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Use of Spatial Phase Difference Method to Detect Microwaves Associated with Stator Coil Partial Discharge in a Generator

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SUMMARY

This paper presents a new system for detecting electromagnetic waves emitted from partial discharges (PD) due to material defects in high-voltage electric machinery and apparatus. PD is a symptom and/or a direct cause of the deterioration of insulation systems used in high-voltage stator coils. This system can detect PD by using the spatial phase information of the microwaves emitted from PD, which are voltage pulses of very short duration. We describe the properties of this system which is composed of two double-ridge-guide-horn antennas, two preamplifiers, a gigahertz interference receiver (GHz-2ch-down-converter) of original design, two A/D (analog to digital) converters, and a personal computer. We experimentally show that this system can be used for detection of the microwaves emitted by PD occurring in the stator coil. The result of this work is the development of a new noncontact PD detection system for generators, which can be operated by station personnel. © 1997 Scripta Technica, Inc. Electr Eng Jpn, **121**(2): 16–26, 1997

Key words: Stator coil; partial discharge; microwave; GHz interference receiver (GHz-2ch-down-converter), spatial phase difference method.

1. Introduction

With recent information technology developments, better and safer electric power supply has been in demand, along with technology for diagnosing breakdowns of electrical apparatus so as to maintain functions and prevent such breakdowns [1–12].

Generators in power stations are required to generate higher voltages and higher electric powers and to have the ability to start and stop frequently. Consequently, the conditions of generator operation have become very severe. Thus, the insulation system of the stator winding may deteriorate earlier than ever due to the stress accompanying the severe operation of turbine generators [3–5].

In cases of insulation breakdown in aging generators, stator core damage occurs in up to 55% of all accidents [11, 12]. Long outages are unavoidable and high costs are paid for repair of turbine generators.

The development of diagnostic techniques for the insulation systems of turbine generators is strongly desired in order to avoid accidents and to aid in planning generator maintenance by monitoring the condition of the insulation system [3–5, 12–15].

Insulation breakdown of the stator winding tends to occur in voids existing in the insulation system. Partial discharges (PD) which originate in the voids are especially a symptom of breakdown in solid materials and in composites made from two or more kinds of material [1–5, 12–15].

Therefore, measurement and analysis of PD are important in assessing the condition of the insulation system [16–19].

PD originating in voids in the stator winding are 1-ns to 5-ns phenomena [13–15]. Generally speaking, the PD emit electromagnetic waves whose bandwidth extends to the gigahertz region (microwaves) [20, 21]. From this point of view, we describe a new system which can detect PD, the symptoms and/or direct causes of insulation deterioration, by receiving microwaves emitted by PD.

This system is composed of two double-ridge-guide-horn antennas, two preamplifiers, a gigahertz interference receiver (a GHz-2ch-down-converter) of original design,

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two A/D (analog to digital) converters, and a personal computer. This system receives microwaves emitted from PD with two antennas, the received signals are down-converted, and the PD signal can be detected by using the spatial phase difference method [22–24]. The down-converter can convert the received gigahertz signal, whose frequency band can be tuned from 2 GHz to 3 GHz at intervals of 100 MHz, to a lower-frequency signal whose bandwidth is from 1 kHz to 500 kHz. The spatial phase difference method is based on a time-space correlation function and is able to detect PD signals by estimating the phase difference between the measurement points in the spatial-frequency domain, that is, a spatial phase difference which is equal to the time of arrival difference between two points in the time domain [25–28].

In this paper we describe the evaluation of the system's performance and discuss its effectiveness in terms of a partial model of a stator coil removed from a turbine generator (rated capacity 75 MW; insulation system of polyester resin).

2. The Spatial Phase Difference Method

Figure 1 shows the principle of the spatial phase difference method. This method estimates the phase difference in the spatial-frequency domain, that is, the spatial phase difference among several antennas that receive the electromagnetic signals emitted from PD sources in an arbitrary time period [22–24].

In this paper we estimate the time difference of arrival between two antennas ($t_{12} = t_2 - t_1$), by transforming the spatial phase difference to a time difference in the time domain.

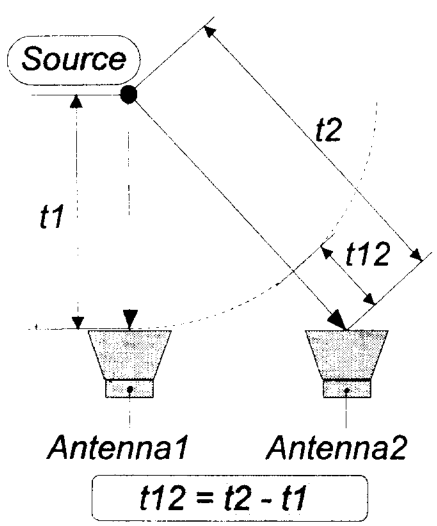


Fig. 1. Principle of spatial phase difference method.

The algorithm of this method is shown in Fig. 2. The procedure for estimating the time difference between the measurement points of the electromagnetic wave is described below. This method is based on a time-spatial correlation function using maximum likelihood estimation [25, 26].

The received signals at the two spatially separated antennas are mathematically defined as

$$x_1(t) = s(t) + n_1(t) \tag{1a}$$

$$x_2(t) = \alpha\, s(t - D) + n_2(t) \tag{1b}$$

where $x_1(t)$ and $x_2(t)$ denote the antenna outputs, $s(t)$ is the PD source signal, $n_1(t)$ and $n_2(t)$ are uncorrelated random processes, α is an attenuation factor, and D is the time difference of arrival between two antennas, that is, D ($= t_{12} = t_2 - t_1$). We try to estimate the time difference D.

The cross energy density spectrum between $x_1(t)$ and $x_2(t)$, obtained by Fourier transform in an arbitrary time period, is

$$G_{12}(f) = X^*{}_1(f) X_2(f) \tag{2}$$

where $X_1(f)$ and $X_2(f)$ are the power spectra of $x_1(t)$ and $x_2(t)$, and the asterisk denotes the complex conjugate. The spatial phase difference between the two points is invariant if the PD source does not move in space, so that ensemble averaging, which can restrain background noise effectively, is available. We apply ensemble averaging to Eq. (2), the cross energy density spectrum. The number of repetitions of this method for the cross energy density spectrum is the same as the number of acquired data sets.

The time difference D can be obtained from the inverse Fourier transform of the cross energy density spectrum. However, if the S/N (signal to noise) ratio is small, it is difficult to estimate the time difference $\tau = D$. We apply maximum likelihood estimation as a weighting function to detect a small signal [25, 26]:

$$W(f) = \frac{C_{12}(f)}{|G_{12}(f)|[1 - C_{12}(f)]} \tag{3}$$

where C_{12} is the magnitude squared coherence, given by

$$C_{12}(f) = \left| \frac{(G_{12}(f))^2}{G_{11}(f) G_{22}(f)} \right| \tag{4}$$

Here

$$G_{11}(f) = |X_1(f)|^2 \tag{5a}$$

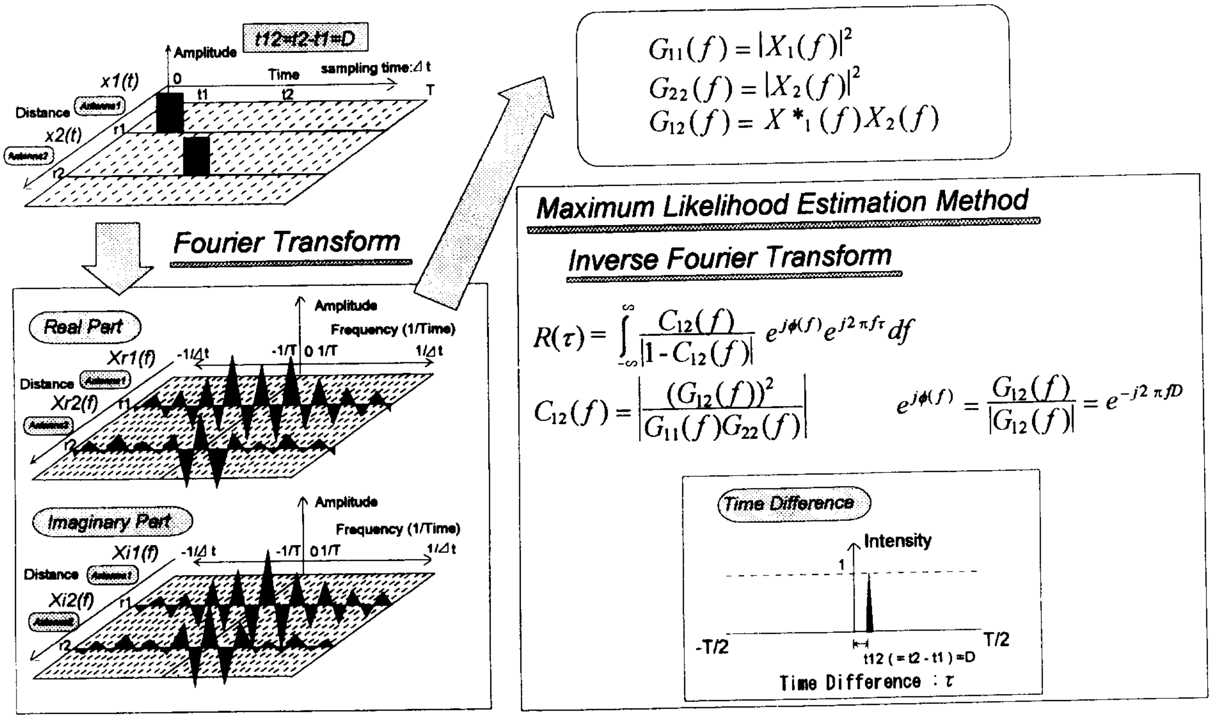


Fig. 2. Algorithm of spatial phase difference method.

$$G_{22}(f) = |X_2(f)|^2 \tag{5b}$$

are the energy density spectra of $X_1(f)$ and $X_2(f)$, respectively.

Then $R(\tau)$, the time difference function, can be obtained from the inverse Fourier transform of the product of the cross energy density spectrum and the weighting function:

$$\begin{aligned} R(\tau) &= \int_{-\infty}^{\infty} W(f)\, G_{12}(f)\, e^{j2\pi f\tau}\, df \\ &= \int_{-\infty}^{\infty} \frac{C_{12}(f)}{|1-C_{12}(f)|} \frac{G_{12}(f)}{|G_{12}(f)|} e^{j2\pi f\tau}\, df \\ &= \int_{-\infty}^{\infty} \frac{C_{12}(f)}{|1-C_{12}(f)|} e^{j\phi(f)} e^{j2\pi f\tau}\, df \end{aligned} \tag{6}$$

where

$$e^{j\phi(f)} = \frac{G_{12}(f)}{|G_{12}(f)|} \tag{7}$$

If the background noise signals $n_1(t)$, $n_2(t)$ of Eq. (1) are uncorrelated, the spatial phase difference $\phi(f)$ of Eq. (7) is equal to the time difference D:

$$e^{j\phi(f)} = e^{-j2\pi fD} \tag{8}$$

In the case of arrival time difference $\tau = D$,

$$e^{j\phi(f)} \cdot e^{j2\pi f\tau} = 1 \tag{9}$$

$R(D)$, which is the correlation function of Eq. (6), has its maximum value.

Accordingly, the arrival time difference D between the two received signals can be obtained from the spatial phase difference in the spatial-frequency domain.

We define the intensity by transforming $R(\tau)$, a function of the time difference:

$$Intensity(\tau) = \left\{\frac{R(\tau)}{R(D)}\right\}^2 \tag{10}$$

The intensity has a maximum value of 1, for an arrival time difference $\tau = D$.

3. PD Detection System

3.1 System component

Figure 3 shows the noncontact PD detection system. The specifications of the antenna (double-ridge-guide-horn

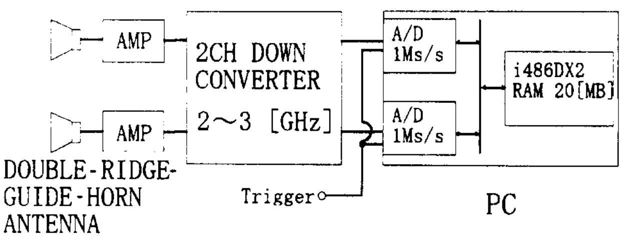


Fig. 3. PD detection system.

antenna), preamplifier, A/D converter, and personal computer are shown in Tables 1 to 4. The specifications of the GHz-2ch-down-converter are given in detail in the following section.

Regarding the processing of the system, the electromagnetic waves emitted from the PD source are received with the two antennas, and the signals are passed through the preamplifiers, and then input into the down-converter. The signals output from the down-converter are simultaneously input into the personal computer using A/D converters (sampling frequency: 1 MHz). The trigger signal which starts the A/D converters is generated when the value of the applied voltage is 0, that is, zero-cross. The microwaves emitted by the PD can be detected and the arrival time difference between the two antennas can be estimated by the spatial phase difference method using the two acquired digital data sets.

The noise level of the system is −110 dBm.

3.2 GHz interference receiver

In this paper our objective is receiving microwaves (center frequency between 2 and 3 GHz) emitted from PD, so an exclusive receiver is needed. The GHz-2ch-down-converter (GHz interference receiver) is shown in Fig. 4, and the specifications are given in Table 5. The down-converter has two input terminals and two output terminals (that is, two channels). The center frequency of the built-in local generator of the down-converter can be tuned from 2 GHz to 3 GHz at intervals of 100 MHz.

The signals input into the input terminals of the down-converter are simultaneously passed through the bandpass filters (bandwidth between 2 and 4 GHz) and the SHF (superhigh frequency) amplifiers (gain: 40 dB) built into the down-converter. Then the center frequencies of the input signals are down-converted by mixing the input sig-

Table 1. Specifications of double-ridge-guide-horn antenna

Model	3115 (EMCO)
Frequency range	1–18 GHz
Power gain	10.7 dB
Beamwidth	E-plane 53°
	H-plane 48°

Table 2. Specifications of preamplifier

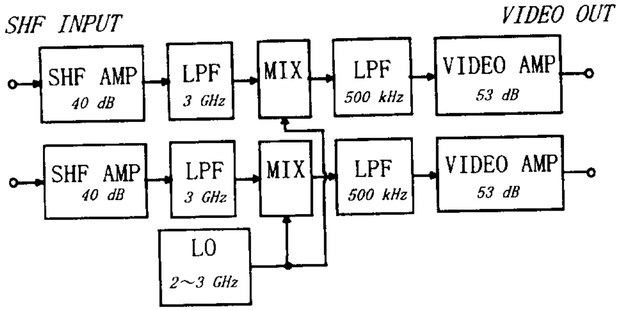
Model	8449B (HP)
Frequency range	1–26.5 GHz
Gain	26 dB
Gain flatness	±3 dB
Noise figure	<8.5 dB(1–12.7 GHz)
Output power (1 dBC)	+7 dBm

Table 3. Specifications of A/D converter

Model	DAS-50 (Keithley)
Input channels	4 single-ended
Resolution	12 bit
Data acquisition rate	1 MHz
On-board memory	2 MB
A/D ranges	±2.5 V, ±5 V, ±10 V
	0–5 V, 0–10 V

Table 4. Specifications of computer

Model	apricot XEN-LSII (Mitsubishi)
CPU	i486DX2 (66 MHz)
Main memory	20 MB
External memory	500 MB
Language	C language



SHF AMP :SHF Amplifier
LPF :Low Pass Filter
MIX :Mixer
VIDEO AMP:Video Amplifier
LO :Local Oscillator

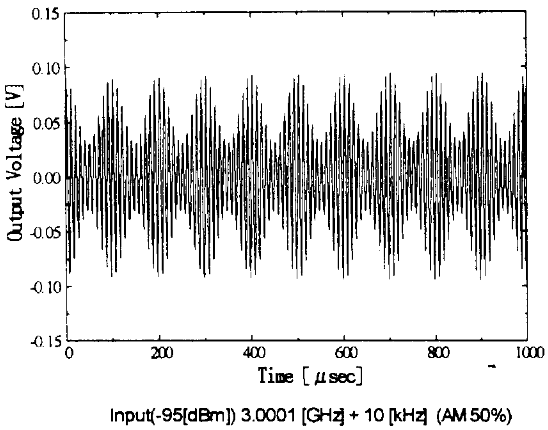
nals and the signals generated by the built-in local generator:

$$f_{out} = |f_{in} - f_{local}| \tag{11}$$

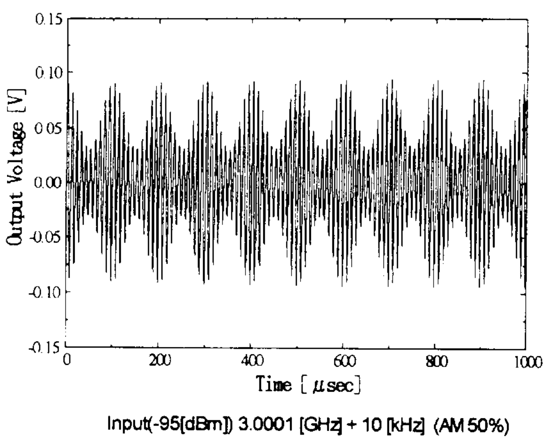
where f_{out} is the center frequency of the output signals of the down-converter, f_{in} is the center frequency of the input signals, and f_{local} is the center frequency of the signals generated by the built-in local generator. This method can down-convert the center frequency of the input signals without changing the distribution of their frequency spectrum. This method is useful for detecting particular signals, because the wideband signal is down-converted to a fixed lower narrow-band signal, and then the single narrow-band signal is amplified: that is, only the particular frequency component of the signal has to be amplified.

Table 5. Specifications of GHz-2ch-down-converter

(1) SHF input	
Frequency range	2–3 GHz
Input level	–95 to –75 dBm
Input LPF	Elements: 9, ripple: 0.01 dB
	Chebyshev characteristic
Connector	N–R
Impedance	50 Ω
(2) Built-in local oscillator	
Oscillator	YIG-tuning oscillator (2–4 GHz fundamental harmonic)
Frequency control	Phase tuning by higher harmonic of reference signal
Frequency range	2–3 GHz
Frequency interval	100-MHz steps
SSB phase noise	under –80 dBc/Hz
Reference signal	100 MHz—crystal oscillator
Frequency stability	$\pm 5 \times 10^{-6}$ (operating temp. 0–50°C)
(3) Video output	
Frequency range	1–500 kHz
Output level	–40 to +10 dBm
	over 60 dB
(4) Operating temp.	0–40°C
(5) Power source	ac 100 V, 50/60 Hz
(6) Power dissipation	about 50 VA



(a) Output of Ch1



(b) Output of Ch2

Fig. 5. An example of converting frequency.

The down-converted signals are output after passage through low-pass filters (cutoff frequency 500 kHz) and amplifiers (gain 53 dB) built into the down-converter. The frequency bandwidth of the signals output from the down-converter is from 1 kHz to 500 kHz and the total gain of the down-converter is 75 dB (continuous sine wave conversion).

We now show an example of the down-conversion relationship between the input and the output of the down-converter. Figure 5 shows the signals output from the down-converter, after an arbitrary amplitude-modulated wave (center frequency 3.0001 GHz, output −95 dBm, modulation frequency 10 kHz, modulation factor 50%) generated by an oscillator (HP 8648C, Hewlett Packard) was simultaneously input into the down-converter using a power splitter. The input signals were down-converted as shown in Fig. 5:

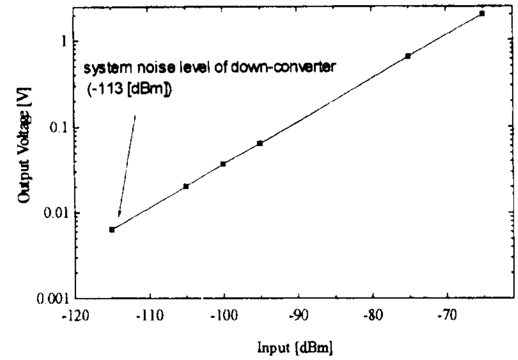


Fig. 6. The amplitude of output versus input.

$$f_{in}(3.0001\ \text{GHz}) - f_{local}(3.0000\ \text{GHz}) = f_{out}(100\ \text{kHz})$$

The down-converter performed according to specifications as the modulation frequency of the signals (10 kHz) was not changed between the input and the output of the down-converter without changing the center frequency of the input signals. Therefore, the down-converter can down-convert the center frequency of input signals without changing their frequency spectrum distribution. Down-conversion of both channels was done simultaneously, because there was no time difference between the two signals.

Figure 6 shows the level characteristic for the input and output of the down-converter.

The level characteristic was the same at every center frequency from 2 GHz to 3 GHz at intervals of 100 MHz. The noise level of the down-converter was −113 dBm (noise figure 4 dB). The input signal from −113 dBm to −65 dBm was proportional to the peak voltage of the output signal in logarithmic representation, as shown in Fig. 6. The down-converter had enough efficiency to detect minute signals, from the designed minimum level (−95 dBm) to the maximum level (−75 dBm).

4. Simulation Using a Partial Model of the Stator Coil

We confirmed that the system was able to detect PD occurring in the insulation of the stator coil by a simulation as shown in Fig. 7. This coil was a partial model of a stator coil removed from an aged turbine generator. This simulation was done in a laboratory with a good electromagnetic environment. The background noise received with the antennas located in this laboratory was almost at the thermal noise level (−110 dBm), that is, this level was almost the same level as the noise of the system, and thus the background noise could be assumed to be uncorrelated.

Figure 8 shows the experimental circuit used in this simulation. Table 6 shows the specifications of the partial

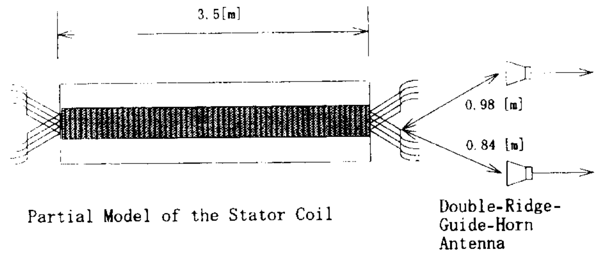
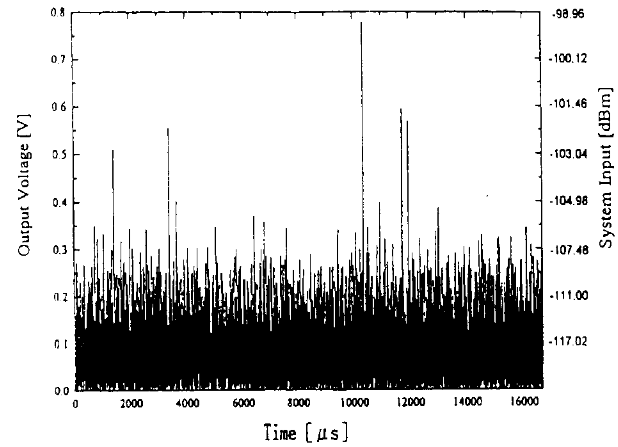


Fig. 7. Partial model of the stator coil and the station of the two antennas.

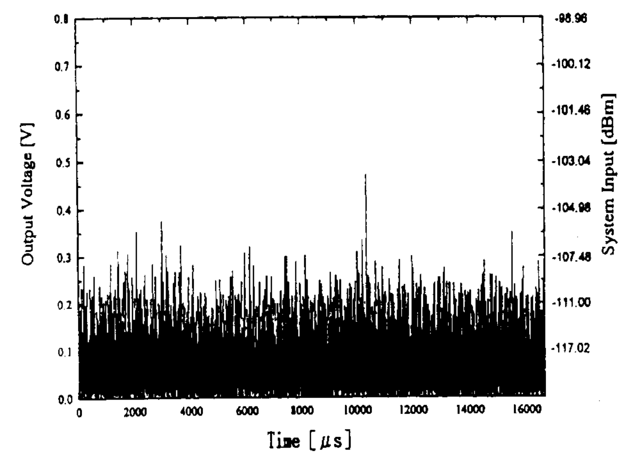
model of the stator coil. We applied an ac voltage of 10 kV (to ground) to one of the stator coils to produce PD, then received the microwaves (GHz-band electromagnetic waves) emitted from PD associated with the deterioration occurring in the insulation system of the stator winding. This coil was considered to be deteriorated by average aging [12], that is, average deterioration in normal use, because the strength of the insulation system was about 3000 pC, as measured by the PD detector shown in Fig. 8.

Figure 9 shows the output signals received and down-converted by the system when the center frequency of the built-in local oscillator was tuned to 3 GHz. The received signals are represented by the output voltage [V] of the down-converter and the input intensity [dBm] of the signals received with the antennas. The time window is 16.67 msec, which is one period of the applied voltage (the frequency of the applied voltage was 60 Hz). The received signals were pulse-shaped waves. It is difficult to discriminate the PD signals from background noise by mere threshold processing of the amplitude of the signals, as shown in Fig. 9.

We then applied the spatial phase difference method to the received signals.



(a) Antenna1



(b) Antenna2

Fig. 9. The received signals emitted from PD of the stator coil.

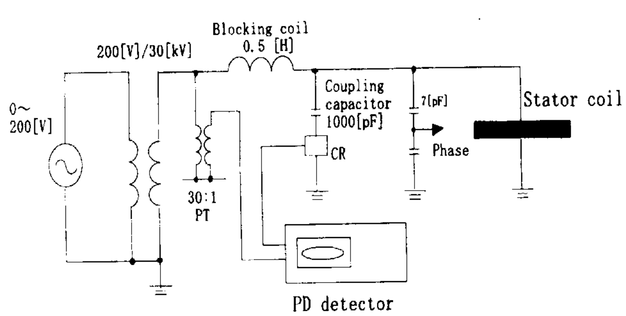


Fig. 8. An experimental circuit.

Table 6. Specifications of the partial model of the stator coil

Rated capacity	75 MW
Rated voltage	13.8 kV
Core length	3.5 m
Insulation system	Polyester resin
	Operating time:
	27 years since 1964

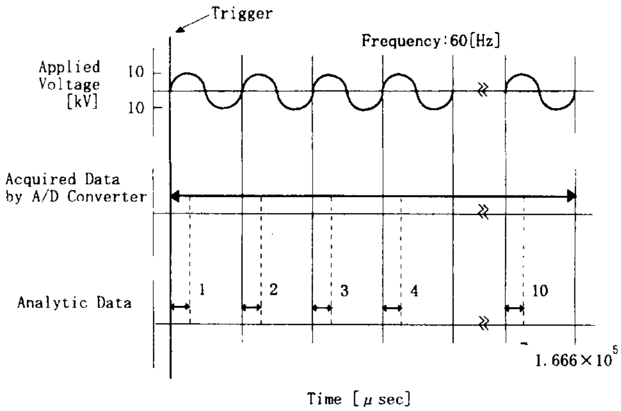


Fig. 10. Averaging method.

We used the data obtained from received signals whose time window was between 0 and 4096 μs as analytical data, of almost the same duration from 0° to 90° of the applied ac voltage cycle, because it is reported that most PD occur from 0° to 90° and from 180° to 270° of the applied ac voltage cycle [14]. Furthermore, we prepared 10 data sets of the received signals obtained from 10 periods of the ac applied voltage cycle to apply ensemble averaging in the frequency domain as shown in Fig. 10. In the case of several existing PD sources, this system cannot estimate the location of each PD source individually, but only whether the PD source occurs in the stator winding or not, because it analyzes the synthetic signals emitted from them.

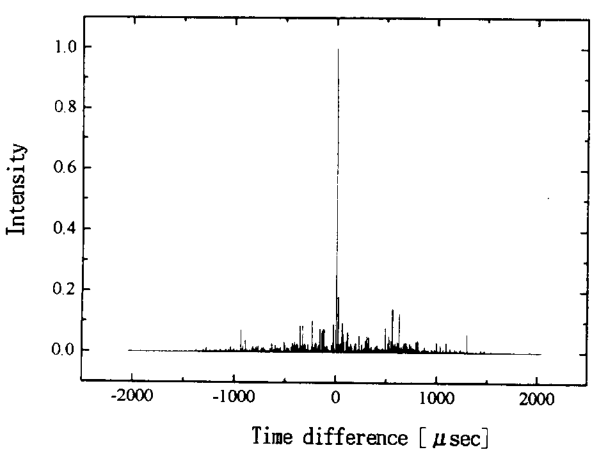


Fig. 11. The arrival time difference between two antennas.

Figure 11 shows the results obtained using the spatial phase difference method. The intensity was a maximum of 1, when the arrival time difference between two antennas was 0 μs. On the other hand, the intensity was low except at 0 μs. Therefore, the system could reliably detect signals which were correlated between the two antennas at a time difference of 0 μs. It was thus confirmed that the developed system was able to detect microwaves emitted from PD sources.

5. Conclusions

This paper presents a new system that can perform contact-free detection of partial discharges associated with the symptoms and/or direct causes of deterioration of the insulation system of a stator coil removed from an aged turbine generator. The properties of the system are illustrated by a simulation. The system is composed of two antennas that receive microwaves emitted from the PD, two preamplifiers, a GHz-2ch interference receiver of original design, two A/D converters, and a personal computer that stores and analyzes the digital data. The spatial phase difference method is applied to the acquired digital data. The results of this work are as follows:

(1) The developed down-converter can down-convert the center frequency of the input signals without changing their frequency spectrum distribution.

(2) As a simulation, the system was applied to a partial model of a stator coil removed from an aged turbine generator (rated capacity 75 MW, operating time 27 years, insulation system of polyester resin) located in a laboratory with a good electromagnetic environment. It is found that this system can detect microwaves emitted from PD occurring in the partial model of the stator coil.

(3) We have measured microwaves emitted from PD by building antennas in an operating turbine generator, because on-line PD measurement for operating turbine generators is needed to detect insulation deterioration of the stator winding at an early stage.

Acknowledgment

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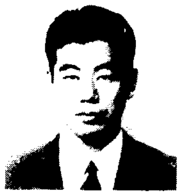

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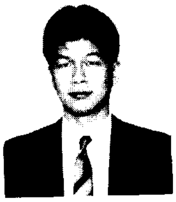  

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