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On-line Partial Discharge Monitoring System for Diagnosis of Insulation Condition in Generators

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SUMMARY

In recent years, with the increase integration of renewable energy such as solar and wind power, the operating pattern of generators is changing and the demand for variable load operation of existing generators has been increasing as well. This may accelerate deterioration of electrical insulation of stator coil windings. A useful method for monitoring/diagnosing electrical insulation conditions of in-service generators is online partial discharge monitoring technology, a technology that can increase machine reliability and avoid costly unplanned outages. We have developed a new on-line monitoring system for partial discharge with non-contact sensors with a high-voltage line and its location of installation is outside of generator. It can be installed easily without disassembly and re-assembly of the generator. We also developed an effective noise-separating algorithm that make use of the time difference principle to identify and remove noise signals that may get in from the power system. With our developed phase correction technique, the signal of the non-contact partial discharge sensor is used as reference voltage waveform, therefore the proposed on-line partial discharge monitoring system is isolated from a high voltage line of the power station. The proposed system was built and experimentally tested in some power stations. The results confirm effectiveness of the proposed monitoring system as well as the high reliability of the noise-separating algorithm.

KEYWORDS

Generator - Stator Coil - Insulation - Partial Discharge - Online - Monitoring - Diagnosis - Isolated Phase Bus

1. INTRODUCTION

In recent years, the ever increasing integration of renewable energy sources such PV or wind turbines into the electrical grid necessitates a variable operating pattern of electric generators, a phenomenon that puts high stress cycles on the generator stator coils. This may accelerate deterioration of coil insulation, putting the generator at high failure risks. For this reason, on-line partial discharge technologies, which can provide continuous monitoring and diagnosis of generator conditions, are becoming of paramount importance to ensure machine's reliability and availability, and also to avoid costly unplanned outages or maintenance.
Conventionally, there are two types of partial discharge sensors, slot coupler type and capacitor type. A slot coupler type sensor is installed inside stator slot. For its installation, lengthy outage period is required as the generator needs to be disassembly to reach to the stator slots. On the other hand, a capacitor type sensor is connected directly to the high-voltage line. It may not need that long outage period. it has the problem of its insulation deterioration. To solve these problems, development of a non-contact type sensor for on-line partial discharge monitoring system has been on-going, however, with this type of sensor, the detected signal of partial discharge is relatively small and it is difficult to separate it from noise that may get in from surrounding electric power systems.
To tackle above drawbacks, in this work, we have developed a new on-line partial discharge monitoring system that utilizes non-contact sensor type. The proposed sensor does not contact with a high-voltage line and its location of installation is outside of generator. [1][2][3][4]

2. THE PROPOSED ON-LINE PARTIAL DISCHARGE MONITORING SYSTEM

2.1 System Overview

The non-contact sensor of the proposed on-line partial discharge(PD) monitoring system is a plate-type electrode that is installed on isolated phase bus (IPB), and is coupled with a IPB conductor as a capacitor without actually contacting the conductor as shown in Fig. 1. The sensors can be easily installed on IPBs and that no such major outage is needed.

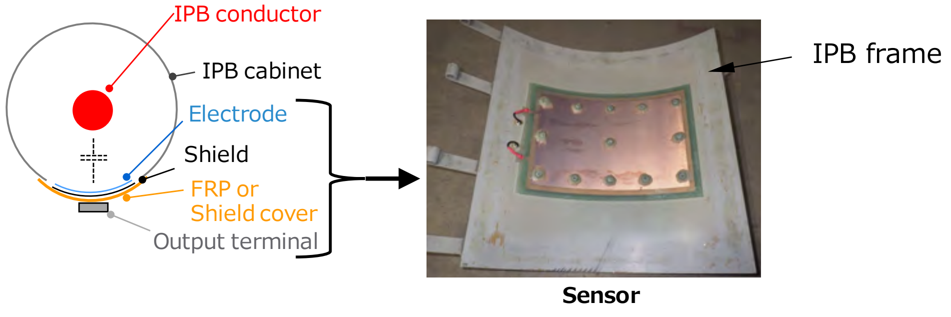


Fig.1 Non-contact senor installed on IPB frame

To put on-line PD (partial discharge) monitoring system with non-contact sensors into practical use, high reliable noise-separating techniques are absolutely necessary, because the signal-to-noise ratio of non-contact sensors is low compared to the amount of noise originating from electric power system and electric equipment in power station. Additionally, the PD signal can be greatly attenuated through a long distance propagation from the PD location to the installation location of sensors.

We also developed a noise separating algorithm that mainly makes use of time difference principle, along with frequency filter and signal analysis, to segregate the noise included in the PD signals. The system diagram is shown in Fig. 2.
A reference waveform is necessary for analysis of PD signal. In a conventional on-line PD monitoring system, a signal of potential transformer is used as a reference waveform. To isolate on-line PD monitoring system from existing main circuit and measuring equipment of power station, we developed the method to extract a reference waveform from signal of non-contact sensors for partial discharge.

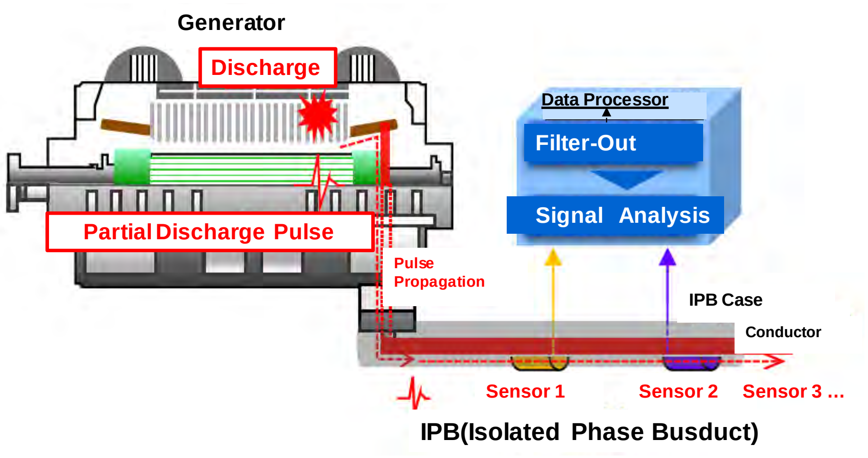


Fig. 2 The proposed on-line PD monitoring system

2.2 Detection Method of Partial Discharge

In the proposed system, the sensor electrode is mounted in the IPB frame in such a way to face the IPB conductor. The gap between IPB conductor and sensor can be represented by a capacitance, C. There is also a gap between sensor electrode and IPB frame which can be represented by a capacitance Co. The detection resistance is represented by R as shown in Fig. 3 below. To measure PD pulse signal, a coaxial cable must be used. Configuring the sensor in this way, high bandwidth band pass filter circuit is formed.

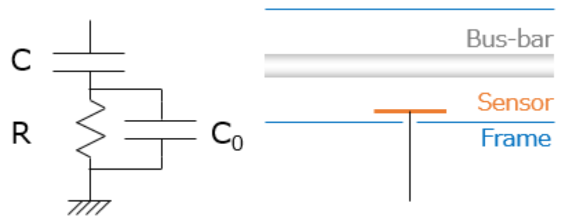


Fig. 3 PD sensor equivalent circuit

The PD signal travels through stator coils, generator terminals all the way to bus-bars. When PD signal travels, the PD signal may deform and attenuate due to reflection. For example, attenuation may happen when PD signal travels from stator coils inside the generator to the bus-bar, outside the generator. The deformation and attenuation may cause frequency reduction of PD signal to several kHz ~ several GHz. Furthermore, to improve detection sensitivity, an impedance converter (impedance transformer) might be effective. The input impedance and output impedance of the impedance converter need to be set separately. In such configured sensor, the electrode size is restricted by the size of the inspection opening on IPB cabinet; the gap between IPB conductor and electrode varies according to the machine rated voltage, and so does the coupling capacitance. Thus, detection characteristics may vary as well.

In that case, by using an impedance converter, sensor detection characteristics can be effectively adjusted by adjusting sensor circuit parameters, i.e. C, Co, R. The sensor electrode needs to be placed in such way not to harm insulation characteristics, making the capacitance, C, small in range of a few Pico farads. Further, attenuation gets even bigger when PD signal is at high frequency range due to inductance of the travelled path. To investigate frequency characteristics, a sine wave signal is applied between conductor and cylindrical frame, and the results are shown in Fig. 4.

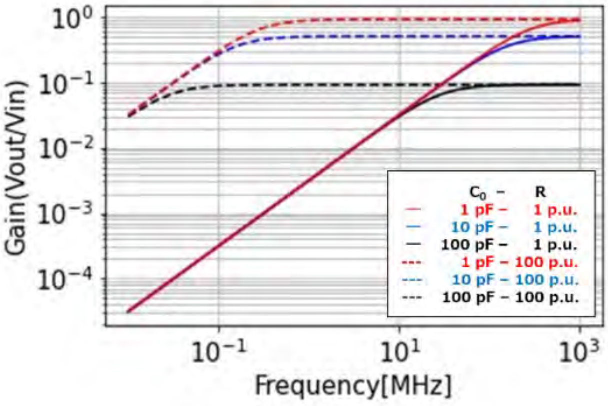


Fig. 4 Detection sensitivity (Frequency characteristic)

The graph in Fig. 4 shows the impact of the capacitance Co. As shown in Fig. 4, as the capacitance Co is large, the gain drops and cut-off frequency tends to decrease.
As the on-line PD detection system is used in in-service generator which is connected with power system, noise from surrounding equipment/apparatus easily affect the PD detection system. Particularly, when there is equipment that inverter driven such motors, the impact of inverter switching noise is great because its switching frequency is high. Furthermore, noise may also originate corona discharge of overhead wires insulators or transformers bushings. Due to the fact that noise component is in range of several MHz, in order to improve the ratio of PD signal to noise (S/N), detection frequency is preferred to be in range of several MHz or more. In on-line PD detection systems, it is necessary to take into consideration two things: first is to place sensor electrode apart enough from the IPB conductor, and second is to minimize capacitance of the gap between sensor electrode and IPB frame. Also, it is a must to pay enough attention to the electrical insulation characteristics of the gap between the IPB conductor and sensor electrode.

2.3 Noise Separating Technique

We could separate signals coming from generator side (mainly PD signals) from signals coming from the power grid side (external noise) by using a separation technique described in [5]. In this separation method signal separation can be achieved by identifying signal time difference detected by several sensors placed in different locations. For example, given that there are two sensors A and B placed in the generator side and the transformer side, respectively, as illustrated in Fig. 5, if a signal is first detected by sensor A, then after some time (in range of tens of nanoseconds) detected by sensor B, this signal is said to be coming from generator side, and mostly probably is a PD signal. Conversely, if a signal is first detected by sensor B, then detected by sensor A, this signal is believed to a noise signal coming from the surrounding power system. Although distance between sensors may vary from one plant to another, our data shows that distance could be best in range of 2 m up to 20 m.

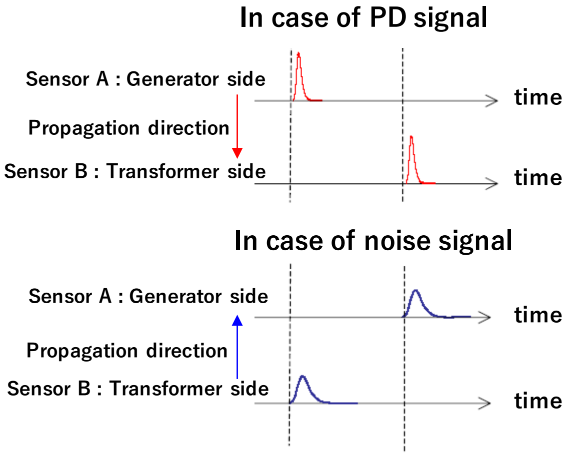


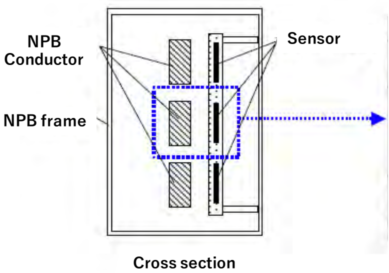
Fig. 5 The principle of difference time separating technique

2.4 Evaluation of Electric Field Around Sensor Vicinity

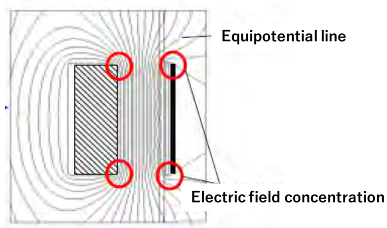
Given that sensor is to be installed in high-voltage line's vicinity, installing the sensor too close to conductor may cause electrical breakdown when the electric field threshold is exceeded due to the disturbance or concentration of electric field. This risk can be mitigated by keeping an appropriate distance between conductor and sensor in such a way electric field becomes uniform. While the electric field can be kept uniform in IPB, it is not the case for non-segregated phase bus (NBP) that has angular conductors, making it necessary to study the effects on the electric field (disturbance or concentration etc.) in that vicinity. This helps improve safety and reliability of the sensors installed near high-voltage lines vicinity.

We evaluated electric field around the sensor vicinity of a rectangular shape model of NPB as shown in Fig. 6 (a). In the model, the sensor is fixed 70 mm apart from the conductor, and the phase voltage of vicinity between conductor and sensor becomes E/√3, where E is the generator rated voltage, in this case, E=6,9 kV.

In Fig. 6 (b), the electric field strength and potential distribution of selected area from Fig. 6 (a). It can be seen that electric field strength gets higher in the areas marked with red circles in Fig. 6 (b) due to narrow spacing of equipotential lines. In that case, the maximum electric field strength observed during generator operation was about 250 Vpeak/mm, that is less than 10 % of the electric field strength required for air breakdown.[6] Therefore, installing the sensor in the NPB or IPB vicinity may not trigger any breakdown/flashover process, and consequently may not adversely affect the generator.



(a) Cross section of a rectangular shape NPB



(b) Distribution of equipotential line

Fig. 6 An example of electric field strength evaluation around sensor

Furthermore, as mentioned earlier, the gap between IPB conductor and sensor acts as a capacitance, C. A part of flowing current on IPB conductor may possibly flow through that capacitance as charging current. For example, considering rated IPB current is 3000 A, and the capacitance C is around 3 pF, a charging current of about 4 μA may flow through C. In other words, the charging current that flow through C is just a $1/10^9$ of the rated current, giving no impact on both generator and the sensor itself.

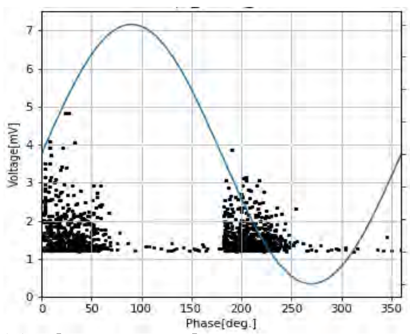
3. WORKSHOP PERFORMANCE VALIDIATION

In this section, to evaluate the detection performance of PD measurement system, we describe results of two experiments carried out on a model bar and on an actual generator.

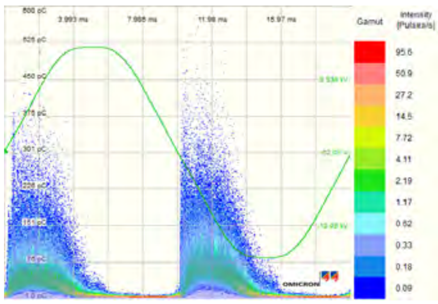
3.1 Validation on a Model Bar

In the model bar experiment, PD signal was measured in two scenarios: (1) surface discharge, and (2) discharge in delamination between conductor and insulation. We used both the proposed PD measurement system as well as conventional off-line system to detect PD signal and compared the results of both. The applied voltage was 10 kVrms-50 Hz, and the measurement was done on 50 cycles, 500 cycles for the proposed and conventional systems, respectively. The applied voltage (reference voltage) for evaluating PD phase characteristics was measured using a high voltage probe. Fig. 7 demonstrates surface discharge characteristics and Fig. 8 demonstrates internal discharge characteristics obtained from the experiments. (a) and (b) in Fig. 7 and Fig. 8 show the phase resolved partial discharge (PRPD) pattern of the proposed system and that of conventional system, respectively.

Referring to Fig. 7 (a), the characteristics of PD are that it quickly rises and peaks in a symmetrical, triangular pattern in both positive and negative cycles. The PD pattern of internal discharge in Fig. 8 (a) is similar to that of surface discharge in Fig. 7 (a) but with a sharper rise as can be seen in the figure. Furthermore, comparing results of the proposed PD system and the conventional system, it can be seen that detected PD in both systems show almost identical characteristics, for example, quick rise, symmetrical triangular pattern.

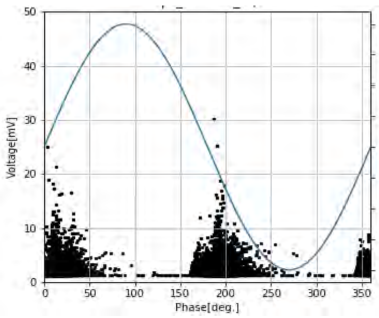


(a) The proposed PD measurement system

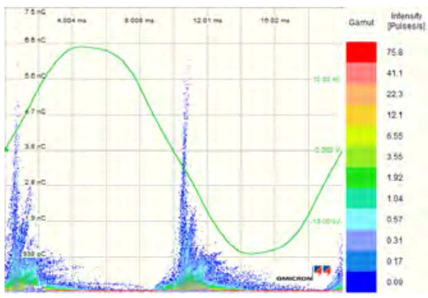


(b) Off-line measurement data

Fig. 7 Surface discharge PRPD pattern



(a) The proposed PD measurement system



(b) Off-line measurement data

Fig. 8 Internal discharge PRPD pattern

3.2 Validation on an Actual Generator

Next, we demonstrate results of system performance validation on an actual generator inside our workshop. Here, a 1270MVA-26kV turbine generator was used. In this validation experiment, 26 kVrms voltage was applied to a single phase of the generator, and the reference voltage was obtained from secondary side of the potential transformer. Fig. 9 shows the experiment setup of the validation test.
The characteristics of PD detected by the on-line system shown in Fig. 10 (a) is it forms a two identical but reversed round shapes in both positive and negative PD. Using the time difference separation technique described in section 2.3, we effectively removed the noise which is believed to be coming from outside generator, resulting in clear PD characteristics shown in Fig. 10 (b). Furthermore, PD characteristics detected by the off-line system are almost identical to those of the proposed on-line system as shown in Fig. 10 (b), and Fig. 10 (c).
The validation results of both model bar experiment and actual generator clearly demonstrate the effectiveness and reliability of the proposed on-line system. Moreover, the noise separation technique is proved to be successful in segregating the noise that might get into system from surrounding power systems etc.

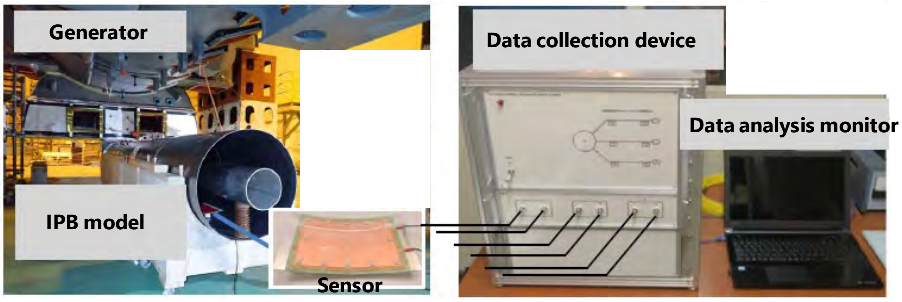
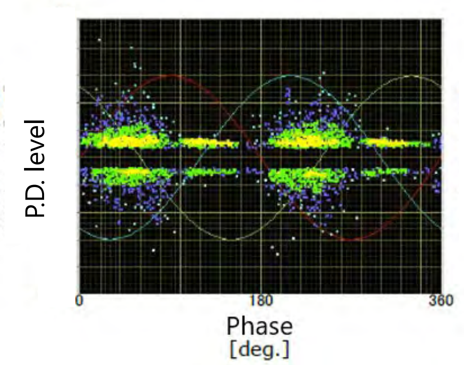
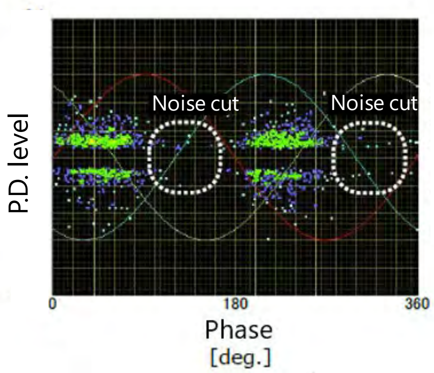


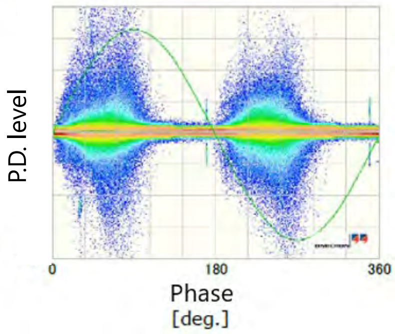
Fig. 9 Experiment setup of generator validation test



(a) PD level before noise separation



(b) PD level after noise separation



(c) PD level for comparison detected by off-line system

Fig. 10 Result of verification test of 1270MVA-26kV Generator

4. MEASUREMENT OF REFERENCE VOLTAGE WAVEFORM

An on-line PD signal analysis requires a voltage waveform with phase information of the operating generator. Generally, in conventional on-line PD monitoring systems, the operating voltage waveform measured by a potential transformer (PT). In case of capacitor type sensor, the operating voltage waveform can be obtained quite simply by just correcting the phase of the measured voltage waveform. The phase correction is an easy task as the capacitance of the capacitor and other electrical constants are fixed, known values. However, since capacitor type PD sensor is directly connected to the main circuit, any failure in PD monitoring system side may potentially cause a trip in the power station.

In the proposed system, in order to avoid the risk of exposing power station to any failure, we also made the measurement of the reference voltage waveform non-contact with the main circuit. Specifically, the signal of the non-contact PD sensor was used as the reference voltage waveform signal. The phase of the non-contact sensor signal differs from actual generator voltage waveform due to the capacitive coupling between the conductor and the non-contact PD sensor and the electrical constant of measurement circuit. The phase and gain characteristics of the voltage measured by the non-contact sensor are evaluated, and the phase of the reference voltage waveform is corrected. For phase correction, the phase correction value is calculated using network analysis, and then is input into phase shift equipment to perform the correction.

A field test of phase correction was conducted in a power station of an 80 MVA class air-cooled generator. Fig. 11 shows the test circuit and Fig. 12 shows the results of the phase shift calculation by network analysis between the reference voltage waveform and the non-contact sensor signal. The calculated phase correction value was 89,3 °. Fig. 13 shows the results of phase correction test. Fig. 13(a) shows measurement data before phase correction and Fig. 13 (b) shows voltage waveform after phase about 90 ° shift correction. The voltage waveform of the non-contact sensor signal after phase correction almost matches the main circuit voltage measured directly from the potential transformer. Therefore, it can be seen that our proposed method for measuring voltage reference waveform successfully works in extracting the operating voltage waveform without exposing the generator neither the PD monitoring system to any risk.

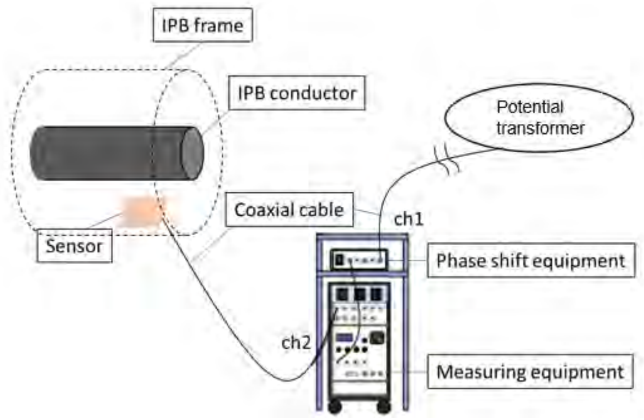


Fig. 11 System configuration of phase correction tested on an 80 MVA turbine generator

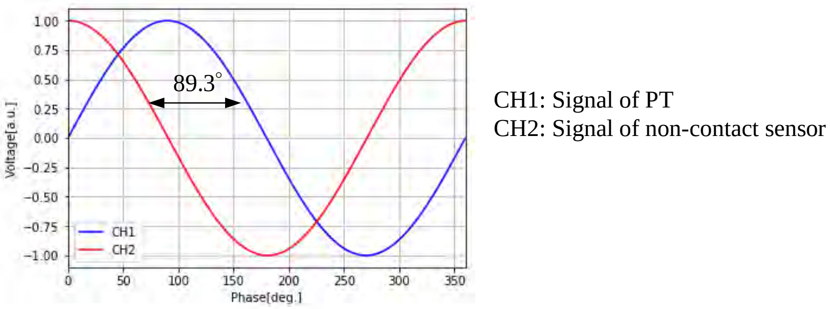
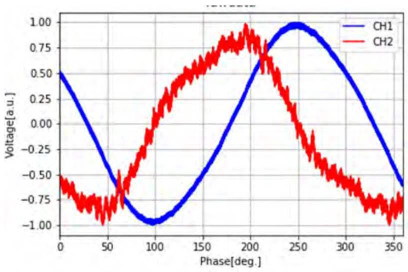
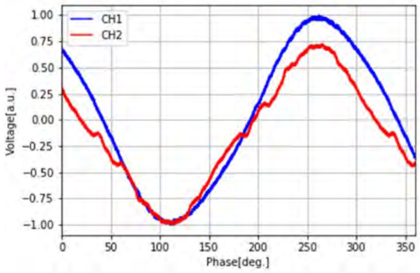


Fig. 12 Network analysis result for 80 MVA turbine generator



(a) Before phase correction



(b) After phase correction

Fig. 13 Result of field test before and after phase correction by approximately 90 ° of 80 MVA turbine generator

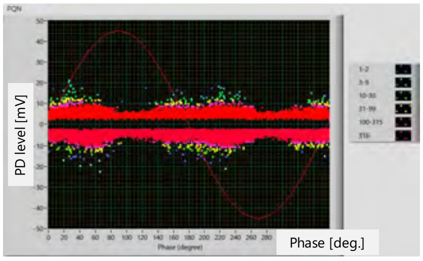
5. FIELD PERFORMANCE VALIDIATION

We installed the proposed on-line PD monitoring system in several operating power stations to validate the system performance including PD detection ability, and noise separating algorithm. Table 1 lists the power stations inside and outside Japan where we installed our proposed system.

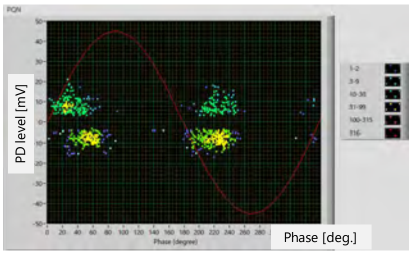
Table 1 Measurement status in power station

No.	Generator Capacity	Cooling Type of Stator Coil	Installation Date	Status
1	800 MVA	Water-cooled	July 2019	During measurement
2	800 MVA	Water-cooled	May 2021	During measurement
3	160 MVA	Hydrogen-cooled	December 2005	Measurement finished
4	80 MVA	Air-cooled	February 2020	During measurement
5	30 MVA	Air-cooled	June 2007	Measurement finished

Fig. 14 shows the PRPD pattern of the measurement results of the 800 MVA class water-cooled generator (No.1). This generator has been in operation for 23 years. Fig. 14 (a) is the data before noise-separating processing, and Fig. 14 (b) is the data after noise-separating process. In the PRPD pattern of Fig. 14 (b), discharge pattern, discharge phase, discharge magnitude, and frequency of discharge occurrence are clarified. In the figure, the recorded PD is characterized by symmetrical round shapes in both positive and negative discharges. These discharge are thought to be discharges in voids and gaps in insulation layer of stator coils. [4]



(a) Before noise separation

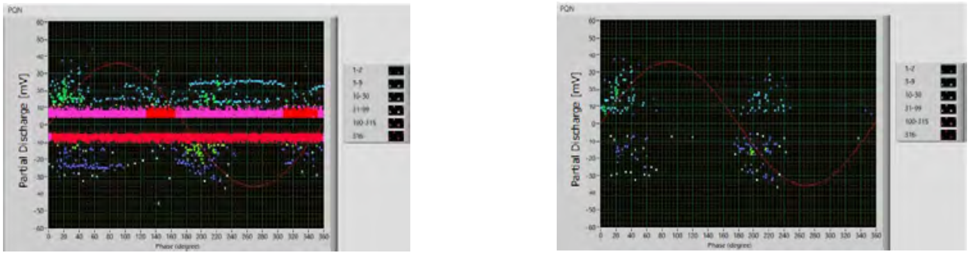


(b) After noise separation

Fig. 14 Field test data of 800MVA generator

Next, Fig. 15 shows U phase PRPD pattern of the measurement results of the 80 MVA class air-cooled generator (No.4). This generator has been in operation for 24 years. In this generator, the replacement work of the outlet connection on the line side and the neutral side had been carried out because surface whitening of coil was confirmed in the coil slot on the line side. In the result, a lot of noise was measured, and crosstalk of PD signal was confirmed. “Crosstalk “means that PD signals from other phases propagates and superimposes.

Fig. 15 (a) is the data before noise-separating process, and Fig. 15 (b) is the data after noise-separating process. From the PRPD pattern after noise-separating processing, discharge pattern, discharge phase, discharge magnitude, and frequency of discharge occurrence can be clearly seen. In this figure, PD was detected between 0 °- 90 ° phase and 180 °- 270 ° phase, and characterized by symmetrical mostly rounded shapes. These PDs are believed to be due voids and gaps in insulation layer of stator coils, as in the previous example.



(a) U phase before noise separation (b) U phase after noise separation

Fig. 15 Field test data of 80 MVA Generator

6. CONCLUSION

We have developed a new on-line PD monitoring system with non-contact sensors for generators. The features of the proposed system include the following:

1) Utilization of non-contact sensors that are easily installed on the IPB of existing power stations
2) A capacitive coupling is used that there is no direct connection between IPB conductor and sensors,
3) Risk from PD monitoring systems posed on the generator main circuit is minimized,
4) Practical phase correction system without directly measuring the operating voltage waveform, and
5) Effective noise separating technique

Performance of the proposed system has been validated in our workshop and in the field. In the workshop validation, two experiments on a model bar and actual generator were carried out. In the field validation, the proposed system has been installed in some power stations inside and outside Japan. Validation results proved that proposed system can effectively detect PD signals, and segregate noise that might get in from the surrounding the power system. The results obtained in this work can be used for further development of online PD monitoring systems.

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