Power Research - A Journal of CPRI, Vol 22(1), 2026 | pp. 11-20

Diagnostic Testing and Condition Assessment of Power Cable System

Dillip Kumar Puhan*, Rajat Sharma, K. Pradeep, Beere Shivanath Kumar and Javadhi Srinuvasa

Central Power Research Institute (CPRI), Bengaluru - 560080, Karnataka, India; dillip2009@cpri.in

Keywords: Damped AC Voltage (DAC), Partial Discharge (PD), Very Low Frequency (VLF)

Article Received: 26-02-2026

Article Revised: 10-03-2026

Article Accepted: 16-03-2026

DOI: 10.33686/pwj.22.1.2026.11-20

*Author for Correspondence

Abstract

Medium Voltage power cables are extensively used in electrical power distribution networks. These cables and accessories normally undergo quality assurance testing at factory after manufacture to detect defects such as voids, contaminations, irregularities at the insulation/shield interfaces, by conducting various physical and electrical tests. However, these cables undergo different stress during their service life period leading to insulation degradation, deterioration, failure and hence forced outages. The on-site diagnostic testing also helps in detecting age related defects in the in-service cables and also to assess extent of aging or deterioration of the cables. By conducting on-site diagnostic testing, ranking of the cables can be achieved. Ranking of the in-service cable helps the utilities in taking vital decision on future course of action as regards to asset management of the distribution network to minimize capital expenditure and maximize reliability. The Central Power Research Institute (CPRI), Bengaluru, a leading research and testing organization supporting the Indian power sector, carries out specialized diagnostic evaluations of Medium-Voltage (MV) power cable systems. These assessments are performed to determine the operational condition and reliability of cables and their associated components. Through advanced testing techniques, CPRI helps utilities and industries identify potential insulation weaknesses, early-stage defects, and other issues that may affect cable performance. Such diagnostic studies play an important role in ensuring the safe operation, reliability, and longevity of power cable networks. The techniques used for diagnostic testing of power cable systems are briefly discussed in this paper. The experience gained indicates that Very Low Frequency (VLF) dissipation factor testing is very sensitive to water ingress in cable system and surface discharges in cable system components. CPRI experience shows that Partial Discharge (PD) test with the application of damped ac voltage is an efficient diagnostic tool for detection, location and recognition of incipient fault at an early stage.

This is an open access article under the terms of the CC BY: Allows others to copy, distribute, and build upon the work for any purpose, provided they credit the original creator

© 2026 The Author(s). *Central Power Research Institute* published by Informatics Publishing Limited

1. INTRODUCTION

During operation, the insulation system of a power cable is exposed to various stresses, including electrical, thermal, mechanical, and environmental influences. Continuous exposure to these conditions can gradually alter the physical and electrical characteristics of the insulating materials. In addition, the presence of impurities, manufacturing defects, sharp protrusions, or air voids within the insulation or at material interfaces can intensify these stresses, leading to progressive deterioration of the insulation system over time[1].

Aging is an important consideration for both MV and HV cables. From the earliest days of cables insulated with paper and oil, it is been known that the dielectric strength of the insulation system decreases with time in operation[2]. The ageing effects depend upon the electrical stress, temperature and the environment in which the cable is installed and laying conditions.

The primary aging mechanism for XLPE-insulated cables is treeing. Treeing occurs in two basic forms. Electrical treeing is a rapid-degradation phenomenon that usually initiates at an imperfection. Once initiated, electrical tree grows rapidly over period of seconds or minutes until they progress through the insulation and creates a line to ground fault.

Water treeing, on the other hand, is a slowly developing degradation phenomenon that initiates at a defect or impurity. These trees initiate and grow only if moisture is present in the insulation in sufficient quantities. Water tree grows slowly over time, generally over many years. They can lead to initiation of electrical trees, which are usually considered the final failure mode for a cable. Neither tree type will occur unless there is sufficient localized voltage stress, created by chemical or physical contamination, to cause the tree to initiate and propagate.

It should be noted that stress enhancement is a complex phenomenon. Localized stress enhancement is a function of the permittivity/conductivity of the contaminant as well as its size and shape. Because aging processes are driven by localized voltage stress, it is extremely important to minimize all types of contamination and irregularities within the cable.

2. DIAGNOSTIC TESTING IN THE FIELD

Diagnostic testing of cable systems[3] is typically performed to confirm that a newly installed or repaired circuit is free from significant installation defects and has not been exposed to serious mechanical damage during handling or laying. These tests are also used to evaluate the condition of aging cable systems and estimate the probability of potential failures in the near future. Such assessments may form part of a broader asset management strategy for cable networks or be applied specifically to reduce the risk of failure in critical power circuits. Several diagnostic techniques are commonly employed in the field to examine the condition of power cables.

2.1 Insulation Resistance (IR) Measurement

The IR measurement is the elementary test practiced by the maintenance engineers for testing of HV equipment. It reflects the moist/contaminated condition of the insulation. The IR will be usually high (several hundred Mega Ohms) for a dry insulation system. The IR measurements are sensitive to changes in temperature, humidity, and external leakage due to dirty terminations. Polarization Index (PI) can be used as an index of dryness of the insulation. For calculating PI, the IR is measured after 1 minute of voltage application and after 10 minutes. The PI is the ratio of IR value measured at 10 minutes divided by the value measured at 1 minute. The PI should be higher than or close to unity. An PI of less than 1 would indicate abnormal condition.

2.2 Dielectric Response methods

Dielectric response techniques such as dissipation factor (tan δ), leakage current measurement, recovery voltage analysis, Polarization/Depolarization Current (PDC), and dielectric spectroscopy are commonly used to evaluate the overall condition of cable insulation through offline testing. Among these, recovery voltage, depolarization current, tan δ measured at Very Low Frequency (VLF), and dielectric spectroscopy are particularly useful for assessing cables affected by water treeing degradation. These measurements may

be performed over a range of frequencies or within the time domain using different time intervals. When an electric field is applied to an insulating material, several polarization and conduction processes occur within the dielectric. Any deterioration in the insulation alters these electrical responses. For instance, the presence of water trees in extruded insulation or moisture in laminated insulation typically leads to increased polarization effects and higher dielectric losses.

2.3 VLF (0.1 Hz) Tan Delta and Capacitance Test

In recent years, tan delta testing at very low frequency[1,4], usually 0.1 Hz has been found to be effective for XLPE cable in-service. The dissipation factor testing at power frequency poses problems as the reactive power required to energize long length cables is quite high and size of the testing transformer becomes huge. In recent times, VLF (0.1Hz) testing of power cables has gained wide acceptance and has replaced the less informative and potentially damaging DC voltage test. The reactive power required at 0.1 Hz decreases to 1/500 in comparison to power frequency and the size of the testing source reduces drastically.

In recent years, Very Low Frequency (VLF) dissipation factor (tan δ) testing has become an effective technique for evaluating the condition of extruded power cables. The Central Power Research Institute (CPRI) has carried out VLF tan δ measurements on aged cables in service to determine the degree of insulation ageing, as well as on newly installed cables to establish baseline commissioning data that can be used for future condition monitoring. The measured baseline tan δ values and their variation with increasing test voltage have shown strong sensitivity to insulation ageing and the presence of contaminants within the XLPE insulation, making this method useful for assessing cable health.

Many researchers in the European countries have shown that 0.1 Hz testing is capable of revealing presence of the water trees in the XLPE insulation. Water trees are microscopic, branch-like structures that develop within the insulation of power cables due to the combined effects of moisture and electrical stress. These structures typically originate from imperfections such as voids, contaminants, or sharp protrusions present in the insulation material. Additional factors, including mechanical damage to the cable, Ultraviolet (UV) radiation induced cracking of the outer sheath, and the presence of water or oil along the cable route, can accelerate this degradation process. Over time, the growth of these tree-like channels weakens the insulation and may eventually lead to cable failure.

The section of the cable affected with water trees exhibits interfacial polarization imparting increased AC conductivity that results in increased dielectric losses in the insulation. The VLF dissipation factor is sensitive to the increased dielectric loss and its variation with test voltage reveals presence of water trees in the insulation. The VLF tan delta testing can be used as an effective diagnostic tool for assessing deterioration level of the extruded cable insulation and there by ranking the cables.

Normally for a healthy XLPE cable, the VLF tan delta is low and the tan delta – voltage characteristic is a flat horizontal line. The XLPE insulation does not exhibit voltage dependent characteristic of tan delta.

2.4 Partial Discharge Measurement

Partial Discharge (PD) testing[5] is an important diagnostic technique used to evaluate the condition of power cable insulation, as it can detect early-stage defects within the insulation system. Partial discharges occur when localized electrical breakdown takes place in small regions of the insulation, often due to imperfections such as voids or contaminants. Over time, these discharges can damage the insulation and contribute to its progressive deterioration during service. If the intensity of the PD activity is high, it may accelerate insulation degradation and, in extreme cases, result in premature failure of the cable insulation.

The partial discharge testing at power frequency poses problems as the reactive power required to energize long length cable is quite high and size of the testing transformer becomes huge. In recent times, Very Low Frequency (VLF) AC testing and Damped AC testing of power cable has gained wide acceptance.

VLF AC testing method utilizes ac signals in the frequency range of 0.01 Hz to 1 Hz.

To produce Damped AC (DAC) voltages, the test object - primarily the capacitance of the cable under test - is first charged to the required voltage level within a short duration. Once the desired voltage is reached, the stored energy is released through an electronic high-voltage switch and a specially designed air-core inductor. This process generates a decaying oscillatory voltage waveform. The frequency of this oscillation depends on the relationship between the inductance of the air-core coil and the capacitance of the cable, as described by Equation 1.

$$f_{DAC} = \frac{1}{2\prod\sqrt{(L*C)}} \quad (1)$$

The frequency of Damped AC (DAC) voltage varies from tens of hertz to few kilohertz depending upon the cable capacitance and wave shaping circuit used by the test system. VLF AC and Damped AC partial discharge test system both use principle of Time Domain Reflectometry (TDR) to determine location of probable PD source along the length of the cable including accessories.

With damped alternating voltage in the range of kilohertz and very low frequency range from 0.01hertz to 0.1 hertz , the PD magnitude, inception voltage and occurrence may differ from those of power frequency voltage.

3. CPRI EXPERIENCE

The Central Power Research Institute (CPRI) performs diagnostic evaluation of medium-voltage power cable systems for utilities, industrial facilities, and power generation plants to determine the condition of cables operating in their networks. This assessment is carried out using suitable diagnostic techniques. Detailed analysis of the obtained test results enables the identification of insulation deterioration, as well as the detection and location of developing faults through partial discharge measurements. Based on these findings, cables can be condition-ranked, which assists organizations in prioritizing maintenance and replacement activities.

3.1 Case Studies

3.1.1 33kV, 3x300 sq. mm XLPE cables (2011 & 2012)

In commissioning tests IR measurement, Power frequency withstand test, VLF tan delta test were performed at site on 05 Nos. of newly installed cables during 2011. 03 Nos. of cables exhibited voltage dependency of VLF Tan delta and diagnostic tests were repeated on these cables during 2012 to monitor the trend. The data obtained on these cables are presented in Table 1 to 5 and Figure 1 to 5.

Table 1. Circuit-1 cable (2011)

Phase	IR @2.5kV DC (GΩ)	VLF-TD @ U_0 (10^{-3})	HV Test @ U_0, 50Hz	VLF-TDTS @ U_0 (10^{-3})	VLF-DTD (10^{-3})
R	7.12	0.5	Withstood	0.0	0.1
Y	6.95	0.6		0.0	0.1
B	4.88	0.5		0.0	0.0



Figure 1. Tan delta - voltage characteristics.

IR values are normal. VLF tan delta values are low and lie in the normal permissible range 1.2 x 10^{-3} for a new cable system. The condition of the cable is ranked as 'Normal'. No action required.

IR values are normal. VLF tan delta values R & Y core exceeds the permissible range 1.2 x 10^{-3} for a new cable system marginally and exhibits voltage dependency. Repeated the tests after 1 year to monitor the trend. The condition of the cable is ranked as 'Moderate'.

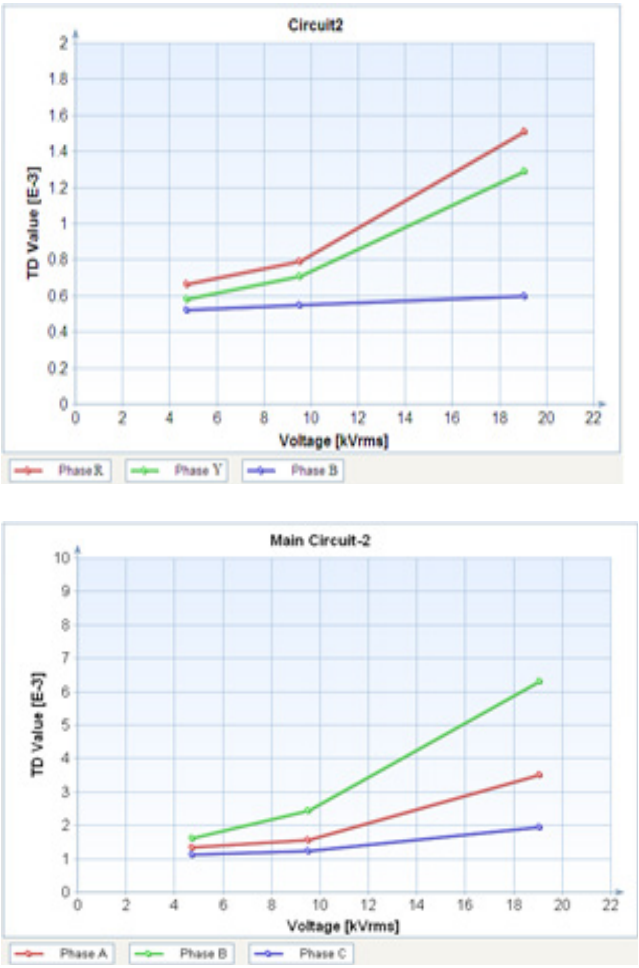


Figure 2. Tan delta - voltage characteristics (2011and 2012) circuit-2 cable.

Table 2. Circuit-2 cable (2011 and 2012)

Phase	IR @2.5kV DC (GΩ)	VLF-TD @ U_0 (10^{-3})	HV Test @ U_0, 50Hz	VLF-TDTS @ U_0 (10^{-3})	VLF-DTD (10^{-3})
R	7.67	1.5	Withstood	0.0	0.8
Y	10.6	1.3		0.0	0.7
B	12.2	0.6		0.0	0.1
R	4.33	3.5	---	0.0	1.2
Y	4.52	6.3	---	0.2	4.7
B	5.20	1.9	---	0.0	0.8

Table 3. Main spare cable (2011)

Phase	IR @2.5kV DC (GΩ)	VLF-TD @ U_0 (10^{-3})	HV Test @ U_0, 50Hz	VLF-TDTS @ U_0 (10^{-3})	VLF-DTD (10^{-3})
R	26.6	0.5	Withstood	0.0	0.1
Y	20.9	0.5		0.0	0.0
B	30.1	0.4		0.0	0.0

IR values are normal. VLF tan delta values are low and lie in the normal permissible range 1.2 x 10^{-3} for a new cable system. The condition of the cable is ranked as normal. No action required.

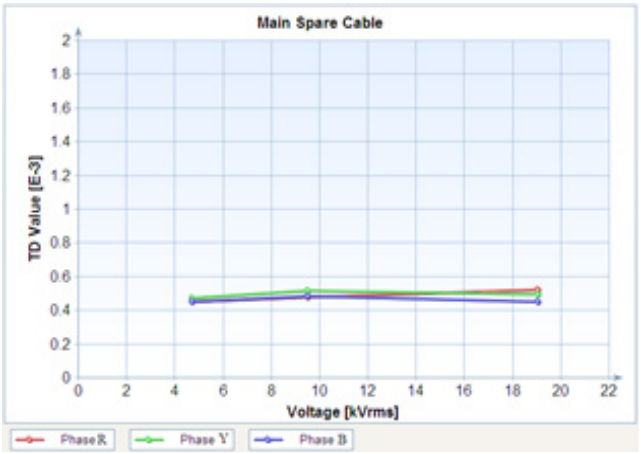
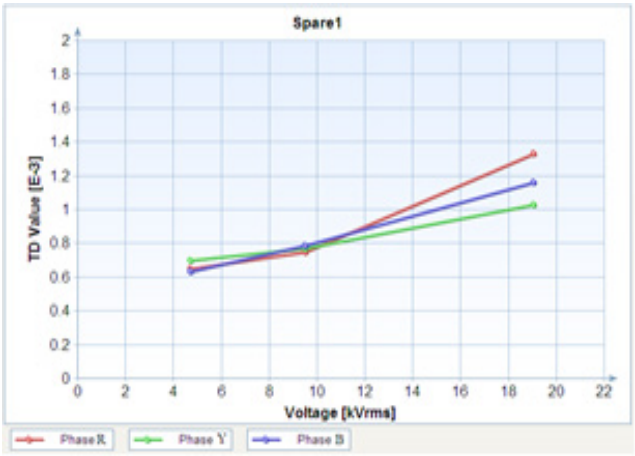


Figure 3. Tan delta - voltage characteristics (2011) main spare cable.

Table 4. Spare-1 cable (2011 and 2012)

Phase	IR @2.5kV DC (GΩ)	VLF-TD @ U_0 (10^{-3})	HV Test @ U_0, 50Hz	VLF-TDTS @ U_0 (10^{-3})	VLF-DTD U_0 (10^{-3})
R	7.74	1.3	Withstood	0.1	0.7
Y	7.28	1.0		0.0	0.3
B	9.14	1.2		0.0	0.6
R	255	1.0	---	0.0	0.7
Y	260	0.9	---	0.1	0.5
B	236	0.6	---	0.0	0.3

IR& PI values are normal. VLF tan delta values R core exceeds the permissible range 1.2 x 10^{-3} for a new cable system marginally and all the three exhibits voltage dependency. Repeat the test after 1 year to monitor the trend. The condition of the cable is ranked as 'Moderate'.



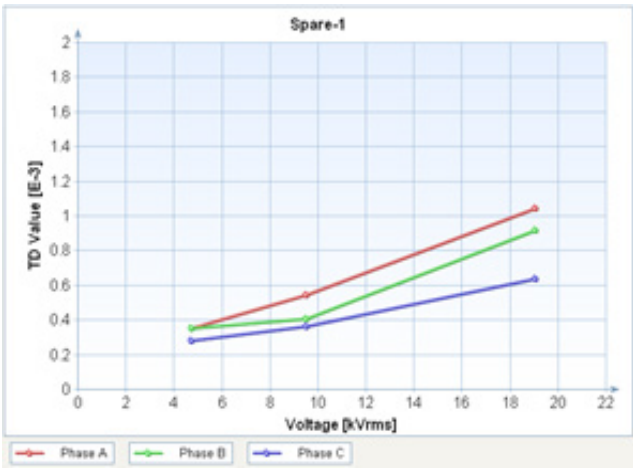


Figure 4. Tan delta - voltage characteristics (2011 and 2012) spare-1 cable.

IR values are normal and. VLF tan delta values R core exceeds the permissible range 1.2 x 10^{-3} for a new cable system marginally and all the three exhibits voltage dependency. Repeat the test after 1 year to monitor the trend. The condition of the cable is ranked as 'Moderate'.

Table 5. Spare-2 cable (2011 and 2012)

Phase	IR @2.5kV DC (GΩ)	VLF-TD @ U_0 (10^{-3})	HV Test @ U_0, 50Hz	VLF-TDTS @ U_0 (10^{-3})	VLF-DTD U_0 (10^{-3})
R	7.80	**1.6**	Withstood	0.0	0.9
Y	6.60	**2.9**		0.1	2.0
B	7.63	**1.8**		0.0	0.9
R	187	0.8	---	0.0	0.5
Y	198	0.5		0.0	0.3
B	159	0.7		0.0	0.3

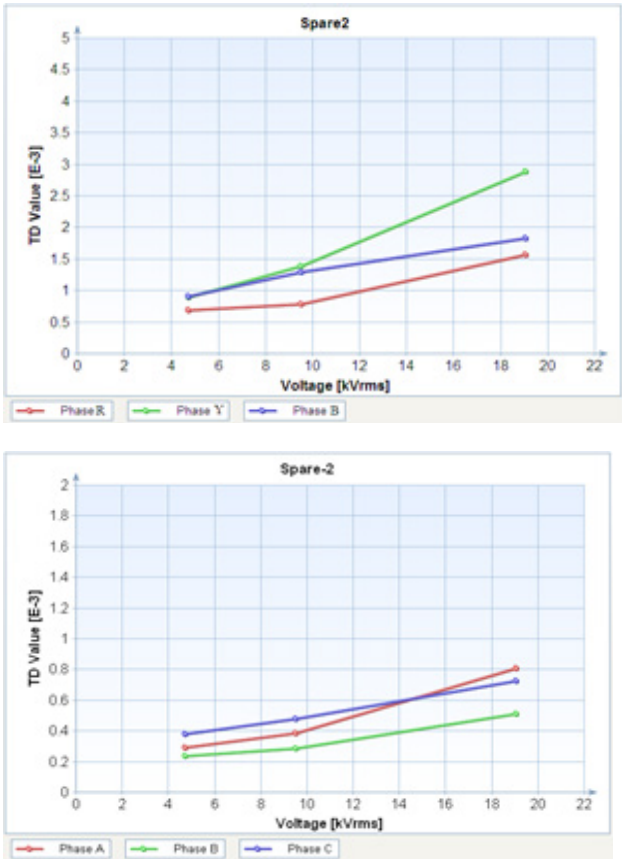


Figure 5. Tan delta - voltage characteristics (2011 and 2012) spare-2 cable.

3.1.2 33kV, 3x300 sq. mm XLPE Cables (2014 & 2015)

As per the recommendation of CPRI, diagnostic tests (IR, VLF Tan delta and PD test with damped AC voltage) were conducted in the 2014 and 2015 to monitor the trend in the insulation condition. The data obtained from these tests are presented in Table 6 to 10 and Figure 6 to 10.

Table 6. Circuit-1 (2014 and 2015)

Phase	IR (GΩ)	PI	VLF-TD @ U_0 (10^{-3})	Cap (nF)	VLF-TDTS @ U_0 (10^{-3})	VLF-DTD (10^{-3})
R	1.11	1.58	18.8	1194	0.2	12.4
Y	0.93	1.55	18.4	1196	0.1	11.9
B	1.60	0.81	22.7	1191	0.2	15.8
R	**0.126**	**0.97**	86.9	1100	8.2	41.4
Y	**0.112**	**1.42**	80.2	1096	4.4	0.1
B	**0.386**	**1.26**	47.6	1103	5.6	40.6

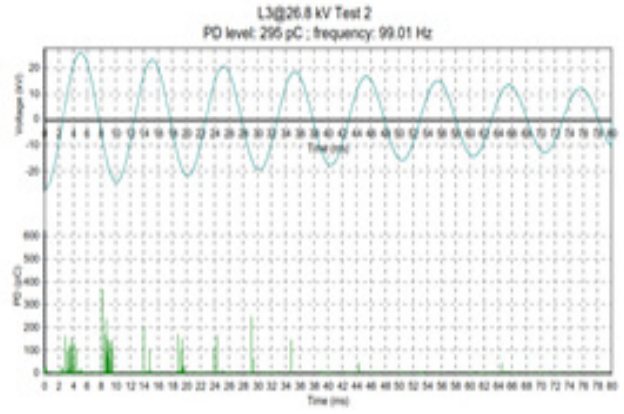


Figure 6. DAC partial discharge pattern circuit-1 cable (2014).

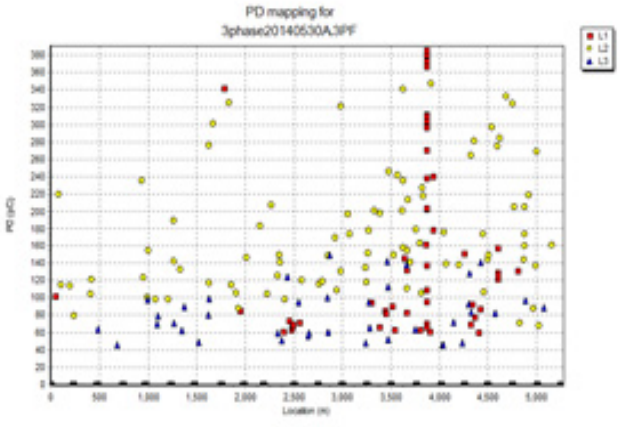


Figure 7. PD Mapping circuit-1 cable (2014).

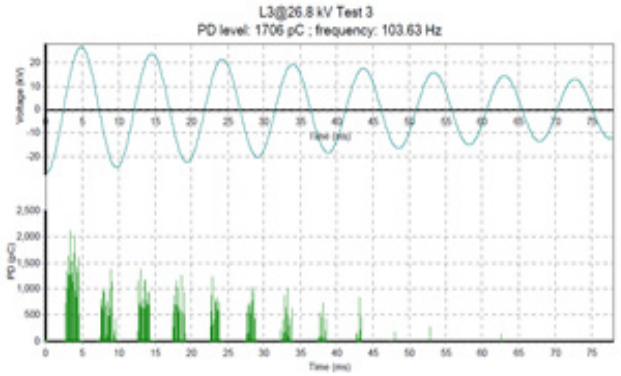


Figure 8. DAC partial discharge pattern circuit-1 cable (2015).

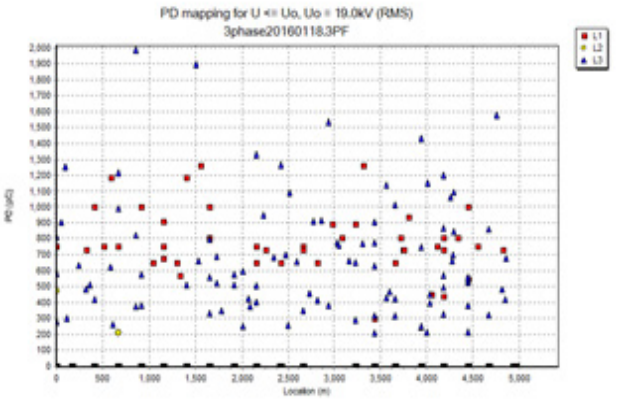


Figure 9. PD mapping circuit-1 cable (2015).

Cable exhibits high dielectric losses and hysteresis characteristic of tan delta. The cable exhibits PD at multiple sites along the length. It is recommended to inspect the cable at three locations for the possible mechanical damage or cut or metallic protrusions or ingress of moisture. The condition of the cable is ranked as 'Critical'.

Cable is not healthy in view of high dielectric losses and substantial partial discharges almost at all the joints of the cable. It is recommended to replace these two high risk joints and repeat the tests. The condition of the cable is ranked as 'Critical'.



Figure 10. Dissected photo of the joint-1 replaced.



Figure 11. Dissected photo of the joint-2 replaced.

Table 7. Circuit-2 (2014 and 2015)

Phase	IR (GΩ)	PI	VLF-TD @ U_0 (10^{-3})	Cap (nF)	VLF-TDTS @ U_0 (10^{-3})	VLF-DTD (10^{-3})
R	56.5	0.05	4.0	1138	0.0	1.9
Y	4.32	0.64	3.8	1136	0.0	1.7
B	50.8	1.04	4.1	1133	0.0	1.8
R	1.46	1.53	6.6	1140	0.2	3.4
Y	1.45	1.53	6.1	1138	0.1	2.9
B	1.46	1.57	6.6	1135	0.1	3.1

The cable is generally healthy. However, in view of symptoms of on-set of water treeing phenomenon in the XLPE insulation, it is recommended to repeat the diagnostic testing after two years. The condition of the cable is ranked as 'Moderate'.

Table 8. Main spare (2014 and 2015)

Phase	IR (GΩ)	PI	VLF-TD @ U_0 (10^{-3})	Cap (nF)	VLF-TDTS @ U_0 (10^{-3})	VLF-DTD (10^{-3})
R	33.9	1.26	4.7	1091	0.3	2.8
Y	39.5	1.63	5.3	1089	0.1	3.0
B	25.0	1.52	10.7	1095	0.3	7.6
R	0.280	1.15	11.6	1095	0.1	4.0
Y	0.368	1.27	8.6	1099	0.0	3.2
B	0.201	1.18	11.5	1086	0.0	2.7

The cable is generally healthy. However, in view of relatively higher dielectric losses, it is recommended repeat the diagnostic tests after one year to monitor trend. The condition of the cable is ranked as 'Moderate'.

Table 9. Spare-1 (2014 and 2015)

Phase	IR (GΩ)	PI	VLF-TD @ U_0 (10^{-3})	Cap (nF)	VLF-TDTS @ U_0 (10^{-3})	VLF-DTD (10^{-3})
R	261	2.11	5.5	95	0.1	0.6
Y	615	1.39	4.6	97	0.1	2.7
B	909	1.51	7.6	96	0.1	4.5
R	0.023	0.96	520.5	91	36.3	-261.6
Y	0.017	1.11	646.2	92	39.6	-270.0
B	0.051	0.96	331.9	90	4.0	22.2

2014: The cable is generally healthy. However, in view of relatively higher dielectric losses, it is recommended repeat the diagnostic tests after one year to monitor trend. The condition of the cable is ranked as 'Moderate'.

2015: The cable is not healthy. In view of intense surface discharge activity in the terminations, the heat shrinkable terminations are not healthy. In view of this, it is recommended to replace terminations and repeat the tests. The condition of the cable is ranked as 'Critical'.

Table-10. Spare-1 (2014 and 2015)

Phase	IR (GΩ)	PI	VLF-TD @ U_0 (10^{-3})	Cap (nF)	VLF-TDTS @ U_0 (10^{-3})	VLF-DTD (10^{-3})
R	2.40	0.70	11.0	45	1.6	7.3

Y	0.70	4.02	12.7	45	0.1	4.6
B	2.21	0.51	10.0	45	0.1	7.2
R	0.426	1.10	103.4	45	12.4	-201.0
Y	0.189	1.39	71.5	45	5.3	-185.6
B	0.115	1.99	112.8	45	11.6	-590.9

2014: The cable is generally healthy. However, in view of relatively higher dielectric losses, it is recommended repeat the diagnostic tests after one year to monitor trend. The condition of the cable is ranked as 'Moderate'.

2015: The cable is not healthy. In view of spark over observed at the end of cable termination and hissing sound heard for all the three cores, it is recommended to replace the terminations and repeat the tests. The condition of the cable is ranked as 'Critical'.

4. CONCLUSIONS

Based on field experience in conducting various diagnostic tests the following conclusions are drawn.

- VLF dissipation factor testing is very effective tool for condition assessment of service aged medium voltage power cable system.
- In addition to VLF Tangent Delta (VLF-TD), VLF Differential Tangent Delta (VLF-DTD) and VLF Tangent Delta Temporal Stability (VLF-TDTS) are vital diagnostic indicators and very sensitive to insulation degradation of MV power cable system. It is evident from test data that negative VLF-DTD corresponds to surface discharge. Very high value of VLF-TDTS corresponds to surface discharge.
- Partial Discharge (PD) test with the application of damped ac voltage is an efficient diagnostic tool for detection, location and recognition of incipient fault at an early stage. It can help utilities in avoiding forced outages in critical power cable networks.
- Results obtained from diagnostic testing can provide valuable input for asset management planning, supporting decisions related to maintenance strategies, equipment replacement, and overall evaluation of system condition. These insights help utilities and industries plan appropriate actions to ensure reliable operation of their cable networks.

5. ACKNOWLEDGEMENTS

The authors are thankful to Management of Central Power Research Institute, Bangalore for giving permission to present the paper.

6. REFERENCES

1. Mallikarjunappa K, Ramaprasath S, Keri CD, Sudhindra A. CPRI, Bangalore, very low frequency tan delta testing and condition assessment of medium voltage polymeric cables.
2. Long-life XLPE-insulated power cables, Edited by Harry Orton, Orton Consulting Engineers, Canada & Rick Hartlein, National Electrical Energy Testing Research and Application Center, USA.
3. IEEE Std 400TM-2012, IEEE guide for field testing of shielded power cable systems rated 5kV and above.
4. IEEE Std 400.2TM-2013, IEEE Guide for field testing of shielded power cables using very low frequency (less than 1Hz).
5. IEEE Std 400.3TM-2006, IEEE Guide for guide for partial discharge testing of shielded power cables in a field environment.