Journal of Engineering Science and Technology Review 15 (SI) (2022) 41 - 48
Special Issue in honor of Prof. T. Tanaka

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Review Article

A Review of Insulation Diagnostic Technique for Assessing the Health Condition of Power Transformer and Cable

Mohd Aizam Talib*, Mohd Basri Abd Ghani and Huzainie Shafie Abd Halim

TNB Labs Sdn. Bhd, Kajang, Malaysia

Received 15 December 2021; Accepted 26 February 2022

Abstract

Transformer and cable are among the critical components in electrical distribution substation. Monitoring the health condition of these asset will assure the continuous of electric supply and reduce its potential failure. In the current market driven, conventional time-based maintenance and replacement are no longer feasible. Condition based maintenance and online condition monitoring are gaining importance recently. There are variety of diagnostic methods have been developed to assess the condition of in-service power transformer and cable. Some of the techniques have gained outstanding importance to the utility professionals. This paper reviewed the insulation diagnostic technique used for assessing the health condition of transformer and cable. The case studies on detecting the incipient faults and preventing transformer and cable failure were also presented.

Keywords: cable, diagnostic assessment, transformer

1. Introduction

Power transformer and cable are critical components in power system network and plays an important role in distributing the electricity from generation plant to end customer. Many of these installed assets are approaching of their design life and power utilities are concerned about its reliability and availability. Insulation degradation is one of the factors that cause failure of transformer and cable. Practicing engineers currently use a number of diagnostic techniques to assess the insulation condition of these aged assets. Some are considered as routine testing while others are classified as advanced diagnostic testing and require an experience engineers and technical expert for data interpretation and analysis [1, 2].

The insulation system in transformer made up from cellulose paper and hydrocarbon mineral oil. A paper wrapped around each part of transformer winding make it electrically insulated and oil perform a function as insulation medium and dissipated heat from winding and core to tank wall [3]. Increasing of temperature due to overloading, presence of moisture caused by leaks and high concentration of oxygen deteriorates the insulation system and reduce transformer lifetime [4].

Transformer failure can be due to incipient fault or active fault. At the initial stage, the incipient fault may not severe but it progressively develops into serious and active fault. The degradation of paper and oil insulation, high oxidation rate and contamination or excessive overheating are the main causes of these incipient faults. The breakdown of hydrocarbon chain and cellulose polymer generated significant of gases and dissolved in oil. The identification of these gases and its quantity allow determination of fault types and could be very useful for any predictive maintenance [5]. The active faults are the one that appear on the components of transformer; winding, magnetic circuit, bushing and load tap changer. It may be a turn-to-turn shorts fault or turn-to-earth shorts fault, shorted lamination and mechanical damage. These faults always result in high currents and overheating leading to insulation breakdown and permanent damage to transformer.

The active fault may detected using electrical, thermal and mechanical diagnostic methods. Some of the techniques are conventional routine testing and others are considered as advance diagnostic testing. Analysis of basic insulation parameters such as resistance, capacitance and loss factor are the most common diagnostic testing of power transformer. The analysis of insulating parameters by time and frequency domain response allows further assessment on the effect of moisture, contamination and ageing to the insulation degradation. The adverse effect of short circuit forces which damage coils, leads, magnetic circuit and tap changer could be detected by analysing the transfer function signal of the transformer winding [6,7].

The recent advances in sensor technology, signal processing and high-speed computing shows acoustic emission based analysis are now become important diagnostic tool for monitoring of faults in power transformer. Loosening of core clamping, vibration in the structure assembly and partial discharge in winding insulation are the potential source of vibration in transformer tank [8].

Conversely, power cable relatively less complex components in comparison to transformer. In general, there are two types of main insulation used for power cable either paper or polymeric based insulation material. Another important factor needs to be considered for reliability of cable is accessories used in the cable system. Large percentage of power cable failure is contributed by the cable joint and termination [9].

There are many reasons why a cable may fail in service, with the failure at its most serious resulting in fire or other serious fault. Similarly, the service life of a cable can be significantly reduced if it has been expected to operate outside of the optimal operating conditions it was designed for and

*E-mail address: aizam.talib@tnb.com.my
ISSN: 1791-2377
doi:10.25103/jestr.147.07

caused the ageing of insulation system. This process usually results in embrittlement, cracking and eventual failure of the insulating and sheathing materials, exposing the conductor and risking a potential short circuit, a likely cause of electrical fire.

Thus, it is critically important to understand the mechanisms of failure and assess the level of performance using diagnostic testing. The excessive electrical stress or bulk deterioration of the insulation can occur as a result of several factors. Manufacturing imperfection or poor workmanship can cause contaminant or void in insulation and tend to increase the local stress leading to either initial failure or higher rates of aging [10]. The cable overheating due to excessive conductor current or mechanical damage tends to reduce the dielectric strength. The impact can be restricted to short lengths if the adverse thermal environment or mechanical stress is localized. Breaks in seals or metallic sheaths cause water ingress in cable and tend to reduce the dielectric strength and increase the stress in the area surrounding the moisture [11-13].

This paper reviewed the diagnostic and monitoring techniques practically used by power utilities in assessing the health status of in-service power transformer and cables. The successful of those techniques for early fault detection was also presented.

2. Diagnostic methods and analysis of transformers

Using suitable diagnostic techniques may help the engineers to identify the adverse effects of insulation degradation, short circuit currents, overvoltages or overcurrent which may cause the failure of transformers. Modern transformer diagnostic methods are broadly categorized into three parts: chemical analysis, electrical analysis and mechanical analysis.

2.1 Chemical Diagnostic Methods

The decomposition of carbon-hydrogen and carbon-carbon bonds of insulating oil due to abnormal overheating and internal faults will released small quantities of gases. The amounts and types of gases are indicative of the severity and type of fault occurring in the transformer. Analysis of gases dissolved in oil is valuable in predictive and preventive maintenance program.

Low intensity discharge such as partial discharge of cold plasma generated mainly of hydrogen (H_2) and less quantities of methane (CH_4) and ethane (C_2H_6). The decomposition of mineral oil from 100 °C to 500 °C relatively produces high quantities of methane (CH_4) and ethane (C_2H_6) and traceable of ethylene (C_2H_4). As the intensity of electrical discharge increases and reached arcing that produces temperatures from 1000 °C to 3000 °C, the quantities of acetylene (C_2H_2) become pronounces [14]. The relative of gases concentration dissolved in oil as a function of temperature and its fault type is illustrated in Fig 1.

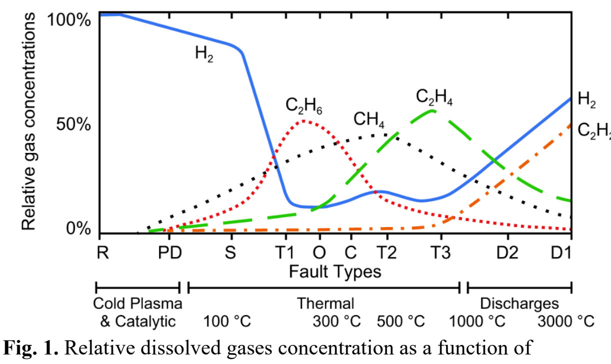

Fig. 1. Relative dissolved gases concentration as a function of temperature and fault type in insulating oil [14].

Various diagnostics interpretation methods have been developed and used by utilities to analyse the gases dissolved in oil and assess the transformer condition. These interpretation schemes are generally based on defined principles such as gas concentrations, key gases, gas ratios, and graphical representations. The common schemes used are Key Gas Analysis, Dornenburg and Rogers Ratio Methods, IEC Ratio and Duval Triangle and was mentioned in IEEE C57.104 and IEC 60599.

Key Gas Analysis relates the presence and percentage of gases into several fault types. The relationship of key gases and fault types are summarized as follows: (i) H2: corona, (ii) CH_4 and C_2H_6: low temperature overheating of oil, (iii) C_2H_4: high temperature overheating of oil, (iv) C_2H_2: arcing, (v) CO and CO_2: overheating of cellulose insulation [14, 15].

The Doernenburg ratio method used four gas ratios; CH_4/H_2, C_2H_2/C_2H_4, C_2H_2/CH_4 and C_2H_6/C_2H_2 to identify the incipient faults in transformer as corona discharge, thermal and arcing. The fault gas levels must be exceeded specified baseline values, to ascertain whether there really is a problem with the transformer. If at least one of the gas concentrations for H_2, CH_4, C_2H_2 and C_2H_4 exceeds twice the limit values, then the ratio is considered valid. Finally, if all four succeeding ratios for a specific fault type fall within the predetermined values, the diagnosis is confirmed [16].

The Roger ratio [17] use similar key gases as Doernenburg ratio but with different gas ratio composition. Faults in transformer are diagnosed via a simple coding scheme based on ranges of four gas ratios; CH_4/H_2, C_2H_6/CH_4, C_2H_4/C_2H_6 and C_2H_2/C_2H_4. The detectable condition of transformer are normal ageing, partial discharge with or without tracking, and electrical and thermal faults of varying severity.

The Duval Triangle Method [18-20] uses values of only three gases CH_4, C_2H_4 and C_2H_2 and transformed the gases co-ordinates into triangular map. This triangular plot has each side of the triangle representing a 0 to 100% value of each of the three gases. Plotting of the results then places the data somewhere within the triangle. The area within the triangle is then divided into seven separate regions corresponding to different fault classifications as illustrated in Fig 2.

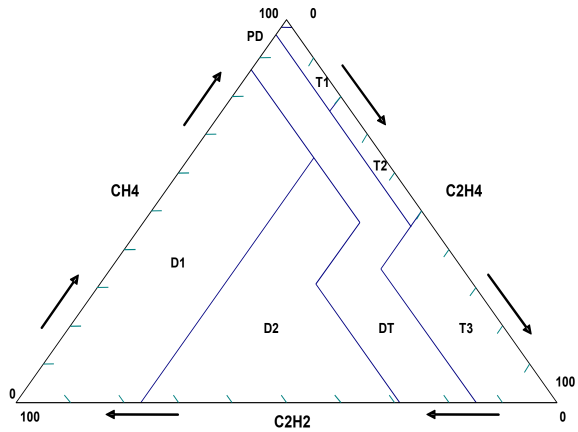

Fig. 2. Duval triangle method [18].

The other important parameters in chemical diagnostic method is furans analysis. It is by-product generated from cellulose chain polymer and glucose monomer caused by pyrolysis, oxidative and hydrolytic degradation of paper insulation [21]. Study by Stebbins [22] found that paper ageing leads to the production of five types of furanic compounds: 2-furfural (2-FAL), 5-methyl-2-furfural (5-MEF), 5-hydroxymethyl-2-furfural (5-HMF), 2-acetylfuran (2-ACF), and 2-furfurylalcohol (2-FOL). The 2-FAL also referred to as 2-furaldehyde can remain stable for years and therefore widely used to predict the paper DP value.

2.2 Electrical Diagnostic Methods

The presence of moisture and oxygen degraded the insulation system and the process are accelerated by thermal and electrical stresses which eventually reduce the transformer life. Monitoring the moisture content is therefore are very important to assess the ageing level particularly for paper insulation. In recent years, modern electrical diagnostic methods have been developed to correlate and estimate the moisture content in paper insulation based on time and frequency domain of dielectric response measurement [23, 24].

In frequency dielectric spectroscopy, the dissipation factor value is measured at wide range frequency from 0.01 mHz to 1kHz. It is made by calculating the sample impedance at each frequency step by knowing the voltage and measuring the current. The value of dissipation factor changes according to different conductivity and moisture in the insulation [25]. According to [26], the frequency range of 1000-10 Hz is dominated by the cellulose insulation. Oil conductivity causes the steep slope at 1- 0.01 Hz. The insulation geometry; ratio of oil to pressboard determines the local maximum at 0.003 Hz. Finally, the properties of the cellulose appear again at the frequencies below 0.0005 Hz, here reflecting moisture, acids and other conductive ageing by-products. The response of dielectric in frequency domain is depicted as in Fig 3.

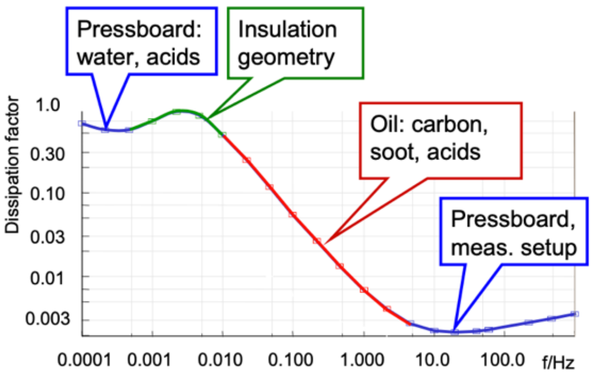

Fig. 3. Dielectric response of insulation in frequency domain [26].

On the other hand, time domain response measured the polarization and depolarization current during charging and discharging of insulation material. In this technique, a ripple free dc voltage was applied for a specific duration, i.e. 10000s. The current arising from the activation of the polarization process is corresponding to different insulating materials and conductivity of the test object [27,28]. Then, the voltage is removed and the object is short-circuited. The previously activated polarization process now exponentially discharge the current in the opposite direction. The value of current is being judged by dc conductivity, higher the value higher will be the moisture in the insulation and vice versa [29]. Fig 4 shows the dielectric response in time domain method.

2.3 Mechanical Diagnostic Methods

A very large electromagnetic forces arising from over-currents or over-voltages during through faults or tap-changer faults can caused winding deformation eventually will results in damaging the inter-turn insulation and shorted turns, which means the immediate end of transformer life [30]. Thus, there is increasing interest in detecting winding deformation damage prior to failure under further short circuits.

Frequency Response Analysis (FRA) is an effective diagnostic tool used for finding out any possible winding displacement or mechanical deterioration inside the transformer. This method relies on the fact that winding in transformer can be represented as a complex network of capacitance, resistance, self-inductance and mutual inductance components. When a fault occurs in the winding, the values of these parameters are altered and hence the frequency response from the winding will also change accordingly [31]. The measurement involves of injecting a signal of known frequency into one end of the winding and measuring the response at the other end and later its transfer function is calculated, as shown in Fig 5. The FRA test result displays a graph of frequency versus magnitude and phase for each of the tested winding structures.

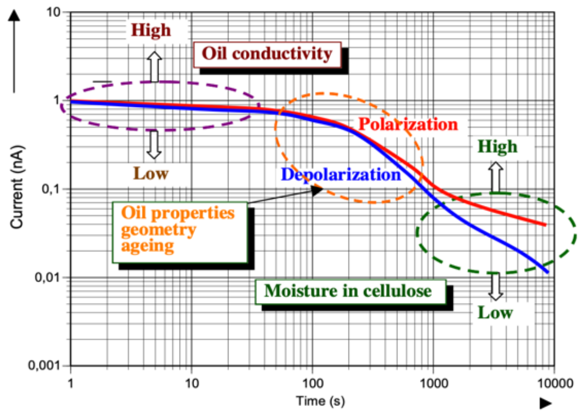

Fig. 4. Dielectric response of insulation in time domain [29].

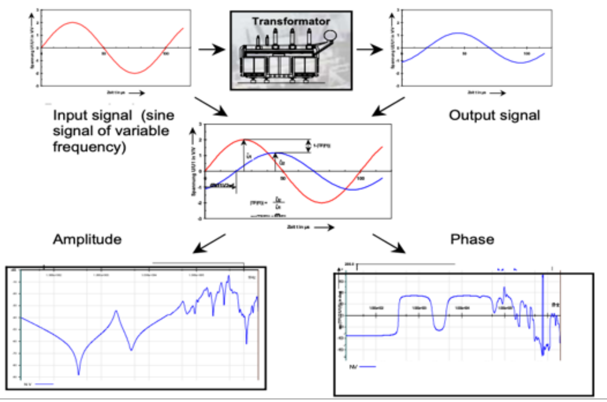

Fig. 5. Principle of FRA measurement[31].

The interpretation of FRA response can be realized by examining the individual responses of the various regions and shapes of the response curve. At low frequency range below 2 kHz (region A), the frequency response begins with the decreasing magnitude due to the magnetizing inductance of the core and bulk capacitance of the transformer. The response at intermediate frequency range between 2 kHz to 20 kHz (region B) is affected by coupling between windings, which depends significantly on the arrangement and connections of the windings. In high frequency region between 20 kHz and 1 MHz (region C), the response is determined by the winding leakage inductances together with the winding series and ground capacitances. Beyond the frequency of 1MHz (region D), the trend of the frequency response is irregular and complex, influenced by the tap leads and the measurement earthing leads [32, 33]. The four regions of frequency response are illustrated in Fig 6.

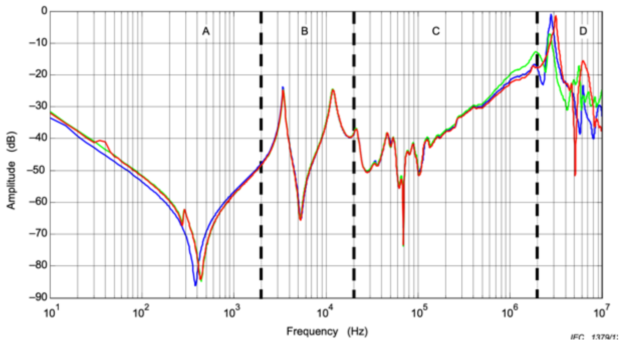

Fig. 6. Regions of FRA response [32].

3. Diagnostic method and analysis of cables

Over the years, several testing methods have been developed that can provide a better indication on the integrity of cables, joints and terminations. The main objectives are to evaluate and locate insulation degradation that will cause cable or accessory failure. In most cases, non-destructive testing are widely used for monitoring the health status of power cable whereby trending of the test results will be monitored closely thus giving more information compared to spot test reading [34]

3.1 Tangent Delta Test at Different Voltage and Frequency

Tangent delta or dissipation factor is a diagnostic method to determine the quality of the cable insulation. Theoretically, cable approaches the properties of perfect capacitor provided that the insulation is free from defect. As represented in tangent delta model as shown in Fig 7, the voltage and current are phase shifted by 90º. If there is an impurity or defects in insulation, the resistance of the cable will decrease resulting in an increase in resistive current. Therefore, it will no longer be a perfect capacitor and the angle of voltage and current will be less than 90º. This angle is called delta (δ) or loss angle and will indicate the level of resistance in the insulation. The greater the angle means the worse the cable is [35].

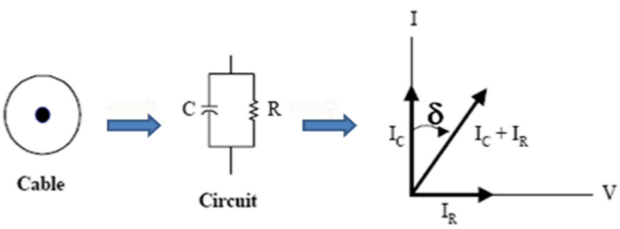

Fig. 7. Tangent delta model representation.

Tangent delta typically measured by varying the voltage or frequency. The first is known as tip-up test and later is called frequency dielectric spectroscopy. If the insulation of the cable is perfect, the tan delta will not change as applied voltage is increased. If the cable has experienced aging, defective parts, water tree contamination, thus changing the capacitive nature of the insulation, then the tangent delta will be higher at the higher voltages [36]. The increase in loss angle with the increasing voltage indicates high resistive current element in the insulation as shown in Fig 8.

Dielectric spectroscopy is a measurement of tan delta over a range of voltage and frequency. By varying the frequency and the voltage, the response can provide more information about the insulation of power cable [37, 38]. The tangent delta below 1Hz is sensitive to degradation due to water trees in XLPE cables. As frequency increases, the tangent delta will decrease. When the voltage is varied, the tangent delta remains relatively the same, thus indicating the good condition of cable as shown in Fig 9.

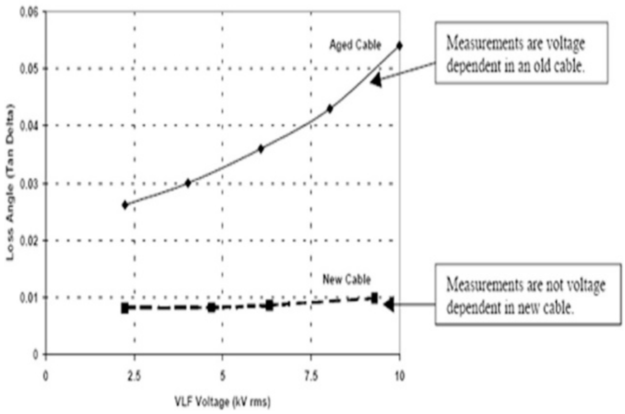

Fig. 8. New and Aged Medium voltage XLPE cable [36].

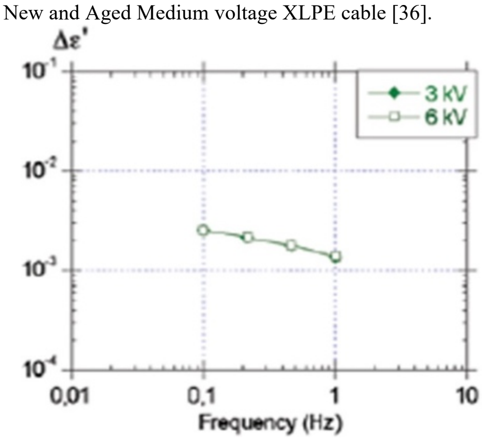

Fig. 9. New and Aged Medium voltage XLPE cable [37].

The comparison of dielectric spectroscopy measurement on new and aged cable is shown in Fig 10. When voltage is varied from 3kV to 6kV, the tangent delta for new cable stays relatively the same, thus indicating the good condition of the cable. Nevertheless, the tangent delta of old cable is increases with voltage, thus indicating that water tree has present in the insulation [39].

When making frequency dielectric spectroscopy measurements on cable circuits containing accessories, users should be aware that the presence of certain types of accessories could dominate the results obtained. In particular, accessories that utilize stress grading materials may results in high value of tangent delta at elevated voltage. Using tangent delta measurement test it is not possible to find the location of the cable defects. For any value of tangent delta, there could be many minor defects or a few major defects which difficult to be discriminated.

3.2 Partial Discharge Measurement

Partial discharges (PD) are small electric sparks or discharges that occur due to defect in the insulation. In medium voltage cable systems, PD mostly occur at the cable joint due to the poor workmanship during the cable jointing, aging or exposed to surrounding environment [40-42]. As a result, PD can cause damage to the insulation of cable joint leading to unexpected premature failure of cable [43].

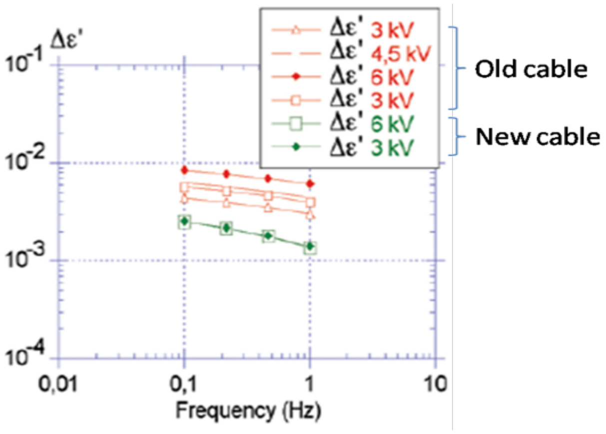

Fig. 10. Comparison between new and aged power cable under dielectric spectroscopy measurement [39].

PD measurement can be done through online and offline testing method. Obviously, online PD testing does not require and supply disconnection or an outage but the test can only be performed at the operating voltage level. In comparison, the offline testing allows the voltage to be adjusted and hence able to simulate transients or other over-voltage conditions. In general, both online and offline partial discharge testing can complement each other. A simple online partial discharge testing can be used to scan the cable circuit experiences partial discharge which later can be diagnose using offline partial discharge testing along with the localization of the defective point [44,45].

Currently, there are two alternatives for PD measurement either using Very Low Frequency (VLF) or Damped Alternating Current (DAC). In VLF test, decreasing the testing frequency could effectively reduce the power required for energizing the cable system, and hence the capacity of testing power supply could be reduced. Meanwhile, DAC test applies DC power to charging the test object and take the capacitance of cable system to interact with the additional inductor to create natural resonance and formed damping oscillating AC voltage [46] as shown in Fig 11.

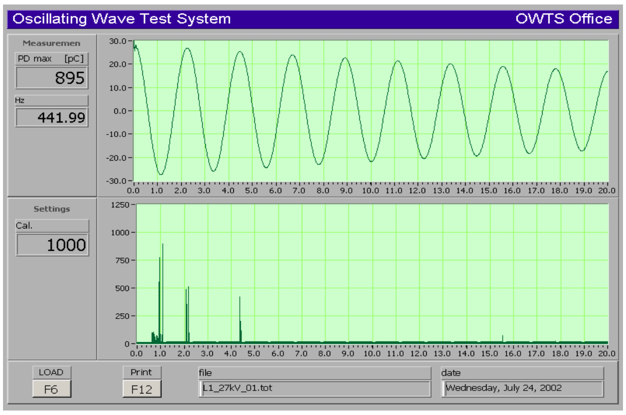

Fig. 11. Partial Discharge Testing using Damped AC [46].

The measurement instrument will record the voltage waveform and PD waveform, which are used to determine the existence of PD phenomenon. In the case where the pulse signal appearing at specific quadrant in the voltage cycle, it showing the evidence of PD activities. Further analysis on pulse waveform allows the PD sources along the tested cable to be located as illustrated in Fig 12.

There is no standard or guideline with regard to the acceptable limits of partial discharge magnitude for field testing. The detected apparent discharge magnitude, *q*, may or may not play a significant role in determining the severity of the defect, particularly when comparing different defects. For example, a few pC detected from an electrical tree in an extruded insulation may require an immediate repair or replacement; however, thousands of pC of partial discharge between the cable neutral and ground shield is tolerable in that same extruded insulation.

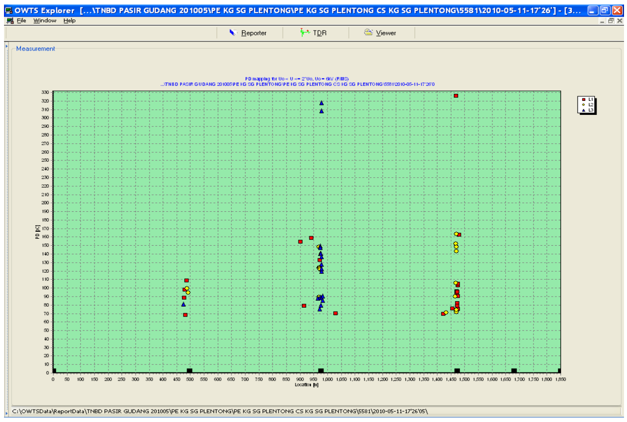

Fig. 12. Partial Discharge Map – PD magnitude and location of PD sources along the tested cable [46].

If the defect type is known, the PD magnitude, along with other parameters, may give a general indication of the condition of a defect in both extruded and fluid impregnated cables. There is usually a statistical variation in the PD magnitudes when measurements are made over a short time for a particular defect site. Many studies have attempted to correlate PD characteristics with various defect types in extruded cables and accessories to determine whether a particular type of defect has unique PD characteristics [47]. Condition assessment based using partial discharge testing must consider all the key parameters as highlighted in IEEE 400.3 [48] prior to making any maintenance action.

4 Early fault prediction

The right application of diagnostic methods has allowed potential faults to be determined at the early stage and appropriate maintenance actions can be taken to avoid equipment failures. A cases studies presented a successful of diagnostic and monitoring of transformer and cable.

4.1 Diagnostic Assessment of Transformer

The trending of fault gases results since 2015 shows the concentration of ethane, methane and acetylene are above the specified limit in accordance to IEC 60599, which indicated the possible of overheating fault at low and high temperature in the transformer. The routine electrical testing conducted on the transformer during maintenance work shows inconsistency result in winding resistance measurement on red phase winding. The results deviated more than 5% when compared between its phases particularly on tap position 10 to 17. The other test results are acceptable.

Prior to internal inspection of the transformer, Acoustic Emission (AE) measurement was conducted by placing 16 piezoelectric sensors around the transformer tank to locate the possible fault location as in Fig 13.

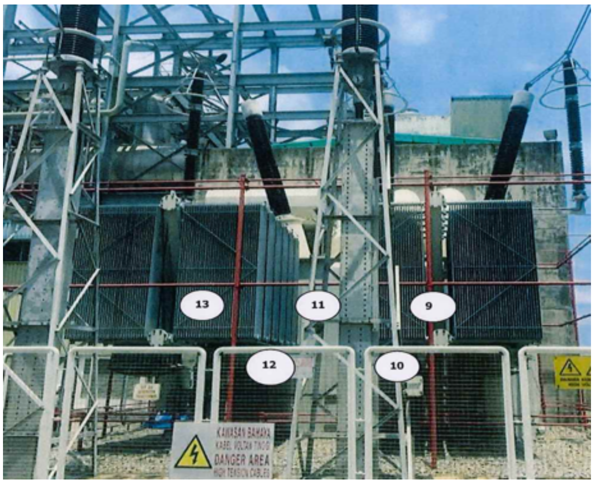

Fig 13. Location of piezoelectric sensor 9 to 13 on transformer tank.

During 24 hours of AE measurement, 17 events have been triggered involved of 2 areas as shown in Fig 14. The activities are concentrated at the areas of red phase winding.

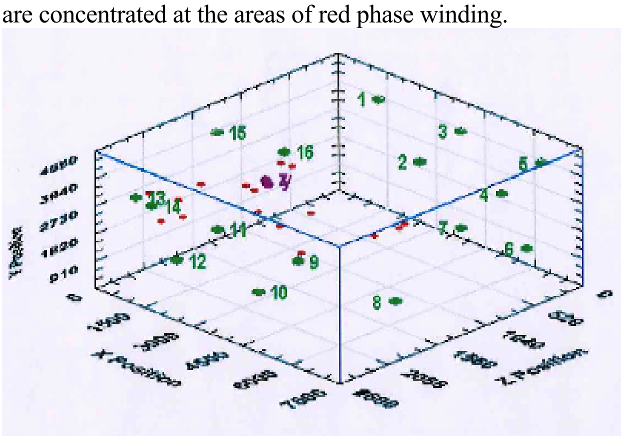

Fig. 14. Possible of fault location in transformer.

The internal inspection of the transformer was observed a carbonization and overheating sign at the red phase changeover selector contact as shown in Fig 15. Later, the maintenance action was taken to dismantle and repaired the changeover selector contact.

Fig. 15. Carbonization and overheating sign on changeover tap selector.

4.2 Diagnostic Assessment of Cable

A 20 years single core 22 kV medium voltage underground xlpe cable of 476 meters in length were tested using insulation resistance measurement and very low frequency tangent delta test. The insulation resistance measurement by applying 5 kV dc voltage for one minute indicate the cable relatively in good condition and consistence between the phases. However, the dielectric absorption has categorized the cable in age condition. The results of insulation resistance are summarized in Tab 1.

Table 1. Insulation resistance measurement and dielectric absorption test results.

Reading/Phase	Red	Yellow	Blue
Insulation Resistance (IR) @ 5kV DC	IR reading @ 60 secs		
	4.92 GΩ	3.86 GΩ	3.95 GΩ
	IR reading @ 30 secs		
	4.82 GΩ	3.75 GΩ	3.91 GΩ
Dielectric Absorption Ratio (DAR)	1.02	1.03	1.01
CLASSIFICATION	Age	Age	Age

Tangent delta test was subsequently performed to get a clear picture on the cable health assessment. The result had indicated that the yellow phase having high mean tangent delta value with significant stability percentage as shown in Fig 16.

Insulation resistance measurement was repeated after the tangent delta test to note any changes on the dielectric strength of the cable. The insulation resistance measurement was found to be relatively high, however, yellow phase has indicates a reduction of insulation resistance value as listed in Tab 2.

Based on the tangent delta assessment, action need to be taken for yellow phase. As prior partial discharge test did not show any particular location of concern, a withstand voltage test is performed to asses dielectric strength of the insulation. The withstand voltage of 2Uo for 15 minutes duration is applied. The cable experience breakdown shortly during the withstand test and cable fault thumper and pin pointing had found cable insulation failure as shown in Fig 17. Failed sample was brought back to laboratory for further analysis as observation at site indicates irregularity of whitish marks on the XLPE insulation as illustrated in Fig 18.

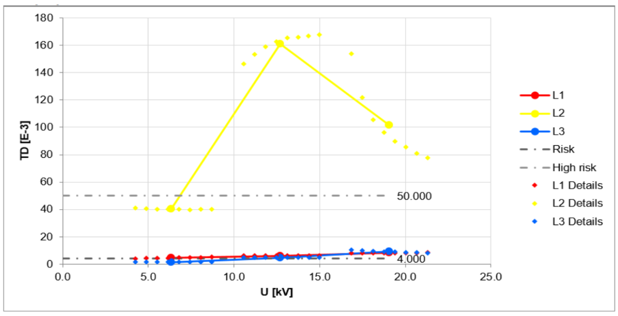

Fig. 16. Tangent delta measurement responses at 0.5, 1.0 and 1.5Uo.

Table 2. Insulation resistance measurement and dielectric absorption test results after tangent delta test.

Reading/Phase	Red	Yellow	Blue
Insulation Resistance (IR) @ 5kV DC	IR reading @ 60 secs		
	2.88 GΩ	880.00 MΩ	2.80 GΩ
	IR reading @ 30 secs		
	2.74 GΩ	846.1 MΩ	2.72 GΩ
Dielectric Absorption Ratio (DAR)	1.05	1.04	1.03
CLASSIFICATION	Age	Age	Age

Microscopic examination on the cable sample was conducted and revealed that the failed sample had suffer from water tree degradation. Extensive vented tree type of water tree was observed form the outer insulation screen as shown in Fig 19. This has indicated that water may have ingress through the outer sheath/ jacket of the cable and made contact to the surface of XLPE insulation for quite some time.

Fig. 17. Excavation at site found failure puncture on XLPE insulation.

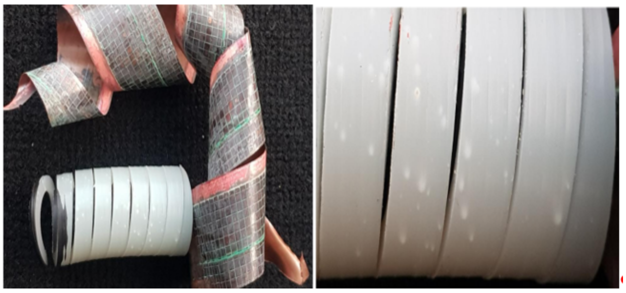

Fig. 18. Signs of corroded copper screen and whitish mark on xlpe insulation.

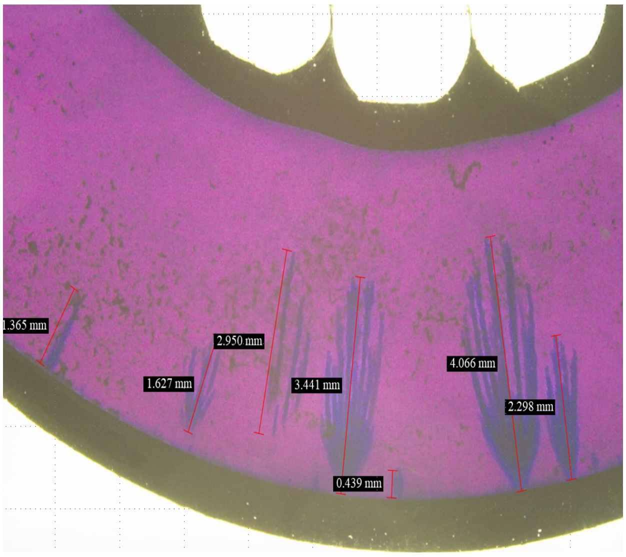

Fig. 19. Extensive vented tress form outer screen was observed from the inspected samples.

5 Conclusions

The degradation of insulation system in power transformer and cable or any abnormal conditions that may causes incipient faults can be discovered or detected by several diagnostic testing tools. No single method can be considered as the best and accurate diagnostic method. The comprehensive assessment of transformer and cable require combination and holistic analysis of electrical, chemical and mechanical testing data. The presented case studies demonstrated that through structured diagnostic approach, the incipient faults occur in transformer and cable can be determined at the early stage and appropriate maintenance action can be taken to avoid failure during in-operation.

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