Phased-resolved partial discharge patterns of 10 kV stator coils under different experimental conditions

Ailiang Kang¹,², Muqin Tian¹,²,³, Lingyan Lin¹,², Jiancheng Song¹,², Wei Li¹,² and Lu Li¹,²

¹Shanxi Key Laboratory of Mining Electrical Equipment and Intelligent Control, College of Electrical and Power Engineering, Taiyuan University of Technology, Taiyuan 030024, China
²National & Provincial Joint Engineering Laboratory of Mining Intelligent Electrical Apparatus Technology
³E-mail: tianmuqin@163.com

Abstract. The most five common types of partial discharge (PD) activities involving 10 kV motors, namely internal discharge, slot discharge, corona discharge, surface tracking and bar-to-bar discharge, were researched in this paper. PD was induced on some 10 kV coils with modern epoxy-mica insulation system through off-line experiment under different conditions. The phased-resolved partial discharge (PRPD) patterns of different types of PDs were recorded to characterize different PDs. This research can provide a reference in off-line fault diagnosis and be useful for the PD online monitoring of high voltage motors.

1. Introduction

The groundwall insulation of high voltage motors is a laminated system consisting of numerous layers of mica-paper tape on a fibreglass backing material impregnated and consolidated with a synthetic resin, usually epoxy or polyester-based [1]. Because of manufacturing process, small voids are inevitable present into the insulation. In addition, groundwall insulation is continuously aged with time through a combination of electrical, thermal, mechanical and ambient stresses, finally resulting in insulation failure [2]. Therefore, the insulation system is the most vulnerable part, but at the same time, it is also the most important section for ensuring the high voltage motor operation. A report for motor failure survey from EPRI indicates that more than 37% of their failures are caused by groundwall insulation faults [3].

The occurrence of PDs is one of the most symptoms that the insulation has been degraded, meanwhile, the PDs can accelerate the insulation degradation in turn. The molecular structure of the groundwall insulation will be changed because of PD. In general, this change is irreversible and repair is essential when motors are out of service. It is well known that different types of PDs can degrade the groundwall insulation at different portions and the PD activities are strongly influenced by the local conditions where PDs occur. Although stator winding failures reduce a lot since the vacuum pressure impregnation (VPI) systems has been introduced in the 1960’s, some high energy PDs, e.g. corona discharge, slot discharge, bar-to-bar discharge, surface tracking can absolutely lead to insulation failure even make the machine out of service in a short period of time. For instance, Figure 1 shows the groundwall insulation being burnt at the slot exit because of the intensive corona discharge [4]. This insulation failure eventually developed into the line-to-earth fault and the...
The groundwall insulation has to rewind. Figure 2 depicts the semi-conductive coating and the groundwall insulation being eroded by slot discharge and the stator coils must be removed from stator [5]. Thus, it is greatly important to carry out the online monitoring system for high voltage motor, from which we can understand the insulation condition.

**Figure 1.** The insulation system burnt by corona discharge occurring at the slot exit.

**Figure 2.** The insulation system eroded due to slot discharge.

Understanding the relationship between PD types and PRPD patterns is the first and the most important step in the online monitoring system. However, one type of PD may develop another type of PD under different experimental conditions. In addition, the PRPD pattern can change with the experimental condition even if it is the same type of PD. It calls for large amounts of experiments to understand the development of each discharge and the PRPD pattern change law under different conditions. In this paper, five common types of PD are induced under laboratory conditions and PRPD patterns are recorded under different experimental conditions.

2. **Experimental description**

The groundwall insulation of the experimental coils is a F-class modern epoxy-mica insulation system with the thickness of 2.04 mm. The coils are subjected to preconditioning before experiment was commenced. Their surfaces are checked to ensure that the semi-conductive coating is in perfect condition, and cleaned with alcohol to remove contamination. A voltage of 50 Hz is applied across each coil and gradually increased to 15 kV, in order to detect pre-existing internal defects by observing whether only typical symmetrical PRPD patterns of internal discharge occurrence [6]. The eligible coils are prepared for the next test.

In order to induce slot discharge, the coils are processed by abrading the insulation surface at the straight position with the dimension of 35 mm × 30 mm × 0.7 mm. To induce corona discharge, experiment coils are processed by moving away the junction section of semi-conductor and stress grading paints. The space of two adjacent coils are reduced to 3 mm so as to induce bar-to-bar discharge. For inducing surface tracking, the oil contamination is painted on the end arm surface of the coil. There is no need to make any preconditioning to induce internal discharge because small voids are present into any 10 kV coils. Figures 3-6 shows experimental set-up of each type of discharge. After that, all the experiment coils are inserted into a stator core.
3. Experiment results

In the experiment, we find that internal discharge can occur when the discharge inception voltage is as low as 3 kV. And the amplitude is always below 400 pC when the voltage is as high as 10 kV. Additionally, internal discharge is characterized by symmetry both in the amplitude and in the discharge number during both voltage half cycles, as shown in Figure 7. With the improvement of insulation materials, modern epoxy-mica insulation system can withstand internal discharge for more than 40 years, therefore, failure of groundwall insulation from this type of discharge is of very low probability. However, small voids may become bigger voids or delamination through a combination of various stresses, which can induce more intense discharge and lead to excessive insulation degradation.
Figure 7. PRPD patterns of internal discharge recorded at 10 kV under 20 °C.

Figure 8. PRPD patterns of slot discharge recorded at (a) 20 °C and (b) 80 °C under the voltage of 6 kV.

The PRPD patterns of slot discharge are recorded at 20 °C and 80 °C, respectively, as shown in Figure 8. From these figures we can know that all patterns have a steep increase at the onset of the pattern during the negative voltage half-cycle, meanwhile, the geometric shape of PRPD pattern becomes from the triangle to the quadrilateral gradually with the increase of temperature.
Figure 9 shows the PRPD patterns of corona discharge which is recorded at 7 kV and 10 kV, respectively. It is clear seen that the PRPD pattern is asymmetry from one voltage half cycle to the next, with much larger in amplitude and number in the negative voltage half cycle, which is similar to slot discharge pattern. However, the shape of corona discharge pattern is much more rounded than the one of slot discharge. Furthermore, with the increase of voltage, the corona discharge is more intense, while the asymmetry regarding to the amplitude and number is gradually disappeared and the PRPD pattern becomes symmetrical but with much larger amplitude compared to that of internal discharge pattern.

Figure 10 shows the PRPD patterns of bar-to-bar discharge which is recorded at 20 °C and 80 °C, respectively. Compared to the above three types of PDs, bar-to-bar discharge is more difficult to

![PRPD patterns of corona discharge recorded at (a) 7 kV and (b) 10 kV under 20 °C.](image-url)
induce, which needs higher voltage. Meanwhile, the PRPD patterns consistently keep symmetric with almost constant amplitude under any condition, but with a little larger amplitude under higher temperature.

Figure 10. PRPD patterns of bar-to-bar discharge recorded at (a) 20 °C and (b) 80 °C under the voltage of 10 kV.

In the experiment, surface tracking is the most difficult to induce, with the discharge inception voltage as high as 12 kV. Surface tracking also gives asymmetric PRPD pattern. However, compared to other patterns, a few discharges with very large amplitude occur around 30 ° of phase angle. With the increase of voltage, the large amplitude discharges can be found around 220 °, as shown in Figure 11.
4. Conclusions

In this paper, the five most common types of discharge occurring in high voltage motors are discussed. The experimental models are introduced and the PRPD patterns are studied. It can be seen that different discharges have different PRPD patterns, while the PRPD patterns may be different for the same discharge under different experimental conditions, which increases the difficulty to accurately estimate the PD type and the discharge severity.

In the experiment, we find that slot discharge and corona discharge are the severest among the five types of PD, because they usually have larger discharge amplitude and number at rated voltage. In addition, the occurrence of surface tracking requires not only the very high voltage, but also an abnormally high resistivity contaminated by oil and carbon dust mixture, which leads to it the most difficult to induce in the experiment. Meanwhile, internal discharge is always not harmful because the modern epoxy-mica insulation system has excellent resistance to normal discharge. It is hoped that readers can get some useful information through our research.

Acknowledgements

This research was financially supported by the State National Natural Science Foundation (grant number U1510112), and Key Research and Development Project of Shanxi Province (grant number 201803D121008).

References

[1] Peter T, Li R, et al. 2008 Condition monitoring of rotating electrical machines The Institution of Engineering and Technology

[2] Claude H and Mario B 2005 Partial discharge signal interpretation for generator diagnostics IEEE Transactions on Dielectrics and Electrical Insulation 12(2) 297-319

[3] Greg C S, Ian C, et al. 2014 Electrical insulation for rotating machines: design, evaluation, aging, testing, and repair IEEE Wiley

[4] Chuanyang L, Jiancheng S, Ailiang K, et al. 2014 PD patterns of stator windings by in-factory experiment Proceedings of 2014 International Symposium on Electrical Insulating Materials 168-171

[5] Greg C S, Clyde V M, et al. 2008 Impact of slot discharges and vibration sparking on stator winding life in large generators IEEE Electrical Insulation Magazine 24(5) 14-21

[6] Ailiang K, Muqin T, Jiancheng S, et al. 2018 Contribution of electrical-thermal aging to slot partial discharge properties of HV motor windings Journal of Electrical Engineering & Technology 14(3) 1287-1298