors early signs of deterioration.

2.2 Discharge Source Detection Technology

When PD is detected by a monitoring unit at a substation, it is essential to identify the source and correct

Photo 3　Ultrasonic partial discharge detector

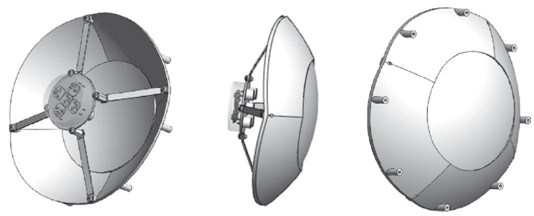


Fig. 3　5-axis parabolic antenna

the cause of the discharge. From an early date, JFE Steel developed a device to identify the sources of discharges. **Photo 3** is the most recent model, which detects the ultrasonic waves generated by PD. The first-generation model, developed around 2000, received the 35th Prize of the Japan Society for the Promotion of Machine Industry. The manufacturer, JFE Advantech Co., Ltd., has carried out model upgrades for this ultrasonic PD detector, which has been manufactured and sold continuously up to the present and is actively used even now[3)] by users all over Japan.

This device employs a mechanism whereby the faint ultrasonic sound generated by PD is collected using a parabolic antenna. While using a parabolic antenna increases sensitivity, it also has the drawback that the detectable area is limited due to its sharp directionality, so time is required to search for the source of a discharge.

To overcome this drawback, we developed an antenna with multiple focal points. **Figure 3** shows an example of a 5-axis parabolic antenna.

The 5-axis parabolic antenna enables high sensitivity and high-speed visualization, equivalent to pointing five parabolic antennae simultaneously at an area where PD is suspected. **Photo 4** shows an example of the discharge source detected and identified by the 5-axis parabolic antenna.

2.3 Partial Discharge Diagnosis of Rotating Machinery

Partial discharge is unavoidable in the stator windings of electric generators and large-scale motors

Photo 4 Specific example of partial discharge sources

because high-voltage coils are arranged in the slots of the iron core. For this reason, motor and generator manufacturers use mica, an inorganic substance, as an insulating material at the slots to increase tolerance to discharge. However, even using mica is not adequate to protect rotating machinery. Once PD starts, it will progress until it starts to erode the semiconductive coating and the insulation, ultimately leading to a fault due to dielectric breakdown. Since spare parts are generally not kept for large-scale rotating machinery, a dielectric breakdown failure will have a severe impact on factory production. Therefore, since 2000, JFE Steel has worked to prevent failures in advance by installing capacitive couplers to detect PD in rotating machinery and performing online monitoring of PD utilizing these devices. Although noise in acquired data is unavoidable in rotating machinery, clear separation of the noise and PD signals is possible by using an algorithm that separates noise from PD and identifies the cause of PD.

Figure 4 is an example of the signal acquired with a conventional measurement device. The partial discharge signal and exciter noise are superimposed, making separation of the PD signal from the noise impossible.

Figure 5 shows an example that was measured with a modern measurement device at the same location and time as Figure 4 above. First, the PRPD (Phase Resolved Partial Discharge) pattern of the pulse signals is resolved by an algorithm called T-F mapping by assigning an equivalent time length (T) and equivalent bandwidth (frequency range, F) for each acquired pulse signal. By mapping in this way, slow pulses cluster on the upper left-hand side of the map and fast pulses cluster on the lower right-hand side of the map. These parameters are mapped by “F” on the X-axis and “T” on the Y-axis, and a TF map showing the frequency of the pulse signals on the X-axis and the wavelength on the Y-axis is created. Because the clusters on the T-F map correspond to characteristic signal sources, we can identify the cause of the PD. Conversely, each signal cluster on the T-F map can be put back on the PRPD graph to indicate the pulse signals occurring at the

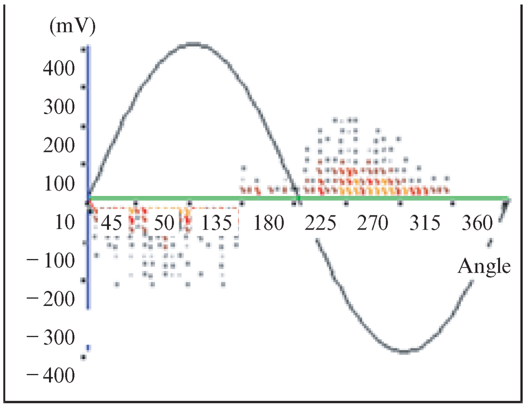


Fig. 4 Conventional on-line diagnostic measurement waveform

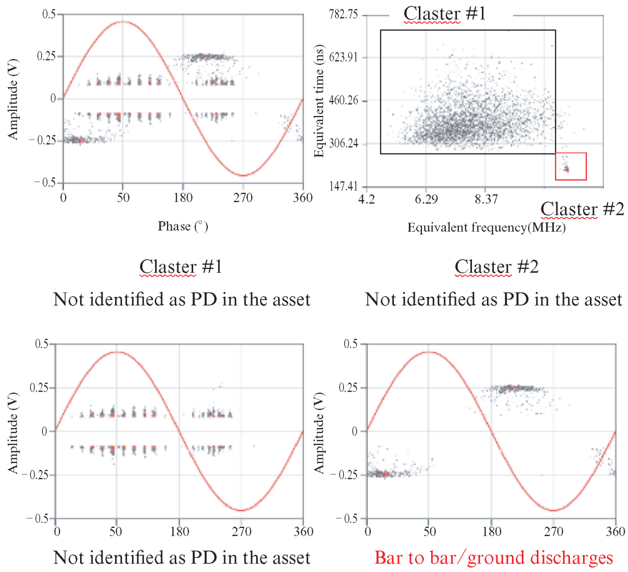


Fig. 5 Modern on-line diagnostic measurement waveform

source.

The result of this analysis is illustrated by the example in Fig. 5, where Cluster #1 is exciter noise and Cluster #2 is the PRPD pattern of a partial discharge.

Thus, modern online diagnostic techniques can be utilized to separate partial discharge from noise and accurately identify and manage harmful PD.

3. Conclusion

Among various efforts to implement the Smart Maintenance concept at JFE Steel, this article has introduced some online monitoring devices and a PD location and diagnosis technology for rotating machinery. As mentioned in the Introduction, production shutdowns for maintenance are impossible in the steel industry, where steel production depends on the continuous operation of the blast furnace. Subsequently, much effort has been devoted to developing online technologies for detecting incipient equipment deterioration since the early days. We will continue to achieve even more automated Smart Maintenance by integrating the knowledge gained to date with IT and AI technologies.

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