CHAPTER 4

How to Start

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This chapter represents the state of the art at the time of release.
Readers are encouraged to consult the link below for the version of this chapter with the most recent release date:

http://www.neetrac.gatech.edu/cdfi-publications.html

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4.0 HOW TO START

The section of a diagnostic technology should be made near the start of the process, but not right at the start, of the diagnostic testing process. At first sight, the choice may appear to be simple and might be based on prior experience or recommendations from colleagues/fellow utilities or sales/marketing materials. However, the decision is actually quite complex and requires a review of many influencing factors. This chapter provides guidance on how to optimize the selection process.

Section 4.1 provides a historical perspective of diagnostics and serves to provide information such that prior experience and recommendations of colleagues/fellow utilities can be used in the right context.

Section 4.2 charts several paths such that a user may best benefit from the accumulated experience of utility practitioners. It addresses the selection of the optimal test location and gives a five step process for arriving at a short list of diagnostics to consider. The prime benefit of such a process is that the decision making is transparent and each part of the decision making process is preserved for future review.

4.1 Evolution of Cable System Diagnostics

Research into the evolution started with a survey to establish the use of cable system diagnostics in North America was conducted in 2006 as part of *CDFI Phase I* and this provided one of the first industry wide estimates of diagnostic test deployment on electric utility systems. NEETRAC repeated the survey in 2014 using interviews with knowledgeable personnel. The work is now complete and results are reported for 103 utility entities in Canada and the US. Typically, the utilities contacted had more than 200,000 customers and information could be gathered for more than 70% of these utilities. Consequently, the sampling is believed to be representative of the utilities in the US and Canada.

The information was captured at the utility operating company level so that regional variations and preferences could be captured. Furthermore, there can be much discussion over what constitutes “utility use”. In this work, to be considered a diagnostic used by a utility, the technique has to be part of a normal/established activity for determining cable system asset health on new and aged systems. Thus, pilot studies and laboratory experiments are not included. Some information is available for Mexico; however the usage could not be established to the same level as for entities in Canada and the US, thus data for Mexico are not included at this time.

Each utility entity is considered on its own and given equal weighting, which addresses the fact that individual operating companies within a utility corporation (e.g. AEP, Exelon, FirstEnergy, PPL etc.) often have different approaches. This is very much in line with the manner in which diagnostic test usage was reported in the initial study of 2006. It is important to note in this approach that each respondent is considered equally (same weighting regardless of entity size). Viewed in this manner, over 73% of utilities surveyed report they do not employ cable system diagnostics. The most widely deployed technique reported to date is Simple VLF Withstand.

The operating entity approach detailed above gives equal weighting to all entities independent of the size of the operating company. Another perspective may be gained if it were possible to consider the utility size. In principle, the optimal way to incorporate this would be to use the size of the underground MV system. However, this is known and knowable for only a very small fraction (5% – 10% of the sample) of the respondents. The main issue with the reduced number of respondents would be "confirmation bias" (i.e. the folks using diagnostics would be systematically more likely to provide the length information and thus bias the survey). Thus, it was determined that the information would be more useful if the large number of respondents was retained and some other means of size adjustment established. One approach is to use the number of customers served by a utility as an alias for the size of the underground system. It is recognized that this weighting is not entirely correct but it is reasonably pragmatic. Using this approach, each utility response was weighted by the reported number of customers that the utility serves. This perspective estimates that the use of diagnostics increases from 26.5% to 43.9% when adjusted for size.

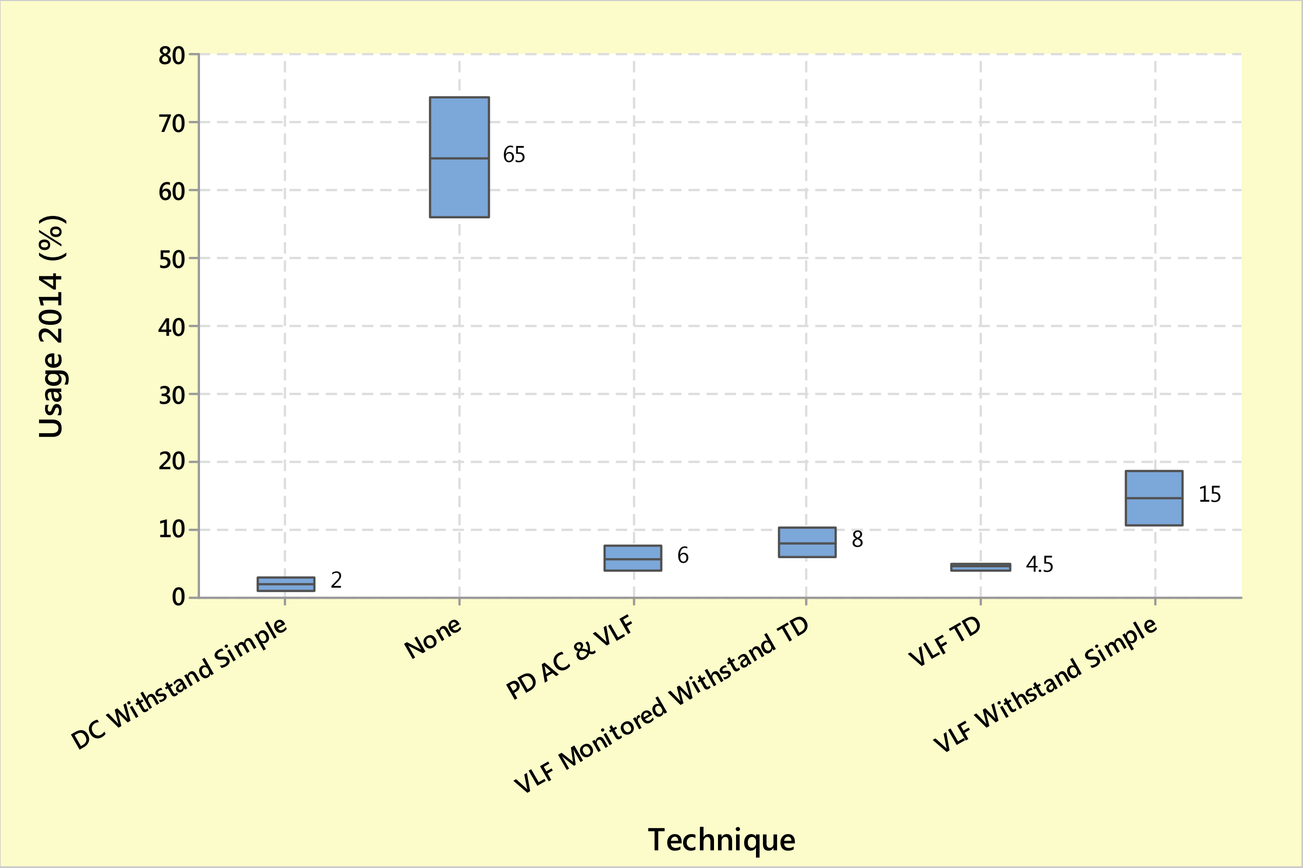

Figure 1: Range of Usage for the different diagnostic techniques - 2014

As mentioned, neither the entity approach or customer approach described above are likely to provide the "correct" usage; however, they most likely define the upper and lower ranges of the usage. Thus, it is possible to refine the estimated diagnostic usage with a process somewhat analogous to Bayesian Analysis which combines available estimates and engineering knowledge to provide a more accurate/complete estimate. Figure 1 shows the improved estimates by providing likely ranges for each diagnostic technique (drawn from the two different approaches) as well as the "no use" category. At this time, it is recommended that the midpoint of these ranges be used if a single value is needed. The analysis completed thus far suggests that, for example, the VLF Simple Withstand usage lies somewhere between 10.8% and 18.7%, with 15% being a reasonable number to use if a range is not appropriate.

Multiple voltage sources are available for use by those utilities that currently deploy diagnostics on their systems. These include using resonant ac (10 – 300 Hz), Very Low Frequency (VLF), damped ac (DAC), and dc. These sources may be used in one of two modes: diagnostic (Tan δ, PD, etc.) or withstand (Simple and Monitored). This analysis takes the same quasi-Bayesian approach described above to estimate the usage ranges. It is not possible to establish the most common testing mode as Withstand (HiPot) and Diagnostic modes overlap.

The preceding information described the survey that was completed in 2014. Additionally, the basic information from the entity only analysis completed in 2006 can be applied to develop an estimate for 2006. This has been done using the same approaches outlined above to provide a side by side usage evolution of diagnostic techniques (see Figure 2 through Figure 5). In the figures below the following terms are used: TD = Tan Delta, PD = Partial Discharge, VLF = Very Low Frequency AC waveforms, AC = AC waveforms with frequencies in the range 10 to 300 Hz (usually derived from resonant systems), Withstand = Hipot, DAC = Damped AC or Oscillating Wave.

At first sight this analysis may appear to be only from a historical interest. However, the changes reflect changes in equipment, improvements in application knowledge and standards activities that have been ongoing during the intervening eight years.

2006

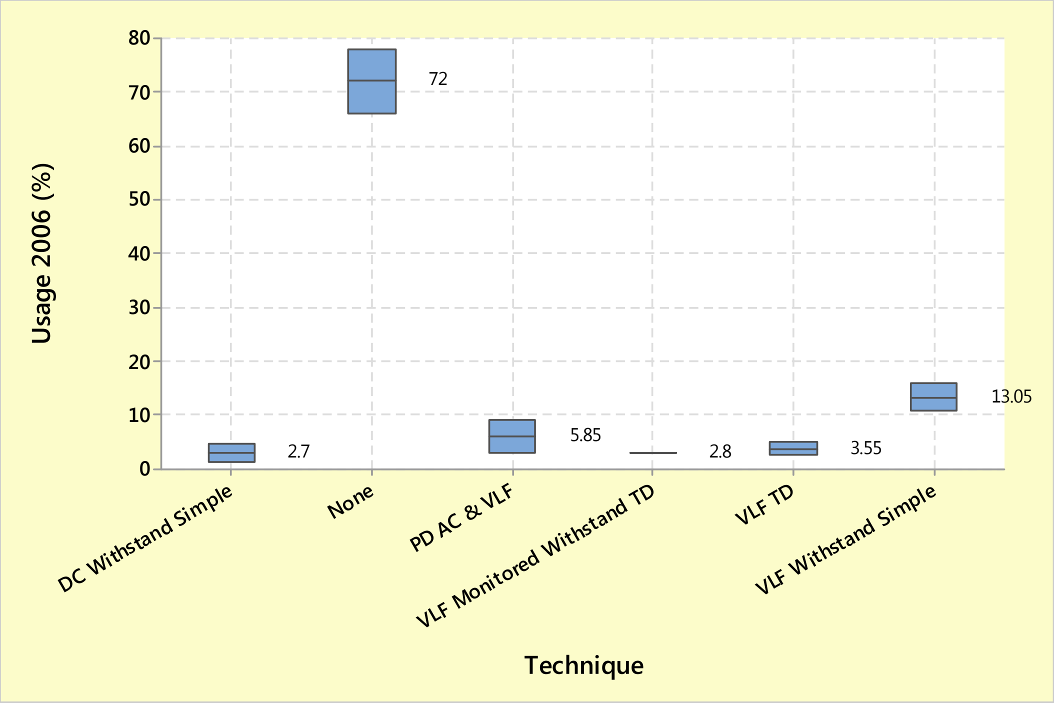

Figure 2: Range of Usage for the different diagnostic techniques – 2006

2014

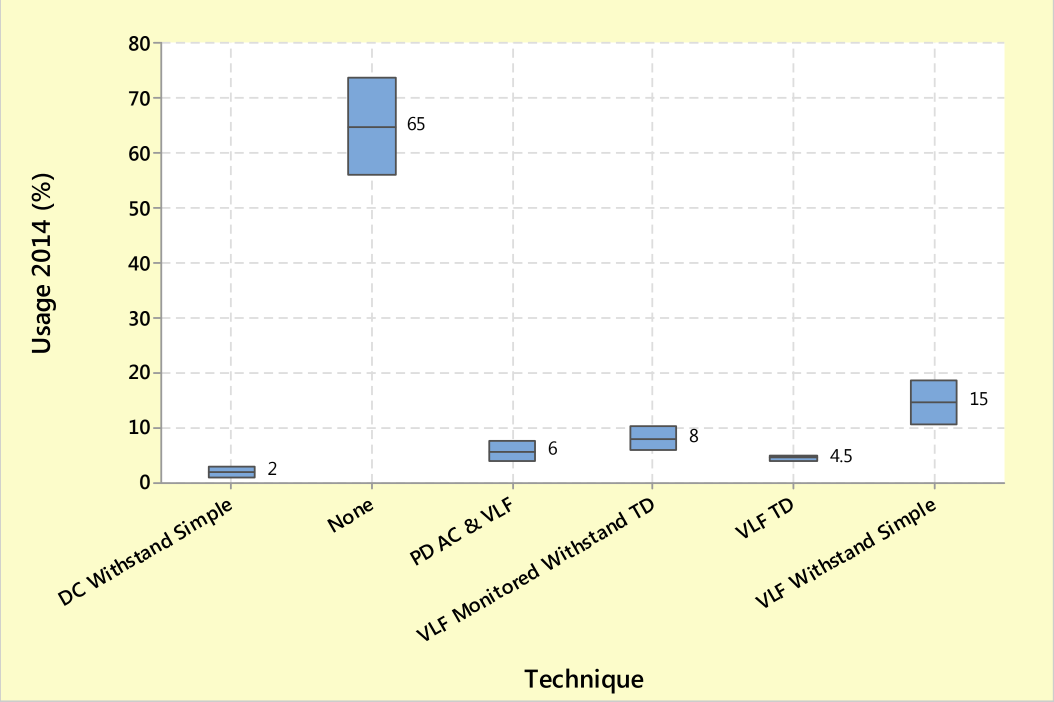

Figure 3: Range of Usage for the different diagnostic techniques – 2014

2006

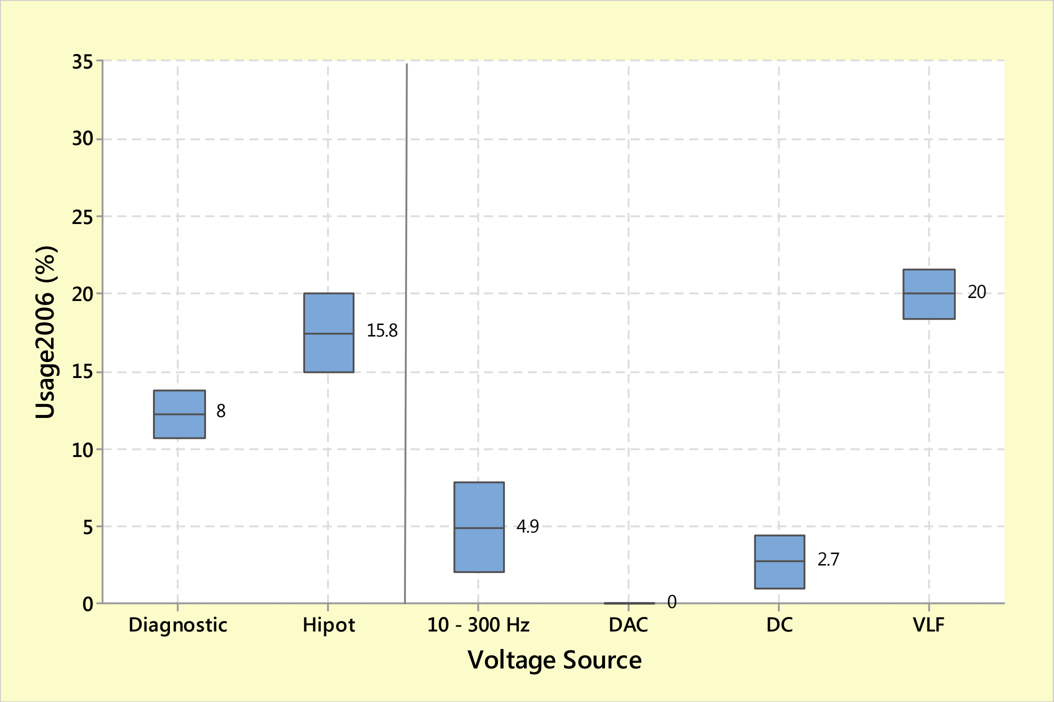

Figure 4: Usage for diagnostic approaches (left) & voltage sources (right) – 2006

2014

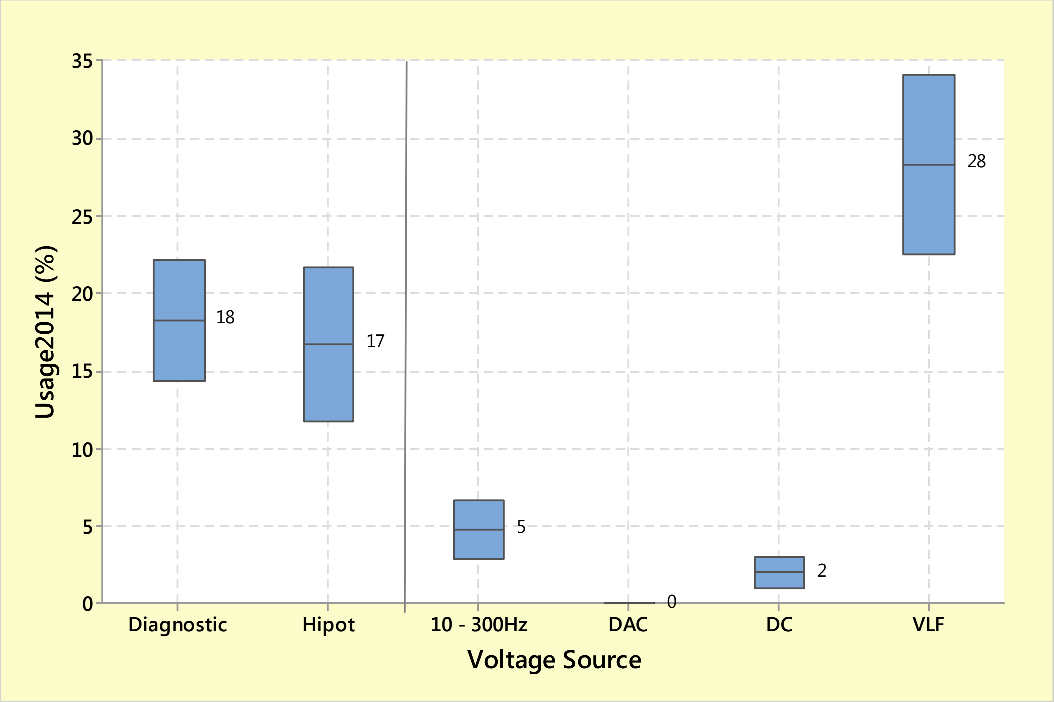

Figure 5: Usage for diagnostic approaches (left) & voltage sources (right) – 2014

Inspection of the cable diagnostic testing technology usage above at MV enables the techniques to be grouped into two broad categories: Mainstream & Niche.

a) Mainstream techniques
   i. Time- Domain Reflectometry (TDR);
   ii. Tan δ at Very Low Frequencies (VLF);
   iii. Simple Withstand Tests at Elevated Very Low Frequencies (VLF);
   iv. Simple Withstand Tests at Elevated Resonant ac – HV & EHV only;
   v. Monitored Withstand Tests at Elevated Very Low Frequencies (VLF) with simultaneous monitoring of Tan δ;
   vi. Monitored Withstand Tests at Elevated Resonant ac with simultaneous monitoring of PD – HV & EHV only;
   vii. Partial Discharge (PD) at elevated Resonant ac or Very Low Frequencies (VLF) Voltages.

b) Niche techniques (not routinely deployed but where equipment maybe/has been commercially available);
   i. Partial Discharge (PD) at elevated Damped ac (DAC) Voltages;
   ii. Combined Diagnostic Tests at Very Low Frequencies (VLF) using sequential PD and Tan δ;
   iii. Dielectric Spectroscopy;
   iv. DC Leakage Current;
   v. Polarization and Depolarization Current;
   vi. Recovery Voltage.

At the diagnostic technique level, evolutionary key takeaways are:

Time-Domain Reflectometry (TDR)

- Usage is difficult to determine.
- The level of usage is estimated to be in the range of 6% -10% in 2014, which is up from the 5% - 8% level of 2006.

VLF Tan δ

- Since 2006 the greatest evolution is in the areas of VLF sources and Tan δ measurement / interpretation. In 2006 the devices were large, complicated to set up and difficult to transport - a trailer or van was required. In 2014 these devices are now portable (one man can move them) with complete integration of the VLF source and Tan δ measurement device in one box.
- The level of usage has increased from 3.5% to 4.5%. However, this likely underestimates that activity as there are a number of users who, between 2006 & 2014, adopted Tan δ and then migrated to Monitored Withstand.
- The guidance provided in the updated IEEE Std. 400.2 has very likely supported the change.

Simple Withstand

- The use of Simple dc Withstand has continued to decline with the conversion to Simple VLF Withstand. The rate of conversion would likely have been higher but it has been limited by the availability of funding for new VLF test units.
- The growth of Simple VLF Withstand has continued (13.5% - 15%) both from adoption and transfer from dc.

Monitored Withstand

- The biggest growth over this period was in the area of the Monitored Withstand: 2.8% in 2006 to 8% in 2014.
- The drivers of the growth have been two-fold:
    - Miniaturization / simplification / availability of the equipment
    - Guidance & familiarity stimulated by IEEE Std. 400 & IEEE Std. 400.2

Damped AC (DAC) Partial Discharge

- This technique shows great promise for PD detection in the field by utilities; however, there are currently no users of this technique in the USA or Canada.

Partial Discharge

- The use of PD in the offline mode has been essentially static over the time period in the utility space

VLF Simple Withstand

- The estimates for 2014 show that VLF is the most preferred of the test voltages
- The increase in usage since 2006 (20% - 28%) is notable and statistically significant

Withstand (Hipot) vs Diagnostic

- In 2006 Withstand (Hipot) was the most preferred mode of operation
- In 2014 the use of withstand (Hipot) increased by 1.2%, while diagnostic tests have increased by 10%
- In 2014 both withstand (Hipot) and diagnostic tests usage are equal

In all the above comments it is important to recall that in this work, for a technique to be considered a utility diagnostic used by a utility, the technique has to be part of a normal / established activity for determining cable system asset health on new and aged cable systems. Thus pilot studies, industrial applications, commercial energy generation (wind farms etc.) and laboratory experiments are not included. Usage estimates that include these applications might be at variance with those provided here.

4.2 Choosing the Most Appropriate Diagnostic Program for an MV Cable System

As noted in other chapters "there is no one *right* approach" to cable system diagnostic testing. Each situation/cable circuit/area/region/utility is likely to have conditions and priorities that will dictate an approach that is unique for that segment. This section offers a general perspective on how the information included in other chapters of this report can be used to select the most appropriate diagnostic for the circuit or set of circuits under consideration.

The preceding section has shown how the usage of diagnostics has changed over the relatively short span of this project. Thus it is unwise to use the simple expedient approach of using previous experience / recommendations to guide the choice as the whole arena has changed so dramatically.

At first sight, the diagnostic selection process would appear to be solely based on technical principles. However, experience gained from 10 years of conducting the CDFI research (from surveys of practitioners, internal discussions and working with more than 25 CDFI participants) shows that diagnostic testing decisions are very often based on a variety of perspectives, including asset management, reliability engineering, dielectric science as well as a very good dose of social science.

The social science perspective can cause the most difficulty for engineers. However, it is a vital part of the diagnostic selection process because it requires engineers to consider topics that are qualitative in nature, such as,

- risk tolerance;
- interfaces with field personnel (including the operators and test crews before, during and after test);
- likely outcomes from the test;
- skill level required to perform the test;
- decision making process during the test; and
- decision making process after the test is performed.

The comments and guidance included in this chapter encompass all of these elements and thus may be considered as a tabulated (rather than software based) expert system.

Thus this chapter is primarily directed towards:

- Personnel who are not familiar with diagnostic testing
- Experienced personnel who are looking to test in new geographic areas and / or test cable systems they have not previously tested

The approaches discussed are offered as only as suggestions and are based on what has worked for others unfamiliar with the topic. It is important to recognize that any approach should start from the needs of the program (essentially the social science) rather than first choosing a diagnostic technology and then trying to find a good location to use it.

4.2.1 Getting Started

To begin, it is important to remember the following:

1) Treat the cable circuits as a system – not simply a cable or a cable accessory. It is not possible to perform a diagnostic test on just a segment of cable or just an accessory. All cable circuits consist of both elements so the circuit it must be treated as a system.
2) Gather as much information as possible about the cable system including its age, accessory types, cable design, insulation type and the failure history
3) Establish why diagnostic tests should be performed on your cable system.
4) Establish the potential diagnostic technologies are available for performing the evaluation and what it takes to deploy each technology (skills required, switching by field crews, etc.).
5) Establish your options for corrective actions (run to failure, repair, rejuvenate, replace).

So ‘why perform diagnostic tests on a cable system’? Interestingly, the reasons are quite varied. Outlining the reason(s) does not directly dictate the specific diagnostic test approach to take. However, a clear understanding of why you are performing diagnostic tests on your cable system will help guide the decisions that need to be made once diagnostic data is obtained.

There are a number of drivers/motives for performing diagnostic tests on cable systems, including a need to:

1. Help assure that a new system was properly installed
2. Help assure that an existing system was effectively repaired
3. Improve cable system reliability (reduce failures)
4. Prevent failures before they occur
5. Optimize the use of maintenance dollars
6. Optimize the use of capitol (cable replacement) dollars
7. Follow a management directive to use a specific diagnostic technology

4.2.2 The Process - SAGE

The NEETRAC research has led to the development of the acronym SAGE to describe the four basic phases of an effective diagnostic program. SAGE was first developed in *CDFI Phase I* and has been refined in *Phase II*.

These elements are described as follows:

Selection: This phase encompasses two actions:
a) choose the cable circuits to be tested; and
b) determine the constraints for the testing

Taken together, these actions lead to the selection of the most appropriate diagnostic technology to use for the evaluation.

Action: This phase involves answering the question: What actions are likely to be taken as the result of the diagnostic outcomes (results) or interpretations? The actions are in two groups (Act or Not Act) and may include replacement, defer action, rejuvenation, and/or repair. These actions are chosen based on what is most suitable for the cable system topology and most prevalent failure mechanisms (local or global degradation).

Generation: This phase has been expanded to include two sequential parts:
a) Generating the test data
b) Using the measured data (singly or in combinations) to determine a final result which may involve placing the cable system segments or circuits into an act or not act class or to establish a health index.

Ultimately these two parts help to establish the preferred remediation (Action).

Evaluation: This phase provides answers to the questions: Are the methods employed for Selection, Action, and Generation giving the expected results - lower rates of failure and increased times between failures? Can the diagnostic elements be improved?

Figure 6 illustrates how the four components function together over time to produce, if implemented properly, a reduction in the failure rate. Note that this benefit is not realized immediately nor does it cease once the program has ended - there is a lag before the benefit is fully realized. Furthermore, failure rates do not begin to change until the actions directed by the diagnostic testing (Generation) are well underway. Selection, Generation, and Action are each defined stages in time while the Evaluation component is ongoing throughout the entire test program and beyond.

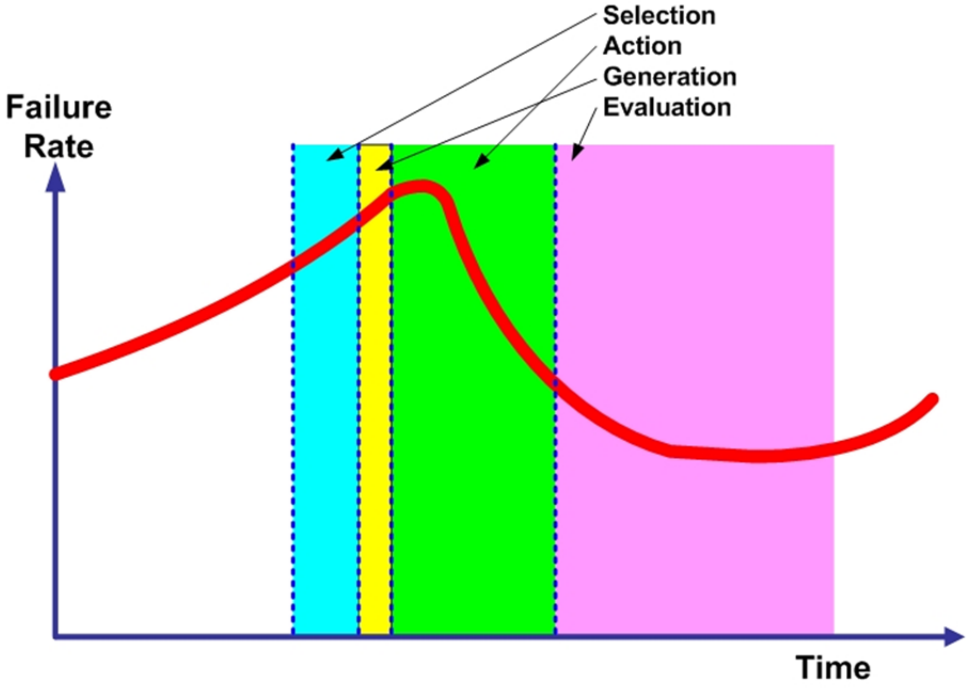

Figure 6: Effect of SAGE on the Failure Rate of a Target Population

Note: the failure rate in Figure 6 continues to increase during the Selection and Generation phases. Only after the actions are completed does the failure rate start to decrease. After some time, the failure rate will begin to increase again and this would retrigger the SAGE process. Each phase of the SAGE process is discussed in more detail in the following sections of this chapter.

4.2.2.1 Selection

The selection phase represents the first stage of the SAGE process. This process should be performed *before* a diagnostic technology is chosen. Elements of the selection process that help the user decide which circuits to test are outlined as follows:

Choosing the cable circuits to be tested
The utility should use all available data / knowledge to identify those circuits that may be susceptible to failure within a chosen time horizon, generally 5-10 years. These circuits may be in

areas that have historically experienced higher than usual failure rates or may simply be of critical importance to system operation or a combination of both. Regardless of the criteria used, the size and composition of this population greatly affects potential reliability improvements and economic savings resulting from the program.

These circuits constitute the "target population" that will be tested and acted on using one or more diagnostic tests. Important considerations for the Selection process are:

System Construction

- How are the circuits used in the system?
- Is the system a radial, looped or network system?
- What level of redundancy is present?
- Can circuits be easily isolated without impacting customers?
- What is the cable design?
    - ➢ voltage class
    - ➢ insulation thickness
    - ➢ insulation material (Polyethylene, EPR, fluid impregnated paper)
    - ➢ metallic shield type (tape, LCT, wires)
    - ➢ jacket (yes or no)

Available Historical Data

- Number of circuits of the same type in service
    - ➢ their ages
    - ➢ their failure histories
- If data are not available then simple heuristics may suffice – see Table 1.

Failure Projections

- How fast are failure rates increasing?
- If there are cable or accessory designs in use, in which are the failure rates increasing fastest?

Prevalent Failure Mechanism

- What causes the most failures?
- What is the failure the mechanism?
    - ➢ electrical (electrical or water trees)
    - ➢ mechanical (damage)
    - ➢ environmental (neutral corrosion)
    - ➢ inherent (manufacturing imperfections)
    - ➢ thermal in nature (overheating connectors)?

Objective

- Is the objective to:
    - ➢ improve reliability?
    - ➢ reduce maintenance costs?
    - ➢ garner knowledge of system health before determining action to take?
    - ➢ a combination of all three?

- Has a budget been allocated to achieve the objective?

The above information is invaluable in determining which circuits to test. However, the relative importance of a circuit(s) is also essential since they will often supply important customers where an outage would result in notable economic or newsworthy consequence for the utility.

Determine the testing constraints
It is very important to establish in advance what you can and cannot do or accept during a diagnostic test program. A list of things to consider is outlined below.

Acceptability of Failure During Testing
- How much risk of failure can be tolerated?
- Is a failure tolerable during testing if circuits are subjected to elevated test voltages?

This is important because in many cases once a cable segment fails, testing in that area is curtailed until a repair can be affected. This will noticeably impact the throughput/efficiency of the test program.

Tolerance of Uncertainty
- How accommodating is the organization of uncertainty? Does your organization insist that answers be black or white or is it accepting of shades of grey?

Performing Tests and Interpreting Results
- Will testing be performed by internal resources or subcontractor resources?
- Who will interpret the test results?
- Is the test interpretation processed internally or externally or by a subcontractor?
- Is the subcontractor part of the remediation process and therefore subject to bias when making the interpretation?

Acceptance of Complexity and Transparency
- Is it institutionally acceptable to have a complex process for interpreting the results or is a simple answer required?
- Does your company accept an answer without knowing how the data is processed (opaque process), or does your company want to know, or be able to know at some future date, exactly how the test results are used to make recommendations (transparency)

Note that as the information content of a diagnostic technique increases, so does the complexity.

Nimbleness of Decision Making - as the information content of a diagnostic technique increases so does the need for real time decision making Is it institutionally appropriate for decisions to be devolved to test crews or a subcontractor; both of these are often stakeholders in the remediation process

Cost of the Diagnostic
- Does the estimated cost (cost per circuit = cost per day / throughput) of the diagnostic represent a large portion of the replacement cost of the component?

Resolution of the Diagnostic

- Does the diagnostic provide enough information to classify the components into the desired number of subpopulations?

The two part process above (choosing the circuits and establishing the constraints) results in very good context information but is difficult to make actionable. The following example (Table 1) illustrates how a company could collate this information as a means of classifying the circuits they may want to test. The example area contains 14 circuits, which are classified by a two dimensional selection matrix which balances failure rate against the impact of service failures.

Table 1: Example Selection Matrix - Qualitative – Residential Customers

FAILURE RATE	More than Twice Average Failure Rate	2 circuits		
	Between Average and Twice Average Failure Rate		2 circuits	2 circuits
	Less than Average Failure Rate	3 circuits	2 circuits	3 circuits
		Failure in Service has a Low Impact	Failure in Service has a Medium Impact	Failure in Service has a High Impact
		IMPACT OF FAILURE		

Numeric information (number of circuits) is preferred to describe the cells. However, this information may not be available. When that occurs, the cost of an outage could potentially be used as an alias for the impact of service failures. The example in Table 2 is similar to Table 1, but the data used is based upon the economic cost of a failure ($ pa) using the established DOE model discussed in Chapter 14. In this table, the cost of an outage (failure) for the circuit(s) represented in the cell is shown in bold. It is a function of the number of customers on the circuit(s) along with the impact cost of an outage per 1000 customers. The cost of a failure per 1000 customer is a function of the SAIFI and SAIDI rates for the circuits in question.

Table 2: Example Selection Matrix – Semi Quantitative – Residential Customers

FAILURE RATE	140% Average SAIFI (High SAIFI)	**$600** 100 customers $6k/1000 customers	**$0** 0 $8k/1000 customers	**$0** 0 $10k/1000 customers
	Average SAIFI	**$0** 0 $4k/1000 customers	**$1200** 200 customers $6k/1000 customers	**$1800** 200 customers $9k/1000 customers
	60% Average SAIFI (Low SAIFI)	**$900** 300 customers $3k/1000 customers	**$1000** 200 customers $5k/1000 customers	**$2100** 300 customers $7k/1000 customers
		50% Average SAIDI	Average SAIDI	160% Average SAIDI
		IMPACT OF A FAILURE		

Ultimately, some decision making overlay is required. Work in the CDFI has shown that that a new user of diagnostics should approach testing somewhat differently than an experienced user.

The differences are shown in Table 3 and Table 4. One of the most significant errors that new users make is that they immediately attempt to test in the upper right hand area, where their experience level is not sufficient to deal with the multitude of issues associated with an area that has a large number of problems. A much more effective strategy is to start testing in either of the green areas and then move to the green areas of Table 4 as experience increases.

<table>
<tr><th colspan="5">Table 3: Interpretation of the Selection for a <u><i>New</i></u> User of Diagnostics</th></tr>
<tr><td rowspan="3">FAILURE RATE</td><td>More than Twice Average Failure Rate</td><td rowspan="2">Useful for gaining experience, but benefits are likely low</td><td></td><td>Not optimal for a new user - too many issues to handle/consider</td></tr>
<tr><td>Between Average and Twice Average Failure Rate</td><td colspan="2">Useful for learning, with increasing benefits but also increasing risks</td></tr>
<tr><td>Less than Average Failure Rate</td><td colspan="3">Not optimal – likely low benefit</td></tr>
<tr><td colspan="2" rowspan="2"></td><td>Failure in Service has a Low Impact</td><td>Failure in Service has a Medium Impact</td><td>Failure in Service has a High Impact</td></tr>
<tr><td colspan="3">IMPACT OF FAILURE</td></tr>
</table>

<table>
<tr><th colspan="5">Table 4: Interpretation of the Selection for an <u><i>Experienced</i></u> User of Diagnostics</th></tr>
<tr><td rowspan="3">FAILURE RATE</td><td>More than Twice Average Failure Rate</td><td rowspan="2">Not Optimal – likely low benefit</td><td></td><td>Optimal – maximum benefits (with maximum risks)</td></tr>
<tr><td>Between Average and Twice Average Failure Rate</td><td colspan="2">Optimal - increasing benefits / risks</td></tr>
<tr><td>Less than Average Failure Rate</td><td colspan="3">Not Optimal – likely low benefit</td></tr>
<tr><td colspan="2" rowspan="2"></td><td>Failure in Service has a Low Impact</td><td>Failure in Service has a Medium Impact</td><td>Failure in Service has a High Impact</td></tr>
<tr><td colspan="3">IMPACT OF FAILURE</td></tr>
</table>

4.2.2.2 Action

The Action stage of the SAGE process refers to the establishment of possible repair and replacement actions based on the results from the diagnostic test. Ideally, a specific action can be established for each circuit tested based on the condition indicated from the diagnostic test. The goal is to perform the minimum level of actions that will restore the circuit to reliable operation for the next several years.

Each action has an associated cost and level of reliability improvement that it will deliver. For example, the cost of replacing a bad splice in a 500 ft segment is very different from the cost of replacing the entire segment. On the other hand, the reliability of the repaired segment is not likely to be as high as the reliability of the replaced segment. An economic analysis can be used to quantify the value for one action compared to another.

When considering cable systems, the list of available actions is relatively short and includes:

a) Wholesale Replacement – complete replacement of the entire target population;
b) Targeted Replacement – replace only the segments that the diagnostic test indicates are degraded;
c) Repair – remove short length(s) of cable and replace with two joints and a piece of cable or replace problematic accessories;
d) Rejuvenation – liquid injection (PE-based insulations); and
e) Do Nothing.

The choice of actions will affect the choice of diagnostic technique(s) since some diagnostics are unable to locate specific points of degradation within a given segment. Furthermore, the composition of the target population might limit the actions a utility is able to take.

Once a suitable approach for each diagnosis exists, tests may be performed on the target population to generate the diagnostic data. This constitutes the next phase of the process – the Generation phase.

4.2.2.3 Generation

The generation stage of the SAGE process starts with the choice of a suitable diagnostic followed by testing on the target population of circuits. By definition, the diagnostic techniques measure specific characteristics of the circuit thought to be symptomatic of known failure mechanisms.

Generation has two sequential parts:
a) generating the test data; and
b) using the measured data (singly or in combinations) to determine a final result (Action Class or a Health Index).

The different diagnostic technologies available for generating test data are discussed in Section 4.3. However, at this point it is useful to consider some examples.

The first example is for cable diagnostic tests made using Tan δ (dielectric loss measurements). The actual measured values are:

- sequences (usually 6) of Tan δ data at 0.5Uo;
- sequences (usually 6) of Tan δ data at 1.0 Uo; and
- sequences (usually 6) of Tan δ data at 1.5Uo.

These measurements permit, derived parameters to be calculated:

- Tip Up;
- Tip Up of the Tip Up (Tu Tu);
- Standard deviation of Tan δ at 1.0Uo; and
- Mean Tan δ at 1.0 Uo.

The derived parameters enable, one of two determinations can be made:

a) The tested cable segment can be placed in one of the three classifications:
    i. action required (AR);
    ii. further study (FS); or
    iii. no action required (NA).

OR

b) A Health Index can be calculated used to indicate where the tested cable segment lies along the spectrum of cable segments tested to date i.e. *this segment is the* x^{th} *percentile of all similar cable systems tested to date.*

The second example is for cable diagnostic tests made using Damped ac (DAC) partial discharge measurements. In this case the actual measurements indicate one of the following and are qualitatively/subjectively used to determine whether or not the tested cable segment falls into the action required, further study or no action required category:

- discharge present above the background noise below $1U_0$ at location X;
- discharge present above the noise in range of U_0 to $1.4U_0$ at location X; or
- discharge present above the noise above $1.4U_0$ at location X.

Although numerical values may be ascribed to this type of measurement, there is no adequate or definitive method of interpreting the different numbers such that the tested cable circuit may be placed into a specific condition category. This means that partial discharge measurements made on similar cable circuits cannot be compared and partial discharge measurements made using different technologies cannot be compared.

4.2.2.4 Evaluation

The final stage of the SAGE process is the evaluation stage. This is the stage where utility engineers ask themselves: Are we getting what we expected? This question covers many issues, but can be summarized in two key topics: (1) Cost and (2) Reliability. A diagnostic program must deliver improved reliability at a lower cost as compared to other maintenance strategies to be considered effective. Evaluation tools, such as those presented in Appendix A can be used to assess the impact the program has made on system reliability. Furthermore, the utility can then adjust in real time to improve program performance. The evaluation phase represents an ongoing process that remains in place until the need again arises to conduct another diagnostic program.

Commissioning diagnostics are used shortly after a system is installed or after a repair. When diagnostics are used for this purpose, the health (classification) of the system is not of primary interest. The engineer simply wants to know if there are any significant defects caused by installation workmanship. Generally, most new components are factory-tested (recognize that the standards and implementations may be quite different from component type to component type) so there is an expectation that there are no built-in defects. Thus the goal of performing the diagnostic test is to help ensure that the system is free from gross defects. Importantly, the test technology and test conditions selected for commissioning tests are generally not designed for aged systems and should not be applied to aged systems. However, when new components or cable segments are installed on an aged system, modifications to the test program may be required.

Condition assessment diagnostics are applied to aged cable systems. This is much more of a process approach rather than spot check assessment using a pass/fail criterion. Consequently, it is important to focus on classification and avoid doing harm (further weakening) to the system.

4.2.3 Information on the Diagnostic Techniques

Utility engineers have voiced a desire for guidance on the experience levels necessary for conducting diagnostic tests and interpreting test results (the Generation phase of SAGE). Table 5 provides basic information garnered from the research activities on available diagnostic techniques, their expected output and who is involved.

Table 5: Typical Diagnostic Technique Deployment

Technique		Testing performed by	Interpretation of Raw Data	Form of Output to end user	Condition Assessment performed by
Time Domain Reflectometry (TDR)		Utility or Provider Technician	Utility or Provider Technician or Engineer	TDR Trace	Utility or Provider by comparison with library of curves
Offline Partial Discharge Resonant ac		Provider Engineer	Provider Engineer	Report with classification data [1]	Provider using Proprietary Criteria [4]
Offline Partial Discharge VLF		Provider or Utility Technician or Engineer	Utility or Provider Engineer	Data or Report with numeric data [2]	Provider or Utility using Knowledge Rules [5]
Offline Partial Discharge DAC		Utility or Provider Technician			Utility or Provider using Knowledge Rules [5]
Online Partial Discharge		Provider Technician or Engineer	Provider Engineer	Report with classification data [1]	Provider using Proprietary Criteria [4]
Tan δ (VLF)		Utility Technician	Utility Technician or Engineer	Numeric data [2]	Utility using Knowledge Rules from IEEE Std. 400.2™ or CDFI Tools
Withstand	AC Resonant	Utility Technician	Utility Technician or Engineer	Survival data [3] (Pass / Fail)	
	VLF				
Monitored Withstand	PD	Provider or Utility	Provider or Utility Engineer	Survival data [3] (Pass / Fail) & numeric data [2]	Utility using Knowledge Rules from CDFI Tools
	Tan δ	Utility Technician	Utility Technician or Engineer		

[1] Classification Data – results are described in terms of the membership of a number of classes ranging from good to poor performance (A, B, C; Repair, Replace, etc.); no information is conveyed about the relative position within a class (it is not possible to prioritize within a class); class membership can be determined by either Proprietary Criteria or Knowledge Rules.

[2] Numeric Data – results are described in terms of a continuous variable (inception voltage, loss, count etc).

[3] Survival Data – two classes: Pass / Not Pass; no information is conveyed about the margin within a class.

[4] Proprietary Criteria – the membership in a class (see footnote 1 above) is determined by multiple criteria for the measured and system data which are <u>not open to scrutiny</u>; the receiver of the classification data (see footnote 1 above) is unable to reassess the class membership as they do not (generally) have access to the measured data or the criteria; the receiver of the data has no means to verify whether the criteria have changed (improved of degraded).

[5] Knowledge Rules – the membership in a class (see footnote 1 above) is determined by multiple criteria for the measured and system data which are <u>open to scrutiny</u>; the receiver of the classification data (see footnote 1 above) is able to reassess the class membership as they have

access to the measured data and the criteria; the receiver of the data has a means to verify that the criteria have remained unchanged over time.

As discussed earlier, the assessment provided by diagnostic testing technologies generally falls into two location categories: global and local. Table 6 describes which diagnostic tests are most commonly used for global and local assessments.

Table 6: Local vs. Global Assessments for Diagnostic Techniques

Technique		Identifies Local Defects	Identifies Global Degradation
Time Domain Reflectometry (TDR)		X	
Offline Partial Discharge (AC Resonant)		X	
Offline Partial Discharge (VLF)		X	
Offline Partial Discharge (DAC)		X	
Online Partial Discharge		X	*
Tan δ (VLF)			X
Withstand	AC Resonant	X**	
	VLF	X**	
	DC (PILC Only)	X**	
Monitored Withstand	AC Resonant PD	X	
	VLF PD	X	
	Tan δ	X**	X

* While traditional PD measurements focus on local defects, online providers sometimes provide an assessment that is related to global condition assessment.

** The location is determined by TDR when dielectric puncture occurs

4.2.4 Choosing the most appropriate diagnostics - Selection

4.2.4.1 Basic Approach

In principle, the issues outlined in Section 4.2.1, Table 1 through Table 6 with the detailed information in the diagnostic specific chapters provide sufficient information to select the most appropriate diagnostic. However, those with little or no diagnostic testing experience may find the information provided below to be a more convenient way to start the selection process.

The approach uses five questions help to identify options to consider:

1. Who do you anticipate will perform the tests?
2. How would you best describe your tolerance to dielectric failures on test (FOT)?
3. How would you best describe the <u>majority</u> of cable circuits in the portion of the system under consideration?
4. How would you describe the age of the cable system?

5. Do you know what is failing?

Questions 1 and 2 are used in Table 7 to select the appropriate table with which to consider the outputs from Questions 3 to 5.

The diagnostic suggestions take into account both the reliability engineering (electrical engineering and dielectric science) and social science elements of the decision making process. Some of the main rule of thumb/experience/heuristic based approaches are provided below:

Time-Domain Reflectometry (TDR)

- This test should be utilized on all but the most complicated / long circuits to obtain at a minimum the length of the cable system.
- It provides useful information on the number of joints in a cable circuit.
- It can be difficult to interpret when multiple joints are present.
- It does not provide quantitative data on the condition of the cable neutral.

VLF Tan δ

- Test protocols are well defined and exist in approved industry standard (IEEE 400.xx).
- Assessment tools are available for interpreting the data into “No Action Required”, “Further Study”, and “Action Required” classes for all insulation types.
- A Health Index can be determined.
- Is often conducted and interpreted by utility personnel.

Simple Withstand Voltage

- Test protocols exist (AC Resonant & VLF) and are described in approved industry standards (IEEE 400.xx).
- AC Resonant, DC & VLF voltages meet the criteria for Withstand Tests.
- VLF withstand tests are useful for evaluating hybrid cable systems.
- This is the most straightforward diagnostic test to interpret and perform.
- This test is almost always conducted by utility personnel.

Monitored Withstand Voltage

- Test protocols are available (AC Resonant & VLF) and are described in an approved industry standard (IEEE 400.xx).
- Assessment tools are available, for VLF Tan δ, to make decisions in real time while the test is being performed, significantly increasing test program efficiency.
- Can be conducted and interpreted by utility personnel.

Partial Discharge (Damped AC (DAC))

- Technique is promising; however, there are no users of this technique in USA or Canada.
- May be conducted and interpreted by utility personnel.

Partial Discharge (AC Resonant & VLF)

- There is limited agreement in the industry on condition assessment if PD is present.
- No industry standard is available for interpreting PD measurements in the field.

- This is the most difficult diagnostic to employ in the field.
- This technique remains too complicated for most utilities to conduct and interpret on their own, although recent automation efforts are improving usability.

It is important to recall that all the tables in this chapter should be useful for an experienced user but are designed for:

- People first embarking on diagnostic testing; and
- People who have performed some diagnostic testing but are considering moving to a different location / cable type / mode of operation.

4.2.4.2 Specific Guidance

Questions 1 and 2 (above) are used in Table 7 to select the appropriate table with which to consider the outputs from Questions 3 to 5. Table 7 summarizes the research findings and provides specific diagnostic technique suggestions based on a user's tolerance for failures on test (FOTs) and who is anticipated to conduct the test.

Table 7: Initial Diagnostic Screening Matrix

How would you best describe your tolerance to dielectric Failures on Test (FOT)	Who do you anticipate to undertake the tests?	
	Utility Personnel	**Sub-Contractor**
Acceptable to avoid Failures in Service (FIS)	See Table 8	See Table 9
Should be Minimized but Acceptable to avoid Failures in Service (FIS)	See Table 10	See
Not Acceptable (Very Few) even to avoid Failures in Service (FIS)	See Table 12	See Table 13

Table 8 through Table 13 use the research results to suggest reasonable tests to consider based on what is known about the cable circuits under consideration from Table 7. If the text is in light blue, the indicated test(s) might be undertaken but have a low likelihood of rendering useful information.

Table 8: Acceptable Risk of Failures on Test (FOT), Test by Utility Personnel

	How would you describe the age of the cable system?			
		New	**Old**	
How would you best describe the majority of cables in the cable system	**Extruded**	**TDR – Chapter 5 & 11 And Simple VLF Withstand – Chapter 9**	**Don't know what is failing**	**TDR – Chapter 5 & 11 And Simple VLF Withstand – Chapter 9**
				TDR – Chapter 5 & 11 And Monitored VLF Withstand – Chapter 10
				TDR – Chapter 5 & 11 And VLF Tan Delta – Chapter 5
			I think that accessories are failing	**TDR – Chapter 5 & 11 And Simple VLF Withstand – Chapter 9**
				TDR – Chapter 5 & 11 And Monitored VLF Withstand – Chapter 10
	Hybrid	**Simple VLF Withstand – Chapter 9**	**Don't know what is failing**	**Simple VLF Withstand – Chapter 9**
			I think that accessories are failing	**Simple VLF Withstand – Chapter 9**
	Paper	**Simple VLF Withstand – Chapter 9, if possible consider TDR – Chapter 4 & 11**	**Don't know what is failing**	**Simple VLF Withstand – Chapter 9, if possible consider TDR – Chapter 5 & 11**
		Simple DC Withstand – Chapter 9	**I think that accessories are failing**	**TDR – Chapter 4 & 11 And Simple VLF Withstand – Chapter 9**

Table 9: Acceptable Risk of Failures on Test (FOT), Test by Sub-Contractors

	How would you describe the age of the cable system?			
		New	Old	
How would you best describe the majority of cables in the cable system	Extruded	TDR – Chapter 5 & 11 And Simple VLF Withstand – Chapter 9	Don't know what is failing	TDR – Chapter 5 & 11 And Monitored VLF Withstand – Chapter 10
				TDR – Chapter 5 & 11 And VLF Tan Delta – Chapter 5
				TDR – Chapter 5 & 11 And Simple VLF Withstand – Chapter 9
			I think that accessories are failing	TDR – Chapter 5 & 11 And Monitored VLF Withstand – Chapter 10
				TDR – Chapter 5 & 11 And Simple VLF Withstand – Chapter 9
	Hybrid	Simple VLF Withstand – Chapter 9	Don't know what is failing	Simple VLF Withstand – Chapter 9
			I think that accessories are failing	Simple VLF Withstand – Chapter 9
	Paper	Simple VLF Withstand – Chapter 9, And TDR – Chapter 4 & 11	Don't know what is failing	Simple VLF Withstand – Chapter 9, And TDR – Chapter 5 & 11
		Simple DC Withstand – Chapter 9	I think that accessories are failing	TDR – Chapter 4 & 11 And Simple VLF Withstand – Chapter 9

If the text is in light blue, the indicated test(s) might be undertaken but have a low likelihood of rendering useful information.

Table 10: Minimal Risk of Failures on Test (FOT), Test by Utility Personnel

		How would you describe the age of the cable system?		
		New	Old	
How would you best describe the majority of cables in the cable system	Extruded	TDR – Chapter 5 & 11 And Simple VLF Withstand – Chapter 9	Don't know what is failing	TDR – Chapter 5 & 11 And Monitored VLF Withstand – Chapter 10
				TDR – Chapter 5 & 11 And VLF Tan Delta – Chapter 5
			I think that accessories are failing	TDR – Chapter 5 & 11 And Monitored VLF Withstand – Chapter 10
	Hybrid	Simple VLF Withstand – Chapter 9	Don't know what is failing	Simple VLF Withstand – Chapter 9
			I think that accessories are failing	Simple VLF Withstand – Chapter 9
	Paper	Simple VLF Withstand – Chapter 9, if possible consider TDR – Chapter 4 & 11	Don't know what is failing	Simple VLF Withstand – Chapter 9, if possible consider TDR – Chapter 5 & 11
		Simple DC Withstand – Chapter 9	I think that accessories are failing	TDR – Chapter 4 & 11 And Simple VLF Withstand – Chapter 9

Table 11: Minimal Risk of Failures on Test (FOT), Test by Sub Contractors

	How would you describe the age of the cable system?			
		New	Old	
How would you best describe the majority of cables in the cable system	Extruded	TDR – Chapter 5 & 11 And Simple VLF Withstand – Chapter 9	Don't know what is failing	TDR – Chapter 5 & 11 And Monitored VLF Withstand – Chapter 10
		TDR – Chapter 5 & 11 And Offline PD – Chapter 7 or 8		TDR – Chapter 5 & 11 And VLF Tan Delta – Chapter 5
			I think that accessories are failing	TDR – Chapter 5 & 11 And Monitored VLF Withstand – Chapter 10
				TDR – Chapter 5 & 11 And Offline PD – Chapter 7 or 8
	Hybrid	Simple VLF Withstand – Chapter 9	Don't know what is failing	Monitored VLF Withstand – Chapter 10
				Simple VLF Withstand – Chapter 9
			I think that accessories are failing	Simple VLF Withstand – Chapter 9
	Paper	Simple VLF Withstand – Chapter 9, And TDR – Chapter 4 & 11	Don't know what is failing	Simple VLF Withstand – Chapter 9, And TDR – Chapter 5 & 11
		Simple DC Withstand – Chapter 9	I think that accessories are failing	TDR – Chapter 4 & 11 And Simple VLF Withstand – Chapter 9
				TDR – Chapter 4 & 11 And Online PD – Chapter 7 or 8

If the text is in light blue, the indicated test(s) might be undertaken but have a low likelihood of rendering useful information.

Table 12: Failures on Test (FOT) Not Acceptable, Test by Utility Personnel

		How would you describe the age of the cable system		
		New	Old	
How would you best describe the majority of cables in the cable system	Extruded	TDR – Chapter 5 & 11	Don't know what is failing	TDR – Chapter 5 & 11 And VLF Tan Delta – Chapter 5
			I think that accessories are failing	TDR – Chapter 5 & 11 And VLF Tan Delta – Chapter 5
	Hybrid	Nothing Available	Don't know what is failing	Nothing Available
			I think that accessories are failing	Nothing Available
	Paper	Nothing Available	Don't know what is failing	Nothing Available
		Nothing Available	I think that accessories are failing	TDR – Chapter 5 & 11

If the text is in light blue, the indicated test(s) might be undertaken but have a low likelihood of rendering useful information.

Table 13: Failures on Test (FOT) Not Acceptable, Test by Sub Contractors

		How would you describe the age of the cable system		
		New	Old	
How would you best describe the majority of cables in the cable system	Extruded	TDR – Chapter 5 & 11 And Offline DAC PD – Chapter 7 & 8	Don't know what is failing	TDR – Chapter 5 & 11 And VLF Tan Delta – Chapter 5
				TDR – Chapter 5 & 11 And Offline DAC PD – Chapter 7 & 8
			I think that accessories are failing	TDR – Chapter 5 & 11 And VLF Tan Delta – Chapter 5
				TDR – Chapter 5 & 11 And Offline DAC PD – Chapter 7 & 8
				Online PD – Chapter 7
	Hybrid	TDR – Chapter 5 & 11 And Offline DAC PD – Chapter 7 & 8	Don't know what is failing	Nothing Available
			I think that accessories are failing	Online PD – Chapter 7
	Paper	TDR – Chapter 5 & 11 And Offline DAC PD – Chapter 7 & 8	Don't know what is failing	VLF Tan Delta – Chapter 5
				Online PD – Chapter 7
				Offline DAC PD – Chapter 7
		Online PD – Chapter 7	I think that accessories are failing	Online PD – Chapter 7
				Offline DAC PD – Chapter 7

If the text is in light blue, the indicated test(s) might be undertaken but have a low likelihood of rendering useful information.

The Decision Tables (Table 8 - Table 13) above can be quite intimidating as they display the plethora of options and the potential solutions revealed by this research. In an effort to make them more understandable, two Case Studies are presented to demonstrate their use.

Case 1:
Assume that you are a new user, the failure rate is 150% of average and failures in service have a high impact. Table 3 shows that we know that diagnostic testing is a reasonable thing to do (Useful for learning, with increasing benefits but also increasing risks).

Now we need to answer additional questions (see section 4.4.1):

1. *Who is the service provider?* Diagnostic testing would be performed by a sub-contractor.
2. *What is the acceptability of Failures on Test (FOT)?* Failures on test are acceptable but should be minimized.
3. *What is the cable type?* Majority of the cables on the system are extruded
4. *What is the cable age?* Old
5. *What is failing?* Accessories

With this information, Table 7 tells us that we should go to Table 11. Table 11 indicates to us that the following diagnostic test technologies are recommended and directs us to the specific chapter for further guidance:

1. **TDR – Chapter 5 & 11**
2. **Monitored VLF Withstand – Chapter 10**
3. **Offline PD – Chapter 7 or 8**

Case 2:
Now assume that you are a new user, the failure rate is 250% of average and failures in service have a low impact. Table 3 shows that we know that diagnostic testing should be very beneficial (Optimal – maximum benefits with maximum risks).

Now we need to answer additional questions:

1. *Who is the service provider?* Diagnostic testing would be performed by a utility crew.
2. *What is the acceptability of Failures on Test (FOT)?* Failures on test are acceptable.
3. *What is the cable type?* Hybrid (mixture)
4. *What is the cable age?* Old
5. *What is failing?* Don't know

With this information, Table 7 tells us that we should go to Table 8. Table 8 indicates to us that the following diagnostic test technologies are recommended and directs us to the specific chapter for further guidance:

1. **Simple VLF**

A blank assessment template is provided below as a convenient method for recording the circumstances for your situation and the answers to the five questions.

FAILURE RATE	More than Twice Average Failure Rate			
	Between Average and Twice Average Failure Rate			
	Less than Average Failure Rate			
		Failure in Service has a Low Impact	Failure in Service has a Medium Impact	Failure in Service has a High Impact
		IMPACT OF FAILURE		

Describe Area chosen for Testing:	
Relevant History of Cable System	
1. Who do you anticipate to undertake the tests?	
2. How would you best describe your tolerance to dielectric Failures On Test (FOT)?	
Table 7 indicates Table	
3. How would you best describe the <u>majority</u> of cables in the cable system?	
4. How would you describe the age of the cable system?	
5. In your Old Cable System - Do you know what is failing	
Consider the following Diagnostics (Taken from relevant Table (Table 8 to Table 13)	

4.3 Summary

The complexity of cable system diagnostic testing can be daunting for those unfamiliar with the process. The research information in this chapter is intended help by condensing a plethora of information on diagnostic testing into a series of easy to follow steps or processes. The discussion is designed to help potential cable diagnostic technology users a way to focus on the relevant issues. It does this by providing an overview of how to approach diagnostic testing with a quick review of available technologies and how they might reasonably be deployed under a given set of circumstances.

It is important to reinforce the fact that these are general guidelines. Someone with an advanced knowledge of diagnostic testing may choose to take a different approach and still achieve positive outcomes. However the intent is to point unfamiliar users in the right direction such that they can avoid costly mistakes and maximize the potential value of performing a cable system diagnostic test program.