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On-line PD Monitoring System with Microstrip Antenna for Synchronous Generators

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SUMMARY

On-line partial discharge (PD) monitoring for high voltage rotating machine is one of useful insulation diagnostic methods from the view point of condition-based maintenance. Up to now, various on-line PD monitoring systems are developed and applied: for instance, using slot RTD wiring, stator slot coupler (SSC) or inductive sensors.

An on-line PD monitoring system using microstrip antenna (patch antenna) has been developed for high voltage rotating machines such as induction motors or synchronous generators. This system consists of microstrip antennas, PD detectors and a personal computer. Microstrip antenna is a small and flat one which detects electromagnetically radiated PD signals from stator or rotor windings. The frequency of electromagnetic wave detected with the antenna is normally ultra high frequency (UHF) range and depends on the structure of the antenna. It was designed to detect electromagnetic wave of 1.8 GHz around which background noise level is relatively low. Because of its small and flat shape, it is easily installed inside or outside the machine housing without interfering with machine design, manufacturing or operation. It also means that microstrip antennas do not cause a failure of stator winding because they are completely insulated from high voltage stator windings.

Some distinctive PD patterns such as gap type discharge or surface discharge were obtained from generator stator bars in which insulation defects were intentionally given. Those PD patterns are confirmed to be useful for analyzing actual stator windings.

This on-line PD monitoring system has been applied to some synchronous generators. Among them, PD data before and after stator rewinding were obtained from a generator with a long period of operation. We confirmed that the PD level after rewinding is lower than that before rewinding. This system can be used for on-line PD monitoring and PD evaluation of synchronous generators.

KEYWORDS

Partial Discharge - PD - Rotating Machine - Microstrip Antenna - Patch Antenna - On-line - Frequency - Generator - Motor - Electromagnetic

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1 INTRODUCTION

High voltage rotating machines such as induction motors used in a factory or synchronous generators in a power plant are required to operate continuously without unexpected insulation failure. Hence, the importance of condition-based maintenance (CBM) has received considerable attention. On-line partial discharge (PD) monitoring for high voltage rotating machine is one of useful insulation diagnostic methods from the standpoint of condition-based maintenance. Up to now, various on-line PD monitoring systems are developed and applied to them: for instance, using slot RTD wiring, stator slot coupler (SSC) or inductive sensors [1].

An on-line PD monitoring system with microstrip antenna (patch antenna) has been developed for high voltage rotating machines. It was designed to detect electromagnetically radiated PD signals sensitively over a large area of generator windings. In this paper, the characteristic of microstrip antenna, system configuration, PD patterns and PD data analyses are described.

2 SYSTEM CONFIGURATIONS AND MICROSTRIP ANTENNA

The configuration of the on-line PD monitoring system with microstrip antenna and the characteristic of microstrip antenna are described in this chapter.

2.1 System Configuration

This system consists of microstrip antennas, PD detectors and a personal computer. Fig.1 shows a schematic diagram of the system applied to a large turbine generator. Microstrip antennas are placed near generator windings [1].

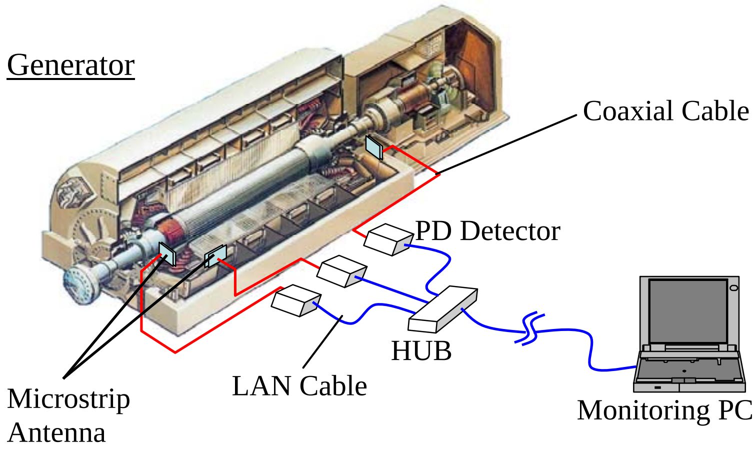


Fig. 1 System configuration applied to large turbine generator.

2.2 Microstrip Antenna

Microstrip antenna is a small and flat one which detects electromagnetically radiated PD signals from stator or rotor windings. The frequency of electromagnetic wave detected with the antenna is normally ultra high frequency (UHF) range and depends on the structure of the antenna.

2.2.1 Structure of Microstrip Antenna

A structure of a microstrip antenna is shown in Fig. 2. A dielectric substrate with relative permittivity ε_r and thickness t [m] is laid on a ground plate, and a patch conductor with length L [m] and width W [m] is placed on the dielectric substrate [2]. The resonance frequency f_r [Hz] of the antenna is determined by ε_r and L if the voltage standing wave ratio (VSWR) is less than 2. The bandwidth of the antenna B_w which is the ratio to the central frequency f_r is also determined by t, L, W, ε_r and f_r. They are expressed by Eq. (1) and Eq. (2) respectively. Thus a microstrip antenna for PD detection can be designed to have narrow bandwidth. The length G shown in Fig. 2 relates to the peak gain of the antenna. The length of each side is 116 mm as shown in Fig. 2.

$$f_r = \frac{c}{2L\sqrt{\varepsilon_r}} \tag{1}$$

where $c =$ the speed of light in a vacuum (3.0×10^8 m/s)

$$B_w = 3.77 \times \frac{\varepsilon_r - 1}{\varepsilon_r^2} \times \frac{W}{L} \times \frac{t \cdot f_r}{c} \tag{2}$$

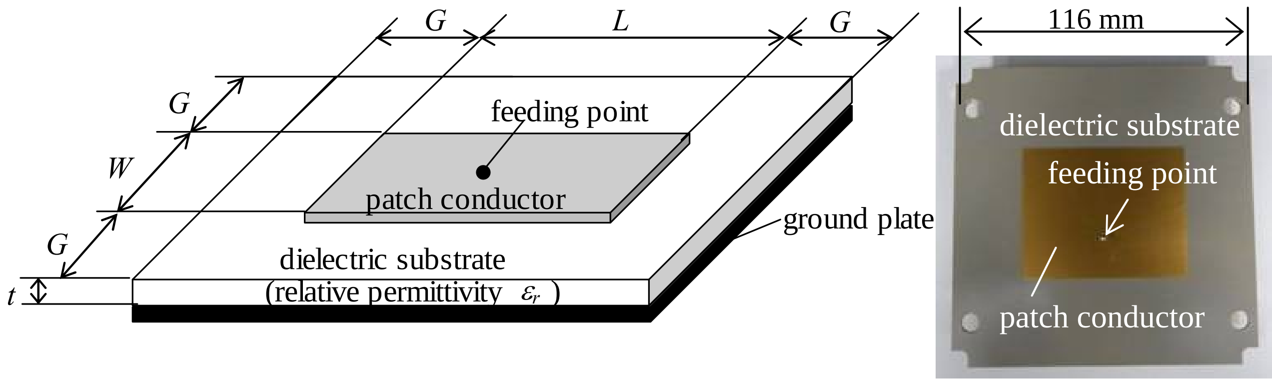


Fig. 2 Antenna structure.

2.2.2 Frequency Characteristic of Microstrip Antenna

The microstrip antenna was designed to have the resonance frequency f_r of 1.8 GHz around which noise level is relatively low, and the antenna has narrow bandwidth in order not to be affected other than PD signals. PD measurement which detects electromagnetically radiated PD signals is available around 1.8 GHz [3]. PD magnitude received by the antenna is expressed in [dBm].

2.3 PD Detector

PD signals received with the microstrip antenna are sent to the PD detector and processed in it. Fig. 3 illustrates the components of the detector. It consists of a bandpass filter, logarithmic amplifier, peak hold circuit and A/D converter [3]. The input PD signal ranging from -90 dBm to -30 dBm is transformed to the output voltage from 0 to 10 V through the detector so that users can easily understand how large PD magnitude is. Fig. 4 shows piled-up PD detectors.

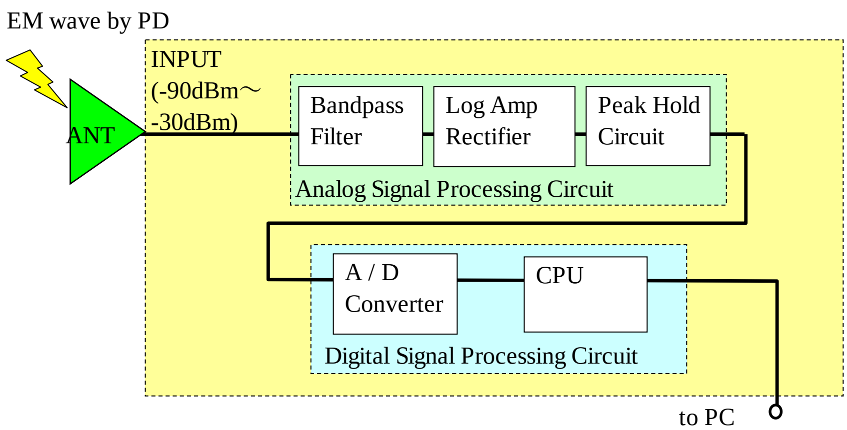


Fig. 3 Block diagram of the detector.

Fig. 4 PD detectors.

3 PD MEASUREMENTS AND ANALYSES

This on-line PD monitoring system has been applied to a number of motors with rated voltage of 6.6 kV, and its availability as an on-line PD monitoring tool was confirmed [4]. This time, the system was applied to synchronous generators. Some distinctive PD patterns such as gap type discharge or surface discharge were obtained from generator stator bars on which insulation defects were intentionally given. Those PD patterns were confirmed to be useful for analyzing actual stator windings.

3.1 PD Properties

Some PD properties were examined with stator bar specimens as shown in Fig. 5. The specimens mainly consist of cupper conductors, vacuum-pressure impregnated (VPI) mica insulation, semiconductive coating on the insulation and stress grading coatings on the insulation. The rated voltage of the specimen is 16.5 kV (1.0 p.u.).

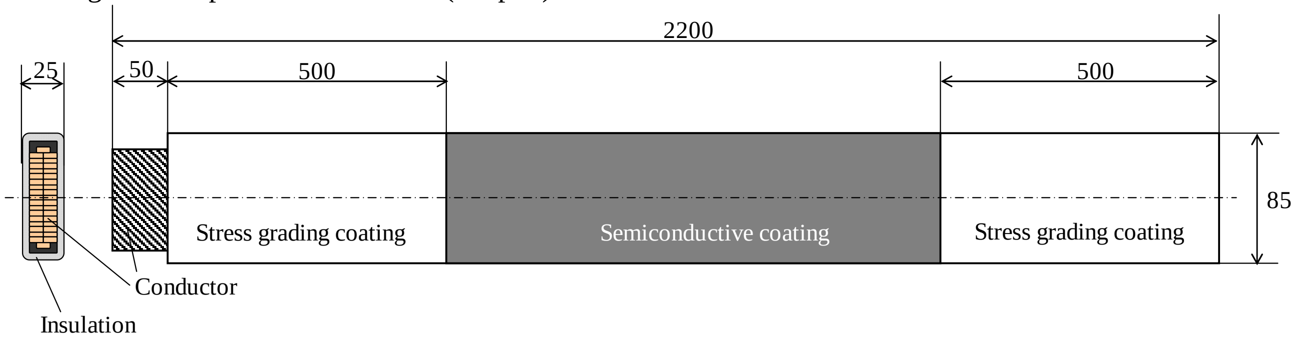


Fig. 5 Structure of specimen used for PD properties examination

3.1.1 PDs in Internal Voids

First, PD phase characteristics were measured with intact specimens. The microstrip antenna was placed near semiconductive coating with the distance of 300 mm from the center of the specimen as shown in Fig. 6. Since the microstrip antenna has directional characteristics, it should face PD sources within an angle of ±20 degrees. Fig. 7 (a) is a PD phase characteristic and (b) is a cumulative characteristic. In graph (a), every PD signal with magnitude is plotted against applied voltage phase. In this system, PD pulse signals are displayed with positive value regardless of polarity. In graph (b), PD magnitude at 50 pulses per second (pps) for 50 Hz machine and 60 pps for 60 Hz machine are used to evaluate the level of PD [1]. Since the duration of measurement is 5 seconds, the PD magnitude at 60 pps equals the PD magnitude at 300 pulses. The PD magnitude at 60 pps is displayed in graph (b).

Fig. 7 (a) shows a PD pattern. These PDs are probably caused by internal voids in the insulation. This mound-like shape corresponds to the PD pattern of internal discharge exemplified in IEC 60034-27 [5].

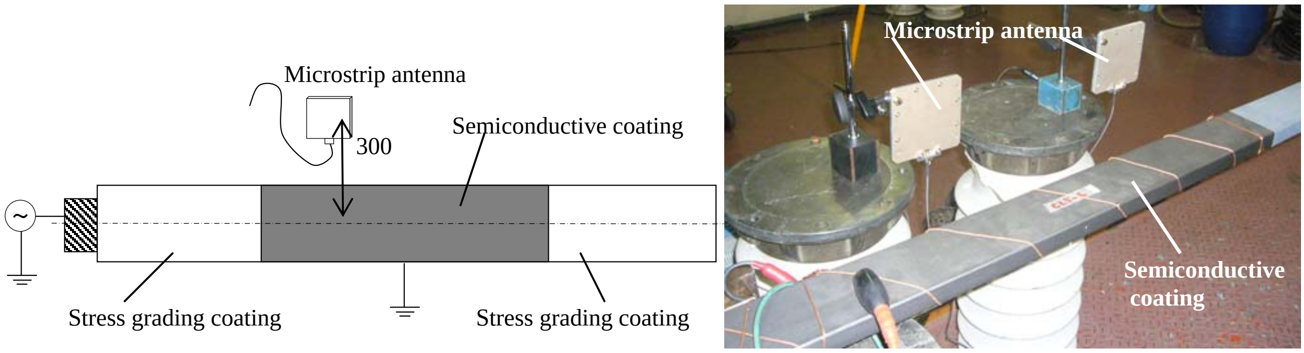
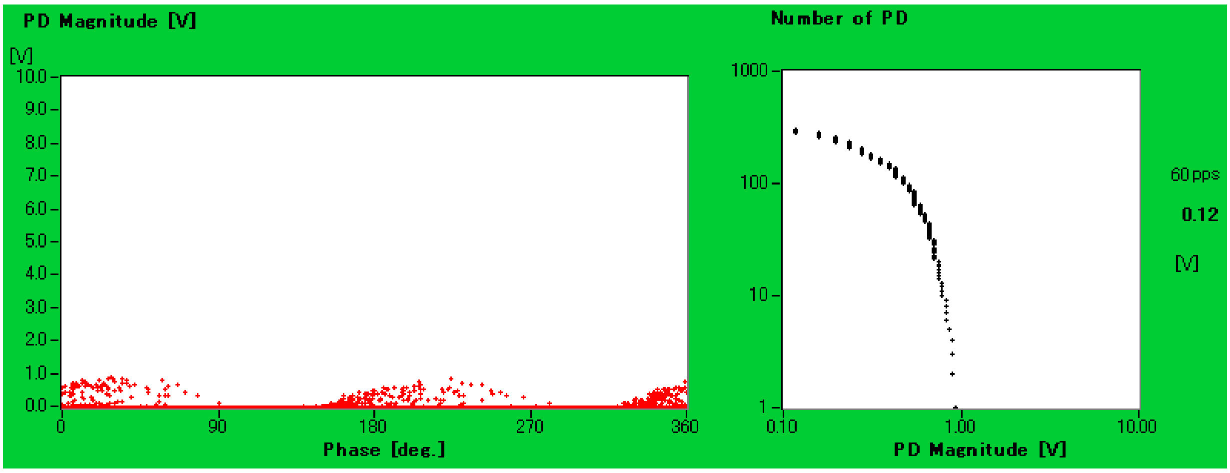


Fig. 6 PD measurement with an intact specimen.



(a) PD phase characteristic (b) Cumulative PD characteristic

Fig. 7 PD data measured on an intact specimen. Applied voltage was 1.2 p.u. (a) All PD events measured in 5 seconds were plotted against stator voltage phase. This PD pattern is caused by internal PDs generated in voids. (b) Cumulative PD characteristic.

3.1.2 PDs in a gap

It is possible that gap type PD occurs between two bars in end windings or between a bar and grounded metal parts such as finger plates of the stator core. A grounded conductor bar (ϕ10mm) was placed over the stress grading coating with a gap as shown in Fig. 8 to simulate this condition. The electric potential of the stress grading coating at the conductor bar is the same as applied AC voltage since it was placed apart from the semiconductive coating. PDs were visually observed as shown in Fig. 9. Fig. 10 shows gap type PD patterns. In the case of narrow gap (e.g., 3 mm), PDs are active because less energy is required to discharge in the gap. But in the case of long gap (e.g., 10 mm), a certain level of electric field is needed to discharge in the gap. Hence PDs are not so active and form a PD pattern like floating cloud. This PD pattern is occasionally observed on operating synchronous generators.

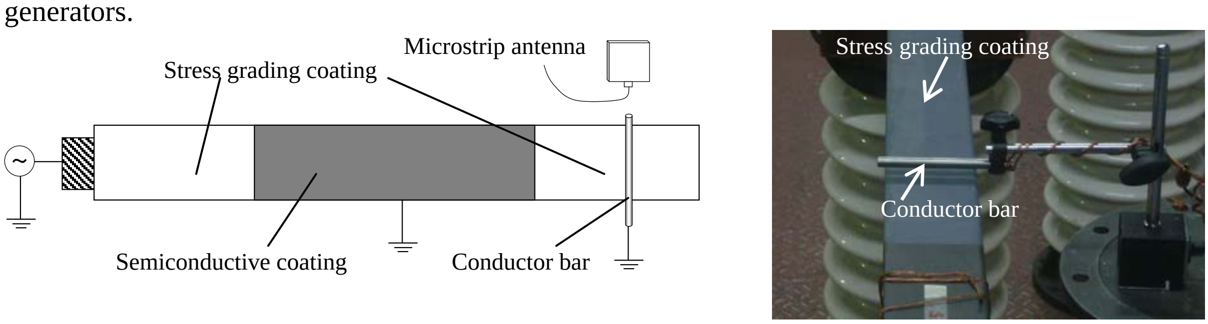


Fig. 8 Gap type PD measurement with a conductor bar.

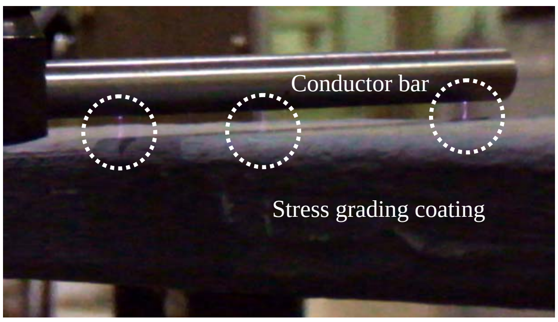
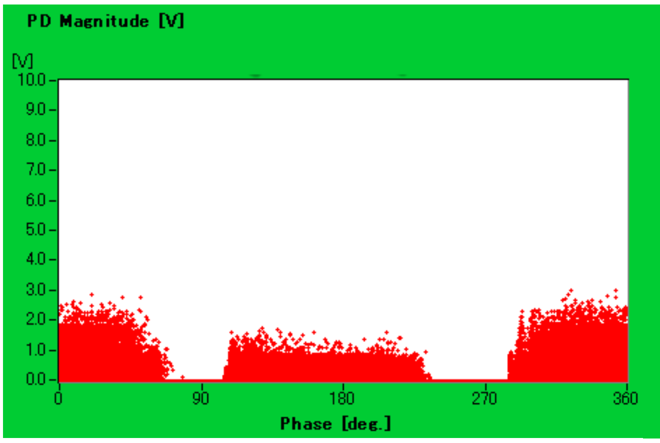
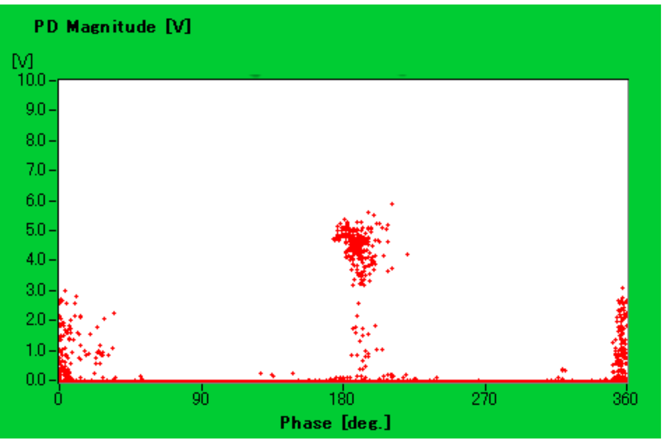


Fig. 9 PDs are visually observed in the gap when applied voltage is 1.3 p.u., and gap is 4 mm.



(a) Applied voltage is 1.0 p.u., and gap is 3 mm.



(b) Applied voltage is 1.3 p.u., and gap is 10 mm.

Fig. 10 Gap type PD patterns.

Another gap type PD measurement was performed with a grounded conductor plate to simulate finger plates of the stator core. Fig. 11 is a schematic drawing of the apparatus used for the measurement. The grounded conductor plate was placed over a specimen with 7 mm gap. Since the semiconductive coating is grounded, the electric potential of the semiconductive coating is zero. Let the position at the interface between semiconductive coating and stress control coating be $x = 0$ mm. The electric potential gradually increases with an increase in position x because of the characteristic of the stress grading coating. Although no significant PDs were measured when the edge of the plate is at $x = 0$ mm, gap type PD pattern was obtained when it was located at $x = 30$ mm. Fig. 12 is a PD pattern at $x = 30$ mm.

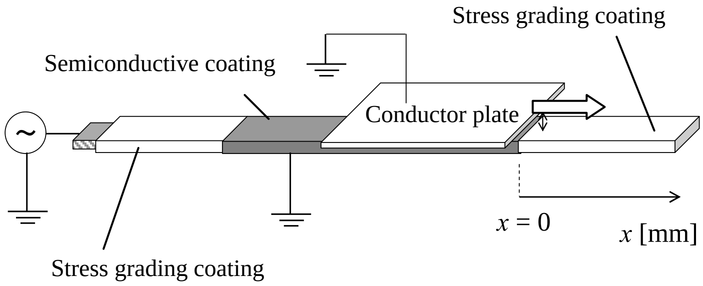


Fig. 11 Gap type PD measurement with a conductor plate. The plate is located at $x = 0$ mm.

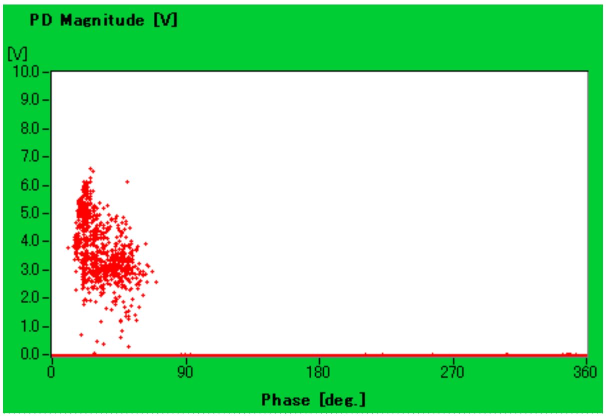


Fig. 12 Gap type PD. The plate was located at $x = 30$ mm. Applied voltage was 1.0 p.u.

3.1.3 Surface Discharge

PDs will occur at the junction between semiconductive coating and stress grading coating if the stress grading coating is not formed properly. Fig.13 represents this condition. A part of the stress grading coating is stripped off at the junction of a specimen. PDs were visually observed at the stripped zone as shown in Fig. 14. Fig. 15 is a surface PD pattern.

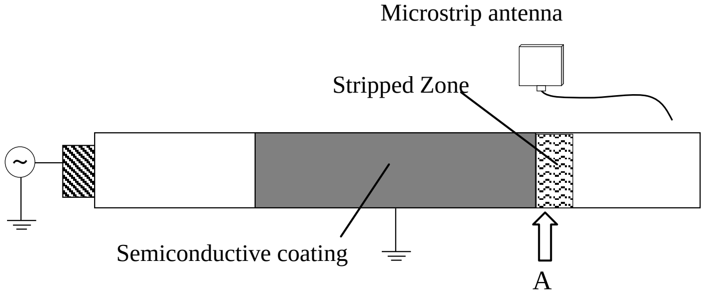


Fig. 13 PD measurement on stripped zone.

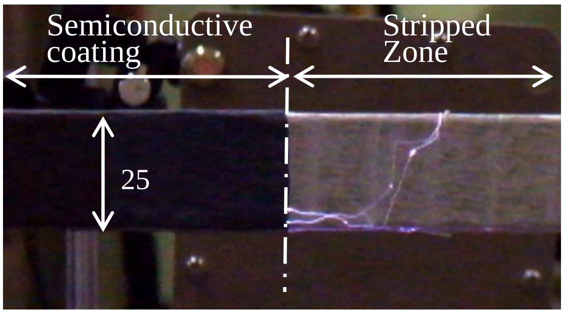


Fig. 14 PDs are visually observed on the stripped zone. This is a side view from the view point A. Applied voltage is 2.0 p.u.

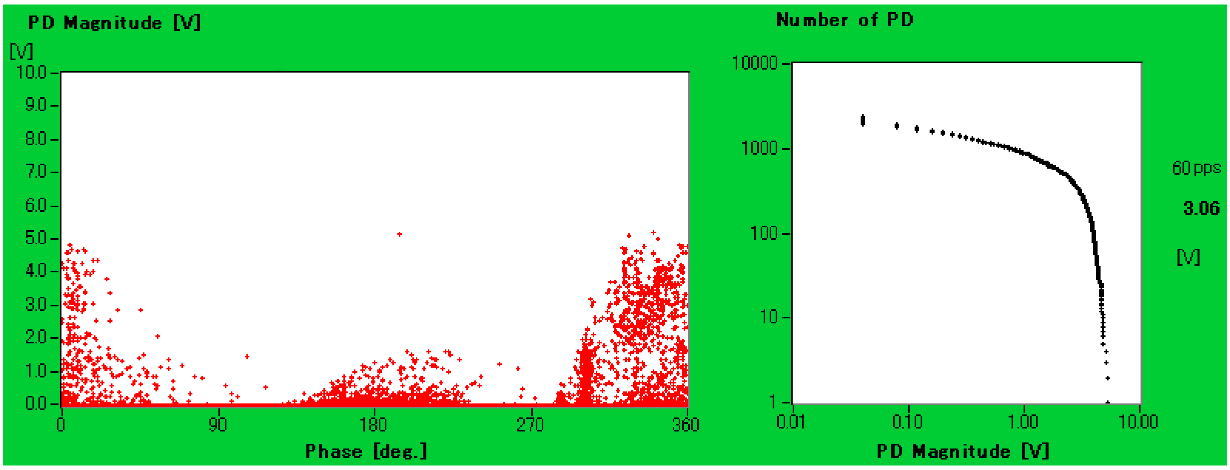


Fig. 15 PD pattern of surface discharge. Applied voltage was 2.0 p.u.

3.2 PD Comparison between aged stator windings and new ones

Generally, microstrip antennas are placed near exciter side end windings and turbine side ones. They face stator end windings as shown in Fig. 16. Because of their small and flat shape, they are easily installed inside the machine housing without interfering with machine design, manufacturing or operation. It also means that the microstrip antennas do not cause a failure of stator windings because they are completely insulated from high voltage stator windings [1].

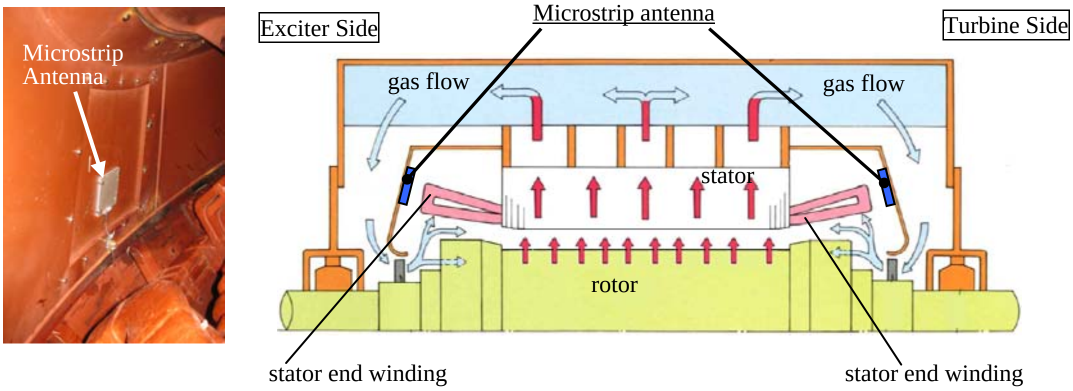
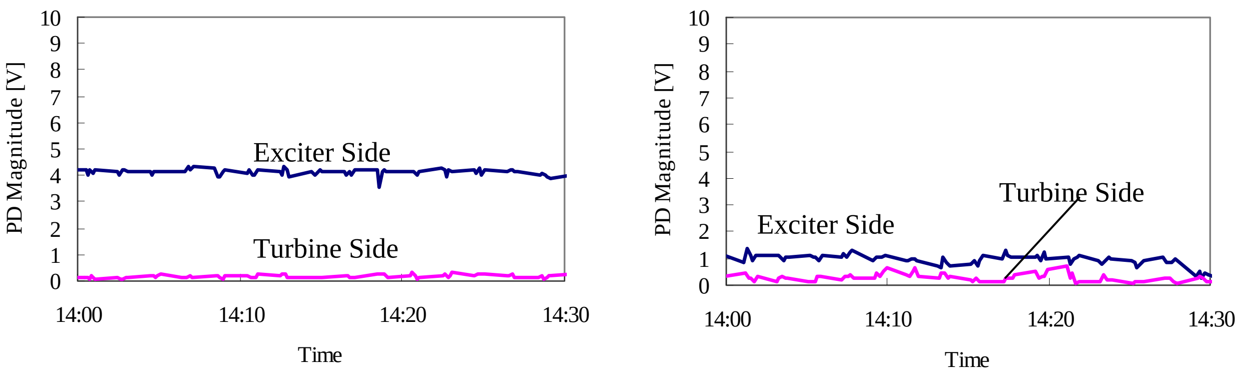


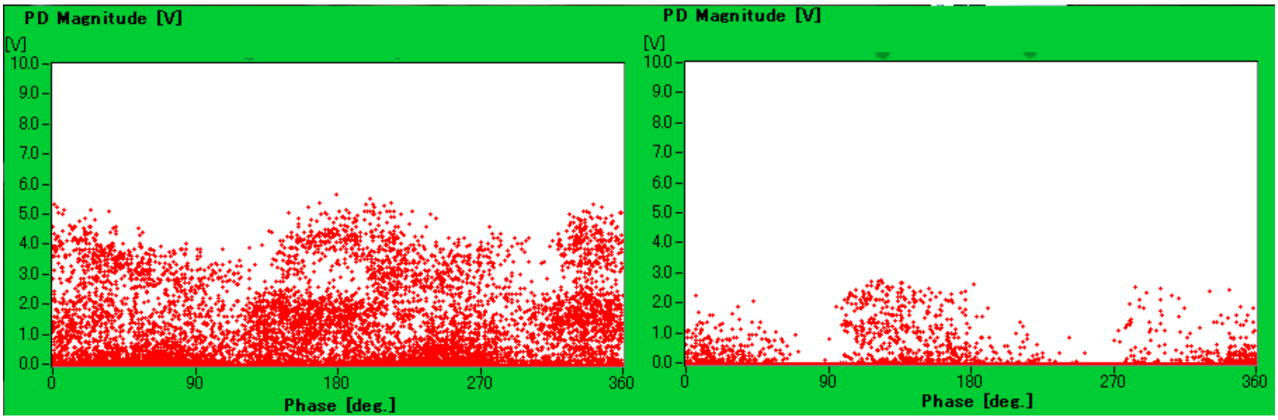
Fig. 16 Cross-section of a large turbine generator. Antennas are placed near stator end windings.

Fig. 17 shows PD data of a turbine generator whose rated voltage is 16 kV. All the stator windings were replaced with new ones after 15 years operation. Although relatively high PD magnitude was measured at the exciter side before rewinding, it decreased after rewinding. The PD magnitude at the turbine side was negligible both before and after rewinding. The PD magnitude at the exciter side is still higher than that at the turbine side after rewinding, but the reason is not identified. PD patterns before and after rewinding are shown in Fig. 18.



(a) before rewinding (b) after rewinding

Fig. 17 PD Comparison between aged stator windings and new ones.



(a) before rewinding (b) after rewinding

Fig. 18 Comparison of PD phase characteristics at exciter side.

3.3 Correlation between PD Magnitude and Qmax

In addition to on-line PD measurement, offline PD measurements with the microstrip antenna were performed on a turbine generator. The correlation between PD magnitude obtained with the microstrip antenna and maximum partial discharge Qmax measured by conventional coupling capacitor method can be seen [1].

4 CONCLUSIONS

The following conclusions were derived.

(1) The on-line PD monitoring system with microstrip antenna has been developed. It consists of microstrip antennas, PD detectors and a PC. Microstrip antennas are easily installed inside the machine housing without interfering machine design, manufacturing or operation.

(2) The resonance frequency of the microstrip antenna was determined to be 1.8 GHz around which back ground noise level is relatively low.

(3) Some PD properties such as void, gap or surface discharge were obtained with stator bar specimens. They were confirmed to be useful for analyzing actual stator windings.

(4) PD data before and after stator rewinding were obtained from a generator with a long period of operation. PD magnitude after rewinding is lower than that before rewinding. This system can be used for on-line PD monitoring on synchronous generators.

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