NORTH AMERICA HAS A SIGNIFICANT underground electric distribution system that is nearing the end of its design and service life. The cost of global replacement of aging underground facilities is prohibitive. Consequently, utilities require an enterprise approach to managing underground power cable systems (cables, joints, and terminations) in order to develop prudent investment and maintenance practices.

Utility power cable fleets consist of many millions of feet of cable installed under city streets, suburban developments and, in some cases, in the countryside. Utilities have a long underground system history, with some of these systems installed as early as the 1920s. Increasing failure rates on these older systems are now adversely affecting system reliability, and it is readily apparent that something must be done to manage the consequences of this trend.

Industry-leading utilities have approached this challenge by considering cable assets from a full-life-cycle...
There is still much to learn, but cable diagnostic testing is a rapidly developing field, and increasingly useful technologies are available for assessing the condition of underground cable systems.

perspective. This includes rigorous accessory and cable specifications and procurement practices, high-quality installation techniques, the use of precise operating parameters, the use of monitoring and diagnostics, the implementation of optimal maintenance approaches, and detailed data collection and retention philosophies, as detailed below.

- **Specification and procurement**: This begins with well-informed manufacturing specifications for new cable and cable systems that meet or exceed accepted industry specifications. The procurement process should be supported by a knowledgeable involvement on the part of the utilities, which can include effective incoming inspection programs and vendor audits.

- **Installation**: This refers to techniques for managing the installation, commissioning, and ongoing operation of cable systems within accessory and cable design parameters. Installation by its very nature is a dynamic undertaking with numerous challenges to be overcome on a daily basis; consequently, investments in training, feedback mechanisms, and dissemination of best practices deliver significant value. The importance of this area is evidenced by forensic analyses, which have demonstrated that more than 70% of service failures contain contributions from poor installation practices.

- **Monitoring and diagnostics**: Once in service, comprehensive monitoring and surgical diagnostic methods, technologies, and tools can be used to ascertain cable condition and provide an indication of remaining life. One of the most practical tools available to a utility is a coherent program of forensic analyses of field failures, as these indications of failure modes serve to guide the informed choice of diagnostic protocol.

- **Modeling and prediction**: Predictive modeling can provide the basis for taking appropriate actions, such as routine inspection and maintenance, a capital replacement program over a number of years, or a targeted and staged rejuvenation program that helps utilities avoid unpredictable peaks and unexpected cost increases associated with increasing failure rates.

Utilities take a variety of paths to manage cable system assets and obtain the answer to the “remaining life” question. Some use sophisticated modeling while others use simplistic rules of thumb and local know-how. Perhaps the most promising research results for cable system asset managers come from the use of advanced diagnostics as part of a targeted diagnostic program.

Cable system diagnostic technologies have made improvements recently, yet there are still many challenges and uncertainties for utility cable engineers. In response, the U.S. Department of Energy has been supporting the Cable Diagnostic Focused Initiative (CDFI) since 2004; its objective is to provide utilities with improved diagnostic tools, methods, and understanding. The CDFI effort has been led by the National Electric Energy Testing, Research, and Applications Center (NEETRAC). Recent CDFI results are promising, and work continues with a focus on the diagnostic technologies and how best to apply them.

### Specifying the Cable System

The utility distribution engineer must select the most suitable components (cable, joints, terminations, and so on) and installation methods to provide the customer with a safe, continuous, trouble-free power supply that can withstand unexpected demands and overload conditions. Many installations have specific requirements that need to be addressed by the engineer at the specification stage. Both the design and the materials selected require attention to details to ensure long, reliable life. The selection of the right material for each system component will ensure a maximum in-service life with a minimum of concern while operating in its specific environment. A comprehensive understanding of cable and cable accessory performance by utility cable design, installation, and operating engineers is a very important factor in the longevity of power cable systems.

Traditionally, power cable engineers have been very conservative in sizing and operating cables. Normally, systems were operated under a light load; if a particular segment approached its design ampacity, it was immediately replaced by a larger size (provided cost was not an issue) or deloaded (if possible). These methods were based on sound engineering judgment, as engineers did not have the technology to access more detailed information (such as the system “hot spot” maximum operating temperature) and thus could not make use of less conservative approaches. With technology advances and improved materials, however, power cables can now be operated much closer to their operating tolerances and, depending on the circumstances, even above them for short periods. In turn, this places an equivalent burden on the design and installation of the accessories (primarily the joints and their connectors) that are now required to match the performance required of the cables.

Recent innovations in cable technology focus on the concept that the “total systems” approach to longevity encompasses:

- exclusion of water (using conductor blocking to keep water out of the cable strands, robust cable jackets to
provide mechanical protection for the cable cores and their neutrals, and effective housing methods to prevent the ingress of moisture from joints

✔ better control of the electric stresses (by providing a smooth interface between the insulation and the semi conductive shields, excluding stress raising contaminants from joint and cable insulations, and using improved tools for accessory installation)

✔ updated manufacturing technologies (including true triple extrusion, controlled lapping and impregnation of paper cables, and injection molding of accessory components)

✔ improved test procedures (such as the use of defined test methods for system components like terminations, joints, and cables and industry standards like IEEE Standard 400 for field-testing of the complete cable system).

Leading utilities actively participate in industry organizations such as the IEEE Insulated Conductors Committee (ICC) to stay abreast of the latest trends and issues regarding underground cables and accessories. This interaction keeps utility cable engineers informed and engaged on critical issues. Organizations like the Association of Edison Illuminating Companies (AEIC) Cable Engineering Committee and the Insulated Cable Engineers Association (ICEA) are also important agents acting on behalf of the industry to publish specifications and guidelines dedicated to cable engineers. A number of the important specifications in this area are detailed in the “For Further Reading” section.

Cable purchasing specifications should reference these standards, as well as international standards in some cases. The cable purchasing specification should focus on the attributes that directly affect the reliability of a given utility’s system, however. They should therefore not be unreasonably tight, as that may eliminate some good solutions by driving manufacturers to “pass the specification” rather than address the needs of the utility and its system. Failure to focus on the true needs will invariably lead to increased operational and procurement costs.

It was noted that utility involvement and vendor qualification are important elements in assuring reliability. In parallel with this, there is a growing interest in continual improvement through regular inspection of the delivered product. These inspections are typically performed by an independent laboratory. The fact that samples receive a repeat inspection, modeled on those detailed in specifications, provides an assurance that the product not only passes the minimum specification requirement but offers the customary performance a utility expects. The utility can therefore expect that the significant service life it provides will be in line with that provided by past and present installations.

One large utility has used this approach over the past seven years, identifying more than 100,000 feet of defective cable that otherwise would have ended up installed on its system (see Figure 1). This represents a very small percentage of all the cable sampled, but the added step of independent testing has allowed the utility to avoid future cable failures, customer outages, and the associated cost of emergency repairs. Collating the data obtained in such studies for different utilities provides significant value.

One example of such a collation is shown in Figure 2, where data from the inspections from a number of utilities have been collated to produce a histogram of the defect sizes...
detected within incoming inspections. These processes not only ensure that a consistent quality of product is installed on the system but supply the underlying data for continuous improvement activities in partnerships between manufacturers and utilities.

**Metrics for Cable Systems Management**

An effective asset management effort requires accurate asset data. The degree of accuracy and the extent of such data vary widely across the industry. This section discusses a number of the issues that are currently being addressed by practitioners in this area.

Accurate population data are important as they are the base from which component failure rates are computed. The best population data sets include cable age by voltage and insulation type and may also include such information for individual sections of cable. Rich population data sets would also include splice information, by age and joint type. Some utilities go so far as to record information on the individual who constructed the splice.

Component failure rates are a critical input to any asset management decision process. Cable and splice replacement and population data form the basis for developing failure rates. Such data must differentiate between replacements due to upgrade and those due to genuine failure. Although average cable system component failure rates generally increase with age (see Table 1), some specific components commonly have higher-than-average failure rates. Also, failure rates may increase substantially during periods of high load. In addition to compiling failure rate data, some utilities conduct failure analysis, which is useful in identifying specific component issues such as manufacturing defects or issues with training of splicing or construction employees.

Reliability performance is another metric useful in assessing the performance of cable system assets. Customer outage minutes (as indicated by the system average interruption duration index, or SAIDI) due to various cable system components by age and voltage class are useful in asset management decisions. Reliability performance takes into account such factors as system design, which influences the impact of component failures on customers. Certain system designs may limit the impact of failures on customers while others may not. Reliability data can be used to identify the worst-performing circuits, which are a potential source of customer dissatisfaction and high operation and maintenance costs.

Actual component failure rates, feeder failure rates, and customer reliability performance as well as diagnostic results are specific metrics that provide more information than can be inferred from the overall age of a cable system. It is not uncommon for older assets to actually perform better than some younger ones (in Table 1, old accessories only account for 55% of the failures reported in service, as compared with 76% for cable). Identifying the worst-performing assets and replacing them is more cost effective than wholesale replacement based on average age. Component failure rates and reliability performance data can be used to develop failure rate models that can then be used to project system reliability into the future for various scenarios of cable system asset replacement levels. For utilities operating in dense urban systems supplied by underground networks where cable failures generally do not result in customer outages, feeder failure rates may provide information useful for prioritizing capital projects. In order to guide capital investment, some utilities have developed advanced probabilistic tools that consider component failure rates, network design, and the overall risk of network loss among other factors in their calculations.

The strategies for managing large, aging cable asset bases include reactive replacement (run to failure), targeted replacement of underperforming asset classes, installation of sectionalizing switches, expansion of automation, and surgical replacement of susceptible components identified by diagnostics. Reactive replacement results in a gradual but steady increase in failure rates over time that will eventually become unsustainable. Proactive, wholesale replacement may be designed to maintain or reduce average asset age or failure rate but in either case may require a substantial capital investment to achieve. Targeted replacements of high-failure-rate assets can help optimize capital spending as long as performance data accurately reflect system behavior. Installation of sectionalizing switches and expansion of automation can improve reliability for end customers and advance system flexibility for the “smart grid” but do not address the core component reliability issues.

It is useful to review the experiences of Con Edison of New York to identify the challenges that utilities face and how they might be overcome. Con Edison has a detailed cable asset database that includes voltage class, insulation type, conductor size, and installation date. In addition, the company conducts detailed failure analysis on distribution cables and splices and so can calculate accurate and detailed failure rates for components. Reliability studies have shown that paper-insulated lead-covered (PILC) cable has significantly elevated failure rates during summer heat waves. The company began a program in the mid-1980s to remove PILC cable and thus improve network reliability. Because primary feeder failures do not generally result in customer interruptions, Con Edison cannot use end customer reliability performance as a metric in optimizing network feeder cable.

<table>
<thead>
<tr>
<th>Component</th>
<th>Old (%)</th>
<th>Other (%)</th>
<th>New (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accessories</td>
<td>55</td>
<td>24</td>
<td>21</td>
</tr>
<tr>
<td>Cable</td>
<td>76</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>Connectors</td>
<td>70</td>
<td>16</td>
<td>14</td>
</tr>
</tbody>
</table>

**Table 1. Semiquantitative analysis of age profile of service failures from selected utilities.**
replacement. In addition, the load carried by feeders that fail is transferred to remaining in-service feeders, increasing their likelihood of failure. This characteristic of network systems can result in cascading failures at high loads. The company has developed an asset management process that computes avoided feeder failures per dollar spent on cable replacement by using its network reliability index (NRI) tool. The NRI is a measure of network reliability calculated by considering such factors as feeder component failure rates as a function of age, voltage, and loading as well as a feeder’s contribution to the overall reliability of the network. The NRI model simulates network behavior over a 20-year period using a Monte Carlo method. The calculated NRI values are then used to rank the relative reliability of Con Edison’s networks. This lets the utility prioritize the removal of PILC to optimize the reliability gain.

Figure 3 shows schematically the investment required to achieve a given improvement in reliability based on a feeder’s asset grouping. The feeder groupings reflect the NRI ranking of the network containing that feeder. Group I feeders offer the largest increase in reliability per dollar spent.

Although component failure rate data can be used to identify and target a specific, poorly performing class of components, not every component within such a class may be defective or likely to fail in the near future. Diagnostic technologies that are able to identify specific sections of cable or splices with defects allow surgical replacement of susceptible components and can help to optimize capital spending.

**Cable System Diagnostics**

Industry cable research has determined that many cable system failures are caused by isolated cable lengths or isolated defects within a specific circuit segment. The key to managing this process is thus to be able to accurately find these “bad actors” and proactively replace them before their repeated failures degrade overall system reliability. Various cable system diagnostic testing technologies have been developed in an effort to identify cable system deterioration factors. Diagnostic testing is performed to identify potential failures within cable systems and then again after repair to verify that the repair work performed did indeed remove the problem or problems detected.

These technologies are generally divided into two categories. The first category involves techniques that assess the global or “bulk” condition of a cable length. Though a variety of techniques may be employed, the general approach is to measure electrical losses within a given cable circuit length. The second category involves techniques that assess localized defects within a cable circuit length. Again, various techniques are used to accomplish this goal, but they almost always involve the measurement of localized electrical discharges within a cable system.

Implementing cable system diagnostics effectively involves the management of a number of different disciplines. The issues are increasingly being mastered, but the work is made very complex by the fact that most cable circuits were never installed with diagnostic testing in mind (see Figure 4). Frequently, these circuits contain multiple branches or multiple cable and accessory types, each with its own aging and failure mechanisms (see Figure 5). Utilities report that between 4% and 80% of their service failures are attributed to accessories (joints and terminations). A natural consequence is that different diagnostic techniques are often needed to detect different bulk and localized problems.

**Diagnostic Technologies**

The basic cable diagnostic testing technologies used to assess cable circuit conditions are listed in Table 2. A number of surveys have been conducted recently in an attempt to gain a better understanding of how utilities employ diagnostics in a proactive manner, which is the first step in any

**Figure 3.** Effect of investment on reliability improvement for different asset classes.

**Figure 4.** Typical cable system installations. (Images courtesy of National Electric Energy Testing, Research, and Applications Center.)
asset management process. The survey results in Table 2 show that approximately 30% of the responding utilities use diagnostics proactively on their cable systems. Furthermore, subsequent feedback has indicated that this fraction is growing.

Different diagnostic testing technologies are designed to assess different cable system characteristics. In many cases, more than one technology should be utilized to establish a reasonably complete picture of the cable system’s condition. This is a particularly complex problem for hybrid cable circuits that contain more than one type of cable insulation and/or more than one type of cable joint or cable termination. Whether a cable circuit is simple or complex, diagnostic tests must be employed carefully to assure that results will be meaningful.

### Selection of Appropriate Diagnostic Techniques

Diagnostic techniques are generally used either to ensure the satisfactory performance of newly installed equipment (commissioning tests) or to assess the state of health of older components or systems. Diagnostics are employed to increase the efficiency of reliability improvement programs. This work contains four basic elements that can be summarized as:

- **Selection**: Choose the cable circuits for testing that will produce a significant improvement in reliability. Typically this is based on age, failure rate, or other engineering judgment.
- **Action**: What actions will be performed as the result of certain diagnostic outcomes or interpretations? The actions are separated into two groups (action or no action) and may include replacement, defer action, rejuvenation, and/or repair. These actions are chosen based on those most suitable for the system topology and most prevalent failure mechanisms (local or global degradation).
- **Generation**: Diagnostic tests generate data well fitted to the type of maintenance actions and prevalent failure mechanisms.
- **Evaluation**: Are the methods employed for selection, action, and generation giving the expected results, i.e., lower rates of failure and increased times between failures? Can the diagnostic elements be improved?

A convenient mnemonic for this four-part scheme is SAGE. Figure 6 illustrates how the four SAGE components function together over time to produce (if implemented properly) a reduction in the anticipated failure rate. It is useful to note that this benefit is not seen immediately nor does it cease once the program has ended: there is both a lag and persistence. Furthermore, failure rates do not begin to change until the program is close to completing the actions directed by the diagnostic testing (generation). Selection, generation, and action are each defined stages in time, while the evaluation component is

<table>
<thead>
<tr>
<th>Diagnostic Technology</th>
<th>Approximate Percentage of Responding Utilities Using the Diagnostic in a Proactive Manner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic techniques</td>
<td>No use reported</td>
</tr>
<tr>
<td>Dissipation factor/dielectric spectroscopy at 60 Hz, very low frequencies (VLF), or various different frequencies</td>
<td>30</td>
</tr>
<tr>
<td>Partial discharge (PD) at operating, elevated 60 Hz, elevated VLF voltages</td>
<td>20</td>
</tr>
<tr>
<td>Polarization and depolarization current</td>
<td>No use reported</td>
</tr>
<tr>
<td>Recovery voltage</td>
<td>No use reported</td>
</tr>
<tr>
<td>Time domain reflectometry (TDR)</td>
<td>20</td>
</tr>
<tr>
<td>Withstand tests at elevated VLF, 60 Hz ac, or dc voltages</td>
<td>50</td>
</tr>
</tbody>
</table>

**Figure 5.** Estimate of the size of the cable technologies installed on U.S. utility systems.

**Figure 6.** Effect of SAGE on the failure rate of a target population.
ongoing throughout the entire test program and beyond. Furthermore, after some time the failure rate will begin to increase again, and this will be observed during the evaluation phase.

As discussed earlier, there is a wide range of cable system diagnostic testing techniques available to evaluate the condition of underground cable systems. For many of these techniques, there are also different variations on the same basic technology. In order to determine the correct technique to use for a given application, an engineer needs to consider:

- **Effectiveness:** Does the technique probe the most likely failure mechanism for the group of cable systems under study?
- **Maturity:** Has the technique been deployed long enough to ensure it is effective? Much of the benefit of diagnostic testing comes from a comparison with historical measurements on other circuits. Useful comparative data may not be available for immature, changing, or evolving technologies and techniques.
- **Accuracy:** How often does the technique deliver the correct assessment?
- **Clarity:** Does the technique provide an answer to the person making the asset management decision in an effective manner? Red/green and go/no go outcomes are easy to understand but do not inherently provide information for prioritization. Can the results be acted on in a straightforward manner?

Consequently, the selection of the appropriate diagnostic is challenging. This is particularly true because an approach that worked successfully on asset group A may not work on asset group B, even for the same utility. This is because the age, construction, and risk profile is likely to differ between the two groups. This problem is well suited to artificial intelligence methods whereby information (such as the age of the cable system to be tested, the type of insulation system used, and likely remediation actions) can be solicited from the user. The response data are then used to interrogate a database of inputs from international experts and users of diagnostics on cable systems to determine the most appropriate diagnostic approaches.

The authors have found this method, based on the cumulative experience of the practitioners, particularly effective in dealing with the uncertainty that occurs prior to undertaking field tests, which makes precise (crisp-decision) flow charts unwieldy and difficult to construct. The end result is a fuzzy logic approach that determines the level of consensus among the experts and thereby provides a short list of techniques for the appropriate situation (see Figure 7). Such a list is particularly valuable in that it not only shows options that might be considered appropriate but the relative strength of the recommendations.

Figure 7 illustrates the very common situation where the decision as to what diagnostic is the most appropriate is not clear-cut (note the clustering of four of the techniques around the green threshold). This approach has been used quite successfully in the 2010 update of IEEE Standard 400.

**Diagnostic Accuracy**

In the area of proactive asset management—be it in areas as diverse as cable systems, generators, transformers, or wood poles—accuracy is a crucial characteristic. Accuracy is important because asset managers implicitly ask themselves, how certain are we that this device is truly a poor performer while this other device is truly a good performer?

There are many ways to define the accuracy of diagnostic testing procedures. The approach the authors prefer is to sort the tested cable system circuits into two categories based on the interpreted results from diagnostic devices or the providers of these services. The authors then work with the utilities to follow the performance of these circuits (assuming they are left untouched in the system) in service for a period of years. The categories used for the sorting are:

1. **Pass:** Those circuits that the diagnostic test results indicate are “good” (do not require action) and are not expected to fail within a specified time horizon.
2. **Not pass:** Those circuits that the diagnostic test results indicate are “bad” (do require action) and are expected to fail within a specified time horizon.

There are, fundamentally, two forms of accuracy: overall and condition specific. In this article, we choose to consider condition-specific accuracies. The condition-specific accuracy of testing procedures is based on the percentage of circuits that were correctly diagnosed as having a particular condition. In other words, it is based on what percentage of segments diagnosed as “good” did not fail and what percentage of segments diagnosed as “bad” did fail. Consider the following example.

**Figure 7.** Typical recommendations for a particular cable system test scenario (techniques listed alphabetically).
Suppose that in a test of 100 circuits it is determined after a period of years in service that 80 of them are truly “good” (not going to fail) while the remaining 20 are actually “bad” (going to fail). Suppose that after testing the entire population, the results shown in Table 3 are obtained.

A number of utilities have provided diagnostic data and service performance records that have enabled the calculations outlined above to be conducted for a number of dielectric and discharge diagnostic techniques deployed in various areas of the United States. The outcomes are shown in Figure 8. The accuracies cluster in the “very useful” quadrant of the plot, where the median accuracy is 100% at identifying the portions of the cable system that do not require action. In these cases, the portions identified as being OK did not fail in service for a period of several years after the diagnoses were made. This quadrant is labeled “very useful” because the common experience is that even in regions with below-average reliability, there are many cable circuits that are truly in good condition (i.e., there are only a few bad apples). Thus, there is a low risk associated with not addressing a poorly performing segment of these populations.

The ability to accurately identify the segments that contribute to the poor reliability is not as good with half of the accuracies, which fall in the range of 0.1–10%. An accuracy of 10% may be interpreted as follows: for every ten segments identified as requiring action, only one actually failed in service within a reasonable period of time. The consequence of this level of accuracy is that a utility must act on every segment tagged as requiring action, as no further prioritization may be performed. When the segments for test are efficiently selected, this is not a significant problem since the number of circuits diagnosed as requiring action is generally low. It does mean that an indiscriminate deployment of diagnostics is very unlikely to be an efficient use of resources, however.

The authors recognize that the performance detailed in Figure 8 is a historic representation of the approaches (measurement techniques, interpretive methods, and reporting) used from 2001 to 2007. Unfortunately, it takes time to amass enough service experience to be able to determine the accuracies. This work shows that it is exceptionally important for potential improvements in the techniques to be effectively verified by utility performance studies: not every change is necessarily an improvement. Accuracies carry significant value, as they determine the ultimate effectiveness and hence the value of diagnostic programs.

### Value of Diagnostic Programs Within Asset Management Strategies

At first sight, it seems a very straightforward proposition to determine the benefits derived from diagnostic programs. It seems all that is needed is a simple financial calculation, with the cost of the diagnostic employed placed on one side and...
of a number of alternative programs on the other. In fact, the two most common alternative programs are:

- **Business as usual (i.e., address failures and replacement as needed)**
- **Wholesale replacement of a section of the system.**

Experience has shown, though, that determining the true cost of the diagnostic program can be accomplished but requires considerable effort in order to obtain the basic cost data for the disparate steps of the calculation. The total cost of a diagnostic program (see Figure 9) includes both short-term and long-term costs. These can conveniently be broken down into four primary cost elements:

- **Selection cost:** costs associated with the review of historic data, forensic analyses of prior failures, and the short-listing of the appropriate diagnostics
- **Diagnostic testing cost:** the cost of deploying the diagnostic in the field, including the cost of utility resources (typically in the form of line crew time)
- **Corrective action cost:** the costs of addressing all of those components that are diagnosed as requiring action (as noted above, the state of the art of diagnostic accuracy requires that all assets need to be addressed even as it is understood that a number of them will, in fact, not fail—see Figure 8)
- **Consequence cost:** the costs associated with the recognition that any diagnostic will misdiagnose some assets as “good” (and thus not in need of treatment) when in fact they will fail at some point in the diagnostic horizon (in general, these costs are considerably higher than individual treatments due to the fact that such failures occur in a different environment than the earlier ones: diagnostic and remediation costs have been incurred, and this portion of the system has been given a “clean bill of health”).

Utilities, to some degree, have estimates of the selection, diagnostic test, and corrective action costs. The consequence cost, however, is not well understood in quantitative terms while qualitatively it is recognized as being the largest component.

### Table 4. Details of selected diagnostic programs where benefits have been observed.

<table>
<thead>
<tr>
<th>Utility Alias</th>
<th>Diagnostic Approach</th>
<th>System</th>
<th>Time Span of the Assessment (Years)</th>
<th>Type of Benefit (See Benefits List Above)</th>
<th>Value of Diagnostic Program</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Combined diagnostic: Dielectric loss, then PD</td>
<td>XLPE</td>
<td>4</td>
<td>1 and 2</td>
<td>Statistically significant improvement in reliability at reduced cost (&lt;60% of historical budget)</td>
</tr>
<tr>
<td>B</td>
<td>Combined diagnostic: VLF withstand, dielectric loss, and PD</td>
<td>XLPE</td>
<td>1.5</td>
<td>1 and 5</td>
<td>Cost savings equal to 16 times the cost of diagnostic program</td>
</tr>
<tr>
<td>C1</td>
<td>Combined diagnostic: dielectric Loss and PD</td>
<td>XLPE</td>
<td>4</td>
<td>1, 2, and 5</td>
<td>Cost savings equal to ten times the cost of diagnostic program</td>
</tr>
<tr>
<td>C2</td>
<td>Monitored withstand: VLF withstand, dielectric loss</td>
<td>PILC</td>
<td>2</td>
<td>2 and 5</td>
<td>Annual failures reduced by 50%</td>
</tr>
<tr>
<td>D1</td>
<td>PD</td>
<td>PILC</td>
<td>8</td>
<td>1 and 4</td>
<td>Low level of future failures predicted by diagnostic and confirmed in service</td>
</tr>
<tr>
<td>D2</td>
<td>Combined diagnostic: VLF withstand, dielectric loss, and PD</td>
<td>XLPE</td>
<td>-</td>
<td>4</td>
<td>Confirmed that (prediagnostic) quick-response remediation actions were justified; provided definitive information for future work</td>
</tr>
<tr>
<td>E</td>
<td>VLF withstand</td>
<td>PILC</td>
<td>1</td>
<td>1 and 3</td>
<td>Improved efficiency of proactive program</td>
</tr>
<tr>
<td>F</td>
<td>VLF withstand</td>
<td>PILC</td>
<td>6</td>
<td>1, 2, and 3</td>
<td>Statistically significant reduction (50% to 90%) in the failure rates of remediated assets</td>
</tr>
<tr>
<td>G</td>
<td>PD</td>
<td>PILC</td>
<td>7</td>
<td>2</td>
<td>Significant cable replacements guided by diagnostic resulted in reduced number of failures in service</td>
</tr>
<tr>
<td>H</td>
<td>VLF withstand</td>
<td>PILC</td>
<td>8</td>
<td>1 and 2</td>
<td>Improved reliability with essentially no detrimental effect attributable to the diagnostic</td>
</tr>
</tbody>
</table>
Recently this problem has been successfully addressed in a number of sophisticated Monte Carlo simulations that use the disparate utility data as the inputs. The utility derives benefit from the diagnostic program when the sum of all four of these costs is less than the cost of the alternative program.

It is important to realize that diagnostic programs can produce benefit for a utility in five ways:

1) reduced spending on corrective actions
2) improved reliability through avoided failures
3) less costly diagnostic techniques (if comparing different diagnostic programs)
4) feedback on the correctness of decisions already completed
5) identification and quantification of previously unknown issues, thereby enabling active management.

Table 4 shows some basic details of selected utility diagnostic programs where sufficient information is available to conduct an independent assessment of the value of the diagnostic program. A striking finding is that there is a range of benefits (see list above) that can be ascribed to different programs. The table shows the programs where benefits are observed; however, it would be incorrect to assume that every program results in a benefit. A number of programs (not included in Table 4) have been evaluated where the costs outweigh the benefits. Inspection of these programs has identified some common reasons why they did not provide a benefit. These included:

- Too small a cable system was used for the test.
- The selected diagnostic was not appropriate for the failure modes.
- The selected test area did not have a sufficient density of issues for the diagnostic to be effective.
- Reporting of the analysis and results was unclear.

Summary and Conclusions

Effective management of the cable system is an industry imperative. Industry-leading utilities have approached this challenge by considering cable system assets from a full-lifecycle perspective, including rigorous specification and procurement practices, high-quality installation techniques, use of tight operating parameters, use of monitoring and diagnostics, implementation of optimal maintenance approaches, and detailed data collection and retention philosophies.

Accessory and cable selection and purchasing methodologies, including factory acceptance testing, updated manufacturing methods, and independent laboratory analysis, have driven improved service performance. These methods, including exclusion of water, better control of the electric stresses, updated manufacturing technologies, and improved test procedures, have resulted in more reliable cables and cable accessories.

An effective fleet asset management effort requires accurate cable asset data, as these are the data from which component failure rates are computed. Component failure rates are a critical input to any asset management decision process. Reliability performance is another metric useful in assessing the performance of cable system assets. Component failure rates and reliability performance data can be used to develop failure rate models, which can then be used to project system reliability into the future for various scenarios of cable system asset replacement levels. Strategies for managing large, aging cable asset bases include: reactive replacement (“run to failure”); targeted replacement of underperforming asset classes; replacement of underperforming components identified by diagnostics; installation of sectionalizing switches to improve outage response and increase system reconfiguration flexibility; and expansion of automation, including monitoring and control.

There are various cable diagnostic testing methodologies available to ascertain the condition of cable systems. There is no doubt that cable system diagnostic testing can be effective. Yet it must be approached with care. To be effective, the appropriate technology must be matched to the circuit to be tested. Setting accurate and reasonable expectations is a critical part of the cable testing process. It is important to realize that:

- Diagnostic tests do not always yield accurate results, nor are the tests intended to be able to predict exactly when a cable will fail.
- There can be risks as well as benefits. Depending on the technology employed, cables sometimes fail during the test or shortly thereafter.

It is also possible that any given “weak condition” detected by a test may or may not lead to an immediate cable failure. The above statements are not intended to give a negative connotation to diagnostic testing, but these issues need to be recognized and considered before a testing program is initiated. When applied properly, diagnostic testing will provide information that can be used to effectively lower cable system failure rates. Several existing diagnostic programs show unambiguous improvements in reliability. There is still much to learn, but cable diagnostic testing is a rapidly developing field, and increasingly useful technologies are available for assessing the condition of underground cable systems.

For Further Reading


Biographies

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