Integrating Diagnostic and Factory Tests to Maximize Reliability of New Critical Power Cable Systems

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ABSTRACT

One of the more important challenges in power cable testing is finding an optimal balance between diagnostic technologies to be deployed and achieving the highest effectiveness possible for the particular case under consideration. Therefore, this paper discusses methods and experiences with diagnostic testing to support the asset management of new critical Medium Voltage (MV) power cable systems from the factory to commissioning to service. The discussion is based on a case study that is a bay crossing in the USA. It corresponds to a new power cable system that is considered de facto critical mainly because of its restricted accessibility once in service as well as economic impact. The case study illustrates the deployment of diagnostic technologies from the factory to commissioning to maximize reliability, avoid unexpected problems as well as minimizing risks and costs.

KEYWORDS

VLF, Diagnostic Testing, Asset Management, Condition Based Maintenance, Critical Infrastructure

INTRODUCTION

Utilities all over the world, and especially in North America, are facing a significant future challenge to maintain and renew their ageing assets [1]. Utility assets (like most equipment) degrade over time and eventually reach the point at which their performance is lowered sufficiently that they can no longer perform their intended functions. Equipment populations with assets that are far enough into this process produce service failures [2].

Effective asset management strategies require the availability of appropriate information on the performance of the assets themselves. In essence, the extra information comes from an effective diagnostic program whose results enable the utility to undertake “smart maintenance” in that only those assets that will likely impact the reliability in the near future receive some form of remediation.

To address this need for underground cable systems, voltage sources were developed during the last two decades that utilize AC frequencies in the range of 0.02-300 Hz [3][5]. The possibility of augmenting the withstand capability with diagnostics such as dielectric loss and partial discharge further increases the usefulness.

Guidance on use and interpretation of cable diagnostic technologies has focused primarily on single diagnostics for single phaseconventional land distribution cable systems. The need for the use of coupled diagnostics on critical cable systems, where the risk profile is quite different to conventional distribution cable systems, is not currently addressed in the literature. In this context, critical cable systems may be considered as those associated with

- long length subsea / river crossings,
- power plants, and
- life safety systems.

These applications are considered critical because their risk of failure profile and related consequences are significantly different to traditional distribution applications and require a number of extensions to the standard diagnostic testing paradigm.

Therefore, the work reported here discusses methods and experiences with diagnostic testing and corresponding analyses to support the asset management of new critical Medium Voltage (MV) power cable systems from the factory to commissioning to service.

Asa noted before the issues apply to a wide range of applications, however in this paper how these are addressed is discussed in a case study based on a subsea bay crossing to an island in the southern US. Specifically, the case study corresponds to a new power cable system that is considered *de facto* critical because its restricted accessibility once in operation. Additionally, the cable system delivers electrical power to a high-profile tourist area with high impact on the local economy.

The case study is used to illustrate the deployment of diagnostic technologies from the factory to commissioning to maximize reliability, avoid unexpected problems, and minimize risks and costs. Special attention is given to the approach that was designed to address the installation of joints required to complete the system span using a myriad of complimentary diagnostic technologies.

Other approaches, complementary to diagnostics, that are briefly discussed are: (1) cable system technology selection, (2) cable quality assurance, (3) verification of cable integrity after transportation, and (4) future performance assessment.

Important lessons learned from each of the items above are presented and discussed in the paper. The work that is reported here can be used as guidance by utility engineers to maintain reliable operation of their important new cable critical cable assets and it constitutes the main contribution of the paper.

CRITICAL POWER CABLE SYSTEM

The definition of a critical MV power cable system could change from utility to utility; specific cases may require unique parameters to define whether the system is critical or not. However, there are categories that apply to each case to be able to establish the system criticality, they are as follows:

- **Impact to the end customer:** This category includes power cable systems that support critical infrastructure (e.g. hospitals, airports, governmental agencies, high profile customers, dense commercial/industrial/tourist areas, etc.). It is also important to consider that this category also carries the highest impact on the utility's public perception.

- **Reliability:** This category includes power cable systems that may impact reliability indices (i.e. SAIFI and SAIDI) to level that are not tolerable by the utility.
- **Circuit Access / Location:** Power cable systems whose location and/or access are difficult (e.g. power plants, subsea applications, etc.). In this case, there may be a considerable investment to built the cable system with future repairs not been possible because of access.
- **Maintenance Strategy:** It some cases criticality is determined by the ability, or lack, to address any issues on the cable system. There are cases where repair or replacement requires considerable additional work or costs leading to prolonged downtime.
- **Other:** Any other parameters that may arise for a particular case that cannot be covered by the bulk categories described above.

In general, the definition of the criticality of a cable system may require more than one of the categories previously described. In terms of diagnostic testing and considering the work reported here, new critical power cable systems include new systems that are de facto critical or new systems replacing an existing critical one. In any case, the risk of failure under testing for voltages above the rated cable system voltage is generally considered to be minimal if the system is properly installed and in fact desirable when compared to future failures in service. Recommended actions taken as well as a case study appear in the paper, this constitutes the main contribution of the work reported here.

DIAGNOSTIC TECHNOLOGIES DEPLOYED IN MV NETWORKS

Modern distribution networks are increasingly dependent on underground MV power cable systems to cope with the increased stresses that climate change is imposing over conventional overhead lines. As power cable systems age, there are inherent factors such as water ingress, poor workmanship, and use of inappropriate designs that will cause the systems to fail. Failures can manifest in the cable or in the accessories; however, it has been traditionally accepted by the technical community that accessories (i.e. joints and terminations) constitute the “weakest spots” in MV power cable systems. If the interest is to maximize the highest possible level of reliability, then it is necessary to deploy testing and diagnostic methods on both new and service-aged systems. Guidance on diagnostic methods deployment can be found in standards and guides (i.e. IEC 60502-2 and IEEE 400 series).

When it comes to diagnostics for MV cable systems, diagnostic techniques can vary depending on the context of the cable system. TDR (time domain reflectometry), VLF (very low frequency) Tan δ, PD (partial discharge), and jacket puncture testing are the fundamental methods that are typically deployed. Almost every type of power cable system can be assessed with these methods. Despite the lack of agreement on acceptance criteria for some of them, they are well known and documented. Testing devices these days are not difficult to deploy and the fundamental techniques can be considered as the essential tool package for power cable systems condition assessment.VLF Tan δ and PD testing are the two primary core methods that are widely used.

At its inception, the initial goal of the VLF Tan δ measurements was to assess the development / existance of water trees or water ingress in deteriorated polymer insulated cables. In any case, VLF Tan δ has shown to be an effective technique that is dependable in providing insight for both global and localized condition assessment frameworks.

Generally, PD testing on MV cables is done offline. An effective test strategy is usually deployed to: (1) reduce the risk of false negative results by increasing the likelihood of detecting defects that cause PD, (2) separate such defects from noise, (3) identify the defect location with low uncertainty and thus allowing for precise repairs, and (4) provide condition assessments that can be pass/fail or potentially deferred action at different levels of action ideally correlating with performance later observed for in-service conditions.

When looking at trending and thresholds as criteria for condition assessment, there is a lack of overall direction, especially for older cable systems. There is no standard other than recommendations and user experience. In addition, general guidelines would probably never be realized due to the differences between test voltage sources, calibration procedures,data acquisition schemes, and their frequency response.

Lastly, proper data handling is crucial for all measurements that can be carried out for cable diagnostic testing. The amount of measurement data, as well as other metadata such as age, location, historical trends, and others, require the use of a well-established asset management strategies.

Diagnostic technologies were limited in the past and thus were handled differently. Nowadays, with the current broad use of diagnostics methods by utilities, technology evolution, sensor deployment, and metadata, only by applying proper asset management strategies, it will become possible to increase the reliability and thus dependability of MV power cable networks in their new operating framework.

FRAMEWORK TO ACHIEVE HIGHEST RELIABILITY

As discussed in the previous section, new critical power cable systems involve new systems that are either new installations and/or replacement of existing critical cable infrastructure. Such cases enable the diagnostic process to be deployed:

- from the begining with material construction to system operation
- In support of converntional factory based methods such as Vendor Selection, Witnessed Factory Acceptance Tests and Factory Assessments.

A typical integration scheme is depicted in Fig. 1.

In terms ofthe deployment includes the following stages:

1. **Factory Tests (FAT):** The suite of complimentary electrical and material tests performed by the manufacturer. These are usually witnessed by a representative of the end user.
2. **Cable Quality Assurance (Cable QA):** Perform dimensional checks and quality checks to ensure that the cable complies with all specifications and quality required

by the utility and industry standards.

3. **Commissioning Diagnostic Tests (SAT & IAT):** Electrical tests performed on site that include installation and acceptance tests.
4. **Operation Performance (MT):** Maintenance tests and observation of trends as the systems ages. Additionally, follow-up tests after diagnostics may be used to further enhance the condition assessment with the goal of better understanding the aging rate or speed of degradation.

In all these stages a utility is more willing to invest time energy and effort in the reliability processes. This is usually realized using multiple complimentary diagnostics applied before a system is energized as well as for service life. This is in comparison to most existing cable systems where a single or limited diagnostic approach is usually employed.

However implied, substantial utility involment is needed throughout all stages to gain optimal benefit. This involvement can be accomplished directly from utilty technical human resourses or consulting services independently reporting to the utility

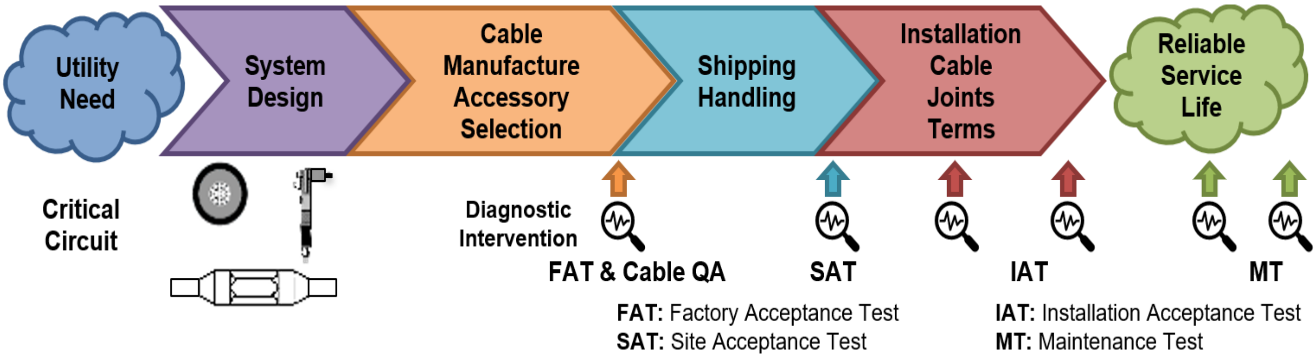

Fig. 1: Framework for Recommended Actions Taken to Maximize Reliabiliby of New Critical Power Cable Systems

CASE STUDY

The case study presented here corresponds to a new cable system that was considered *de facto* critical by the end user. Specifically, the cable system is a bay crossing in the USA with limited to no accessibility once it is put into service. In addition, the cable system provides electric power to an area with high economic impact and has a significant impact on SAIDI / SAIFI.

The cable system is a feeder-type and it is composed of four parallel runs (three phases for normal operation and the fourth run as spare phase). The cable is a 25 kV design, large conductor, filled extruded insulation, and jacketed. The total length of each completed phase is approximately 3,650 m (~12,000 ft) and includes one field joint per phase located approximately at the midpoint of the cable system run. The cable system is operated at 7.2 kV nominal. The cable and joint installation process is illustrated in Fig 2. The on-site cable system geographical layout appears in Fig. 3.

Filled insulation was the utility choice for the cable to be manufactured in MV production plants. Given the conductor size, the production lengths was limited to 6,000 ft (complete reel) and thus to cross the bay jointing was required somewhere in the middle of the crossing. Eight (8) cable reels, four (4) joints, and eight terminations were required to a complete cable system assembly. Two cable runs were installed and jointed simultaneously. The end user had made a number of similar installations in previous years with this cable / jolint / installation method. However project after action reports and commissioning tests had indicated that the cable systems were not of the quality that they desired. Thus on this project it was determined that the a more comprehensive test plan would be employed.

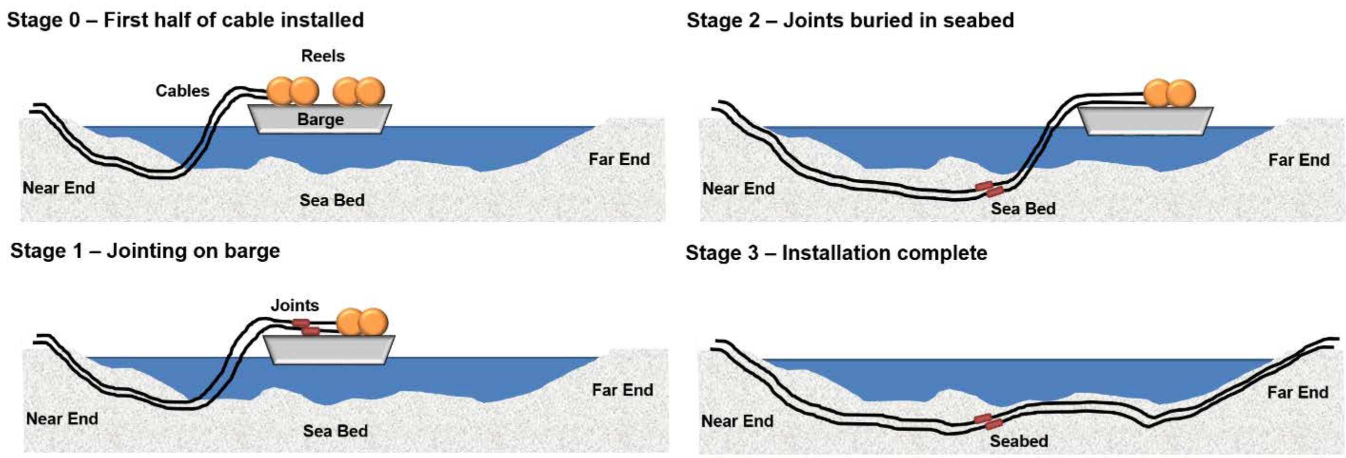

Fig. 2: Illustration of Cable Joint Installation Stages

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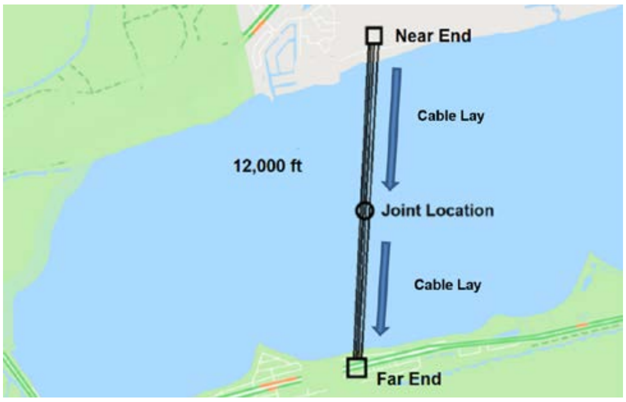

Fig. 3: On-site Cable System Geographical Layout

Factory Acceptance Tests

As part of the integrated quality process the end user required independent witnessing of the acceptance tests at the factory and a review of the manufacturing records. Factory Acceptance Tests (FAT) were conducted on a number of occasions for all reels and cumulative results are shown in Fig. 4.

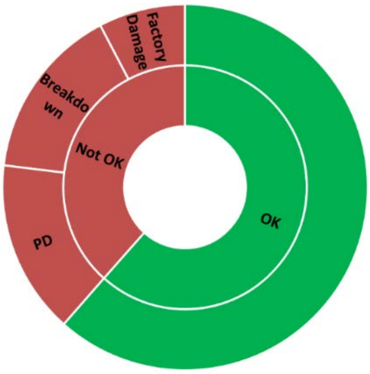

Fig. 4: Factory Acceptance Test Results

The manufacturer elected to undertake their own Withstand and PD tests in advance of the FAT. No issues weer reported with these tests. However Factory Damage, Breakdown and PD were detected when the FAT's were conducted under witness, This necessitated subsequent manufacturing campaigns to "remake" the failed cables.

Fig. 4, summarises the outcome of all the FAT activities; approximately one third (5) of all manufactured reels (13) had issues (PD (2), breakdown during withstand testing (2) and factory damage (1)) that required "remakes".

The FAT work also identified a mistake in the commercial processes for this project where cable attributes agreed by end user and manufacturer engineering groups, had not been integrated in the contract documents. Thus the cable had been correctly manufactured to the contract but lacked an important engineering attribute. This reaffirms the need to undertake a thorough review of manufacturing documents, prior to starting manufacture.

Clearly even at this stage the FAT had provided value to the end user by identifying weaknesses / errors in the manufacturing process

Cable Quality Assurance

It is common in the FAT process that the quality records of the manufacturer are reviewed to ensure consistency between the lengths used for a project. This review was undertaken for this project.

The end user required additional sampling of the cables that successfully completed the FAT. These samples received additional independent quality assurance tests were conducted on all shiping reels to reassure the end user that that the cable met the end users specifications. No issues were found in any of the reels. Then, the reels were shipped to the installation site.

Site Acceptance Tests

As there was a considerable distance from the manufacturing facility to the installation site, with loading / unloading of large heavy reels. The end user requested that Site Acceptance Tests (SAT) be conducted to ensure that the cable reels did not suffer any damage during transportation and The tests that were deployed are shown in Table 1.

Table 1: Site Acceptance Tests

Test Seq	Test	Test Voltages [U_0]	IEEE Guide
1	Visual Inspection	-	-
2	TDR	-	400
3	VLF Tan δ	0.5, 1.0, 1.5**	400.2
4	PD using DAC	0.5, 1.0, 1.5, 1.7*	400.4
5	MWT PD using VLF	60 min**	400.2
* Unipolar ramp to test voltage, voltage of first oscillation ** Constant amplitude sinusoidal oscillation			

No issues were found after factory handling and transportation.

Installation Acceptance Tests

As a result of the critical nature of the cable system multiple and complimentary, and in some cases duplicate (for confirmation), diagnostics were deployed during the different joint installation stages that are shown in Fig. 2.

Tests deployed for each stage are shown in Table 2.

TDR tests were selected to get accurate lengths / locations for the cables and the joints. Moreover these would serve as useful reference materials to assess neutral corrosion during maintenance tests.

Damped AC (DAC) was selected for the PD assessment of the joint as the equipment is compact and straightforward to use / interpret. The long ramp time (with reference to the decaying voltage), the measurement of test voltage only for the first oscillation and the different oscillation frequencies, were not considered an issue in the PD measurements for the application of SAT (Table 1) and IAT (Table 2). Previous testing had shown that this approach was able to identify / locate PD in a similar manner to other voltage sources, though the individual PD characteristics were not comparable.

Monitored Withstand using Very Low Frequency (VLF) sinusoidal voltages is well established in testing of land based cables, with tabulated voltages and times for testing. The condition of the cable system is monitored using PD. This study employed a VLF frequency of 0.1 Hz. This approach to withstand testing was selected because a controlled and consistent voltage exposure (in terms of magnitude and time) is a pre requisite for "proof testing" of these cables. One other key advantage was that the same equipment could be used to directly determine the Tan δ of the cable system. These data would serve as the baseline for the maintenance program envisaged by the end user.

Table 2: Installation Acceptance Testing Stages

Test Seq	Test	Test Voltages [U_0]	IEEE Guide
Stage 1 – Joint Installation Acceptance on Barge			
1	TDR	-	400
2	PD using DAC	0.5, 1.0, 1.5, 1.7*	400.4
3	MWT PD using VLF	30 min**	400.2
4	PD using DAC	0.5, 1.0, 1.5, 1.7*	400.4
Step 2 – Joint Submergence Integrity Acceptance on Seabed			
1	TDR	-	400
2	PD using DAC	0.5, 1.0, 1.5, 1.7*	400.4
3	MWT PD using VLF	60 min**	400.2
Stage 3 – Final Site Acceptance Test - Complete			
1	TDR	-	400
2	PD using DAC	0.5, 1.0, 1.5, 1.7*	400.4
3	VLF Tan δ	0.5, 1.0, 1.5**	400.2
4	MWT PD using VLF	30 min**	400.2
* Unipolar ramp to test voltage, voltage of first oscillation ** Constant amplitude sinusoidal oscillation			

DAC energization was not considered to be appropriate for the withstand (proof) and Tan δ testing. This was because the multiple shot approach proposed for "DAC withstand" has not been proven to be effective, DAC provides a poor quality estimate of the dielectric loss at an indeterminate voltage in the decaying oscillations and the testing conditions (oscillation frequency, voltage application (ramp puls oscillation), time of application) would vary between the different lengths of the SAT & IAT.

Electrical tests for installation acceptance were deployed as three test stages during the bay crossing. They were as follows:

1. Stage 1 – Jointing on barge: completed half crossing, joint assembly on barge, and test terminations.
2. Stage 2 – Joints buried in seabed: completed half crossing, joint assembly laid on seabed not buried, and test terminations.
3. Stage 3 – Installation complete: final Commissioning for completed full crossing, joint assembly buried under seabed, and final pre-molded terminations to connect with switchgear.

The Near to Far End bay crossing view is shown in Fig. 5.

Fig. 5: Near to Far End Bay Crossing View

Table 3 provides the Installation Acceptance Test results.

As seen in Table 3,three major issues were found during the IATs, for Cables 1, 2 & 3.

Table 3: Installation Acceptance Tests Results

Phase	Stage 1 Joint on Barge	Stage 2 Joint on Seabed	Stage 3 Final
Cable 1	√	Joint mechanical damage	Abandoned
Cable 2	PD at Joint replaced§ √	√	√
Cable 3	PD at Joint replaced§ √	√	√
Cable 4	√	√	√
Cable 5§§	√	√	√
§: And retest after new joint installation §§: Replacement for cable 1 after been abandoned after the joint mechanical damage			

In Cable 1 major mechanical damage was inflicted on the joint during installation. This was observed in the TDR trace (Fig 6.) after the joint was trenched. A comparison of TDR traces with the joint on barge and after trenching showed a high negative reflection coming from the joint location, this indicated that the joint integrity had been compromised. VLF voltage was used to verify that there was no capability to withstand voltage. Inspection of the recovered joint indicated that the most likely cause of the mechanical damage was poor tension control as the joint was installed / trenched.

It is interesting to reflect that even though the joint was not operational, the TDR trace did not show a complete break as the "far end" and "joint" peaks are visible. The definitive identification comes from the comparison of the traces of Stage 1 and Stage 2. This highlights that the skilled and experience of the test engineer is very importance and that simple "checklist" assessments can miss important elements.

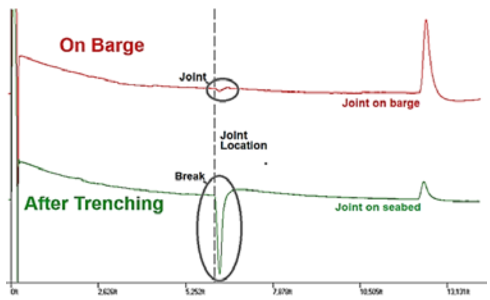

Fig. 6: TDR for Before and After Trenching for the Joint that Suffered Mechanical Damage

After recovery, of the joint the first run of Cable 1 from the Near End to the barge could not be reused due to water inundation (see missed engineering attribute in FAT section) and it had to be abandoned. Therefore, Cable 5 had to be placed into manufacture to replace Cable 1.The other two issues (Table 3) that were found for Cables 2 and 3 were related to PD activity detected at the joint in both cases with inception voltages below 1.7 U0 – Stage 1 Test 2. An example of the PD detected at the joint for Cable 2 using DAC energization is shown in Figure 7. The system criticality meant that it was valuable to spend the extra time and effort getting a confirmation with an independent diagnostic technique. Thus the presence of PD at this location was confirmed with measurements using VLF. As expected the PD characteristics were different for the two different exitation methods, but the onset and locations were essentially identical.

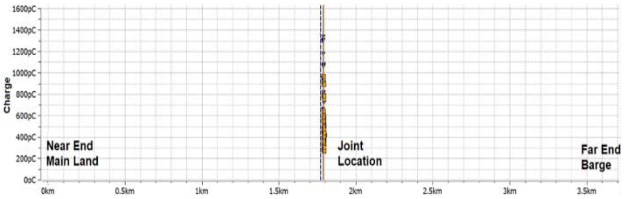

Fig. 7: Example of PD Detected in the Joint for Cable 2

These data enabled the utility to undertake appropriate remediation procedures with the replacement joints; thereby, ensuring that the Stage 1 & 2 tests could be completed. Without the diagnostic testing, the sections would have been placed directly into service without the ability to intervene for a failure in service.

The joints that showed PD were subsequently dissected and issues were found. The forensic evaluation identified the issues at the insulation shield cutback on both cables. The cutback was irregular leaving insulation shield semi conductive filaments at the cutback interface (see Fig. 8).These filaments would distort the high stress at the interfaces and are the most likely cause of the PD activity detected at the joint. No other installation issues were observed during the joint forensic analysis.

One important lesson learned here was that it is advantageous to conduct interim testing at the jointing stage prior to final / complete installation. This permits an improperly installed accessory to be addressed straightway, thereby minimizing costs.

It is instructive to note that the above cutback defects were unlikely to cause immediate failure of the joint. However, these would most likely have reduced the service life of the joints significantly. Given the difficulty inherent in replacing such a joint at this location, it was important to avoid introducing such defects into these systems.

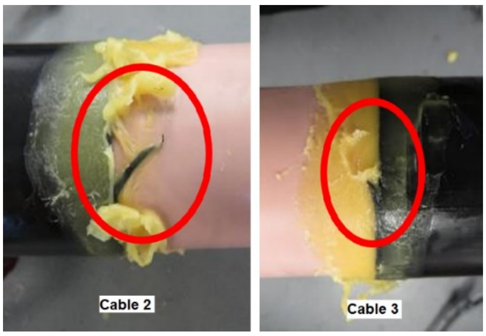

Fig. 8: Cut-back Defects Fund in the Joints of Cable 2 and 3 that Showed PD.

Maintenance Tests

After a final successful commissioning, a proactive maintenance approach was advised to the utility. This involved conducting regular maintenance tests over a period of 3 to 5 years and considering VLF Tan δ measurements as reference baseline values to monitor treding in degradation. A throughout visual inspection of ends as well as jacket pucture testing was also recommended. The system has been in operation since 2019 and no failures has been reported.

CONCLUSIONS

The work presented here showed how to deploy diagnostic testing to maximize the reliability of new critical power cable systems and it has yielded the following conclusions:

- An extensive combined FAT and SAT program that was designed to mitigate manufacturing and installation issues on a bay cable crossing.
- This program avoided two manufacturing, two accessory installation and one subsea instrallation defects from being placed into service.
- As the defects were identified quickly mitigation procedures could be put in place by the cable manufacturer, the accessory installers and the subse contractor; such that they likelihood of reoccurrence on future projects is lowered.

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GLOSSARY

DAC: Damped Alternating Current
FAT: Factory Acceptance Test
IAT: Installation Acceptance Test
MT: Maintenance Test
MV: Medium Voltage
MWT: Monitored Withstand Test
PD: Partial Diacharge
SAIDI: System Average Interruption Duration Index
SAIFI: System Average Interruption Frequency Index
SAT: Site Acceptance Test
Tan δ: Dissipation Factor
TDR: Time Domain Reflectometry
U_0: Phase-to-Ground Design Voltage
VLF: Very Low Frequency