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Development of Diagnostic Technologies for Electrical Facilities and Portable Instruments Utilizing These Techniques†

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Abstract:

Detecting partial discharge as a precursor phenomenon of breakdown is effective for insulation deterioration monitoring of electrical facilities. JFE Advantech developed techniques based on two types of acoustic wave, Acoustic Emission (AE) and ultrasound, for diagnosing the electrical facilities in operation. The diagnostic technique with AE has been applied to power distribution facilities such as cable terminals, molded buses, multi-circuit switches, etc. The developed AE diagnosis technique was verified by a field verification with a large number of AE measurements of actual facilities. The ultrasound emitted from the corona discharge has a specific cycle, which is effective for distinguishing between signals from the partial discharge and background noises. JFE Advantech has packaged this unique technique into a portable, small and light-weight hardware which satisfies both of improvement of operability and diagnosis reliability at the actual field.

1. Introduction

A stable supply of electric power is necessary and indispensable in the various types of social infrastructure in the living environment including steel works. Electrical facilities for electric power transmission and distribution, which support industrial activity and daily life, have been deployed in every part of the living environment, and an enormous number of these facilities are in operation. Because power systems are constructed as networks, the possibility that a partial abnormality may degrade the functions of the entire system is a concern. Thus, it can be said that maintenance and condition monitoring of these electrical facilities are extremely important from the viewpoint of stable power supply.

Various types of equipment are used in the final stage of power transmission and distribution, including electric cable joints and terminal devices such as terminals, disconnect switches and high voltage branching units, devices in distribution switchboards, circuit breakers, etc. High reliability is demanded in these devices, as they are positioned in the final part that supplies electric power to customers. On the other hand, due to the nature of electric power supply, equipment stops for inspections of the equipment condition, in other words, power interruptions, cannot be carried out frequently. Therefore, diagnostic technologies which can be used while equipment is in operation are considered necessary.

Focusing on partial discharge, which is a precursor phenomenon of insulation breakdown, JFE Advantech is engaged in the development of diagnostic technologies for detecting deterioration by detecting phenomena that accompany partial discharge and portable diagnostic devices utilizing these techniques as condition monitoring and diagnosis techniques for electrical facilities in operation.

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2. Diagnosis of Electrical Facilities in Operation: Detection of Deterioration by Partial Discharge

Partial discharge is a very small discharge that occurs due to internal defects of insulation materials, damage of the insulation surface, etc., and is a phenomenon that occurs in the initial stage of deterioration, before insulation reaches final insulation breakdown. When partial discharge occurs in organic insulation materials, which are representative insulation materials, deterioration is not limited to direct erosion of the insulation material, but also includes progressive physical and chemical deterioration due to ozone, active oxygen and other substances formed by the discharge, and finally reaches insulation breakdown[1)].

When partial discharge occurs in insulation material, the following secondary phenomena also occur:

(1) Generation of electrical pulses
(2) Emission of electromagnetic waves
(3) Emission of elastic waves which propagate inside the object
(4) Emission of inaudible ultrasonic waves
(5) Generation of audible sound and vibration
(6) Degradation of the insulation material

In other words, the occurrence of partial discharge can be detected by capturing these physical phenomena. The detectability of partial discharge, including the level of partial discharge that can be detected, discrimination of the phenomena and noises, the detection distance from the sensor to the point where the partial discharge occurred, etc., as well as the scale of the detection device, differs depending on which of these physical phenomena is used to detect partial discharge. Therefore, it is important to select the detection technology corresponding to the equipment where the condition is to be determined, its environment and the level of condition monitoring.

Among the above-mentioned physical phenomena, we focused on the following, which are technology seeds of JFE Advantech, as technologies which are capable of detecting partial discharge with comparative ease in the field while also offering high reliability.

- Acoustic emission (AE)
- Ultrasound

In diagnosis by AE, as described in Chapter 3, there are restrictions on the places where sensors can be installed in electrical facilities because it is necessary to place the sensor in contact with the object of diagnosis. However, advantages of detection of partial discharge by AE are that partial discharge can be detected with a simple device, not only at the surface of the insulation, but also inside the insulation, in the internal parts of equipment, etc., and analysis of the occurrence interval of AE is easy[2)].

On the other hand, when a partial discharge phenomenon is exposed to the outside, the ultrasonic waves accompanying the partial discharge are emitted outside of the object. This means that partial discharges inside insulation and in the interior of equipment cannot be detected by ultrasound. However, as merits of the ultrasound method, unlike AE, remote or noncontact detection at a distance from the object is possible, and as with AE, analysis of the occurrence interval is also easy[3)].

3. Development of Insulation Deterioration Detection Technology for Underground Facilities Using AE

3.1 Principle of AE

Among the physical phenomena that occur in partial discharge, emission of the elastic waves which propagate through the object in the frequency band of several tens of kilohertzes to several megahertzes are called acoustic emission (AE). The causes of AE are not limited to partial discharge, but also include events such as fatigue crack propagation and fracture of materials, surface contact/sliding and so on. Acoustic emission waves propagate in both solids and liquids. Since it has the distinctive feature of high sensitivity to minute damage, it is used in equipment diagnosis in a wide variety of industrial fields. In the general industrial field, applications of AE include health diagnosis of pressure-resistant vessels, corrosion diagnosis of the floor plates of petroleum storage tanks[4)], diagnosis of low speed rotating bearings[5)], etc.

In electrical facilities, AE is used to detect defects of the internal part and interface of insulation in cable terminals, bushings[6)] and other cable components, disconnect switches, etc., and to detect abnormalities in oil-immersed transformers[7)] and gas insulated switchgear.

3.2 Condition Monitoring of Underground Facilities

In recent years, undergrounding, in which electric power transmission lines are buried underground has promoted, centering on urban areas. In these underground facilities, ethylene propylene (EP) is widely used in the power cable terminals and joints connected to various facilities. With promotion of undergrounding, facilities in long-term operation are continuing to increase, and an increase in facility accidents caused by progressive deterioration is a concern.

Because replacement of components requires a power interruption, it is necessary to carry out renovations in a planned manner, corresponding to the deterioration of the components with time. However, in individual components which are exposed to environments with various temperature and humidity conditions, the degree of deterioration does not necessarily display a clear correlation with years of use. Considering this fact, deterioration diagnosis of individual components while in operation is indispensable, but until now, no technology for deterioration analysis of the insulation of insulating rubber components in operation had been established.

Therefore, JFE Advantech carried out a joint study of the applicability of AE to diagnosis of cable terminals and joints of underground facilities with Tokyo Electric Power Company Incorporated, which has a need for this technology[2,8,9].

The study was divided into the following two steps.

(1) In the first step, the detectability of partial discharge by AE was studied by partial discharge tests by using a specimen with an artificial defect.

(2) In the second step, AE measurements were performed with actual equipment in operation and components removed in the field, and the effectiveness of this technique was evaluated.

As these studies made it clear that field application of facilities diagnosis by AE is possible, development of diagnosis hardware for simple AE diagnosis in the field was carried out, and its effectiveness was confirmed.

3.3 Partial Discharge Test Using Specimens with Artificial Defect

For facilities diagnosis by AE, first, it is necessary to clarify the behavior of the AE accompanied partial discharge in components of the actual shape. For this, partial discharge tests were conducted by applying high voltages to specimens with artificial defects and components removed in the field.

3.3.1 Test specimens

The specimens used here were EP rubber molded buses which had been removed from actual equipment. These buses were used in as conductors connecting three electrical switches in a high voltage cabinet used at a customer's service entrance. Among the three phases, an artificial defect simulating a pinhole defect was made directly under the surface of the rubber component so that a partial discharge would be generated inside the EP rubber of the center phase, and a test specimen combining the three phases was then prepared by assembling the components. **Figure 1** shows the position of the artificial defect and the locations of the AE measurements using the AE sensor.

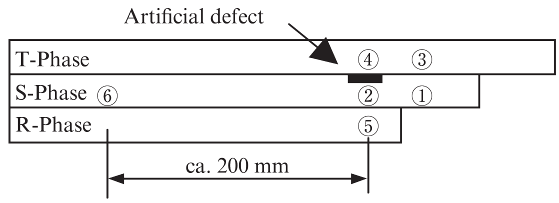

Fig. 1 Position of artificial defect and locations of acoustic emission (AE) measurement (①∼⑥)

3.3.2 Measurement device

The measurement device comprises an alternating current power supply for applying a high voltage, the partial discharge detection device and the AE measurement system. **Figure 2** shows the block diagram of the measurements.

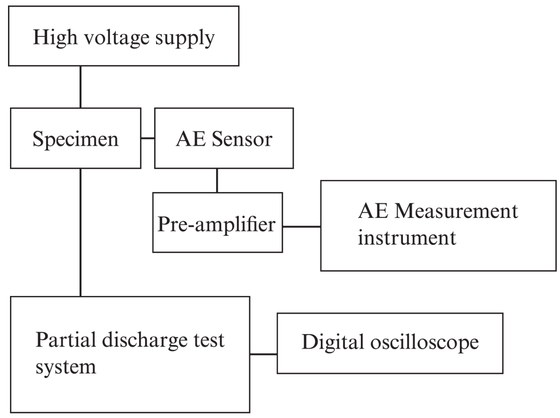

Fig. 2 Experimental system of partial discharge (PD) test

In the AE measurement system, an AE sensor, preamp, general-purpose AE measurement instrument and digital oscilloscope were used. The AE waveforms were recorded in the tests, and post-analysis was performed.

As the specimen surface potential was grounded, the AE sensor was placed in contact with the specimen by using grease as a couplant while holding the sensor by hand using insulated gloves.

3.3.3 Experimental results

(1) AE Amplitude

Partial discharge occurred when a direct current high voltage was applied to the specimen. The partial discharge quantity was measured with the partial discharge detection system and the amplitude of the AE waveform was obtained at different applied voltages.

The relationship between the AE amplitude and partial discharge is shown in **Fig. 3**. The partial discharge quantity increased with the applied voltage, and similar increasing results were also obtained with the AE amplitude[9]. This confirmed the fact that the amplitude of the AE generated accompanying partial discharge has a strong correlation with the degree of the generated partial discharge, in other words, the partial discharge quantity. Accordingly, it can be said that the degree of partial discharge can be estimated from the amplitude of the measured AE, and it is con-

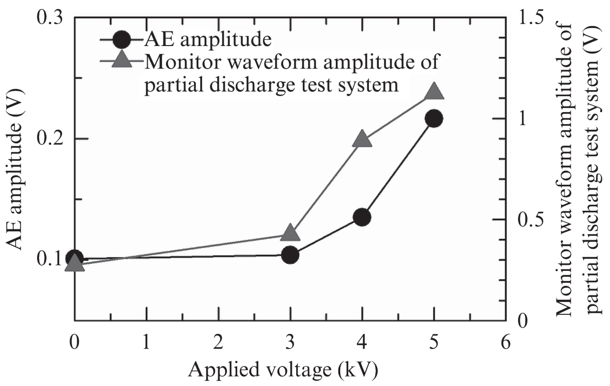

Fig. 3 Relationship between acoustic emission (AE) amplitude and partial discharge during direct current (DC) high voltage supply tests[9)]

sidered possible to evaluate the progress of deterioration if the same component is measured at a fixed point.

(2) Periodicity of AE

The condition of AE generation was investigated by applying a 50 Hz alternating current high voltage like that in electrical facilities in actual operation. In this case, the applied voltage was constant to obtain a condition in which partial discharge was generated stably. Measurements were then performed while changing the location of the AE sensor from point ① to ⑥ in Fig. 1. The AE envelope waveforms at the respective points are shown in **Fig. 4**.

Clear periodicity can be seen at almost all points, and its period is 0.01 s (100 Hz), which coincides with 2 times the power source frequency[9)]. Because a partial discharge occurs when the potential caused by a defect exceeds a certain threshold, a concentrated partial discharge is basically generated 2 times in 1 cycle under alternating current voltage. Based on this fact, it can be said that the measured AE waveform is caused by a partial discharge; in other words, the AE generated accompanying a partial discharge basically has a periodicity of 2 times the power source frequency. Depending on the mode of generation of partial discharge, there are also cases in which partial discharge occurs in only one electrode, and at this time, the AE is generated with the same period as the power source frequency.

From Fig. 4, in addition to periodicity, large amplitudes were also measured at ① and ②, which were close to the artificial defect, and the amplitude decreased with increasing distance from the artificial defect. This is considered to be because AE attenuates as the AE transmission distance in a rubber component becomes longer. Based on this fact as well, it can be said that the measured AE is an AE accompanying partial discharge.

The results of basic tests using a wide variety of test specimens, including terminal insulation material, terminal connection parts, a high voltage branching unit terminal (load break elbow) and others in addition to the molded bus clarified the fact that detection is possible by AE if a partial discharge on the order of 50 pC occurs due to an internal defect in a rubber insulation component, and reliable diagnosis is possible by using the generated periodicity and the change in amplitude due to the measurement location.

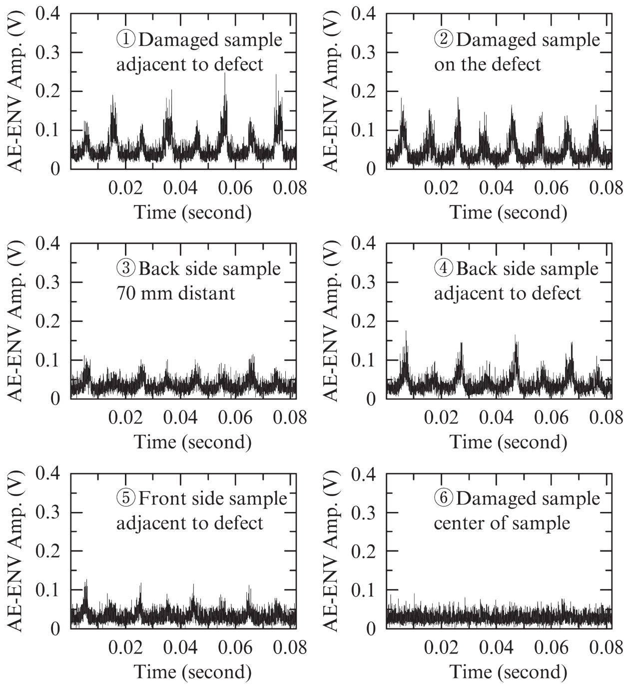

Fig. 4 Acoustic emission envelope (AE-ENV) waveforms at each sensor position[9)]

In addition, the same types of components, which had been installed adjacent to components where insulation breakdown occurred during operation, were removed and partial discharge tests were performed. Partial discharge of 30–60 pC occurred, and a partial discharge pulse waveform, which was generated with a period of 2 times the power source frequency and AE generated synchronized with that waveform were detected[8)]. This confirmed the fact it is possible to detect the occurrence of partial discharge in deteriorated components in actual environments by AE.

3.4 Verification of Applicability in Actual Field

The tests described in Section 3.3 confirmed the possibility of detecting the occurrence of partial discharge due to deterioration in actual environments by AE. Therefore, the applicability of AE measurement in actual environments was verified by measuring AE in actual equipment in operation, and the appropriateness of this technique as a diagnostic technology were verified based on the accumulation of examples.

Acoustic emission was measured in equipment in operation at more than 2 000 locations with various lay-

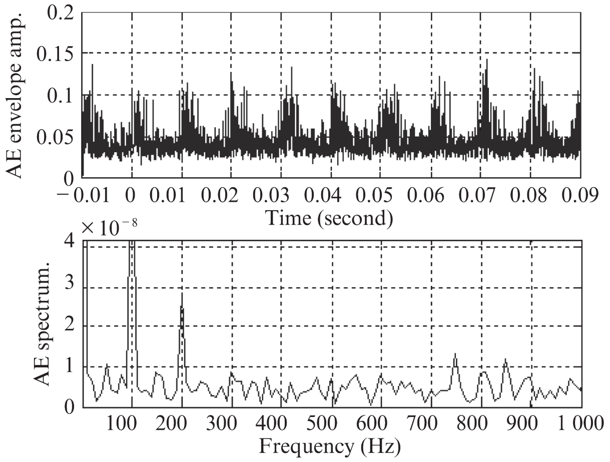

Fig. 5 Typical results of acoustic emission (AE) measurement for actual equipment under operation (Upper: AE envelope waveform; Lower: its frequency analyzed spectrum[10])

ing conditions, laying times, and manufacture dates, and the applicability of this technology was verified. As a result, AE having the same frequency as the power source or a frequency of 2 times the power source was detected in 30 components[7]. **Figure 5** shows an example of the detected AE envelope waveform and the results of frequency analysis by fast Fourier transform (FFT)[10]. As in the results of the partial discharge tests, a condition in which AE occurs remarkably at a period of 2 times the power source frequency can be seen.

These results verified the fact that the condition of equipment deterioration can also be detected in actual power distribution equipment by detection of partial discharge by AE measurement while the equipment is in operation.

It may be noted that JFE Advantech and Tokyo Electric Power Company Incorporated jointly received the 50th Shibusawa Award (The Japan Electric Association) for these development and verification activities.

3.5 Expansion of Application Range of Power Distribution Facilities Diagnosis by AE

In the series of actual environment measurements, components other than the EP rubber components discussed up to this point were also measured and the applicability of AE was verified in order to expand the range of application of partial discharge diagnosis by AE. As the result of this study, the components with which partial discharge diagnosis by AE was judged to be applicable are as follows[2].

• Underground Facilities
  Power supply distribution box:
    Terminal connection part (EP Rubber)
    Molded disconnect switch (MDS) electrode, MDS Bus (Epoxy resin)
  Multi-circuit switch:
    Terminal connection part (EP Rubber)
    Multi-circuit electrode (Epoxy resin)
  High voltage branching unit:
    Load break elbow (EP Rubber)
  Pad mounted transformer:
    Load break elbow (EP Rubber)
• Overhead Facilities
  Pole transformer:
    Compact transformer primary fuse holder (Epoxy resin + Metal)
  Overhead conductor:
    Internal insulation cylinder (EP Rubber)
  Overhead arrestor:
    Internal gap (Porcelain + Metal)

3.6 Development of Portable AE Diagnostic System

In order to use partial discharge detection by AE in the field, a portable-type diagnostic system which enables simple and reliable AE diagnosis was developed. The AE insulation deterioration diagnosis system AE-210, which was the first-generation model, was released in 2005[11] and was used by customers in diagnosis of power distribution facilities. In 2012, JFE Advantech developed a more compact portable diagnostic system, AE-210 SE. This device retains the strong points of the first-generation model while realizing an even more compact size and lighter weight. **Photo 1** shows the appearance of AE-210 SE.

The design concept, which prioritizes workability in the field, was as follows.

(1) Adoption of sensor head unit with built-in preamp
(2) On-the-spot display of periodic analysis results by color liquid crystal display
(3) Battery drive

Photo 1 Photo of acoustic emission (AE) insulation deterioration diagnostic system “AE-210SE”

Photo 2 Typical acoustic emission (AE) measurement situation at an actual field[10]

(4) Compact size and weight with excellent portability
(5) Simple operability with the minimum possible number of operations

In particular, in the design of the sensor head, use while wearing high voltage insulated gloves and the attachability of the sensor in narrow spaces were considered, and the dimensions were determined based on opinions regarding workability in measurements from personnel in the field. **Photo 2** shows an example of the situation of AE measurement (MDS electrode)[10] in the field using AE-210.

The body of the diagnostic system comprises a measurement circuit that measures very weak AE with good sensitivity, a digital circuit that performs signal processing of the measured waveform by AD conversion and digitalization, a color display part that displays the measurement result with good visibility, and a memory card that records the measured waveform and diagnosis value. In the signal processing section, envelope detection of the AE waveform and periodic analysis by FFT are combined, and the characteristic power source frequency synchronous component for partial discharge is extracted.

Conventionally, in waveform observation with a digital oscilloscope, judgment of detection of partial discharge was sometimes difficult when periodicity was not clearly expressed in the waveform. However, with the developed detection system, periodicity analysis in the field has resulted in a great improvement in recognition of the partial discharge component, while numerical display of the strength of the component synchronized with the power source frequency based on the periodic analysis results enables any user to judge easily whether AE due to a partial discharge has been detected or not.

4. Development of Ultrasonic Corona Discharge Checker

In corona discharge and creeping discharge, in which a partial discharge occurs on the surface of an insulator, the partial discharge is accompanied by sound in audible-to-ultrasonic range (several tens of kilohertzes), which is radiated simultaneously into the surrounding space. Therefore, it is possible to detect these partial discharge events by measuring sound.

Here, power distribution facilities are the object. Because sound in the range of several kilohertzes and under frequently exists in the spaces where these facilities are installed[3)], ultrasound of 40 kHz is used, as this is a frequency band which contains little disturbance noise. As an advantage of ultrasonic diagnostic technology, unlike the AE described above, it is not necessary to place the sensor in contact with the object of measurement, which means that noncontact diagnosis is possible.

Like AE, it is known that the period of ultrasound generated by partial discharge is synchronized with the frequency of the power source[3)]. Using this fact, it is possible to distinguish the ultrasound accompanying partial discharge from disturbance noise, even in the same ultrasonic frequency band.

4.1 Development of Corona Discharge Checker MK-720

A wide variety of portable discharge detector products using ultrasound already exists, and the above-mentioned fact that the period of the ultrasound generated by partial discharge is synchronized with the power source frequency is also already known. There were few measurement devices which incorporated these two points except JFE Advantech corona discharge detection system MK-710.

On the other hand, when MK-710 was developed, there were limits to miniaturization of the hardware technology. Therefore, the corona discharge checker MK-720 was developed as a successor model, based on the design concept of improving convenience by further miniaturization and lighter weight. The main features of MK-720 are as follows.

(1) Based on the periodic analysis of ultrasonic waves, extracts only the ultrasonic component caused by partial discharge
(2) Simple operability, as measurement is started by a single button
(3) Real-time processing by high speed FFT of the built-in signal-processing processor
(4) Compact, lightweight and battery-driven
(5) Improved sensitivity and directionality by sound collection using a parabola
(6) Records received ultrasonic waveform data
(7) Quantification of measurement results by a unique logic ((Ratio of frequency component strength synchronized with the power source frequency to total strength) = (Discharge component rate))

The appearance of the corona discharge checker MK-720 is shown in **Photo 3**. An example of the situa-

Photo 3 Photo of corona discharge checker “MK-720”

Photo 4 Typical measurement situation using corona discharge checker “MK-720”

tion of use of MK-720 is shown in **Photo 4**.

4.2 Example of Partial Discharge Detection by MK-720

The following shows an example of partial discharge detection by MK-720 at a 275 kV disconnect switch, which is an extra high voltage facility. As a result of measurements with MK-720 from a location more than 3 m from the disconnect switch, the discharge component rate, which is an index of the occurrence of partial discharge, was on the order of 1–3% at virtually all points, but showed a somewhat high value of 9% at a certain point.

MK-720 records the waveform and also records the results of periodic analysis of that waveform. The ratio of the strength of the various obtained frequency components to total strength is shown in **Fig. 6**[12]. In graphing, the horizontal axis values were normalized by the power source frequency. That is, (Horizontal axis) = 1 corresponds to the power source frequency.

From the results of the periodic analysis, the power source frequency and its integral multiple high frequency components can be clearly seen, and is considered that corona discharge occurs at those parts.

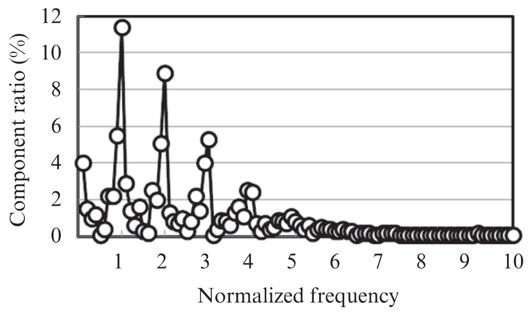

Fig. 6 Frequency spectrum of ultrasonic wave emitted from insulator of 275 kV disconnector[12]

The estimated cause of the partial discharge in this example was a dirty insulator, and the discharge will presumably subside if the dirt is washed away by rainfall.

5. Conclusion

In order to realize improved reliability and efficient maintenance of electrical facilities, diagnostic technologies based on the techniques of detecting partial discharge by measuring AE and ultrasound were developed and those technologies were packaged in portable diagnostic systems as condition diagnosis technologies for use with facilities in operation.

The AE technology was developed through a process of field verifications by measurement of a large number of actual facilities, and has made it possible to perform condition diagnosis of electrical facilities, such as EP rubber components, which had been difficult in the past. In the future, expansion of the range of applications to diagnosis of power transmission and transformation facilities, which are more upstream processes of the electric power system, can be expected.

In the case of ultrasound, a diagnostic device with excellent portability and operability was developed based on conventional technology. In the future, the authors hope to improve diagnostic performance in the directions of higher sensitivity and wider range, and to achieve innovations in maintenance technologies which provide higher efficiency and reliability.

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