Abstract — Industrial plant engineers are required to provide safe and reliable electrical cable infrastructure that will assure maximum uptime at the lowest possible cost. As electric systems age and the availability of maintenance crews decrease, reliability of the entire system is at risk. To ensure continued reliability, industrial sites are engaged in the decision process to either replace the cable, which is very costly, or repair it at discrete locations to extend its life. Engineers assigned this responsibility are able to make better power cable system reliability decisions when predictive diagnostic tools are applied.

This paper is an overview covering best practices for commissioning new installations and applying predictive diagnostic programs to aging industrial shielded extruded dielectric cable systems rated 5kV and higher. This paper will examine failure mechanisms in extruded cable and accessories. It will also cover the IEEE 400 Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cables providing clarification between non-destructive diagnostic and destructive withstand tests. A discussion will follow which describes the adverse effects of withstand testing when the objective is to assure system reliability. Case studies from actual petrochemical facilities and other industrial sites will demonstrate the ability of defect specific diagnostics to pinpoint defects and avoid future unplanned service outages. Lastly, the use of taped metal shield will be addressed, examining the aging process that may cause it to be less reliable than other shield designs and limit the ability to assess future cable system performance.

Index Terms — cables, defects, electrical trees, medium voltage, partial discharge, predictive diagnostics, testing, water trees.

I. INTRODUCTION

There is an increased demand for refinery and petrochemical facilities to operate reliably and safely while extending the traditional maintenance cycle. The electrical cable infrastructure is a vital link and is required to operate at the highest level of reliability to maximize production uptime.

Medium voltage power systems most widely used in industrial installations comprise cables with extruded insulation, such as crosslinked polyethylene (XLPE) and ethylene-propylene rubber (EPR), and cables with laminated insulation, i.e. fluid-impregnated paper-insulated lead-covered (PILC). These cables, which power vital processes, are installed underground and in cable trays throughout industrial facilities such as petrochemical plants. The cable systems range from 5kV to 35kV class and, typically are designed with taped copper shields. As cables and their accessories age, their propensity to fail in service increases. Experience obtained while conducting predictive diagnostic evaluations of over 12,000km of cable demonstrates that cable deterioration manifests itself through discrete defects. Some examples of discrete cable insulation defects are electrical trees, water trees eventually leading to electrical trees, impurities, delamination of semi-conducting screens, protrusions in extruded insulations and carbonized tracking in laminated insulations [1]. Accessories, on the other hand, typically fail because of manufacturing defects, poor workmanship, impurities, or moisture ingress along interfaces with the cable. Several different testing technologies are available to help identify cables and accessories which are likely to lead to service failure between consecutive scheduled plant maintenance sessions [2]. Some of the authors have been engaged since 1997 in performing cable diagnostic tests in the field by means of an off-line, partial discharge (PD) location technology using a 50/60Hz excitation voltage.

This paper shows how an off-line PD diagnostic test can be used as a commissioning and periodic predictive diagnostic maintenance tool to enhance the reliability of industrial cable systems by reducing the likelihood of service outages. The importance of cable system reliability to the company of one of the authors is articulated, along with past experience with other diagnostic methods. This is followed by a brief review of cable system failure mechanisms and the IEEE standards covering tests intended to ensure their reliability in service. The application of off-line PD diagnostics at particular plants and a discussion of how this dovetails into plant maintenance operations are provided. The implications of copper tape shields on diagnostics and fault finding are briefly discussed.

II. BACKGROUND

Petrochemical process facilities are under continued pressure to maximize uptime between scheduled maintenance shutdowns. Concurrently, intervals between scheduled shutdowns have increased. It is therefore surprising that most test specifications used to determine the condition of critical cable systems today still specify techniques which are classified by IEEE 400 [3] as a type 1 destructive withstand test.

This has led one of the authors to the investigation of non-
destructive alternative methods to determine the condition and future reliability of industrial power cables. The goal of the investigation was to determine an effective way to baseline the condition of newly installed cable systems as well as to diagnose the condition of aged systems.

III. INDUSTRIAL EXPERIENCE

In the recent past, mechanical issues dictated that petrochemical plant maintenance intervals be relatively short, typically one to three years. The electrical preventive maintenance (PM) was accomplished during the mechanical shutdown window. The short interval between shutdowns allowed for a high level of confidence in the effectiveness of the PM activities. Continued economic pressure has resulted in the mitigation of the mechanical issues which used to drive the short maintenance interval.

Over the past 15 years, the authors have seen the PM interval extended from three to four years, then to six and eight years, with some petrochemical sites actively pursuing ten or more years between major maintenance activities. At the same time, the importance of high system reliability has been reaffirmed. A common indicator of this is the often expressed management goal of achieving six-sigma reliability uptime performance. Improvements in reliability are likened to de-bottlenecking the process with low or no capital cost.

With extended intervals between PM and testing activities, it is clear that these facilities are running with a significantly higher risk of failure if traditional DC high potential (hi-potting) maintenance testing, as the measure of medium voltage power cable "health", continues to be used. (see section V.A.1 for details) There is a need to adopt a testing method which provides more than a go/no-go test result. The test needs to be capable of detecting and locating “problem areas” in cable systems before they reach a breakdown failure condition. AC off-line partial discharge (PD) diagnostic testing at line frequency provides the detection and defect characterization which is needed to determine the future performance of the cable system installation and assess the likelihood of failure. AC off-line PD diagnostics locates defects needing repair, which are effectively invisible to other test methods.

IV. CABLE FAILURE MECHANISMS

Industrial sites typically use armored multi-conductor cable systems which are installed in overhead trays with older cables likely to be found in underground conduit ducts. These extruded cables are known to deteriorate at discrete locations throughout their length. Aging tends to concentrate at the sites of imperfections, such as contaminants, protrusions, voids, and semi-conducting screen roughness, all of which, in the presence of water, can encourage the growth of formations known as water trees. Such imperfections invariably create regions of high electric stress which accelerate localized aging. These regions eventually become the sites of electrical trees emitting partial discharge, which, in time, lead to a complete dielectric failure.

Although water treeing may initially assist the initiation of electrical trees, they may later act to delay their growth [1]. Once the sites of imperfections with electrical trees have been detected, located and removed, the remaining length of cable becomes much more reliable and significantly less prone to future service outage. To better understand PD phenomena described in this paper, the following definitions are helpful. Partial discharge (PD) is defined as electrical discharge that does not completely bridge the space between two electrodes. PD Inception Voltage (PDIV) is the voltage threshold at which PD activity is initiated and PD extinction voltage (PDEV) is the voltage at which the PD activity stops.

Cable accessories, such as joints and terminations, often fail because of poor workmanship or water ingress along the interface of the accessory and the cable insulation. Typical defective accessory workmanship issues include uneven semi-conducting screen cut-back, cuts into the insulation, lack of silicone grease, voids, incorrect assembly, and contaminants. These imperfections almost always generate partial discharge when the voltage reaches a certain threshold level. As this level approaches the steady-state operating voltage, damage caused by partial discharge increases and eventually leads to a cable system failure.

V. DIAGNOSTIC TEST METHODS – IEEE STANDARDS

According to IEEE 400 all cable tests can be categorized into two major types: type 1, destructive withstand, and type 2, non-destructive diagnostic. In section 8.1, the IEEE 400 guide states, "if the test falls under the criteria of a withstand by trying to break down (fault) the defects in the time of testing, it is considered a destructive test." In the same section, the standard states that "diagnostic testing allows the identification of the relative condition of degradation of a cable system and establishes, by comparison with figures of merit, if a cable system can or cannot continue operation. Diagnostic testing is considered non-destructive." [3]. Type 1 tests include DC, power frequency AC, and very low frequency (VLF) AC withstand tests. Type 2 tests include general condition assessment, such as tangent delta diagnostic test, and defect specific diagnostics, such as a PD diagnostic test. The major advantages and disadvantages of each type of test are presented in the following sections.

A. Type 1- Destructive Withstand Tests

Destructive withstand tests consist of applying a high electric stress for a prescribed duration. If the system fails, the fault has to be located, repaired, and the test repeated. The advantage of a type 1 test is that it is relatively simple to apply. However, a major objection to the application of a type 1 test without monitoring the cable system’s response with a diagnostic measurement is that failure mechanisms triggered by the test voltage may not lead to failure during the test, but may cause subsequent service failures [3]. Therefore, the absence of failure can not guarantee that new defects have not formed or existing defects have not been further aggravated.

As mentioned previously, there are three common voltage sources which are used for withstand tests namely, DC, power frequency AC, and VLF AC. Although power frequency AC is used for high voltage cables, the focus of this paper is medium voltage applications where DC and VLF AC are the most commonly used withstand tests.
An example of the ineffectiveness of an AC type 1 withstand test to fail workmanship defects in new cable systems was clearly illustrated by a 3-year research effort by the Electric Power Research Institute (EPRI) in the Technical Report 1001725 "Estimation of Future Performance of Solid Dielectric Cable Accessories." [9]. In this study, EPRI created typical workmanship errors including misplaced stress elements, knife cuts to 30% of the extruded insulation, and conducting residue left along the cable insulation shield cutback. Although it is highly likely that these errors would have caused a service failure, all of the workmanship defects survived a 4-month AC withstand at 2 times the operating voltage. One of the conclusions of this study is that while IEEE type 1 tests are designed to be destructive, one can not rely on the test to break down all defects during the withstand period. Therefore, a type 1 test should be applied with a considerable measure of caution when future reliability of a cable system is a concern.

B. Type 2- Non Destructive Diagnostic Tests

The purpose of a non-destructive diagnostic test is to indicate the condition of a cable system and establish whether or not it will perform reliably in service by comparing the test results to guidelines which are generally accepted by industry, such as manufacturer’s specifications. Off-line techniques use moderate voltage levels for a short duration to assure that the test will be non-destructive. The significant advantage of a type 2 test is the ability to measure the cable system’s response to a specific stress level and predict its future performance without creating a fault. However, one of the challenges is that diagnostics require specialized equipment and trained technicians. The two categories of commercially available type 2 tests are discussed below.

1) General Condition Assessment

General condition assessment tests include measurements of dissipation factor (or tangent delta) at a single frequency or a spectrum of frequencies (dielectric spectroscopy), polarization voltage (or return voltage), relaxation current, and others. These tests provide an overall assessment of the deterioration of certain dielectric properties, but cannot pinpoint the location of defects responsible for this deterioration. These tests are generally not recommended for new cable systems as their dielectric properties are still intact. These tests are also generally not well suited for EPR insulated systems because of the wide variation of dielectric properties with different formulations. The authors have been engaged in statistically significant studies such as [13], using a tangent delta test. These studies indicate that a majority (70 to 80%) of aged cable segments tested show substantial signs of aging according to the guidelines of IEEE 400. The outcome of such tests is typically a recommendation to either continue operating the cable system or to completely replace it. This type of recommendation usually leads to an ambiguous and/or uneconomic operation for industrial plants.
2) Defect Specific Diagnostics

Defect specific type 2 tests are intended to locate and characterize individual defect sites. The only such test that is commercially available today is PD diagnostics. The ability to locate and characterize defects and compare the test results to manufacturers’ specifications is perhaps the most significant advantage of the PD diagnostic test. The test can be performed on-line at operating voltage level, or off-line at an adjustable voltage level which simulates the effect of overvoltage transients encountered in the cable systems during operation.

a) On-line PD Test

The on-line PD test has the obvious advantage that it does not require disconnecting the cable. In some cases, PD in severely degraded terminations and joints can be detected if they are readily accessible. Although on-line PD testing is a useful tool, as with any test method, it is vitally important to understand its limitations. These limitations include (a) the low percentage of defects which are detectable at the operating voltage level, (b) the lack of a reliable sensitivity assessment, and (c) the likelihood of a relatively high percentage of false positive readings.

A very low percentage of defects can be detected at the operating voltage level. This is most likely because extruded cable insulation can not tolerate continuous PD activity for an extended period of time. For this reason, it is very unlikely that serious defects will be detected with the on-line method during the relatively short time between the PD activity’s initiation at operating voltage and failure. In some studies, such as [8], it has been shown that less than 3% of defect sites in cable systems with PD have been reported to be active at or below operating voltage level. This is a great concern as an on-line test can deem a cable system to be defect free only to have a transient voltage turn on a defect a short time later and the cable system fails without warning.

A sensitivity assessment can not be performed according to IEEE 400.3 while a circuit is live. Therefore, since the sensitivity of the on-line test can not be determined, the test results are not dependable and can not be compared to factory test standards. For more information on factory PD test specifications refer to Table 1. For more information on sensitivity assessment refer to section VI.B.

On-line test results inherently yield a relatively high percentage of false positive readings. During the test, the cable is left connected to the rest of the power system including switchgear, electrical buses, motors, transformers, and transmission lines. PD activity from external sources interferes with the on-line test and appears to be originating from the cable under test. This challenge of false readings is only complicated if the access points to the cable system are more than a few hundred feet apart. The authors have several experiences where PD was detected by on-line testing only to find that the PD activity continued to appear in the cable under test at 0kV (when the cable was switched off)

b) Off-line PD Test

The off-line PD diagnostic test has several major advantages over all the other diagnostic methods. According to IEEE 400 section 7.4, “if the cable system can be tested in the field to show that its partial discharge level is comparable with that obtained in the factory [off-line PD diagnostic] test on the cable and accessories, it is the most convincing evidence that the cable system is in excellent condition.” [3]. The off-line PD diagnostic test has the distinct advantage in that each defect site can be located and characterized, and results for each cable component can be compared with their associated factory PD test specification. This advantage enables the off-line PD diagnostic test to use the last 40 years of factory PD test experience and specifications and apply it to field applications.

There are three critical parameters which must be met in order for the test to be comparable to the factory PD specifications. These parameters are the voltage source frequency, the test sensitivity, and the test voltage level. All the factory test specifications require a power frequency measurement (approximately 50/60Hz). Frequency is important because PD activity is known to be frequency dependent [12]. Each component of a solid dielectric cable system (terminations, joints, and cable insulation) has specific test requirements for sensitivity (typically around 5 picoColumb (pC)) and a minimum voltage level at which PD activity can appear. (see Table I) The requirement by the standards to perform PD diagnostic testing at elevated voltage levels is predicated on the fact that cable systems during normal operation will be subjected to overvoltage transients due to lightning or switching [7]. The off-line PD diagnostic test not only can yield factory test comparable results but, as a defect specific diagnostic, it can provide the predictive assessment and details necessary to take precise corrective action.

TABLE 1
STANDARDS AND SPECIFICATIONS

<table>
<thead>
<tr>
<th>Standard</th>
<th>Specification*</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 400.3</td>
<td>pC Calibration/Sensitivity Assessment Procedure</td>
</tr>
<tr>
<td>IEEE 48 Terminations</td>
<td>No PD ≥ 5pC up to 1.5Uo</td>
</tr>
<tr>
<td>IEEE 404 Joints</td>
<td>No PD ≥ 3pC up to 1.5Uo</td>
</tr>
<tr>
<td>IEEE 386 Separable Connectors</td>
<td>No PD ≥ 3pC up to 1.3Uo</td>
</tr>
<tr>
<td>ICEA S-93-639 MV Extruded Cable</td>
<td>No PD ≥ 5pC up to 4Uo</td>
</tr>
</tbody>
</table>

*Uo is the cable system’s operating voltage

VI. OFF-LINE 50/60HZ PD DIAGNOSTIC METHOD

The cable to be diagnosed is disconnected from the system and the following test steps are implemented: (a) system mapping by low voltage time-domain reflectometry (b) sensitivity assessment test; (c) PD magnitude calibration test; (d) PD detection and location test under voltage stress conditions; (e) data analysis and reporting [4].

A. System Mapping by Time-Domain Reflectometry (TDR)

An adjustable low voltage pulse, in the range of 10V, and 20-200ns wide, is injected from the near end of the cable. The signal travels the length of the cable, undergoing reflections at impedance transitions along the cable system. This low-voltage TDR operation determines the cable length and locates cable joints (splices) and other irregularities, such as metal shield corrosion or breaks.
B. Sensitivity Assessment

The purpose of this step is to determine the value in pC of the smallest PD signal detectable under the test conditions. The setup is illustrated in Figure 1.

A calibrated pulse of known charge magnitude is injected at the near end. The PD estimator detects and records the response. If the reflected signal cannot be seen above the filtered noise level, a larger signal, such as 10pC, is injected. This process is repeated until the reflected signal is observable. This determines the smallest PD signal which can be resolved under the test conditions.

C. PD Magnitude Calibration

The calibrated pulse generator is connected to the cable at the remote end. A large signal, such as 50 or 100pC, is injected. The corresponding signal recorded at the near end is evaluated by integrating it with respect to time \( q = k \int v dt \). The constant, \( k \), is adjusted until the PD magnitude read is 50 or 100pC. The instrument is now calibrated for measuring the apparent charge, \( q \), of the PD.

D. Off-line PD Testing

In Figure 1, the pulse generator is replaced by a 50/60Hz resonant transformer. The voltage is rapidly raised to the cable operating level (1.0 Uo) where it is maintained for several minutes, as a conditioning step. The voltage is then ramped to its maximum value (such as 2.0 or 2.5 Uo) for approximately 5 seconds. It is finally returned to zero as quickly as possible. During this stress cycle, several sets of data are captured, as shown in Figure 2, each set encompassing one or more entire 50/60Hz period. The rising and falling parts of the voltage help determine PD inception voltage (PDIV) and extinction voltage (PDEV), respectively.

E. Data Analysis and Reporting

Figure 3 illustrates a typical data set. Prior to analysis, noise mitigation filters are applied. A cursor moving from left to right stops at each signal whose magnitude exceeds a preset value dictated by the remaining background noise, and displays the signal in a time-expanded frame. The PD magnitude, the phase angle at which it occurred, and its location (pinpointed using reflectometry methods) are determined and stored. At the end of the analysis, all the needed data is built into a report showing the condition of each individual phase (Figure 4). This includes cable length, joint locations, shield disruptions, defect sites, defect characteristics and recommended actions (based on IEEE/ICEA [6] standards in Table I).
Each phase of a three-phase system has an associated chart, which maps the cable system’s response, and specific recommendations which detail suggested actions. Figure 5 gives an example of one phase of a three-phase system. The X axis corresponds to the length of the cable and the Y axis to the test voltage, represented in per unit (PU) or, alternatively as Uo. For clarification, 2.0 Uo is equal to 2 times the operating voltage.

The example in Figure 5 illustrates a plot of defects identified in a newly installed cable system in early 2007. There is a cable insulation defect at 4,295 ft appearing at the operating voltage (1.0 Uo) and another at 6,575 ft appearing at 1.3 Uo. Clearly, according to Table I, these two defect sites do not comply with IEEE/manufacturer’s specifications, and most likely will cause a failure during the lifetime of the cable system. However, the off-line PD diagnostic test is likely to be the only test which can find both of these defects. A DC test would have most probably missed detecting both sites because there is no apparent conduction to detect in these types of extruded insulation defects. A VLF AC withstand might have failed one of the defects but, the other would most likely go undetected. A tangent delta test would not have detected either of these sites because there is virtually no measurable change of dielectric losses associated with these defects. An on-line PD test would have missed one of the cable insulation defects because the inception voltage is higher than the operating voltage. The on-line PD test might have detected the defect at 1.0 Uo but, because the cable is directly buried and not accessible every few hundred feet, the test would not be able to determine the precise location of the defect site.

The comprehensive results of the off-line PD diagnostic test provide the decision maker the information to make the best economic decision for the cable system. The options are to (a) repair the two cable defects, (b) repair the joint and replace the cable section from 4,295 ft to 6,575 ft or (c) replace the entire cable system. In this case the cable was directly buried and the recommendation was to repair the two points because the cost of two repairs was much less than the other two options involving the replacement of cable. After completing the repairs and conducting a retest, the cable owner has the assurance according to IEEE 400 and factory test specifications that the cable system is in excellent condition and will provide a lifetime of reliable service.

VII. CASE STUDY

In this section, examples of actual diagnostic test results recorded during the past 7 years at petrochemical plants are exhibited. A case study of the findings from one of the author’s facilities is described. The following tables illustrate the results of off-line PD diagnostic testing at three industrial plants in the United States.

A. Existing Aged System Tests

<table>
<thead>
<tr>
<th>TABLE II</th>
</tr>
</thead>
<tbody>
<tr>
<td>SITE A PD RESULTS– XLPE AND EPR INSULATION</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cables Tested (3 phase)</th>
<th>44</th>
</tr>
</thead>
<tbody>
<tr>
<td>Termination Defects</td>
<td>40</td>
</tr>
<tr>
<td>Splice Defects</td>
<td>9</td>
</tr>
<tr>
<td>Cable Sections recommended for replacement</td>
<td>3</td>
</tr>
</tbody>
</table>

Petrochemical plant site A was experiencing an average of 1 failure every 3 years leading up to the off-line PD diagnostic test. On a regular basis, all of the plant cables were subjected to a DC maintenance test performed according to IEEE recommendations prior to 2001. The cables routinely passed the DC test but continued to fail in service. Fault records and subsequent off-line PD diagnostics confirmed that the terminations were the weakest points on the system. After
performing the off-line PD diagnostic test, the results were then used to make specific repairs to the 40 defective terminations and 9 defective splices. Since the test in 2000, the site has not experienced a single failure. If the failure rate prior to the off-line PD diagnostic tests and repairs had continued, this plant would have experienced 2 more costly unplanned outages to date.

### TABLE III
SITE B TEST RESULTS—EPR INSULATION

<table>
<thead>
<tr>
<th>Cables Tested (3 phase)</th>
<th>23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable Insulation Defects</td>
<td>1</td>
</tr>
<tr>
<td>High Attenuation Cables (Tape Shield Condition)</td>
<td>8</td>
</tr>
</tbody>
</table>

At site B, only one defect was identified and, due to the specific characteristics of the PD site, immediate action was recommended. Because of operating requirements, the cable owner decided to switch the cable back to service. The following day, the cable failed at the exact specified PD location of 276ft (see report diagram in Figure 6). Had the recommended action based on the off-line PD diagnostic test been followed, another significant unplanned outage would have been avoided.

![Fig. 6. PD results from site B which failed one day after immediate action was recommended.](image)

**B. New Cable Commissioning**

### TABLE IV
SITE C TEST RESULT—NEW EPR INSULATION

<table>
<thead>
<tr>
<th>Cables Tested (3 phase)</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Termination Replaced</td>
<td>1</td>
</tr>
</tbody>
</table>

During a planned outage, a petrochemical facility in southeastern Texas installed 12, 500kcmil, 15kV class armored cable systems with 220mils of EPR insulation, cold shrink terminations and joints. The 12 cables were installed by a reputable contractor with highly trained technicians in a tray system from a main substation to a remote substation. The cable owner requested that the installation contractor perform a DC high potential test (IEEE type 1 test). Each cable passed the DC test without a problem, indicating that all the cable systems were fit for energization. Following the DC test, the cable owner requested an off-line PD diagnostic test according to the standards indicated in Table I above. The off-line PD diagnostic test located a termination which had severe partial discharge activity well below the IEEE 48 requirements on one of the cables approximately 2,615ft in length. Further investigation revealed that the contractor had difficulty installing a cold shrink termination and had accidentally displaced the stress control material, which is supposed to fill in the step created by the cable’s outer semi-conducting layer cutback, and was contaminating the insulation between the semi-conductive shield and the conductor. According to the manufacturer’s specification, this termination was not installed correctly and most likely would have caused a cable system failure. The termination was replaced and a retest with the off-line PD diagnostic test proved that no PD activity greater than 5pC existed up to 1.5Uo (per IEEE 48), and therefore the new termination was built correctly. With its ability to indicate the exact location of substandard cable system components in a predictive and non-destructive manner, the off-line PD diagnostic test is clearly the most cost effective means to assure reliability and avoid costly unplanned outages.

![Fig. 7. Typical example of cold shrink stress control tube not overlapping the semi-conductive shield](image)

**VIII. AGING OF METALLIC TAPE SHIELDED CABLES**

The metal shield of a power cable plays two important roles: (a) it provides a means to maintain the insulation semiconducting screen at ground potential throughout its length and (b) it provides a conducting path for any 3-phase imbalanced current that may exist in the neutral conductor. The metal shields historically used in industrial installations consist of overlapping copper tape layers, spirally wrapped around the cable insulation semiconducting screen. Other metal shield configurations, typically used by electric utilities, include concentric neutral wires or flat straps and longitudinally corrugated (LC) cylindrical sheets.

The focus of this section is to address the concern of future reliability on tape shielded cable systems. The popularity of this type of shielding in industrial applications is generally inherited from the old PILC cable design. Experience has shown that under power frequency operation, a wound tape shield can be less reliable than a round concentric wire or flat strap shield due to a corrosion process and its poor fault current carrying capability. During fault finding operations and PD diagnostic testing, the metal shields are required to propagate high frequency signals without undue attenuation. Taped shields would perform this operation eminently, as long as their overlapping layers are not corroded. However, in service, moisture ingress between overlapping layers tends to corrode the shield metal, interrupting the electrical contact
between overlapping layers. This forces the high frequency signals to propagate helically rather than axially in a straight line [5]. Any such helical motion of the signal is equivalent to an attempt to propagate through an electrical choke (or inductor). For such high frequencies, corroded overlapping layers on aged cable systems can appear very much like an open circuit and this makes modern fault finding and PD diagnostics difficult to perform. Although general condition assessment tests do not rely on the propagation of high frequency signals, the results of the test are significantly affected by the corrosion process [10] and may render them unusable.

If the industry continues to use tape shielded cable, which will limit the use of modern fault finding techniques on aged cable systems, the industry will experience longer outages, because faults can not be easily located, and more frequent outages because older, more destructive methods will need to be used. Although diagnostics work very well on newly installed tape shielded cable, if tape shielded cable continues to be specified, the industry will not be able to effectively monitor cable assets throughout their lifetime. Therefore, it is the recommendation of the authors to consider specifying an alternate type of metallic shield, such as round or flat concentric wire with 33% or more cross-sectional area (as compared to the conductor).

IX. DISCUSSION

Petrochemical plants and refineries can not continue to endure the status quo concerning the reliability of medium voltage cable systems. In order to address the issues at hand a three-pronged approach is necessary. First the cable shield specification should be changed from a tape shield to a round or flat concentric wire design. Second the inept IEEE type 1 testing methods should be dropped from the specifications. Third, an off-line PD diagnostic test should be adopted into the specifications.

Although the copper tape shield has been used successfully for many years, it has finally reached a point at which its benefits may no longer outweigh its limitations. These limitations include the restricted use of powerful tools such as modern fault location and non-destructive diagnostics. The continued use of the tape shield is likely to limit the ability for the industry to adequately maintain the systems which increasingly are facing lengthening maintenance cycles and higher demands on reliability. It is recommended that, as the industry starts to replace its aging cable system infrastructure, it chooses a cable construction that will not only serve its power design needs but, also its reliability and maintainability needs. Experience has shown that a wound tape shield can be less reliable than a round concentric wire or flat strap shield due to a corrosion process and its poor fault current carrying capability. Therefore, it is recommended that the industry select a round or flat strap concentric shield design so that the cable system’s future performance can be predicted, its dielectric health monitored, and its reliability and life maximized.

Evidence from across the electric power industry is mounting and it is becoming abundantly clear that continuing to use an IEEE type 1 test (destructive withstand) is not an option for critical cable systems which are needed to supply reliable power during ever lengthening maintenance cycles. The financial impact of an outage alone is far too great a risk for the industry to take a chance on a type 1 test which can not predict future performance and may create more damage. The industry must discontinue the use of the DC test as a measure of dielectric integrity on extruded cable systems because (a) it is no longer supported by IEEE, (b) it can not detect most defects, and (c) it can harm aged extruded cable insulation.

New cable systems have discreet workmanship defects and aged cable systems age discreetly. Therefore, the replacement for the DC test should be an IEEE type 2 non-destructive diagnostic test utilizing defect specific technology. The only defect specific technology which can fulfill the IEEE recommendation for a method which can produce results comparable to the cable and accessory manufacturers’ partial discharge (PD) test is the off-line PD test. The off-line PD diagnostic test has the distinct advantage over all other known cable test methods in that each defect site can be located and characterized, and results for each cable component can be compared with their associated factory PD test specifications, which are built on a foundation of 40 years of industry experience. As demonstrated in the example illustrated by Figure 5, applying an overvoltage allows the off-line PD diagnostic test to be far more predictive than an on-line technique, as this latter is unable to measure PD activity which will only turn on during transient overvoltage events. The off-line PD diagnostic test is the one clear choice for a predictive assessment which can assure the reliability of critical industrial plant cable systems.

X. SUMMARY AND CONCLUSIONS

This paper has introduced off-line partial discharge (PD) diagnostics as the most effective, predictive diagnostic tool for medium voltage cable systems. A summary of the important conclusions made in this paper are provided below.

- Extruded dielectric medium voltage cables used throughout the petrochemical industry do not age uniformly but deteriorate at discrete locations throughout their length.
- High electric stress areas generated from sites of imperfections, such as contaminants, protrusions, voids, and semi-conducting screen roughness, and electrical...
It is recommended that the industry consider changing its DC or VLF AC withstand testing does not prove reliability but can actually diminish reliability. 

IEEE standards and guides no longer support the use of the DC test as an acceptance or maintenance test for either new or aged extruded cables and accessories. 

By applying the DC maintenance test on aged extruded cable systems cable owners are running significantly higher risk of service failure after switching the system back into service. 

General condition assessment tests are not a good economic choice for industrial applications. 

When a cable cannot be taken out of service, an on-line test can be a useful tool to detect PD activity in defects which appear at the operating level but, due to inherent limitations, it cannot determine if a system is reliable (is defect (PD) free). 

Off-line PD testing at power frequency effectively determines the locations and characterizes the nature of discreet defects before failure. 

Off-line PD diagnostic testing is an effective commissioning and periodic predictive diagnostic maintenance tool to enhance the reliability of industrial cable systems. 

As a tape shielded cable ages, the ability to perform non-destructive diagnostics and the use of modern fault location equipment in the field may be limited. 

It is recommended that the industry consider changing its current cable specification from a copper tape shield to round or flat concentric wire shield so that cable systems can be maintained with the highest reliability with the longest life expectancy.

XI. REFERENCES


[6] ICEA S-93-639 / NEMA WC74, IEEE Shielded Power Cable 5-46 kV, Insulated Cable Engineers Association Inc, South Yarmouth, MA 


XII. VITA

Gary Hartshorn – Gary Hartshorn (M70) received a Bachelor of Science degree from Iowa State University in 1970. He worked for an electric utility for 15 years in transmission and distribution operations. Joining a Lyondell Chemical predecessor company in 1985, he worked in engineering and electrical and instrumentation maintenance groups. He currently serves as a Regional Reliability Consulting Engineer for Lyondell and chairs Lyondell’s Electrical Best Practices Team.

Benjamin Lanz – Benjamin Lanz received a BSEE from the University of Connecticut in 1999. Since 1997, he has worked for IMCORP in Storrs, CT and now holds the position of Sr. Application Engineer. He was instrumental in the development of the IMCORP Defect Specific Diagnostic Technology and has extensive cable reliability program consulting and field testing experience in North America and Europe. He is an active member of the IEEE PES and a voting member of the IEEE Standards Society. He serves as the Vice Chairman of the Insulated Conductors Committee C16, which is responsible for IEEE 400 and C26, the MV Underground Cable Reliability Group. He has published several papers on cable reliability and diagnostics in the context of field application and regularly presents on the topic.

Bruce Broussard – Bruce Broussard graduated from the Louisiana State University 1982 with a Bachelor of Science degree in Electrical Engineering. He worked for Eaton Corporation from 1982 -2006. He is currently the Vice President of Operations for IMCORP in Storrs, CT. He has published papers in various publications on such topics as cable reliability in wind farm applications, cable diagnostics as a commissioning tool and cable system asset management.