Paper

On-line Partial Discharge Measurement of Hydrogenerator Stator Windings using Acoustic Emission Detection Techniques

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The on-line partial discharge testing has been used to provide useful information to diagnose and monitor the integrity of stator winding insulation of hydrogenerators. We are aiming for the establishment of a method of on-line diagnosis of insulation deterioration on hydrogenerator stator winding by acoustic emission (AE) detection method. We have developed a new AE measuring system that is controlled by output signal of hydrogenerator. In this paper, it was clarified that the insulation deterioration of hydrogenerator stator winding depended remarkably on the temperature of stator winding during a starting operation period.

Keywords: on-line insulation diagnosis, partial discharge, hydrogenerator stator winding insulation, acoustic emission sensor

1. Introduction

Nowadays electricity companies have as main drivers the need of cost savings and the increasing liability awareness. Power apparatuses are significant infrastructures that support society today. In such a situation, we must manage many hydrogenerators effectively over holding reliance of power supply. So gravity of technical business, which contains supervising of driving condition, driving support, conserving and diagnosis, has been increasing. Especially, a demand of life-prolonging driving and diagnosis of life on hydrogenerators have been driving for 30 years tend to increase. Further, in tendency of society, for example environmental protection, pursuing economy and deregulation of power supply, establishment of technology is needed on efficiency conserving of hydrogenerator. The on-site measurements and on-line monitoring of trends in partial discharge (PD) patterns is already of great value in providing early warnings and preventive maintenance actions. Condition-based maintenance (CBM) will be overviewed for plant and substation high voltage equipment, e.g. in case of generator, GIS and cable insulation diagnosis. The maintenance technology of a hydrogenerator is trending toward the introduction of CBM (1). The PD testing is a promising method of stator winding insulation of hydrogenerator conditions monitoring. Therefore, the on-line PD testing has been used to provide useful information to diagnose and monitor the integrity of stator winding insulation of many hydrogenerators.

Recently, the on-line PD measurements have been made on the stator winding of hydrogenerators with many kinds of PD detection methods (2). The on-line PD measurements are accompanied by several physical manifestations: electrical pulses and resulting radio frequency pulses, acoustic pulses, light, as well as chemical reactions within the cooling gases that are either air or hydrogen (3).

The electrical detection methods are very sensitive to the electromagnetic interference. Also, the sensitivity of electrical PD detection methods decreases with increased capacitance of the test object. Thus, it is well known that these methods are not very sensitive when applied to capacitors and other large power apparatus where the capacitance are very high. As well, the electric partial discharge detection methods rarely provide a basis for location of the partial discharge in the case of large

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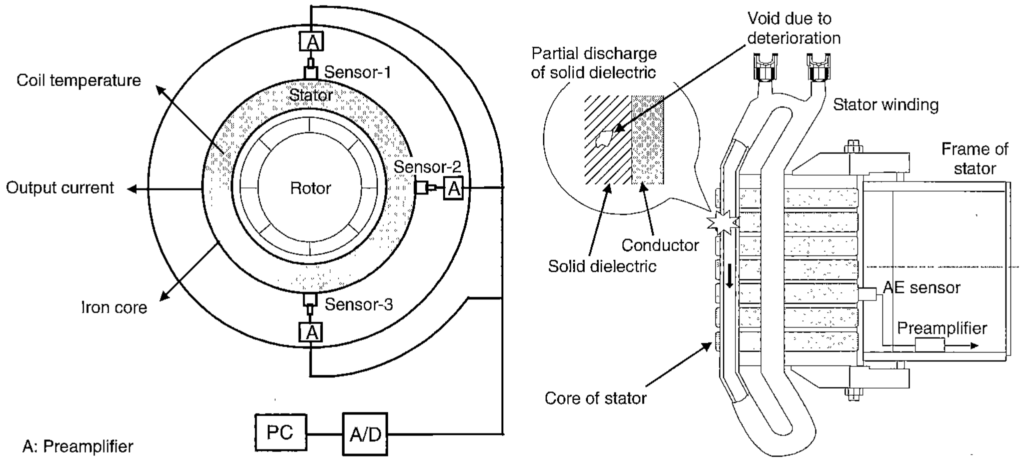


(a) Top of view (b) Side of view

Fig. 1. Schematic diagrams of experimental apparatus using an acoustic emission detection techniques in a field test

test objects with complex structure such as power transformers, switchgears, etc. In such situations, the AE detection method for on-line hydrogenerator stator windings insulation has some advantages over the electrical PD detection methods (4). The AE detection method is immune to electromagnetic noise, which can greatly reduce the sensitivity of electrical methods, especially when, applied under field conditions. The sensitivity of AE detection method does not vary with test object capacitance hence these methods are widely applied to large capacitors and other apparatus having large capacitance. Also, the acoustic PD detection methods can be extended to facilitate PD location in many situations (2). In some situations, the combination of acoustic and electrical PD detection has been very effective in avoiding false alarms of on-line PD monitoring apparatus. Thus, the on-line insulation diagnosis system using AE sensor techniques is also most useful to stator winding insulation of hydrogenerator conditions monitoring (5).

We have already investigated that the on-line PD measurements can be useful for assessing the conditions of complete stator winding with AE sensors as well as of individual form-wound coils and bars (5). Noise reduction is a major issue when performing on-line testing because rotating hydrogenerators are not operated in an ideal environment for measuring these signals. The on-line PD measurements testing need to separate the AE signal generated by the PD from the AE signal including the machine noise. We have succeeded that the AE signal could be separated in to the machine noise level and the AE signal level produced by the PD (6).

In this paper, we have developed a new AE measuring system that is controlled by output signal of hydrogenerator. We have measured the AE signals by many AE sensors, and analyzed the AE signals by Fast Fourier transform and Wavelet analysis. The field test was performed on three class hydrogenerators for 3.5 kV and 6.6 kV and 11.0 kV in rated voltage. Using this new system, it was found that insulation deterioration of hydrogenerator stator winding was very high at the starting operation period. In particular, for 6.6 kV class hydrogenerator, the off-line the measurement of loss tangent was carried out as a function of voltage up to 6.6 kV in voltage together with AE signal measurement.

Table 1. Specifications for 3.5 kV, 6.6 kV and 11.0 kV class hydrogenerators

Voltage class	3.5 kV	6.6 kV	11.0 kV
Capacity[kVA]	1,250	6,250	20,700
Rated Power[kW]	980	5,000	18,600
Insulation material	Epoxy	Epoxy	Epoxy
Insulation type	B	B	B
Rated voltage[kV]	3.5	6.6	11.0
Rated current[A]	207	547	1,087
Poles	20	12	24
Rated revolution[rpm]	360	600	300
Recoil[year]	1974	1977	1968

2. Experimental Apparatus and Procedures

The specifications for three kinds of class hydrogenerators were shown in Table 1. The 3.5 kV class hydrogenerator was manufactured in 1928; afterwards the stator winding was recoiled in 1974. The 6.6 kV class hydrogenerator was manufactured in 1940; afterwards the stator winding was recoiled in 1977. The 11.0 kV class hydrogenerator was manufactured in 1968. Figure 1 shows the schematic diagrams of experimental apparatus for a filed test. The three AE sensors were directly set on the iron core of stator windings as shown in Fig. 1(b). An AE sensor was used: type-703 (NF Electric Instruments, Model AE-703S, Resonance frequency : 70 kHz). The AE signals were amplified enough to analyze with the preamplifier (NF Instruments, Model 9917, Band width of frequency: 2 kHz~1.2 MHz).

Measurements for three kinds of hydrogenerators were performed from 2000 to 2002 at interval time of variable measurement time using developed an automatic data collecting AE measuring system. These data of AE signals were analyzed using the FFT, the envelope processing techniques and Wavelet analysis (5). Simultaneously, the stop time of hydrogenerator (stop time) and the temperature of stator winding (coil temperature)

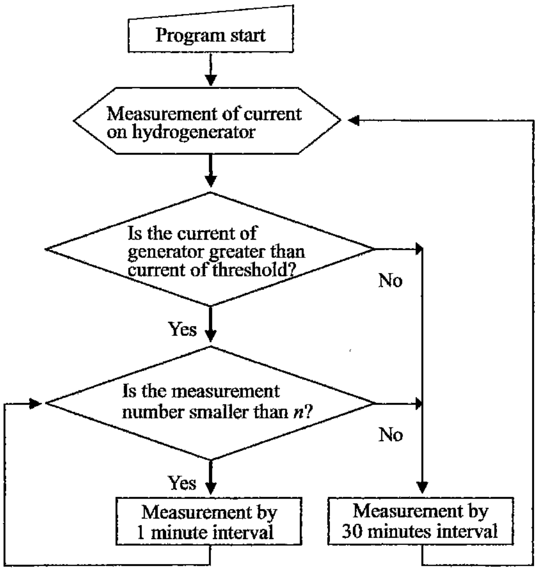


Fig. 2. Flow chart of AE measuring program controlled by output signal hydrogenerator

were measured together with the AE signals. A temperature detector is usually a resistance temperature detector (RTD).

For 6.6 kV class hydrogenerator, at the same time offline the measurement of loss tangent, that is tan δ, was carried out as a function of voltage up to 6.6 kV in voltage. Then, the AE signals were investigated with the loss tangent testing. Measurement of loss tangent was carried out by means of a Schering bridge method.

We have developed an AE measuring system to measure the AE signals at starting period of operation of hydrogenerator. As a result, an AE measuring system were developed to measure AE signals at shorter interval at starting period of operation and longer interval at normal operation period of operation using a LabVIEW software. Figure 2 shows a flow chart of an AE measuring system program controlled by output signal hydrogenerator. As a result, we could investigate the characteristics of PD versus time for starting hydrogenerator with this system in detail.

3. Experimental Results and Discussion

We have already published that the relation between the intensities of AE signals according to applied voltage and electric charges of partial discharge was investigated, it was found that the AE amplitude increased significantly over 6.4 kV for 11.0 kV in rating voltage hydrogenerator and was proportional to the value of the electric charges ⁽⁴⁾.

Figure 3 shows the relationship between tanδ (open circle symbols) and intensity of AE signals (closed circle symbols) as a function of voltage at u-phase for 6.6 kV class hydrogenerator. As seen in this figure, it was found that the characteristics of intensity of AE signal are closely connected with the tan δ. Figure 4 shows a sample of measured AE wave and analyzed AE wave with an AE measuring system for 6.6 kV class hydrogenerator. In this window, the upper graph shows filtered wave (cut-off frequency: 10 kHz) that was investigated as machine noise ⁽⁶⁾) and the bottom graph shows plots of intensity of AE signal by PD at each time. Therefore, we can display the on-line measurement results of AE signals on the monitor of a Personal Computer at real time.

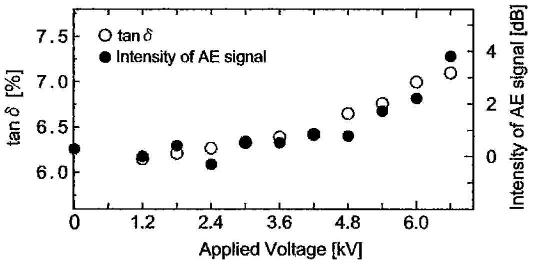


Fig. 3. Relationship between tanδ and intensity of AE signal as a function of voltage at u-phase for 6.6 kV class hydrogenerator

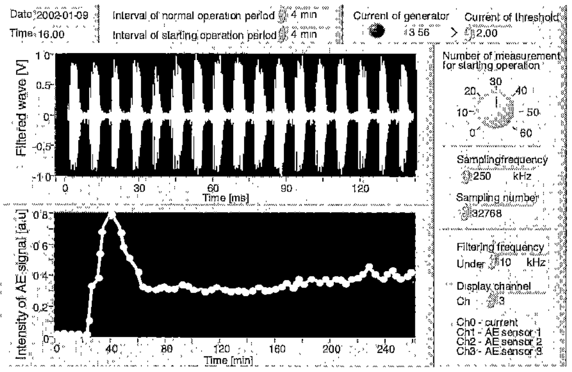

Date 2002-01-09
Time 16.00
Interval of normal operation period 4 min
Interval of starting operation period 4 min
Current of generator 3.56 > Current of threshold 2.00
Number of measurement for starting operation
Sampling frequency 250 kHz
Sampling number 32768
Filtering frequency Under 10 kHz
Display channel Ch 3
Ch0 - current
Ch1 - AE sensor 1
Ch2 - AE sensor 2
Ch3 - AE sensor 3

Fig. 4. Sample of measured AE wave (upper)and analyzed AE wave (bottom) with an AE measuring system for 6.6 kV class hydrogenerator

Conception of the wavelet transform has been used for AE signal analysis in the field of exploration for partial discharge ⁽⁵⁾. The wavelet transform is effective for the analysis of the varying signal, e.g. AE signal. The wavelet transform of a signal $y(t)$ is defined by

$$Y(\omega, t_0) = \frac{\omega}{L} \int_{\frac{L}{2\omega}+t_0}^{-\frac{L}{2\omega}+t_0} y(t)g(t)dt \cdots\cdots\cdots\cdots (1)$$

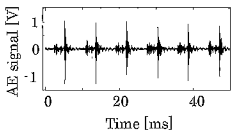
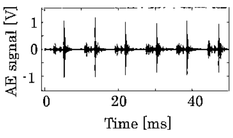
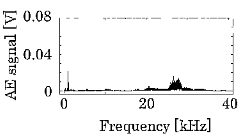
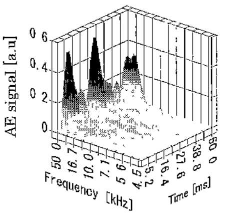
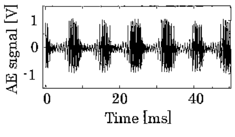
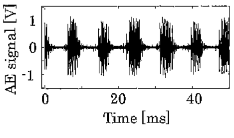
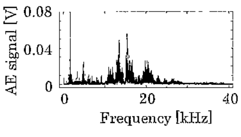
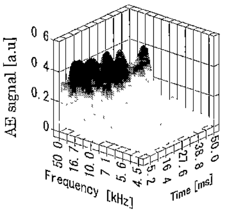
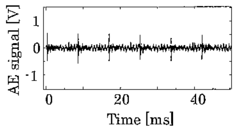
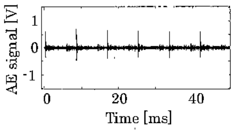
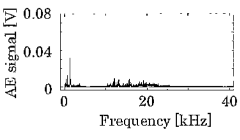
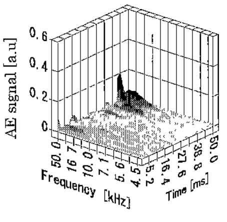
The function of Fourier transform is given by

$$g(\omega, t) = \begin{cases} \cos\omega t + j\sin\omega t & -\dfrac{L}{2\omega} < t < \dfrac{L}{2\omega} \\ 0 & \text{otherwise} \end{cases} \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

It was confirmed that the wavelet transform was very useful to analyze the varying AE signal.

Typical AE signals resulting from PD, filtered AE waves, spectral distribution of FFT transforms and distribution of Wavelet transformed waves using three AE sensors for 3.5 kV, 6.6 kV and 11.0 kV class hydrogenerators are shown in Table 2. As shown in this table, it was found that the measured AE signal by using AE sensor is very important for monitoring the stator windings insulation of hydrogenerators.

Table 2. Typical AE signals resulting from PD, filtered AE waves, spectral distribution of FFT transforms and distribution of Wavelet transformed waves for 3.5 kV, 6.6 kV and 11.0 kV class hydrogenerators

Class	AE signals Filtered	AE waves	FFT transforms	Wavelet waves
3.5 kV				
6.6 kV				
11.0 kV				

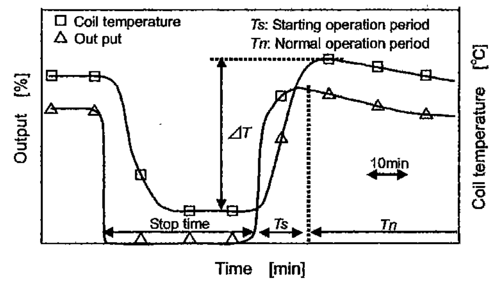


Fig. 5. Conceptual model of correlation between output and coil temperature of hydrogenerator versus time

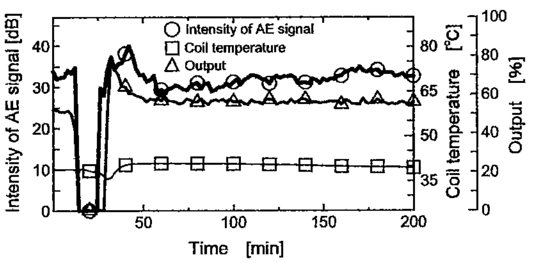
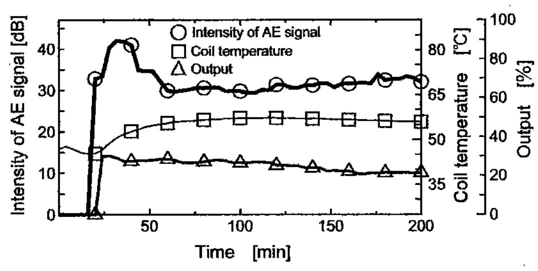


Fig. 6. Time dependence for intensity of AE signals, coil temperature and output percent for 3.5 kV class hydrogenerator at on-line measurement

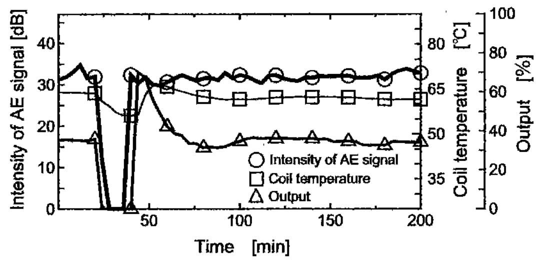
Figure 5 shows a conceptual model of correlation between output and coil temperature of hydrogenerator versus time (7). Although properties of output and coil temperature change with cooling method and system of each hydrogenerators, the coil temperature may increase suddenly at the starting operation period of hydrogenerator and may be stabilized at high temperature at normal operation period of hydrogenerator as shown in Fig. 5. In this case, the property of coil temperature is remarkably affected by the temperature of circumstance and stop time of hydrogenerator. The coil temperature variation ΔT, as shown in Fig. 5, of the 3.5 kV class hydrogenerator change from room temperature to approximately 40°C, on the other hand, of the 6.6 kV class hydrogenerator change from room temperature to approximately 85°C. Also, the coil temperature of the 11.0 kV class hydrogenerator change from room temperature to approximately 40°C.

Figure 6 shows time dependence for intensity of AE signals (open circle symbols), coil temperature (open square symbols) and output percent (open triangle symbols) for 3.5 kV class hydrogenerator at on-line measurement. From this figure, it was found that the intensity of AE signal reaches at 40 dB in maximum with increasing coil temperature at the starting operation period and after that is stabilized at 33 dB in average at the normal operation period.

Figure 7 shows time dependence for intensity of AE signals, coil temperature and output percent for 6.6 kV class hydrogenerator as a function of stop time of hydrogenerator at on-line PD measurement. Fig. 7(a) shows the case of longer stop time of hydrogenerator (stop time : 204 hours), intensity of AE signal reaches at 43 dB in maximum with increasing coil temperature at the starting operation period of hydrogenerator and after that is stabilized at 30 dB at the normal operation period of hydrogenerator. This property is similar to



(a)Longer stop time: 204 hours



(b) Shorter stop time: 0.3 hours

Fig. 7. Time dependence for intensity of AE signal, coil temperature and output percent for 6.6 kV class hydrogenerator as a function of stop time of hydrogenerator at on-line measurement

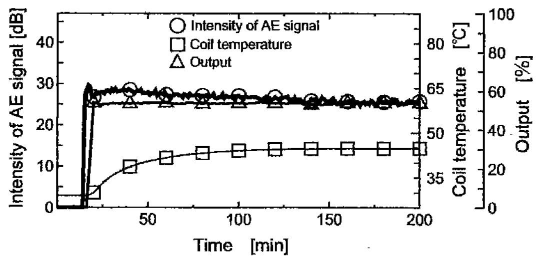


Fig. 8. Time dependence for intensity of AE signals, coil temperature and output percent of 11.0 kV class hydrogenerator at on-line measurement

the characteristics shown in Fig. 6. On the other hand, Fig. 7(b) shows the case of shorter stop time of hydrogenerator (stop time: 0.3 hours), at stop time the coil temperature is about 55°C. In this case, as stator winding temperature is very high within starting operation period, intensity of AE signals may be stabilized instantly even at the starting operation period of hydrogenerator.

Figure 8 shows time dependence for intensity of AE signals, coil temperature and output percent for 11.0 kV class hydrogenerator at on-line measurement. From this figure, it was found that the intensity of AE signal reaches at 30 dB in maximum with increasing coil temperature at the starting operation period and after that is stabilized at 28 dB in average at the normal operation period.

It is proposed that the new conceptual model of criteria for judging the insulation deterioration in epoxy-resin insulated stator windings taking characteristics of PD in starting and normal operation conditions of hydrogenerator into consideration. As a result, it is seemed that the trend of the relationship insulation withstand of stator windings and signals of PD are necessary to assess characteristics of not only $\mathrm{PD_n}$ but also $\mathrm{PD_s}$, where $\mathrm{PD_n}$ corresponds to the averaged PD magnitude in normal operation period and $\mathrm{PD_s}$ corresponds to the maximum PD magnitude during starting operation period (7).

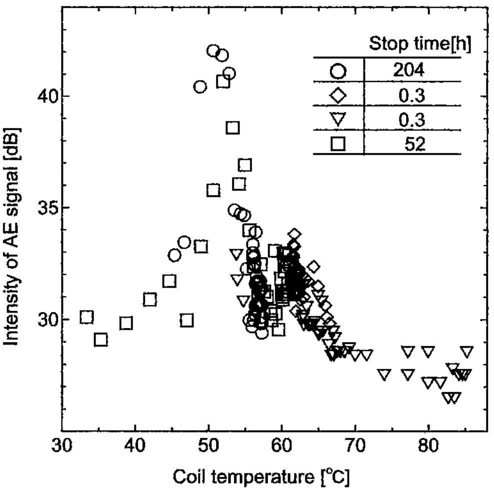


Fig. 9. Characteristics for intensity of AE signal versus temperature of stator winding as a function of stop time for 6.6 kV class hydrogenerator

Figure 9 shows the characteristics of AE signals versus coil temperature as a function of stop time for 6.6 kV class hydrogenerator. It can be said from the figure that AE signal increases at first with increasing coil temperature, reach a maximum and indicate a decreasing tendency thereafter. When the stop time is longer, the difference in coil temperature between stop of hydrogenerator and operation of hydrogenerator become large, and the effect of moisture absorption of stator windings and humidity appears to be large. As a result, it was found the AE signal increase abruptly. On the other hand, when the stop time is shorter, it was found the AE signal decrease with increasing coil temperature. When the stop time is shorter, the difference in coil temperature between stop of hydrogenerator and operation of hydrogenerator become small, and the effect of moisture absorption of stator windings and humidity appears to be small. From a series of experimental results, it was recognized the AE signal, that is, the partial discharge remarkably depends on the operating conditions. A degree of insulation deterioration of the generator windings was influenced the characteristics of temperature, load, humidity (3) and moisture absorption (8), etc. In the case of longer stop time in 6.6 kV class hydrogenerator as shown in Fig. 7(a), as the effect of coil temperature, humidity and moisture absorption may become large, it would seem that the PD activity is remarkable. On the other hand, in the case of shorter stop time in 6.6 kV class hydrogenerator as shown in Fig. 7(b), as the effect of coil temperature, humidity and moisture absorption may become small, it would seem that the PD activity is not remarkable.

Figure 10 shows the characteristics of intensity of AE signal versus coil temperature at starting operation period with measuring time at less than 30 minutes for 3.5 kV, 6.6 kV and 11.0 kV class hydrogenerator in detail. It will be seen from the figure that AE signal

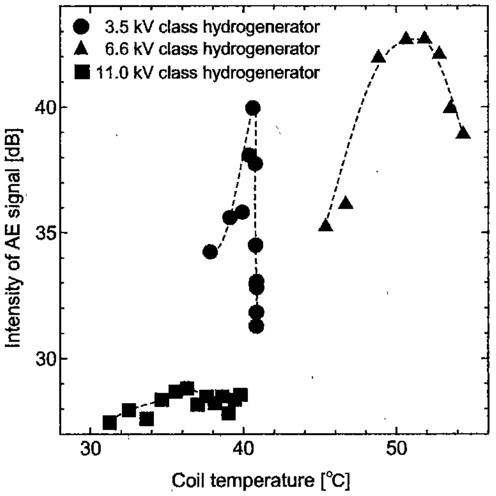


Fig. 10. Characteristics of intensity of AE signal versus coil temperature starting operation period with measuring time at less than 30 minutes

increases at first with increasing coil temperature, reach a maximum and indicate a decreasing tendency thereafter. Therefore, it was found that the PD depended on the coil temperature, and the maximum of PD magnitude occurs within 30 minutes at starting operation.

Completely explanation for effect of output of hydrogenerator on intensity of AE signal measured in the present work requires the further study.

4. Conclusions

For the purpose of establishing a deterioration criterion required for diagnosing the insulation deterioration of epoxy-resin insulated stator windings of hydrogenerator, we have investigated and analyzed data concerning AE signals in operation for 3.5 kV, 6.6 kV and 11.0 kV class hydrogenerators using developed an AE measuring system. An AE detection method for on-line hydrogenerator stator windings insulation has some advantages over the electrical PD detection methods. The AE detection method is immune to electromagnetic noise, and it can be extended to facilitate PD location in a hydrogenerator.

Typical AE signals resulting from PD, filtered AE waves, spectral distribution of FFT transforms and distribution of wavelet transformed waves were investigated for each hydrogenerator.

As a result, it was found that the intensity of AE signals for on-line monitoring of stator winding was remarkably influenced by the characteristics of the temperature of stator winding. Then, the AE signal increases at first with increasing coil temperature, reaches the maximum and indicates decreasing tendency thereafter. Also, it was found that the PD depends on the coil temperature, and the maximum of PD magnitude occurs at starting operation within 30 minutes.

We have proposed the taking the characteristics of change of PD with years of service into consideration, the trend of PD produced at the start and normal operation period of hydrogenerator are necessary to an evaluation method of insulation deterioration in hydrogenerator stator windings by PD characteristics. To establish an on-line PD monitoring of hydrogenerator winding require the machine data, operating data of the machine and winding data for further study.

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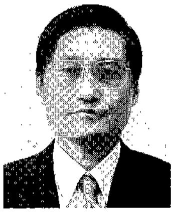
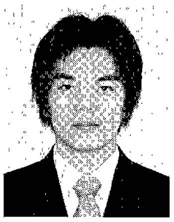
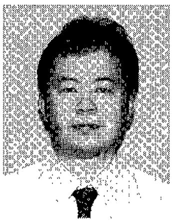


Tadamitsu Kaneko (Member) was born on October 12, 1954. He received his B.S. degree from Miyazaki University and his M.S. and D.Eng. degrees from Kyushu University in 1978, 1980, and 1987, respectively. He served at Kyushu University as a research associate from 1980 to 1988. He moved to Civil Aviation College, Ministry of Transport as an associate professor. In 1993, he moved to the Faculty of Humanities, Miyazaki Municipal University as an associate professor. Since 1999, he has been a professor. His research interests include monitoring, diagnostics and maintenance technology in electric power field. He is a member of the Electrical Engineers of Japan and the Institute of Electrostatics Japan.

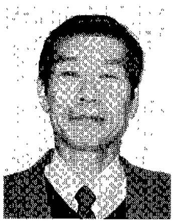


Akito Takemura (Student Member) was born in Miyazaki, Japan, on January 5, 1980. He graduated from Department of Electrical and Electronic Engineering, Faculty of Engineering, Miyazaki University in 2002 and currently studying in the Graduate School of Miyazaki University. His subject of research is development of diagnosis of insulation deterioration on hydrogenerator stator windings using acoustic emission detection techniques.

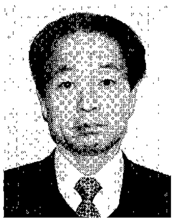


Osamu Takenouchi (Member) was born in Kumamoto, Japan, on December 15, 1966. He received a D.Eng. in Graduate School of Marine Science and Engineering from Nagasaki University in 1997, and is presently an assistant professor at Civil Aviation College. He has worked on surface discharge on electrolyte. The Institute of Electrostatics Japan, the Japan Society for Aeronautical and Space Sciences member.

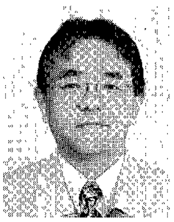
Youl-Moon Sung (Member) was born on November 2, 1966. He graduated from Pusan National University in Feb. 1992, Korea. Obtained his M.S. and Ph.D. from the same university in Feb. 1994 and Aug. 1996 respectively. Undertook a post-doc. from Aug. 1997 to Jul.1999 in Kyushu University. He is a research associate from Aug. 1998 to Jul. 1999 in Kyushu University. Currently is a research associate in Miyazaki University.



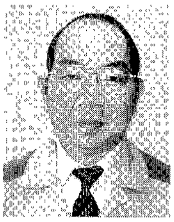
Masahisa Otsubo (Member) was born on January 10, 1947. He received his B.E. degree in electrical engineering from Miyazaki University in 1969 and his D.Eng. degree from Kumamoto University in1993. He became a research associate in electrical engineering of Miyazaki University in 1970, and has been an associate professor in the Department of Electrical and Electronic Engineering since 1993. Since 2003, he has been a professor. His research interests include the dielectric insulation of polymers, insulation diagnostics of electric power installation, and discharge plasma phenomena. He is a member on the Electrical Engineers of Japan and the Institute of Electrostatics Japan.



Chikahisa Honda (Member) was born February 12, 1943. He graduated form the Department of Electrical Engineering, Kyushu University, in 1965. He then joined the Department of Electrical Engineering as a research associate in 1965 and became an associate guest professor in the Department of Energy Conversion Engineering, Graduate School of Engineering Sciences, in 1989. Since 1993, he has been a professor in the Department of Electrical and Electronic Engineering, Faculty of Engineering, Miyazaki University. He holds a D.Eng. degree. He is engaged mainly in research on laser-aided plasma diagnostic. He received a Society Award from the Japan Society of Applied Physics in 1987. He is a member of the Electrical Engineers of Japan.



Yoshio Tsuruta (Non-member) was born on August 1, 1956. He graduated form the Department of Electrical Engineering, Miyakonojo National College of Technology in March 1977. Now, he is a president of Kodensya Co., Ltd.



Kazuhiro Tanaka (Non-member) was born on August 5, 1947. He joined the Kyushu Electric Power Co., Inc. in 1966. He became a group manager of the department of power generation and transformation in Miyazaki branch July 2000. Now, he is mainly engaged in a comprehensive planning of hydrogenerator power stations and substations, a survey of new technology and a design of hydrogenerator power stations.