Detection of Wide-Band E-M Signals Emitted from Partial Discharge Occurring in GIS Using Wavelet Transform

Masatake Kawada, Ampol Tungkanawanich, Zen-Ichiro Kawasaki, *Member, IEEE*, and Kenji Matsu-ura

***Abstract*—Recently, diagnostic techniques have been investigated to detect a partial discharge (PD) associated with a dielectric material defect in a high-voltage electrical apparatus. Gas Insulated Switchgear (GIS) is an important equipment in a substation, it's highly desirable to measure a partial discharge (PD) occurring in GIS which is a symptom of an insulation breakdown. As it is important to develop a noncontact method for detecting the insulation fault, this paper proposes a new method to detect the wide-band electromagnetic (E-M) wave emitted from PD using the Wavelet transform. The Wavelet transform provides a direct quantitative measure of spectral content, "Dynamic spectrum," in the time-frequency domain This paper experimentally shows the "Dynamic spectrum" of the wide-band E-M wave emitted from PD in the time-frequency domain. This method is shown to be useful for detecting the symptom of the insulation breakdown occurring in GIS.**

I. Introduction

IN RECENT years, it has been very important to develop a diagnostic technique to maintain the proper functioning of electrical equipment and prevent a breakdown [1], since a high-information-oriented society needs a high-quality electrical power supply. Gas Insulated Switchgear (GIS) is an important equipment in a substation, it is highly desirable to measure a partial discharge (PD) which is a symptom of an insulation breakdown occurring in GIS.

Essentially, GIS is designed not to need maintenance. However in case of an insulation breakdown, it takes a long time for its restoration and the breakdown causes serious damage to system operation.

Therefore, it's very important to develop the diagnostic technique to detect a characteristic symptom, that is, PD occurring in GIS. When PD occurring in GIS is to be detected during operation of the apparatus, a sensor is placed inside or on the surface of the apparatus for a better detection sensitivity in many cases. This internal diagnostic technique may attain a higher S/N ratio. However it's not applicable to live high-voltage apparatus from the safety viewpoint. It therefore is important to develop a noncontact method for detecting the symptom.

In our previous publication [2], we proposed a noncontact detection method, "Spatial Phase Difference Method" which can locate PD's occurring in GIS. This method is one that utilizes spatial phase difference that is produced when the electromagnetic (E-M) wave emitted from PD is propagated in space.

Especially since it is generally reported that the level of PD increases as the insulation breaks down, therefore, a continuous observation of PD may lead to the prediction of the insulation breakdown.

In this paper we propose a new method to detect PD occurring in GIS and to investigate the "Dynamic spectrum" of PD, in the time-frequency domain by using the Wavelet transform [3], [4]. The Wavelet transform can map any finite energy signal from the time domain to a finite energy two-dimensional distribution in the time-frequency domain (the Wavelet domain), and examine the time of occurrence and the duration of the PD.

Then, we use the same system as in our previous publication [2] and experimentally show the Dynamic spectrum of the wide-band E-M wave emitted from PD as the two-dimensional distribution in the time-frequency domain by using the Wavelet transform. This method is shown to be useful and progressive for detecting PD.

II. Wavelet Transform

The analog signal in the time-domain must be acquired over its entire duration in order to examine the spectral behavior of the signal from its Fourier transform. If a signal is changed in a small neighborhood of some time instant, then the entire spectrum is affected. Indeed, in the extreme case the Fourier transform of the delta distribution $\delta(t - t_0)$, with respect to a signal point t_0, is $\exp(-j2\pi f t_0)$, which certainly covers the whole frequency domain. Therefore, in many applications such as analysis of nonstationary signals and real-time signal processing, the formula of the Fourier transform alone is quite inadequate. The Wavelet transform has been applied to many fields to analyze "Dynamic spectrum" of various phenomena instead of "Power spectrum" by the Fourier transform.

The Wavelet transform of a function $f(t)$, with respect to a given admissible mother wavelet $\psi(t)$, is defined as the equation (1) [3], [4].

$$(W\psi f)(b, a) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} \psi(\frac{t-b}{a}) f(t)\, dt \tag{1}$$

a: the scale parameter
b: the translation parameter

The mother wavelet $\psi(t)$ is scaled by the scale parameter "a" and translated by the translation parameter "b," respectively.

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The authors are with the Electrical Eng. Dept., Faculty of Eng., Osaka University, 2-1 Yamada-oka, Suita, Osaka Japan.

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Any finite energy signal is mapped from the time (or space) domain to a finite energy two-dimensional distribution in the scale-translation (wavelet domain). A wavelet domain coefficient $(W\psi f)(b, a)$ is computed for each scale parameter "a" and translation parameter "b," that is, the Wavelet transform breaks the signal $f(t)$ down into component pieces and these pieces are examined or operated on instead of the function $f(t)$. The mother wavelet $\psi(t)$ is constrained by the following equation (2).

$$\int_{-\infty}^{\infty} \psi(t)\, dt = 0 \tag{2}$$

The mother wavelet is one that oscillates, has finite energy, and has an average value of zero.

We define the "$1/a$" term in the equation (1) as the following equation (3).

$$\frac{1}{a} = 2\pi f \tag{3}$$

f: frequency Hz

The translation parameter "b" is used to translate a time-localization window in order to cover the whole time domain for extracting local information about the function $f(t)$. The energy normalization is performed by the "$1/\sqrt{a}$" term that keeps the energy of the scaled mother wavelet equal to the energy of the original mother wavelet.

In this paper we use the real part of Gabor mother wavelet, which is produced using a Gaussian function, as the mother wavelet given as equation (4), where $\sigma = 8$, voluntarily.

$$\psi(t) = e^{-\frac{t^2}{\sigma^2}}\, \cos(t) \tag{4}$$

It is reported that Gabor wavelet is most localized in time-frequency domain compared with other wavelets. It's easy to discuss the frequency components of PD signal because Gabor wavelet is based on exponential function like the Fourier transform. Therefore we selected Gabor wavelet to analyze E-M signals emitted from PD.

We vary the frequency "f" from 20 to 200 MHz; as shown in Fig. 1, because the frequency bandwidth of the biconical antenna used in this paper is from 20 to 200 MHz. As the record length of an acquired data set is 2.5 μs, the time-localization window is moved from 0 to 2.5 μs by the translation parameter "b." Hence, we observe the Dynamic spectrum of the wide-band E-M wave emitted from PD's in the time-frequency domain for which the time window is 2.5 μs and the frequency bandwidth is from 20 to 200 MHz using the Wavelet transform.

III. Experimental Method

An outdoor 77 kV, a three-phase model gas insulated switchgear (GIS) is used in the experiment to generate corona discharge as shown in Fig. 2. The corona discharge source, which is regarded as PD, is produced in the model GIS. Of the three-phase high voltage buses in the model GIS, one bus is equipped with a needle-shaped electrode and another bus is equipped with a plane-shaped electrode. The gaps of the needle-electrode and the plane-electrode are both 10 mm.

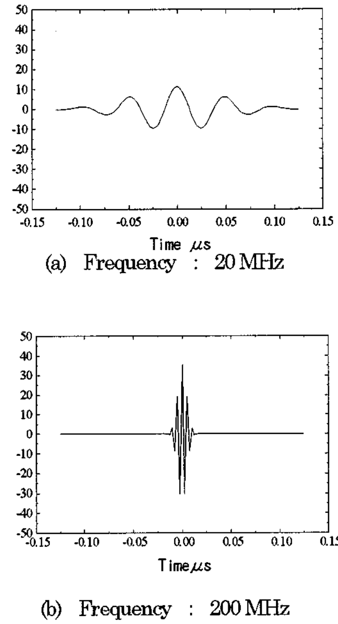

Fig. 1. Gabor mother wavelet (Real part) for the frequency (a) 20 MHz, (b) 200 MHz. The mother wavelet is one that oscillates, has finite energy, and has an average value of zero.

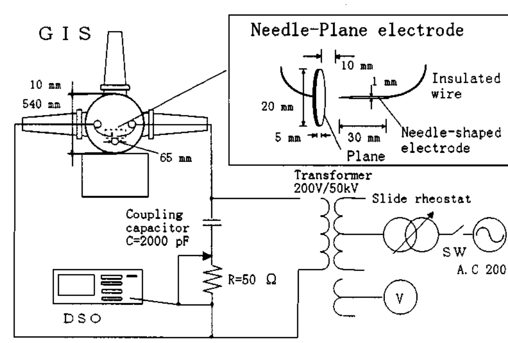

Fig. 2. An outdoor 77 kV, a three-phase model GIS used in the experiment to generate corona discharge. PD is generated in the GIS using the needle-electrode and the plane electrode.

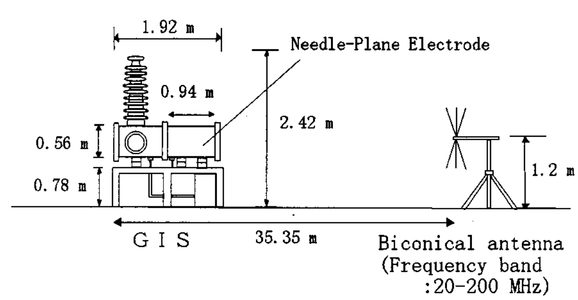

Fig. 3. The measurement site of the wide-band E-M wave emitted from the PD. The antenna is wide-range biconical antenna (band-width: 20–200 MHz).

A single-phase A.C. voltage to ground is applied to the bus provided with the needle-electrode.

No voltage is applied to the other two phase buses. The gas (SF_6) pressure is 101 kPa (the pressure of the atmosphere).

The wide-band E-M signal emitted from PD is received by an external antenna as shown in Fig. 3. The antenna is a wide-range

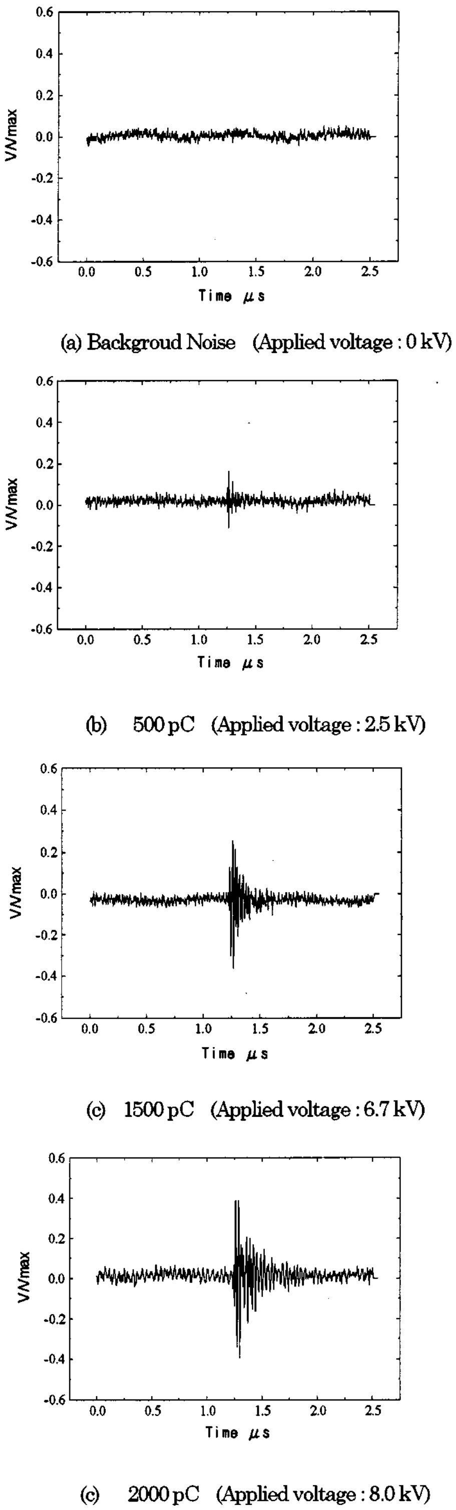

Fig. 4. The wide-band E-M wave emitted from PD received by the antenna. The discharge levels of PD are at (a) 0 pC (background noise), (b) 500 pC, (c) 1500 pC and (d) 2000 pC, respectively.

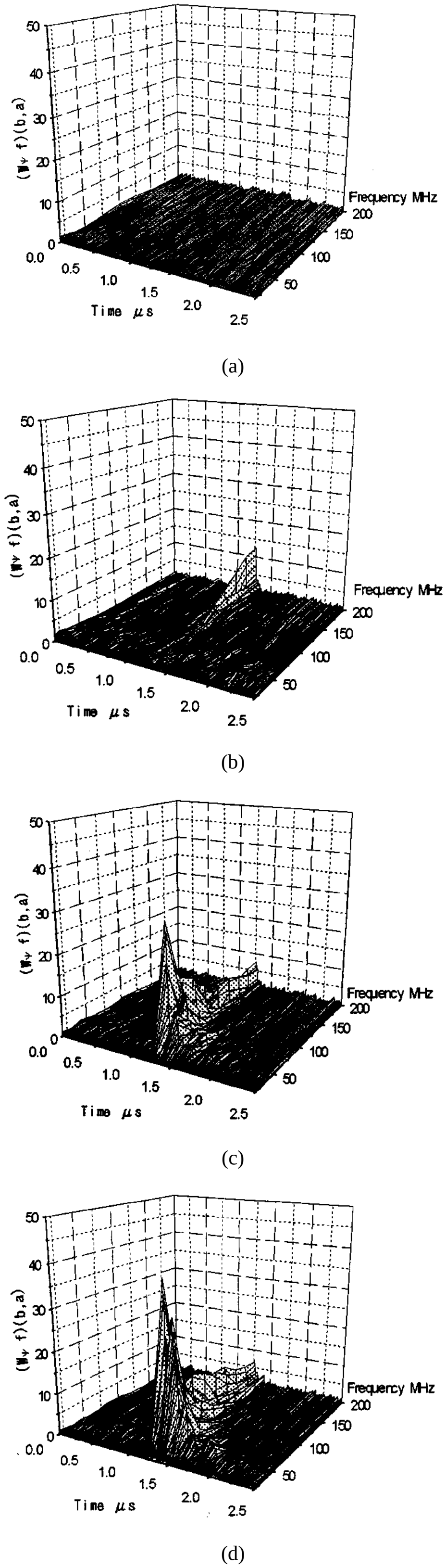

Fig. 5. Dynamic spectrum of the wide-band E-M wave emitted from PD. This figure shows the Dynamic spectrums of PD at (a) 0 pC (background noise), (b) 500 pC, (c) 1500 pC and (d) 2000 pC, respectively which result from the Wavelet transform.

biconical antenna (the bandwidth: 20–200 MHz, the manufacture's model number: EMCO 3014C). The signal received by the antenna is input into a digital storage oscilloscope (DSO). The sampling interval is 2.5 ns, and the record length is 2.5 μs. The DSO is controlled by a computer through the GPIB. The waveform data taken into the computer are recorded in

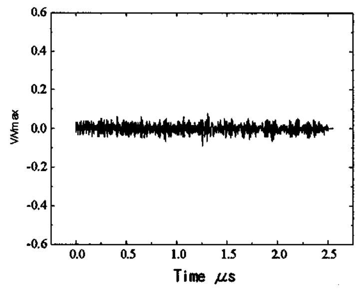

Fig. 6. The E-M wave received with the antenna. The discharge level of PD is 170 pC buried under a continuous wave (FM radio).

a magnetic disc. A 50 Ω resistance is inserted in series with the ground wire of the GIS and the discharge level of PD is measured by measuring the current pulse flowing through the resistance.

IV. Time-Frequency Analysis of Partial Discharge

The magnitude of the applied voltage is varied to change the discharge level of PD. Fig. 4 shows the wide-band E-M wave received by the antenna arbitrarily located at 35.35 m from the PD site for PD levels of 0 pC (background noise), 500 pC, 1500 pC and 2000 pC, respectively. It is difficult to estimate the discharge level of PD by measuring the amplitude of the E-M wave emitted from PD, because the amplitude decreases inversely with distance and is attenuated by the weather such as rain, snow and so on. If there are many PD sources, the amplitude is affected because the E-M waves emitted from them interfere with each other.

Fig. 5 shows the Dynamic spectrum of the received signal which is analyzed by the Wavelet Transform. The Dynamic spectrum is represented as the magnitude of the components. The time window is 2.5 μs and the frequency bandwidth is from 20 to 200 MHz. This figure shows that, when PD occurs and how long PD lasts. Clearly, when the discharge level of PD is at 500 pC, the main components of the transform of the E-M wave lie in the high frequency band (120–200 MHz).

On the other hand, when the discharge level is increased such as 1500 pC and 2000 pC, the main components of the transform shift to the lower frequency band (20–80 MHz). Therefore it is important to detect the components of the lower frequency band (20–80 MHz) of the E-M wave emitted from PD for the insulation diagnosis. Furthermore, the duration of the discharge at the 2000 pC level is longer than that for the 500 pC and 1500 pC levels. This result shows that when the discharge level is increased, the duration of the low frequency band components becomes longer. The above result agrees qualitatively with the report that, when the applied voltage is increased, the duration of the current associated with PD is increased [5].

V. Detecting E-M Signal of Minute PD Buried Under Continuous Wave

It is necessary to detect minute PD in the range of a few hundred pC in order to apply the method to the practical insulation diagnosis of GIS. Furthermore it's necessary to detect the E-M wave emitted from minute PD buried under a continuous wave such as FM radio.

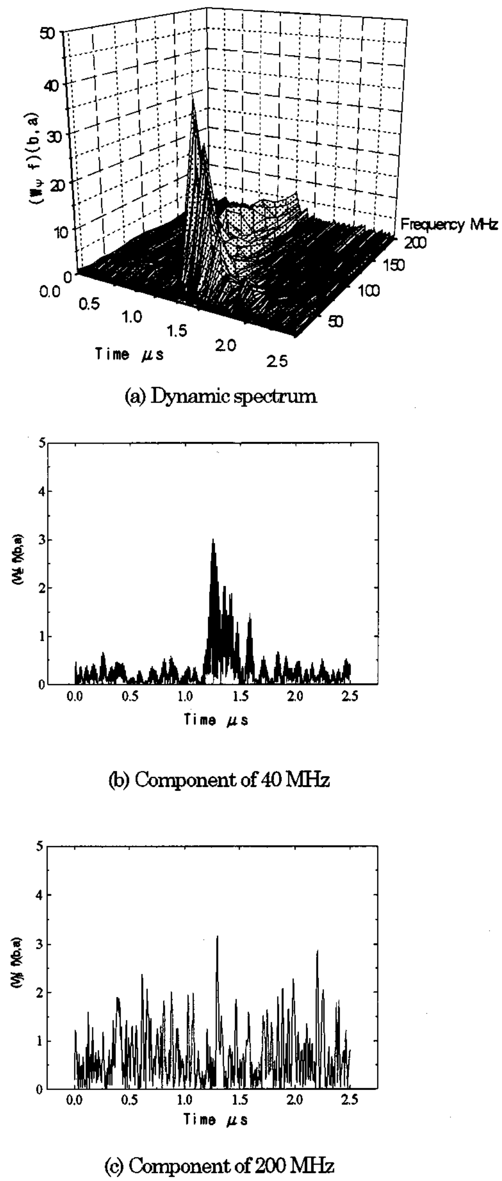

Fig. 7. The Dynamic spectrum of the E-M wave emitted from minute PD buried under a continuous wave (FM radio). The E-M wave of PD can be dearly distinguished from the continuous wave.

Fig. 6 shows the E-M wave emitted from minute PD's for which discharge level is 170 pC. The distance between the discharge site and the antenna is 3.36 in which is selected to minimize attenuation with distance. It is hard to distinguish the E-M wave of PD from other signals by amplitude.

Fig. 7 shows the Dynamic spectrum of the received signal as analyzed by the Wavelet transform. This figure shows that the time of occurrence of PD is about 1.25 μs and the PD signal can be clearly distinguished from the continuous signal which is FM radio.

Therefore, this system is very useful for detecting the E-M wave emitted from minute PD buried under the continuous wave such as FM radio.

VI. Conclusion

We propose a new method to detect a partial discharge (PD) occurring in GIS by using the Wavelet transform, which provides a direct quantitative measure of spectral content, the "Dynamic spectrum" in the time-frequency domain, in this paper. As it is important to develop a noncontacting method for detecting the insulation fault, we analyzed the E-M wave emitted from PD.

Clearly, there was a correlation between the discharge level of PD and the Dynamic spectrum of the E-M wave emitted from PD. The results demonstrate that, when the discharge level of PD was low, the main components of the transform of the E-M wave were in the high frequency band (120–200 MHz), and as the discharge level was increased, the components shifted to the lower frequency band (20–80 MHz) and the duration of the lower frequency band increased.

The minute PD in the range of a few hundred pC could be clearly distinguished from the continuous signal such as FM radio. Therefore, this system was very useful for detecting the symptom of the insulation breakdown occurring in GIS.

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Masatake Kawada received his B.S and M.S. degrees in Electrical Engineering from Musashi Institute of Technology, Tokyo, Japan, in 1993 and 1995, respectively, and Dr.Eng. degree in Electrical Engineering from Osaka University in 1998. At present, Dr. Kawada is joining Department of System Management and Engineering in Nagoya Institute of Technology. His research interests are development of diagnostic techniques for high voltage power apparatus, sensing technology, application of signal and image processing techniques, neural networks and wavelet transform. He is a member of IEEJ, the Japanese Society of Applied Physics and Japan Society of Medical Electronics and Biological Engineering.

Ampol Tungkanawanich received B.S. degree in Electrical Engineering from Chulalongkorn University (Tailand) in 1995 and is presently a master course student in Department of Electrical Engineering, Osaka University. His researches are development of diagnostic techniques for high voltage power apparatus and fault analysis on power. He is a student member of IEEJ.

Zen-Ichiro Kawasaki received his B.S., M.S. and Dr. of Eng. degrees from Osaka University, Osaka, Japan, in 1973, 1975 and 1978, respectively. In 1979 he joined the Research Institute of Atmosphere in Nagoya University, Aichi, Japan. In 1989, he joined the Department of Electrical Engineering, Osaka University. He is engaged mainly in research on electromagnetic field theory, environmental electromagnetic engineering, development of lightning monitoring systems and insulation diagnostic techniques for high voltage power apparatus. He is the Recipient of a Society of Award of the Japan Society of Atmospheric Electricity. He is a member of IEEE, IEEJ, AGU, the Meteorological Society of Japan, and the Japan Society of Atmospheric Electricity. He is a member of the Joint Committee of the Science Council of Japan and of the Radio Research Laboratories.

Kenji Matsuura received his B.S. and M.S. degrees in Electrical Engineering from Osaka University, Osaka, Japan, in 1960 and 1962, respectively. In 1962, he joined Sumitomo Electric Industries, LTD. In 1977, he joined the Department of Electrical Engineering, Osaka University. He is engaged in research on generation, transmission, conversion, and control of electric power. Dr. Matsuura is a member of the IEEJ and the Energy and Resources Society.