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Assessment of 23 kV Capacitive Coupler for On-line Partial Discharge Measurements

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Abstract - The partial discharge (PD) measurement is a very effective method to assess the winding insulation condition of high-voltage machines, since most of the insulation failure processes are directly or indirectly caused by PD. On-line PD measurements, which can detect insulation defects of winding in the early stages on rotating machines in operation, have been accepted as the most important technique. The epoxy mica capacitive coupler is currently and extensively used for on-line detection of PD pulses of high-voltage rotating machines. To evaluate the feasibility of developing a capacitive coupler that is easier to manufacture at a lower cost compared to epoxy mica couplers, a 100 pF capacitive coupler made of ceramic material is designed, fabricated and tested for on-line PD measurements of 23 kV electrical machines. A series of electrical tests and accelerated aging tests are performed on the ceramic coupler to evaluate the performance requirements, long-term reliability and thermal stability for in field application. The test results show that the newly developed ceramic coupler provides equal and improved performance at a lower cost compared to epoxy mica couplers, and estimated voltage life is anticipated to surpass 100 years.

Keywords: Electric machine, Partial discharge, On-line monitoring, Ceramic coupler

1. Introduction

Industrial surveys and other studies on machine reliability show that the winding insulation is the most vulnerable component in high voltage (HV) rotating and stationary electrical machines [1-2]. Since the insulation of the electric machine windings is continuously exposed to a combination of thermal, electrical, mechanical and environmental stresses during operation, the insulation material deteriorates gradually over time. Winding insulation problems must be taken seriously since they not only lead electrical machines to catastrophic failure that results in forced outages, but can also cause casualties or serious injuries due to fire, electric shock or arc flash hazards. Therefore, many off-line and on-line diagnostic testing methods have been developed over the last century for monitoring the winding insulation condition to guarantee reliable operation of electric machines [2].

The partial discharge (PD) test is one of the most important and commonly used tests for winding insulation of high voltage machines, since many of the HV winding insulation failure processes have PD as a direct cause or symptom. The on-line PD test has become a popular test for insulation condition assessment, since insulation problems can be detected at an early stage if PD activity can be monitored while the machine is in operation. Many different types of sensors such as the capacitive coupler, stator slot coupler and current transformer have been developed for detecting PD pulses. The epoxy mica capacitive coupler (EMC) developed in North America is currently the most extensively used type of sensor for on-line PD detection in electric machines.

A new capacitive coupler based on ceramic material for on-line PD measurements is evaluated in this paper to develop a capacitive coupler that is easier to fabricate at a lower cost compared to epoxy mica couplers. Ceramic couplers are known to have many advantages over epoxy mica couplers such as ease and simplicity of manufacturing, consistency in performance/quality and low cost, and have been developed and used for off-line PD measurements. The only known potential problem for conventional ceramic couplers has been thermal instability issues when used for on-line PD monitoring. In this paper, a 105 pF ceramic capacitive coupler is designed and fabricated for on-line PD measurements of 23 kV electric machines (generator windings and mold transformers). A series of electrical tests are performed on the ceramic coupler to verify whether it meets the performance and reliability requirements of 23 kV capacitive couplers such

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as the measurements bandwidth, AC withstand and dry flashover voltage, PD inception voltage, and dissipation factor. In addition, a series of accelerated aging tests are performed to evaluate the long-term reliability and thermal stability of the ceramic coupler for field deployment. The test results show that the newly developed ceramic coupler provides equal and improved performance at a lower cost compared to epoxy mica couplers, and has an estimated voltage life of over 100 years, which is more than three times the life expectancy of electric machines.

2. Ceramic coupler development

The most common type of sensor for on-line PD measurements for electric machines currently in use is the (6.9~28)kV, 80 pF EMC. The bandwidth of this capacitive coupler is in the range of (10~100)MHz assuming that attenuation up to 5 dB is within the measuring range. For 25 kV EMCs, the minimum requirement for the withstand voltage at 60 Hz is 50 kV, and the minimum requirement for PD extinction voltage is below 3pC for a 25 kV input. EMCs have excellent electrical properties since it has sufficient layers of epoxy impregnated mica splitting as the main dielectric. Thin mica insulation sheets (approximately 0.3 mm) with a 0.025 mm metal electrode attached are laminated and then impregnated with epoxy to form epoxy mica couplers. The fabrication process is difficult since the thin mica and metal electrodes must be laminated and such difficulty of fabrication results in an increase in the coupler cost. Other potential problems of these couplers include the introduction of voids during the fabrication process, and the inconsistency of the overall performance and quality of the couplers. The objective of this work is to develop a lower cost capacitive coupler based on ceramic material that has a simple manufacturing process with equal or improved performance and reliability. The performance requirements and the design and fabrication process for the ceramic coupler for on-line PD measurements are summarized in this Section.

2.1 Requirements

The minimum performance and reliability requirements for the 23 kV ceramic capacitive coupler to be developed are determined based on the requirements of the epoxy mica coupler of the same rating and based on the safety requirements for measuring PD on-line for 23 kV electrical systems. The requirements for the measurements bandwidth, AC withstand and dry flashover voltage, PD inception voltage, and dissipation factor for the 23 kV ceramic coupler to be developed are listed in Table 1.

Table 1. Specifications of ceramic coupler

Items	Requirements
Measurement bandwidth MHz (based on 5dB attenuation)	10~100
AC withstand voltage kV	50
AC dry flashover voltage kV	70
PD(3 pC) inception voltage kV	25
Dissipation factor % (at 13.3 kV and room temperature)	0.5

2.2 Design and fabrication

A ceramic compound with a dielectric constant insensitive to temperature, and the rating linearly changed with temperature, has been selected for the 23 kV, 105 pF ceramic coupler. To satisfy the most important bandwidth requirement and meet all the other requirements stated in Clause 2.1, a ceramic compound that has a dielectric constant of approximately 500 and consists of 90% $SrTiO_3$ and additives has been selected as the material for the ceramic element of the coupler. For forming the ceramic element, the ceramic compound was molded into a cylindrical shape under high temperature (1410℃) and high pressure (62 ton). Liquid silver was printed and molded at 750℃ on both sides of the cylindrical ceramic element to form the electrodes. Two identical cylindrical ceramic elements with a capacitance value of 640 pF were connected in series to form the ceramic element, as shown in Fig. 1, to increase the partial discharge inception voltage (PDIV). To determine the dimensions of the series ceramic elements for design, the PDIV was measured in a shielded room with the samples immersed in silicon oil by increasing the applied voltage in 1 kV/s increments using commercial off-line PD equipment, as shown in Fig. 2. The measured PDIV according to IEC 60270 from the three 320 pF ceramic elements were 19 kV, 20 kV and 20 kV, respectively.

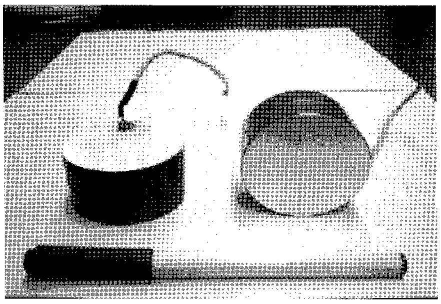

Fig. 1. Photograph of 320 pF ceramic coupler elements

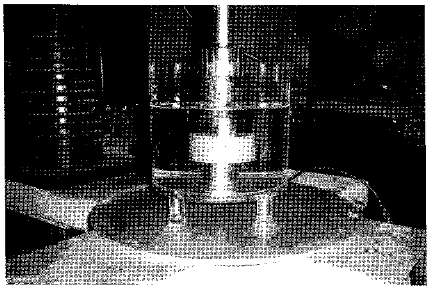

Fig. 2. PDIV test overview of 320 pF ceramic coupler elements

The ceramic elements were molded with epoxy resin to improve the surface flashover, discharge properties and to provide mechanical support to the electrodes. The completed 105 pF, 23 kV ceramic capacitive coupler with the 6 series ceramic elements (640 pF each) molded with epoxy resin is shown in Fig. 3. One of the advantages of ceramic couplers is the low cost compared to epoxy mica couplers due to the simple manufacturing process, as described in this Section.

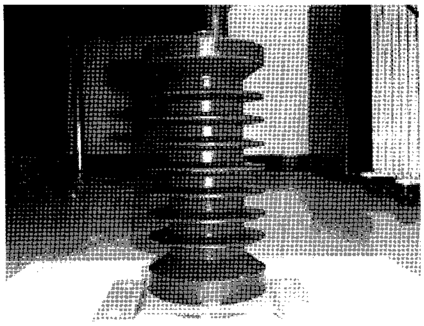

Fig. 3. Ceramic coupler for 23 kV class

3. Evaluation of electrical characteristics

The performance requirements for the 23 kV ceramic capacitive coupler (CC) described in Section 2 such as the measurements bandwidth, AC withstand and dry flashover voltage, PD inception voltage, and dissipation factor, are tested to evaluate whether the sensor developed in Section 2 can be used for on-line PD measurements in 22.9 kV electrical systems. The frequency response of the ceramic coupler was measured using a commercial network analyzer to check if it meets the measurements bandwidth requirement of (10~100)㎒ for up to 5dB. It can be seen from the frequency response shown in Fig. 4 that the coupler can measure signals with frequencies from 7 ㎒ to 100 ㎒, assuming that attenuation of up to 5dB can be measured. The bandwidth is wider than that of the 25 kV, 80 pF epoxy mica coupler previously mentioned (10~100) ㎒, which implies that PD occurring over a wider frequency range can be measured with the ceramic coupler.

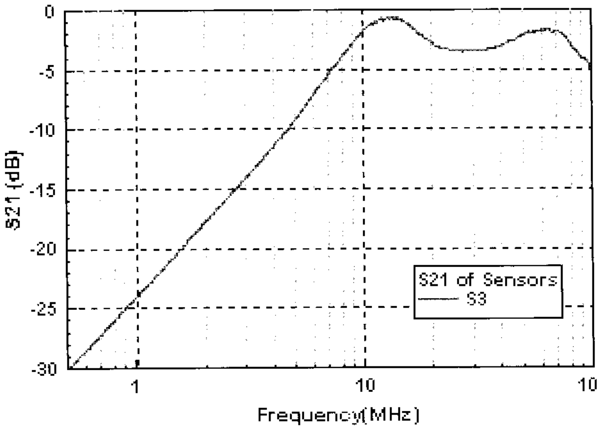

Fig. 4. Bandwidth of ceramic coupler for 23 kV class

To test the 60 Hz withstand voltage requirements, 51 kV was applied for 1 minute to five ceramic coupler samples, and all samples were capable of withstanding the applied voltage. Since the five samples successfully endured the minimum required voltage, the voltage was increased until flashover occurred under dry conditions according to ANCI C29.11. The measured flashover voltage compensated for standard atmospheric conditions was at least 90 kV for the five samples, which indicated that the ceramic coupler satisfies the minimum withstand and flashover voltage requirements.

The PDIV of the samples were measured in a shielded room with the applied voltage increased in 1 kV/s increments using a commercial off-line PD equipment. The measured PDIV of the five 23 kV CC samples according to IEC 60270 was at least 35 kV, which is 2.6 times higher than the rated voltage, and 1.4 times higher than the minimum requirement.

The dissipation factor (DF, tanδ) of the coupler samples were measured to evaluate the dielectric loss characteristics at power frequency using a commercial Schering bridge (Tettex 2809A). The tanδ measurements of the two samples at different voltage levels and different temperature conditions are summarized in Fig. 5 and Fig. 6. It can be seen that the tanδ is below the maximum requirement of 0.5% for the two samples at different voltage levels and different temperature conditions, and insensitive to voltage and temperature variation.

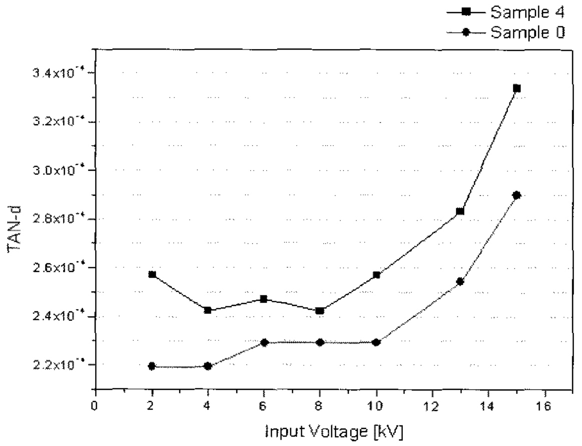

Fig. 5. Dissipation factor of two ceramic couplers at different voltages

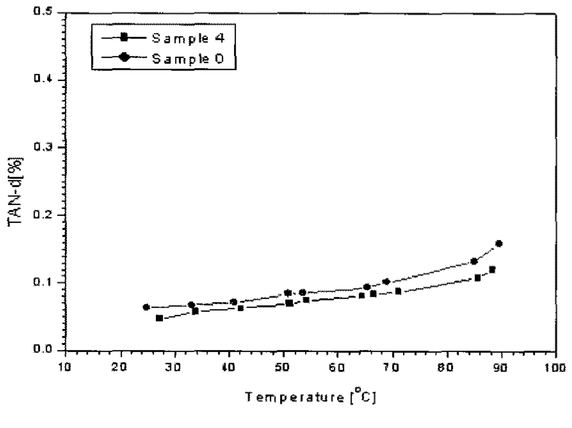

Fig. 6. Dissipation factor of two ceramic couplers at different temperature under 13 kV

It can be observed that the maximum tanδ is below 0.2% at 90℃, which implies that the thermal runaway in ceramic compound based couplers is unlikely to occur. It can also be seen that the measured values of tanδ for the two samples are consistent, which is important in the manufacturing and field deployment stages.

The tanδ measurements as a function of temperature and voltage were already shown in Fig. 5 and Fig. 6. It can be observed that the value of the tanδ of the selected ceramic compound is sensitive to temperature, and insensitive to the applied test voltage against operating condition.

It can be seen that all the tests for the electrical characteristics of the 23 kV CC met the requirements introduced in the beginning of the section. The test results can be summarized as listed in Table 2.

Table 2 Test results of ceramic coupler

Items	Results
Measurement bandwidth ㎒ (based on 5dB attenuation)	7~100
AC withstand voltage kV	51
AC dry flashover voltage kV	90
Lightning impulse voltage (BIL) kV	150
PD(3 pC) inception voltage kV	35
Dissipation factor % (at 13.3 kV and room temperature)	0.1

4. Evaluation of long-term reliability

In addition to testing the coupler for basic electrical performance and reliability requirements as shown in Section 3, it is important to evaluate the long-term reliability to guarantee that the coupler would continuously function after deployment in the field. In this study, a 13 kV CC was constructed and tested to simulate a 23 kV CC due to limitations in the ratings of the test transformer available in our facilities. The 13 kV CC was constructed in the same way as described in Section 2, but 4 ceramic elements were connected in series instead of 6. The photograph of the 13 kV CC used for long-term reliability evaluation is shown in Fig. 7. Accelerated aging tests and life estimation are presented in this Section to evaluate the long-term reliability under thermal, mechanical, and electrical aging. The methodology and basis for each aging test and test results are presented in this Section.

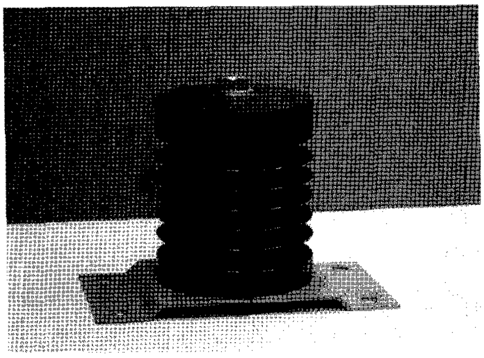

Fig. 7. 13 kV ceramic coupler for long-term reliability evaluation

4.1 Evaluation methodology of long-term reliability

Mechanical vibration was introduced to the samples according to the periodical vibration condition for thermal life evaluation stated in IEEE Standard 275, 1992. The vibration test bench shown in Fig. 8 was used to vibrate the samples at (0.2~0.3)㎜ (1.5 gravitation acceleration) at 60Hz for 1 hour. The test is usually repeated 10~20 times for rotating machines, but was repeated 100 times in the evaluation. Accelerated thermal aging was not introduced for the first 50 vibration cycles. After 50 cycles of vibration, the samples were placed in a 180℃ oven for 3 hours and left at room temperature for thermal aging and cycling. The thermal aging cycle was repeated 16 times between the vibration cycles up to the 100th vibration cycle. The specimens were electrically aged by applying 30 kV for 2500 hours.

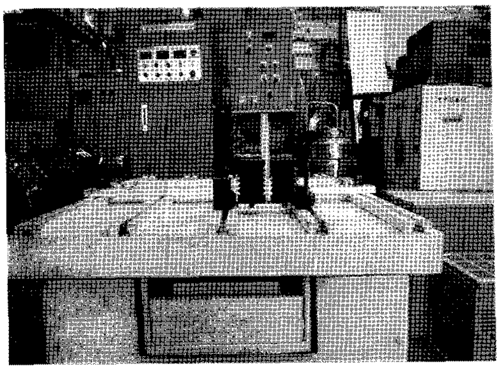

Fig. 8. Overview of vibration test for reliability evaluation

The samples (sensors A, B and C) used for long-term reliability evaluation were different from the ones used in the testing in Clause 3. The initial PDIV measurements for samples A, B and C were 21 kV, 22 kV and 21.5 kV, respectively, and the initial measurements of tanδ were approximately 0.03% for the sensors.

4.2 Evaluation of mechanical and thermal reliability

To evaluate mechanical and thermal reliability during vibration and thermal aging cycles, the PDIV and tanδ measurements were obtained at each of 10 times aging cycles.

The PDIV measurements were shown in Fig. 9 for the two sensors A and B with accelerated mechanical and thermal aging described in Clause 4.1. It can be seen that the PDIV for both sensors was not decreased after the 50th vibration cycle when thermal aging was initially introduced. Also, the PDIV was not decreased after the 100th vibration cycle and the 16th thermal aging cycle.

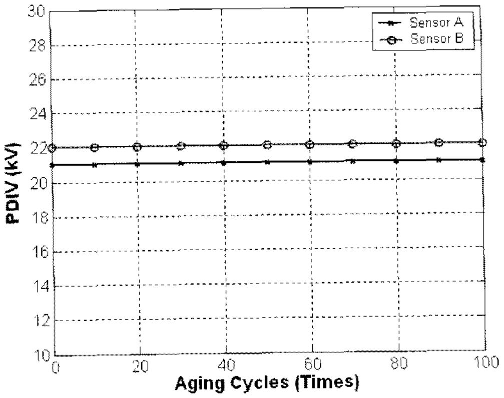

Fig. 9. PDIV during the vibration and thermal aging cycles

The tanδ measurements for sensors A and B with accelerated mechanical and thermal aging were shown in Fig. 10. It can be seen that the tanδ for both sensors was not increased after the 50th vibration cycle. Also, the tanδ was not increased to below 0.01% after the 100th vibration cycle and the 16th thermal aging cycle.

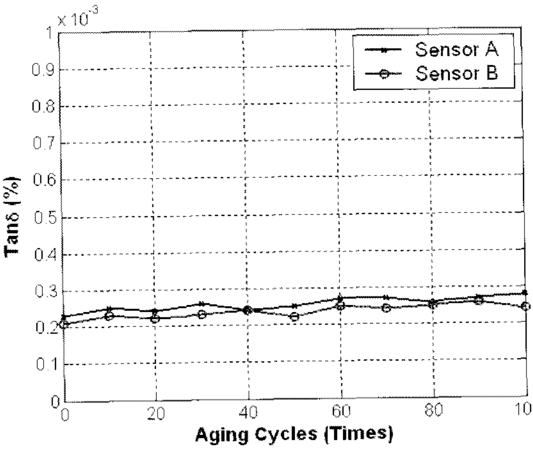

Fig. 10. tanδ during the vibration and thermal aging

It has been shown that the PDIV and tanδ were stable and maintained within an acceptable level under accelerated thermal and mechanical aging. Therefore, the developed sensor has been proved a sufficiently stable property against accelerated thermal and mechanical aging conditions.

4.3 Evaluation of electrical reliability

Two mechanically and thermally aged sensors (sensor A and B) and an unaged sensor (sensor C) were used for electrical reliability evaluation by applying 30 kV for 2500 hours. The PDIV and tanδ measurements were obtained at 0, 400, 800, 1200, 1600, 2000 and 2500 hours of the accelerated electrical aging. The applied voltage of 30 kV was higher than the PDIV of sensors.

It can be seen from the PDIV measurements, shown in Fig. 11, that the initial PDIV for sensors A, B and C were 21 kV, 22 kV and 21.5 kV, respectively, did not change after 2500 hours of accelerated electrical aging.

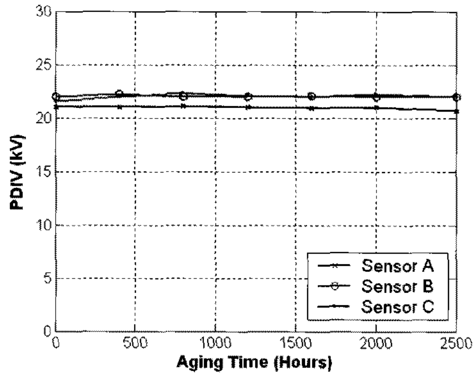

Fig. 11. PDIV during the accelerated electrical aging

The tanδ measurements for sensors A, B and C with accelerated electrical aging were shown in Fig. 12, did not increase after 2500 hours of accelerated electrical aging.

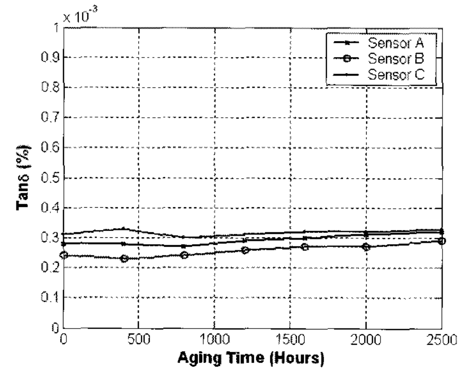

Fig. 12. tanδ during the accelerated electrical aging

It can be observed that the PDIV and tanδ measurements shown in Fig. 11 and Fig. 12 are stable and insensitive to electrical aging.

It has been shown that the PDIV and tanδ were stable and maintained within an acceptable level under accelerated electrical aging. Therefore, the developed sensor has been proved a sufficiently stable property against accelerated electrical aging conditions.

4.4 Evaluation of electrical life

The voltage life, L, of the dielectric material under electrical aging can be estimated from the following equation, so-called inverse-power model, which was experimentally determined [7-9]:

$$V^n L = const \qquad (1)$$

where V is applied voltage, L is the time in years, the life constant, n, depends on the electrical aging mechanism and dielectric material.

It has been experimentally determined that n is 3~4 for corona degradation in gas, 10~11 for corona or tree degradation in oil, 10~12 for mica insulation, and 6~12 for epoxy mica insulation[10-11]. Since the ceramic coupler consists of ceramic compound ($SrTiO_3$) and epoxy insulation, both materials must be taken into account for determining the value of the life constant, n. The value of n for the epoxy resin mold was determined as 6~12, and the value of n is unknown for $SrTiO_3$. However, the aging rate of the dielectric ceramic compound is very slow compared to epoxy resin in general, and it is estimated in EIA/IS-692 that the minimum value of ceramic materials is 7.45. Therefore, the value of n for epoxy resin was determined to be 6, which is the minimum estimated value for epoxy resin, to estimate the voltage life for the worst case situation. An additional safety margin of 20% was considered in the value of n for the ceramic coupler (n=4.8) for a conservative estimate of voltage life. From the above, the minimum voltage life estimate of a 23 kV CC can be calculated from:

$$(V_2 / V_1)^n = (L_1 / L_2) \qquad (2)$$

Considering that the 13 kV CC (with 4 ceramic elements connected in series) lasted 2500 hours when 30 kV was applied, this is equivalent to applying 45 kV to a

CC with 6 ceramic elements connected in series from the electrical strength point of view. Therefore, the lifetime of the 23 kV CC with 6 series elements can be estimated from (2), as shown in (3).

$$(45/13.28)^{4.8} = L_1/\{2500/(24\times 365)\} \qquad (3)$$

The estimate of the minimum lifetime of the ceramic coupler was 100 years, as shown in (3), which indicates that the CC would last for 100 years under electrical degradation.

5. Conclusion

A 23 kV ceramic capacitive coupler, which has many advantages over epoxy mica couplers such as ease and simplicity of fabrication, consistency in performance/ quality, and low cost, has been developed and evaluated in this paper for on-line PD measurements. A series of electrical tests performed on the ceramic coupler has shown that it meets all performance and reliability requirements such as the bandwidth, withstand/dry flashover voltage levels, PDIV, and tanδ. In addition, accelerated aging tests were performed to evaluate the long-term reliability and thermal stability of the developed ceramic coupler under thermal, mechanical, and electrical stresses for field deployment. It has been shown that the PDIV and tanδ were stable and maintained within an acceptable level under thermal, mechanical, and electrical aging. The test results show that the newly developed ceramic coupler provides equal/improved performance at a lower cost compared to epoxy mica couplers, and has an estimated voltage life of over 100 years, which is three times longer than the life expectancy of electric machines.

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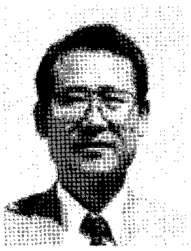

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