



Application of Polarization and Depolarization Current in High Voltage Insulator - A Review

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DOI: <https://doi.org/10.30880/ijie.2020.12.02.019>

Received 29 December 2019; Accepted 27 January 2020; Available online 28 February 2020

Abstract: Deterioration of cable insulator can be caused by many factors such as aging, fault and breakdown. These factors are caused by the presence of moisture, impurities and heat due to high temperatures in an insulator. The maintenance and replacement for insulation system in power cables, power transformers and electric machine stator are generally expensive and time consuming. Thus, the performance and ability of an insulator can be monitored through polarization and depolarization current (PDC). Polarization and depolarization current (PDC) is a non-destructive test method that is used to analyse many factors that affects the behaviour of an insulator in time domain. This paper presents the review on application of polarization and depolarization current test method on different type of insulator. The factors that affects the performance of different type of insulator will be discussed in this paper. Moreover, the theory of polarization and depolarization current will be explained in order to understand the behaviour of polarization and depolarization current curve when fault occurs. Last but not least, this paper will provide a review on the different type of factors that affects the performance of different types of insulation.

Keywords: insulator, polarization and depolarization, current, transformer, power cable, polymer composite

1. Introduction

Insulation testing method can be divided into destructive and non-destructive. Preventive measure of electronic equipment should be taken due to high cost of maintenance and replacement. Frequency Domain Spectroscopy (FDS) Return voltage measurement (RVM) and Polarization and Depolarization current (PDC) are non-destructive method used to monitor the dielectric response of power transformer insulation system (Sixth, Power, & Conference, 2003). PDC

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and RVM method is displayed in time domain whereas FDS is performed in frequency domain (Mishra, Haque, Baral, & Chakravorti, 2017). Nowadays, non-destructive insulation diagnosis by polarization depolarization current (PDC) testing method is one of the potential method used to observe the insulation performance (Saha, Purkait, & Müller, 2005). Advantage of polarization and depolarization current is it can differentiate two dielectric phenomena, polarization and conduction (Bhumiwat, 2010). Besides that, high voltage insulator can be tested at lowest voltage without any stress due to the ability of measuring current as low as 10^{-12} A (pA). RVM and FDS methods have limitations compared to PDC. RVM fails to diagnose when the length of the cable is too long whereas, FDS requires higher power capacity to operate in high frequency.

Journal has reported on the causes of failure in hydro generators which can be divided into few groups as shown in Fig. 1 (Brutsch, Tari, Frohlich, Weiers, & Vogelsang, 2008). Fig. 2 shows the source of insulation failure (Brutsch et al., 2008). It shows that insulator is the primary cause of the hydro generator failure. Failure of insulator can be classified into three phenomena which is breakdown, degradation and ageing. The degradation occurs in long term and failure occurs unexpectedly. However, the impact on dielectric strength for degradation is less compared to insulation failure (Notingher et al., 2009). Researcher (Charge, 2007) has rectified the difference in characteristic of breakdown, ageing and degradation of insulation system as shown in Fig. 3 and explanation is elaborated in Table 1.

PDC measurement is used to test the ageing extent of the cables (Wu et al., 2017). Moreover, polarization and depolarization (PDC) method is used to determine the moisture content and conductivity of insulation materials in transformer. Previous studies have reported that PDC measurement is also used to measure the aging and fault caused by power cables in power transmission system (Lii, Wui, & Reni, 2016). Most of PDC testing has been done mainly on transmission line which is power cable and transformer insulator. The factors that contributes to power cable failure is moisture, water tree, electrical treeing, partial discharge and pollution (Hernanz, Campayo Martín, Motrico Gogeoascoechea, & Zamora Belver, 2006). Whereas, the primary reason that causes insulation in transformer to fail is moisture and aging (Mousavi & Hekmati, 2019). This paper presents the application of polarization and depolarization in electrical power system eg. Transformer, power cable and polymer composite and factors that affects the polarization and depolarization current assessment.

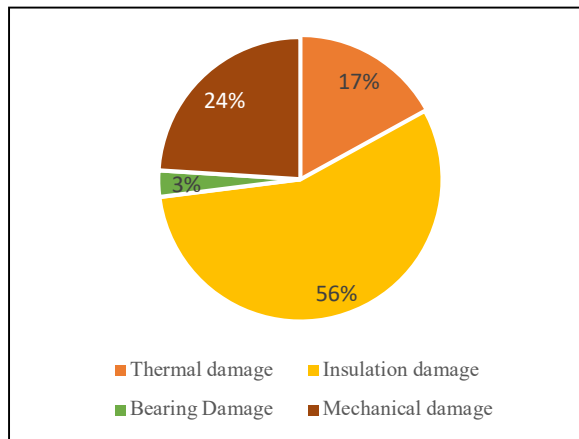


Fig. 1 - Type of damage on hydro generator

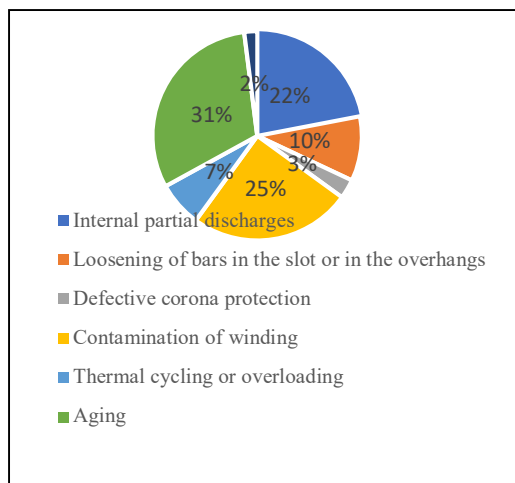


Fig. 2 - Causes of insulation failure

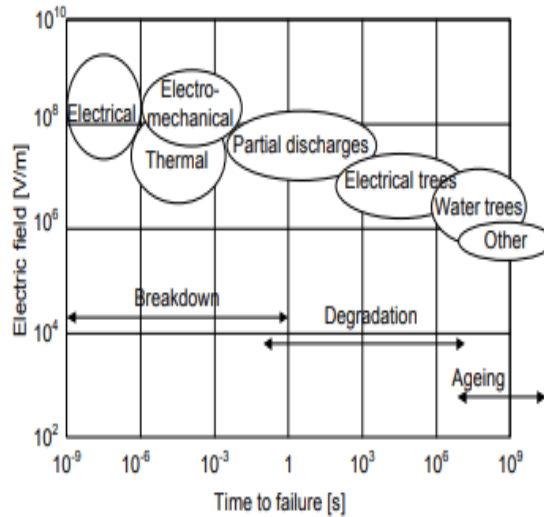


Fig. 3 - Categories of insulation failure

Table 1 - Classification of insulation

Process/ Characteristic	Breakdown	Degradation	Ageing
Speed	Fast: Occurs within 1s	Less than required service life: hours to years	Continuous process: entire service life
Area	Continuous filament: bridges electrodes	Occurs in weak parts: may form fractal structure	Assumed to occur throughout insulation
Size	>mm: dependent on energy of event	>µm: may form larger structure	>nm: molecular scale
Indication	Direct observation (normally by eye-hole through insulation)	Observable directly: may require microscopic or chemical techniques	Difficult to observe: may even be difficult to prove existence
Outcome	Catastrophic: insulation cannot be used afterwards	Leads to breakdown: reduces breakdown voltage	May lead to degradation: may not reduce breakdown voltage
Examples	Mixed mode Thermal Intrinsic Electromechanical Avalanche	Partial discharge Water tress Electrical trees	Bond scission Nano-voids Non-electrical changes (oxidation) Trap formation

2. Theory of Polarization and Depolarization Current (PDC)

The polarization in a solid dielectric material can be seen during presence of electric field. The polarization that is found in every solid material are orientation polarization, induced polarization, interfacial/boundary polarization and electron polarization. Induced and orientation polarization has response time is approximately 10^{-2} s while electron polarization is around 10^{-14} s.

Interfacial/boundary polarization exist when there is two different solid material between electrodes. In addition, the response time for interfacial/boundary polarization is the shortest compare to other polarization which is 10^{-2} s to 10^4 s (Zhao et al., 2016). Polarization and depolarization current of an object is measure by applying DC voltage across a test object under time domain. Fig. 4 (a) and (b) shows the basic PDC measuring circuit and waveform produced from polarization and depolarization current (N. A.M. Jamail, Piah, Muhamad, & Kamarudin, 2014; Kasri et al., 2013; Saha et al., 2005; Wu et al., 2017; Zainir et al., 2013). According to theory, the polarization current, I_{pd} as shown in Fig. 4 (a) and (b) is measured by applying charging voltage U_0 across test object for a period of t_p . Polarization current vary according to two conditions; conductivity of the test object and activation that occurs within test object of different polarization process. The dielectric response function ($f(t)$), relative permittivity (ϵ_r) and conductivity (σ) represents the test object dielectric material as it consists of one or several dielectric material (N. A.M. Jamail et al., 2013). The polarization current in a test object can be expressed as (Fofana, Hemmatjou, & Meghnefi, 2011; N. A.M. Jamail, Piah, Muhamad, & Kamarudin, 2014; N. A.M. Jamail et al., 2013; Nor Akmal Mohd Jamail et al., 2013; Kuffel, Zaengl, & Kuffel, 2000; Muhamad, Phung, & Blackburn, 2009; Talib, Muhamad, Malek, & Jamail, 2013; Zainir et al., 2013):

$$I_p(t) = C_o U \left[\frac{\sigma}{\epsilon_r} \right] + f(t) \quad (1)$$

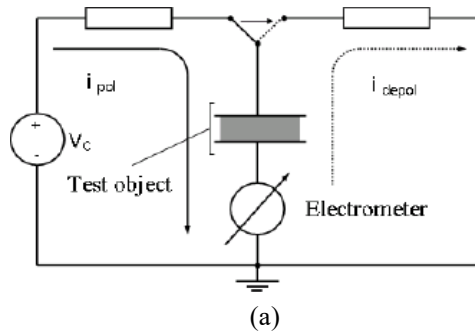
The depolarization current, i_d is measured after the test object is short circuited. As mention, depolarization current is the activation that occurs in polarization that gives rise in opposite direction as same period as polarization current. The negative voltage U_c produced at t_c is due to the sudden voltage drop to zero as stated by the superposition principle (Fofana et al., 2011). The depolarization current of test object can be expressed as (Fofana et al., 2011; N. A.M. Jamail, Piah, Muhamad, & Kamarudin, 2014; N. A.M. Jamail et al., 2013; Nor Akmal Mohd Jamail et al., 2013; Kuffel et al., 2000; Muhamad et al., 2009; Saha, 2003; Setayeshmehr et al., 2008; Talib et al., 2013; Zainir et al., 2013):

$$I_d(t) = [f(t) - f(t + t_c)] \quad (2)$$

Where U_0 is the step voltage (charging voltage), C_o is geometrical capacitance of the test object and T_c is charging time of test object.

The DC conductivity (σ), of the test object can be obtained from the measurement of polarization and depolarization current. The equation (1) and (2) is combined to express the dc conductivity after the test object is being charged for a period of time with the aim of $f(t + t_c) \cong 0$ (Ekanayake, Saha, Member, Ma, & Ieee, 2010; N. A.M. Jamail, Piah, Muhamad, & Kamarudin, 2014; N. A.M. Jamail et al., 2013; Kasri et al., 2013):

$$\sigma \approx \frac{\epsilon_r}{C_o U_o} [i_p(t) - i_d(t)] \quad (3)$$



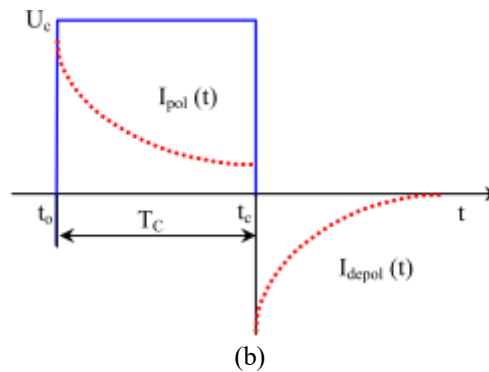


Fig. 4 - (a) Test arrangement for PDC measuring technique; (b) Principle of polarization and depolarization

3. Application of Polarization and Depolarization Current Method in Different Type of Insulator

3.1 Transformer

Polarization and depolarization current (PDC) method for the assessment of insulator performance has gained attention over the decades due to non-destructive testing method. The failure in an insulation system of power cable and power transformer has been diagnosed using PDC technique. Researcher (Fofana et al., 2011) has reported the effect of thermal transient on the PDC measurement of oil-paper insulation. Despite the influence of various parameters such as moisture content and aging condition, the polarization and depolarization current of the oil-paper insulation increases when the temperature increase. Talib et al. studies the effect of dielectric response and conductivity of mineral insulating oil which is caused by overheating condition of in service transformer (Talib et al., 2013). The mineral insulating oil possesses higher polarization and depolarization current compared to normal oil. However, the conductivity of the overheating mineral oil was higher compared to normal oil. This is caused by the higher carrier mobility form when the hydrocarbon chain of mineral insulating oil breaks down.

Besides that, study on the moisture content, aging and temperature of oil impregnated pressboard of power transformer was presented by researcher (Setayeshmehr et al., 2008). The polarization and depolarization current increase as the pressboard was tested under 500h to 2000h which proves that ageing of pressboard has an effect of PDC current. Table 2 shows the influence of ageing time on the conductivity of oil and paper (Setayeshmehr et al., 2008).

Table 2 - Conductivity of Oil and paper based on ageing time

Ageing period(h)	σ_{oil} (fS/m)	σ_{paper} (fS/m)
500	234.6	58.4
2000	723.4	78.7

Fig. 5 demonstrate the magnitude of polarization and depolarization current increases when the temperature of transformer increase provided the temperature of insulating oil is at 20°C (Setayeshmehr et al., 2008). This is caused by the linearity loss changes in dipole moments. Fig. 6 shows the behaviour of polarization and depolarization current with different moisture content in insulating oil under constant transformer temperature (Setayeshmehr et al., 2008). The conductivity for both oil and paper increases as the temperature and moisture.

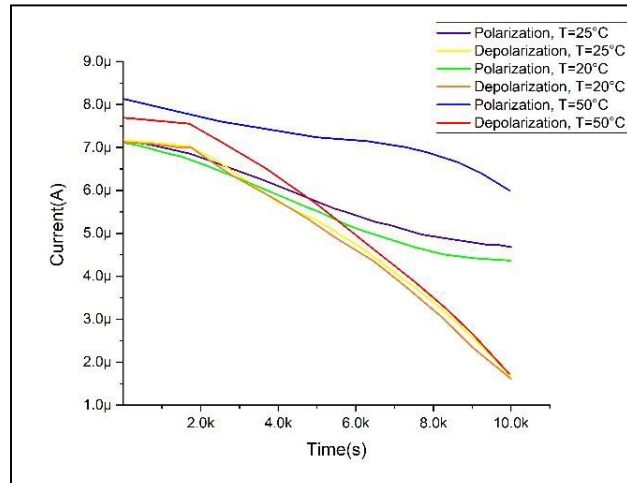


Fig. 5 - Polarization and depolarization current (PDC) of insulating oil under three different transformer temperature with 20ppm moisture content

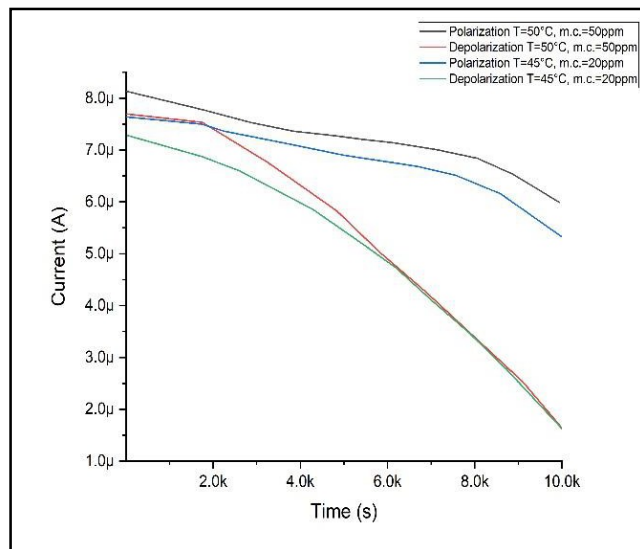


Fig. 6 - Polarization and depolarization current (PDC) of insulating oil under different moisture content with 20°C transformer temperature

Researcher (Zhou, Zhang, Zhang, & Zhang, 2016) has also reported on the aging condition of oil paper insulation using PDC method. It is also shown that the polarization and depolarization current increase with longer aging time. Fig. 7 and Fig. 8 displays the behaviour of polarization and depolarization current of oil impregnated insulation paper with varied aging period (Zhou et al., 2016). The polarization and depolarization current of thermally aged oil impregnated kraft paper was studied (Raj et al., 2018). The sample was heated under 140°C with interval of 50 hours until 150 hours. The result shows that polarization and depolarization current increase with increase in aging time. On top of that, the conductivity of the sample increases with aging time.

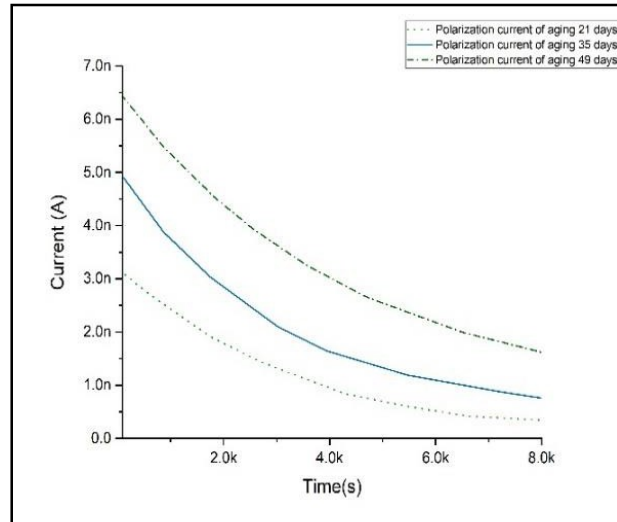


Fig. 7 - Polarization current of oil impregnated insulation paper with varied aging period

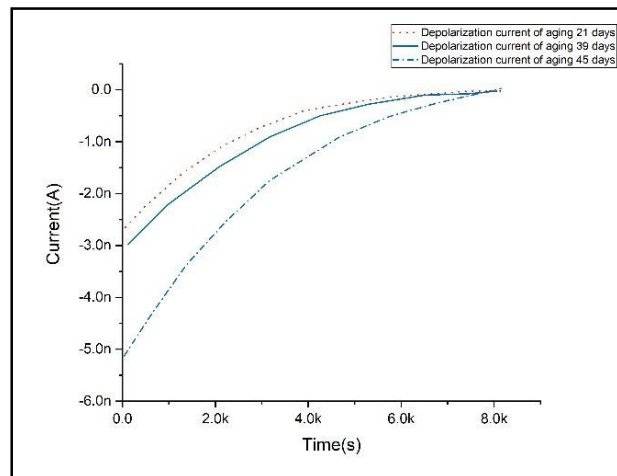


Fig. 8 - Depolarization current of oil impregnated insulation paper with varied aging period

Other than aging time, moisture content and temperature, journal has reported on the effect of conductivity and polarization and depolarization current due to formation of copper sulphide in paper-oil insulation (Flora & Rajan, 2016). The polarization and depolarization current characteristic were observed in increasing layer of paper by varying the temperature. Formation of copper sulphide due to the corrosive sulphur in mineral oil increases the magnitude of polarization and depolarization current. Besides that, the polarization and depolarization current increases as the number of contaminated Cu_2S paper layers increase. This study also proved that the conductivity of the paper and oil increase with increase in thickness and temperature. Fig. 9 and Fig. 10 shows the polarization and depolarization current of contaminated Cu_2S and clean paper insulation under $25^\circ C$.

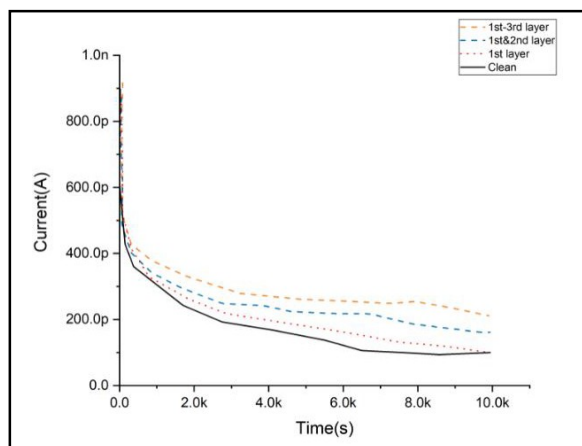


Fig. 9 - Polarization current of clean and Cu_2S contaminated sample under $25^\circ C$

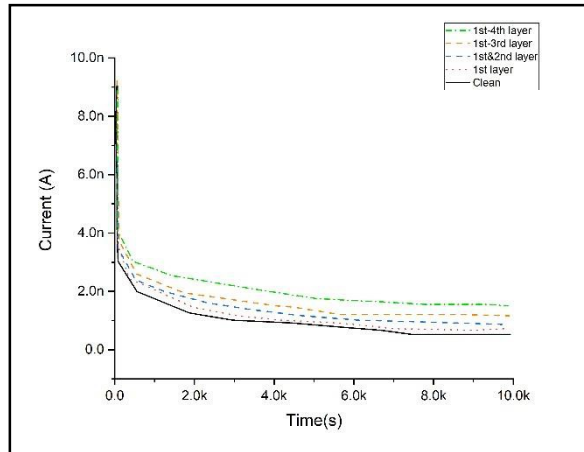


Fig. 10 - Depolarization current of clean and Cu₂S contaminated sample under 25°C

Fig. 11 and Fig. 12 shows the polarization and depolarization current of contaminated Cu₂S and clean paper insulation under 90°C.

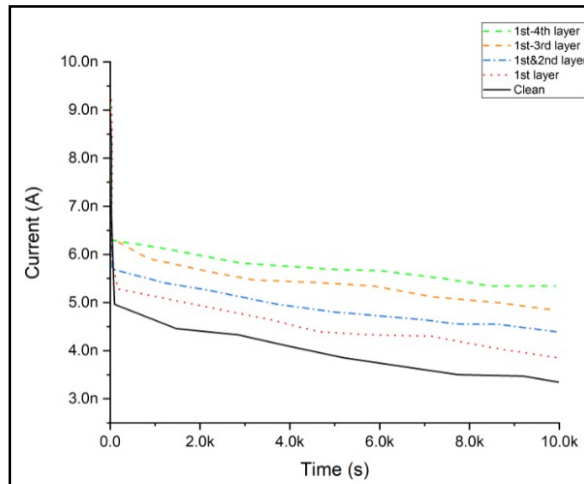


Fig. 11 - Polarization current of clean and Cu₂S contaminated sample under 90°C

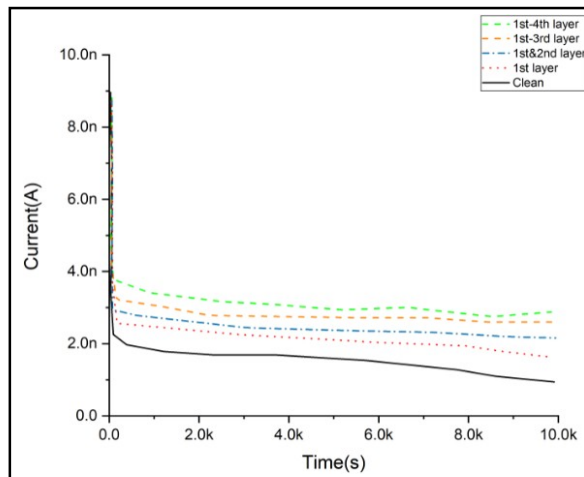


Fig. 12 - Depolarization current of clean and Cu₂S contaminated sample under 90°C

The growing interest on PDC pattern of biodegradable oil insulated transformer was studied by researcher (Muhamad et al., 2009). This journal demonstrates the conductivity and dielectric response of mineral oil and biodegradable oil under different moisture conditions such as wet, dry and normal. High dielectric strength of biodegradable oil has lowest conductivity under three different condition although it has highest moisture content compared to mineral oil. Highest conductivity for both oil was reported under wet condition. Journal (Patra & Burjupati, 2018) reported on the moisture

content and geometrical parameter that affects the dielectric response of pressboard (OIPB) and natural ester oil impregnated paper (OIP) using polarization and depolarization current. Polarization and depolarization current for both OIP and OIPB is higher with higher percentage of moisture content. Whereas the geometrical parameter of the sample was varied with different thickness for both OIP and OIPB. It shows that as the sample thickness increases, the polarization and depolarization current decrease.

3.2 Power Cable

Power cable used as overhead line or underground has the tendency to polarize regardless of insulation condition and voltage rating that leads to deterioration of material. Insulation assessment of power cables that implements PDC method has been introduced since 2002 (Kachler, Alff, Houhanessian, & Zaegl, 2000). Journal (Bhumiwat, 2010) reported on PDC measurement of aged XLPE cable, aged oil filled cable, condition after free water and presence of moisture due to cracks. Table 3 reported on the problems that occurs in power cable (Bhumiwat, 2010). Study on polarization and depolarization current of 10kV XLPE aged cable was presented in journal (Ye et al., 2015). Approach in improving the accuracy of pdc testing was reported. Aging of XLPE cables has been studied using PDC method by researcher (Zhao et al., 2016). The cable is divided into different aging period for 40 days with 10 days interval. It is found that the magnitude of polarization and depolarization current increase with aging period.

Table 3 - Classification of problems in power cable

Polarization	Thermal aging by-products
	Oxidation by-products
	Chemical by-product from XLPE manufacturer
	Water trees in XLPE
	Aging molecules at interfaces
	Moisture in cable (adsorbed state)
Conduction	Free water in XLPE cable
	Tracking or leakage path
	Free water in cable joint
	Surface humidity
	Conductive contaminants
	Impurities
	Carbon dust or metal debris

3.3 Polymer Composite

The effect of nanofillers on the polarization and depolarization current of polymer composite for high voltage application was studied by researcher (N. A.M. Jamail, Piah, Muhamad, Salam, et al., 2014). It is proven that 5 wt% of SiO_2 is the optimum percentage of nanofiller with highest resistivity owing to the lowest polarization current recorded. Furthermore, the conductivity of the composite was low at 1-5 wt% of SiO_2 nanofiller. A journal reported on the condition of polarization and depolarization current involving polymeric materials for high voltage application (Kumar, Haque, Ghosh, Chatterjee, & Dalai, 2017). Polymethylate (PMMA), PTFE, Polypropylene (PP) and High-Density Polyethylene (HDPE) were used under different temperature to observe the polarization and depolarization current. It shows that the polarization and depolarization current vary from temperature and material properties. Apart from this, the presence, size and quantity of void in a polymer based insulation that affects the conductivity was investigated based on PDC method (Bashir & Equipment, 2016). The bigger the size of void and larger number of voids increases the polarization and depolarization current of the sample. Void allows more current to flow in the sample because the presence of void initially lowers the dielectric strength of the insulation as a result of low permittivity of void. Thus, the conductivity of the sample is the highest with biggest void size. On the other hand, researcher (Veena, Renukappa, Meghala, Ranganathaiah, & Rajan, 2014) has reported on the effect of nanofiller such as SiO_2 , Al_2O_3 and ZnO on polarization and depolarization current by varying temperature, electrification time and electrode material (Patel, Kishorekumar, & Gupta, 2009). The journal reported that SiO_2 has the highest polarization and depolarization current compared to other two nanofiller. Investigation on the relationship of polarization and depolarization current of epoxy resin with In_2O_3 doped 15% Sn (ITO) nanocomposite was reported by researcher (Bouzidi, Jilani, Omri, & Guermazia, 2015). As a result, the polarization and depolarization current of nano-ITO/epoxy was observed the highest at 20.8kV/mm compared to clean epoxy.

4. Conclusion

In a nutshell, high voltage insulation condition can be monitored through PDC measurements. This paper reviewed and displays comparison results of polarization and depolarization current for transformer, power cable and polymer composite. Besides that, the factors that contribute to insulations failures are breakdown, ageing and degradation. Liquid

and solid insulation are subjected to failure caused by aging, presence of moisture, contamination and overheating condition. From the results shown, it can be concluded that the polarization and depolarization current results can be used to determine the performance of solid and liquid insulations. The insulation that is subjected to failure as listed above displays higher polarization and depolarization current. The result obtain from PDC graph are strongly influenced by the insulation conductivity. Higher values of conductivity of insulation are caused by higher polarization and depolarization currents. Evaluation of high voltage insulation condition can be studied by the PDC graph pattern.

Acknowledgement

The authors gratefully acknowledge the Research Management Centre of Universiti Tun Hussein Onn Malaysia under grant GPPS vote H025, Grant Tier 1 vote H090, Kvolt Focus Group Team and High Voltage Laboratory UTHM for the equipment support.

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