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Analysis of Correlation Among Partial Discharges, Ozone Emission, and Ultraviolet Radiation in High Voltage Motor Stator Windings

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Abstract: In this research, a normal winding and simulated defective winding were created to examine the correlation between partial discharges, ozone concentration, and ultraviolet radiation in high-voltage motor stator windings. In the simulated defective winding, the semiconductor layer was removed so that discharges could occur easily between the winding surface and the iron core. A high voltage was applied to both normal and defective windings to measure the partial discharge magnitude, ozone concentration, and ultraviolet radiation. Subsequently, the results were compared and analyzed. The electrical partial discharge magnitude, ozone emission, and ultraviolet radiation measurement methods and properties were explained, and all test results and correlations were analyzed.

Keywords: Partial Discharge, Ozone, Ultraviolet Radiation, Stator Windings

1. Introduction

Defects in the insulation system of the stator windings in high voltage (high voltage) motors occur during production or due to thermal, mechanical, electrical, or chemical deterioration after long-term operation. Eventually, such a deterioration leads to dielectric breakdown if not stopped [1]. Shutdowns caused by dielectric breakdown of the stator windings require long recovery periods, which causes huge economic loses. Consequently, the importance of isolation diagnosis to evaluate the quality of insulators in high voltage-motor stator windings is increasing progressively. Generally, in diagnostic methods that evaluate the insulation state of stator windings, the test voltage is set within the rated voltage, and insulation resistance tests, polarization index tests, alternating current tests, dissipation factor tests, and partial discharge tests are the types of tests mainly performed [2–3]. Partial discharges occur when the application of a high voltage to the stator-winding insulation system causes an abnormal voltage that exceeds the dielectric strength of the defective part. Partial discharges are not only accompanied by electrical signals, but also by various phenomena such as ultrasonic waves [4], ultraviolet radiation, and heat. Particularly, when a discharge occurs in air, ozone is generated [5-7].

In this research, a high AC voltage was applied to a simulated defective winding in which the semiconductor layer was removed to induce discharges in the slot, and to a normal winding to measure the partial electrical discharge magnitude, ozone, and ultraviolet radiation. In addition, the correlation between the ozone, ultraviolet radiation, and partial discharge patterns according to defects was analyzed.

2. Test Specimen Creation and Test Method

To examine the characteristics of the ozone, ultraviolet emission, and partial discharge according to defects when applying a high voltage, a 6.6-kV high voltage-motor stator winding with artificial defects and a normal winding were tested and analyzed. Figure 1 shows the normal winding, which has the semiconductor layer to reduce the potential difference between the stator winding and the iron core, and Figure 2 shows the defective winding whose semiconductor layer was removed from the winding surface so that discharges could occur easily inside the slot, between the winding and iron core [8].

The normal winding was inserted in the A phase, and the defective winding that simulated the slot discharge was inserted in the B and C phases. Windings of the same type were connected and no neutral point connection was made to separate the different phases. Independent tests were performed for each phase, ensuring that no voltage would reach the B and C phases while a high voltage was being applied to the A phase.

Figure 1. *Normal winding.*

Figure 2. *Winding without semiconductor layer.*

Figure 3. *High voltage motor sample and enclosure.*

Ozone is generated when partial discharge occurs is heavier than air and goes down to the bottom. However, in actual high voltage motors, external cooling air enters, cools the stator winding at a constant flow rate by the action of a fan on the rotor shaft, and then is drained out. Therefore, to achieve a constant flow of cooling air, an enclosure that covers the entire high voltage motor sample was constructed, as shown in Figure 3. A vent was put on one side, and a fan on the other so that external air would be sucked inside, passing through the high voltage motor, and then expulsed outside.

The test was performed using a high-voltage application device (PSK 50 kV, Haefely), and connecting and partial discharge measuring instrument (LDS-6, Doble) to a 1000-pC coupling capacitor. Further, an ozone monitor (OEM-106, 2B Technologies) and ultraviolet camera (LUMINAR, OFIL) measuring instruments were used.

3. Test Results and Discussion

The AC voltage applied between the copper conductor and iron core was increased in steps of 1 kV until the dielectric breakdown of the stator winding sample to measure the partial discharge magnitude and ozone concentration. Ultraviolet radiation filming was performed simultaneously. Dielectric breakdown occurred at 30 kV in the A phase (normal winding), and at 21 kV and 18 kV in the B and C phases, respectively, which did not have semiconductor layer. Figure 4, 5, and 6 show the discharge pattern screens, which indicate the partial discharge pulse location according to the test voltage phase at 15 kV prior to the dielectric breakdown.

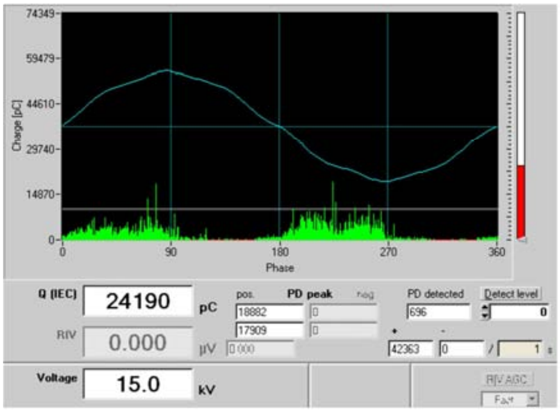

Figure 4. *A-phase partial discharge measuring screen.*

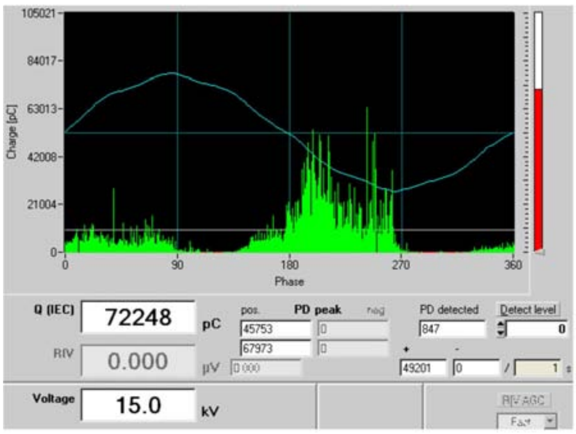

Figure 5. *B-phase partial discharge measuring screen.*

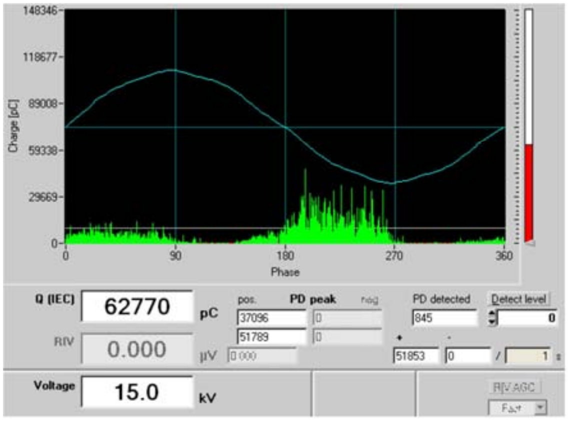

Figure 6. *C-phase partial discharge measuring screen.*

As shown in Figure 4, the A phase (normal winding) shows an internal discharge pattern in which the magnitude of the partial discharge pulse that occurs when phase angle of the voltage is 0°–90° is almost the same as when it is 180°–270°. This is what happens when discharges occur in gaps inside primary insulators, and represents the most common pattern. In Figure 5 and 6, it can be observed that the magnitude of the partial discharge pulse that occurs in the B and C phases without the semiconductor layer when the phase angle of the voltage is 180°–270° is greater than when it is 0°–90°, representing a typical slot discharge pattern. This occurs when discharges take place between the winding surface and the iron core [9]. Thus, the results of the pattern analysis that show the discharge pulse location in accordance with the test voltage phase revealed that while internal discharge is observed in the normal winding, slot discharge is observed in the winding without the semiconductor layer. Accordingly, it was verified that the sample was appropriately prepared.

To compare the partial discharge magnitude and ozone generation in the normal and defective windings, Figure 7 and 8 show a graph between the applied voltage-partial discharge and applied voltage-ozone amount measured at 17 kV, which is before the occurrence of dielectric breakdown. As shown in the graph of Figure 7 and 8, in both the normal winding and the winding without the semiconductor layer, the partial discharge magnitude and ozone concentration increased with increasing test voltage. When the same voltage was applied to both samples, the partial discharge magnitude and ozone concentration were found higher in the B and C phases (no semiconductor layer) than in the normal winding.

The increasing trends of the partial discharge magnitude and ozone concentration depending on the applied test voltage were similar and it was verified that the ozone concentration was directly proportional to the partial discharge magnitude. Thus, the ozone concentration measurement can be used as a good indicator of partial discharge magnitude, which is a main cause of deterioration in stator windings.

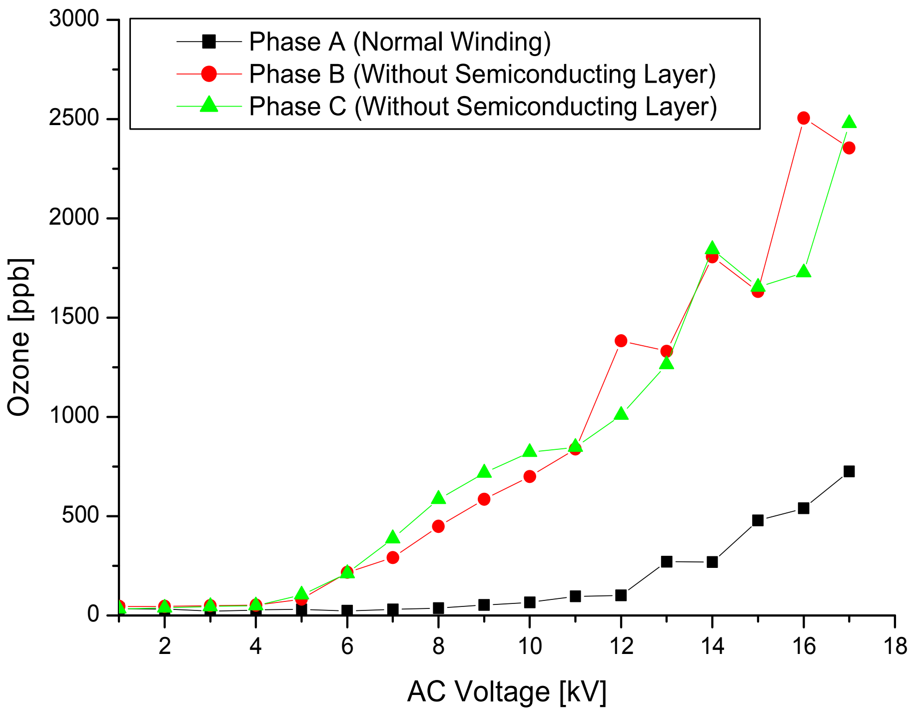

Figure 7. *Voltage-ozone generation characteristics.*

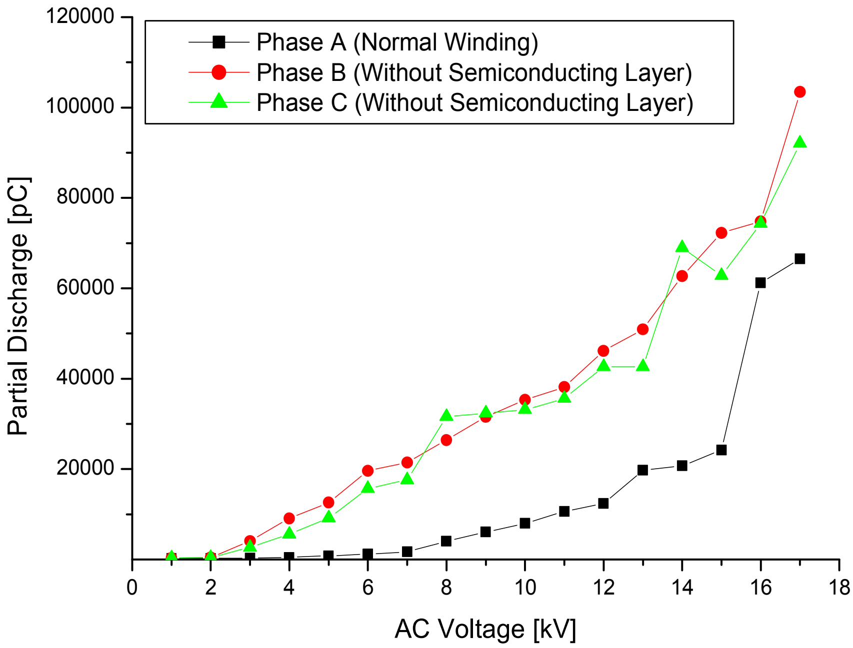

Figure 8. *Voltage-partial discharge characteristics.*

As given in Table 1 and from Figure 9 and 10, when the partial discharge magnitude of each phase was approximately 62,000pC, the ozone concentration is higher in the B and C phases, in which slot discharge is observed, than in the A phase, in which internal discharge is observed. When the stator winding rubs against the iron core due to vibrations causing damage to the semiconductor layer, partial discharge occurs between the winding surface and the iron core. Such slot discharge defects were verified to be more effective as a method of measuring the ozone concentration than discharges that occurred in the internal gaps of primary insulators [10]

Table 1. *Ozone concentration at the same partial discharge magnitude(62,000pC).*

Phase	Category	Measured value
A	Partial discharge [pC]	61 169
A	Voltage [kV]	16.0
A	Ozone concentration [ppb]	539
B	Partial discharge [pC]	62 674
B	Voltage [kV]	14.0
B	Ozone concentration [ppb]	1806
C	Partial discharge [pC]	62 770
C	Voltage [kV]	15.0
C	Ozone concentration [ppb]	1654

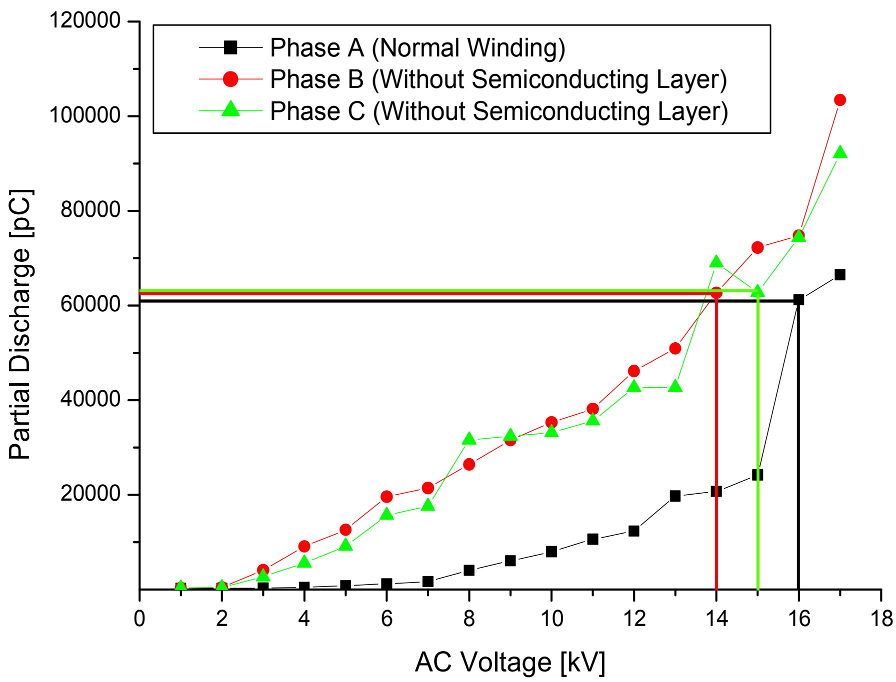

Figure 9. *Voltage at the same partial discharge magnitude(62,000pC) (A phase: 16 kV, B phase: 14 kV, C phase: 15 kV).*

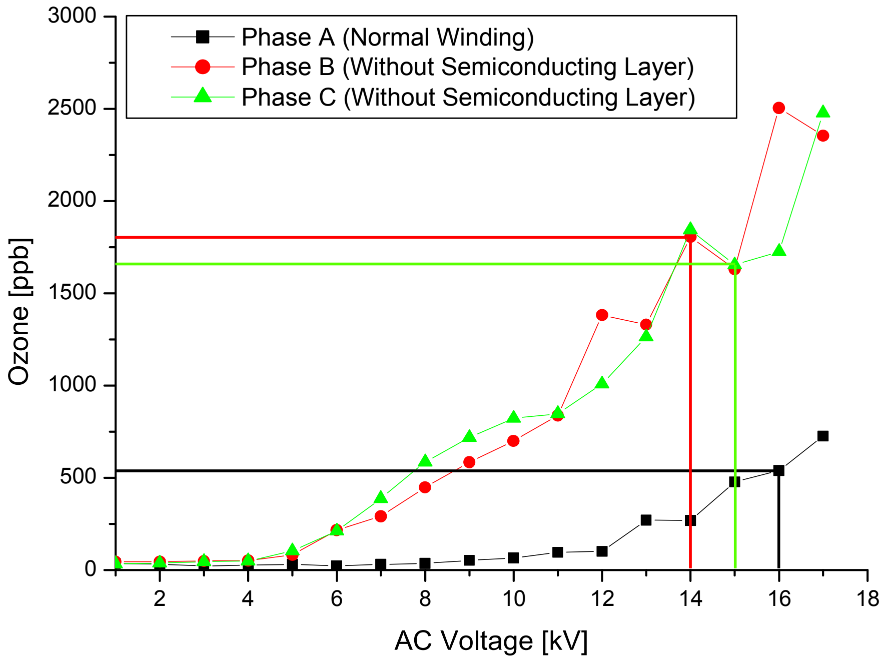

Figure 10. *Ozone emission at the same partial discharge magnitude (62,000pC) (A phase: 539.6ppb, B phase: 1,806 ppb, C phase: 1,654 ppb).*

Figure 11, 12 and 13 show the measurement screen for ultraviolet radiation generated at each phase at 15 kV. The parts where the ultraviolet radiation is emitted are indicated with red dots. When looking at the ultraviolet radiation measurement results, it can be easily recognized visually that there are points where discharges occur, emitting ultraviolet radiation, and points where they do not. The A phase (normal winding) showed lower ultraviolet emissions at the same voltage than B and C phases, which represent defective windings. This shows the occurrence of discharges caused by the potential difference between the iron core end and the stator-winding surface because the B and C phases do not have a semiconductor layer to reduce the potential difference between the winding surface and the iron core.

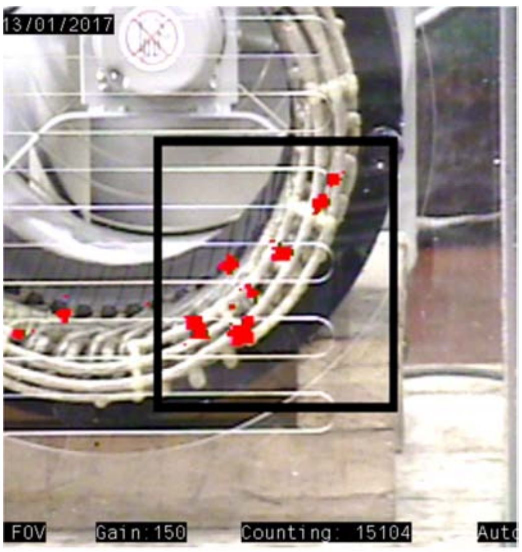

Figure 11. *A-phase ultraviolet radiation measurement screen.*

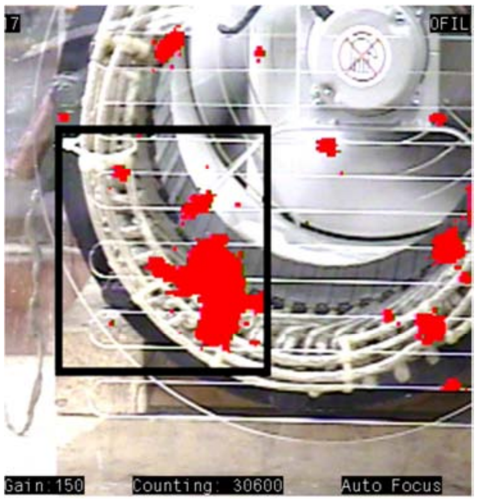

Figure 12. *B-phase ultraviolet radiation measurement screen.*

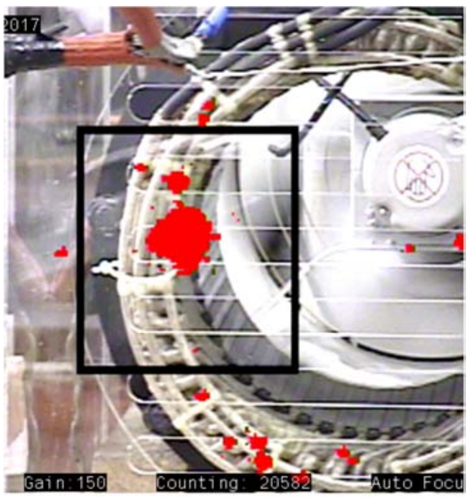

Figure 13. *C-phase ultraviolet radiation measurement screen.*

It can also be noticed that the ultraviolet emission is more concentrated in the terminal region where the winding is exposed to the outside, more than in the midpoint of the iron core, where the stator winding is inside the iron-core slot. Therefore, since discharges occurring inside the slot are difficult to verify using ultraviolet radiation measurement methods, such methods are more effective in identifying the location of defects where discharges occur in the terminal winding regions than to identify the total amount of partial discharge.

4. Conclusion

In this research, ultraviolet radiation measurement, electrical partial discharge test, and ozone concentration measurement were performed on an high voltage-motor stator winding prepared through normal methods and a defective winding whose semiconductor layer was removed from the winding surface to simulate slot discharge. The characteristics of each test method were compared and analyzed. The results after comparing each characteristic and its correlation through the partial electrical discharge test, ozone concentration measurement, and ultraviolet radiation measurement are explained below.

The electrical partial discharge magnitude and ozone emission concentration were found to be strongly in direct proportion with the test voltage. Thus, ozone concentration measurement can be a good indicator for evaluating the degree of defect in the stator windings. Since ozone concentration measurement is a chemical method, the degree of defect can be measured regardless of the noise from the site, which was one of the biggest shortcomings of electrical partial discharge test methods. In addition, ozone concentration measurement is also effective in the verification of the state of deterioration of the winding surface, because even under the same partial discharge magnitude conditions, slot discharges in the stator winding surface are bigger than the discharges in internal gaps of the primary insulators.

Ultraviolet radiation measurement methods work better in the terminal regions where the windings are exposed to the outside and ultraviolet radiation is more visible than in places where the winding is inside the slot. Thus, this is a very useful method for finding the location of defects, more than to identify the total magnitude of partial discharges that occur in the stator windings. Electrical tests were used to estimate the approximate location of defects such as internal discharges and slot discharges through the analysis of the pattern and magnitude of discharges that occur in windings that are inside slots. However, ultraviolet radiation measurement was very useful in finding the location of discharges at the terminal windings.

Until now, only conventional electrical partial discharge tests have been performed to evaluate the insulation state of high voltage motors. However, by performing ozone concentration measurement and ultraviolet radiation measurement additionally, diagnosis methods can be diversified and the reliability of the diagnosis can be significantly improved.

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