Effect of Aging and Moisture on Dielectric Characteristics and Partial Discharge in Dry Paper, Oil and Oil-Impregnated Paper

Bahman Tavakoli and S. M. Hassan Hosseini*

Abstract— *This paper has been focused on partial Discharge (PD) over solid dielectric oil impregnated paper (OIP) in different condition. This condition is arranged as: temperature, humidity and different voltages. As we can see PD is completely related to voltage regulation. In other mean with increasing the voltage magnitude PD magnitude is increased to 50Pc.PD over different temperature and humidity is changed. For example, in the same voltage with dehumidify is reduced to 1.5nC. In this condition, 2 important parameters* $\boldsymbol{Tan\delta}$ *and Capacitance are changed like PD.* $\boldsymbol{Tan\delta}$ *in different voltages is changed to 1.2 to 2.8 as like ae Capacitance.*

Keywords— Partial discharge, polymerization degree, capacitance, electric conductance, dielectric loss Coefficient.

1. INTRODUCTION

Since power equipment is very expensive, they should be monitored carefully. One of the most important tools in such devices is insulator. Permanent operation of these devices depends on insulation condition. In long-term operation, temperature, moisture, oxygen and acids existing in mineral oil degrade the insulator [1]. Statistics has been shown that break-down of insulator plays the most important role in disruption of power devices; using good insulator increases reliability of the system. Moisture affects insulator in 3 aspects including: 1- speeding up insulator aging, 2- reducing dielectric strength and 3- creating bubbles in high temperature which reduce lifetime of insulators. This paper allows a better understanding of PD in oil-impregnated paper. Multi transmission line (MTL) is a method that can decrease a simulation error in PD detection [2]. Insulation studies can be divided into three categories including: electrical, thermal and mechanical. The Most important mechanical part is insulator's degree of polymerization (DP) [3]. Under normal condition, increasing temperature of the insulator might increase losses which is not sufficient for degrading the insulator. However, partial discharge might change insulator loss and damage the insulator due to the generated heat. Considering moisture of the paper and its thermal aging, insulator lifetime might vary from several months to several years. The electric potential distribution in the dielectric is described by the field model.

The basic governing equations of the field model are as follows:

$$\nabla . D = \rho_f \tag{1}$$

where D is the electric displacement field, ρ_f is the free charge density or unpaired charge density.

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In according to moisture diffuses in the paper, moisture diffusion time constant can be calculated using the following equation:

$$\tau = \frac{d^2}{\pi^2} \ . D_0 \tag{2}$$

where d is thickness of the paper, D_0 is moisture scattering coefficient which is a function of temperature and can be calculated with following equation. Scattering coefficient shows amount of material which diffuses from a region with unit gradient concentration to another point in unit time:

$$D = D_0 e^{\frac{E_0}{K_B}(\frac{1}{T_0}-\frac{1}{T})} \tag{3}$$

where K_B is Boltzman constant (K_B=8.617× 10^{-5} ev/k), T_0 is 298k; D_0 and E_0 are given in the following table: [4]

Table 1. Values of D_0 and E_a for oil and OIP

	D_0(m²/s)	E_a(ev)
2.62× 10^{-11}	0.070142	oil
1.34× 10^{-13}	0.69573	oil impregnated paper

2. METHODOLOGY

2.1 Preparing Insulator

Paper layers are cut in 5 cm x 5 cm pieces. Paper is impregnated with oil using the following procedure [5]. 1- Layers of the paper were vacuum (~5 mbar) dried at 120^0C and 24 hours. 2-The temperature of the oven was lowered to 60^0C.The oven chamber was first filled with dry air and then oil that was already pre-heated up to 60^0C was put in to the vacuum oven. Both oil and layers of paper were vacuum dried for 24 hours at 60^0C. 3) The vacuum chamber was filled with dry air. The layers of paper were immersed in the oil and left to impregnate for 1 day under vacuum 60^0C. 4- The heater was turned off and layers of OIP were left inside oil for 24 hours to cool down. Dielectric frequency response (DFR) is one of the modern detection tools which operates based on dielectric response of the insulator. Traditionally, measuring tanδ in power transformers is performed at 50/60 Hz frequency. Measuring tanδ at other frequencies is usually performed off-line. Off-line measuring has a fundamental shortcoming which is our stress is not equal to real stress. Experiments of this study are conducted at 50 Hz. Dielectric loss of insulator can be described as follows:

$$W_d = 2\pi f c u^2 tan\delta \quad (4)$$

In the above equation, w_d is dielectric loss, f is 50 Hz, C is capacitance, u is voltage and tanδ is dielectric loss tangent. Considering the direct relationship of this coefficient with dielectric loss, tanδ affects dielectric losses significantly. For instance, considering Table 2, loss coefficient for transformers is in 0.5% alert range and acceptable loss coefficient should be between range of 0.1% to 0.5% [7]. A finite element method is a numerical method where use for approximate partial Discharge in solution the integral equation [6]. According to IEC60422 standard, dielectric loss coefficients for transformers with different voltages are classified in Table 3 [10].

2.2. Measuring of Tangent delta

Table 2. Examples of Loss tangent [7, 8]

	Samples of tanδ in 20^{0}C		
	warning	old	new
Power transformers with oil insulation	<0.5%	0.3%-0.5%	0.2%-0.4%
bushings	<0.5%	0.3%-0.5%	0.2%-0.3%

Both capacitance and loss coefficient at frequency F can be described as follows [9]:

$$C = \frac{1}{2\pi f x} \quad (5)$$

$$Tan\delta = \frac{1}{2\pi f c R} \quad (6)$$

Table 3. Classification of transformers according to IEC-60422 standard

Transformer type	Classification
Power transformer with 400 kV voltage and upper	O
Power transformer with 170 kV voltage and lower than 400 kV	A
Power transformer upper than 72.5 kV and lower than 172 kV	B
Power transformer with medium voltage and lower than 172 kV	C
Protected transformer with 170 kV voltage	D
Protected power transformer with 170 kV voltage and upper	E

Table 4. Values of tanδ for the transformers according to IEC-60422

Categories	Good	Relatively good	Weak
O,A	>0.5%	0.1%-0.2%	<0.5%
B,C	>0.5%	0.1%-0.5%	<0.5%
D	>0.5%	0.1%-0.3%	<0.5%
E	>0.5%	0.1-0.3%	<0.5%

2.3 Measuring of Electrical Permittivity

Like tanδ , this factor is also sensitive to aging, moisture, voltage increasing and temperature. Relationship of this parameter with tanδ is defined as follows: if permittivity is defined as e*=e'-je" where e' and e" are real and imaginary parts, respectively, tanδ would be as below:

$$Tan\delta = e''/e' \quad (7)$$

Indeed, there is an empirical relationship for calculating permittivity with related permittivity to capacitance:

$$\varepsilon_r = 0.0564Cd \quad (8)$$

In Eq. 9, C is insulator capacitance and d is insulator diameter which increases by increasing number of insulator layers. In order to calculate ε_r, it is sufficient to calculate value of C and used the above equation to calculate its value. Variations in oil conductance do not affect loss coefficient of this insulator in which dynamic of the electric field can be defined as below [11].

$$-\nabla.(\delta + i\omega\varepsilon_r)\nabla V = 0 \quad (9)$$

where δ is electric loss argument, ε_r is electric permittivity, ω=2πf is angular frequency and V is voltage; in Eq. 11, electric field distribution indicated voltage gradient defined as follows:

$$E = -\nabla v \quad (10)$$

A well-known model called XY model has been used to determine permittivity in OIPs. This model can be used to break oil or paper while measuring dielectric. Direct evaluation of moisture is almost impossible because there is no correct information from insulator available, but there are techniques for indirect evaluation of moisture [15]. XY model is also investigated to obtain linear behavior of permittivity in oil-impregnated paper and oil; this is usually done in low voltages due to linear behaviors in these voltages and a formula is also described for pure oil.

$$\varepsilon^*_{tot}(\omega,T) = B\varepsilon^*_{OIP}(\omega,T) + \frac{1-B}{\frac{1-A}{\varepsilon^*_{oil}(\omega,T)} + \frac{A}{\varepsilon^*_{OIP}(\omega,T)}} \quad (11)$$

In the above equation, all free oils in voids are represented as a layer of oil with thickness (1-A) and width (1-B) which can be estimated by measuring thickness of void in oil-impregnated samples. $\varepsilon_{tot}^{*}(\omega,T)$ is complex permittivity of the whole system, $\varepsilon_{OIP}(\omega,T)$ is permittivity of oil-impregnated paper and $\varepsilon_{oil}^{*}(\omega,T)$ is oil permittivity. In addition, in linear behavior, oil permittivity can be calculated as follows:

$$\varepsilon_{oil}^{*} = 2.2 - j\frac{\sigma(t)}{\varepsilon_0\omega} \tag{12}$$

In the above equation $\sigma(t)$ represents electric conductance of oil. Estimated area is about 30% (for example 0.7 B) and samples which their thickness is less than 5% (for instance 0.95 A) are estimated. In the experiment conducted at 20ºC, electric conductance is 0.23Ps/m and at 80ºC, it is 3.3Ps/m [12], [13].

Current density and electric permittivity are described as follows [14].

$$J(t) = J_{transport} + \frac{\partial D}{\partial t} \tag{13}$$

$$J_{transport} = \sigma_{DC}.E \tag{14}$$

$$\frac{\partial D}{\partial t} = \frac{\partial(\varepsilon E)}{\partial t} = (\varepsilon_0\varepsilon_r' - j\varepsilon_0\varepsilon_r'')E \tag{15}$$

$$J = (\sigma_{DC} + \omega\varepsilon_0\varepsilon_r'')E + J\omega\varepsilon_0\varepsilon_r'E \tag{16}$$

where J(t) is total current density, $J_{transport}$ is conductance current density, D is displaced electric field, σ_{DC} is electric conductance, E is electric field, ε_0 is permittivity of vacuum, ε_r' is real part of permittivity and ε_r'' is the imaginary part of permittivity.

2.4 Ion Mobility in Aged Oil

In order to find oil aging, oil color can also be used. Fresh oil is bright white but when oil is aged, its color changes to dark yellow and when its color changes to dark brown, its aging has increased. Displacement of ions in fresh oil is 4.5×10^{-10} m^2/Vs while as it ages one weak, its displacement increases to 9.4×10^{-9}m^2/Vs. displacement of ions in sine voltage can be estimated using the following equations: [21]

$$V = \mu.E \tag{17}$$

$$\int v.dt = \int \mu.Edt = \frac{\mu v}{d}\times\int \sin(\omega t)dt \tag{18}$$

$$d = \frac{\mu v}{d}\int_0^{\frac{1}{f}} \sin(\omega t)dt \tag{19}$$

$$\mu = \pi f d^2/V \tag{20}$$

where V is floating speed, μ is displacement of ions, E is electric field, v is peak sine voltage, d is air gap, ω is angular frequency and f is frequency of the applied voltage. The following figure, oil color in different conditions including, fresh, semi-ages and aged has been shown.

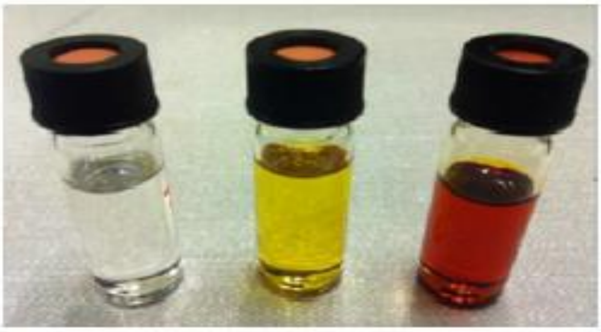


Fig. 1. Aging oil considering IEC611125- fresh oil (bright white), after one-week aging (dark yellow), after 2 weeks aging (dark brown) [21]

2.5 Phase Response Partial Discharge Analysis (PRPDA)

PD source is introduced as voids filled with air, which exists between OIP layers. When these voids are larger, PD domain is larger and its break-down time is shorter. When experiment starts, strong discharges appear on the insulator and vanish after a short time. Number and maximum PD domain increase with time until peak value is reached. Finally, both parameters are decreased and break-down occurs. In general, as aging increases, amplitude and number of PD pulses increase. The following figure shows PD circuit using detector impedance put in series with the test sample. When voltage is established, capacitor charges and its charge are transferred to the test sample. This current passes the impedance and appears as voltage.

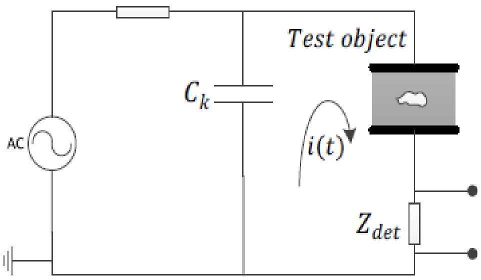


Fig. 2. PD circuit measurement (lab simulation) [21].

PD is OIP diffuses in voids existing between layers. Continuing PD to the surface might create a path on the surface of paper which results in flashover. Products decomposed in the paper include impure samples like carbon, carbon-dioxide and etc. [16]. In the following, two important factors of moisture and aging in insulators are studied and all results are given in discussion section.

When cellulose layers are put in OIP under operating condition, they are gradually involved with water, oxygen and high temperature. Polymer branches of cellulose are broken through chemical interactions and converted to smaller branches; at this step, mechanical strength of the paper is lost and some voids are created in the paper. When insulator is exposed to thermal stress, oil on the surface of paper evaporates; oil evaporation generates some citric acid which creates moisture; for better insulation operation, moisture should be reduced [17].

Main reasons of transformer failure include design, type of material, fire/explosion, improper maintenance, flood, loose connections, lightning, moisture and aging. Aging of insulator can be divided into electrical and non-electrical categories. Non-electrical aging is mainly due to mechanical part of the insulator, for example, reduction in DP of the insulator. Electrical aging includes over voltages applied to the insulator by an electrical field. PD which is applied as electric current pulses to the insulator might also be an example of electrical aging. Aging of insulator system reduces both mechanical and electrical strength of the dielectric. Factors like delamination, crack, wrinkle and damages of the insulator layers speed up aging procedure. Abrasion of the insulator speeds up thermal aging, if temperature exceeds normal temperature. An aged OIP has low DP. Materials which can decompose and solve in oil for this insulator include: water, carbon and carbon-dioxide. Thermal aging is performed at 120ºC for 30 days; it is recommended no to perform aging at temperatures above 125^0C because the insulator is decomposed [20]. Mathematically, aging can be described as follows.

$$A = f(P) \tag{21}$$

where P indicated insulator characteristics and A is aging. Amount of aging is also described as follows.

$$R_A = dA/dt \tag{22}$$

A simple solution for integrating the above equation assuming constant amplitude and considering employed stresses during time can be written as follows:

$$A = R_A (S_1, S_2 \dots S_n)\, t \tag{23}$$

$S_1, S_2 \dots S_n$ are applied stresses.

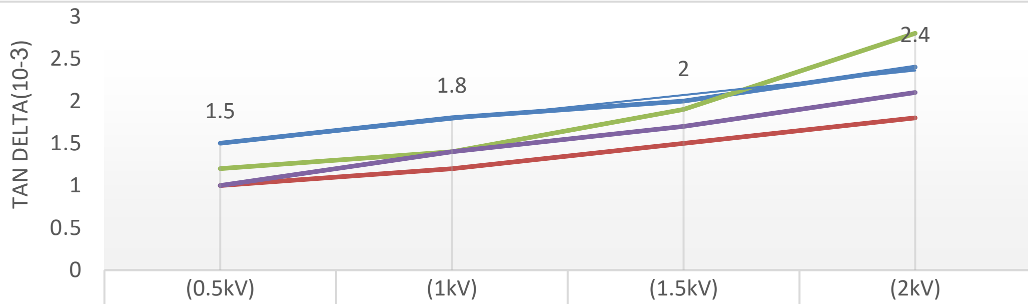
When aging time is defined as lifetime (L), the above equation can be described as follows [18, 19].

$$A_L = F(P_L) = R_A (S_1, S_2 \dots S_n)\, L \tag{24}$$

3. RESULTS AND DISCUSSION

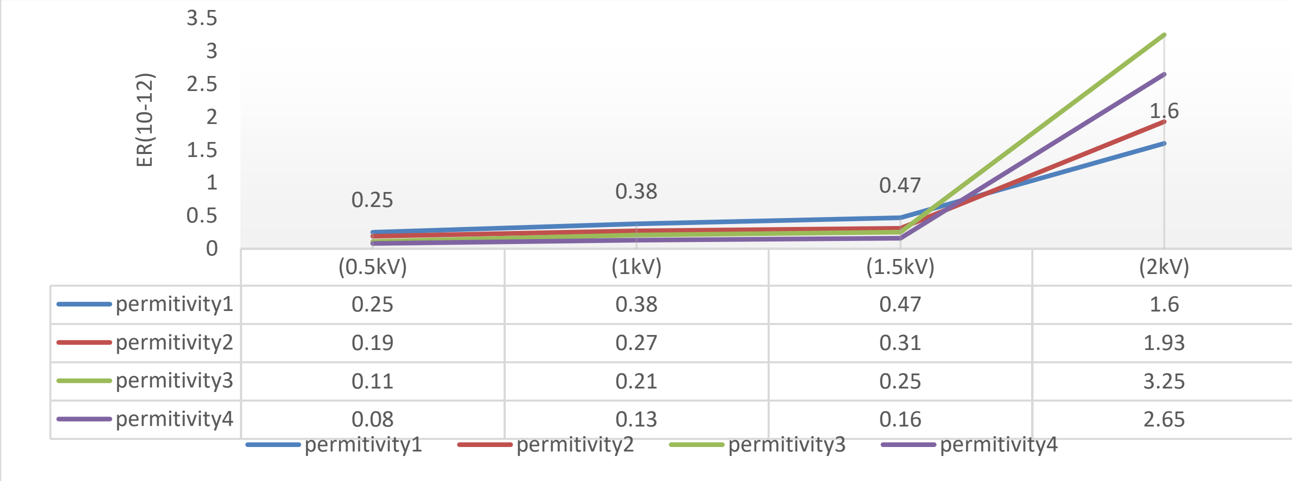
3.1 Dielectric Loss Coefficient

According to the experimental studies, tanδ is not only sensitive to voltage but also it is sensitive to moisture. The studied sample is a 4-layer paper impregnated with oil at 2 kV with tanδ of 2.8×10^{-3} which is reduced to 2.1×10^{-3} through dehumidification which is followed by decrease in dielectric loss. Disruptive material like moisture, carbon and sodium increase this factor; increasing tanδ above 0.5% is dangerous and the insulator should be replaced immediately. Indeed, tanδ is a way to find impurities in the insulator; when its amount exceeds eligible value at normal voltage and temperature, it can be inferred that there are a lot of impurities in the insulator. These impurities might include carbon, sodium or excess moisture which can cause problem at high voltages. It should be mentioned that these factors significantly depend on temperature, moisture and voltage. Following figures shown changes of dielectric loss Coefficient at different voltages for several insulators.



	(0.5kV)	(1kV)	(1.5kV)	(2kV)
1 dry paper	1.5	1.8	2	2.4
oil	1	1.2	1.5	1.8
4OIP layers	1.2	1.4	1.9	2.8
4 OIP layers demoisturised	1	1.4	1.7	2.1

Fig. 3. Tanδ in different voltages.



	(0.5kV)	(1kV)	(1.5kV)	(2kV)
permitivity1	0.25	0.38	0.47	1.6
permitivity2	0.19	0.27	0.31	1.93
permitivity3	0.11	0.21	0.25	3.25
permitivity4	0.08	0.13	0.16	2.65

Fig. 4. Electrical permittivity in different voltages.

3.2 Permittivity and Capacitance

Considering the studies conducted on capacitance, it was found out that capacitance of a dry paper is 56.7 pF while increasing number of layers to 4 and impregnating the paper with oil reduces capacitance to 28.85 pF; by dehumidifying the insulator, its capacitance reaches 23.5 PF. When insulator is delaminated or single-layer, it has one capacitance. An insulator should have a constant capacitance. By increasing moisture in OIP, its capacitance is also increased as a result of increasing permittivity. As mentioned above, dielectric losses are $W_d=2\pi fcu^2\tan\delta$; on the other hand, in ideal case $C_{1L}=C/n$, where C is capacitance of several layers of paper, C_{1L} is capacitance of one layer of paper and n is the number of layers and it can be said that effect of loss factor on dielectric loss is higher than capacitance. Another condition which can be found out using capacitance is short circuit between layers; this parameter is also sensitive to voltage and temperature. Usually, a bad insulator has high temperature dependency and its curve varies with temperature variations, significantly.

3.3 Phase Response Partial Discharge Analysis (PRPDA)

In partial discharge experiments, PD is first tested on oil and purpose of this section is to compare parameters obtained from PD particularly break-down voltage of different insulators. Amplitude of PD, number of iteration pulses and break-down voltage are obtained for different insulators under different conditions (aging, dehumidification). Experiments are performed Wavelet transform techniques were compared in different frequency bands for the correct distinction of partial discharge location [18]. Parameters obtained for maximum PD load and breakdown voltage are Q_{max} = 3.6Pc and $V_{breakdown}$ = 17.5 kV and number of PD iterations is 2372. Finally, the oil has been broken. It can be seen that maximum load is very low like noise and important result of this experiments is weak diffusion of PD in mineral oil and fast break of oil after diffusion of oil with low amplitude. Figure 8 shows PD changes between 0 to 360 degrees for mineral oil. Horizontal axis is 0 to 360 degrees and vertical axis indicates amplitude of PD pulse.

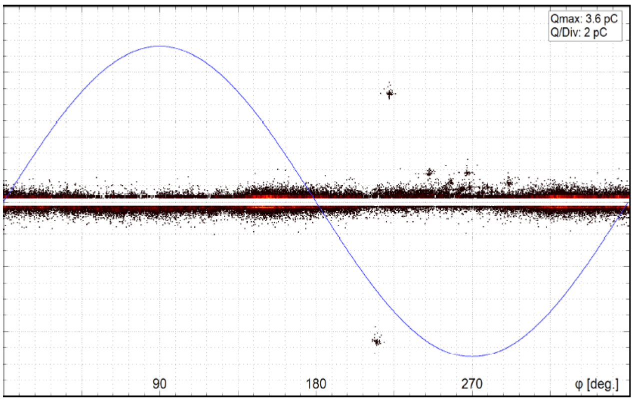


Fig. 5. Changes of PD for oil.

Next experiment is performed on dry paper. 4 layers of dry paper are put between electrodes and PD test is performed according to IEC60270 standard. It can be seen that break-down voltage of paper is much lower than that of oil and number of PD pulses which have resulted in break-down of the paper is reduced. Figure 8 shows changes of PD between 0 to 360 degrees for 4 layers of dry paper. In this case, maximum load is Q_{max}=2.8nC, break-down voltage is $V_{breakdown}$= 4.6 kV and number of PD pulses is 446. Comparing these insulators, it can be seen that break-down voltage of mineral oil is much higher than dry paper but PD amplitude might increase in some insulators like dry paper, poly-ethylene and rubber due to their type and permittivity. Glass and mica are also robust against PD. The following figure shows experiments performed on 4 layers of dry paper.

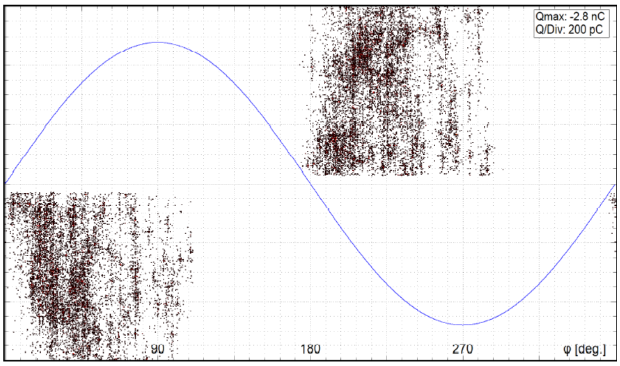


Fig. 6. Changes of PD for 4 layers of dry paper.

Considering main purpose of this paper which is to investigate OIP, OIP test is performed with 4 layers. Figure 10 shows experiment results. As can be seen, by increasing number of layers and insulator type, break-down voltage increased; in this case $V_{breakdown}$=32.5 kV, PD amplitude is 59.2 pC and number of PD iterations is 2385. It can be seen that PD in OIPs has higher diffusion compared to oil, but its endurance against break-down is higher and its maximum amplitude is lower than PD paper; so, this might be one of the reasons why this insulator is used in industry. Variations of PD in a complete cycle are shown in the following. Multi-layer paper is used because moisture absorption in multi-layer paper is slower than single-layer paper [16].

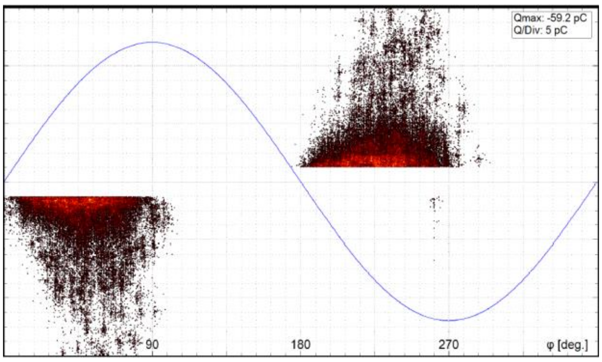


Fig. 7. Variations of PD for 4 layers of OIP.

High moisture level in transformers causes problems like limited maximum loading capacity and speeding up aging (IEEE Std. C 57-91 1995). At high moisture levels, OIP break-down decreases and at 8% moisture, break-down strength might decrease 50% [2]. In the initial studies on 4 layers of OIP, break-down voltage has increased 32.5 kV which has reached 50kV. Reducing moisture content of the insulator might increase lifetime of the insulator and prevent gradual degradation of the insulator. Its diagram in a 0 to 360-degree cycle is shown in the following figure.

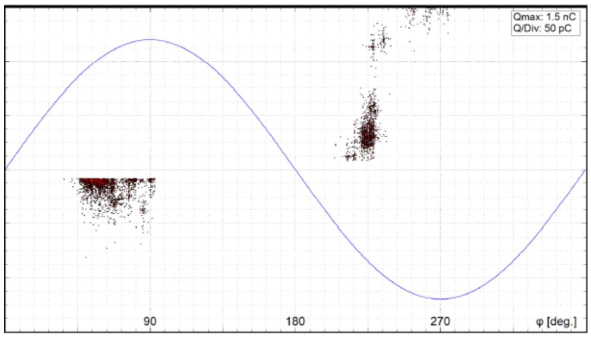


Fig. 8. PD changes for 3 layers of OIP after dehumidification.

Aging of all insulators should be considered which significantly reduces break-down voltage. By applying thermal aging on OIP insulator, its break-down voltage decreased to 30 kV despite dehumidification. Figure 10 shows variations of PD for 3-layers OIP after dehumidification. After 30 days thermal aging at 120ºC, was seen that PD amplitude has increased to 122Pc and its number of iterations has reached 3170 but break-down voltage has decreased to 30 kV. Figure 11 shows variations of PD for 8 layers of aged paper.

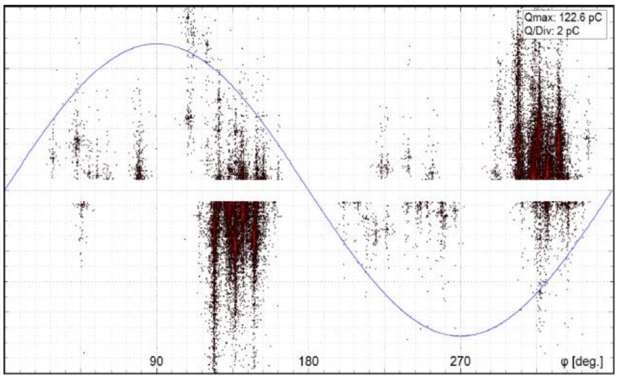


Fig. 9. Variations of PD for 8 layers of aged papers.

For deeply understand of these phenomena we can study PD in kind of voids (cylindrical, cubical) [22].

4. CONCLUSION

In different references PD is investigated but this paper is focused on PD magnitude and repetition in different voltage and different condition. As it showed OIP has higher break-down voltage and lower PD amplitude compared to dry paper and mineral oil. In addition, for example Ref 7 is focuses on high and medium voltage in OIP but we are investigated PD over dry paper, oil and OIP from low voltages to high voltages. By increasing number of paper layers, break-down voltage increased. By increasing number of layers and considering that layers are put in parallel, capacity is reduced. In other hand, loss factor is investigated, it was seen that tanδ increases by increasing voltage and temperature; but dielectric loss in dehumidified OIP is lower than OIP but in Ref 12 it just focuses on frequency responses. For example: in a 4-layer paper, break-down voltage is 4.6 kV and loss factor is 2.6×10^{-3} for 4-layer OIP, break-down voltage is 26.7 kV and loss factor is 1.8×10^{-3}. Therefore, reducing loss factor will reduce insulator capacitance, dielectric loss and temperature particularly at high voltages.

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