52nd Annual

Transmission and Substation Design and Operation Symposium

Cable Testing Anomalies for Windpark Testing Applications: Cable Fault Location, Test and Diagnostics

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Abstract

The US wind industry added approximately 7.6GW of new wind-turbine generation capacity within the US in 2018 according to the American Wind Energy Association (AWEA) and the total wind generation capacity within the United States is approaching 100GW. Demand is still growing for wind-turbine based generation in the US and facilities are constructed in the most expedient and cost-effective manner to meet demand. In the process of meeting those demands, design philosophy, complexity of installation, environmental conditions and deficient workmanship practices may result in reduced system reliability and service life.

Moreover, within the wind park industry, there are specific challenges related to Cable Fault Locating (CFL) and Cable Test and Diagnostic (CTD) applications. Long runs of cable, the inability to sectionalize properly, cross-bonding issues, limited to no possibility to use Time Domain Reflectometry (TDR) technique, and cable accessory failures, are some of the unique challenges that are common throughout the industry. Additionally, utilization of native backfill versus engineered backfill, can result in physical sheath damage and higher thermal stresses resulting in loss of life and potential unexpected downtime of the wind generation system.

This paper describes the challenges encountered and the methods to overcome these challenges. Authors will elaborate on methods to more effectively troubleshoot and fault locate on these systems. Furthermore, a testing and diagnostics methodology section will cover the fundamentals of diagnostic test methods including sheath fault, tan delta and offline-PD testing to improve system reliability and prevent loss of generation.

I. Introduction

Renewable power-generation industry growth shows no sign of abating or slowing down in the near-future. Facilities have undergone a natural evolution over time from the earliest wind-farm sites to the more recently constructed facilities. The newer facilities have incorporated a wide variety of improvements with both economic and technical considerations. Substation construction practices have become standardized due to hundreds of sites being constructed within the United States as well as around the world. Feeder construction practices have benefited as well with millions of linear foot length of medium voltage (MV) feeder cables being installed to interconnect a multitude of wind-turbines based generation in the field.

Design and Installation practices involving soil conditions, topology of system configurations, cable rating calculation, soil-backfill practices, cable sizing and ratings, and site operational and economic considerations have evolved over time to mitigate issues observed with system reliability and other economic impacts.

Primary goal for engineering and ownership is to lower the cost per circuit mile of construction, maximize the amount of MW generation for a given site with the least amount of capital expended on generation feeder investment, as well as maximizing the reliability and operability of constructed systems. Many of these improvements have been driven by equipment specifications, and construction practices as well as the implementation of a greater number of junction-boxes or locations that allow for system sectionalizing for commissioning, maintenance as well as system testing, and troubleshooting applications.

II. Engineering and Economic Considerations

System topologies of strings, terrain limitations, and circuit lengths have a major impact on troubleshooting and routine testing. Shorter cable segments are required to enable prompt evaluation of a system, while aiding in cable-fault location should a failure occur. Large variations in cable sizes, types, and circuit length are present in field installations. Various sizes could impact the maximum effectively cable length that can be tested based on circuit length for both CFL and CTD methods available. The cost per linear foot of installed length was streamlined based on economic analysis over time, and this resulted in a smaller list of cable size variation.

There were limitations to the understanding of the impacts of the usage of native soils and the possible physical damage due to improper screening that may result from presence of jagged rocks. Failures can run the gamut from sheath damage during cable pulling and installation, to non-engineered or improperly screened native backfill causing damage to cable systems with rocks being driven into cable jackets and ultimately damaging the cable system to a point of failure. Engineered soil driven designs add significantly to costs of wind-farm construction and is the practical rationale for relying on native soils where possible. The primary goal during system design phases of projects is to achieve stated ampacity goals with a given cable selection with minimum soil modifications being required. This requires proper material screening to reduce the probability of damage to cable sheaths as well as adhering to proper cable installation practices.

Practices involving cross-bonding and variant grounding schemes could also contribute to issues observed in the field. Cross-bonded, single-point grounded, dual-grounded, commonly bonded neutral networks junction-boxes, and splice locations have impacts on troubleshooting activities and should be accounted for when performing both cable-fault-locating, and cable-diagnostics.

Additionally, the economically designed windfarms had limited accommodations built into the systems to account for the need to service, repair, as well as the ability to sectionalize long runs of cable. The lack of standardized construction practices with cable test in mind has resulted in particularly difficult cable fault locating activities within older facilities. Junction boxes deployed in the field at a set interval can add significant costs to facility construction but have the added benefit of allowing for timely testing and restoration of service post-cable-fault event.

III. Cable Fault Location (CFL)

CFL practices and equipment rely upon the ability of a surge device or thumper to utilize an onboard TDR, perform a voltage breakdown test to determine the flash-over voltage of the faulted cable system, and deliver a surge of energy with the appropriate voltage level to the cable system to aide in approximating the location of the fault within the cable system. This in turn will emit an electromagnetic pulses and acoustic waves from arcing forming within the cable system to be used for fault locating purposes.

Basic TDR functions require two parallel paths to ascertain a given length of a cable system. A low-voltage pulse (30V - 160V) is sent downstream between these two parallel conductors with the cable systems bulk insulation, as the media between the two conductors. In this case, one conductor is the core of a MV cable, and the second conductor is the concentric neutral of the cable system. This low-voltage pulse can determine the overall length of the cable to an open-circuit or a short-circuit location. If the cable system is intact to the very end of the cable run, the total system length will be displayed on the TDR interface. Refer to Figure 1 through Figure 3.

TDR units typically have accuracies can range from 0.1 to 1% error of the actual length of the cable. Any minor error over an exceptionally long length of cable may result in quite a wide area to fault locate within, however in this example, the fault location can be narrowed down to a 15ft to 150ft region or area vastly reducing the time required to locate the faulted cable segment and repair the system to restore generation.

The relative error will increase as the cable length increases. The primary take-away from this point, would be that approximating the location of a fault down to 15ft to 150ft area within a 15,000ft length system will vastly improve detection and repair capabilities to a relatively short timeframe. Additionally, where cross-bonding, single-point grounding, and are concerned, these construction methods should not cause issues with TDR traces as long as the neutrals are tied together as a common return for the cross-bonding scenario and there is a method to bridge the open end of a single point grounded run for the purposes of testing to approximate distance if proper steps are taken by the qualified personnel performing the test.

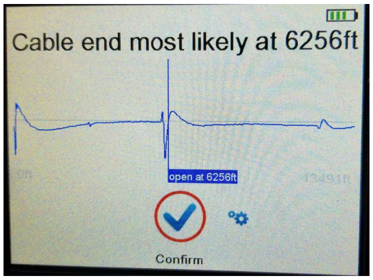

Cable end most likely at 6256ft

Figure 1: TDR response showing a short located at 6,256ft distance from junction-box to junction-box within a wind park. Image taken from a portable Surge/Thumper Unit with an integrated radar unit. Refer to FIGURE 16 for site overview.

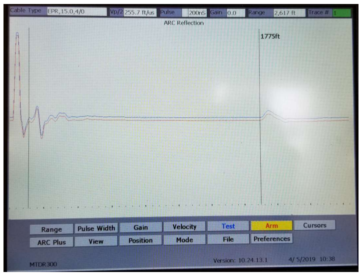


Figure 2: Example above contains a TDR trace with an open conductor at a 1,775ft distance.

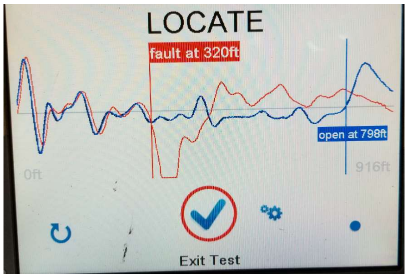


Figure 3: TDR unit trace which includes both the low-voltage and high-voltage trace. The fault location has been identified and the length of the circuit is now known.

In instances of where jackets and insulation are compromised, the low voltage TDR system alone cannot determine the magnitude and location of the system defects. In this case, a HV surge pulse is required to allow the TDR unit to locate the section of damaged cable. The HV pulse will bridge the damaged section of cable by creating a temporary arc that the TDR unit can detect. This allows for localization of damaged segments of cable on long circuit runs.

Additionally, the surge unit or thumper unit could cyclically feed an arc event at the location of cable damage to allow for further localization or pinpointing with electromagnetic, acoustic detection, and voltage gradient measurement devices. This will allow for accurate fault location activities down to the exact location of failure. The pinpointing device will allow for detection from a 100ft distance and closes the gap of distance that may have remained post TDR unit usage.

Cable fault locating options are limited by the surge or thumper system having the ability to adequately charge the cable system. If a thumper utilized to fault locate is less than 5 times the capacitance of the cable it is being used on, there is little chance for success. Ideal ratio would be closer to 10 times the cable capacitance.

If a unit is undersized it will not be able to find any faulted or damaged segments within an exceptionally long or large cable system due to limitations on the ability to flash-over open gaps within the failed cable or an inability to deliver sufficient energy to overcome attenuation effects associated with impedances inherent within the cable. Undersized systems will not have enough remaining energy to feed a large energy release or thump at the fault location. This will in turn limit the possible avenues available to locate a faulted segment of cable with a pinpointing device. Pinpointing devices perform better when a thumper is sized adequately for the size of cable system under test and a large thump or energy release at the cable fault location will result in a larger electro-magnetic and acoustic energy release, thereby ensuring that fault-locating activities are more successful.

To overcome the issues mentioned above, the appropriate surge or thumper device will need to be of the appropriate kV, Joule rating and must be equipped with a TDR unit. An ideally sized thumper unit should be larger than the cable capacitance by a factor of 10. With the proper surge or thumper device available, pinpointing activities will be fast and efficient and aide in system restoration when required.

IV. Sheath Fault Testing

Sheath fault testing is an effective tool that can be used to identify the cable sheath damage due to installation practices, related to improper laying of cable within the trench, and improper rock screening mitigation. In instances where improperly screened native backfill, less than optimal quantities of engineering soils are present, or poor installation practices have occurred, a sheath-fault test can be used to identify where a cable may have been compromised. This allows for repairs or splicing to occur as needed within the MV cable system. This type of testing is particularly important for direct buried systems such as those present in windfarms. Due to the aforementioned native rocky backfill soil damaging cable, a sheath fault test will allow for a measurement to be made between two cables to aid in locating the section of cable that is damaged.

Sheath fault testing is a required step of commissioning testing as part of IEC requirements in other parts of the world. Within the United States, this has not been universally adopted as of yet. Many wind park constructors are beginning to adopt the sheath fault test as part of commissioning activity, however this is primarily IEC driven at this time.

V. Very-Low-Frequency (VLF) Testing

VLF testing is a highly effective global assessment tool to determine the voltage withstand capabilities of a cable system that has been installed as well as functions as a highly effective maintenance test to determine if there are gross defects within a cable insulation system. VLF testing systems detect gross defects and critical water tree damage. (Note: VLF testing may add significant amounts of stress to aged systems and Tan Delta testing should be considered as a first line test before considering VLF testing.)

The primary difference between utility and wind park generation sites, is the extremely long distances between points of disconnect. This results in large segments of cable flagging as either a pass or a fail. Ideal scenario would allow for compartmentalization of the system to narrow the region impacted by system damage.

Weak spots or locations of compromised bulk insulation are typically due to physical damage, primarily external, and electrical degradation in nature and manifest in the form of water tree and electrical treeing activity. Water tree growth is a normal occurrence within energized systems, and typically does not manifest to a significant degree till the system has been energized for a minimum of 3-5 years. VLF testing on cables with less than this requisite age would be identifying factory defects, workmanship defects and issues or general gross-defects. Figure 4 is an example of uniform water-tree growth in cable.

Where water-tree growth is concentrated in one location and in this particular example, bridging 50% of the bulk insulation within the cable system. VLF testing would drive this cable to a planned failure during a planned outage and would require either repair or replacement of a segment of the cable system. Figure 5 is an example of a localized water-tree growth. Refer to figure 6 for a depiction of cable that will eventually fail in-service and result in a cable-fault. A path will ultimately form from the core of the conductor to the concentric neutrals or to an earth return path. Electrical tree activity results in cable-fault scenarios, which result in a loss-of-generation. Refer to figure 4 through figure 7 for reference information related to water-tree growth patterns as well as electrical tree examples.

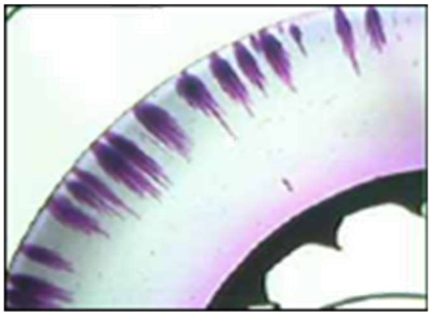


Figure 4: Uniformly Distributed water-tree growth within an aged cable.

Figure 5: Localized Water Tree growth.

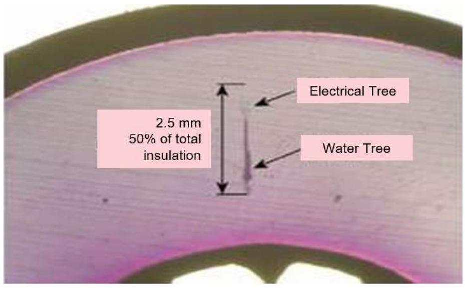


Figure 6: Water-Tree and Electrical Tree activity example with growth originating from the center of the XLPE cable sample.

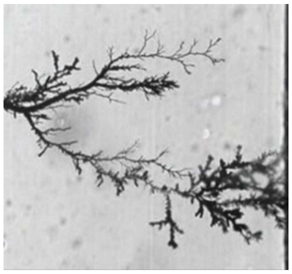


Figure 7: Electrical-Tree growths are accelerated under VLF testing conditions and converted into electrical-trees.

The primary draw-back of utilizing VLF testing without a companion test such as tan delta and partial discharge testing alone is that VLF testing is a pass-fail test method and does not allow for localization of damaged regions of the cable under test. Additionally, if a cable were to fail VLF testing, it has effectively flashed over to ground and must be repaired prior to re-energization. Refer to figure 7 for a depiction of a water-tree converted to an electrical-tree. General rule is extruded-dielectric insulation degrades if it is energized and does not self-heal after the system has been compromised. When performing VLF tests on new or existing systems, it is highly recommended to have materials and personnel on hand to repair damage that may arise as part of this suite of testing methodologies.

VLF testing does not create weak-spots or initiate damage within cable systems. VLF testing grows existing electrical-trees in an accelerated period of time to allow for fault-location and repair activity to occur without a system outage. Refer to NEETRAC Project Numbers: 04-211/04-212/09-166 for additional information. With that being stated, it is important to remember, VLF testing locates existing deficiencies (and does not create new problems) within cable systems under controlled conditions. It is an integral part of commissioning testing when in-servicing new facilities and runs of cable. VLF testing can also benefit from the same system accommodations that are recommended for all CFL and CTD applications, as test sets do have limitations as to how large a cable system can be effectively tested (refer to CFL and PD sections of document for additional information).

VLF test levels are prescribed within IEEE 400.2. IEEE recommends 30-60-minute test durations for VLF testing. (NOTE: IEC standards also dictate test levels that are different than those listed within IEEE.) The "Dortmunder Energie und Wasser Experience Report", covering a period from 1987-1997, concluded that it is recommended that a 60-minute test is performed to have a high probability of locating 97% of weak spots within cable systems. The study also found that statistically, there was a reliability improvement of fault-free operation (NOTE: Faults referenced here would be those caused by electrical-tree activity alone.) for 3 to 5 years after performing VLF tests for 60-minutes. This resultant increase in system reliability on a distribution system will directly translate into similar gains in reliability for a generation site. The minor time-investment related to an additional 30-minutes in testing improves the faults located from 75% within the first half-hour to 97% of faults within a cable system at 60-minutes of test time. Refer to figure 8.

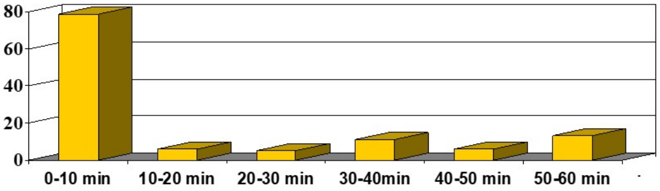


Figure 8: Dortmund benchmark study performed between 1987-1997.
"Dortmunder Energie und Wasser" Experience Report 1987-2007.

The test parameters for VLF testing for new installations, acceptance testing, as well as maintenance testing are outlined within IEEE 400.2, Table 3. Based on IEEE 400.2 recommendations, the current time recommended for testing is 30-minutes, unless the circuit is deemed critical enough to warrant a 60-minute test. VLF testing is an integral part of a commissioning testing, maintenance testing, as well as post-repair test regimen and allows for the identification of weaker cable segments and cable accessories avoiding unplanned outages. The recommendation is to couple a VLF testing system with a partial-discharge system to obtain the most complete results related to the health of any cable system. Additionally, there is a monitored withstand test that performs both VLF and PD testing simultaneously

VI. Tan Delta (Tan Δ) Testing

Tan-Delta testing is a powerful tool used to assess the health of aged MV power-cable installed in the field. Tan-Delta testing relies upon a VLF technologies to perform tests that is utilized to ascertain the level of resistive losses within cable systems.

Tan-Delta cable testing as with VLF testing allows for the assessment of the global health characteristics of the entire cable system. Tan-delta testing typically has more value if performed as a stand-alone test and not specifically tied into an automatic test sequence as this can be utilized to determine level of system health by allowing for a gradual increase in voltages within a stepped voltage test for a reduced time-period as compared to a standard VLF test, which would be performed for 30-minutes. This can allow for the test to be cancelled if results are exceptionally poor to allow for investigation of the cable system and allow for possible system improvements to prevent failure. The inclusion of a dual-test mode is common in some equipment within the industry however with VLF and Tan Delta testing being performed concurrently. This feature difference is merely a matter of preference ultimately for an end-user.

Due to tan-delta test sets utilizing VLF units as sources, the same system sizing requirements are tied to tan-delta measurements. Exceptionally large systems may present challenges, equipment shall be adequately sized to the sample under test. Conversely, some system designs should take into consideration the practical limitations of test equipment on the market and add junction-boxes to the system to allow for sectionalizing to take place. This has the added benefit of a segmented health-check on a large system. Rather than assessing 28,000ft of cable, an assessment can be made at a fractional length. This allows for isolation of problematic sections from the greater system and allows for targeted assessment with VLF and PD test sets.

The dielectric losses measured by the tan-delta test sets are primarily determined by conductivity losses within cable insulation. New cable that has not been energized will have low-losses due to a lack of water-tree growth within the cable bulk-insulation. (NOTE: New Cable should not be tan delta tested within the first year of operation. TR-XLPE for example is still stabilizing and test results can be very high.) As water-trees grow within the bulk-insulation, the Insulation resistance increases. As this value increases, the Tan Delta value will increase. The higher the value of Tan Delta the closer the cable system is approaching an end-of-life condition or a cable-fault event resulting in a loss-of-generation and service. Refer to Figure 9 and Figure 10.

$$\tan\delta = \frac{I_R}{I_C} = \frac{1}{\omega RC}$$

Figure 9: Dielectric Losses (Tan Delta) Formula

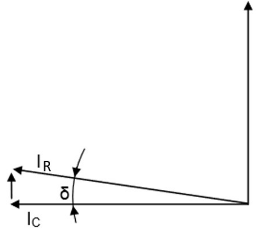


Figure 10: The dielectric losses, tanδ can be calculated based on the formula within figure 9. Newer cables have low to no conductive losses, which will result in a Tan Delta value approaching zero.

Tan Delta values measured in field conditions will closely align with what is shown in Figure 11. Under ideal conditions, new cable will yield a low value Tan Delta resultant and will remain the same at elevated voltage levels. For a typical tan-delta result, refer to Figure 12 for an example resultant from a field installed cable.

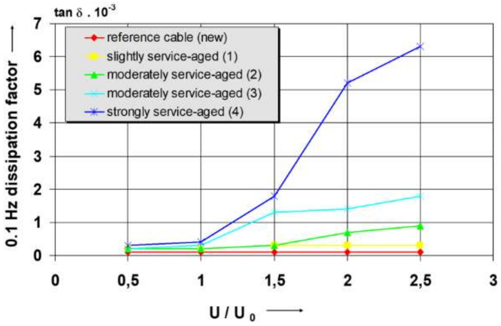
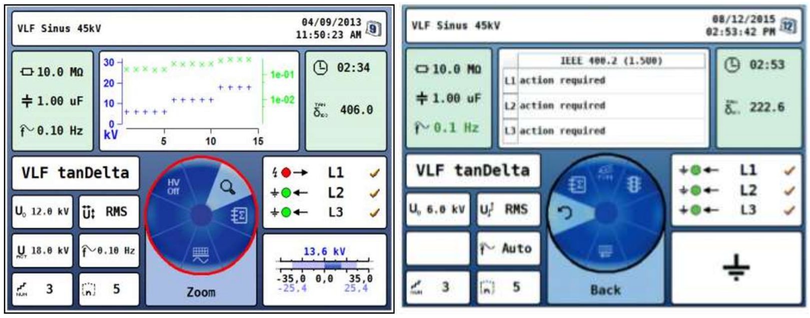


Figure 11: Tan Delta values will trend higher as cables age and water-tree growth or another bulk-insulation degradation occurs. New cable from a manufacturer should approximate the red plot as there are no appreciable losses due to degradation in new cable from the factory. Source of this information is from Jicable, Versailles, June 1995, Paper B.9.6

Variance in Tan Delta in cable systems can be caused by high-humidity, surface contamination and chemical curing properties of bulk cable insulation that has been recently manufactured. Precautions should be taken to minimize the contributions of environmental conditions on tan-delta results such as shielding the sample under test from humidity or in extreme circumstances, conditioning the air in the area where testing is occurring.

The key function of Tan-Delta testing is to test aged cable systems. This test method has limited utility for a newly installed run of cable. Recalling the primary mode of failure within extruded cable systems or plastic systems, XLPE and EPR systems, is the growth of water-trees, and water-tree growth requires a cable to be energized for a prolonged period of time, this test will have little to no value within a new cable system, and may have limited value within an aged system as a stand-alone testing methodology due to the lack of ability to demonstrate or localize where the damaged or suspect portion of cable is located. This test requires a companion test to allow for classification and localization of issues. The method of testing is dictated by IEEE 400.2 with prescribed test levels and criteria for interpretation of resultants to assess the health of cable systems in the field.


VLF Sinus 45kV
04/09/2013
11:50:23 AM
10.0 MΩ
1.00 uF
0.10 Hz
02:34
406.0
VLF tanDelta
U₀ 12.0 kV
RMS
U 18.0 kV
0.10 Hz
3
5
13.6 kV

VLF Sinus 45kV
08/12/2015
02:53:42 PM
10.0 MΩ
1.00 uF
0.1 Hz
IEEE 400.2 (1.500)
L1 action required
L2 action required
L3 action required
02:53
222.6
VLF tanDelta
U₀ 6.0 kV
RMS
Auto
3
5

Figure 12: Example Test results from a Tan Delta test set. IEEE 400.2, Table 4 through Table 8 can be utilized to determine health of the sample cable under test.

Within a windfarm system, given the exceptionally long lengths of services within facilities, a non-localized test result does not provide enough information alone to determine where a problem may be located along a long length of cable. Tan-delta testing can be used to evaluate the magnitude of degradation within a cable system, however due to the outdoor conditions of a windfarm, there are precautions that must be taken to improve environmental testing conditions (humidity, temperature, and contamination on the surface of the object under test), as well as the physical configuration and location of the sample under test to improve the accuracy of the test results. Refer to Figure 13**.**

Segments of cables within windfarms can be as long as 28,000ft or more before junction-box locations where sectionalizing can occur. The installation of junction-boxes would also aide in being able to segment the system to determine which portions contain the more compromised bulk insulation to aid in either analysis or repair work. Tan-delta testing works well with a companion test. That companion test methodology is Partial Discharge testing. Partial-discharge testing coupled with tan-delta testing may allow for localization of damage within a run of cable. The key function of Tan-Delta testing is to test aged cable systems. This test method has limited utility for a newly installed run of cable. Good commissioning testing methodologies such as sheath testing, VLF withstand and PD diagnostic testing will be of greater value.

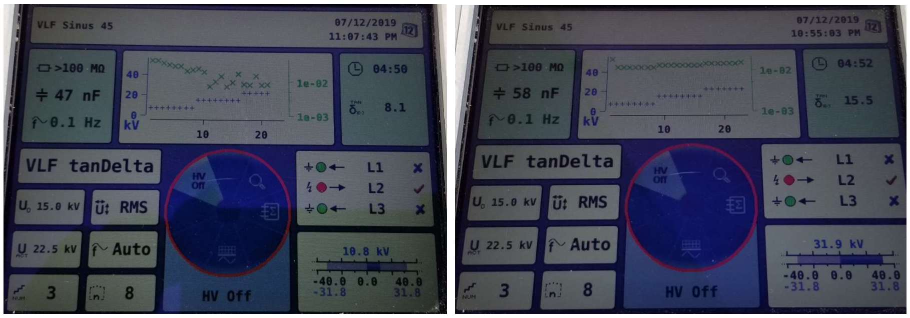


Figure 13: The screen capture on the left demonstrates the impact of testing in high-humidity conditions. The results do not align with expected results. The screen capture on the left is the same cable after multiple tests. Results stabilized after a dry out period along with other physical mitigation measures. Compared to results in Figure 12, these results are aberrant due to high humidity.

VII. Partial Discharge (PD) Testing

Partial Discharge testing relies upon localized capacitive discharge events within a cable system to be detected via highly sensitive equipment. This method of testing is highly sensitive, and precautions must be taken to reduce background noise levels, improve base calibration results, as well as reduce or eliminate PD activity caused by the test-connections connected to the sample under test.

Partial discharge testing can be utilized to determine the location and magnitude of issues within a cable system. This method of testing can diagnose and locate issues during all phases of a cable systems life cycle, including installation, and commissioning phase of life, mid-life maintenance, as well as end-of-life failure. Partial discharge testing methodologies exist in a few varieties. For the purposes of field testing of cable systems, offline practices will be the primary focus of this document.

Within a wind park facility, this method of testing allows for the identification of specific locations within a large cable system that are damaged or are trending toward failure. PD testing allows for commissioning tests are sensitive enough to detect issues prior to energization. Due to the fact that a majority of failures are caused by workmanship, handling, and installation issues. Workmanship issues result in faults in splices, terminations, elbows and t-bodies, and are primarily caused by improper cut backs, misalignment, or the usage of the incorrect materials. Material handling issues due to incorrect cable-pulling techniques, transportation damage, burial and compaction processes.

PD testing may be performed using various waveshapes: near-power-frequency technologies like Damped Alternating Current (DAC) or Cosine Rectangular VLF (Slope), or other technologies like 0.1 Hz Sine VLF. Refer to Figure 14 for example PD test results for cosine-rectangular and sinusoidal testing methods. The depicted comparison series of PD technologies were part of a test that was performed at 1.7 times operating voltage during a PD-test in the field. This test was performed in Germany on a direct buried system and was meant to serve as a side-by-side comparison. Refer to Figure 15 through Figure 17 for cosine-rectangular output traces from a PD test set, the first image shows a damped AC (DAC) output and the second figure demonstrates the localization capabilities of PD test sets.

Cosine-rectangular based and the similar power-frequency test methods will detect low-magnitude PD activity within large cable systems. Amongst the most important pieces of information derived from PD testing are the partial discharge inception voltage (PDIV) and the partial discharge extinction voltage

(PDEV). PDIV is the voltage at which PD activity begins, and PDEV is the voltage at which PD activity ceases or is extinguished. In instances where the PDEV is below the operating voltage, the damaged section within the cable is a continually being etched away, which will ultimately result in a cable failure.

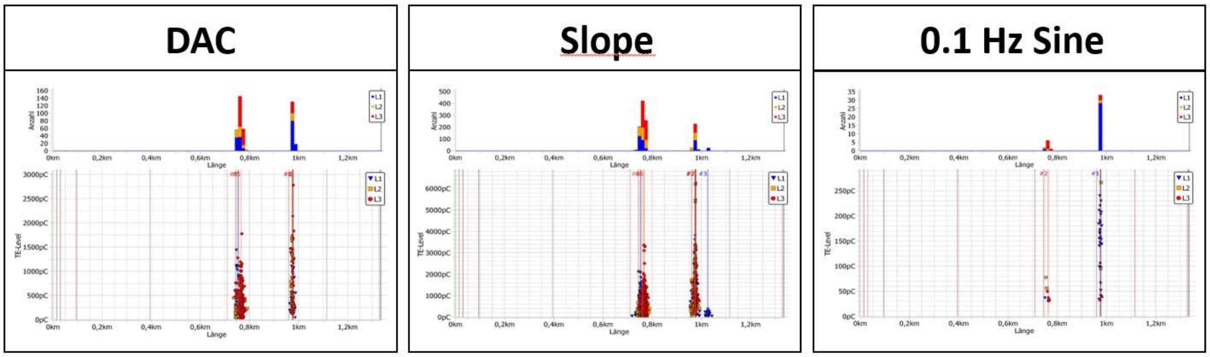
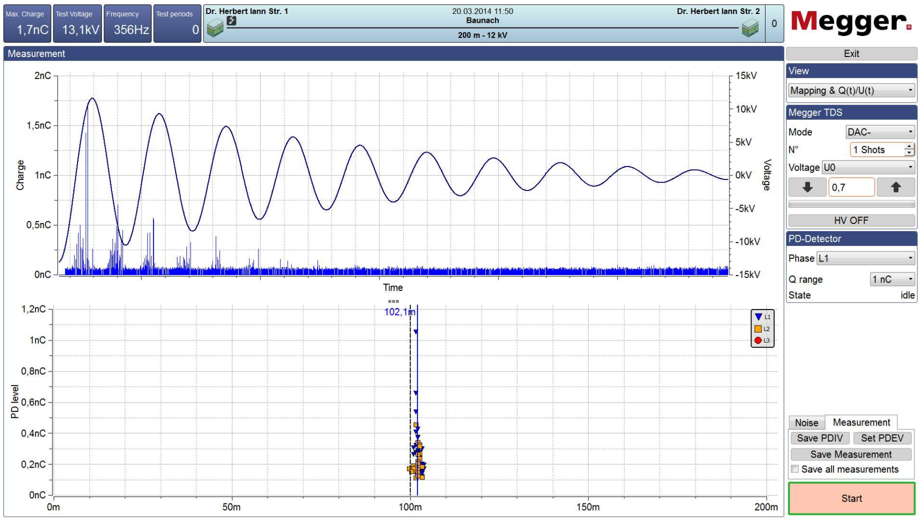


Figure 14: DAC (Damped-AC), Slope (0.1 Hz Cosine Rectangular VLF) as well as 0.1 Hz Sinusoidal VLF Side-by-Side comparison.



Max. Charge 1,7nC
Test Voltage 13,1kV
Frequency 356Hz
Test periods 0
Dr. Herbert lann Str. 1
20.03.2014 11:50
Baunach
200 m - 12 kV
Dr. Herbert lann Str. 2
View: Mapping & Q(t)/U(t)
Megger TDS
Mode: DAC-
N°: 1 Shots
Voltage: U0
0,7
PD-Detector
Phase: L1
Q range: 1 nC
State: idle

Figure 15: Depiction of a typical DAC PD test with both PDIV and PDEV events observed within the image. PD quantity and magnitude being more pronounced at higher-voltage levels. The PD activity clustered at the 100-meter location is localized at a direct-buried inline cable splice.

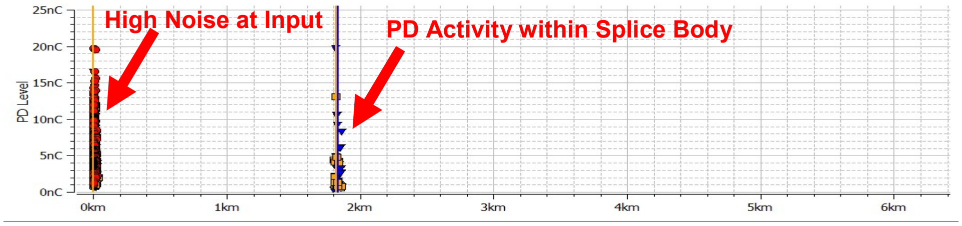


Figure 16: PD Testing within a Windfarm in Mexico. Cable Length was approximately 6.5km, XLPE, 35kV Rated Cable installed in 2014. PD activity noted at 0km is a combination of cable accessory / termination derived as well as non-ideal connections being utilized on the 2-Hole NEMA terminal of the cable sample under test. The activity seem at 1,818-meters however is a localized issue within a cable splice that was improperly constructed.

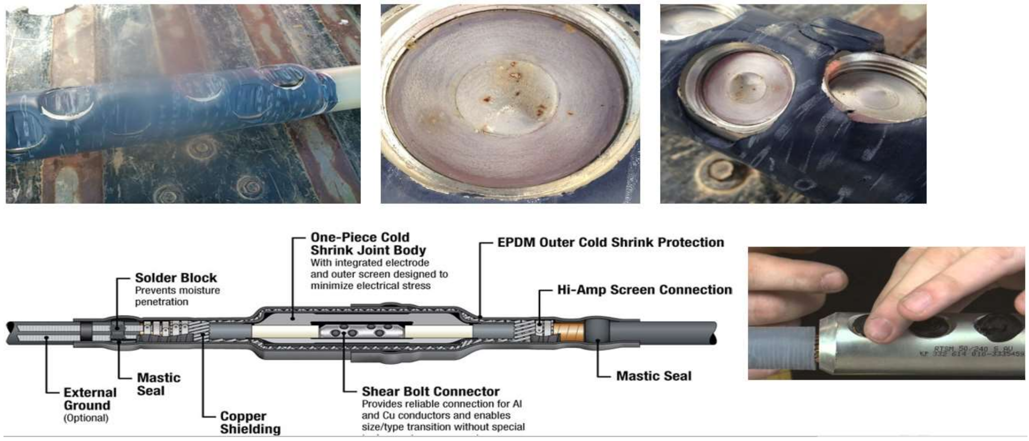


Figure 17: PD Testing within a Windfarm in Mexico. Location of PD activity was between shear bolt locations and the cold-shrink splice body. Air-void within splice construction required mastic material to fill in the void to prevent discharge activity.

Appropriate measures should be taken to align with the maximum cable length and ratings associated with test equipment and ensure that the PD test set have adequate capability to charge the cable system under test. Additionally, field measurements can be distorted or decay prior to reaching the partial discharge test set due to attenuation of signals within the cable system due to signal degradation.

Partial discharge test sets have a large degree of functionality in general for cable testing performed in a wide array of applications. The limitations to the various methods become quite pronounced however within a wind facility due to exceptionally long lengths and large capacitance values of cables within these systems.

A sinusoidal PD device may have difficulty to adequately detect and localize PD activity within an exceptionally large system. The DAC or Cosine-Rectangular system will have a length of cable limit that will vary between cable size and types, however a cable run length between 8,000 and 16,000ft length can be evaluated effectively to provide useful results for field analysis and localization of suspect cable segments. A generalized recommendation for all PD test equipment would be to install junction boxes at a reasonable distance from one another. This will allow for all partial-discharge units on the market to test cable segments within windfarms with the maximum degree of accuracy.

There are a few steps that can be taken to mitigate for exceptionally long cable runs, such as a 28,000ft length, 35kV rated, 345mil, 1250kcmil XLPE run of cable post-installation if the goal is to perform accurate field measurements of partial discharge activity within a cable system. One recommendation could be to ensure that the cable interconnections feeding wind-turbines have sectionalizing capabilities within the string at a reasonable interval (approximately between 10,000 to 15,000 ft distance from junction-box to junction-box, dependent upon cable size and ratings). Junction Boxes, and/or switching cabinets would be an example of a point of disconnection or test location.

These locations would allow for the system to be broken into smaller segments that could allow for maintenance testing to occur on systems as they age, as well as facilitate commissioning tests on newly installed systems. In the example shown within Figure 18 and Figure 19, the 6,256ft segment was a short segment that allowed for accurate partial discharge testing and localization. The 28,000ft segment of cable could not be tested reliably as the test-set had insufficient capacity to test such a large cable-set. Ideally the 28,000ft run would have been segmented two more times with junction-boxes, however due to the topology of the area the cable was run inside of a highly eroded ravine and there were access limitations as well from a construction perspective. This resulted in the original design placing a junction box around 28,000ft from the substation. This segment of cable has been historically difficult to fault-locate on and presents challenges to partial discharge testing as well.

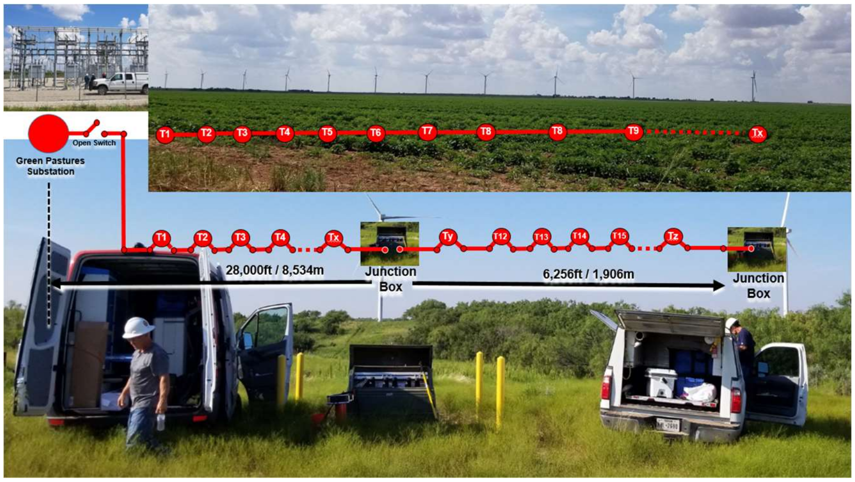


Figure 18: Example of long-continuous runs of cable with limited sectionalizing capabilities for both CFL and CTD activities. 28,000ft segment between substation and Junction Box create a challenge for cable test activities. Design recommendation for similar installations would be to recommend that a junction-box is installed within the 28,000ft run of cable to aide in future maintenance efforts.

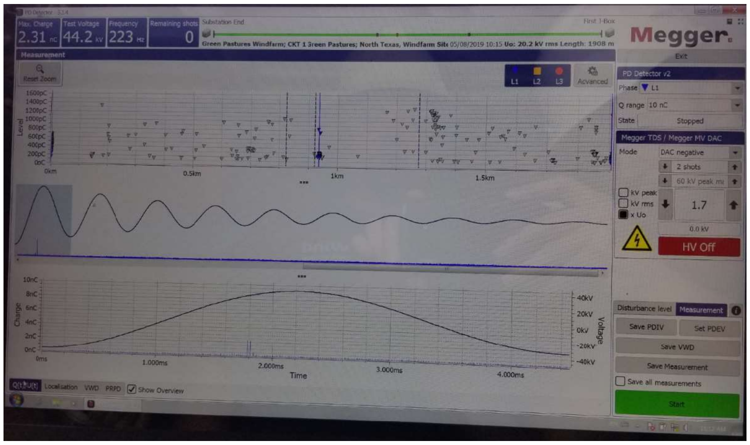


Figure 19: Partial Discharge activity observed on a 6,256ft cable segment within a windfarm. Activity measured was below a 1000pC PD level and was localized on a splice that has recently been repaired.

Shorter cable segments will allow for units to adequately charge the cable system to obtain measurements, as well as allow for signals to be received by the test unit. Recommendations of system length will vary based upon the size of cable system from a capacitance (2uF) standpoint. There is a major economic driver to avoid placing junction-boxes where possible for parties constructing wind-farms due to the high per unit costs of the structures.

Alternatives to breaking the system apart via design (junction-boxes) alone would include intrusive methods of testing that would require physically breaking splices apart. For this reason, partial-discharge testing performed with most offline methods will be limited for systems constructed with exceptionally long runs of cable with high capacitance values as well as attenuation. Systems designed in this fashion will also forgo any benefits associated with partial discharge testing to perform quality checks on workmanship defects as well as locate defects within cable systems during a commissioning test program due to exceptionally long cable lengths. The only indication of issues on long cable runs will be an outage due to cable failure or a failure during a VLF test and global health assessment checks via tan-delta testing for cable insulation degradation as well as sheath fault testing to ascertain if the jacket of the power-cable has been compromised. REFER to Figure 20 through Figure 21 for high-level diagnostic test information.

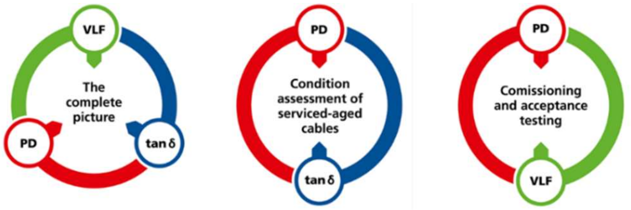


Figure 20: Simplified Overview of Cable Test methods. Test methods are complimentary to one another, and a single test methodology alone is insufficient to adequately diagnose and locate issues within any given cable system.

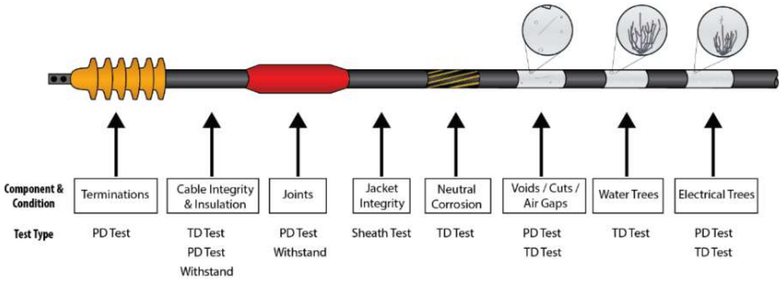


Figure 21: Generalized overview of applications related to various cable testing methods.

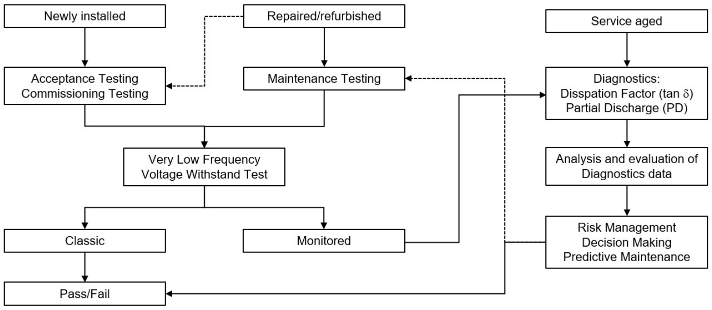


Figure 22: Cable Test and Diagnostic Testing Overview

VIII. Summary

Windfarm system topologies, geography, environmental factors, workmanship issues, installation practices, overall system design philosophies all play a role in the ability to effectively in-service test/commission, maintain, and fault locate within windfarms. Due to a multitude of factors, including but not limited to, economics, soil-rho conditions, local native soil rock concentrations, expansive and contracting soil conditions these issues can create a situation where it may be exceptionally difficult to perform field cable testing within a facility.

CFL issues can be mitigated for with the proper TDR unit as well as appropriately sized surge or thumper device, including voltage, and energy considerations for any given cable length, size and system capacitance value. Consideration should be given to procure or utilize pinpointing equipment that rely upon potential differences within the earth, acoustic as well as electro-magnetic pulses to aide in narrowing down the exact location of cable defect or failure. Multiple testing methodologies are available to aide in approximating fault locations within exceptionally long point-to-point cable network that are characteristic of windfarm circuits. Appropriate safety precautions should be undertaken to eliminate inadvertently testing healthy cable systems due to the large inherent capacitance values of cable systems.

Mitigation measures should be put in place in the form of proper commissioning testing or preventative maintenance programs to avoid costly down-time due to cable-failure events. The recommended testing methodologies to accomplish this would be to properly utilize VLF, Tan-Delta, sheath-fault and Partial-Discharge testing methods as well as monitored withstand testing to identify issues long before an outage or loss-of-generation event were to occur. Most of the causes of failure start from the day of installation. Improperly constructed terminations, or a suspect cable splice can be identified and addressed prior to energization of facility. Minor upfront time investment will pay significant dividends downstream.

VLF testing is an effective way to determine relative state of the cable systems bulk insulation, however this is a pass and fail test and does not allow for localization of damage. Voltage is applied for a prescribed period of time and will result in an insulation breakdown if a weak spot is detected. These weak spots are regions where electrical trees have been grown in an accelerated test (30 to 60 minutes) timeframe and will improve the reliability of cable systems that pass this test. Post-failure of the cable under planned conditions, the run of cable under test is now considered failed and requires replacement, repair and/or maintenance attention.

Tan Delta testing is an effective tool for aged cable systems to determine relative health level and remaining strength of bulk insulation within extruded cable systems. Tan Delta testing alone however, just as with the VLF testing method above, does not allow for localization of damage locations within cable systems and shall be used in conjunction with other methodologies to effectively allow for in-servicing / commissioning testing activity as well as service and repair related activities. Additionally, proper understanding of environmental factors that influence test results as well interpretation of Tan-Delta values will allow for proper mitigation methods to be employed to improve the accuracy of test results within a wind-farm application.

Partial-Discharge testing methodologies such as DAC, Cosine-Rectangular, and Power-Frequency test methodologies allow for testing of large and long cable systems. PD testing is governed by IEC 60270. PD testing is sensitive enough to detect future fault locations that have not adequately degraded to a point of failure. This allows for the detection of factory defects within cable accessories, and cable systems, as well as check the efficacy of cable terminations, and cable accessory construction, as well as junction-box testing within the field to determine failures prior to energization of the main system avoiding costly down-time and outage windows, as well as reducing material, labor costs associated with unplanned outages, and lost revenue due to loss of generation.

Proper application of CFL and CTD testing practices will increase the life of strings within wind parks as well as allow for timely restoration of service in the event of an outage due to cable failure. Proactive testing is always more economical than reactive fault location and restoration requirements.

IX. Conclusion

Cable fault location and diagnostic testing within wind parks will remain a challenge, however these challenges can be mitigated for with proper system design, installation practices (junction-box placement, native-soil screening to remove rocks, use of engineering soils where required, proper compaction of refilled cable trenches), routine maintenance, and the availability of the appropriate equipment (thumper with proper voltage rating, joule rating, and a TDR unit to fault-locate if required).

With properly sized surge unit, TDR set, and associated tools, most, if not all, faults can be located with relative ease. This is also the case for diagnostic equipment as a properly segmented wind park allows for ideal test conditions for all vendors with the highest degree of result accuracy. Wholesale change of design practices is not required per say, however excessively long continuous runs of cable installations may not be the most ideal design moving forward. Properly positioned junction-boxes will aid in restoration of power as well as allow for routine maintenance to occur with relative ease.

X. REFERENCES

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