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Partial discharge analysis through Lissajous figure at low air pressures

Z Shi[1], C Zhang[1] and M Given[2]

[1] School of Electrical Engineering, Guangxi University, 39 Keyuan Ave., Nanning, 530000, China
[2] Department of Electronic and Electrical Engineering, University of Strathclyde, 204 George Str., Glasgow, UK

E-mail: eee0619@sina.com

Abstract. The condition of electrical insulation is significant to the safety of electric power systems, especially to the More Electric Aircraft (MEA) that carries hundreds of people. The property of insulation will be reduced by aging and degradation which caused by partial discharge (PD). This has become a topic of extensive research and investigation. This paper represents the PD detection in terms of Lissajous figures which is a composite of two orthogonal oscillations with integral proportional frequencies. It can be used to calculate the total charge of PD transferred per cycle and the total energy of PD per cycle, thus the average charge and energy of a single PD activity can be recognized accompany with the current pulse PD detection method based on IEC 60270. These parameters could be useful to evaluate whether the insulation was damaged or how badly the damage was, hence to provide references to engineers for insulation condition judgment and design service plan.

1. Introduction

Modern aviation industry are interested in developing More Electrical Aircraft (MEA) which has larger electric capacity than the traditional aircraft. Many mechanical, hydraulic and pneumatic powered components in Boeing 777 for example, were replaced by electrical machines and electronic devices in Boeing 787 [1]. The increasing electric capacity brings new challenges to the aircraft power system which works at reduced air pressures. The insulation problems are very likely to cause electrical failures, which is greatly influenced by the event of Partial Discharge (PD). Thus, PD must be well recognized and monitored in low pressure conditions to protect the electric power system in MEA from electrical failure to avoid possible disasters.

PD detection technologies has been well developed and applied at atmospheric pressure. The research of PD is focused on evaluation and prediction of condition of insulation currently, especially for the oil-paper insulation evaluation of power transformer through dielectric response technology and dielectric dissipation factor [2, 3, 8]. However there seems to have been little attempts on the condition evaluation of polymer insulation which widely applied in aircraft power system at lower pressures. Basically, polymer insulation is easier to be degraded by ion bombardment caused by PD than other solid insulation such as ceramics and mica [4, 9, 10], and corona discharge as a special type of PD also has significant influence to the insulation and cause power loses [11]. Greater PD level generates more ion to cause worse damage to polymer insulation, which can be presented in terms of apparent charge and discharge energy of PD event. Therefore the condition of polymer insulation can be reflected by the above parameters.

This paper reports the PD detection of ETFE insulated twisted pair over a range of pressures using the Lissajous figure analysis. The charge transferred and discharge energy of PD in a cycle is calculated. Accompany with the current pulse PD detection method based on IEC 60270, which measured the number of PD event per cycle the average charge transferred of a single PD event was also obtained. These could be useful to evaluate whether the insulation was damaged or how badly the damage was, hence to provide references to engineers for insulation condition judgment and design service plan.

2. Experimental Method

2.1. Test System

The samples were made up of a single core unshielded Ethylene-Tetraflourethylene (ETFE) insulated wire. The stranded conductor had a diameter of 0.7 mm and the outer diameter of the wire was 1.1 mm leading to an insulation thickness of 0.2 mm for the samples. The cable is rated to operate at voltages of 600 V a.c. and 850 V d.c. and it conforms to the following standards: IEC 60332-1; IEC 60332-3; NF C 93-524; MIL W22-759/18 or /16. Lengths of the wire were formed into twisted pairs while under a tensile load of 27 N as directed in BS EN 60851-5 [5] for wires with an outer diameter of between 1.06 and 1.4 mm. These samples were placed into the sample holder shown in figure 1.

Figure 1. ETFE twisted pair sample in holder.

The PD event was measured using Lissajous figure, which is a composite of two orthogonal oscillations with integral proportional frequencies. The applied voltage was controlled in the range of 0 to 7.5 kV with an accuracy of ± 25 V. A 2.2 nF measuring capacitor was connected in series with the testing sample. The configuration of the test system is shown in figure 2.

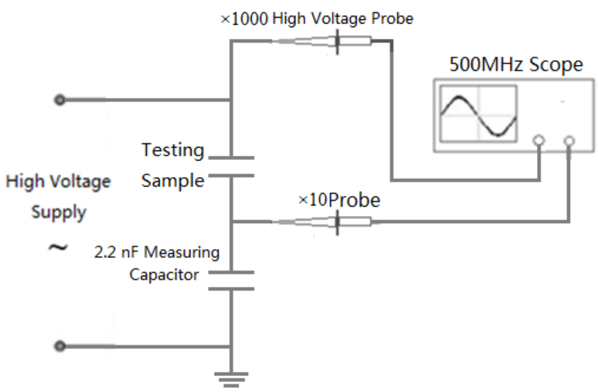


Figure 2. Configuration of PD measurement system.

The 2.2 nF measuring capacitor is very much larger than the capacitance of the testing sample in series with it, therefore most of the voltage will be divided on the testing sample. A ×10 probe was connected between the testing sample and measuring capacitor, thus the total applied voltage and the voltage divided on the measuring capacitor will be the X and Y axis on the Lissajous figure.

2.2. Measurement Techniques

The sample and holder were placed in the vacuum chamber and connected to the power supply. The test pressures used and the corresponding altitudes based on information provided in [6] are shown in table 1. The partial discharge activity was measured over a range of 2 to 3 kV above the inception voltage.

Table 1. Pressures used and corresponding altitudes.

Pressure (bar)	Equivalent Altitude (m)
1.0	0
0.70	3000
0.50	5500
0.36	8000
0.20	12000
0.11	15000

Once the appropriate pressure had been established in the test system the voltage across the sample was increased until initial partial discharge activity was observed. The PD initiation voltage V_i, was defined as the voltage where partial discharge activity of the order of 100 pC was first observed. The voltage was then increased from this inception voltage to the first integral multiple of 0.5 kV which was larger than V_i. The PD activity was recorded for a period of 1 minute (3000 cycles). The test voltage was then increased by a step of 0.5 kV. Six of these 0.5 kV steps were used at 1 bar, while 5 voltage steps were used at lower pressures.

3. Experimental Results

3.1. Introduction of Lissajous Figure

The discharge area in the testing sample is the gas gap between the two twisted wires, thus there was Dielectric Barrier Discharge (DBD) occurring in the gas gap. The typical Lissajous figure has the form of a parallelogram, schematically shown in figure 3. In the Lissajous figure of DBD, the AB and CD sides of the parallelogram are the 'passive phase' of DBD [7, 12, 13, 14], there is no discharge occurred in this phase. The slope of the AB and CD sides represents the capacitance of the twisted pair. The BC and DA sides can be regarded as the 'active phase' of DBD [7], the PD events are occurring in this phase and the sides were observed non-smooth as compared to the 'passive sides' , as shown in figure 4 which is an result of the experiment. The slope represents the capacitance of the dielectric of the twisted pair.

The energy of PD can be calculated by [7]:

$$E = \int Q \cdot dV = A_{Lissajous} \tag{1}$$

where V is the applied voltage, Q is the charge transferred during PD occurring and $A_{Lissajous}$ is the area of the parallelogram. The measured Lissajous figures were the composite of the two 50 Hz sinusoidal voltages divided on the testing sample and the measuring capacitor, thus the calculated energy is the total discharge energy of a cycle.

The charge transferred in a quarter cycle can be calculated by:

$$\Delta Q = \Delta U \cdot C \tag{2}$$

where ΔU is the value between the bottom and the top of the side on the right hand side that across the X axis (BC side in figure 3), as shown in figure 4. C is the value of the measuring capacitor. Thus the total discharge quantity in a cycle is:

$$Q_{total} = 2\Delta Q \quad (3)$$

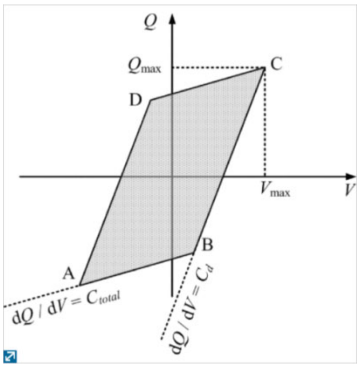
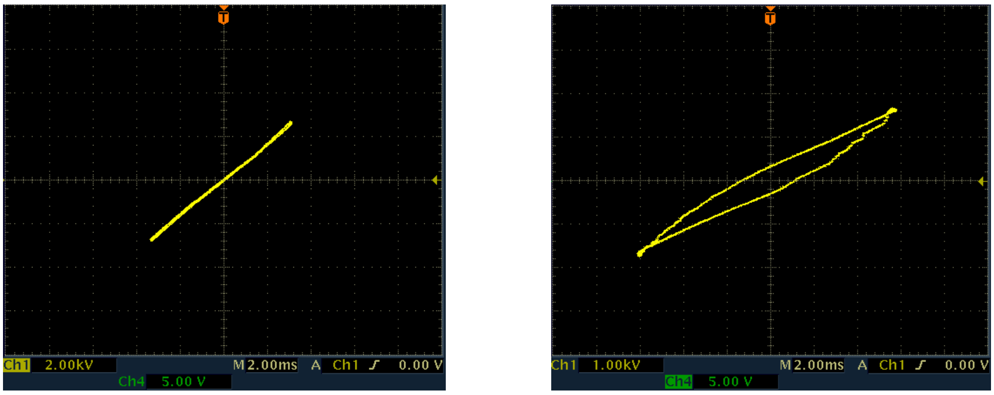


Figure 3. Typical Lissajous figure of DBD [7].

Figure 4. Calculation of charge transferred per cycle with measured Lissajous figure.

3.2 Test Results
The Lissajous figure was a line when the applied voltage was not sufficient to initiate PD, as shown in figure 5a. The figure was expanding and becoming the form of a parallelogram when the applied voltage was higher than the PD initiation voltage, as shown in figure 5b. The X axis is the applied voltage and Y axis is the voltage across the measuring capacitor. The BC side had a crossing point with the X axis, the value of this point is the actual breakdown voltage of the gas gap after a voltage drop across the dielectric layer of the wire.



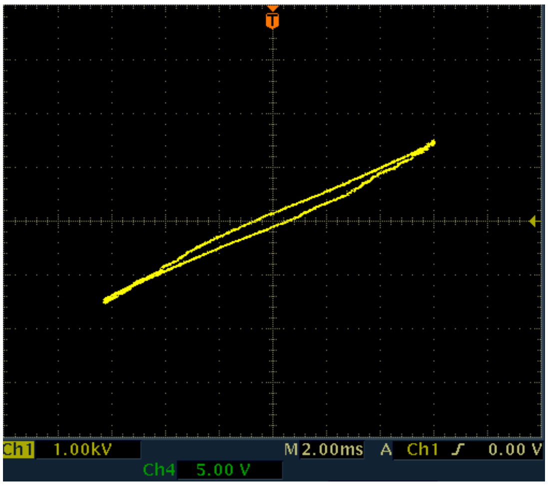
(a) (b)

Figure 5. Lissajous figure representing: (a) – non-discharge and (b) – discharge.

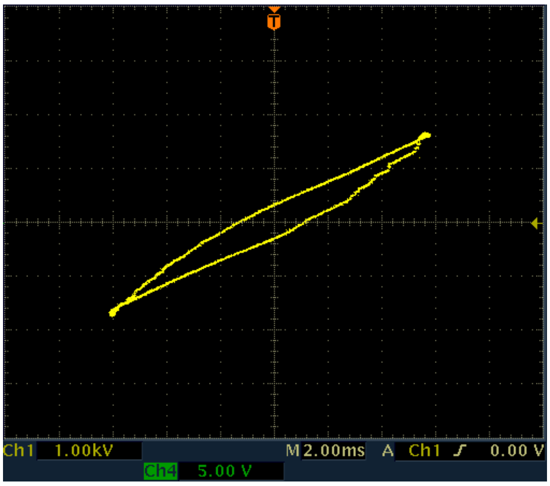
The Lissajous figures were measured at the low pressures of 0.7 bar, 0.5 bar, 0.36 bar, 0.2 bar and 0.11 bar, figure 6 shows the recorded figures at each of the testing pressures under the applied voltage of 3.0 kV.

It is observed in figure 6 that the Lissajous figure looks more like a parallelogram as the pressure decreased. The actual breakdown voltage of the gas gap was increasing with the applied voltage from 0.7 bar to 0.36 bar, but it does not change below 0.36 bar. This phenomenon indicates that smaller gaps breakdown first at higher pressures. The charge transferred in a quarter cycle also increased with the pressure reduced, the discharge energy of a cycle does not change significantly from 0.2 bar to 0.11 bar.

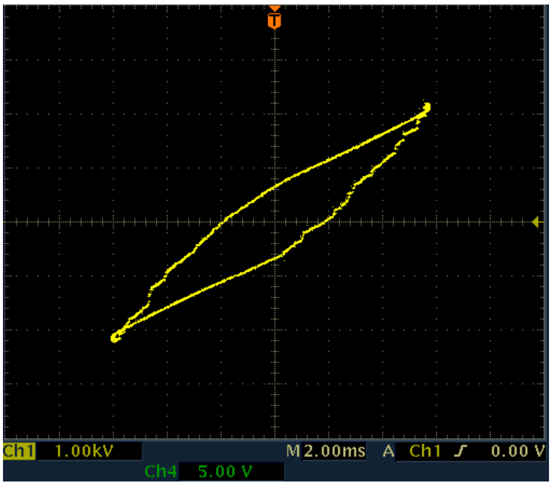
The actual breakdown voltage of the gas gap may has small variation with a certain applied voltage at a particular pressure. Two Lissajous figures in figure 7 had a 200 V of difference in the actual breakdown voltage of the gas gap, which was recorded at 0.2 bar with 3.0 kV applied voltage. The different actual breakdown voltage illustrated the randomness of PD events which were occurring in different gaps between the twisted wires.



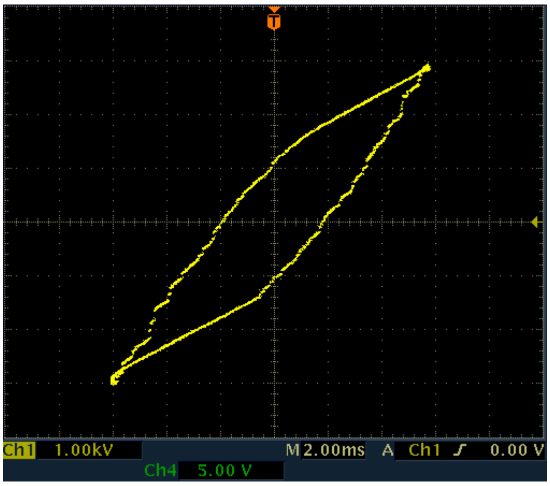
(a) 0.7 bar at 3.0 kV



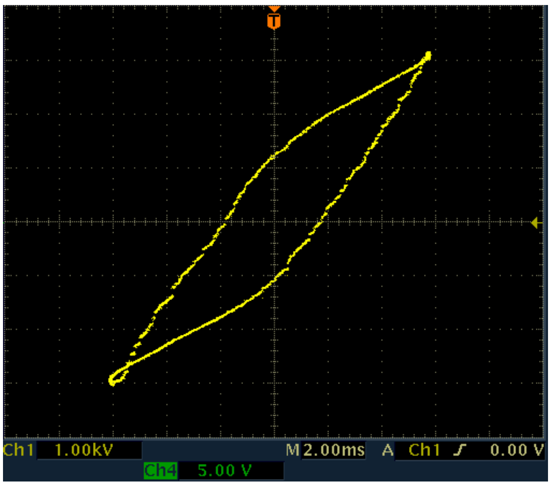
(b) 0.5 bar at 3.0 kV



(c) 0.36 bar at 3.0 kV

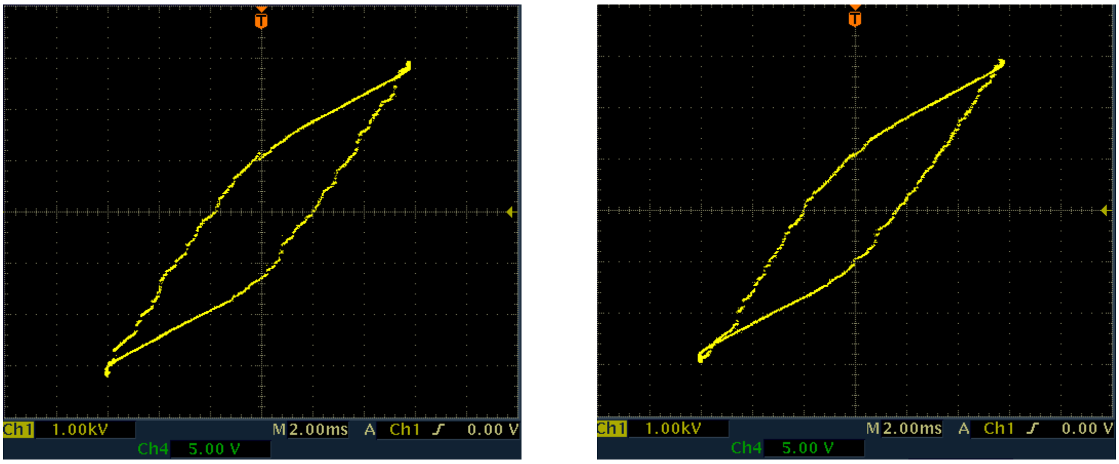


(d) 0.2 bar at 3.0 kV



(e) 0.11 bar at 3.0 kV

Figure 6. Lissajous figure at low pressure conditions.



(a) 1000 V actual breakdown voltage (b) 800 V actual breakdown voltage

Figure 7. Variation of actual breakdown voltage of the gas gap under the same testing voltage and pressure.

4. Analysis and Discussion

As the important parameters of PD which is useful for insulation condition evaluation, the charge transferred and discharge energy in a cycle had been calculated. The relationship between the charge transferred per cycle and the pressures with a certain applied voltage of 3.0 kV is shown in figure 8.

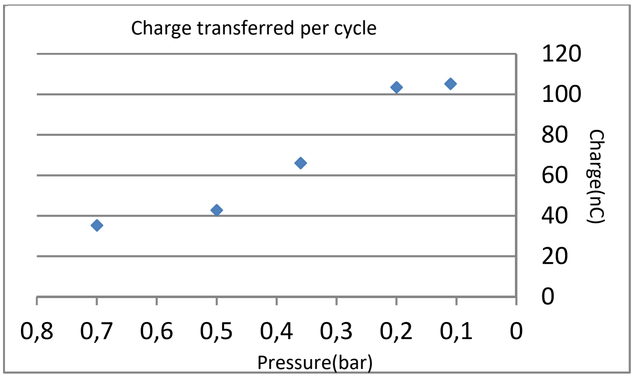


Figure 8. Charge transferred per cycle vs. pressures.

The charge transferred per cycle was increasing with the pressure was decreasing, which reflected the PD was more significant at lower pressure with a certain applied voltage in the tested range. It was increasing more rapidly when the pressure decreased below 0.5 bar and became flatten from 0.2 bar to 0.11 bar. This is reasonable because according to Paschen's Law, the increasing trend should be flattened and turned to decrease with the pressure decreased further under the same applied voltage [9]. The discharge energy per cycle was also increasing with the pressure was decreasing, but it did not change significantly from 0.2 bar to 0.11 bar, which well matched the trend of charge transferred per cycle, as shown in figure 9.

The PD was also detected by the current pulse method based on IEC 60270, which recorded the PD count to calculate the average charge amount of a single PD event. This method recorded all of the PD events for one minute period in every testing case, thus the total PD count divided by 3000 would be the average PD count per cycle. The Average charge amount of single PD event can be calculated using the charge per cycle from the Lissajous figure divided by the average PD count per cycle, as listed in table 2 with 3.0 kV applied voltage for each tested pressure.

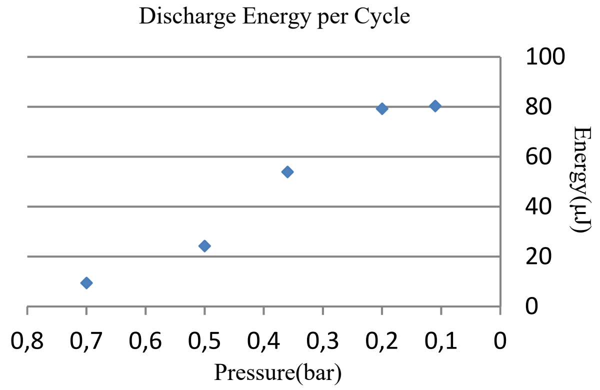


Figure 9. Discharge energy per cycle vs. pressures.

It can be seen that the average charge of single PD event was degreased with the pressure, which seems it does not match the law of PD strength increases as the pressure reduces with a certain applied voltage. This could be explained as smaller gas gaps were breakdown at higher pressures while larger gas gaps were breakdown at lower pressures. Meanwhile, smaller gas gaps has larger capacitance which appeared large amount of charge during PD occurred.

Table 2. Pressures used and corresponding altitudes.

Pressure (Bar)	Average PD Count per Cycle	Average Charge of Single PD (nC)
0.70	2.4	14.67
0.50	6	7.12
0.36	10.8	6.1
0.20	19	5.44
0.11	21	5.0

The parameters of the charge transferred per cycle, the discharge energy per cycle and the average charge amount of single PD event had been recognized through this work, which could be useful for the insulation condition evaluation in low pressure environment. The damage caused by PD of different polymer dielectrics with different levels of the above parameters will be recorded and graded as varies insulation condition level in the future work, consequently a data base could be established. Thus the tested data of electrical and electronic devices can be compared to that in the data base to judge the insulation condition, which makes the insulation condition evaluation applicable.

5. Conclusion

Several important parameters of PD in varies low pressures were calculated through the Lissajous figures which measured in this work. The charge transferred per cycle and discharge energy per cycle both increased with the pressure dropped but the increasing trend began flattened from the pressure of 0.2 bar and below with a certain applied voltage. The variety of actual breakdown voltage of the gas gap was also observed in a particular testing case, which proofed the PD was occurring in different gas gaps of the testing sample. The average charge amount of a single PD event was also worked out with the data recorded by current pulse detection method. This parameter shown a decreasing trend with the reducing pressure, which can be explained as the smaller gaps with higher capacitance were breakdown at higher pressures while the larger gaps with lower capacitance were breakdown at lower pressures.

The above parameters are able to use on the insulation condition evaluation. A data base of graded insulation condition level was proposed in the future work, which can be established by concluding the damaged conditions of varies polymer dielectrics caused by PD with particular values of the above parameters. Thus the tested data of the electrical and electronic devices can be compared to that in the data base and the judgment of insulation condition will be applicable.

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