Investigation of Partial Discharge Activity in the Slot of a Hairpin-wound Stator

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***Abstract* – The reliability of electric vehicles is a key aspect for the entire market. Namely, the lifetime of the electric motor is critical. Therefore, it is necessary to know the stress, ageing factors and the condition of the motor. Higher frequency harmonics, steep slew rates and increasing voltage levels driven by state-of-the-art inverters increase the electric stress imposed on the motor winding insulation, which may lead to partial discharges (PD). If PD occurs, the lifetime of the electrical machine can be reduced to unacceptable levels. Hence, the qualification and lifetime evaluation of inverter-fed machines are of high relevance. It is difficult to identify the exact cause of PD when a complete stator is tested because of its complex structure. In order to investigate PD phenomena in the turns of a hairpin-wound stator, a miniaturized test block representing a single slot of the stator is constructed, in which multiple conductors can be placed. The winding configuration is based on a symmetric three-phase delta connected winding in which, each phase has three parallel paths, i.e., conductors from multiple parallel paths of the same phase are present in each slot in various combinations. The aforementioned test setup is used to investigate the partial discharge inception and extinction voltages (PDIV and PDEV) of various turn-to-turn configurations.**

Keywords: partial discharges(PD), inverter-fed machines, hairpin-wound stator, miniaturized test block, partial discharge inception(PDIV)

I. INTRODUCTION

The automobile companies pay attention to the motor size, the power density and the speed. With higher overall performance in terms of efficiency, power and torque density, electrical motors with hairpin wound stator are gaining increasing popularity while have been widely used. But the qualification test and the lifetime analysis of the motor need to be discussed and studied.

Several studies have tried to explain PD activities in the inverter-fed random wound motor. The simplest approach was by using the twisted enameled magnet wires to model the wound motor windings [1]. They varied the parameters of the applied voltage, the material of the samples and the test environment to investigate the influence factors of the PD activity and the breakdown position of the motor. The research shows that environmental conditions, such as the temperature and the humidity, can strongly affect the electrical insulation capacity of the motor winding [2]. The parameters of the applied voltage, including peak to peak value, rise time and repetition rate, are also the factors to determine the partial discharge inception voltage (PDIV) and the breakdown position of the winding [3]. Other works have compared the detection methods used in the inverter-fed random wound motor [4-6]. Some research methods allow rejection of the noise and enable the acquisition of PD pulses in inverter-fed motor [7]. But the predominant model used in these studies is the twisted enameled magnet wires. Few studies have examined the PD activities in the motor with hairpin winding.

Due to the uneven voltage distribution along windings, the model proposed previously can't simulate the different winding configurations. Therefore, the purpose of this study is to establish a miniaturized test block that can be used to simulate the slot of a hairpin-wound stator. This work will present the PDIV, PDEV and PRPD patterns of various turn-to-turn configurations, and make a brief discussion on the influence of the material and the configuration of the winding.

II. MINIATURTURIZED TEST BLOCK

A. Hairpin Winding Configuration

The hairpin windings are square coils of hairpin shape inserted to stator slots, whose end turns are welded. The electrical motor used for testing is designed with 54 slots and each slot lodges 8 bars of a single phase covered by electrical insulation paper. Fig.1 shows the structure of the hairpin wound stator. Each of its three phases has three parallel paths and the three phases are in delta connection, seen in Fig.2.

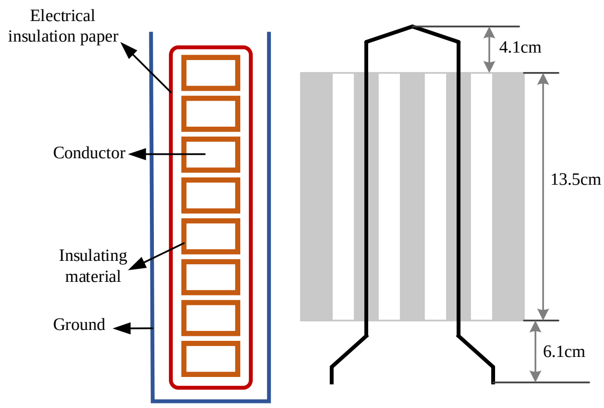


Figure 1. Structure of haipin stator

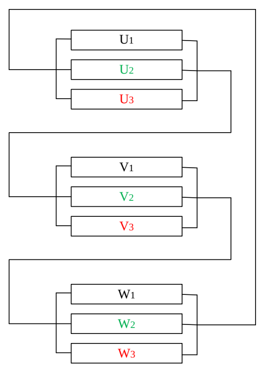


Figure 2. Electrical equivalent circuit with parallel paths

In different slots, the position of the hairpin coils from different parallel paths of the same phase is different. There are 6 possible configurations of the hairpin coils in the slot, shown in Fig 3.

U_3	U_2	U_2	U_1	U_1	U_1
U_1	U_1	U_3	U_1	U_2	U_1
U_1	U_2	U_1	U_1	U_2	U_2
U_2	U_1	U_2	U_1	U_3	U_2
U_3	U_2	U_2	U_1	U_1	U_1
U_1	U_1	U_3	U_1	U_2	U_1
U_1	U_2	U_1	U_1	U_2	U_2
U_2	U_1	U_2	U_1	U_3	U_2
(a)	(b)	(c)	(d)	(e)	(f)

Figure 3. Configurations of the hairpin coils

B. *Miniaturized Test Block*

According to the structure of the hairpin stator, a miniaturized test block was built to investigate the turn to turn isolation in the slot. The pictures and the structures in Fig.4 highlight the structure of the miniaturized test block. The test block consists of a block, 8 hairpin windings and connectors. The block is used to simulate the turn to turn isolation of the stator slot with different connections of the winding. The hairpin winding and the block are isolated by the electrical isolated paper.

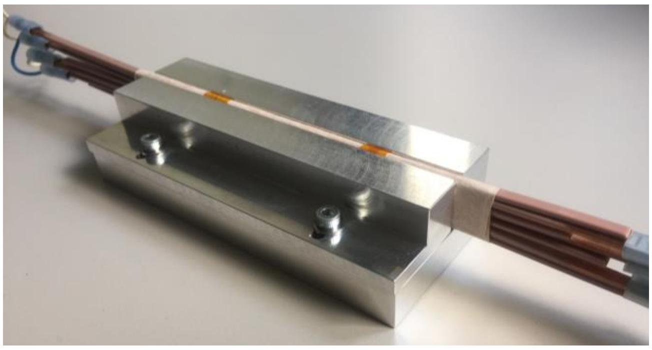


Figure 4. Structure of miniaturized test block

C. *Experiment*

The test system adopted is a typical PD detection circuit [8], shown in Fig.5. Some of the hairpin windings in the block are connected to the high voltage supplied by a voltage transformer and to a 2000pF capacitance in parallel. So that the turn to turn isolation of the winding can be investigated with different winding configurations. The PD signals are analyzed through the software supplied by Omicron.

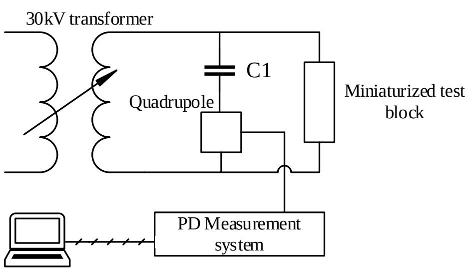


Figure 5. Test system schematic diagram

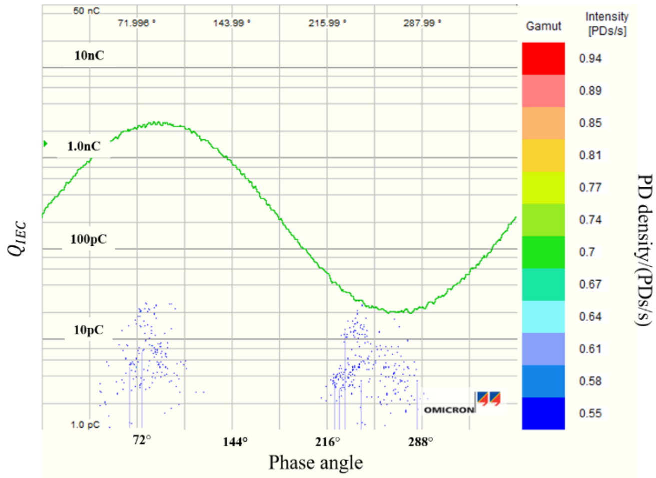
The experiments are performed at four voltage cycles. The first cycle is from 0V to rated voltage, lasting 1 min. In the second stage, the test block is connected to the rated voltage for 30 seconds. Then, the voltage supply will rise until the PD activity appears and then the voltage rises to 1.2PDIV. So that the PDIV and phase resolved partial discharge pattern (PRPD pattern) of the test block can be recorded. In the final cycle, the supplied voltage decreases slowly and PDEV can be obtained.

III. Results and Discussion

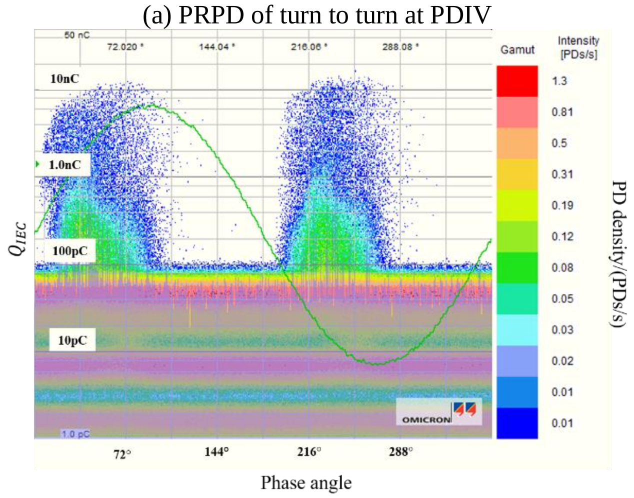
A series of experiments are carried out with 6 configurations and 3 isolating materials. The winding configurations are in consistence with the ones shown in Fig. 3. PD in different winding configurations was measured by connecting one parallel path (U_1) to the high voltage with the other two parallel paths (U_2 and U_3) and the block grounded. This method measures PDIV turn to turn and phase to ground (Configuration(d)).

A. *PRPD Pattern of Turn to Turn Discharges*

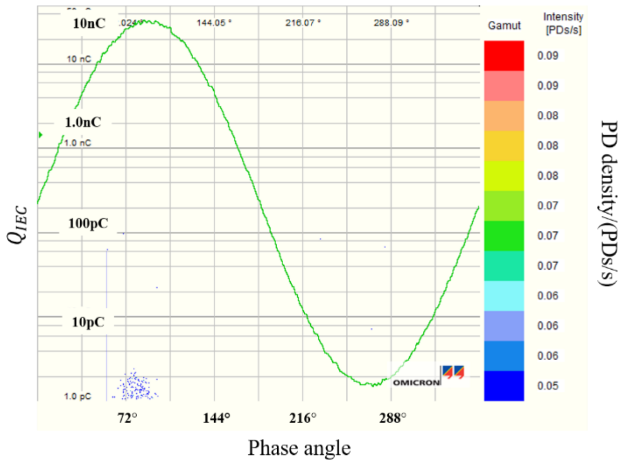
For the characterization of PD, PRPD patterns are used, which is helpful in analyzing the type of PD. PRPD shows the occurrence of PD related to the phase of the voltage. In Fig.6 the PRPD patterns of the turn to turn discharge and phase to phase discharge are shown.



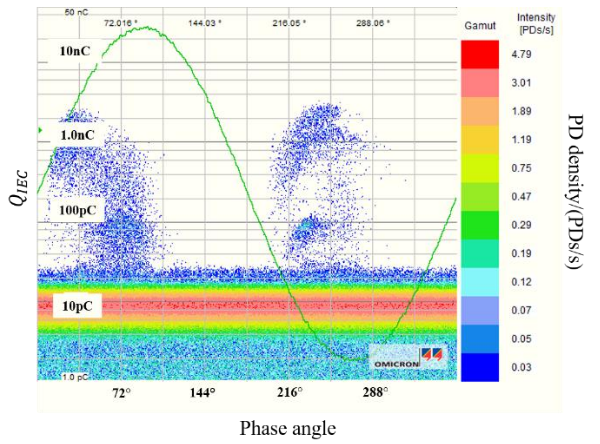
(a) PRPD of turn to turn at PDIV



(b) PRPD of turn to turn at 1.2PDIV



(c) PRPD of phase to ground at PDIV



(d) PRPD of phase to ground at 1.2PDIV

Figure 6. PRPR of turn to turn discharges and phase to ground discharges in the test block

The ignitions of the PD events start in the area of highest voltage gradient (see Fig. 6 (a) and (c)). When the applied voltage is further increase, discharges occur over a broader part. The PD magnitudes vary more. The broadening of the pattern can be explained with the inception voltage to encounter the discharges. The increasing voltage also enhanced the field strength, leading to the increase of the number of the discharges and the discharge quantity. In general, the pattern has similar characteristic for 3 different materials. From identification point of view, the PRPD patterns of turn to turn discharges and phase to ground discharges are a typical of surface discharge [9].

B. Results different winding configulations

The PD tests are repeated 10 times on each configuration. All the hairpin wingdings are provided by the manufacturers. Among them P130 is the same as the one used in the motor. Results from PD tests of Material P130 are shown in Fig. 7. PD quantity Q_{IEC} has been measured at 900V.

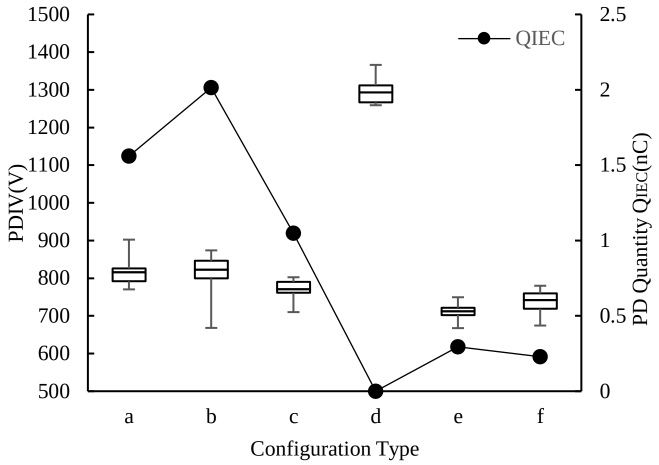


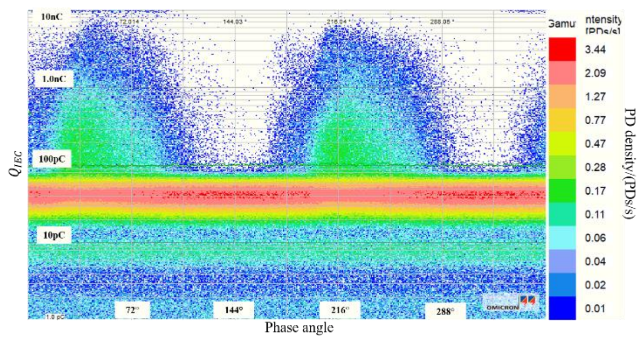
Figure 7. PDIV and Q_{IEC} mean values of different configulations

The PD behavior is expected to relate to the winding configuration, because the configuration is associated with the distribution of electric field and magnetic field. Experimental results demonstrate that the symmetry of the winding affects the PDIV and the discharge levels.

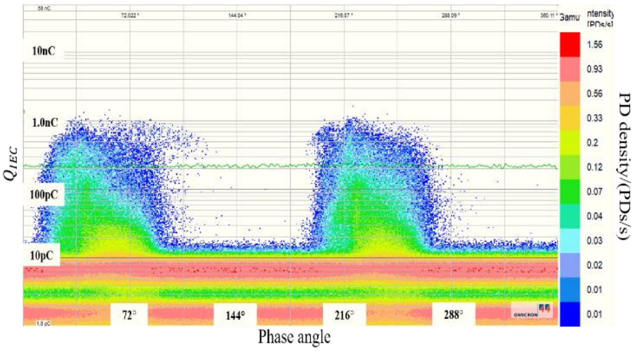
The symmetry of the configuration results in the uniform distribution of the electric field and magnetic field, which in turn, increases the PDIV of the winding. As can be seen in Fig.7, the PDIV of phase-to ground discharges are higher than that of turn-to-turn discharges. The PDIV of Configuration (b) is the highest among all the turn-to-turn discharges. In Configuration (e), the winding connected to the high voltage and connected to the ground is dissymmetrical, whose PDIV is lower than other configurations. Whereas the PD activities fall between the hairpin conductor connected to the high voltage and the conductor connected to the ground. When there are more conductor pairs in the slot, the charge level will be higher when the applied voltage is higher than PDIV. To evaluate this, the PD quantity Q_{IEC} has been measured at 900V. There are 7 conductor pairs in Configuration (b) while there are only 4 pairs in Configuration (a), so the Q_{IEC} of Configuration (b) is higher. The discharges also occur over a broader part once the applied voltage is higher than PDIV, as shown in the PRPD patterns in Fig.8.

C. Results of different insulating materials

Measurements of the PDIV have been done on 3 different materials P130, PI100 and Peak100, with 6 configurations. P130 and Peak100 are the same material with different thickness. The insulating material of P130 is thicker. The results of the PDIV test are shown in the Table I.



(a) PRPD of Configuration (a)



(b) PRPD of Configuration (b)

Figure 8. PRPD pattern of Configuration (a) and Configuration (b)

TABLE I. PDIV TESTS OF PEAK 130

Configuration	**P130**		**PI100**		**Peak100**	
	PDIV(V)	***PDEV(V)***	***PDIV(V)***	***PDEV(V)***	***PDIV(V)***	***PDIV(V)***
(a)	791.6	782	621.7	607.9	743	684
(b)	871.8	801	657.4	631	810	793
(c)	770	720.5	525.4	493.9	691	627
(d)	1296	1268	912.7	882.5	1190	1101
(e)	710.4	682.6	560.2	503.8	660.8	605.8
(f)	728.0	692.7	600.7	554.7	723.3	660

The PDIV test shows that the PDIV varies with the insulating materials. With the thickness rising, the PDIV increases. However, the insulation levels of different configuration have a good correspondence. It also affirmed the influence of the symmetry of the configuration on the PD activity in the slot.

IV. CONCLUSSION

Partial discharge activity in the slot of a hairpin-wound stator was reproduced in a miniaturized test block representing a single slot of the stator. Typical PRPD patterns for the turn to turn and phase to ground were recorded and identified. The PRPD patterns are typical surface discharges, with PD magnitudes increasing with voltage.

Furthermore, the PDIV tests of the 6 different winding configurations show that the PDIV varies considerably with different configurations. The results indicate that the symmetry of the configuration has an effect on the PDIV. The higher the symmetry is, the more uniform the voltage distribution is, leading to a higher PDIV.

In addition, through the analysis of the PDIV and PDEV of the winding with 3 different materials, it is found that some PD parameters, such as PDIV and PDEV, are depending on the insulating material, but the influence of the winding configurations are consistent with all the testing materials.

This research provides a method to investigate the PD activity of in the slot of a hairpin-wound stator. It also provides the reference for the design of hairpin winding motors.

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