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Field Partial Discharge Measurements on Extruded Dielectric Transmission Cable Systems – State of the Art

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Technical Update, March 2008

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PRODUCT DESCRIPTION

This report describes a review of technical literature, Electric Power Research Institute (EPRI) technical reports, and industry guides to determine the current state of the art for field partial discharge (PD) measurements on extruded dielectric transmission cable systems. Emphasis is placed on the interpretation of field PD measurement test results.

Results and Findings

There are numerous recent publications on the topic of field PD measurements on extruded dielectric transmission cable systems. Seventeen presentations at the 2007 JICABLE conference in Versailles, France, pertained to field PD measurements. However, only two recent publications were located that pertained to field PD measurements on laminar dielectric transmission cables.

The technical literature review indicates that considerable improvements in field PD measurement instrumentation and methods have been made during the past decade. However, there are still several different methods for measurement and for analysis of test results. The variety of methods makes test reports difficult to understand. A review of field test reports indicates that few, if any, of the commercial PD testing services comply with the recommendations of IEEE Standard 400.3, *Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment*, regarding the information that should be covered in test reports. Recommendations for future work to improve the quality and understanding of field PD measurement test reports include the following:

- Develop a guide for preparing technical specifications for field PD measurements on extruded dielectric transmission cable systems.
- Prepare a consumer report for commercial field PD testing services based on round-robin tests similar to those conducted in an EPRI project that was performed almost 10 years ago and documented in the EPRI report *Evaluation of Field Diagnostic Techniques for Transmission Cable Accessories* (TR-112676).
- Develop and conduct a hands-on field PD measurement training seminar by unbiased experts for EPRI member companies.

Challenges and Objectives

The challenges and objectives of this project are the following:

- To review technical publications, industry guides, and transmission cable commissioning test reports in order to determine the state of the art for field PD measurements on extruded dielectric transmission cable systems
- To recommend future research work to develop a detailed outline of a guide to improve the quality and understanding of field PD measurement test results

Application, Value, and Use

Considerable advances have been made during the last decade for field PD measurements on extruded dielectric transmission cable systems. Several techniques have been developed and offered to utilities as a commercial service. However, interpreting the field PD measurement results is often difficult and sometimes confusing. This report provides a review of technical publications, EPRI research reports, and industry guides that cover field PD measurement methods, and it presents a concise description of the existing issues. EPRI members can use the results and determine an approach for future research projects in this field.

EPRI Perspective

Power utility engineers must understand PD measurement methods and test results on extruded dielectric transmission cable systems. This report describes the state of the art and provides recommendations for future research. Continuing EPRI research in this area will be guided by the recommendations developed in this project.

Approach

The team used the following approach to determine the current state of the art for field PD measurements on transmission cable systems:

1. Reviewed EPRI technical reports pertaining to field PD measurements, which were developed from 1999 through 2006.
2. Reviewed IEEE and Conference Internationale des Grandes Reseaux Electriques (CIGRE) guides on field PD measurements. CIGRE Technical Brochure No. 182, *Partial Discharge Detection in Installed HV Extruded Cable Systems*, and IEEE Standard 400.3, *Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment*, are especially relevant to the objectives of this project.
3. Reviewed field PD measurement test reports prepared by seven commercial PD testing services.
4. Interviewed cable engineers who had reviewed PD test reports in order to obtain their opinions on methods to improve the test report information that describes the analysis of test results.
5. Prepared recommendations for future work to improve the understanding of field PD measurement test results.

Keywords

Diagnostics
Extruded dielectric
Partial discharge
Testing
Transmission cable
Underground transmission

CONTENTS

1 INTRODUCTION

There have been significant advances in the procedures and equipment for performing field partial discharge (PD) measurement on extruded dielectric transmission cables during the past decade. A number of different techniques and equipment for field PD measurements have been developed and are now offered to utilities as a commercial service. However, interpretation of field PD measurement results is a complex task and sometimes confusing to utility engineers. Confusion about the interpretation of field PD measurement results is frequently due to one or more of the following reasons.

- The interpretation of "real world" PD measurement results has always been difficult, mainly because it is often difficult to distinguish between electrical noise and electrical signals created by PD defects. There are many instances in field, factory, and laboratory PD measurements where engineering judgment must be applied to the results displayed or recorded by PD detection equipment. In some of these cases it may not be possible to determine with certainty that the measured signals are, or are not the result of PD defects in the cable system.
- Many different methods are used to perform commercial field PD measurements. Most of these commercial measurement methods have certain advantages and disadvantages, but there is no single method that is considered best for all applications. Therefore, utility cable engineers must invest time to understand the complex technical issues that differentiate the commercial PD testing methods. This task is complicated by the fact that most commercial PD testing services are reluctant to disclose the details of their measurement methods.
- Commercial PD testing services have produced many technical publications and made numerous presentations at technical conferences touting the advantages of their instrumentation and measurement methods. Since these publications and presentations rarely cover the disadvantages of their measurement methods, a comparison between the capabilities of competing vendors is confusing and often results in contradictions.
- The PD measurement test reports provided by commercial field PD testing services sometimes lack the information and clarity that are necessary to understand the test results.
- Field PD measurement on transmission cable systems is still a relatively new and evolving technology. Most experts in this area agree that the accuracy of the measurement results will improve as experience with the technology increases.

Several industry guides that cover field PD measurement methods have been published during the past several years. These guides provide impartial information on the different methods for performing field PD measurements. One of these guides[1] includes recommendations on information that should be included in test reports.

[1] IEEE Standard 400.3 Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment, The Institute of Electrical and Electronic Engineers, 2006.

Five EPRI research projects[2, 3, 4, 5, 6] that were included in the literature review for this project also provide useful information and comparisons of commercial field PD testing methods.

The primary objectives of this report are to:

- Summarize results of a technical literature review on field PD measurements, industry guides, and transmission cable commissioning test reports
- Identify issues that lead to confusion concerning interpretation of field PD measurement results
- Make recommendations for future work to alleviate some of the confusion in interpreting the results of field PD measurements on transmission cable systems.

Chapter 2 of this report contains a summary of the EPRI reports and other technical publications that were reviewed for this project. Observations about recent technical publications pertaining to field PD measurements are included in this chapter.

Chapter 3 contains a summary of the field PD measurement methods as well as a comparison with laboratory PD measurements.

Chapter 4 includes a summary of commercial field PD measurement technologies. It discusses differences in commercial measurement methods as well as a list of commercial PD measurement services that are available in North America.

Chapter 5 is a summary of the transmission cable field PD measurement reports that were reviewed and information gaps that were identified in the interpretation of these reports.

Chapter 6 contains a list of recommended research projects that were identified to assist utility engineers in planning and understanding field PD measurements using commercial services.

Appendix A contains a tabular listing of the EPRI technical reports and technical publications. This tabular listing includes abstracts and summaries of the publications with a ranking of their applicability to the objectives of this project.

Appendix B contains scopes of work for the recommended follow-up projects on the interpretation of field PD measurement results.

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[2] *Evaluation of Field Diagnostic Techniques for Transmission Cable Accessories*, EPRI, Palo Alto, CA, and NEETRAC – A Center of Georgia Institute of Technology, Forest Park, GA: 1999. TR-112676.
[3] *Testing of XLPE Transmission Cable Terminations at Three Utilities,* EPRI, Palo Alto, CA: 1997. TR-108073.
[4] *Evaluation of Partial Discharge (PD) Testing Technology for Transmission Class Cables,* EPRI, Palo Alto, CA: 2006. 1012338.
[5] *Demonstration of Commissioning Tests for Extra-High Voltage Cross-Linked Polyethylene Cable Systems at Los Angeles Department of Water and Power*, EPRI, Palo Alto, CA and Los Angeles Department of Water and Power, Los Angeles, CA: 2002. 1001856.
[6] *Assessment of Extruded 345-kV Cable Technology*, EPRI, Palo Alto, CA: 1998. TR-110906.

2

REVIEW AND INTERPRETATION OF FIELD PD MEASUREMENT LITERATURE

The technical literature review for this project included the following.

- EPRI research projects related to transmission cable field PD measurements
- Industry guides on field PD measurements
- Technical publications related to field PD measurements and measurement results

There are many technical papers that have been published concerning cable partial discharge measurements; however, the majority of them focus on PD measurements in testing laboratories. The literature search screened the large collection of publications on cable PD measurements to focus on transmission cable field PD measurements and interpretation of the measurement results. The literature search and review also focused on technical documents that were published after 1998 because a previous EPRI report, *Evaluation of Field Diagnostic Techniques for Transmission Cable Accessories* (TR-112676), contains the results of a comprehensive literature search on the subject up to and including 1998.

The literature review task also included a review of field PD measurement test reports for several major EHV XLPE transmission cable projects that were completed in 2006 and 2007.

The major focus of the literature review was on extruded dielectric transmission cables because the majority of the work on field PD measurements has been for this type of cable system. As a result, most of the published literature on field PD measurements addresses XLPE transmission cable systems. The limited number of technical publications that did address field PD measurements on laminar dielectric transmission cables was, however, included in Appendix A.

2.1 Review and Cataloging of Technical Publications

The applicable technical publications that were located were entered into a spreadsheet database for record keeping purposes and to assist in efficiently retrieving relevant information in subsequent phases of the project. The spreadsheet summary, which is contained in Appendix A of this report, contains fields with the following information.

- **Reference Number** – Sequential reference numbers were assigned to the papers as they were added to the spreadsheet database. Subsequent sections of this report refer to the reference numbers in square brackets, e.g. [xx].
- **Title** – The complete title of the publication
- **Authors** – The authors of the publications
- **Publication Date, Source, and Identification** – The publication date, source, and retrieval information was listed to facilitate retrieval of the papers by others.

- **Author's Abstract or Summary** – The author's abstract or summary was copied into the spreadsheet when they appeared in the publication.
- **Review Summary** – A summary of each of the papers related to the objectives of this project was prepared and included in the database.
- **Applicability to EPRI Project** – A number from 1 to 10 was assigned to each paper to rank the usefulness of the reference to the project objectives.
- **Laboratory of Field PD Measurement Results** – This field of the spreadsheet indicates (yes or no) whether or not the paper contains laboratory or field PD measurement results. This field was included in the database to distinguish technical papers that are practical in nature versus general or theoretical discussions of measurement methods.
- **Details of Test Reports Provided** – This field indicates whether or not the paper or EPRI technical report includes interpretations of field PD measurements. This field was included to distinguish papers that include field measurement test reports versus papers that focus on other aspects of field PD measurements.
- **Addresses Interpretation of Test Results** – This field indicates whether the paper describes methods for interpretation of the results of transmission cable field PD measurements.

2.2 Summary of Technical Publications

The technical publications that were identified as being relevant to the project objectives generally fell into one, or more of the following categories.

- **Measurement Methods** – These papers described methods that have been developed specifically for field PD measurements on transmission cables. The majority of these papers focus on increasing the sensitivity of the field PD measurements, methods of eliminating ambient electrical noise, and finding the location of PD sources that have been detected. Examples of these references are [8, 9, 10, 11, 16, 17, 18, 20, 30, etc.]

- **Commissioning Test Results** – A number of the documents describe the commissioning test procedures that were performed prior to placing new transmission cable circuits in service and results of the tests. These publications generally included PD measurements as well as other tests such as AC high-voltage withstand tests. Many of these papers were written by the organizations that provided field PD measurement services. Some of them repeat the same information presented at different technical conferences. [4, 13, 15, 25]

- **Industry Guides** – CIGRE and the Insulated Conductors Committee (ICC) of the Institute of Electrical and Electronic Engineers (IEEE) have recently published guides for performing field PD measurements. [6, 7, 9]

- **Comparison of Field PD Measurement Services** – Several of the EPRI technical reports describe round robin PD tests performed on the transmission cable systems. [1, 4, 5, 9]
- **Transmission Cable Condition Assessment** – A number of the publications describe tests that were performed to evaluate the condition of in-service transmission cable circuits. [5, 10, 19, 30]
- **Basic Research** – This category of publications focuses on the theoretical aspects of field PD measurements such as attenuation of PD signals in transmission cable systems and the size of defects that create partial discharges.[3, 20, 27, 29]

2.3 EPRI Technical reports

The following EPRI technical reports were specifically identified by EPRI for inclusion in the literature review.

2.3.1 Evaluation of Field Diagnostic Techniques for Transmission Cable Accessories (TR-112676)

This technical report (TR-112676) describes extensive round robin testing of XLPE transmission cable systems with intentional defects. The testing was performed at the National Electric Energy Testing, Research and Applications Center (NEETRAC) which is a center of Georgia Institute of Technology. The tests were conducted in 1998.

Three 91 m (300 ft) long, 115 kV XLPE test circuits with two terminations and two joints were constructed containing known defects capable of producing partial discharge signals of various magnitudes, durations, and repetition rates. The defects were intended to be representative of installation or manufacturing problems encountered in actual commercial installations. A significant amount of time and effort was required to develop the intentional defects that consistently produced partial discharges with a relatively constant PD magnitude at rated voltage.

Ten vendors of diagnostic services or equipment that was commercially available or nearing commercial availability were asked to evaluate the condition of the installed test circuits. Eight of the vendors participated in the round robin tests. These included both acoustic and electrical PD detection methods. Table 2-1 contains a summary of the commercial testing services and their PD detection methods.

None of the eight commercial PD measurement services correctly distinguished the cable and accessories with defects from those without defects. Significant differences in PD severity were reported by the measurement services for the same defects.

In summary, the comparison of PD test methods indicated that there were significant differences in the measurement methods and effectiveness of commercially available field PD measurement methods at the time that the comparative testing was performed. It demonstrated that some of the field PD measurement methods were more effective than others. However, none of the field PD measurement methods was completely effective in identifying PD defects in transmission cable accessories while correctly identifying those accessories without defects.

It should be noted that this research project was performed during relatively early stages of commercial field PD measurements and that significant advances have been made in this technology since that time. Some of the commercial testing services covered by TR-112676 are no longer in existence or no longer offer commercial PD testing services.

Table 2-1
Commercial PD Measurement Services and PD Measurement Methods [1]

Diagnostic Provider	Technique	Excitation Frequency	Preferred Maximum Test Voltage	Coupling Sensor	PD Detection Bandwidth
Cutler Hammer	Time Domain Reflectometer (TDR) location, signal ID by oscilloscope, phase resolved PD	60 Hz	1 V_o	CT on neutral, 100 kHz to 50-80 MHz response band	1-20 MHz
Detroit Edison	HF attenuation location/signal ID by spectrum analysis and oscilloscope	60 Hz	1 V_o	Current transformer around cable	Not Reported
KEMA	TDR/spectrum	60 Hz	1 V_o	Cable current transformer	Not Reported
Lemke	TDR/phase resolved PD	60 Hz	1 V_o	Cable current transformer with differential amp	30 MHz to 300 MHz
Power Diagnostix	TDR/phase resolved PD	0.1 Hz and 60 Hz	1 V_o	Cable current transformer	Not Reported
SINTEF	Acoustic/phase resolved PD	60 Hz	1 V_o	Ultrasonic microphone coupled to fiberglass rod	10k – 100kHz or 10k – 50 kHz
UE Systems	Acoustic and RF	60 Hz	1 V_o	Direct contact ultrasonic microphone & loop antenna	7 MHz
Ultra Power Technologies	TDR/filters	60 Hz	3 V_o	Coupling capacitor	Not Reported

2.3.2 Evaluation of Partial Discharge (PD) Testing Technology for Transmission Class Cables (1012338)

This evaluation of PD testing technology for transmission cables was completed by the University of Connecticut in 2006. It addresses PD measurements for both extruded dielectric and laminar dielectric (HPFF) transmission cables. Its primary focus was on the attenuation of the electromagnetic pulses produced by PD as it travels along extruded dielectric and laminar dielectric transmission cables.

The primary conclusions by the principal investigators were:

- PD pulse attenuation in HPFF cables in air (i.e. without the steel pipe) is much greater than other transmission cable types because of the cable metallic shield construction. This conclusion is based on analytical calculations as well as testing performed on reels of HPFF cable in a cable factory. Prior to this technical report, it was generally assumed that the high amount of high frequency pulse attenuation in HPFF cable is due to the eddy current losses that occur in the ferromagnetic steel pipe that surrounds the cables. The authors conclude that based on the measured properties of HPFF and transmission class solid dielectric cable, PD monitoring appears to be more realistic for the latter than for the former.
- It is possible to perform PD measurements on XLPE transmission cables using capacitive sensors with better sensitivity compared to measurements performed using inductive RF sensors.
- Off-line PD measurements may require a minimum of five minutes with the test voltage applied or the use of an ionizing source to perform effective PD measurements.

2.3.3 Demonstration of Commissioning Tests for Extra-High Voltage Cross-Linked Polyethylene Cable Systems at Los Angeles Department of Water and Power (1001856)

The objective of this project, which was completed in 2002, was to investigate the practical aspects of performing variable frequency, series resonant (VFSR) AC withstand testing and PD commissioning tests on the first major 230 kV XLPE transmission cable project in the US. This cable system is 4.3 miles in length and contains 60 pre-fabricated cable joints. This was the first time that VFSR testing had been performed on installed transmission cables in North America.

The commissioning tests included round robin PD testing performed by five commercial testing companies on terminations at one end of the circuits and at two splice vaults. The commercial testing services that participated in the round robin PD tests were:

- DTE Energy Technologies using a combination of commercial test instruments and proprietary external inductive sensors.
- HV Technologies using LDIC commercial PD test equipment with inductive sensors in splice vaults and a capacitive coupling device at the cable terminations.
- IMCORP using proprietary test equipment located at one substation and at a splice vault
- KEMA using a combination of commercial test instruments and external inductive sensors
- Sumitomo (now J-Power) using external capacitive sensors and proprietary test equipment. Sumitomo also supplied the transmission cable system and was responsible for performing PD measurements on all joints and terminations prior to placing the circuit in service.

A secondary objective of the round robin PD tests was to compare the practical considerations for the various testing services such as setup time, measurement time, and any special requirements for performing the PD measurements.

Four of the five testing services detected no PD in the transmission cable and accessories. The fifth testing service detected PD in one splice vault and recommended follow up testing.

This project demonstrated that field PD measurements with sensitivities ranging from 2 to 50 pC are possible in field conditions. There was better agreement among the five commercial testing services concerning the test results compared to the earlier NEETRAC round robin tests. However, there still was a lack of agreement by all testing services and there were no known PD defects in the cable system.

2.3.4 Testing of XLPE Transmission Cable Terminations at Three Utilities (TR-108073)

This project describes field PD measurements that were performed by one contractor (KEMA) on 69 kV and 115 kV XLPE cable terminations in 1997. The PD measurements were performed at Southern California Edison, Public Service of Colorado, and Philadelphia Electric Company. Significant partial discharge levels were detected on three of the 14 cable terminations where measurements were made.

2.3.5 Best Practices for HPFF Pipe-Type Cable Assessment, Maintenance, and Testing (1011489)

This project, which was funded by the New York Power Authority (NYPA) and EPRI, was the only EPRI technical report that included field PD measurements on pipe-type cable systems. The objective of this project was to perform a condition assessment of relatively short (< 365 m) 345 kV HPFF cable systems at the NYPA Blenheim – Gilboa pumped hydro generation facility. The diagnostic tests performed were:

- Off-line electrical PD measurements performed by three different commercial PD measurement services using VFR series resonant test equipment.
- Acoustic PD measurements performed at the same time as the electrical PD measurements.
- Rated voltage insulation dissipation factor (DF) measurements.
- Pipe fluid sampling and dissolved gas analysis (DGA)
- X-ray inspection of the joints and riser pipes

One of the two electrical PD testing services detected no PD signals. The other electrical PD measurement service and the acoustic PD measurements detected significant PD activity but at different locations.

One conclusion from the electrical PD measurements was that the attenuation of high frequency PD pulses is very high in pipe-type cable and that it would be difficult to achieve effective PD measurements on pipe-type cables with circuit lengths significantly longer than 365 m (1200 ft). This is because of high attenuation of PD pulses that occur at distances of greater than approximately 365 m (1200 ft) from the ends of the cable circuit. Conversely, present field PD measurements are capable of detecting PD pulses for relatively short distances from the ends of the circuit.

2.3.6 Assessment of Extruded 345-kV Cable Technology (TR-110906)

The primary subject of this EPRI report is a description of prequalification tests that were performed in 1995 at Hydro-Quebec's Research Institute on XLPE cable systems in partnership with three international cable manufacturers, Pirelli (now Prysmian), Fujikura (now VISCAS), and Alcatel (now Nexans). This report also contains an in-depth description of VHF field PD measurements that were made on two of the three 345 kV transmission cable systems. The PD measurements, performed intermittently over a period of several years, were made using equipment developed by Hydro-Quebec. This VHF PD detection equipment is similar to equipment that is currently being used by many commercial field PD measurement services.

This report is relevant to the objectives of this project because it describes the reasons for performing distributed PD measurements, the attenuation of the high frequency components of PD pulses, technical reasons for performing VHF PD measurements rather than conventional HF PD measurements covered by industry standards, and methods of calibrating VHF PD measurements in terms of apparent charge (pC). It is very useful in understanding many of the key issues in field PD measurements on XLPE transmission cable systems.

2.4 Industry Guides

The literature review included the following guides that have been published by IEEE and CIGRE during the past seven years.

2.4.1 IEEE Standard 400.3 Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment

This relatively new IEEE guide, which was issued in early 2007, is a good introduction into field PD measurements for distribution and transmission cable systems. It covers both extruded dielectric as well as laminar dielectric power cables. It is useful in understanding the key issues in field PD measurements. As is the case with all other IEEE standards and guides, Std. 400.3 is a consensus document prepared by engineers with a wide range of backgrounds and interests. In this case, the guide was prepared by engineers that were employed by commercial PD service providers, university representatives, utility engineers, and consultants. It took seven years to complete the document partially because of significant differences in opinions about the most effective methods for detecting PD in high voltage cables with field measurements, interpretation of the test results, and other aspects of field PD measurements. The user has to keep in mind that this guide is a consensus document and, therefore, contains numerous compromises between the engineers and scientists that participated in its preparation.

Of particular importance to this project are Section 9.1 (Interpretation of Measurement Results) and Section 9.2 (Test Documentation).

Section 9.1 contains a general summary of methods to interpret the PD measurement results. It acknowledges that interpretation of test results is still developing and knowledge is continuing to be accumulated. It also states that the accuracy in condition assessment may improve as:

- More data are collected and are compared with actual cable system performance
- Data are compared with information from the results of dissections of cable parts or accessories which were recommended to be replaced
- Additional testing is carried out on cables and their accessories that were recommended to be replaced
- Periodic measurements are made on the same circuits, i.e., trending. When available, data from previous PD tests on the same circuit will be very helpful in diagnosing the implications of detected PD sources.
- All relevant information about the cable system is known, such as the age type and design of cables and accessories, operating conditions, etc.
- Standardized test and analysis procedures are developed. This will aid the comparison of databases of different PD service providers and also from different utilities.

Section 9.2 of the guide provides recommendations and a list of items that should be included in field PD measurement test reports. It should be noted, however, that these recommendations are general in nature and do not differentiate between field PD measurements performed on distribution and transmission cable systems.

2.4.2 CIGRE Technical Brochure 182, Partial Discharge Detection in Installed HV Extruded Cable Systems

This CIGRE technical brochure, which was completed in 2001, is an excellent user's guide to partial discharge detection (PDD) in extruded dielectric power cables. It was developed by world experts in field PD measurement technology specifically for users rather than other PD measurement experts. The document does, however, state in the introduction that it is not intended to be a consumer guide saying which method is better than another. It does provide the user support in understanding the complicated field of on-site PDD and ultimately making decisions about PD testing.

This guide is unique in that it describes eight practical PD measurement methods including a survey of actual test results to give the user a representative impression about the present options for field PD testing. This information covers PD sensors, the detection frequency of PD measurements, analysis of test data, typical measurement sensitivity (pC) for field measurements, and results from actual transmission cable field PD measurements.

Finally, it covers trends and possible future developments in the technology for field PD measurements.

In summary, this guide is mandatory reading for the end user. A thorough understanding of the material covered by the guide will provide the user with fundamental information to make informed decisions about field PD measurement alternatives and to understand the topics that should be covered in field PD measurement test reports.

2.4.3 CIGRE Technical Brochure 226, Knowledge Rules for Partial Discharge Diagnosis in Service

This CIGRE document, which was completed in 2003, provides detailed information on PD measurements for all types of power system equipment. More specifically, it includes information on PD measurements for transformers, generators, distribution cables, transmission cables, and GIS insulated substation equipment. It also provides guidelines or knowledge rules for insulation condition assessment based on dissipation factor, AC electric strength, and dissolved gas analysis for impregnated laminar dielectrics.

The document is not intended to be a user's guide but covers PD phenomenon, detection methods, typical PD defects, interpretation of test results, and decision making based on measurement results.

The section (Part III) on power cables primarily discusses distribution cable PD measurements, but Sections 3.5 (Relevant PD Quantities), 3.6 (Interpretation of Criteria), and 3.8 (Practical Experiences for Transmission Cables) are of particular relevance to this project.

2.4.4 CIGRE Technical Brochure 297, Practical Aspects of the Detection and Location of Partial Discharges in Power Cables

This CIGRE document, which was completed in 2006, focuses on the location of PD sources based on the time domain reflectometry (also known as time-of-flight) method. It describes methods to predict the velocity of propagation for XLPE power cables as well as the attenuation of PD pulses as a function of distance from the source. It describes practical problems encountered in PD source location.

2.5 Summary

Many technical publications pertaining to field PD measurements on transmission cables have been published since the NEETRAC literature search (EPRI TR-112676) was completed in 1998.

The number of technical publications in the area of field PD measurements on power cables has increased significantly in the past several years. For example, there were 17 papers on various aspects of cable PD measurements that were presented at the Jicable 2007 conference.

Most of the technical papers on transmission cable PD measurements are intended for extruded dielectric cables. Two publications ([28] and [29]) and an EPRI report [5] cover field PD measurements for laminar dielectric transmission cables.

Several industry guides ([6], [7], [8], [9]) on field PD measurements have been published in recent years that provide a good summary of the procedures for field PD measurements, the methods used to detect PD signals, calibration methods, test reports, and safety considerations. Reference [6] is a general guide on field PD measurements for all types of shielded power cables and reference [9] is an excellent reference on field PD measurements for extruded dielectric transmission cable systems.

Two EPRI technical reports ([1] and [4]) present the results of round robin testing performed by commercial field PD measurement services. Reference [1] describes test results for extruded dielectric cable systems performed in a controlled laboratory environment and reference [4] contains a summary of field PD measurements performed during commissioning of a 230 kV XLPE transmission cable system. These EPRI reports, in general, indicate that there have been improvements in the test equipment and test procedures during the past decade; however, there are still inconsistent PD test results between the different measurement methods and commercial test services.

3
FIELD PD MEASUREMENT BASICS

Partial discharge measurements have been performed on high voltage cables and other power system equipment for over forty years[7]. However, PD measurements on high voltage equipment were generally limited to high voltage testing laboratories and manufacturing plants until relatively recently because of difficulties in performing effective PD measurements in the field. The primary limitation in performing field PD measurements has been electrical interference from a number of sources (i.e. radio stations, communications equipment, corona from high voltage lines and substations, electrical manufacturing equipment, etc.). It has only been during the past ten to fifteen years that equipment and testing procedures have been developed that permit field PD measurements to be performed successfully. The first IEEE Guide[8] for field PD measurements on high voltage cable systems was completed in 2006. Currently, there are several industry standards that specify how PD measurements are to be performed on transmission cables and accessories in laboratories and production tests in cable factories. These industry standards also include maximum allowable PD limits. Such standards do not exist for performing field PD measurements.

3.1 Differences between Laboratory and Field PD Measurements

Some of the primary differences between field PD measurements and PD measurements performed at cable factories and laboratories are described in the following sections.

3.1.1 Length of Cable or Cable System

The length of the cable or cable systems (i.e. includes splices and commercial terminations) that are tested in cable factories and laboratories are in most cases much less than in-service cable systems. The magnitudes of the electrical signals that are created by defects in the cable system for laboratory measurements are practically the same at all locations. In other words, the PD created signals in laboratory measurements are not significantly attenuated or dispersed from the location of the defect to the locations where the measurement equipment is attached. Conversely, the length of completed commercial transmission cable systems may be up to tens of km (miles) long and there is significant attenuation of PD signals and PD calibration signals when they travel for distances that are greater than several km (or miles). When PD signals must travel multiple km (or miles) before they reach a measurement point, they are attenuated so much that it is difficult or impossible to detect them even using the latest technology. The CIGRE guide[9] for factory testing of long XLPE submarine cables does not require PD measurements on shipping lengths of long XLPE submarine cables because of this technical limitation.

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[7] Kreuger, F. H., "Discharge Detection in High-Voltage Equipment", Heywood, London 1964.
[8] IEEE Standard 400.3
[9] CIGRE WG 21.02, "Recommendations for Testing of Long AC Submarine Cables with Extruded Insulation for System Voltage Above 30 (36) to 150 (170) kV, Electra No. 189, April 2000

3.1.2 Electromagnetic Shielding of Test Object

It is possible to perform PD testing at factories and testing laboratories in electromagnetically shielded testing enclosures (i.e. Faraday cage) as shown in Figure 3-1. This permits external electrical noise sources to be excluded from the area where the measurements are being performed.

Figure 3-1 Typical shielded room for performing transmission cable PD measurement (courtesy of Southwire)

3.1.3 Measurement Objective

In general, there are different objectives when performing laboratory or factory PD measurements compared to field PD measurements. The logic for selecting the objective of transmission cable field PD measurements is:

- Each shipping length (reel) of transmission cable is thoroughly tested at the factory before it is shipped, which gives a reasonable level of assurance that there are no significant defects in the cables when they leave the factory.
- The same is true for the major insulating components of premolded and pre-fabricated splices.
- Jacket integrity tests are performed on the cables after they are installed to detect any mechanical damage during shipment or installation.
- Operating experience has shown that the most likely cause of in-service failures for new extruded dielectric transmission cable systems are joints and terminations.

Consequently, the primary objective for performing field PD measurements is to detect workmanship problems that may occur during installation of the joints and terminations. The detection of PD in new XLPE transmission cables is not the primary objective of most field commissioning tests.

3.1.4 PD Test Equipment

There are significant differences in PD detection equipment for laboratory and field measurements. The PD test equipment that is used in cable factories and electrical testing laboratories typically detects the lower frequency (< 1 MHz) components of the electrical signals created by partial discharges.

Most field PD measurement equipment is designed to detect the high frequency (> 1 MHz) components of the electrical signals that are caused by partial discharges. This is because field PD measurements are usually made close to splices and terminations and external high frequency noise is significantly attenuated before it reaches the measurement location.

3.1.5 PD Measurement Calibration Methods

The calibration procedures for field PD measurements and laboratory or factory PD measurements are significantly different. As stated in the previous item (PD Test Equipment) laboratory or factory PD detection equipment is designed to detect PD signals in the 100 kHz to 500 kHz range. In this case the laboratory or factory PD measurements are calibrated by injecting short duration current pulses into the cable system [36] with a known charge (pC) in each of the pulses (e.g. 5 to 10 pC calibration pulses are commonly used to calibrate PD measurements which require a measurement sensitivity of 5 pC). The gain of an amplifier in the PD detector is then adjusted until the indication (readout) on the PD detector is equal to the magnitude of the calibration pulse. This is a relatively simple and repeatable process because the attenuation of the PD calibration pulse is relatively small for the length of cable being tested and PD detection instruments respond to the charge in the calibration pulses. This calibration process is well defined in industry standards[10, 11].

The calibration procedure for VHF/UHF frequency PD measurement equipment used in the field is much more difficult [32, 37] and the calibration of VHF/UHF PD detection instruments is not covered by industry standards. In many cases a calibration signal cannot be injected close to the location where the PD measurement equipment is located (typically in a splice vault that is several km from the cable terminations). If a calibration pulse is injected at the remote cable termination, there is significant magnitude attenuation and pulse dispersion by the time it reaches the location where the PD detector is located [8, 37]. So, the attenuated and distorted calibration pulse at the measurement location cannot be related to PD produced pulses that may occur in the joint when PD measurements are performed. Another difficulty is that at VHF/UHF frequencies most instruments respond to the magnitude of PD signals in mV rather than the apparent charge (pC). Consequently, some field PD measurement services report the results in mV rather than in pC for VHF/UHF PD test equipment. It is then difficult, if not impossible, to relate the mV measurement results to apparent charge (pC). References [37] and [38] contain in-depth descriptions of the problems associated with the calibration of VHV/UHF PD measurement in terms of apparent charge (pC). Since most of the PD measurement test experience (factory tests,

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[10] IEC 60270, "High voltage test techniques - Partial discharge measurement".
[11] ICEA T-24-380, “Guide for Partial-Discharge Test Procedure”.

type tests, and in-service measurements) is for PD quantified in apparent charge (pC), it is difficult to perform a comparative assessment of field PD measurements that are reported in mV.

3.2 Sensors for Field PD Measurements

A number of different types of sensors or transducers are used to couple the PD produced electrical signals from the cable system to the PD detection instrument.

3.2.1 Coupling Capacitor and Blocking Impedance

The classical method for coupling PD produced signals from the cable system to the PD detection equipment is a high voltage coupling capacitor that is connected between the cable termination and system ground as shown in the electrical schematic in Figure 3-2. A high frequency blocking impedance (typically an inductor that is designed to have a low series capacitance) is normally placed between the coupling capacitor and the high voltage source to block electrical interference, such as corona, from entering the coupling capacitor and PD instrument.

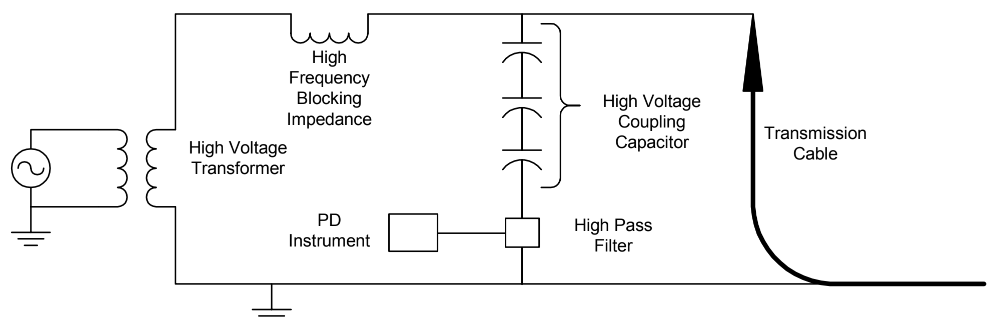


Figure 3-2
Schematic diagram of equipment to couple PD signals from high voltage cable (test object) to PD detection equipment.

If partial discharges are present in the transmission cable system, then short duration traveling wave current pulses travel from the site of the partial discharges to the ends of the cable circuit and then flow into the coupling capacitor which has low impedance to the high frequency components of the PD pulses. The high pass filter or detection impedance at the low potential side of the coupling capacitor separates the power frequency component of the test voltage (50 or 60 Hz) from the high frequency PD current pulses. The PD instrument amplifies the high frequency signals from the high pass filter and displays them on a video display as shown in Figure 3-3 (a) or 3-3 (b). Both of these displays make it possible to visually determine if there is a correlation between the time that the high frequency pulses (vertical lines in 3-3 (a) or 3-3 (b)) occur and the phase of the AC voltage that is applied to the cable system. The ellipse shown in Figure 3-3 (a) corresponds to one complete cycle of the AC test voltage. The transition of the AC test voltage through one cycle occurs by progressing around the ellipse in a clockwise direction (as indicated by the arrow on the top right side of the ellipse). The “+” and “-” markers in the elliptical display correspond to the positive and negative peaks of the AC test voltage. The “0” markers with arrows at the left and right ends of the ellipse correspond to the points in time when the sinusoidal test voltage is passing through zero potential. Figure 3-3 (b) shows the same information except it is a simple x, y plot of time versus test voltage. If the partial discharges occur at imperfections within the high voltage insulation, then the pulses occur ahead of the positive and negative peaks of the AC test voltage as illustrated in Figures 3-3 (a) and (b). High frequency interference may also appear as pulses on the video display of the PD test instrument, but typical electrical interference will not be synchronous with the AC test voltage. So, if the pulses on the display are not repetitive and do not precede the positive and negative peaks of the test voltage, they probably are not caused by partial discharges in the high voltage insulation. References [23] and [25] describe numerous different PD display patterns and are excellent references for the interpretation of test results from laboratory PD measurements.

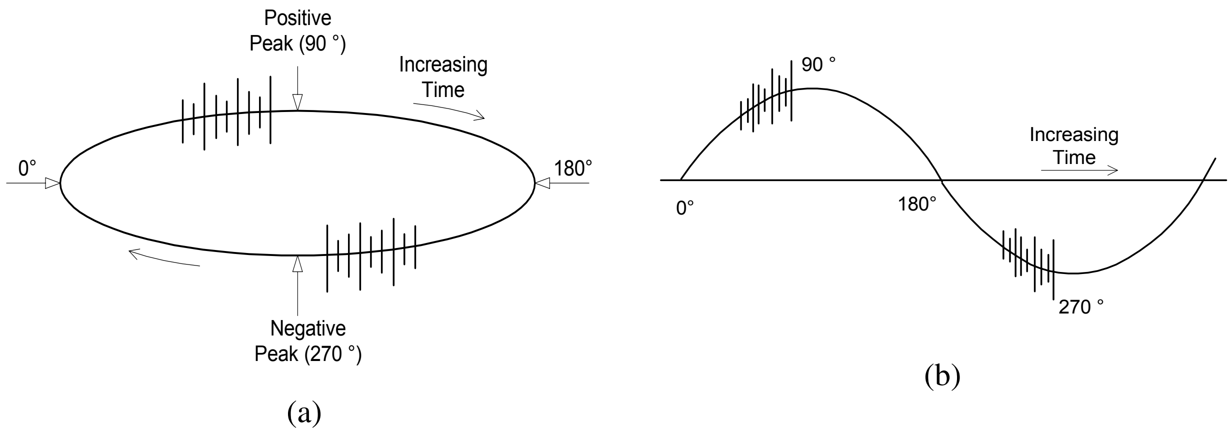


Figure 3-3 Display of typical PD detection instrument

Figure 3-4 shows a PD instrument display that is similar to the display in Figure 3-3 (b). In this case the first half cycle of the test voltage (0 to 180 ˚) is shown in the upper part of the display and the second (negative) half of the cycle is displayed in the lower right side of the picture. Only the positive parts of the pulses are displayed by this PD instrument. In this case, intermittent pulses appear on the display, but they are not symmetrical before the positive and negative voltage peaks as described above.

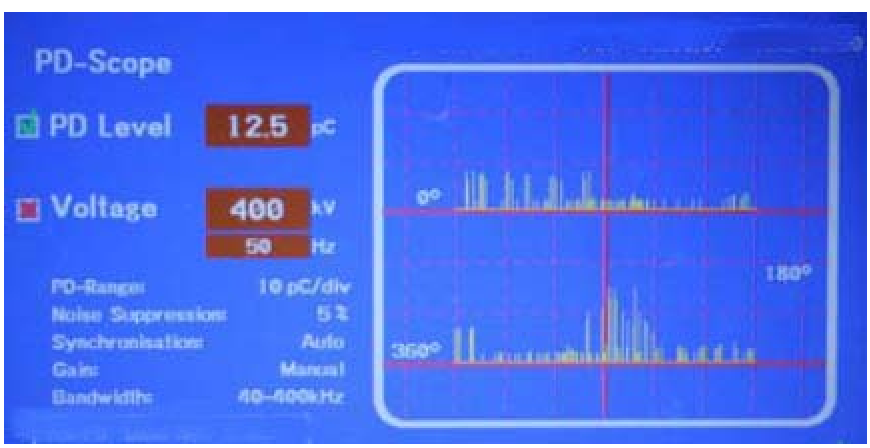


Figure 3-4
PD instrument display with noise pulses

Figure 3-5 shows the coupling capacitor and high frequency blocking impedance used for PD measurements performed in a testing laboratory or for production tests at a cable manufacturing plant. Figure 3-6 shows similar equipment for field PD measurements.

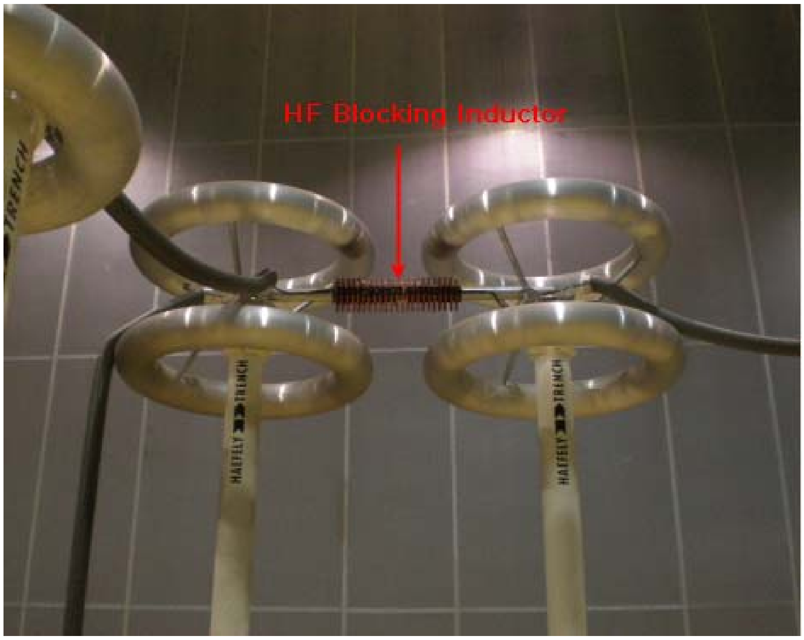


Figure 3-5
Typical PD Test Equipment in Cable Factory (courtesy of Southwire)

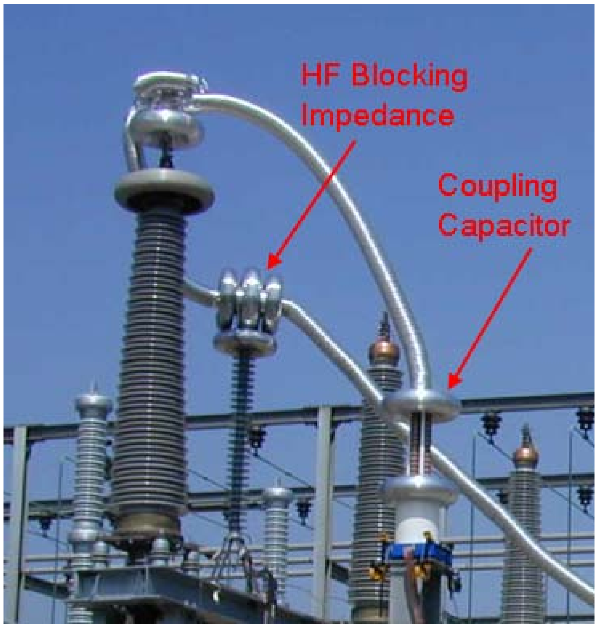


Figure 3-6
Coupling capacitor and series blocking impedance for field PD measurements [4]

3.2.2 External Inductive Sensors

Radio frequency current transformers or Rogowski coils are frequently used to inductively couple the PD pulses from the cable system to the PD detection equipment. Inductive PD sensors are typically placed around the sheath bonding leads (Figure 3-7), or around the links in link boxes as shown in Figure 3-8 (b). Some commercial PD measurement services use a fork shaped inductive sensors that are placed around the cable as shown in Figure 3-8 (a).

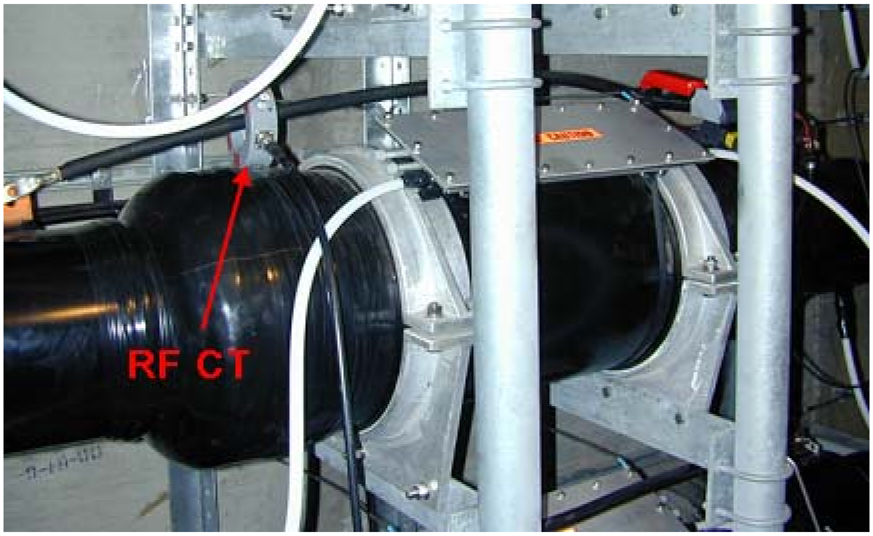
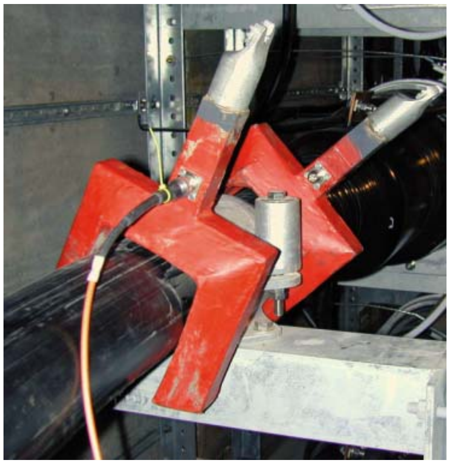
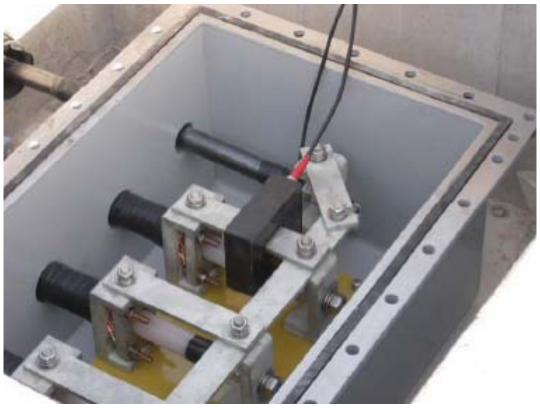


Figure 3-7
Radio frequency current transformer (RFCT) placed around cable bonding lead [4]



(a)



(b)

Figure 3-8. Inductive sensors placed around cable and sheath bonding link [4]

The external inductive sensors are commonly used because it is relatively easy to temporarily apply this type of sensor after the cable system installation has been completed. Several of the technical publications [9] and an EPRI technical report [3] conclude that the external inductive sensors do not produce sensitive PD measurements compared to those performed with integral capacitive sensors that are described in the following section.

3.2.3 Integral Capacitive Sensors

Integral capacitive sensors couple electrical signals produced by partial discharges to the PD instrument by means of the high frequency variations in electric field outside of the high voltage insulation. Integral capacitive sensors are formed by placing a conductive layer on the outside of the high voltage insulation or on the outside of the insulation semi-conductive screen. Figure 3-9 shows a cross section of a premolded transmission cable joint with an integral capacitive PD sensor.

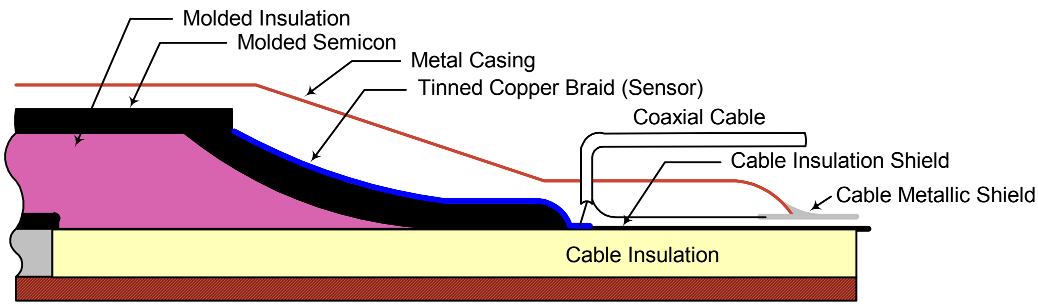


Figure 3-9.
Cross section of premolded cable joint with integral capacitive sensor

Figure 3-10 shows the connector to an integral capacitive PD sensor on a pre-fabricated 345 kV XLPE cable splice

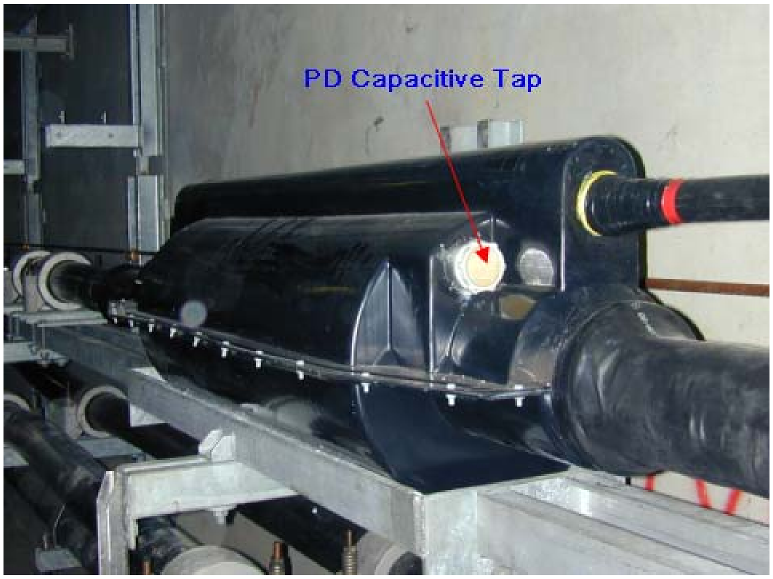


Figure 3-10
345 kV Pre-fabricated cable joint with integral capacitive PD sensor

3.2.4 External Capacitive Sensor

Temporary external PD capacitive sensors are also implemented by attaching metal foil electrodes to the outside of metal joint casings (Figures 3-11 and 3-12) or on the outside of the cable jacket (Figure 3-13).

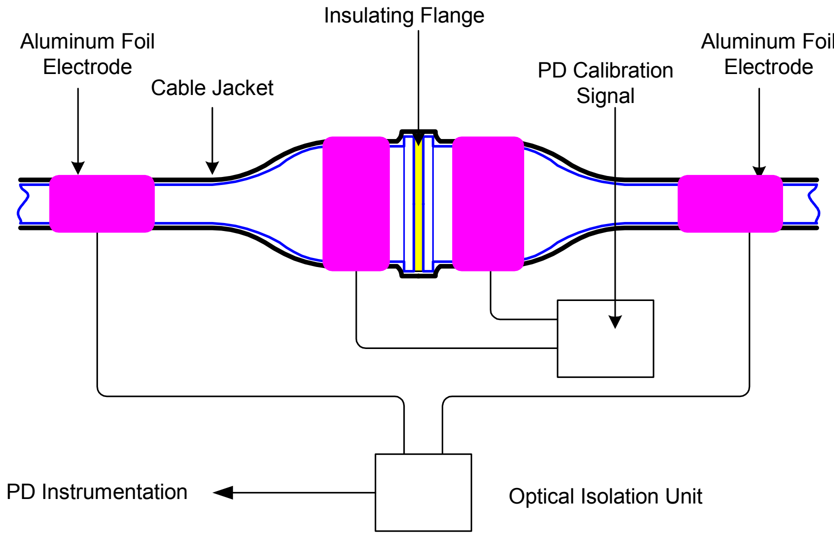


Figure 3-11
Schematic of external capacitive sensors attached to outside of joint casing [4]

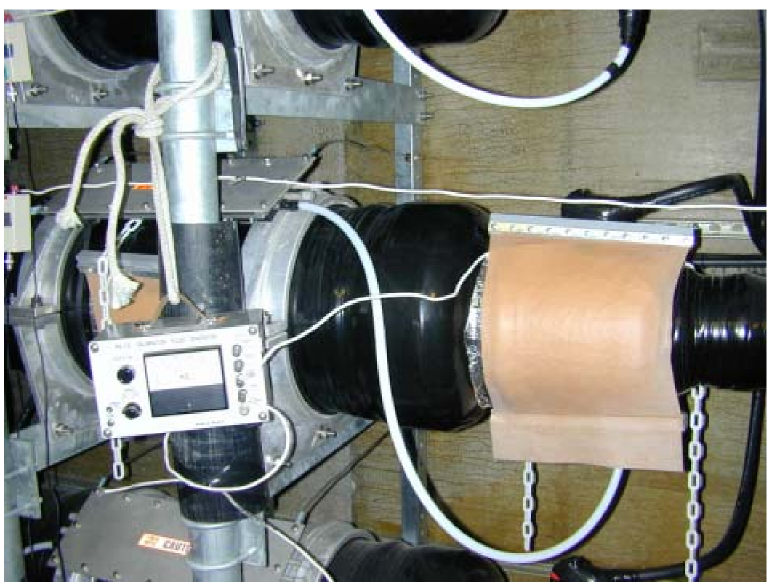


Figure 3-12
External aluminum foil electrodes used for capacitive PD sensor on 230 kV XLPE cable joint [4]

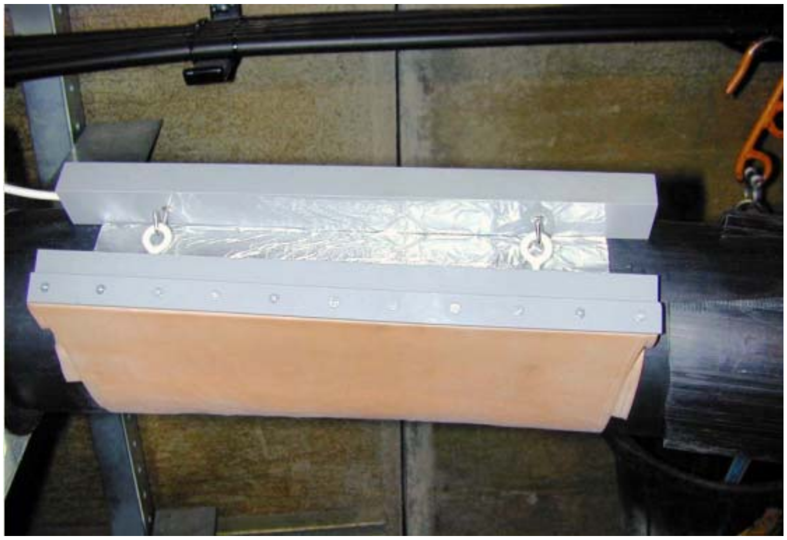


Figure 3-13
Temporary aluminum foil electrode used for temporary capacitive PD sensor [4].

3.2.5 Directional Couplers

Directional couplers combine the characteristics of capacitive and inductive sensors because they respond to both the electric and magnetic fields produced by partial discharges. This type of PD sensor has the advantage of being able to determine the direction that the PD pulse is traveling. When two directional couplers are placed on the opposite sides of a joint their signals may be used to determine if PD pulses are being produced inside of the joint or by defects external to the cable joints. Directional coupler PD sensors typically have a large bandwidth which makes it possible to determine the location of the PD source based on the difference travel times to two of these sensors.

4

COMMERCIAL PD MEASUREMENT TECHNOLOGIES

A variety of sources of field PD measurement equipment and commercial field PD measurement services are currently available to electric utilities in North America. The following is a list of services and PD measurement equipment that are currently available.

- **Field PD measurement services using proprietary PD measurement equipment** – There are companies that have developed their own PD measurement equipment and their normal mode of business is to provide field PD measurement services. The PD measurement equipment, technology for performing the measurements, and analysis of the measurement results are proprietary to the service provider. The equipment and technology generally are not available for sale (with the possible exception of custom designed long-term PD monitoring equipment). Examples of these service providers are IMCORP (Storrs Connecticut), UTILX/CableWise (Kent Washington), IPH GmbH (Berlin Germany) and KEMA (Arnhem Netherlands).
- **Field PD measurement services that use commercially available PD measurement equipment** – These service providers typically have developed proprietary methods for performing the measurements and for analysis of the measurement results. An example of this type of service provider is Kinectrics (Toronto Canada). Kinectrics uses commercially available PD measurement equipment that is manufactured by TechImp and IPEC HV.
- **Manufacturers of commercially available PD measurement equipment** - IPEC High Voltage Ltd. (Manchester, UK), LDIC (Kesselsdorf Germany and Rheinfelden Switzerland), TechImp (Bologna Italy), Omicron GmbH (Klaus Austria), PowerDiagnostix GmbH (Aachen Germany), and SE Technology Limited (Hong Kong) provide most or all of the equipment necessary to perform field PD measurement services.
- **PD Equipment Manufacturers Using Their Commercial Instruments** – Most of the major suppliers of PD measurement equipment also provide field PD measurement services. IPEC HV, LDIC’s US subsidiary HV Technologies (Manassas, Virginia), Omicron, TechImp, and PowerDiagnostix provide field measurement services using commercial equipment manufactured by their respective companies.

4.1 Differences in Commercial Field PD Measurement Methods

CIGRE TB 182, Partial Discharge Detection in Installed HV Extruded Cable Systems [9], describes eight practical field PD measurement methods that were known to the members of CIGRE working group 21.16 in 2001. The members of the CIGRE working group represented nine different countries. The names of the organizations that use the eight different PD measurement methods (identified as methods A through H) were not identified in TB 182.

All eight of the PD measurement methods are electrical detection methods (i.e. none were acoustic measurements). Another common factor among the eight field PD detection methods is that they are all based on detecting PD signals above 1 MHz. The majority of them are designed to detect signals in the 1 MHz to 40 or 50 MHz range. Three of the eight are designed to detect PD signals up to 500 MHz. Typical PD detection sensitivity levels are in the 1 pC to 20 pC range depending on ambient electrical noise. Most of the eight PD measurement methods claim to have field PD measurement experience starting from 1989 to 1998. The eight commercial field PD measurement methods differ in the following ways.

4.1.1 Purpose of PD Measurements

Seven of the eight PD measurement organizations that were covered by CIGRE TB 182 stated that their measurements were intended to detect PD in cable accessories (terminations and joints). One of the organizations claimed that their measurement method covered both cable and accessories. Since the purpose of most of the PD measurements is to detect PD in cable accessories, most of the eight methods rely on measurements made at multiple locations of the underground transmission system, typically at each joint and termination location.

4.1.2 PD Detection Sensors

Three of the practical PD measurement methods use capacitive sensors, three use inductive sensors, one uses directional couplers, and one method uses both capacitive and inductive PD sensors.

4.1.3 On-Line Versus Off-Line PD Measurements

Seven of the PD measurement methods are suited for both on-line and off-line PD measurements. One of the methods is intended only for on-line PD measurements.

4.1.4 Interpretation of Test Results

Three of the eight measurement methods/organizations use automated interpretation of the measurement results. Analysis of measurement results by the remaining five methods (service providers) are manually performed by a PD measurement expert.

4.1.5 Calibration and Units of PD Measurement Results

Measurement sensitivity and typical measurement results were reported in apparent charge (pC) for all eight of the measurement methods. The calibration method reported for the eight measurement methods vary significantly. The following calibration methods were reported.

- **Calibration by construction** – The output of the capacitive sensor is based on the physical geometry of the PD sensor.
- **Special injection coupler** – No further details were provided
- **Injection of calibrated charge pulses** – It was acknowledged that the validity of this method is limited
- **Use of two sensors** – One sensor is used to inject a calibration signal and the other to measure the calibration signal
- **Laboratory measurement performed on integral sensors** – Laboratory measurements were performed on integral PD sensors to determine their output as a function of calibration signals. Quasi-Integration of the sensor output signal was also used to correlate the measurement results to pC.

4.1.6 Time Domain versus Frequency Domain Detection

All of the PD measurement methods that are considered in CIGRE TB 182 are time domain PD measurement methods (i.e. the PD electrical signals are recorded and analysis of the signals is performed in the time domain). IEEE Standard 400.3 also describes a field PD measurement method (used by at least one commercial field PD testing service) that is based on acquisition and analysis of the PD signals in the frequency domain.

Frequency domain PD testing is based on measuring the frequency components of the PD pulses. The frequency spectrum of the time varying PD pulses are obtained by means of a conventional spectrum analyzer. The frequency components can also be calculated from the digitized time domain signal using fast Fourier transform (FFT) calculation methods. In general, the frequency components of PD signals are in the range of a few hundred kHz to up to 1 GHz depending on the distance between the PD source and the point where the measurements are performed. A frequency range of a few hundred kilohertz to 300 MHz is common due to limitations imposed by the frequency bandwidth of the PD detection sensors.

Frequency domain testing normally is conducted using two modes of a spectrum analyzer. Theses are called the full and zero-span modes. In the full span mode, the frequency range scanned can be adjusted to examine signals in narrow-frequency bands as well as wide-frequency bands. Location of PD sources is determined from measurements using narrow-frequency bands and knowledge about attenuation of frequency components as function of distance from the PD source. The signal from the spectrum analyzer zero-span mode is often coupled to a pulse phase analyzer. The pulse phase analyzer is capable of recording PD pulses sorted by their phase angle and magnitude relative to the power frequency voltage.

The frequency domain measurement technique does not provide a direct basis for calibration of the resulting data in terms of apparent charge (pC). PD sources are recognized on the basis of their spectral characteristics and through the use of the zero-span mode of the spectrum analyzer to provide a correlation between the signal in the selected spectral region and power frequency. The relationship between the measured signal and the “severity” of the partial discharges is based on testing experience and laboratory test results.

The frequency domain method is generally more immune to interference from external noise, provided means are used to prevent stray signals from being coupled into the cable tested, when testing is performed on-line. A skilled operator is needed to collect and analyze the data. PD location is often judged from the frequency content of the PD-induced signal in combination with knowledge of the cable type (e.g., the high frequency attenuation characteristics of the cable).

4.2 Summary of Commercial Field PD Measurement Services in North America

It is sometimes difficult to determine the details of the measurement methods and capabilities of the commercial field PD testing services because many of the companies consider this information to be proprietary. However, an attempt was made to summarize the PD measurement methods used by the commercial field PD measurement services that have performed transmission cable PD measurements in North America. The information in this summary was based on the following.

- Test reports provided by the testing services for the EPRI round robin tests described in references [1], [4], and [5].
- Information in the technical specifications for commercial test equipment used by some of the PD measurement services.
- Technical publications written by the commercial testing services
- Field test reports provided to utilities by the commercial testing services

4.2.1 AZZ CGIT (Westboro, MA)

- Method: Acoustic PD measurements using commercially available equipment
- PD Detection Instrumentation: Transinor Acoustic Analyzer (This acoustic PD detection equipment is primarily used for GIS equipment).
- PD Sensors: Ultrasonic pickup
- Measurement Units: mV
- Calibration Method: Comparison of de-energized and energized acoustic signals

4.2.2 DTE Energy/UTILX (Kent, WA)

- Method: Electrical frequency domain measurement of PD signals
- Measurement Frequency: 20 to 100 MHz
- PD Detection Instrumentation: Spectrum analyzer
- PD Sensors: Proprietary external inductive pickup
- Measurement Units: mV and pulses per second
- Calibration Method: Laboratory test experience
- Test Results: Condition assessment (scale of 1 to 5) based on test experience

4.2.3 KEMA (Arnhem, Netherlands)

- Method: Electrical time domain PD detection
- Measurement Frequency: 25 to 50 MHz
- PD Detection Instrumentation: Digital storage oscilloscope and spectrum analyzer
- PD Sensors: Proprietary external inductive pickup
- Measurement Units: apparent discharge (pC)
- Calibration: Field calibration and calculations
- Test Results: Color plot showing intensity of pulses and phase correlation with test voltage

4.2.4 Kinectrics (Toronto, Canada)

- Method: Electrical time domain PD detection
- Measurement Frequency: 0.5 to 200 MHz (depending on sensor used)
- PD Detection Instrumentation: TechImp and IPEC HV commercial equipment
- PD Sensors: External inductive and internal capacitive

- Measurement Units: mV
- Calibration: Perform sensitivity assessment [31], prior to measurements
- Test Results: Phase correlation of PD pulses with test voltage, TechImp proprietary "pulse cluster plots"

4.2.5 HV Technologies/LDIC (Manassas, VA)

- Method: Electrical time domain
- Measurement Frequency: 100 kHz to 400 MHz and 1 to 50 MHz, and 300+ MHz depending on application and sensor used
- PD Detection Instrumentation: LDIC commercial PD test equipment
- PD Sensors: External inductive, internal capacitive, and external capacitive
- Measurement Units: Apparent charge (pC) and mV depending on detection frequency
- Calibration: "Equivalent apparent charge" calibration method
- Test Results: Phase correlation of PD pulses with test voltage

4.2.6 IPH Berlin (Berlin, Germany)

- Method: Electrical time domain
- Measurement Frequency: Up to 500 MHz, depending on PD sensors
- PD Detection Instrumentation: Omicron commercial equipment and IPH proprietary
- PD Sensors: Internal capacitive, inductive directional coupler (recommended), and external inductive (RF CT)
- Measurement Units: Apparent charge (pC)
- Calibration: Off-line calibration of built in sensors, or externally applied calibration pulse
- Test Results: Phase correlated PD pulses, 3-Phase amplitude relation diagram (3PARD) visualization

4.2.7 IMCORP (Storrs, CT)

- Method: Electrical time domain
- Measurement Frequency: 0.5 to 20 MHz (programmable)
- PD Detection Instrumentation: IMCORP proprietary
- PD Sensors: Coupling capacitor/blocking impedance, external inductive, internal capacitive depending on application
- Measurement Units: Apparent charge (pC)
- Calibration: Off-line calibration with calibration pulses
- Test Results: Phase correlated PD pulses with test voltage

4.2.8 TechImp (Bologna, Italy)

- Method: Electrical time domain detection and digital acquisition
- Measurement Frequency: 0.5 to 200 MHz (depending on sensor used)

- PD Detection Instrumentation: TechImp commercial PD test equipment for both manual operation at multiple locations or units designed for remote control and monitoring from a single location.
- PD Sensors: External and Internal inductive and capacitive sensors
- Calibration: Perform sensitivity assessment prior to measurements, “Equivalent apparent charge”
- Test Results: Phase correlation of PD pulses with test voltage, TechImp proprietary “pulse cluster plots” and amplitude-frequency (AF) [39] analysis

4.2.9 J-Power/SE Technologies (Osaka/Hong Kong)

- Method: Electrical time domain
- Measurement Frequencies: 5, 12, 16, 23 MHz, selectable narrow bandwidth
- PD Detection Instrumentation: J-Power/SE Technologies proprietary equipment with remote monitoring via fiber optic cables.
- PD Sensors: Temporary externally applied capacitive and inductive sensors
- Calibration: Calibration at each measurement location with pulse calibrator
- Test Results: Phase, apparent charge, and time 3-D plots

4.3 Effectiveness of Field PD Measurements

It is difficult to obtain accurate information about the effectiveness of field PD measurements for detecting PD defects in transmission cables. Most of the commercial field PD measurement services have made presentations that tout the effectiveness of their PD measurement services. However, information concerning cases where subsequent in-service failures occurred (and where good PD measurement results were reported) is rarely discussed.

The EPRI project [1] in 1998 is the only source of information on testing of the effectiveness of commercial field PD measurements in a controlled laboratory environment and known cable or accessory defects. As noted in Section 2 (Field PD Measurement Literature) none of the commercial PD measurement services was 100% effective in distinguishing the 115 kV XLPE cable and accessories with defects from those without defects. However, advances have been made in both PD measurement equipment and expertise during the past ten years.

Commissioning tests [2], [15], [25] performed on XLPE cable systems demonstrate that field PD measurements are successful in detecting PD defects. The authors of reference [15] report that they have detected PD with magnitudes ranging from 15 pC to 250 pC in 3 out of 80 PD measurements during commissioning tests. There are, however, several notable incidents where in-service failures occurred on XLPE transmission cable systems after field PD measurements reported no PD signals during commissioning tests. Three examples of this apparent failure of the field PD measurements were:

1. **230 kV XLPE Transmission Cable System** – A joint failure occurred approximately three months after successfully passing a one-hour, 1.25 U_o AC withstand test and PD measurements at rated voltage. It appeared that the joint failure was caused by misalignment of the premolded splice body.

2. **345 kV XLPE Transmission Cable System** – Two in-service joint failures occurred within two and a half years after successful completion of a one-hour, 1.25 U_o AC withstand test and PD tests. The sensitivity of the joint PD measurements during commissioning was reported to be 1 pC to 2 pC. The cause of the joint failures has not been determined.

3. **138 kV XLPE Transmission Cable System** – An in-service joint failure occurred approximately one year after commissioning PD tests were performed. No PD signals were detected during the rated-voltage commissioning test. Laboratory analysis of the joint failure was inconclusive.

PD measurements for the above cable systems were performed by three different commercial field PD measuring services.

The above experience from field PD measurements on XLPE transmission cable systems indicates that they are capable in many cases of detecting defects that produce partial discharges. However, it appears that there are some instances where the field PD measurements are not successful in detecting installation defects. There is also the possibility that some defects take a period of time after commissioning to develop.

4.4 Trends in Commercial Field PD Measurements

There have been significant improvements in field PD measurement equipment and methods during the past decade. Some of the trends in commercial field PD measurement services are:

1. **VHF/UHF PD Measurements** – Most electrical PD measurements are being made at frequencies of several MHz to several hundred MHz to improve PD signal to noise ratio.
2. **Distributed Measurements** – The majority of field PD measurements are being performed at each joint and termination locations as compared to one or two measurements made at the ends of the cable circuit.
3. **Use of Commercially Available PD Detection Equipment** – Commercial field PD measurement equipment is available from at least four different manufacturers and PD measurement services are using commercial equipment rather than proprietary equipment. This trend is beneficial because the technical specifications and capabilities of the equipment are available to the end user of the field PD measurement services.

4. **Use of External PD Sensors** - There appears to be agreement in the technical literature that more sensitive PD measurements can be achieved using integral PD sensors in splices and terminations. The integral PD sensors can also be pre-calibrated in some cases for VHF/UHF PD detection to relate the sensor output to apparent charge (pC). However, the current trend in North America is to use temporary external PD sensors that are applied to the splice and termination bonding leads by the PD measurement service. A concern about the use of integral PD sensors in duct bank cable systems is that moisture may eventually penetrate splices in the vicinity of the PD sensor electrical connectors in vaults that are often filled with water.
5. **Simultaneous PD Measurements at Multiple Locations** – Equipment has been developed [13, 18, 21, 39] that makes it possible to simultaneously perform PD measurements at multiple locations. Control and data acquisition are performed at a central location using wireless communication equipment or fiber optic cables. Performing PD measurements at multiple locations makes it easier to complete the measurements within the one-hour AC commissioning test time period recommended by IEC 62067. This technology improvement also facilitates real-time PD measurements.
6. **Real-time Monitoring** – Several of the field PD measurement equipment manufacturers (i.e. TechImp, Omicron, and SE Technologies) have extended the development of equipment for simultaneous measurement locations to remote, real-time monitoring. The effectiveness of this equipment has not been documented in the technical literature. However, it potentially has the advantage of detecting PD defects that take some weeks or months to develop.

5 INTERPRETATION OF FIELD PD MEASUREMENT RESULTS

One of the objectives of this project is to prepare recommendations for future work to assist EPRI member companies in the interpretation of field PD measurement results. Consequently, a number of test reports prepared by commercial field PD measurement services from previous EPRI field PD test projects as well as test reports from commission PD measurements were reviewed.

A number of different methods are used to interpret the results of field PD measurements depending on the PD detection equipment that is used, test experience, length of test circuit, and several other factors which may be proprietary to the measurement service.

5.1 Review of Field Test Reports

A total of fourteen field PD test reports submitted by commercial field PD measurement services for XLPE and HPFF transmission cable system were reviewed. These test reports were prepared by the following PD measurement services.

- AZZ CGIT
- DTE Energy Technologies
- IPH Berlin
- KEMA
- Kinectrics
- HV Technologies
- IMCORP
- J-Power

All of the test reports that were reviewed were prepared between June 2002 and January 2007. The test reports included field PD measurement results for 230 kV and 345 kV XLPE transmission cable systems and 115 kV, 230 kV, and 345 kV HPFF cable systems. Observations from this review of field PD test reports were:

1. **Technical Details** – The amount of technical detail in the test reports varied significantly. For example, some test reports contained detailed information about the equipment and characteristics of the equipment that was used to perform the PD measurements. Other reports had very little description of the equipment that was used, the limitations of the test equipment, calibration method, and explanation of the methods to analyze the measurement results.
2. **PD Measurement Units** – Many different units were used to report the results of the PD measurements. These included apparent charge (pC), PD sensor output voltage (mV), and PD provider defined relative degree of severity.

3. **Interpretation of Test Results** – Interpretation of the test results varied significantly. Some test reports described the methods and significance of the data plots included in the reports. Other reports included a very general summary (e.g. partial discharges were or were not observed and where they were measured), but there was little or no description of the many data plots that were attached in an appendix to the report.
4. **Quality Control** – Several of the reports contained computer generated summaries for each PD measurement location and some of these automated test printouts had significant errors (e.g. incorrect scale values for plots, incorrect test voltage that was used, etc.). It was obvious from these errors that there was little or no quality control of the test report.
5. **Generic Test Reports and Irrelevant Information** – Where possible, a comparison was made of multiple test reports prepared by the same field testing service. The major part of the test reports from one of the testing services was obviously copied from other test reports. The project specific, unique information (other than data plots in appendices) consisted of less than five pages. In one case, the author of the report admitted that some of the computer prepared plots were not really applicable to interpretation of the test results. These plots were included in the test report because they were automatically included by the software provided by the manufacturer of the equipment.
6. **Recommendations** – The majority of the test reports were limited to discussion and interpretation of the measurement results. The reports from one service provider frequently included a recommendation to repeat the PD measurements in the future.

In summary, the quality and clarity of the test reports varied significantly between the service providers. Some of the reports were comprehensive and contained no significant errors. Other reports contained generic information and significant errors. None of the test reports were in total compliance with the recommendations of Section 9 (Test Results and Recommendations) of IEEE Standard 400.3.

5.2 Information Gaps in Interpretation of Test Results

Considering all of the technical publications that are available on field PD measurements and the number of presentations that are made by service providers at industry meetings and conferences, it appears that one of the major obstacles in understanding field PD test reports is due to too much and conflicting information concerning the advantages and disadvantages of PD testing methods and services.

Several cable engineers were interviewed to obtain their perceptions concerning field PD testing and measurement reports. The following is a summary of their comments.

1. There are so many different PD measurement methods and contradictory claims about their advantages that it is difficult to separate fact from exaggerations.

2. Test reports are difficult to understand either because they go into too much technical detail, or there is too little information about the measurements that were performed.

3. IEEE Standard 400.3 helps to understand the fundamentals, but it is too general to provide specific guidance on the different commercially available PD testing services for transmission cables. However, this guide does contain recommendations for general reporting that should be covered or addressed in test reports.

4. There are a limited number of major transmission cable projects and it is difficult to remain current with state of the art PD measurement alternatives.

6 RESEARCH RECOMMENDATIONS

The review of technical literature and EPRI technical reports indicates that there has been a significant amount of work and progress in performing effective field PD measurement services. However, many utility engineers find that it is difficult to interpret test reports prepared by the commercial PD testing services or that there is insufficient information in the reports.

Research recommendations are based on the technical literature review, review of field test reports, and discussions with cable engineers. The following factors were given consideration in preparing research recommendations.

- There are many different methods that are being used for field PD measurements. CIGRE TB 182 identified 8 different field PD measurement methods.
- The commercial implementation of PD measurement methods are in most cases proprietary. Developers are secretive about many details of their equipment, measurement procedures, and measurement results.
- There are different measurement results (mV versus pC versus subjective terms such as serious, critical, etc.) that are not consistent.
- It is difficult to relate field PD measurement results to PD measurements performed in cable factories
- PD pulse magnitude in cable and accessories may change with time and may even extinguish temporarily
- The majority of the field PD test experience is based on distribution (medium voltage) cables. This knowledge base from MV cable measurements is not applicable for HV and EHV cables in some cases.
- Many of the technical presentations at professional society meetings and elsewhere present an overly optimistic picture of the PD measurement service's methods.

The following projects are recommended to reduce difficulties experienced by utility engineers in understanding and making effective use of field PD measurement results. Additional details and cost estimates are contained in Appendix B.

1. Develop a guide for preparing specifications for transmission cable field PD measurements including what information is required in the test reports.

   It is a challenge to write specifications for field PD measurements that apply to most commercial PD measurement services. It appears that technical specifications for field PD measurements have to be based on performance (i.e. measurement sensitivity levels, calibration requirements, minimum acceptable reporting requirements, etc.) rather than requiring specific detection methods or equipment.
2. Prepare a consumer report for field PD testing services based on round robin tests similar to the previous EPRI project [1]. There are numerous challenges for this type of research project. One of the difficulties is how to provide a meaningful comparison of

commercial testing services while avoiding challenges by commercial service providers that may not demonstrate good performance.

3. Develop and conduct a hands-on field PD measurement training seminar by unbiased experts for EPRI member companies. The seminar would include field PD service providers to describe actual examples of their test reports and interpretation of test results.

A
LIST OF TECHNICAL REFERENCES

This appendix contains a list of technical references that were identified as being relevant to the objectives of this project. The list of references also includes a summary of the references prepared by the project principal investigator as well as the author's abstract for the publication.

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
1	Evaluation of Field Diagnostic Techniques for Transmission Cable Accessories	NEETRAC T. Champion	EPRI Report Oct-99	TR-112676	A number of techniques for evaluating the condition of field installed cable systems and cable accessories have recently become available. The enabling technology for these systems has been advances in methods for low level signal measurements in an environment filled with high levels of ambient noise. Three test circuits were constructed containing known defects capable of producing partial discharge signals of various magnitudes, durations, and repetition rates. The defects were intended to be representative of installation or manufacturing problems encountered in actual field installations. Ten vendors of diagnostic services or equipment that was commercially available or nearing commercial availability were identified. Each of these providers was asked to evaluate the condition of the installed test circuits. Results of their measurements were compared with the list of known cable or accessory defects to determine the accuracy of the diagnostic systems and their ability to locate defects.	This report describes the results of a major project to determine the accuracy of commercial PD diagnostic systems and their ability to locate defects in XLPE transmission cables. Eight commercial service providers performed electrical PD measurements on three laboratory prepared 115 kV XLPE cable systems with intentional defects. None of the PD testing services correctly distinguished all of the intentional PD defects from those without PD defects. There were major differences between the results of the PD measurements between the different PD measurement service providers The report also includes a technical literature search with 137 references. Most of these were published prior to 1998.	7	Yes	Yes	Yes
2	Testing of XLPE Transmission Cable Terminations at Three Utilities	KEMA E. Pultrum T. Aabo	EPRI Report May-97	TR-108073	Very high frequency partial discharge (VHF PD) testing was performed on 14 cross-linked polyethylene (XLPE) cable terminations at Southern California Edison, Public Service Company of Colorado, and PECO Energy Company on June 5, 10, and 19, 1996, respectively. Three terminations out of 14 showed evidence of partial discharge activity. This report describes the principles of VHF PD testing, test procedures, and results of the project. Figures and graphs help illustrate the concept behind the innovative VHFPD technique.	PD testing was performed on 14 extruded dielectric cable terminations with rated voltages of 69 kV and 115 kV. The equipment used to make the VHF PD measurements was a combination of commercial and KEMA developed equipment. The report does not indentify what is meant by VHF.	5	Yes	No	No

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
3	Evaluation of Partial Discharge (PD) Testing Technology for Transmission Class Cables	UCONN S. Boggs C. Xu L. Zhang	EPRI Report Dec-06	1012338	The objective of this project is to evaluate options for field partial discharge (PD) testing of transmission class solid dielectric cable, both laminar and solid dielectric. This report presents an introduction into partial discharge testing followed by a mathematical development of partial discharge pulse propagation in shielded power cable which can be used as a basis for predicting PD detection sensitivity. The theory covers both narrow Gaussian PD pulses and broader, asymmetric pulses. A critical literature review summarizes the approaches which have been published for PD detection in transmission class solid dielectric cable. Several approaches have achieved a PD detection sensitivity of better than 10 pC over an entire cable installation and a sensitivity of about 1 pC near the PD couplers, which are usually located at splices although not necessarily at every splice.	This report presents analytical and measurement results of the attenuation of PD pulses in XLPE and pipe-type (HPFF) transmission cables. It concludes that PD measurements on extruded dielectric cables are more "realistic" than for HPFF cables because of high attenuation by the cable. It concludes that much better PD measurement sensitivity can be achieved with capacitive PD couplers compared to RF current transformers. It concludes that 1 to 10 pC measurement sensitivity is achievable for splices and cables up to 1 km. On-line PD measurements may need up to 5 minutes or ionizing radiation source for PD to occur	6	No	No	No
4	Demonstration of Commissioning Tests for Extra-High Voltage Cross-Linked Polyethylene Cable Systems at Los Angeles Department of Water and Power	PDC J. Cooper	EPRI Report Mar-05	1011489	Commissioning tests were performed on a Los Angeles Department of Water and Power230 kV XLPE underground transmission line using field transportable, variable frequency, series resonant test equipment and PD measurements were performed by five different companies. These commissioning tests on a large, commercial EHV XLPE transmission cable system demonstrated that there is a practical and possibly more effective commissioning tests alternative other than the 24-hour rated-voltage soak test currently used by most utilities.	This report describes the results of round robin off-line PD measurements performed by five companies that provide field PD measurement services. Special emphasis was given to practical aspects of the different PD measurement services such as time to set up for measurements, measurement times, etc. Off-line PD testing was limited to splices in two of twenty splice vaults because of test time limitations of the AC withstand test.	7	Yes	Yes	Yes

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
5	Best Practices for HPFF Pipe Type Cable Assessment, Maintenance and Testing	PDC J. Cooper	EPRI Report Mar-05	1011489	An extensive series of test were performed on the New York Power Authority (NYPA) Blenheim-Gilboa 345-kV high-pressure fluid-filled (HPFF) transmission cable systems to determine the condition of the cable systems and determine their power transfer capability based on distributed temperature measurements. Acoustic and electrical PD measurements indicated that there are discharges in the Cable #3, power house end, riser pipe area. The acoustic PD measurement further identified the Phase B riser pipe as the source of the PD. However, digital radiographic inspection of this area did not show any abnormalities. Radiographic inspection of selected areas of the trifurcator casings indicated that there is bending of the cable in the casings and there appears to be some buckling of the shield tapes in Cable #2 and #4 at the power house end trifurcators.	Rated voltage, off-line PD measurements using a variable frequency resonant test set, on-line PD measurements, and on-line acoustic PD measurements were performed on several 345 kV HPFF cable systems. The off-line PD measurements, performed on cable systems #2 and #3, resulted in a sensitivity of 10 to 20 pC. No PD activity was detected. The off-line electrical PD measurement method did not quantify the results in pC but the test report concluded that there was "concerning" levels of PD at one location in cable system #3. The on-line acoustic PD measurements concluded that there was no PD in cable systems #1, #2, and #3. It was also concluded severe PD activity was present on phase B of cable system #3.	7	Yes	Yes	Yes
6	IEEE 400.3 Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment	ICC WG C-19	IEEE Feb-07	Std. 400.3 2006	This guide covers the diagnostic testing of new or service-aged installed shielded power cable systems, which include cable, joints, and terminations, using partial discharge (PD) detection, measurement, and location. Partial discharge testing, which is a useful indicator of insulation degradation, may be carried out on-line or off-line by means of an external voltage source. This guide does not include the testing of compressed gas insulated systems or continuous on-line monitoring at normal service voltage.	This guide covers all aspects of field PD measurements on a level that is understandable by most utility engineer. It was prepared by experts but not intended for use by experts. Section 9.1 (Interpretation of Test Results) provides guidance on the most important issues in interpretation of PD test results. It does not go into the in-depth details of measurement results as is the case in references 7 and 8. Section 9.2 (PD Test Documentation) does provide practical guidance on what should be included in PD test reports for the two major categories of PD detection approaches (time and frequency domain).	8	No	No	Yes

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
7	CIGRE TB 226 Knowledge Rules For Partial Discharge Diagnosis in Service	CIGRE TF 15.11/33.03.02	CIGRE Apr-03	TB 226	This brochure discusses the possibility of interpretation (knowledge) rules to support PD diagnostic of service aged HV components. Based on systematic experience from the field this brochure evaluates and classifies PD quantities, which are found useful for diagnosis monitoring of different HV components. In particular, for different insulation systems of HV components like instrument and power transformers, distribution and transmission power cables, GIS, generator stator insulation general characteristics of typical PD quantities are evaluated under the following restrictions: a) Only by insulation defects induced degradation effects are taken into consideration. b) No acceptance levels for go/no go decisions are discussed. c) No special attention is paid to describe in detail particular detection and measuring techniques. d) No application of post-processing technique e.g. neural networks, advanced statistics, wavelets, digital filtering, etc is discussed.	This document is a very comprehensive description of the PD phenomenon, PD detection methods, typical PD defects, interpretation results, and decision making based on measurement results. It covers PD measurements on most types of commercial electric power equipment (i.e. distribution cables, transformers, transmission cables, power capacitors, etc.). The most pertinent part of the document to this EPRI project is the section on interpretation of on-line measurement results. Section 3.8 (Transmission Cables – Practical Experiences) is also very useful. This and reference 9 are must reading for PD measurement users	8	Yes	No	Yes
8	CIGRE TB 297 Practical Aspects of the Detection and Location of Partial Discharges in Power Cables	CIGRE TF D1.02.05	CIGRE Jun-06	TB 297	For enhancement of the reliable operation of power cables network preventive PD diagnosis tests are increasingly performed. In order to assess the insulation condition on the basis of the obtained data, fundamental knowledge on the PD occurrence is required. The presented brochure deals with both, theoretical analysis and experimental studies on the wave propagation of PD pulses in power cables. Furthermore, practical aspects of the detection and location of PD faults are discussed.	This report focuses on the location of PD sources based on the well known time domain reflectometry method. The task force describes methods to predict the velocity of propagation for XLPE power cables as well as the attenuation with distance.	6	Yes	No	No

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
9	CIGRE TB 182 Partial Discharge Detection in Installed HV Extruded Cable Systems	CIGRE WG 21.16	CIGRE Apr-01	TB 182	The objective of the report is to provide the user both fundamental and practical information on on-site partial discharge detection (PDD). It is not intended to be a consumer guide, saying which method is better than another. Such a serious comparative study was not within the scope of the WG. This report offers the user support in understanding the complicated field of on-site PDD and ultimately in making decisions about PD testing.	The single best, unbiased coverage of on-site (field) PD detections methods and procedures for transmission cable systems. Section 2 (Users Guide) is particularly useful in explaining the key issues involved in field PD measurements. Eight different PD measurement methods are identified and described in a reasonable amount of detail.	9	Yes	No	Yes
10	After-Installation Testing of HV/EHV Extruded Cable Systems – Procedures and Experiences	U. Herrmann A. Kluge R. Plath	Jicable Jun-07	Paper 71	This paper provides an insight into 9 years of IPH experience in after-installation tests of HV/EHV extruded cable systems. From the start, AC tests of very long length of EHV cable systems were performed in combination with sensitive PD measurements to achieve best possible test efficiency.	The paper presents a general discussion of a testing service company's experiences with commissioning tests for HV and EHV transmission cable systems. More emphasis is given to the variable frequency test method than PD measurement results	4	Yes	No	No
11	Partial Discharge Detection in Power Cables: Practical Limits as a Function of Cable Length	A. Cavallini C. Subramaniam G. Montanari	Jicable Jun-07	Paper 80	Power cables behave as transmission lines as regards partial discharge (PD) pulse propagation. Attenuation and dispersion phenomena have, therefore, great influence on the delectability of PD pulses, particularly when long cable routes and detection from terminals are considered. This paper presents an approximate model to infer PD pulse waveform as a function of the distance travelled along the cable and shows results that can provide practical limits for PD detection in cable routes when using IEC 60270-compliant and/or ultra wideband detectors. Considerations on the effect of calibrator characteristics on sensitivity check procedures are, eventually, reported.	Focuses on the attenuation and velocity of propagation of PD pulses in distribution and transmission XLPE cables as well as the sensitivity of PD measurements that can be achieved.	5	No	No	No

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
12	Practical Experiences in on-site PD Diagnosis Tests of HV Power Cable Accessories in Service	E. Lemke T. Strehl W. Weissenberg J. Herron	IEEE International Symposium on Electrical Insulation Jun-06	ISSN: 1089-084X	The presented paper deals with preventive on-site PD diagnostics of HV cable terminations under operation voltage using an ultra-wide-band (UWB) PD probing. In order to assess the detected PD level quantitatively as "equivalent apparent charge" a sensitivity check has been performed. The results reveal that by means of the applied method potential PD defects in GIS-cable terminations could well be recognized where a PD detection sensitivity as low as few pC was achieved.	The authors describe the use of ultra wide bandwidth PD measurements with external sensors. It contains an extensive discussion of the comparison of PD measurement results for UBW vs. the IEC 60270 method (apparent charge). Describes a method to determine the "equivalent apparent charge" or sensitivity of the UBW PD measurements	6	Yes	No	Yes
13	The St. Johns Wood – Elstree Experience – Testing a 20 km Long 400 kV XLPE-Insulated Cable System after Installation	S. Sutton R. Plath G. Schröder	Jicable Jun-07	Paper 84	This paper deals with the 400 kV cable connector between St. Johns Wood and Elstree, one of the largest XLPE cable projects in the world. This cable route is a connecting link to the city of London and was commissioned in 2005	Describes synchronization fo PD measurements performed in the 5 to 10 MHz range via fiber optic cable communication. PD measurements were performed at 20 joint locations simultaneously. Authors claim that the PD measurement sensitivity was "equivalent to laboratory conditions" Part of the calibration was a open air wire at both ends of the cable system and a 500 pC calibrator connected to a test bushing	7	Yes	No	Yes
14	On-site VHF Partial Discharge Detectin on Power Cable Accessories	S. Meijer R. Jongen J. Smit P. Seitz T. Hermans L. Lamballais	Jicable Jun-07	Paper 100	During the on-site installation of power cables, mistakes in installing cable accessories can occur. If this results in insulation defects, partial discharges (PD) can occur. These PD will erode the insulation, can bridge the distance between both conductors which will result in a complete breakdown and failure of the cable system. It is known that PD pulses consist of energy frequencies up to hundreds of MHz. Therefore a VHF/UHF PD detection system is applied to detect partial discharges in a non-conventional way. Aspects that need to be considered during the development of such a system such as detection method, sensor type and location, calibration etc. are presented and discussed in this contribution	This paper reports on 380 kV XLPE cable and 110 kV Oil/XLPE cable field test and laboratory test with artificial PD defects. PD detection was from 5 MHz to several hundred MHz. Wireless communications was used between the PD sensors at the accessories and the instrumentation at the test voltage source. The PD measurement sensitivity in pC was estimated.	7	Yes	No	Yes

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
15	Experience with PD Measurements and Commissioning Tests	E. Pultrum H.-E. Keizer	Jicable Jun-07	Paper 24	The commissioning of new HV cable systems is commonly performed by means of an AC voltage test. The experience has shown that a proper combination of test voltage and duration can indeed detect incipient failures. The combination of such an on-site test with partial discharge measurements is relatively new. This partial discharge measurement may give additional information about accessories installed in the circuit. This paper describes the development, advantages and limitations of on-site PD measurements.	Reports on PD measurements using RF current transformers for about 80 PD measurements. PD was detected in 3 of the 80 cable systems. A sensitivity of 20 to 25 pC. Discussed disadvantages of and reasons for abandoning a high voltage coupling capacitor to pick up PD pulses.	7	Yes	No	No
16	Sensitive PD Detection on High Voltage XLPE Cable Lines Using Field Coupling Sensors	R. Plath R. Heinrich K. Reithmeier W. Weißenberg	Jicable Jun-03		Based on experiences of laboratory and on-site after laying tests the advantages and limits of different sensors for PD detection at high voltage and extremely high voltage XLPE cable accessories as well as suitable methods and measurement devices for evaluation of the measured signals are discussed and compared.	The authors describe the different types of PD sensors (couplers) that are used for field PD measurements. Capacitive, directional coupler and inductive directional coupler sensors are covered. The advantages and disadvantages of each type of PD sensors are described. The comparison indicates that the directional coupler sensor has several advantages compared to the capacitive sensors. The authors report that a sensitivity of a "few" pC for joint measurements is possible.	7	Yes	No	No
17	On-Site PD Detection at Cross-Bonding Links of EHV Cables	W. Weißenberg F. Farid R. Plath K. Rethmeier	CIGRE Sept-04	B1-106	In practice, sensitive PD measurements on long HV cable lengths can only be realized if either PD sensors have been installed inside the accessories or sensitive PD decoupling is possible at joints or in cross-bonded links, if existing. The latter possibility would be of advantage for technical an economical reason for both new installed cable systems and especially cable systems already in service.	The authors state that integral PD sensors are primarily used for EHV cable systems. The recommend PD sensors installed inside of joints and terminations to achieve maximum PD sensitivity. The major focus of the paper is applying add-on inductive PD sensors at the cross bonding link boxes. Test results for field measurements on a 400 kV and a 220 kV XLPE cable system are presented. A measurement sensitivity of a few pC is possible with HF transformers placed around the cross-bonding links.	7	Yes	No	No

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
18	On-Site PD Decoupling and Localization at Cross Bonded HV Cable Systems	W. Kalkner R. Plath K. Rethmeier	International Symposium on HV Engineering Aug-05	G-104	On-site PD measurements performed according to IEC 60270 at the ends of HV cable systems do often not achieve the demanded sensitivity of a few pC and are not suitable for online PD monitoring. However, the main reason for defects in HV cable systems is the condition of the joints due to improper on-site assembly. Therefore, PD measurement has to concentrate on the cable accessories. Integrated field sensors, as capacitive sensors or directional coupling sensors for instance, are operating in the VHF/UHF range and lead to very good results concerning sensitivity. But retrofitting of direct buried HV cable systems with field sensors is often very expensive or even impossible. A new approach of PD decoupling is the use of cross bonding links of long HV cable systems. Inductive sensors can easily be mounted inside of the cross bonding box or around the feeding cable coming directly from the joints. With a synchronous PD acquisition of all three cross bonding links of a joint group a 3PARD visualization can be generated to localize the PD source in phase and joint. This method of PD decoupling is also suitable for measurements on insulating joints or transition joints with external screen connection. The PD sensors can easily be mounted and dismounted without interrupting service of the HV cable system. Additionally a permanent PD monitoring is possible by placing the inductive sensors inside the cross bonding boxes. On-site PD measurements on cross bonding joints and insulating joints were successfully done during AC resonance testing and achieved sensitivities of about 2 PC.	Similar to reference 17; however, more details about the PD detection equipment (Mtronix MPD 540) are given. The center frequency can be adjusted from DC to 20 MHz and the bandwidth is between 9 kHz and 3 MHz The PD measurements system, which uses HF current transformers, simultaneously detects PD pulses on the three joint cross-bonding leads. A method to visualize the results of 3-Phased PD measurements (called "3PARD") is described. Fiber optics isolation is used for safety purposes. It is reported that a measurement sensitivity of 2 pC can be achieved if HF CT's can be applied around the cross-bonding links inside of the link boxes. PD measurements can be performed by placing CT's around the bonding leads outside of the link boxes but the sensitivity of the measurements decreases. Test results for a 150 kV XLPE cable system are described.	7	Yes	No	No

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
19	Experience with Offline PD-Diagnosis on MV Cables – Knowledge Rules for Asset Decisions	F. Petzold M. Beigert E. Gulski	Jicable Jun-07	Paper 46	The detection, location and evaluation of partial discharges (PD) inside the insulation and the accessories of XLPE and PILC cables offer the possibility of an early diagnosis of cable network failures, however, with the need of a clear differentiation between the insulation systems and the accessories. In order to be able to carry out an evaluation of the risk factor of PD defects as exactly as possible, the applied voltage for a PD diagnosis should be within the range of the operating frequency, because the typical PD parameters, such as inception and extinction voltage, PD level and PD pattern then correspond to the relevant values under operating conditions. On the other hand, the electrical stress during the diagnosis measurement should be limited to the extent that no irreversible damage and hence deterioration of the condition of the test objects takes place. The main difficulty is to evaluate the risk of PD occurrences on the reliability of the cable system. If an sufficient amount of PD diagnostic data for the cable components is available statistical methods can be used for determining threshold levels and relevant condition indexes for the asset management.	This paper is primarily about off-line PD testing with the oscillating wave test (OWT) voltage and PD measurements on distribution cables. The authors present test results and discuss interpretation of PD measurements for paper-insulated lead-covered (PILC) distribution cables.	4	Yes	No	Yes
20	Sensitivity of PD Inception to Change of Electrical Design in Polymeric Insulated Power Cable Systems	P. Van Der Wielen N. Van Schaik T. Czaszejko	Jicable Jun-07	Paper 60	A methodology was developed to calculate the partial discharge inception voltage in MV, HV and EHV cable systems for different electrical designs. By doing so, the sensitivity of the PD inception voltage to change in design of the insulation system can be defined and quantified. As the result, the effect on the change of the acceptable maximum size on potential defects may be estimated, indicating the increase of risk on PD inception when changing the design. The methodology and calculations presented quantified the extend to which the quality of the extrusion process	The authors quantify the maximum sizes of discharge free defects (voids and fissure type defects) in extruded dielectric cable systems. They also address the risks from cable design modifications and range of type test approval for variations in cable designs.	4	No	No	No

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
					as well as the precision of accessories assembly must be maintained or improved to assure discharge free operation of cable systems after design modifications. They also show that margins specified in the range of type approval in the current IEC standards are sufficient and that they should not be broadened.					
21	Wireless Sensor Network Based PD Monitoring of Underground Cable Systems	H.-W. Choi B.-W. Min H.-C. Myoung B.-H. Lee S.-M. Cho	Jicable Jun-07	Paper 81	Maintenance of underline cable systems requires periodic measurement of many physical variables at numerous locations. This task can potentially be accomplished with wireless sensor networks. This paper describes the PD-sensing algorithms (Discrete Wavelet Transform) for the inspection of electrical power cables. The diagnostic sensor array includes thermal, visual, dielectric, and acoustic sensors for the measurement of cable status. Laboratory tests demonstrate the ability of integrated sensors to measure parameters of interest with the resolution required by the application. Field tests in the underground cable system demonstrate the ability of the designed platform to sense along the cable, and communicate with the host computer	The authors describe the development of wireless sensor networks (WSN) for PD, and temperature measurements of transmission cable joints and terminations. The WSN transmits the output from four types of sensors for measurement of physical properties of the cable accessories to a central data acquisition computer. Acoustic PD measurements and wavelet based analysis of PD signals are described.	5	No	No	No
22	New Approach for High Voltage Cable On-Site Testing	V. Bergmann P. Mohaupt W. Kalkner	Jicable Jun-07	Paper 99	The focus of this contribution is the application of sinusoidal VLF test-voltage as it is established for medium voltage cable systems, also on high voltage cable systems. Therefore a HV-test-voltage source and a 110-kV test cable system were realized at the TU Berlin. Typical high voltage components were applied for comparing the results of PD measurements gained at 50 Hz and 0.1 Hz respectively. It could be found out that typical PD characteristics as PD inception voltage, maximum PD levels, average PD levels and even visual diagrams as PRPD pattern are very similar at VLF compared to	The authors describe the development of very low frequency (VLF, 0.1 Hz) test equipment for performing AC withstand and PD testing of a 110 kV XLPE cable system. Results of laboratory measurements on a 110 kV cable system with joints and terminations are presented. Intentional PD defects were introduced into the cable termination and joint and the phase resolved PD (PRPD) plots are presented. Tests were performed at 50 Hz as well as	7	Yes	No	Yes

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
					50 Hz measurements. A diagnostic assessment of high voltage cable systems can be successfully performed by PD measurements with applied sinusoidal VLF test voltage.	0.1 Hz and the results compared. The authors conclude that the 0.1 Hz and the 50 Hz PD measurements are similar.				
23	Partial Discharge Measurement and Interpretation	D. Nattrass	IEEE Jun-88	Vol 4 No 3	The overview of partial discharge patterns, their evaluation and determination of origin, should help today's practitioners in the interpretation of results, as well as the accurate discrimination between true partial discharges within an insulating structure and other unwanted conduction or radiation-induced interference signals.	This overview, which was prepared before the advent of field PD measurements, is very useful in recognizing the results of PD measurements displayed as a rotating ellipse on PD detection instruments. The overview applies to PD measurements performed using both narrow and wide bandwidth detectors at frequencies from 40 to 400 kHz	6	Yes	No	No
24	Multi-channel PD Measurements	R. Plath	International Symposium on HV Engineering Aug-05	J-04	The common way to measure PD is to use one coupling capacitor and one PD instrument. This works reasonably well in suitable HV laboratories that are screened and have filters to avoid any external interference. But even under such ideal conditions additional expenses are required, if, for example, HV power transformers are tested for PD. In this case, the measurement tap of each terminal is usually connected to a multiplexer, allowing three-phase PD measurements to compare PD signals from each phase. If, however, more than one PD source is active simultaneously, distinct PD allocation becomes usually impossible. On-site PD measurements interfered by external noise strongly intensifies this problem. Substantial progress has been achieved by avoiding any multiplexing and in stead using simultaneous multi-terminal PD detection on e.g. three channels. Each PD event inside a three-phase machine (e.g. transformer, generator, motor) – occurring on one phase– spreads by different coupling mechanisms into all three phases and causes different PD	The author describes synchronous multi-channel, three-phase partial discharge measurements and the interpretation o f the test results. The analysis of the three-phase PD measurements focuses on a method called 3-phase amplitude relation diagram (3PARD).	6	No	No	Yes

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
					pulse amplitudes at the terminals. This leads to a generalized approach to distinguishing between different PD sources and pulse-type interference by the multi-channel signatures. This approach works with virtually any multi-channel PD detection including different signal bands and types (e.g. HF, VHF, UHF and acoustic).					
25	On-Site AC Testing and PD Measurements of 345 kV/2500 mm2 XLPE Cable Systems for Bulk Power Transmission	J. Kaumanns E. Plieth R. Plath	Jicable Aug-03		Taiwan's first EHV underground cables turnkey project consists of eight 345 kV XLPE cable systems which show pre-fabricated joints leading to a very short installation period. The total scope describes 62 km of 345 kV/2500 mm2 XLPE cables, 122 pieces pre-fabricated joints and 48 pieces of in- and outdoor terminations and includes both, cable laying and assembly of accessories. To ensure the quality of the installation an on-site AC test including a partial discharge (PD) measurement was performed on the XLPE cable systems. A new PD measuring and analyzing technique was able to reduce the external noise level to 1–2 pC for the joints during PD testing even under on-site testing conditions.	Describes the development, installation, and commissioning tests on a large 345 kV XLPE cable system that was installed in Taiwan in 2003. PD testing of the 122 pre-fabricated joints was performed using integral capacitive sensors. Calibration of the PD sensors was carried out by the manufacturer at the factory. The optimal frequency for the PD measurements was 6 – 7 MHz. An on-site check out of the PD measurement system was performed by means of a calibration signal applied at the end of the circuit. The authors report a PD measurement sensitivity of 1-2 pC for all joint positions. One PD defect (a metal particle) was detected at 212 kV during the commissioning tests. The measured PD was 3 to 5 pC.	8	Yes	No	Yes
26	Multiple Localization Method of Partial Discharge Power Cable Joint	C. Min J. Urano A. Kato Y. Sakaguchi G. Okamoto H. Ueno K. Hirotu A. Jinno	International Conference on Electrical Engineering 2001		With an example of PD localization for EHV cable joint on site, multiple method of PD localization is studied in this paper, including (1) method of using metallic foil electrode sensors, (2) method of excitation by X-ray radiation and a foil electrode sensor (3) method of applying acoustic emission sensors and a foil electrode sensor. Compared with the conventional method of PD localization for long distance cables of more than	The authors describe three different methods to locate the site of PD inside of a pre-fabricated transmission cable joint. The three differed in the resolution of the PD location, but all were effective.	6	Yes	No	Yes

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
					hundreds of meters, it is more difficult to localize a PD for a pre-fabricated type of joint of only in a short length of around 2 m, due to the problems in measurement such as the disturbance of pulse reflection, the route of pulse propagating and the difference of pulse propagation velocity. The results of the example also show that this multiple method can give a high accuracy of PD localization.					
27	Evaluation and Comparison of On-Line PD Detection Methods for High-Voltage Power Cable	J.-C. Hsieh C.-C. Tai C.-C Su C.-Y. Chen T.-C. Huang Y.-H. Lin	Asia-Pacific Conf. on Non-Destructive Testing Jun-05		As the high-voltage power cable insulation material growing worse, the aged insulation material can cause serious power supply problems. Most of the damages can be found in cable splice and cable terminators. This article mainly aims at developing the inspection methods for cable joints problem. We investigate the use of acoustic emission (AE) sensor, capacitive coupler (CC), and impulse current measurement methods to detect acoustic emission (AE) sensor, capacitive coupler (CC), and impulse current measurement methods to detect actual spot of the problem and to investigate and compare the advantages and disadvantages of different methods. To speak from the degree of sensibility, the impulse current method has the best sensibility, while the capacitive coupler and AE methods are less sensible. To speak from the noise-resist ability, it is contrary to the degree of sensibility. The impulse method is prone to be interrupted by noise. To speak from the PD signal source location ability, the AE method is better than the other two methods.	The authors describe an investigation to determine the effectiveness of three different types of PD detection for cable systems. These were 1) detection of current pulses in the sheath bonding leads, 2) Capacitive couplers, 3) Acoustic Emission (AE) detectors. The authors conclude that a detection resistance in series with the cable shield is effective but more susceptible to external noise than the capacitive coupler. They conclude that the AE detection method is superior for determining the location of a PD defect in a joint or termination.	7	Yes	No	Yes

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
28	Insulation Diagnosis of High Voltage Power Cables	E. Gulski J. Smit P. Cichecki F. de Vries P. Seitz F. Ptezold	Jicable Jun-07	Paper 53	In this contribution based on field application of advanced diagnostics a systematic approach for condition assessment of high voltage (HV) power cables is discussed. Based on the assumption that there is not one dominant failure process in HV cable networks in addition to partial discharges also dielectric diagnosis has been included to determine the actual condition of service aged cable insulation systems.	This paper presents experience in condition assessment of oil-filled transmission cables using PD and dissipation factor (DF) measurements. The author proposes rules for the assessment of oil-filled transmission cables using PD and DF measurements.	8	Yes	No	Yes
29	New Studies on PD Measurements on MV Cable Systems at 50 Hz and Sinusoidal 0.1 Hz (VLF) Test Voltage	K. Rethmeier P. Mohaupt V. Bergmann W. Kalkner G. Voigt	CIRED 19th International Conference on Electricity Distribution May-04	Paper 0627	Sinusoidal 0.1 Hz VLF test voltage is suitable for cable diagnosis. The diagnostic results are well comparable to measuring data at power frequency. New studies performed by Technische Universitaet Berlin and Hochschule Konstanz are confirming the good comparability of diagnostic results achieved at sinusoidal 0.1 Hz VLF test voltage compared to 50 Hz and 60 Hz power frequency respectively. Specifically the PD inception voltage (PDIV), the PD level and the phase resolved graphical PD pattern are very similar. This makes VLF test voltage in combination with PD measurements a suitable approach for on-site cable testing.	Similar to reference 22 except that the focus and measurement results are for medium (distribution) voltage cables and accessories.	6	Yes	No	Yes
30	A New Approach of Synchronous PD Measurements at Both Ends of a H. V. Gas Pressure Cable System	T. Kumm K. Rethmeier W. Kalkner E. Zinburg	Proceedings of the XIVth International Symposium on High Voltage Engineering Aug-04	F-11	Synchronous PD measurement at both ends of a cable system can be realized by using one of the three phases of the system as a synchronization phase. A synchronization signal travelling along this phase is measured at each cable end by one station of a synchronous multi-terminal measuring system, while another station of this system is used for detection of PD signals from the high voltage stressed tested phase. The equal time base of the two stations of each measuring system and the calculation of the travelling time of the synchronization signal are used to generate a common time base for all measured data sets. On-site investigations have been carried out on a 110 kV external	The authors describe the development of a system for synchronizing PD measurements performed simultaneously at opposite ends of a transmission cable system. Laboratory tests with intentional defects were followed by measurements on a 5.6 km long 110 kV external gas pressure (impregnated paper) pipe-type cable system. The authors conclude that the only feasible possibility for PD measurements of a pipe-type cable system is to perform synchronous PD measurement at both cable ends.	8	Yes	No	No

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
					gas pressure cable system. Investigations with a 0.1 Hz sinusoidal test voltage source were done to examine the suitability of synchronization method for PD testing and to check the PD behavior of the cable system. The paper reports in detail about the main principle of the synchronization method. Results of on-site tests are presented to show practical suitability of the method, too.	Field measurements indicate a propagation velocity of 156 m/microsecond. The test voltage was 0.1 Hz VLF. Simulated PD defects were installed at the ends of the 5.6 km cable system.				
31	Sensitivity Assessment for Partial Discharge Measurements on Solid Dielectric Transmission Cables	H. Sedding M. Fenger	Jicable Jun-07	Paper 140	PD testing has become the corner stone of most asset management programs. However, the results obtained from a partial discharge test depend not only on the conditions under which the test was performed but also on the test equipment it self including the type of sensor used and its location. The issues related to attenuation and dispersion of partial discharge pulses is well known. For testing long lengths of cable, performing a terminal measurement is often not possible. Still, such tests are performed on long lengths of transmission class cable with claims that sensitivities of down to 5pC can be achieved. This paper provides a brief review of partial discharge detection, signal propagation and discusses so called calibration procedures. As well, this paper also presents a framework for a model providing a meaningful sensitivity assessment prior to performing a partial discharge test. Data acquired on different classes of transmission class circuits is presented.	The authors discuss the assessment of field PD measurement sensitivity when using broad band VHF/UHF detection equipment. Data is presented showing the response of transmission cables to simulated PD pulses. The primary conclusions are 1) that distributed PD measurements (as opposed to measurements performed at the ends of the cable circuits) are necessary because of the rapid attenuation and dispersion of PD pulses in transmission cables and 2) it does not make sense to attempt to correlate discharge pulses measured in mV or mA to partial discharge currents. In other words, the authors conclude that calibration of VHF/UHF PD measurement results to pC (as reported from factory production tests) is not possible.	6	Yes	No	No
32	Sensitivity Verification Procedure of VHF PD Detection Systems	S. Meijer R. Ladde A. Jongen J. Smit J. Hermans L. Lamballais	Jicable Jun-07	Paper 101	Partial Discharges (PD) in a power cable system can occur due to different insulation defects. If allowed to continue, PD will erode the insulation, eventually bridge the conductors resulting in a complete breakdown and failure of the cable system. It is known that PD pulses consist of energy frequencies up to hundreds of MHz. Therefore using a VHF/UHF sensor detecting partial discharges	The main focus of this paper is a method to quantify the sensitivity of PD measurements performed with VHF and UHF PD measurement equipment. The factors that most significantly affect the sensitivity of the PD measurements are discussed and methods to determine the PD measurement sensitivity were tried in	6	Yes	No	Yes

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
					is possible. However, the high-frequency behavior of the sensor, the measurement cables, etc. has a strong influence on the response of VHF/UHF PD detection systems. Therefore, calibration is difficult and several related issues are presented analytically and discussed.	laboratory tests. The authors conclude that it is difficult to calibrate VHF/UHF PD detection equipment. However, a sensitivity check can be performed to give at least an idea of detectable PD levels.				
33	Condition Assessment of Power Cable Systems in the Energized State	N. Srinivas B. Bernstein	Jicable June-07	Paper 171	Cablewise technology is an excellent predictive maintenance tool that has been used to assess the condition of electrical equipment in the energized state while operating in electrical utility and industrial plant environments. It is an on-line totally passive technique which allows the measurement of signals at high frequencies emitted by the cable system while it is operating in service. The technique is particularly applicable for identifying the type of defects that cause aging and loss of life of cable system components. The analyses of the results are used to assess the severity of aging in cables, splices, terminations and the electrical equipment connected to the system. This non-destructive, non-invasive approach assists the user in establishing a predictive maintenance program in a proactive manner. This paper describes the rationale for studying signals prior to and after partial discharge inception.	This paper primarily deals with a proprietary field diagnostic method for both PILC and extruded dielectric power cables. This method is based on the detection of "pre-partial discharge" signals. The measurements are made on-line with the cables operating at normal operating temperatures and voltage. The paper primarily focuses on experience with distribution cables.	4	Yes	No	No
34	Revision of Qualification Procedures for HV and EHV AC Extruded Underground Cable Systems	CIGRE Working Group B1.06	CIGRE Aug-06	TB 303	IEC test requirements have evolved over the years from the component-based approach in IEC 840 to the system based approach. Accessories are considered together with the cable, in IEC 62067 and in the most recent edition of IEC 60840. In its meeting in Madrid of 2001, Study Committee B1 decided to install a Task Force to get SC B1 prepared to issue future recommendations for evolutions of IEC 62067 taking into account	Annex 5.3 of this document (Sensitivity of Partial Discharges in XLPE Cable Insulation to Change of Electrical Stress) contains and in-depth theoretical analysis of factors that affect the inception of PD in XLPE transmission cables. It also contains a listing of major EHV XLPE cable projects.	5	No	No	No

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
					the expected innovations in cable technology, the need to reduce the time-to-market and the overall cost to introduce new evolutions as well as service experience collected by the Cable Industry.					
35	Recognition of Discharges	CIGRE WG 21.03	Electra	Electra #11	Various types of response that can be observed with discharge detectors are listed. For each type, the discharge pattern on an oscilloscope and the relation of the maximum discharge magnitude with the test voltage and time are described. A system for diagnosing the possible origin of discharges from their observed characteristics is outlined. In addition, the characteristics of unwanted disturbances and some means of diagnosing their origin are shown. The list is not exhaustive, and variations on the basic response of characteristics should be expected.	This document contains a comprehensive description of possible PD measurement for laboratory or factory production test results using medium frequency (50 – 500 kHz) PD detection instruments	6	Yes	No	Yes
36	Calibration Procedures for Analog and Digital Partial Discharge Measuring Instruments	CIGRE TF 33.03.05	Electra Oct-1998	Electra #180	The revision of IEC 270 is going to introduce several new aspects and procedures for qualifying partial discharge PD measuring systems. An important point is that the specified partial discharge magnitude for alternating voltage tests is defined as the "largest repeatedly-occurring PD magnitude" recorded with a measuring instrument has a certain specified response to pulse trains with different repetition rates. Moreover recommendations are made regarding the correct digital acquisition of the discharge magnitude and processing of PD quantities. The main objective is that PD readings obtained with digital instruments shall be compatible with those obtained with analog instruments. In addition other potentially interesting quantities are defined for digital instruments.	This document contains an in-depth coverage of calibration of PD measurements for power system equipment. It is the basis for IEC 60270, the international standard for calibration of PD measurements. The document covers calibration of newer digital PD detection instruments as well as the older analog medium frequency PD instruments used in laboratories and manufacturing facilities.	6	No	No	No

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
37	Assessment of Extruded 345-kV Cable Technology	J.L. Parpal P.E. Beaudoin M. Belec G. Bouffard L. Daigneault C. Guddemi C. Hudon D. Jean J. Nourry	EPRI Report Jun-1998	TR-110906	Prequalification tests were performed in 1995 at Hydro-Québec's Research Institute on XLPE cable systems in partnership with three international cable manufacturers, Pirelli, Fujikura and Alcatel. EPRI and Hydro-Québec agreed on their end to monitor the partial discharge activity during the long-term test using a commercial recording system. It was shown that it is possible to retrofit couplers on the cross-bonding cable of already installed transmission-type cables and perform PD measurements from the cross-bonding cable by eliminating undesired electromagnetic interference with a combination of frequency filtering and time domain gating. The sensitivity of the High Frequency Current Transformer coupler was determined to be in the range of 65 pC.	This document describes the methods that were used to perform intermittent, long-term, field PD measurements on two, 345 kV XLPE cable system test loops. Of particular relevance is the discussion concerning the calibration of field PD measurements that are performed in the VHF frequency range using high-frequency current transformers and a quadrupole device inserted at the cable splice bonding leads. The single splice failure that occurred was not detected by the PD measurements due to reasons discussed by the authors.	9	Yes	No	Yes
38	Bandwidth and Sensitivity Issues in PD Detection in Power Cables	S. Chandrasenkar A. Cavallini G. Montanari F. Puletti	IEEE Trans. on Dielectrics and Electrical Insulation	Vol. 14 No. 3 Jun-07	An investigation on partial discharge (PD) propagation in power cables is carried out in this paper with the aim of inferring limits for PD detection as a function of the distance between PD source and detector. Although this problem has not an exact solution unless noise levels are not specified, useful information concerning delectability and error in estimates are provided in this paper for both medium and high voltage polymeric cables. The issue of calibrator characteristics with respect to sensitivity to detection is also tackled.	This paper describes modeling of PD pulse propagation in shielded power cables using numerical methods of the EMTP program. Results are compared with experimental test results. The EMTP modeling is then used to predict the lowest magnitude of PD pulses that can be detected as a function of the distance between PD detection equipment and the PD site. Predictions on measurement sensitivity are made for a theoretical ultra wide bandwidth (UWB) to IEC 60270 compliant PD detectors. The analysis is performed for MV and HV cables. The authors also discuss the importance of the characteristics of PD calibrators when making UWB PD measurements	8	Yes	No	Yes

No	Title	Author(s)	Publication	Identification	Abstract (or Author's Summary)	Field PD Measurements State-Of-The-Art Project Summary	Applicability To Project (1 to 10)	Measurement Results	Information On Test Reports	Interpretation of Test Results
39	A Novel Method to Locate PD in Polymeric Cable Systems Based on Amplitude-frequency (AF) Map	A. Cavallini G. Montanari F. Puletti	IEEE Trans. on Dielectrics and Electrical Insulation	Vol. 14 No. 3 Jun-07	A new technique for partial discharge (PD) source location in cable systems is presented in this paper. Such technique, here referred to as amplitude-frequency (AF) mapping, is based on the influence of attenuation and dispersion phenomena on PD pulse time and frequency characteristics. A comparative evaluation with other two well-known location techniques (time-domain reflectometry and arrival time analysis) is presented. The results indicate that while TDR is appropriate for short cable systems, for longer cable systems, location by AF mapping can be obtained directly from PD testing, without additional efforts. The location thus achieved is in most cases, accurate enough to allow maintenance practices to be carried out effectively. In some cases, ATA can be necessary to refine location and resolve ambiguities.	The authors describe the physics of PD pulse attenuation, dispersion, and reflection in extruded dielectric cable systems. Three PD site location methods are described in detail. These are the time-domain reflectometry (TDR), the arrival time analysis (ATA) and a third method proposed by the authors called amplitude-frequency (AF) mapping. The authors conclude that the AF mapping method is particularly well suited to location of PD defects in long cable systems that are more common for transmission cable systems. Application of the three methods from actual field test results are presented.	9	Yes	No	Yes
40	Partial Discharge Pulse Propogation in Shielded Power Cable and Implications for Detection Sensitivity	N. Oussalah Y. Zebboudji S. Boggs	IEEE Electrical Insulation Magazine	Vol. 23 No. 6 Nov/Dec 2007	This article summarizes the theory for PD propagation in shielded power cable for both symmetric (Gaussian) and asymmetric PD-pulse waveforms, based on the assumption that the attenuation constant (dB/m or Nepers/m) of the cable is proportional to frequency. This appears to be the most complete possible analytic exposition of PD attenuation in shielded-power cable, which has obvious applications to field PD measurements of such cable.	The focus of this paper is the development of an analytical model to predict the attenuation of PD pulses in shielded power cables. The material covered is similar to that in reference 3 (Evaluation of Partial Discharge Testing Technology for Transmission Class Cables)	6	Yes	No	No

B
STATEMENT OF WORK FOR RESEARCH RECOMMENDATIONS

This appendix contains scopes of work for two of the recommended follow up projects on the interpretation of field PD measurement results. A scope of work was not prepared for a third proposed research project which focused on round robin testing of extruded dielectric transmission cable systems with known defects by commercial testing services.

B.1 Scope of Work for Guide on Preparation of Specifications for Field PD Measurements

The scope of work for the recommended project to develop a guide for preparation of specifications for field PD measurements on XLPE transmission cable systems would include the following tasks.

1. Summarize Current Field PD Measurement Technologies

   Contractor will be required review industry guides that describe current field PD measurement technology. This review shall include the following industry guides as well as other industry publications that include an unbiased review of field PD measurement methods and equipment.

   - IEEE Standard 400.3 – Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment
   - CIGRE Technical Bulletin 182 – Partial Discharge Detection In Installed HV Extruded Cable Systems

   Contractor will be required to prepare a practical summary of field PD measurement methods for transmission cables based on information contained in the reviewed industry guides. The summary shall include:

   - Industry accepted objectives for field PD measurements on transmission cables
   - Practical description of sources of PD in transmission cable systems and what is known about the effects of PD
   - Field PD measurement methods (i.e. system PD measurements versus distributed measurements on cable system accessories, time domain versus frequency domain measurements)
   - On-line versus off-line PD measurements
   - Types of PD sensors and their impact on measurement results
   - Calibration of field PD measurements
   - Practical limitations in performing field PD measurements
   - Interpretation of field PD measurement results

2. Summarize Commercially Available Field PD Measurement Services

   Contractor will be required to prepare a summary of commercially available PD measurement services including:

   - Contact information for commercial PD measurement services
   - Measurement methods
   - Measurement equipment
   - Experience in performing field PD measurements on transmission cable
   - Methods for analysis of field PD measurement results (i.e. previous test experience, automated test report programs provided by manufacturer of measurement equipment, etc.)

3. Review Field PD Measurements Reports from Utility Commissioning Tests

   Contractor will be required to contact utilities with recent transmission cable construction projects to gather information about field PD measurement experience and to obtain copies of field PD measurement reports when possible.

4. Prepare a Comparison of Commercially Available Field PD Measurement Technologies

   Contractor will be required to prepare an interim report with a practical comparison of commercially available measurement technologies. The Contractor will obtain review comments on the technologies from each supplier. This report shall contain an unbiased comparison of the advantages and disadvantages of measurement methods, equipment, and calibration techniques, using established objective criteria.

5. Prepare a Draft Outline of Technical Specifications for Field PD Measurements

   Contractor will be required prepare a draft outline of the topics that will be included in a guide for preparation of technical specifications for field PD measurements. The outline will summarize the information that is proposed for each section of the guide.

6. Review Draft Outline of Technical Specifications with Utility Advisors

   Contractor will be required to plan for and participate in a web cast with EPRI utility advisors, EPRI's technical advisor, and EPRI's project manager to discuss the proposed draft outline.

7. Prepare A Guide for Technical Specifications for Field PD Measurements

   Contractor will be required to prepare a guide for preparing technical specifications for field PD measurements on transmission cable systems. This guide will, as a minimum, cover the following topics.

   - Objectives for field PD measurements for commissioning and condition assessment tests
   - Type of measurements to be performed (i.e. system versus distributed accessory measurements).
   - Acceptable measurement technologies for field PD measurements
   - Coordination of AC high-potential tests with PD monitoring
   - Coordination between cable manufacturer, cable installer, and PD measurement service
   - Scope of work for field PD measurements
   - Calibration of field PD measurements
   - Information to be included in PD test report(s)
   - Required information for vendor proposals
   - Comparison of vendor proposals

8. Prepare Final Report

   Contractor will be required to prepare a final report that complies with EPRI's technical report requirements.

   This task includes obtaining copyright release forms for any photos, figures, and written information provided by parties other than EPRI for inclusion in the final report.

   Contractor will be required to prepare for and present the results of the project at a future meeting of the EPRI Underground Transmission Task Force.

9. Reporting and Administrative

   Contractor will be required to comply with typical EPRI monthly reporting requirements.

B.2 Scope of Work for Seminar on Field PD Measurements

The scope of work for the recommended project to develop and conduct a three-day seminar for field PD measurements would include the following tasks. This scope of work assumes that the seminar would be conducted at the EPRI Lenox Test Facility and that EPRI personnel at this facility will be responsible for scheduling meeting rooms and equipment that is normally required for training seminars at this facility.

1. Seminar Planning

   Contractor will be required to prepare a preliminary seminar outline to be reviewed by EPRI's project manager and EPRI's utility advisors.

   The seminar will, as a minimum, cover the following aspects of field PD measurements on transmission cable systems.

   - Objectives of transmission cable field PD measurements
   - Industry guides for field PD measurements on transmission cables
   - Practical field PD measurement methods
   - Summary of previous EPRI projects related to field PD measurements
   - Differences between field and laboratory PD measurements on transmission cables and accessories
   - Commercially available field PD measurement equipment
   - Field PD measurement calibration issues and practices
   - Current commercial field PD measurement services
   - Preparing effective technical specifications for field PD measurements
   - Interpreting field PD test results
   - Planning for field PD measurements during commissioning tests
   - Commercial considerations during field PD measurements (i.e. repairing defective accessories, repeating system PD measurements if defects are identified, etc.)
   - Industry experience with field PD measurements for transmission cable systems

2. Finalize Seminar Topics and Prepare Cost Estimate

   Contractor will revise the preliminary seminar outline, as necessary, and prepare a cost estimate for conducting the seminar.

   Contractor will review the seminar cost estimate with EPRI's project manager and revise the topics to be covered, if necessary, to comply with EPRI's budget for the seminar.

3. Prepare Seminar Presentation Material

   Contractor will prepare presentation material for the course in the form of PowerPoint presentations by the course instructors.

4. Solicit Seminar Participation by Industry Field PD Measurement Experts and Field PD Service Providers

   Contractor will be required to contact other industry recognized experts in performing field PD measurements on transmission cables to solicit their participation in the seminar.

   Contractor will select at least one other industry expert in field PD measurements as a subcontractor to prepare and present course material. Any industry experts that are selected should not be affiliated with commercial field PD measurement services to insure objective input to the seminar.

   Contractor will be required to contact commercial field PD measurement service providers and solicit their participation in the seminar provided that the service provider is willing to prepare and submit seminar material in advance of the seminar without copyright restrictions. If possible, Contractor will make arrangements for seminar presentations by two field PD measurement services that use different field PD measurement technologies.

5. Seminar Coordination

   Contractor will be required to prepare twelve bound, printed copies of the seminar presentation material.

   Contractor will coordinate with EPRI's project manager and EPRI personnel at the location where the seminar is to be presented on the details of conducting the seminar.

   This task will include schedule coordination for presentations by parties other than Contractor.

6. Conduct Seminar on Field PD Measurements

   Contractor and subcontractors, if applicable, will provide personnel that are experienced in field PD measurements to conduct a three-day seminar.

7. Reporting and Administrative

Export Control Restrictions

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The Electric Power Research Institute (EPRI), with major locations in Palo Alto, California; Charlotte, North Carolina; and Knoxville, Tennessee, was established in 1973 as an independent, nonprofit center for public interest energy and environmental research. EPRI brings together members, participants, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of electricity generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States. International participation represents nearly 15% of EPRI's total research, development, and demonstration program.

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