DESKTOP AND FIELD EVALUATION OF DIELECTRIC RESPONSE DIAGNOSTIC MEASUREMENT SYSTEM FOR MEDIUM VOLTAGE UNDERGROUND CABLE

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ABSTRACT

TNB as a utility company, recognized MVUG cables is a critical asset group as asset performance and life cycle cost has significant impact on service level standards and business objectives of TNB. Asset Operation & Maintenance strategy for MVUG cables has been focus on the continuous development of condition assessment and condition-based maintenance methodology to identify predominantly weak spots or localized insulation defects in joints and terminations. The next phase will involve application of diagnostic technologies to assess the condition and remaining life of global insulation of MVUG cables (both PILC and XLPE), assessment of risk and to prioritize investment on replacement of aging cables and optimized maintenance cycles. This project reported work done to conduct an evaluation of Dielectric Response Measurement based on desktop and field testing analyses and findings on areas related to applicability, suitability and effectiveness of Dielectric Response Measurement in determining the health condition of MVUG Cables.

INTRODUCTION

TNB, the largest utility company in Malaysia has large 11kV and 33kV underground cable networks that are in service for more than 20 years. Asset Management Department of the TNB Distribution Division is continuously in search of advanced diagnostic technique to conduct integrity assessment of the aged cable systems and to find out the health condition of the cables. In view to this, TNB Distribution Division had commissioned a technology assessment project to evaluate the Dielectric Response technologies and measurement systems for possible application to MVUG cable system.

TNBD has embarked on off-line OWTS PD mapping measurement as advance diagnostic tools in Condition Based Maintenance activities for MVUG. Additional dielectric response diagnostics equipment are being planned to complement OWTS e.g. DS, Tan delta, PDC, IRC, RVM with the aim to detect conductive defect which may associates with moisture/water and tracking. The dielectric response technique should be able to identify and detect water tree defect in XLPE cable together with an appropriate severity level indication. It is important to distinguish the dielectric response of cable and its accessories within the system for the ease of maintenance works hence such capability is an added advantage. It is well accepted and agreed by most experts in the world that presence of conductive defect in the form of moisture or carbonization will not be detected by PD diagnostic testing equipment [1].

Water treeing is one of the factors leading to failure of medium voltage XLPE cables in long-term service. To identify water tree degraded XLPE cables or oil-paper cables with high moisture content, diagnostic tests based on dielectric response (DR) measurement in time and frequency domain are widely used [2].

Owing to the large pool of polymeric cables installed by TNB Distribution, a means to identify and discriminate potentially water treed cables in the field is deemed required. As a pre-emptive approach TNBD has addressed the issue of water tree by including this test requirement in their CBM exercise. For this, TNBD seek proven on site dielectric response technique with specific focus on water tree detection technique to be endorsed and applied into the system.

EVALUATION METHODOLOGY

There are two (2) main tasks in this project i.e. Desktop Assessment and Actual Onsite Testing Assessment. In the desktop assessment, information from desktop survey, assessment results and bench marking were compiled and analysed. A set of comprehensive desktop assessment criteria that covered compliance to standard, suitability to MVUG cable system, operability, effectiveness of measurement and support was proposed and applied in assessing different dielectric response diagnostic technologies offered.

Selection of the Dielectric Response Technique

Based on the discussion with TNBD Asset Management, it was decided only a maximum of six (6) participants of dielectric response measurement techniques (i.e. Dielectric Spectroscopy and Tan delta) shall be selected for this feasibility study assignment. It is vital to have various dielectric response dielectric response techniques to be included in this exercise for better comparison / analysis of test results. This will ensure the most suitable dielectric response measurement technology that can be applied within TNB Distribution system for field testing of the selected MVUG cables. At the same time we need to consider the exercise duration as well as the time taken for the shutdown during the testing. It was agreed and decided during the project proposal for TNBR to engage an independent expert collaborator to jointly perform this evaluation project.

This was to ensure the integrity of the findings from this evaluation project. In this evaluation exercises, five (5) dielectric response measurement systems were selected to participate. One Dielectric Spectroscopy (FDS) and the other four were Tan delta measurement technique.

Tan Delta Measurement Technique

In general the principal measurements are based on tan delta measurement. Tan delta is a measure of the degree of real power dissipation in any insulation material and classified as dielectric losses. In the case of underground cables, this test measures the overall dielectric losses rather than the losses resulting from any localized defect. Therefore, Tan delta measurement constitutes a cable diagnostic technique that assesses the general condition of the cable insulation system. Tan delta can be employed to all other primary electrical equipment and various cable types; however, test results must be considered with respect to the specific insulation material and accessory type. In general, the cable insulation system is simply represented by an equivalent circuit that consists of two electrical elements; a resistor and a capacitor see Figure 1.

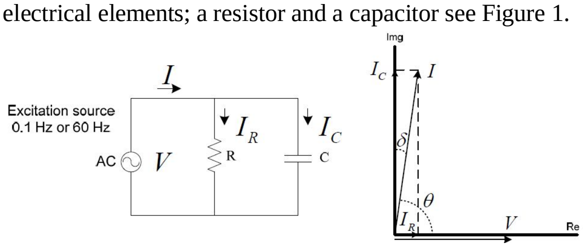

Figure 1: Equivalent circuit for tan delta measurement and phasor diagram.

When voltage is applied to the cable the total current (I) is a combination of the current (I_C) flow through capacitive element and the current (I_R) flow through resistive element. Tan delta is the ratio between the resistive current and the capacitive current. The angle δ is the angle between the total current and the charging current when they are represented as phasors. The terms “tan delta”, “dissipation factor” and “dielectric loss” are used interchangeably. Tan delta test is an offline test; the cable segment under test is disconnected from the network and energized from a separate voltage source fixed AC frequency (i.e. 50 Hz or 0.1Hz). The tested cable is typically energized using a voltage level of 0.5 and up to $2U_0$.

Establishing the success criteria for dielectric loss measurements is complicated in that the values depend not only on the cable system quality, but also on the cable and accessory technologies employed on the tested cable circuit. IEEE Std. 400™ - 2001 initially has established broad performance categories for 0.1 Hz tan delta measurements. However, recent work has lead to an expansion and revision of these levels, thus users should be cautious in the direct application of these earlier values. The values are based on cables tested in various countries. These newer criteria serve to show how an assessment protocol might be constructed after a suitable analysis is performed. It is also important to recognize that data at 50 Hz cannot be compared with those at 0.1 Hz.

As part of the ongoing dissemination of information from the CDFI, NEETRAC has made Table 1 available to the IEEE Std. 400.2™ working group. This is for inclusion in the forthcoming update. The hierarchy for diagnosis using tan delta is as follows [3]:

1. Tan δ Stability – stability is assessed by the standard deviation of dielectric loss at U_0 (other approaches are possible)
2. Tip Up – difference in the mean values of Tan δ at selected voltages
3. Tan δ (mean value at U_0).

Table 1: 2010 CDFI criteria for condition assessment of PE-based insulations (PE, HMWPE, XLPE, & WTRXLPE)

Condition Assessment	Tan δ Stability at U_0 [E-3]		Tip Up ($1.5U_0 - 0.5U_0$) [E-3]		Tan δ at U_0 [E-3]
No Action Required	<0.8		<8		<5
Further Study Advised	0.8 to 5	or	8 to 80	or	5 to 50
Action Required	>5		>80		>50

In addition to Tan delta measurement at fixed frequency, a dielectric loss measurement technique at variable frequency known as Dielectric Spectroscopy was also employed in this exercise.

Dielectric Spectroscopy Measurement Technique (FDS)

Dielectric Spectroscopy is actually a tan delta technique; however, the tan delta is done by measuring the real and imaginary components of a cable insulation system current at a range of applied voltage frequencies, typically 0.001 to 100 Hz. The advantage of this process is that it provides additional information about the cable system insulation. In general, the tan delta varies inversely with frequency (since the capacitive current is directly proportional to the applied AC frequency i.e. 50Hz) and will normally be larger and more easily measured at lower frequencies. The loss current, on the other hand, remains constant with frequency unless there is degradation present in the cable system.

There are two ways to obtain the dielectric loss spectra:

- Frequency Domain Spectroscopy (FDS) – employs variable frequency source to measure conventional current and phase angle
- Time Domain Spectroscopy (TDS) – Measure number of DC currents as a function of time and then transform to the frequency domain using the Hamon Approximation.

This project focuses on FDS approach which employs a variable frequency source and performs conventional current measurement and phase angle calculation. The variable frequency/conventional data are obtained by applying voltages at discrete frequencies and then calculating the real and imaginary parts of the current at that frequency. The tan delta is determined based on the ratio of these two parts. The frequency is then swept to cover several frequency ranges. The data may be interpreted as frequency spectra or via equivalent circuit models. The equivalent circuit model translates the measured "complex" current into a "complex" permittivity where the real part of the permittivity represents the direct capacitance and the imaginary part represents the resistive or loss component. The tan delta then becomes the ratio of the imaginary permittivity to the real permittivity. The effects of age, moisture, and temperature is believed can then be analyzed using either of these approaches [4].

Selection of Test Sample

Actual testing evaluation was performed through onsite testing on actual cable circuits TNBD underground network and control cable sample in the laboratory. Both actual onsite and control laboratory testing was performed to identify the capabilities of the dielectric response systems. Test circuits were selected based on the cable selection criteria. These criteria were selected based on the experience of water tree cables characteristics which are as follows:

- Pure XLPE
- > 15 years
- High water table area
- Frequent failure (insulation)

In addition, actual control sample of XLPE cable were prepared and pre-conditioned to facilitate the laboratory evaluation exercise. Three control samples with known degradation condition were prepared. For onsite testing, five (5) cable samples from medium voltage underground distribution cable network as listed in table 2 were selected. Control cable samples without any cable accessories were prepared for the testing in the laboratory. Three cable samples with known degradation were prepared and pre-condition to facilitate the assessment activity via laboratory evaluation. Each dielectric response system had an opportunity to perform the test on these control samples and to come out with their results hence the condition of the tested cable samples as listed in Table 3.

Table 2: List of cable circuits of TNBD underground network

No.	System	Near End	S/Gear	Far End	S/Gear	XLPE Cable Type	Length	Years
1	33kV	PMU Bukit Jalil (6L5)	VCB TAMCO	PPU GOLF (3P5)	VCB TAMCO	XLPE/1C/630mm2	3092m	>10
2	11KV	PE Sentul Boulevard N.3 (18614)	VCB LKH	PE Sentul Boulevard No.2	VCB LKH	XLPE/3C/240mm2	276m	1996
3	33kV	PPU Section 21 (1P5)	VCB TAMCO	PMU EAST (15L5)	VCB EPE	XLPE/1C/630mm2	~2800m	1991
4	11KV	PE Jln Sg Chandong No.8 (13542)	Felcon Beta	PE Jln Sg Chandong No.6	RMU Toprank	XLPE/3C/240mm2	788m	2001
5	11KV	PE FADARA YATCH	RMU MG	PE TIRAM KIMIA	Felcon Beta	XLPE/3C/240mm2	900m	2001

Table 3: List of control cable samples in the laboratory

No.	System	Sample	Length	Sample Condition
1	11KV	TNBR Sample 1	~2m	Water tree
2	11KV	TNBR Sample 2	~7m	High loss
3	11KV	TNBR Sample 3	~17m	Water tree

FIELD AND LABORATORY EVALUATION

Field study evaluation has been performed using several assessment criteria that are grouped in to three Categories e.g. Field Suitability, Test Management, Data Analysis and Report Preparation. Each Category consists of a few assessment criteria relevant to the category title. The assessment criteria are listed in Table 4.

Table 4: Onsite assessment criteria

Field Suitability	• Compactness – integrated or multiple pieces • Equipment Portability • Equipment handling and manpower requirement at site • Safety features
Test Management	• Test procedure • Test equipment setup (ease and expediency) • Test Protocol preparation • Test Object Library • Test duration
Data Analysis and Report Preparation	• Data and Results Retrieval procedure • Result Presentation • Data analysis and Interpretation • Report preparation • Data security

Scoring and Weighting Criteria

Category Score

The field and laboratory assessment has been performed based on three categories as listed in Table 4. Each Category has a few assessment criteria. The evaluation result for each assessment criterion is expressed in numerical term called "Criterion Score".

Category Weighting Factor

Weighting factors used in the field and laboratory assessment methodology recognize that some group assessment criteria affect to a greater or lesser degree than other group assessment criteria.

Total Score

The Group Scores are then weighted and summed to determine the "Total Score". This "Total Score" will be used to determine the "Overall Ranking" of all the dielectric response system in the order of merits.

Summary of Field and Laboratory Testing

Key observations and findings of onsite field and laboratory testing are summarized in the following Table 5 and Table 6.

Table 5: Summary of findings on dielectric response testing results in the field.

Circuit	Key Findings	Conclusions
C1-33kV	FDS, TD 3 and TD 4 diagnosed cable as in good condition based on low and stability of tan delta values & hence low loss MEGGER measured slightly variable capacitance and tan delta voltage dependency but no current leakage at low frequencies- possible due to joints /terminations	-Cable in good condition *(All manufacturers are consistent in diagnosis integral insulation condition of cable circuit including accessories)*
C2-33kV	TD 1, TD 2, FDS and TD 3 diagnosed cable in good condition – based on tan delta values, stability, capacitance and no voltage dependency.	-Cable in good condition *(All manufacturers are consistent in diagnosis integral insulation condition including accessories)*
C3-11KV	TD 2, FDS , TD 3 and TD 4 diagnosed cable as in critical conditions especially yellow and blue phase. Uncertainty over major contributor to high losses – cables or accessories.	-Cable in critical condition especially Y,B phases (*All manufacturers are consistent in diagnosis integral insulation condition including accessories)*
C4-11kV	TD 1, TD 2, FDS, TD 3 diagnosed cables (all phases) in critical conditions based high tan delta values. Again, uncertainty over contributors – cables & accessories, water-trees and presence of moisture	-Cable in critical condition *(All manufacturers are consistent in diagnosis integral insulation condition of cables including accessories)*
C5-11kV	TD 1, TD 2, FDS, TD 3 and TD 4 diagnosed cable (all phases) to be in critical condition. Again, contributory elements cable or accessories need to be fully investigated.	-Cable in critical condition *(All manufacturers are consistent in diagnosis integral insulation condition including accessories)*

Table 6: Summary of findings on dielectric response laboratory testing results.

	TD 1	TD 2	FDS	TD 3	TD 4
Test Sample 1 (~2m) (W)	Due to the PD activity **the water tree** leakage content cannot be determined separately **(W)**	Obtained a measurement but cannot make any valid conclusions given short length of cable	The cable has **water trees** **(W)**	Wet cable	This cable has been classified as highly **water treed** and is critical **(W)**
Test Sample 2 (~7m) (NW)	TD results show all three phases have very high operating risk. The response of TD over the voltage indicates intensive water tree presence	This cable is showing signs of **deterioration** **(NW)**	This cable does **not show any signs of water tree** deterioration **(NW)**	Very **bad loss factor** **(NW)**	This cable has been classified as highly water treed and is critical
Test Sample 3 (~17m) (W)	The delta TD of all phases indicates the response of **water trees** over the voltage **(W)**	This cable is showing signs of aging but this is expected for a 1995 cable	This cable has **water trees** **(W)**	Unacceptable measurement variation	This cable has been classified as highly **water treed** and is critical **(W)**

SUMMARY OF ANALYSIS/FINDINGS FOR FIELD ASSESSMENT

Key Points of Findings

Field Suitability Assessment:

TD 2 is highest ranked as the HV Unit is portable and easy to handle at site. The system also has enhanced safety features including lockable switch for preventing unauthorized. It is worth mentioning here that from the compactness point of view TD 1 is the best compared to all other systems.

Test Management Assessment:

FDS and TD 2 are at the top of the list as they are superior to other systems under "Test Object Library" criterion. However, FDS scored slightly better than the TD 2 for the "Test Protocol Preparation" criterion. The findings related to "Test Procedure", "Test Equipment Setup" and "Test Duration" criteria indicates comparable capabilities amongst the manufacturers or technology providers.

Data Analysis and Report Preparation Assessment:

FDS, TD 1 and TD 4 are at the top of the list. All three systems are equally strong in some of the identified criteria e.g. "Result Presentation", "Report Preparation" and "Data Security". In "Data and Results Retrieval" criterion, FDS is better than the other two systems as it uses window-based application tools instead of any proprietary software tools. In "Data Analysis and Interpretation" criterion TD 1 and TD 4 systems have an advantage over FDS as they used IEEE 400.2 -criteria for interpretation. Based on evidence of field test results, all dielectric response systems assigned to test the same cable circuit were capable in giving a comparatively consistent results and diagnosis of the global insulation condition of tested cable circuit based on interpretation in accordance with established IEEE standard.

CONCLUSION

Actual testing assessment is an important step in the overall assessment exercise and set of field assessment criteria encompassing field suitability, test management, data analysis/report preparation are applied in the assessment process in coming up with the scores and ranking for each participating system of Dielectric Response measurement.

Based on the test results and diagnosis of cable conditions alone, there is little difference between systems. However, the overall applied assessment criteria are driven by the need to ensure efficiency, consistency, repeatability of DR measurement system in terms of giving the right results and diagnosis of global insulation condition of MVUG cables - as it is applied in the field by users. Hence, DR measurement system has first to be in compliance to established standards in terms of measurement methods, data analysis and interpretation in addition to meeting other criteria. Based on specified approach, broader-based field assessment criteria along with weightage and scoring scheme, TD 2 and FDS are assessed to be the top two dielectric responses /tan delta measurement system after the field assessment exercise. From the assessment it shall be noted that FDS system is capable to clearly detecting Water Tree in the control cable samples. However the interpretation of the testing results requires such expertise.

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