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Considerations on the Long-term Reliability of On-line Partial Discharge Ceramic Sensor for Thermal Power Generators and its Demonstration in the Field

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Abstract – The present study describes the considerations on the long-term reliability of the on-line partial discharge (PD) ceramic sensor for thermal power generators. Voltage acceleration aging tests were carried out under continuous and impulsive thermal aging at more than 100 °C, considering the practical service environment. Experimental results show that the sensors have a life that could last for more than 100 years, excellent dielectric characteristics, and insulation strength. In addition, the ceramic on-line PD sensors were installed in a thermal power generator in Korea for demonstration. The results of the PD calibration and test voltage application prove that the on-line ceramic sensors have satisfactory performances for on-line PD measurement.

Keywords: Partial discharge, Thermal power generator, Voltage acceleration aging test, On-line ceramic sensor

1. Introduction

The solid insulations of the generator stator windings are continuously exposed to a combination of thermal, electrical, mechanical, and environmental stresses during operation. The insulations deteriorate gradually with prolonged use, ultimately rendering them unable to perform. Several aging causes lead to failures of stator winding insulations. One main cause is known as on-line partial discharge (PD). Thus, PD tests have been recognized as one of the most effective tests for the assessment of the condition of the winding insulation of high-voltage generators. PD tests can be divided into off-line and on-line measuring methods. The on-line method has an advantage in terms of its capacity to monitor winding insulation troubles consecutively without interrupting the generators. The off-line method experiences problem in measuring PD only when the generator is not in use. Hence, on-line PD sensors were developed, and the PD measurement method was moved from off-line to on-line for the diagnosis of high-voltage generators [1].

Different sensors, such as the capacitive coupler, stator slot coupler, and current transformer have been used for on-line PD detection for generators. The epoxy mica capacitive coupler (EMC) is the most extensively used type of sensor [1–3]. However, reports state that this type of sensor has disadvantages, such as bad manufacturing process and high production cost. Considering the abovementioned problems, the authors have developed a ceramic type of sensor for on-line PD measurement for thermal power generators [4–5]. This sensor should be electrically connected to insulated phase buses (IPBs) to measure PD signals. In general, the temperature inside the IPB enclosure is higher than the ambient temperature outside due to the bus heat emitted by the load current. Moreover, eddy current losses on enclosures can increase the temperatures to more than 100 °C. In addition, starting and stopping generator operation for maintenances or faults result in heat shock, causing a sharp decrease or increase in temperature inside the IPB. These thermal circumstances surrounding the sensors accelerate the deterioration of sensor insulations; insulation failures of the sensors can cause serious damages to generators. Therefore, the sensors need to possess long-term reliability and exceed the life of the generator under varying thermal environments.

The present paper describes the considerations taken on the long-term reliability of the PD ceramic sensor for thermal power generators and its demonstration in the field. The main component of the ceramic sensor is $SrTiO3$. The voltage acceleration aging tests for the sensors were carried out under continuous and impulsive thermal aging at temperatures of more than 100 °C. The life index of each insulation channel of the sensor was established based on a literature review. The life of the sensor was calculated using the power inverse law applying the life indices. The dielectric loss and the PD were measured by aging. The breakdown voltages before and after the aging test for the sensors were compared. In addition, these sensors were installed in the thermal power plant for demonstrations

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after the aging test. The sensors were proven to have sufficient lives that could last more than 100 years, and a good service performance for on-line PD monitoring of thermal power generators.

2. Theory of Life Assessment for Ceramic Sensor

2.1 Evaluation theory of electrical life

The electrical life, L, of the dielectric material under electrical aging can be estimated from the following equation, so-called the inverse-power model, which is determined experimentally.

$$V^n L = \text{const} \tag{1}$$

where V is the applied voltage, L is the time in years, and n is the life index that depends on the electrical aging mechanism and dielectric material. Eq. (1) can be transformed into Eq. (2) through the acceleration aging test.

$$\left(\frac{L}{L_0}\right) = \left(\frac{V_0}{V}\right)^n \tag{2}$$

where V_0 is the operating voltage of an electrical machine, L_0 is the life of an electrical machine at the operating voltage, V is the acceleration aging test voltage, and L is the life at the acceleration aging test voltage.

2.2 Insulation failure channels of on-line PD ceramic sensor

Fig. 1 shows the structure of the on-line ceramic sensors developed in the present study. The ceramic sensors consist of a series of ceramic elements that sense PD signals and an epoxy resin molding to withstand the high voltage of the sensor electrodes. The insulation failures in the ceramic sensor structure occur through three types of failure channels: the penetrating failure of the elements, the failure of epoxy molding, and the failure of the interface between the element and the epoxy molding. Estimating the insulation lives of the channels is essential when discussing the long-term reliability of the sensors. The decision of life index *n* for each channel is needed to assess the lives of the channels using Eq. (2). First, the life index for Channel 1, which is the failure channel penetrating the elements, was experimentally estimated to be more than 60 [6]. Accordingly, this estimation is used as the life index of the Channel 1. Second, the life index for Channel 2 was established through literature investigation. Life indices for void-free epoxy molding have been reported to be more than 12 according to related literature [7–8]. Thus, 12 is used as the life index of Channel 2. Lastly, the life index of channel 3 was decided. Channel 3 is an interface between the ceramic elements and the epoxy molding. Volker Homburg reported that life indices of the interface between fiber-reinforced epoxy and silicon rubber exist in the range of about 4 to 16 according to interface states and electrical stress methods [9]. Considering the research results on the lives of these interfaces and the fact that the insulation performance of the interface in Fig. 1 may be worse than a single epoxy molding insulation, a 9.6 value was adopted, which corresponds to 80% of the life index of 12 of the epoxy molding of Channel 3.

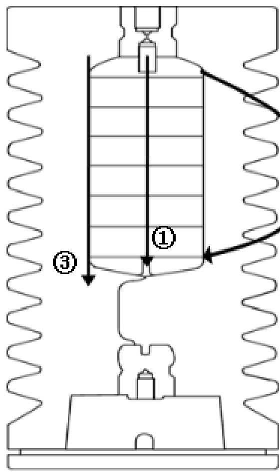


Fig. 1. Insulation failure channels of ceramic sensor

3. Electrical Life Assessment and Demonstration

3.1 Electrical life assessment

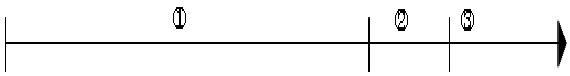
3.1.1 Experimental method

Fig. 2 shows the eight ceramic sensors prepared. The sensors were designed for 18 kV class generators. As explained in Section 1, ceramic sensors may be used under higher temperatures or in heat-shock conditions. The two types of electrical acceleration tests considering the

Fig. 2. Manufactured ceramic sensors

thermally practical conditions discussed above were performed to assess the electrical life of the sensors; test voltages higher than 18 kV were applied for acceleration aging. The current section explains the detailed procedures involved in the two acceleration tests.

a. Acceleration Test I: Voltage acceleration aging considering a high ambient temperature around the ceramic sensors



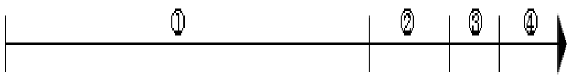
<1 cycle test procedure of acceleration test I>

① Test voltage AC of 30 kV under the test temperature of 100 °C was applied for consecutively 240 h. It then underwent natural cooling up until reaching room temperature after turning the applied voltage off.

② The PD inception voltage and the dielectric loss at 20 kV and at room temperature were measured.

③ The next cycle was then restarted. The test was repeated for 15 cycles.

b. Acceleration Test II: Voltage acceleration aging considering heat shock



<1 cycle test procedure of acceleration test II>

① Test voltage AC of 35 kV under room temperature was applied for consecutively 240 h. The applied voltage was then turned off.

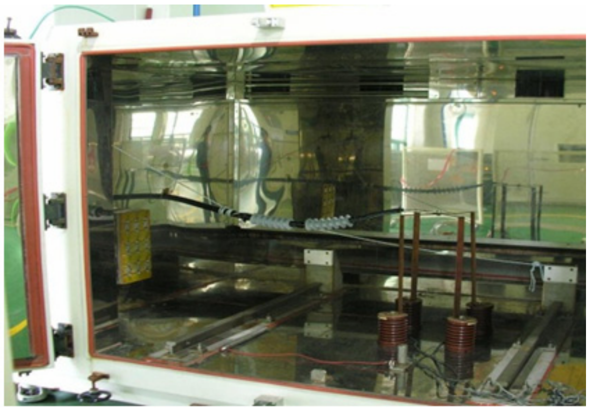
② The temperature was then increased up to 150 °C within 2 h and was heated for 4 h under the same temperature. The sensor was then naturally cooled.

③ The PD inception voltage and the dielectric loss at 20 kV and at room temperature were measured.

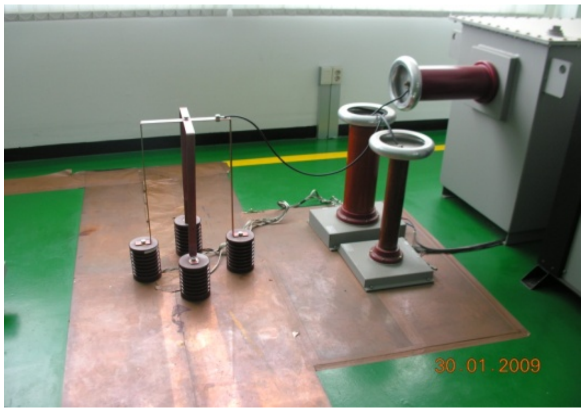
④ The next cycle was then restarted. The test was repeated for 15 cycles.

Figs. 3(a) and (b) show the test scenes. As shown in Fig. 3(a), four ceramic sensors for acceleration Test I were setup in an electrical oven. The test voltage led by a 22 kV class power cable through the oven was applied to the sensors. Acceleration Test II was performed indoor as shown in Fig. 3(b) and four sensors were prepared.

In addition, nondestructive tests such as the measurement of PD inception voltage and dielectric loss were performed periodically during the acceleration aging. The dielectric losses were measured at certain voltages until 20 kV, and the PD inception voltages were measured until the maximum of 30 kV. AC breakdown voltages for new sensors and aged sensors were obtained to observe the effect of aging on the breakdown strengths. The test voltages were increased until breakdown, according to the test procedure in [10].



(a) Acceleration Test I



(b) Acceleration Test II

Fig. 3. Acceleration testing scenes

3.1.2 Experimental results

a. Life assessment of ceramic sensor

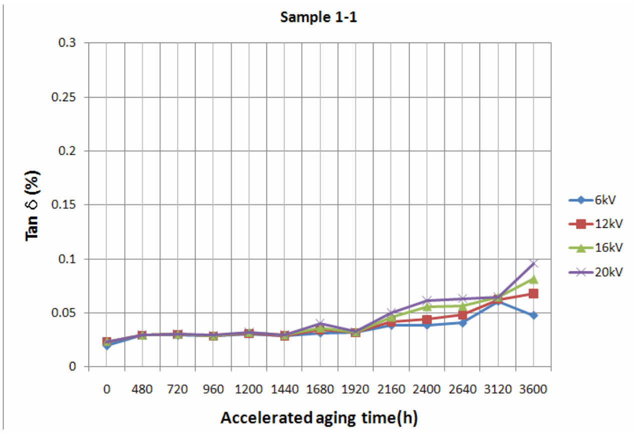
Acceleration aging tests I and II were performed for 15 cycles (3600 h). Insulation breakdown was not found in all of the eight samples (four samples each test). The life of each insulation channel in Fig. 1 was assessed using Eq. (2). As mentioned in Section 2.2, the values of 60, 12, and 9.6 were used as the life indices for Channels 1, 2, and 3, respectively. The base voltage V_0 is 10.4 kV, which is the earth-to-phase voltage of the rated voltage of 18 kV. The life assessment results of the sensors are given in Table 1. All three types of insulation channels have a life exceeding 100 years. These results show that on-line ceramic sensors have sufficient life and long-term reliability in comparison with generator life of ten years.

Table 1. Life assessment results according to acceleration aging tests

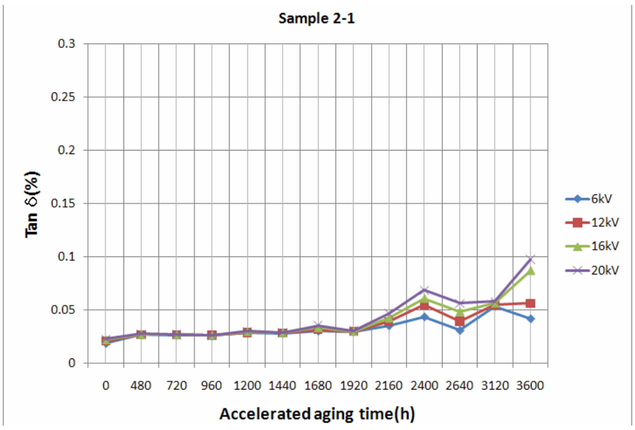
Acceleration Type	Ceramic element (year)	Epoxy molding (year)	Interface (year)
Test I	1.66×10^{27}	1.36×10^{5}	1.07×10^{4}
Test II	1.72×10^{31}	8.70×10^{5}	4.71×10^{4}

b. Nondestructive tests with aging

The dielectric losses and PD inception voltages were measured at the end of each cycle in the two acceleration tests. Figs. 4(a) and 4(b) show the periodically measured dielectric losses during acceleration tests I and II. According to Fig. 4, the dielectric losses of the acceleration tests I and II increased from 0.019% to 0.097% and from 0.019% to 0.1%, respectively. These changes in dielectric losses are similar to those in the epoxy-based insulation and are much smaller than the normal generator cases [11, 12]. From these results, the sensors are considered to have good dielectric characteristics up until the end of their life. PD inception voltages were also measured periodically right after measuring the dielectric loss. The PDs for all eight samples were proven to be free at 30 kV until the end of the acceleration test. Evidently, the ceramic sensors have excellent PD characteristics at 10.4 kV of rated earth–to-phase voltage.



(a) Tan δ according to test method I



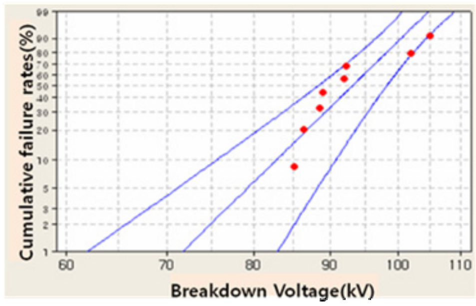
(b) Tan δ according to test method II

Fig. 4. Tan δ with aging time

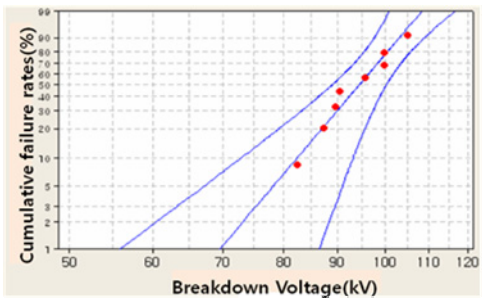
c. Breakdown test before and after aging

The breakdown voltages for the eight new sensors and the eight sensors aged with the acceleration tests were measured to analyze the changes in insulation strengths of the sensors according to aging. The new sensors under the breakdown test before aging were exempted from acceleration aging test. All breakdown failures occurred only at the epoxy molding surfaces, revealing that the three types of failure channels in Fig. 1 were barely deteriorated by the two acceleration aging tests. Fig. 5 shows a Weibull plot with 95% confidence bounds for the breakdown voltages. From the comparison between Figs. 5(a) and 5(b), the distribution of breakdown voltages before aging seems to be similar to that after aging. In addition, the average breakdown voltages for each test were estimated from the Weibull distributions of Fig. 5. The respective breakdown voltages of 92.2 and 93.3 kV respectively indicate that there is no significant difference between the average values according to aging.

As shown in the results of the life assessment and breakdown tests, sensors have long service lives compared with that of thermal power generators. They also show good dielectric characteristics in the duration of their use.



(a) Before aging



(b) After aging

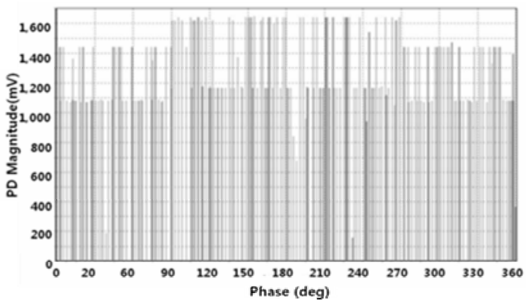
Fig. 5. Breakdown voltages before aging and after aging

3.2 Demonstration of ceramic sensor

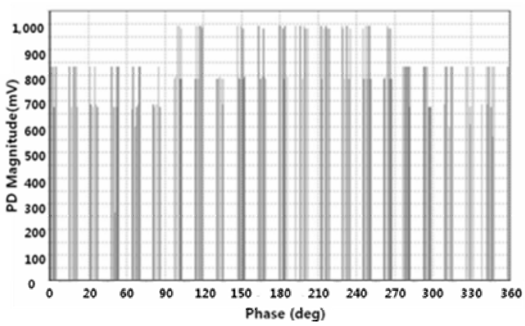
The ceramic sensors with the same properties as the sensors used in the acceleration tests were installed inside the IPB enclosure of a rated voltage of 13.8 kV of a class thermal power generator in Korea. Fig. 6 shows the sample setup of the sensor electrically connected to the bus bar inside the IPB. First, PD calibration test was performed using PD calibrator (MODEL: NG-6). The pulses for calibration were applied into a terminal between earth and phase of the generator. Figs. 7(a) and 7(b) show the response signals from the low voltage side of the sensor when 2500 and 1500 pC were applied. These signals were measured in 120 cycles using the PD measurement system developed in the present study. The ratios of two input calibration PD quantities and two response signal amplitudes in Fig. 7 are 1.67 and 1.65, respectively, indicating that the output amplitudes of the sensors are proportional to the PD quantities.

After calibration, the rated earth-to-phase voltage of the AC of 8 kV was applied to the generator using a test transformer, and PDs were measured by the PD measurement system in 120 cycles. Fig. 8 presents the PD distributions according to the phase of the applied voltage. As shown in Fig. 8, the PD pulses have the typical PD distribution. From the calibration and PD measurement tests results, the ceramic sensors are considered to show satisfactory performances for the on-line PD measurement.

Fig. 6. Ceramic sensor installed into a generator's IPB



(a) 1620 mV:2500 pC



(b) 980 mV:1500 pC

Fig. 7. Response signals of ceramic sensor for PD calibration pulses

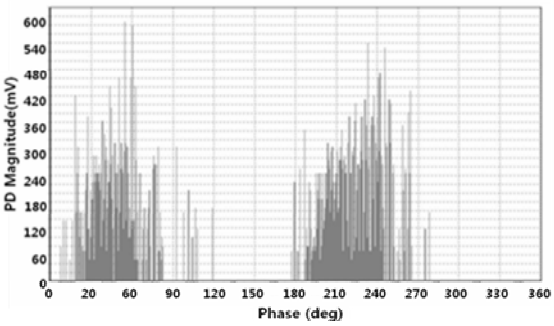


Fig. 8. PD distribution measured by on-line ceramic sensor

4. Conclusion

In the present paper, considerations on the long-term reliability of on-line PD ceramic sensors for thermal power generators and its demonstration in the field were discussed through the acceleration aging test and demonstration tests in the field. The following conclusions were obtained:

(1) All three types of insulation channels that comprise insulations of ceramic sensors have electrical lives lasting more than 100 years under two types of thermal aging.

(2) In acceleration tests I and II, the dielectric losses increased from 0.019% to 0.098% and from 0.019% to 0.1%, respectively, according to the acceleration aging time. In addition, PDs at 30 kV were free in all eight samples until the end of the acceleration aging.

(3) In the AC breakdown tests, the failures occurred only at the epoxy molding surfaces. In addition, the average breakdown voltages for the new sensors and the aged sensors were 92.2 and 93.3 kV, respectively, indicating that the three insulation channels of the sensors are not affected by the two acceleration aging tests.

(4) The calibration and PD measurement tests for the ceramic sensors installed inside the IPB showed that the output amplitudes of sensors are proportional to the PD quantities, and that the PD pulses have the typical PD distribution.

As evidenced by the results of the present study, the ceramic sensors show excellent dielectric characteristics, insulation strength, and satisfactory performances for on-line PD measurements.

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