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Field Testing and Condition Assessment of MV Power Cable System by Very Low Frequency (VLF) AC Testing

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Abstract

A huge capital investment goes for power cables in an electric power system. Reliability and life expectancy of service-aged power cables can be assured by systematic field testing and condition assessment program. Very Low Frequency (VLF) ac Testing proved effective for field testing and condition assessment of shielded Power Cable System. Central Power Research Institute (CPRI), Bengaluru, a premier institute for Indian Power Sector has been conducting diagnostic testing on medium voltage power cable systems to assess the healthiness of the power cable systems and cable system components. In this paper application of VLF testing for withstand and other diagnostic tests and measurements are discussed. Few case studies based on the data obtained from the field testing on MV Power Cable System are presented.

Keywords: Very Low Frequency (VLF), VLF Dielectric Spectroscopy (VLF-DS), VLF Differential Tangent Delta (VLF-DTD), VLF Monitored Withstand Test (VLF-MW), VLF Partial Discharge (VLF-PD),VLF Tangent Delta (VLF-TD), VLF Tangent Delta Temporal Stability (VLF-TDTS)

1. Introduction

The samples of cables and accessories normally undergo quality assurance testing at factory before laying. Manufacturing defects such as voids, contaminations, irregularities at the insulation/shield interfaces, are screened out during production by conducting tests such as partial discharge and AC withstand test. The field testing are conducted on in-service cables to detect defects/problems caused by shipping, handling, improper installation, poor workmanship in preparing joints and terminations, and undetected manufacturing defects. The field 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. The cable insulation system in service is subjected to a combination of electrical, mechanical, thermal and environmental stress. These stresses can cause irreversible changes in the properties of materials in the cable insulation system. These stresses in conjunction with contaminants, defects, protrusions and voids in the insulation or at interfaces cause degradation[1,2].

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.

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2. Very Low Frequency (VLF) AC Testing[3]

Ideally, field withstand testing of cable would be done using the same power frequency as would normally have applied to the cable under operating conditions, but at higher voltage.

However, because of inherent capacitance of long runs of medium-/high-voltage concentric shielded cable, the excessive charging current is beyond the limits of the normally available power sources and test equipment found in the field, except costly ac resonant test systems. When required to perform field testing on long lengths of medium-/high-voltage cable with an alternating current source, an alternative to apply power frequency is very low frequency (VLF, 0.01 to 1 Hz). The charging current of very low frequency at 0.1 Hz is only 1/500 or 1/600 of that at 50 Hz or 60 Hz respectively so that significantly smaller and more portable VLF sources have capability to test cable system of relatively long lengths. The VLF testing has more detection capability as compared to power frequency.

The VLF diagnostic test methods of cable system are as follows:

1. VLF Tangent Delta Measurement (VLF-TD)
2. VLF Differential Tangent Delta Measurement (VLF-DTD)
3. VLF Tangent Delta Temporal Stability (VLF-TDTS)
4. VLF Dielectric Spectroscopy (VLF-DS)
5. VLF Loss Current Harmonics (VLF-LCH)
6. VLF Leakage Current (VLF-LC)
7. VLF Partial Discharge (PD) Measurement (VLF-PD)
8. VLF Monitored Withstand Test (VLF-MW)

Methods 5 and 6 are in limited use.

2.1 VLF AC Voltage Withstand Test

The purpose of withstand test is to verify the integrity of the cable under test. If the test cable has a defect severe enough at the withstand test voltage, an electrical tree will initiate and grow in the insulation. Inception of an electrical tree and channel growth time are functions of several factors including test voltage, source frequency and amplitude, and geometry of the defect.

The voltage levels for installation and acceptance are based on the most used, worldwide practices of from less than 2U0 to 3U0, where U0 is the rated rms phase to ground voltage, for cables rated between 5 kV to 69 kV. The maintenance test level is about 75% of the acceptance test level. One can reduce the test voltage by another 20% if the voltage is applied for longer times. Evidence indicates that increasing the voltage above 3U0 to compensate for reduced test cycles (time) does not replicate performance either on test or in service as compared to the lower voltage, longer time tests.

The recommended minimum testing time for simple withstand test on aged cable circuit is 30 min at 0.1 Hz. If the circuit is considered as important, e.g. feeder circuits, then consideration should be given to extending the testing time to 60 min at 0.1 Hz. The recommended minimum testing time for installation and/or acceptance withstand test on new cable circuits is 60 min at 0.1 Hz. A test time within the range 15–30 min may be considered if the monitored characteristics remains stable for at least 15 min and no failure occurs.

2.2 Tangent Delta/Differential Tangent Delta/Tangent Delta Stability/Leakage Current/Harmonic Loss Current Tests with VLF Sinusoidal Waveform

VLF Tangent delta/differential tangent delta/tangent delta stability/leakage current/loss current harmonics measurements are used to monitor aging and deterioration of cable systems. However, Tangent Delta (VLF-TD), Differential Tangent Delta (VLF-DTD), Tangent Delta Stability (VLF-TDTS) measurements are most commonly used methods in the field. A correlation between an increasing 0.1 Hz tan delta and a decreasing insulation breakdown level at power frequency has been reported. The 0.1 Hz tangent delta, differential tangent delta, and tangent delta stability are mainly determined by the degradation of the cable insulation (water tree), corroding metallic shields, insulation moisture, and degraded accessories. The measurement of tangent delta, differential tangent delta and/or tangent delta stability with 0.1 Hz sinusoidal waveform offer comparative assessment of aging of PE, XLPE, TRXLPE, EPRs, and paper-type insulations and can be used a diagnostic test. The results permit differentiating between new, defective, and highly degraded cable systems. Cable system can be tested in preventive maintenance programs and returned to service after testing. The measurements at VLF can be used to make decisions on cable/accessories replacement, cable rejuvenation, or repair expenditures.

Tangent delta at 0.5U0, U0 and 1.5U0, are measured and differential tangent delta or tip up DTD = TD(1.5U) - TD(0.5U0) is calculated. In addition variation of tangent delta with time at a particular voltage (TDTS), usually over a period of some minutes, can be measured from which the mean and standard deviation of the readings can be calculated. The tan delta stability refers to variation of tangent delta with time at constant voltage. The tangent delta stability is defined as the measurement of standard deviation of tangent delta with time at particular voltage U0.

2.3 VLF Partial Discharge Measurement

A pure, sinusoidal 0.1 Hz voltage is applied to the cable system for VLF partial discharge measurement. The applied voltage of up to two times the rms system line-to-ground voltage may generate partial discharges at insulation defect sites. A travelling wave method may be used to measure the magnitude of PD, locate and record partial discharges from various defect locations in cable, splices, or terminations. VLF-PD measurements are diagnostic tool used to detect, in nondestructive manner, the location and severity of an insulation defect.

2.4 Dielectric Spectroscopy with VLF Sinusoidal Waveform

Measurement over a range of frequencies and voltages, e.g. dielectric spectroscopy, provide information about the status of the insulation. A programmable high-voltage generator and an active bridge have been used to measure loss currents in medium voltage cables at range of voltages and frequencies from 0.1 mHz to 1 kHz.

The loss currents at frequencies below 1 Hz are sensitive to degradation due to water trees in extruded XLPE cables. The loss current also offers comparative assessment of the aging of paper/oil cables. The measured value is primarily influenced by the condition (age, contamination, and moisture ingress) of various cable system components (accessories, cable insulation and metallic shields).

3. Case Studies

3.1 Case 1

Single core, 66 kV, 180 Sq.mm XLPE Cables. Length of Cables: R – Phase 345 m, Y – Phase 337 m, B – Phase 332 m. No joints. The diagnostic test data obtained on these cables are summarized in the Table 1. Figure 1 shows VLF tangent delta versus test voltage.

Table 1. Diagnostic test data for Case 1

Phase	IR (GΩ)	VLF-TDTS ($x 10^{-3}$)	VLF-DTD ($x 10^{-3}$)	VLF-TD ($x 10^{-3}$)	C (nF)
R	156	0.1	1.78	1.88	66
Y	178	0.1	1.56	1.66	63
B	120	0.1	3.02	3.12	64

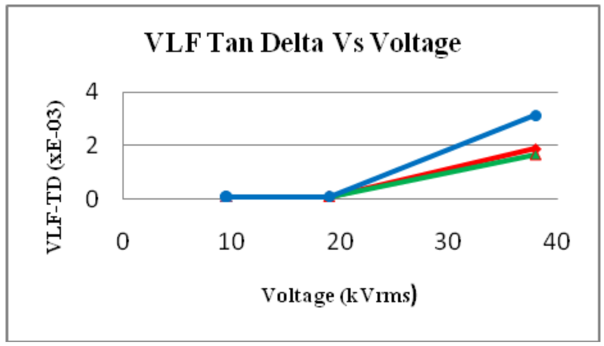

Figure 1. VLF Tan delta vs Voltage characteristic for Case 1.

The IR values are high and lie in the normal permissible range for service-aged XLPE cables. The VLF-TDTS, VLF-DTD and VLF-TD values are low and lie in the normal permissible range for service-aged XLPE cables. The VLF partial discharge (VLF-PD) test was conducted on the cables at Switchyard. No partial discharge activities observed along the length of the cables in all phases.

3.2 Case 2

Single core, 66 kV, 180 Sq.mm XLPE Cables. Length of Cables: R – Phase 326 m, Y – Phase 317 m, B – Phase 318 m. No joints. The diagnostic test data obtained on these cables are summarized in the Table 2. Figure 2 shows VLF tangent delta versus test voltage.

Table 2. Diagnostic test data for Case 2

Phase	IR (GΩ)	VLF-TDTS ($x 10^{-3}$)	VLF-DTD ($x 10^{-3}$)	VLF-TD ($x 10^{-3}$)	C (nF)
R	111	**0.5**	**16.95**	**13.81**	63
Y	131	**0.5**	**14.41**	**14.51**	61
B	161	0.1	3.63	3.73	60

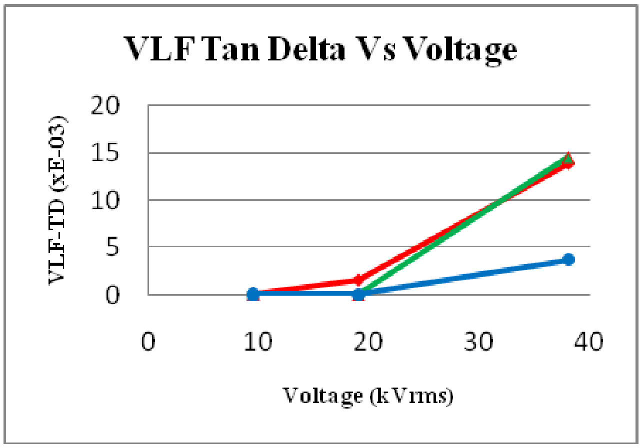

Figure 2. VLF Tan delta vs Voltage characteristic for Case 2.

The IR values are high and lie in the normal permissible range for a service-aged XLPE Cables. The VLF-TDTS, VLF-DTD and VLF-TD values for R & Y phases are higher than the normal permissible range for service-aged XLPE cables. The Partial Discharge (PD) test using VLF has been conducted on the cables at Switchyard. PD magnitude and location are tabulated in Table3. No partial discharge activity observed along the length of the cable for B phase. The PD Mapping along length of cables for R & Y phase shown in Figures 3 and 4. As it can be seen in the Figures 3 and 4, the cable exhibits surface discharge in the termination at Switchyard end. PD Mapping data correlating well with the high VLFVLF-TDTS, VLF-DTD and VLF-TD values and are sensitive to cable system degradation.

Table 3. PD magnitude and location

Phase	Measured at Switchyard	
	Maximum PD magnitude(pC)	**Distance from GT end (Meter)**
R	12000	326
Y	5000	317

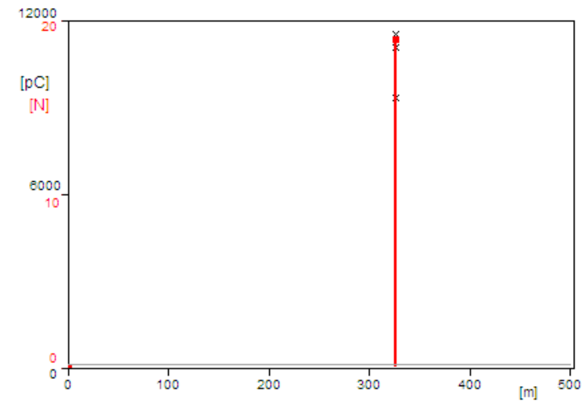

Figure 3. PD Mapping on R Phase.

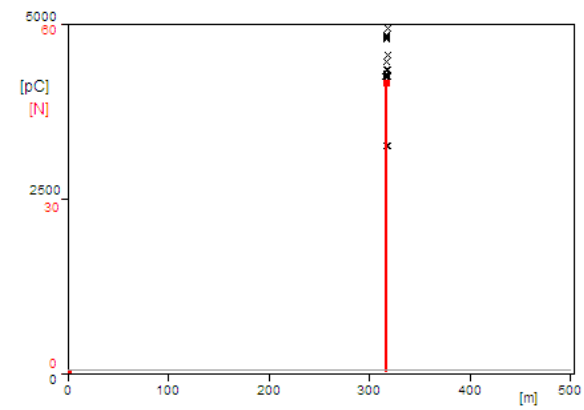

Figure 4. PD Mapping on Y Phase.

3.3 Case 3

Single core, 66 kV, 180 Sq.mm XLPE Cables. Length of Cables: R – Phase 326 m, Y – Phase 320 m, B – Phase 330 m. No joints. The diagnostic test data obtained on these cables are summarized in the Table 4.

Table 4. Diagnostic test data for Case 3

Phase	**IR (GΩ)**	**VLF-TDTS (x 10^{-3})**	**VLF-DTD (x 10^{-3})**	**VLF-TD (x 10^{-3})**	**C (nF)**
R	43	0.1	2.59	2.69	62
Y	456	**0.2**	2.93	3.03	62
B	357	0.1	1.54	1.64	63

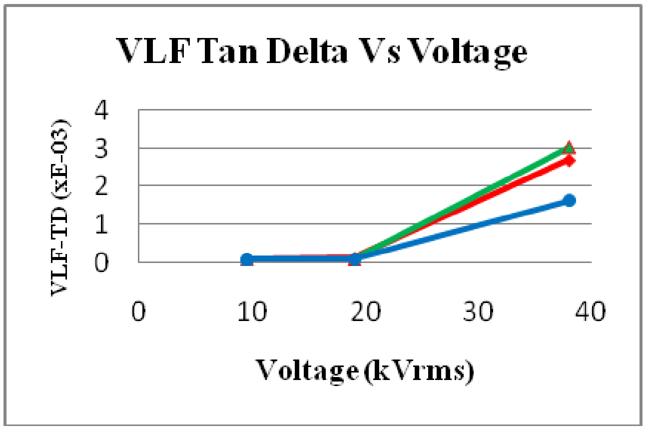

Figure 5. VLF Tangent delta vs. Test voltage.

Figure 5 shows VLF tangent delta versus test voltage. The IR values are high and lie in the normal permissible range for service-aged XLPE cables. The VLF-TDTS, VLF-DTD and VLF-TD values are low and lie in the normal permissible range for service-aged XLPE cables. VLF partial discharge (VLF-PD) test was conducted on the cables at Switchyard. PD magnitude and location are tabulated in Table 5. No partial discharge activities observed along the length of the cable for Y & B phases. The PD Mapping along length of cables for R phase shown in Figure6. As it can be seen in the Figure 6, the cable exhibits partial discharge in the termination at Switchyard.

Table 5. PD magnitude and location for Case 3

Phase	Measured at Switchyard	
	Maximum PD magnitude(pC)	Distance from GT end (Meter)
R	2000	326

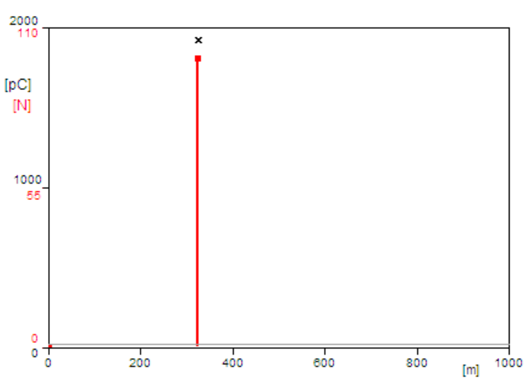

Figure 6. PD Mapping on R Phase for Case 3.

3.4 Case 4

Dielectric frequency response on a new healthy Single Core, 11 kV XLPE cable. The frequency response plot is presented in Figure 7.

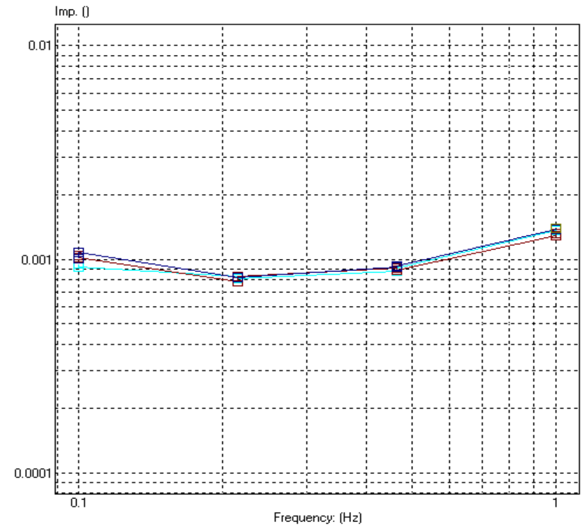

Figure 7. Frequency vs Tan delta characteristic at different voltages.

It can be seen that dielectric losses are independent of voltage and frequency. The dielectric frequency response characteristic is almost flat.

3.5 Case 5

Dielectric frequency response on 23 year old water treed cable Single Core, 11 kV XLPE cable. The frequency response plot is presented in Figure 8.

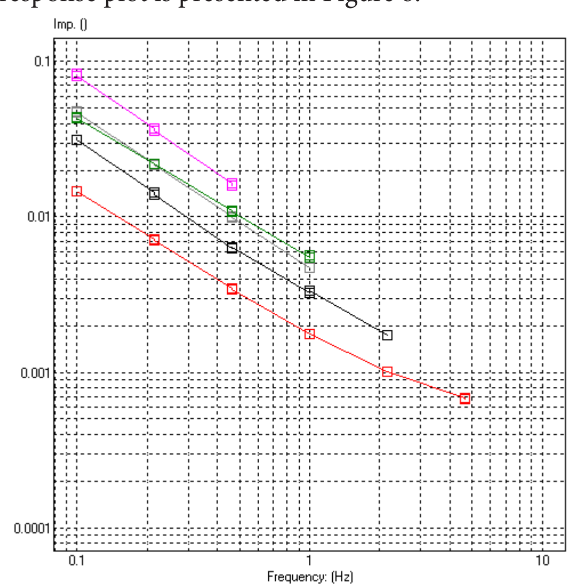

Figure 8. Frequency vs Tan delta characteristic at different voltages.

It can be seen that dielectric losses are exhibiting voltage and frequency dependence characteristics.

4. Conclusions

From above diagnostic tests data presented in the case studies it can be concluded that the VLF –TD, VLF DTD and VLF-TDTS are very sensitive to the degradation of cable system in service. VLF PD is capable of detecting PD location along the length of the cable. Dielectric Frequency Response is effective for water treed cable system. The VLF testing results permit differentiating between new, defective, and highly degraded cable systems.

The measurements at VLF can be used to make decisions on cable/accessories replacement, cable rejuvenation, or repair expenditures.

5. Acknowledgement

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6. References

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