DIAGNOSTIC TESTING OF MEDIUM VOLTAGE CABLES BY PARTIAL DISCHARGE LOCATION RECENT FIELD EXPERIENCE

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SUMMARY

Since its commercialization in 1996, a diagnostic test instrumentation system based on the location of partial discharge (PD) sites in installed cables has been successfully used in the United States, Canada and several European countries, to identify defects which are likely to cause near term failures in service. This paper provides an updated description of the present totally integrated instrument and its attributes. It presents typical results from tests performed in various countries and on different types of cable insulation, and discusses typical questions often raised about this diagnostic method.

INTRODUCTION

The competitive environment recently created by free market electricity supply is imposing unprecedented financial pressures on the utility industry throughout the world. Reduced capital and operating expenditures consistent with improved system reliability and customer satisfaction have become the guiding precepts for power systems, in general, and distribution networks, in particular. Underground distribution cable systems which, in the united States (US) alone, require in the order of $150 billion (thousand million) to replace, are particularly sensitive to these economic and reliability considerations.

A number of diagnostic tests, principally based on polarization-relaxation dielectric phenomena, are currently being advocated for evaluating in-service cables [1,2,3,4]. These would reveal overall changes of certain dielectric properties, but are unable to locate the sites of discrete defects, which are usually responsible for near-term failures in cables and accessories. They require prior establishment of signature files for each type and construction of cable tested. Often, when the test results fall in the gray area between very good and very bad, they fail to provide information leading to clear operating decisions. Defects in installed accessories, such as joints (splices) and terminations, are known to be responsible for a large proportion of outages. These diagnostic test methods are not able to identify the sites of such defects.

In contrast, the diagnostic method based on the location of partial discharge (PD) sites can pinpoint exactly the location of a defect likely to cause a near-term service failure. In cables with extruded dielectrics and in accessories, PD is known to be the precursor of failure. In paper-oil insulated cables, PD may indicate the existence of voids, oil-poor areas, soft spots, protrusions, deformations and, perhaps, water. It may not be able to detect the early existence of moisture, but it is conceivable that, when the insulation has charred and embrittled as a result of thermal degradation induced by moisture, PD may appear. This test is useful immediately after installation and, periodically, as the cable ages in service, to determine whether the cable should be repaired, partially or totally replaced, re-tested or, perhaps, rehabilitated.

The PD diagnostic test method covered by this paper was developed in the mid-nineteen eighties at the University of Connecticut, USA. Since 1996, it has been in full commercial use with over 10 test trucks performing field tests in the USA, Canada and Europe. This paper will describe the instrumentation and the testing procedures. It will provide typical test data generated in America and Europe on cables insulated with both extruded dielectrics and paper-oil. It will briefly review validation test results and will respond to typical questions often asked by concerned cable owners.

INSTRUMENTATION SYSTEM - PROCEDURE

The estimation of PD location, utilizing the principle of reflectometry, is performed by means of a Signal Conditioner, a Pulse Generator, a PD Estimator and an excitation voltage source, using the following sequence of steps:

1. Generation of an echogram to estimate the cable length and identify the location of joints or other features that cause an abrupt change in characteristic impedance.
2. Assessment of ambient amplitude modulated (AM) radio noise and adjustment of the characteristics of an adaptive digital filter to mitigate its effect.
3. Application of a high excitation voltage, at power frequency, to induce PD signals at the sites of defects, and recording, from one end of the cable, a large number of such signals in a relatively short time (a few seconds).
4. Analysis of data to estimate the location of PD sites, and the relative repetition rate and magnitude of PD signals.

If an exact location of the PD site is desired, the following steps are implemented:

- By means of a Location Matcher, the approximate area of the PD along the actual cable length is identified.
- Unearthing a portion of the cable and scanning its surface with a Pointer, while the cable is re-energized with high voltage, the exact location of the PD site is determined.

The instruments and operations mentioned previously are controlled by IMESTI™, a copyrighted, operator friendly software package.

Signal Conditioner

The signal conditioner, shown in Figure 1, consists essentially of a coupling capacitor, a high frequency blocking circuit, a passive (resistive-capacitive) high-pass filter, an amplifier, and protective and matching circuitry. It is placed as close as possible to the termination of the cable under test (test cable), and is connected to the high voltage excitation source by means of a flexible, PD free, high voltage cable

Figure 1. Photograph of a 75 kV Signal Conditioner.

Estimator

The estimator, shown in Figure 2, is the heart of the PD locating system. It comprises a fast digital data acquisition subsystem, a modern Pentium type processor with graphical user interface, matching input circuitry, two special bandpass filters providing external triggering capability, and a variety of data transfer ports.

Figure 2. Photograph of the Estimator

Operating Software IMESTI™

The software package, IMESTI™, helps perform the following operations:

(a) Assess the ambient noise and help in its abatement.
(b) Capture, average and record low-voltage echogram signals.
(c) Analyze these signals to characterize a cable system and identify and locate its discontinuities, such as joints.
(d) Capture, and record PD signals.
(e) Categorize PD sites, average signals as warranted, and display estimates of sites corresponding to each excitation voltage level.
(f) Help operate the internal and external triggers.
(g) Provide for expanded, sophisticated noise mitigation algorithms.
(h) Provide estimates of the locations of cable faults which may occasionally occur during tests.
(i) Estimate the PD magnitude, in pC, and the relative repetition rate.
(j) Provide for an algorithm to assess the overall condition of cables.

Position Matcher

While the estimator indicates, within approximately 1m, the PD site location along the cable length, it fails to show the corresponding location along the surface of the ground where the cable is buried. For direct buried cables, this information is essential, if the defective cable (or accessory) is to be repaired or partially replaced. The matcher is an instrument, which allows the matching of these two locations.

Two general models of matcher were developed. Model A, which is commercially produced, requires that a small test hole be dug in an estimated vicinity of the defect, until the cable is visible. A voltage pulse is applied across a coil wound around the cable. This sets up in the cable a travelling wave similar to a PD signal. The estimator processes this signal and determines the location of the coil along the cable. This allows the field crew to move along the surface of the ground by an appropriate distance in order to dig a 2-3m long trench within which the PD site should lie. Figure 3 illustrates this matcher.

Model B accomplishes the same task, except it does not require the digging of a test hole. In one version, an electromagnetic pulse wave is generated at ground level, in the vicinity of the estimated cable PD site. This sets up a travelling wave along the cable, as in the case of Model A. In another version, a pulse is applied at the measuring end of the cable and is received through an appropriate antenna at ground level, along the cable route. The receiver comprises a microprocessor, which is able to process the signal peaks recorded, in the same manner as the estimator processes PD signals. This provides information on the actual location of the receiver along the cable length. The field crew is, then, able to move until the receiver and the PD estimated locations are matched. This model, which was graphically illustrated previously [5], is expected to become available in 1999.

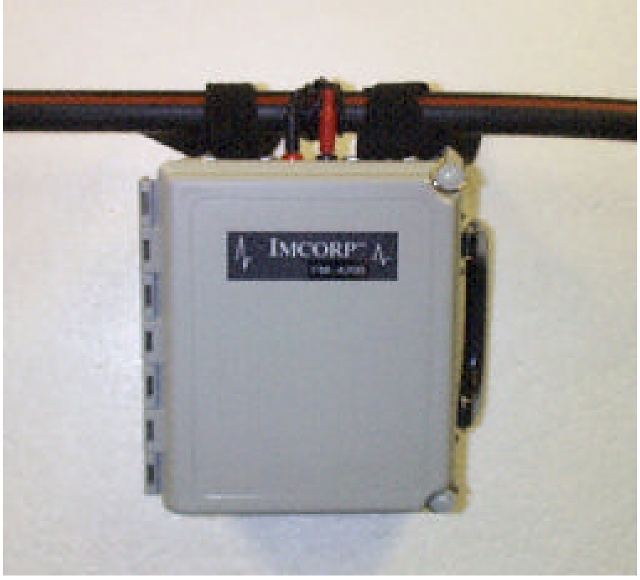


Figure 3. Photograph of Matcher Model A.

Pointer

The pointer, described in a previous publication [5], is a device, which is made to scan the surface of the cable uncovered by the trench mentioned in the previous section. The cable is energized with a voltage high enough to produce PD activity. A set of dual electromagnetic sensors connected in a differential mode trigger an acoustic signal whenever the PD site is between the two sensors. The resolution of the pointer is ± 2cm. Field testing of a prototype began in January 1999.

TEST SETUP

The test setup is illustrated in Figure 4. A resonant transformer with a variable gap reactor fed by a power frequency source, a voltage control cabinet and an estimator are carried on-board a test van. The signal conditioner, placed next to the termination of the test cable, is connected to the transformer output bushing by means of a flexible, PD-free, high voltage cable.

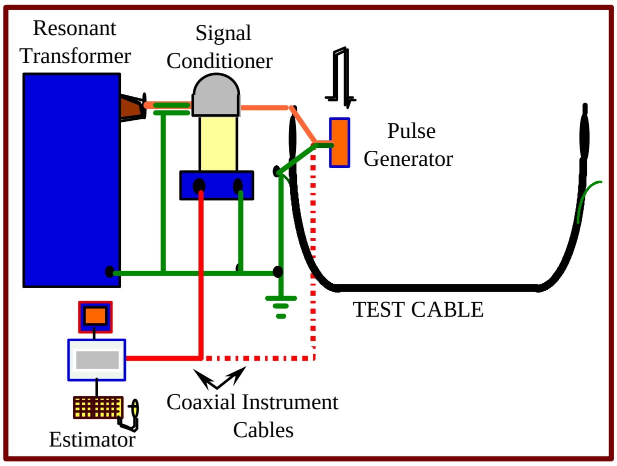
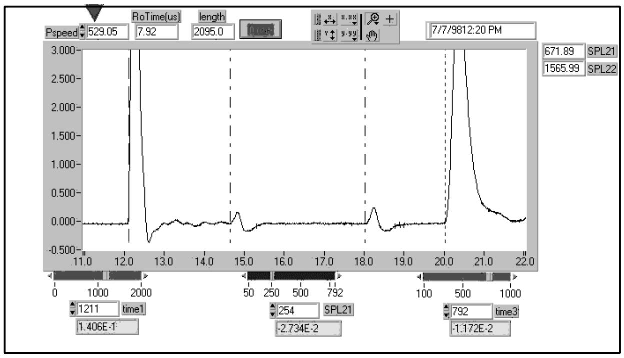


Figure 4. Schematic Diagram of the test setup.

PROCEDURE

Echogram

To obtain an echogram, a low-voltage pulse generator is connected across the cable termination, as shown in Figure 4. Two options are possible: (a) the pulse signal is led to the estimator via a BNC cable (dotted line), bypassing the signal conditioner; (b) the pulse signal is led to the signal conditioner and treated as a PD signal (dotted line disconnected). The remote cable end is left open. Figure 5 is a typical echogram obtained in the field on a cable containing two splices. The splice locations are shown on the upper right hand corner as SPL21 and SPL22.



Pspeed 529.05
RoTime(us) 7.92
length 2095.0
7/7/9812:20 PM
671.89 SPL21
1565.99 SPL22
1211 time1
1.406E-1
254 SPL21
-2.734E-2
792 time3
-1.172E-2

Figure 5. Echogram of a cable with two splices.

Noise Mitigation

Ambient noise is sampled repeatedly and its frequency spectrum determined. The adaptive digital filters of the estimator are then set to eliminate the most offending frequencies, such as powerful neighborhood radio stations. The detection sensitivity can increase 5 to 10-fold when this feature is used. Figure 6 was a signal recorded in a field measurement when the digital filters were deliberately turned off. The PD pattern was almost totally masked by noise. Figure 7 represents the same signal, when the filters were activated. The difference is very clear.

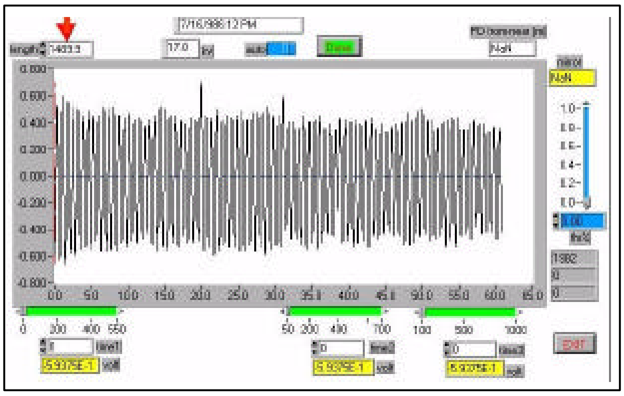


Figure 6. Reflectogram of a PD with filters turned off.

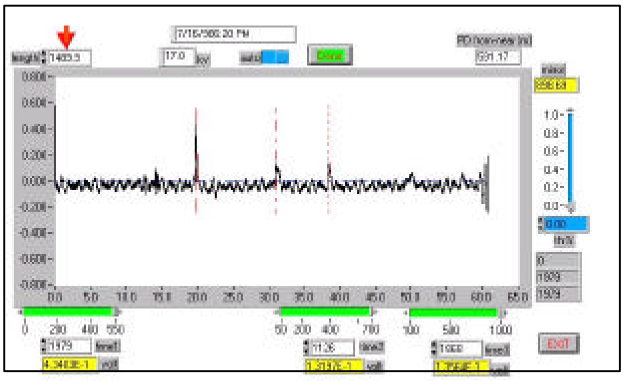


Figure 7. Reflectogram of Figure 6 with filters turned on.

To further enhance the signal/noise ratio, similar PD patterns are grouped and averaged, using a sophisticated signal processing algorithm to line up the starting points of all patterns.

In the presence of very high noise, it may not be possible to detect the presence of small PD signals. In such a case, an external trigger activated by the PD signal, which is processed through a narrow bandpass filter, is utilized. Again, an averaging scheme helps to further enhance the useful signal.

Finally, under extremely high noise conditions, a search for a PD pattern, which may be buried in the recorded signal, is carried out by various signal processing techniques, utilizing the cable propagation characteristics. These techniques, described in previous publications [6, 7], are time consuming in a real field application and used only in exceptional cases.

High Voltage PD Test – Analysis of Results

The reactor gap is adjusted to achieve resonance. The excitation voltage is then gradually increased until a PD is detected or the maximum test voltage is reached. A large number of PD events, for example 30-200, are recorded in 2-5 seconds and the voltage is reduced immediately to zero. The PD inception voltage (PDIV) is noted. After the first PD event has been recorded, the voltage is increased in small steps, such as 2 kV, and a recording is made at each step. To prevent test failures in cables insulated with modern extruded dielectrics, such as XLPE, the test voltage is recommended not to exceed the initial PD inception voltage (PDIV) by more than 4-6 kV if the PD site is determined to be in the cable itself. For other dielectrics or when the PD is in an accessory, the test voltage may be allowed to go higher than this level.

Analysis of the recorded data provides estimates of a PD site location, the PDIV, the relative repetition rate of the PD event and the PD magnitude. The PDIV and the repetition rates are important for assessing the severity of a defect. Contrary to widespread practice, the PD magnitude is a poor indicator of severity, but may be useful for evaluating the sensitivity of the test instrumentation. Unlike other commercial units, the assessment of PD magnitude requires no preliminary calibration by means of special calibration devices. Calibration tests conducted in Italy and France indicated that the deviation from commercial calibration devices was less than 10% [8].

FIELD EXPERIENCE

During the period 1996-98, approximately 2,400 km of medium voltage cable with extruded insulation were tested in the USA and Canada. During 1998, Ultra Power Technologies, Inc. (UPTI) performed all the tests in North America, using the technology described in this paper. Since August 1998, the authors tested medium voltage cables in several European countries. These were insulated with XLPE, old and new technologies of ethylene-propylene rubber (EPR), paper-oil and polyvinyl chloride (PVC).

Pre-1998 North American experience

Four field testing cases and examples of validation tests will be cited.

Case1: Cable Joint Failures

This project was initiated in August 1996, in response to repeated failures on the joints of an 18 km long, 4-6 years old, cable system serving an important shopping center in Northern Indiana. The maximum test voltage available at that time was $2U_o$, or 14.4 kV. One cable defect, 30 defective joints and 7 defective terminations were identified and classified for severity on the basis of their PDIV, as shown in Table 1. Three joints, in particular, had PDIV levels near or below service voltage and were recommended for immediate repair. Within one week, one of these joints failed in service. Following this event, the utility changed all defective components but failed to retest the system. No further failures occurred for an entire year. However, a year later, two additional failures occurred and a retest was undertaken in 1997, using a maximum voltage of $3U_o$.Figure 8. Case 2: Histogram of defective joints.

This test, summarized in Table 1, uncovered that some of the old joints and some newly installed joints were defective. The utility owning the cable system estimated that it achieved net savings of US$735,000 by avoiding a total replacement of the entire circuit [8].

Table 1
Summary of PD test results obtained in 1996 and 1997–Case 1

PDIV kV	Number of Defective					
	Cables		Joints		Terminations	
	1996	1997	1996	1997	1996	1997
PDIV>14.4	NA	0	NA	15	NA	3
13<PDIV 14.4	1	0	10	1	3	0
11<PDIV 13	0	0	8	3	1	1
8.5<PDIV 11	0	0	9	2	3	4
PDIV 8.5	0	0	3	1	0	0
Total	**1**	**0**	**30**	**22**	**7**	**8**

Case 2: Validation of Technology

A 3-week test was undertaken on an 80 km sample of the 12.4 kV, XLPE and EPR insulated cable system of a municipal utility in Colorado to validate the testing method and provide an overall estimate of the condition of the system. The maximum test voltage ranged between 1.5 and $2.5U_o$, the lower limit being dictated by defects with low PDIV, and the upper limit by the utility's fear of overstressing cables of old vintage. The test uncovered one defective cable, 18 defective splices and 5 defective terminations. The PDIV of the cable was approximately $2U_o$. A severe lightning storm (almost a daily event during that season) followed the test and lasted over 24 hours. Approximately 20 hours after the beginning of the storm, the defective cable failed at the location of the estimated PD site. This event showed that (a) the PD test did foresee the cable weakness; (b) the PD location corresponded accurately to an actual cable defect; (c) the rate of deterioration was accelerated by the lightning storm. It further showed that attempts to predict "remaining life" or exact "time to next failure" cannot produce reliable results, as rates of deterioration are significantly influenced by utility-specific environmental and operating conditions, such as lightning events, heat waves, insulation coordination and others.

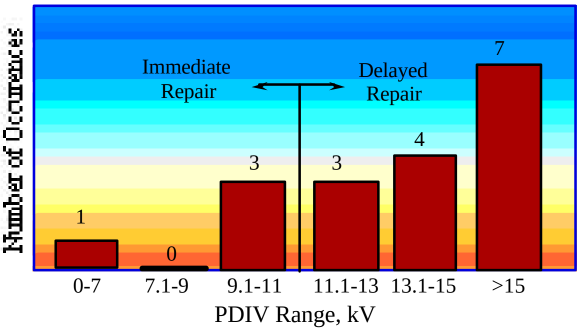
A histogram of the defective joints, sorted by PDIV range, is shown in Figure 8. Assuming that all joints with PDIV 11.0 kV will fail within one year, a total of 5 joint failures per 100 km per year are predicted. Similarly, on the basis of one defective cable, a total of 1.25 cable failures per 100 km per year are predicted. The actual failure rates compiled by the utility were 1.11 and 3.81 for cables and accessories, respectively. PD testing, although performed on a relatively small sample size (80 km), predicted failure rates within comparable ranges.

Figure 8. Case 2: Histogram of defective joints.

Following the tests, the utility removed, dissected and examined all 18 defective joints. In all cases, clear physical evidence pointing at the existence of partial discharge was noted and reported [9].

Case 3: Technology Validation and Joint Evaluation

This project was undertaken in June and November 1997 for a distribution utility in the Province of Ontario, Canada. The main objective was to evaluate the usefulness of the test method while assessing the condition of joints with a history of repeated failures in the 27.6 kV, XLPE cable system. The test voltage for this system was limited to $2U_o$. A limited number of 13.8 kV cable sections were also tested with maximum voltage levels ranging between 1.5 and $3.0U_o$, the wide variation being imposed by the utility for operating reasons. The test results are listed in Table 2, and a histogram of the test results on the 27.6 kV joints is shown in Figure 9.



The relatively low incidence of cable defects is compatible with the failure rates expected for such systems. The tests identified several severely defective 27.6 kV joints, namely those with a PDIV equal to or less than the 16 kV service voltage. This confirmed the reason for the high failure rate.

Table 2
Summary of June and November 1997 PD tests–Case 3.

Test Identification	June 97		Nov. 97	
System voltage, kV	27.6	13.8	27.6	13.8
Cable Length, km	29	23	86	56
Defective Cables, number	0	1	2	2
Defective joints, number	16	3	64	29
Def. terminations, number	8	9	78	30

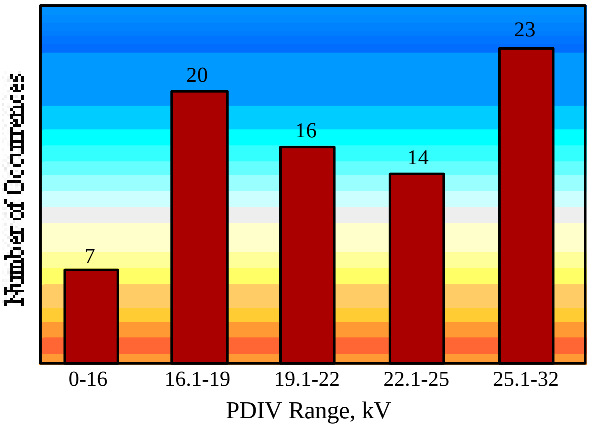


Figure 9. Case 3: Histogram of defective 27.6 kV joints.

Case 4: Assessment of System with Poor Performance

To acquaint an investor-owned utility in Colorado with the PD testing technology and identify the reasons for the relatively poor performance of its 13.2 kV, XLPE cable system, a 3-week test was conducted. On a 90 km long system, 12 defective cables, 153 defective joints and 60 defective terminations were identified. The tests did confirm a high defect rate for both the cable and the joints. If all defective cables were to fail within one year, a failure rate of over 13/100-km/year would be predicted. Approximately one half of the defective joints had PDIV levels below $1.3U_o$. Some of the defective cables and accessories, which were not repaired, were reported to have failed within a few months of the test.

U.S. Experience in 1998

Approximately 2000 km of medium voltage cable with extruded insulation was tested by UPTI in the U.S.A. during 1998. The cable systems tested comprised a total of 11,134 joints. A total of 5,372 PD events were observed. A summary of discharges in the various cable components is shown in Table 3.

Table 3
Percent of PD allocated to cable system components.

PDIV, U_o	Cable %	Joint %	Termination %
0.0 – 1.0	0.8	3.5	2.7
1.0 – 1.3	1.7	10.6	6.9
1.3 – 1.7	3.6	17.3	10.4
1.7 – 3.0	10.6	17.5	14.4
Total	16.7	48.9	34.4

On the basis of this testing experience, and subsequent validation tests, effective criteria were formulated regarding the maintenance options available to the utilities, namely: immediate repair, delayed repair, partial or total replacement or scheduled monitoring (re-testing).

Testing in Europe

Testing in Europe began only in August 1998. The initial tests reported were intended to demonstrate the technology to potential users, and to identify the cable configurations used in the countries visited, namely: Belgium, France, Spain and Italy. Valuable information was acquired on the PD behavior of old technology EPR, PVC and paper-oil insulation. A few salient results follow:

1. A 1.1 km long, 3-phase, 15 kV cable with XLPE insulation was tested in Belgium. Prior diagnostic test by means of tanδ measured at 0.1 Hz had, reportedly, indicated that the cable was very poor. Two phases were tested with a maximum voltage of $2U_o$ and one with $3U_o$. In spite of the high sensitivity achieved, no PD was detected. On the basis of this PD test, the cable was in a serviceable condition.
2. Two paper-oil insulated cables tested in Southern Spain displayed multiple partial discharge sites with PDIV at or near service voltage, indicating that the cables were in poor condition. The utility confirmed this result, mentioning that plans were already on the way to replace them.
3. Two relatively young paper-oil insulated cables were tested outside Rome, Italy. Both cables showed multiple discharges distributed over their entire lengths, with PDIV much below service voltage. Four of the six joints in one of the cables discharged at 5.5 kV, well below the 12 kV service level. The discharge magnitudes ranged between 180 and 1000 pC. The utility confirmed that these cables were plagued with problems.

DISCUSSION

Cable owners often ask the following questions about PD testing: (a) what is the maximum recommended test voltage? (b) Does PD testing create defects which did not exist initially? How often should tests be conducted? How reliable are test results? Of course, additional questions are sometimes asked. These questions will be briefly discussed. (a) The maximum test voltage should cover the entire range of transients seen by the cable during service. Although this differs according to isokeraunic levels and system configurations, it may be safe to say that a voltage between 2.0 and 3.0 U_o will be sufficient for most systems. The higher the test voltage, the more accurate is the predictive quality of the test. (b) Whether PD testing introduces new defects depends on the type of excitation voltage, the sensitivity of detection and the dwell time at PDIV to record the data. The system described in this paper has all the attributes, which minimize the probability of damage caused by testing. (c) Testing is recommended immediately following the installation of a new cable. As the cable ages (after 15 years), periodic tests are recommended at gradually accelerated repetition rates. (d) The test results have proven in the past to be reliable, except in a few instances where operator errors due to lack of experience have been made. Some of the conditions which contribute to marginal results are extremely high cable attenuation and difficult to access cable terminations.

CONCLUSION

A diagnostic test method based on the location of PD sites was described, summaries of typical field results were cited and a discussion of recurring questions was provided. This technology has proven to be viable to its users. With serious cooperation from electric utility companies, effective future improvements can be achieved.

ACKNOWLEDGEMENTS

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