Repeated Field Tests – Utility Case Studies of the Value of Trending

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ABSTRACT

Cable System Management requires an assessment of the health of the cable systems. It is increasingly common for the assessment of aged cable systems to be made through the application of diagnostics measurements. Papers and standards have established benchmarks for diagnostic measurements that help utility engineers to reach a condition assessment. Generally, extremes of healthy and non-healthy cable systems are easily identified independent of the diagnostic technique. However, there is less certainty in the assessment when cable systems lie between the extremes. In such cases, repeat tests and their trending may prove useful in enhancing the condition assessment. Amongst the commercially available diagnostic techniques, VLF Tan δ is the most commonly deployed on cable systems in North America. Therefore, the focus of this paper is the application of repeated field measurements using VLF Tan δ on multiple utility cable systems.

KEYWORDS

Diagnostic Techniques, Very Low Frequency (VLF), Tan Delta, Trending, Decision Tools

INTRODUCTION

Papers and Standards often mention the benefits of establishing a baseline measurement and then following up with repeat tests spaced some reasonable time apart [1-11]. They describe how this provides the best indication of the condition of a cable system. Although an admirable goal, such repeat testing is rarely if ever undertaken. The primary reason is that resources are scarce and consequently it is difficult to complete the initial test program let alone return in a reasonable period to repeat the tests. As there has been little in the way of "practice" to show the benefit of such an approach, the authors decided to undertake such a study.

A number of field tests have been performed on utility cable systems as part of the Cable Diagnostic Focused Initiative (CDFI) [1] since 2006. In recent years (2010 to 2014), the authors have endeavoured to return to these systems to repeat the same tests that were originally performed. The studies discussed in this paper make use of Dielectric Loss (Tan δ) measurements made under VLF (Very Low Frequency) voltages.

This paper describes the following:

- Recent advances in the deployment of VLF techniques following the release of the updated IEEE Std. 400.2 – 2013 [5].
- Determination of the cable asset health using a diagnostic-based Health Index [12].
- Changes in asset Health Index over time.
- Service performance between repeated tests.
- Critical utility decisions required to enable effective repeated tests programs.

VLF TAN δ MEASUREMENTS

Tan δ measurements determine the degree of real power dissipation in a dielectric material (dielectric loss). A comparison relates this measurement to a known reference value for the type of dielectric measured. A judgment establishes the condition of the tested system based on how much the dielectric loss differs from the reference value. Reference values can be based on:

- Values measured on adjacent phases (A, B, C).
- Values measured on cables of the same design and vintage within the same location.
- Values when new.
- Industry standards.
- Experience library.

There are a number of advantages and concerns for VLF Tan δ measurements, which are shown in **Error! Reference source not found.**.

Table 1: Advantages and Concerns of VLF Tan δ

Advantages	Concerns
Assessments are based on well defined features that can be archived and re considered at later dates Energizing test equipment is small and easy to handle Frequency dependency of Tan δ can be established Tan δ is more sensitive at lower frequencies than at 60 Hz due to the reduced magnitude of the capacitive current Can test very long cable systems	Not clear how to consider multiple features when making a single overall assessment of health Testing voltage waveform may not be the same as the operating voltage Frequencies lower than 0.01 Hz may cause space charge formation

Tan δ data are obtained by applying an AC voltage and measuring the phase difference between the voltage waveform and the resulting current waveform. This phase angle is used to resolve the total current (I) into its charging (I_C) and loss (I_R) components. Figure 1 shows an ideal equivalent circuit for a cable, consisting of a parallel connected capacitance (C) and a voltage dependent resistance (R). The Tan δ is the ratio of the loss current to the charging current.

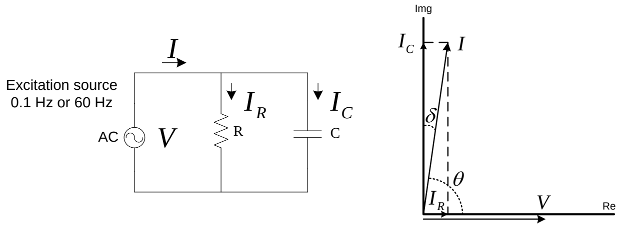

Figure 1: Equivalent Circuit for Tan δ Measurement and Phasor Diagram

REPORTING AND INTERPRETATION

In principle, there are four types of dielectric loss data that may be reported:

- Tan δ magnitude - normally reported as the mean of a number of sequential measurement cycles.
- Differential Tan δ or Tip Up - normally reported as the simple algebraic difference between the means of two different voltages.
- Voltage sensitivity of differential Tan δ or Tip Up of the Tip Up - normally reported as the simple algebraic difference between the means of a number of sequential assessments taken at three different voltages.
- Tan δ stability - normally reported as a standard deviation of sequential measurements at one voltage.

Figure 2 shows examples of measured Tan δ data from cable systems in service.

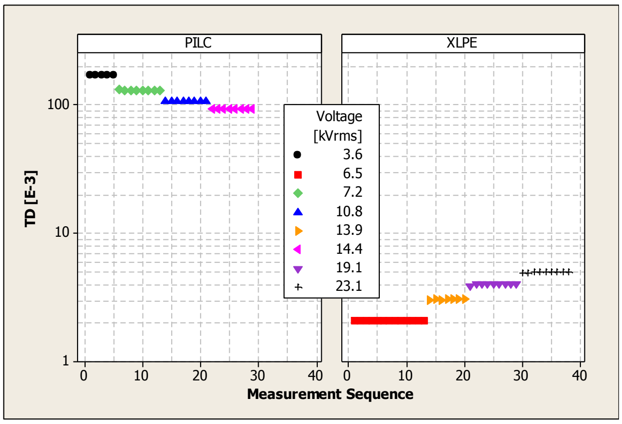

Figure 2: Measured Tan δ data from Cable Systems in Service

ESTABLISHING CRITICAL LEVELS WITH MULTIPLE FEATURES

In the past, engineers have tried to find "perfect" criteria that absolutely separate the Tan δ results of components that go on to fail from those that do not. To do this requires a significant amount of service data on Tan δ and failures, which is difficult to acquire. Even then the multitude of aging scenarios may preclude this. This is especially true for dielectric loss data that are typically collected by utilities. An alternative approach developed by the authors [5, 8, 9] identifies critical dielectric feature levels that separate "usual" from "unusual" data. This is the classic Shewart or control chart approach [13], which uses the mean and standard deviation as a metric to define a "normal" value. In the simplest form, data are unusual if either:

a) One value lies more than three standard deviations from the mean or
b) Two sequential values are more than two standard deviations from the mean.

As a result, knowledge rules for Tan δ can now be further refined and a hierarchy established (see sequence in Table 2). The approach used to determine the critical levels for diagnostic features from these data relies on the collated field data as of the end 2014.

Table 2: Criteria for Condition Assessment of Cable Systems ([10^{-3}] – collation of data to 2014 [5, 8, 9]

Condition Assessment	No Action Required	Further Study Advised	Action Required
Assessment of PE-based Insulations (i.e. PE, XLPE, WTRXLPE)			
TD_{U_0} Stability (standard deviation)	<0.05	0.05 to 0.5	>0.5
	&	**or**	
Tip Up ($TD_{1.5U_0}$ – $TD_{0.5U_0}$)	<5	5 to 80	>80
	&	**or**	
Tip Up Tip Up {($TD_{1.5U_0}$–TD_{U_0}) - (TD_{U_0}–$TD_{0.5U_0}$)}	<2	2 to 52	>52
Mean TD at U_0	**&**	**or**	
	<4	4 to 50	>50

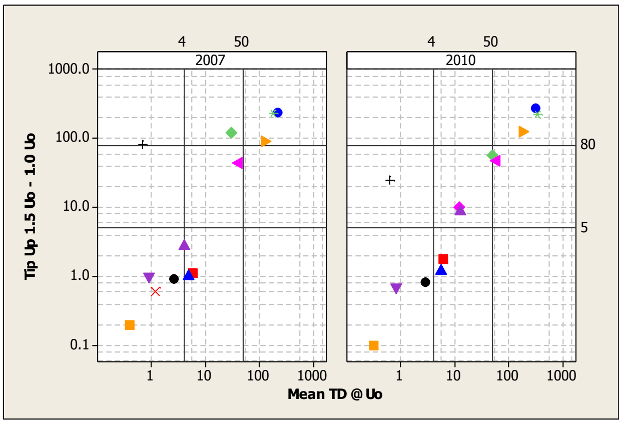

Figure 3: Comparison of 2007 and 2010 Tan δ Results Used for Condition Assessment

Data for tests in 2007 and repeated 2010 are shown in Figure 3 with the areas bounded by levels for two of the four possible features in Table 2. The levels for all of these features are created from the same basic rules:

1. **No Action Required:** it represents 80% of the available data with the best performance.
2. **Action Required:** it represents 5% of the available data with the poorest performance.
3. **Further Study:** it represents the 15% of the data between "No Action Required" and "Action Required".

HEALTH ASSESSMENT

Most treatments of a Tan δ result use a simple set of rules of the type set out in Table 2. Although this has been found to work well for the majority of cases it is not so clear for the cases where:

a) Two or more of the indicators lie in the upper range of the class when it might be argued that the diagnosis should be more severe than the simple levels would suggest or

b) When two features lower in the hierarchy suggest a poorer condition than one with a higher position.

The authors recognised that the data set for polyethylene (PE) based cables was sufficiently large and had a high enough fidelity to enable this conjecture to be tested. Furthermore, it was recognised that visualization of the results from the testing would be assisted if it were possible to find a means by which the outcomes suggested by the disparate metrics could be combined to provide a single measure of health (Health Index or HI).

The approach currently used for this work is Principal Component Analysis (PCA) [9, 13]. This technique was chosen as this would provide a predictive model based on the data, guidance on the appropriate factors to combine, and would likely enable a physical meaning to be ascribed to the resulting composite factors – the Principal Components. The PCA approach identifies linear combinations of the factors that minimize the variance within the data. The advantage is that it now makes it possible to look for patterns in the data when there are more factors than can be handled by simple graphical means, i.e. the plot of two of the possible four features in Figure 3.

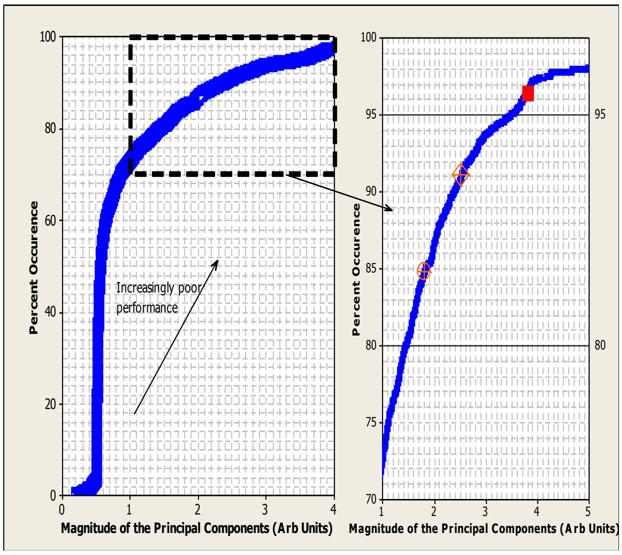

Figure 4: Empirical Distribution for the Magnitude of Principal Components (>1500 cases plotted) for PE based Cable Systems

Figure 4 shows the combined magnitude (resultant being the magnitude of the vector addition) of the first three Principal Components of the four features in Table 2 for all the cases of PE cable systems considered in this study. The first three principal components are selected because they embody most of the data variability. The magnitude of the principal components is the length of the vector that represents the three components and it is represented by the X axis values in Figure 4. The percentage or rank position is given by the Y axis values, which in practice might conveniently be regarded as a Health Index (HI) [11].

In Figure 4, the gradient of the curve at any selected point provides an indication of how sensitive the overall HI is to the diagnostic data. Thus, changes in the HI greater than 70 on the Y axis are caused by large changes in the diagnostic data whilst below this position (HI lower than 70) changes in the HI are observed with small changes in the diagnostic data. The levels for all of the results upon which the HI is based are created from the same basic rules that have been proven for the simple diagnostic feature approach and they are as follows:

- **No Action Required**: it represents 80% of the available data with the best performance – healthiest systems or lowest values of the resultant HI.
- **Action Required**: it represents 5% of the available data with the poorest performance – non-healthiest systems or highest values of the resultant HI.
- **Further Study**: it represents the 15% of the data between the levels of “No Action Required” and “Action Required”.

The symbols in Figure 4 represent some selected case studies. The solid square symbol is a poor performer in 2007 that failed after approximately 27 months of additional service life. This would, in 2007, be described as being within the poorest 4% of all systems upon which data is available; therefore, it would likely have been classified to the level of “Action Required” and subsequent actions may had avoided the failure in service.

Additionally, the open round and diamond symbols are repeated measurements from a cable system in 2007 and 2010, respectively. The magnitude of their Principal Components and respective HI’s were calculated and their positions plotted relative to all the available data. In this case, the cable system degraded from a poorest 15% ranking in 2007 to a poorest 9% ranking in 2010. This is a 2% to 3% rate of degradation in rank position or HI per year in service. Inspection of middle ranges and lower ranks shows that, as might be expected, there is a degradation in rank here as well, but the rate is much lower: approximately 0.33% to 0.5% loss of position per year. Information of this type is invaluable to an asset manager when determining the most appropriate route forward regarding a cable system testing and replacement program. More importantly, this information may be used to understand that the condition assessment is a dynamic process whose speed varies considerable.

SERVICE AND RETEST PERFORMANCE

The service and retest performance is accomplished by the repeated test PCA map with Tan δ assessment class thresholds shown in Figure 5. The map allows for easy comparison of whether an initial condition assessment has remained unchanged, improved, or deteriorated over time. The PCA used in this analysis is the latest embodiment (2014) with four Tan δ features as shown in Table 2. However, prior to 2014, the feature list shown in Table 2 did not exist at the time the authors completed the first field measurements. Therefore, it was necessary to revisit the original data files to extract the required feature information as per Table 2. This was possible since the basic measurement technology has a) remained unchanged since 2006 and b) the data were well catalogued / archived; thus the collected data allowed for new feature extraction. These last points are absolutely crucial in an effective retesting program. The authors have considered the application of retesting to diagnostic embodiments where the results are presented / archived as Pass / Fail. In these cases considering retest has not been possible primarily because there has been insufficient clarify in the original decision methods such that it is not possible to be certain that the same analyses / criteria have been used.

The PCA map in Figure 5 plots the percent PCA rank which relates to the HI index described above in the following manner:

$$\text{Percent PCA rank} = 100 - HI$$

In this way, lower PCA rank values indicate poorer condition and conversely higher values are indicative of better health.

The thresholds to define the action levels then become:

- **No Action Required**: PCA rank > 20 (best 80%)
- **Action Required**: PCA rank ≤ 5 (worst 5%)
- **Further Study**: 5 < PCA rank ≤ 20

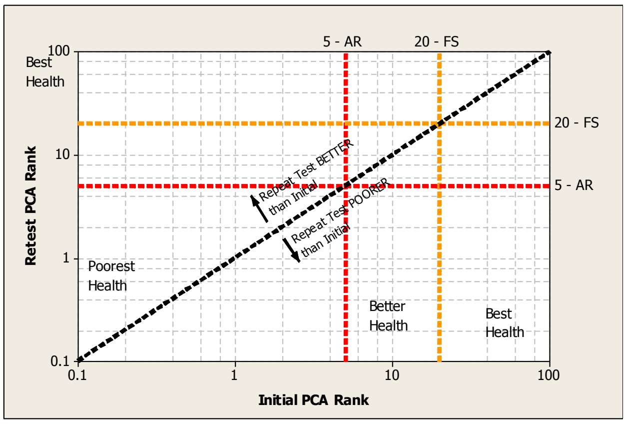

Figure 5: Repeat Test PCA Map with Tan δ Assessment Class Thresholds

- - - - “Action Required” (AR) limit, - - - - “Further Study” (FS) limit

- - - - Theoretical case of repeat and initial tests being the same

The black dashed line in Figure 5 indicates where a system would be plotted had there been no change in its PCA rank. Points that lie above this line are systems where the retest results indicate better health based on the dielectric loss feature measurements compared to the initial test while points below this line represent systems whose health has worsened since the initial test. In Figure 5, cable systems may “move” within the assessment classes they were assigned after their initial tests or they may change classes. For example, a system initially classified as “Further Study” may worsen and be assessed later on time as “Action Required” upon retest; the contrary is also possible, a system initially classified as “Further Study” may improve and be assessed later on time as “No Action Required” upon retest. The changes or “movements” between classes are determined by the aging/degradation mechanisms, operating conditions, and possible maintenance/corrective actions that cable systems may have seen over time between retests.

During the project [1, 8, 9], a number of areas were tested in the past and left in service. Recently tests in the Tan δ arena have been focused on returning to areas that were previously tested. The earliest tests undertaken were performed in 2006 while repeat tests were completed as recently as mid-2013. The tests were performed on three utility distribution systems. In total, 70 cable systems were tested and retested with a total length of approximately 29,000 ft (8,840 m). All tests performed included Tan δ measurements as a function of voltage, time, or frequency. The shortest and longest intervals between initial tests and retest are 1 yr and 5 yr, respectively.

Figure 6 shows the PCA ranks for both the initial and repeat tests. As this figure shows, several systems were nearly unchanged from their earlier tests while a number either improved or degraded with respect to their measured VLF Tan δ results. The median change in PCA Rank was an improvement from 17.4 to 26.6. This represents a move from the Further Study class to the No Action Required class. As mentioned before, this shows that cable system condition assessment is a dynamic process. Figure 6 also shows that systems do move within their respective classes without transitioning to another class.

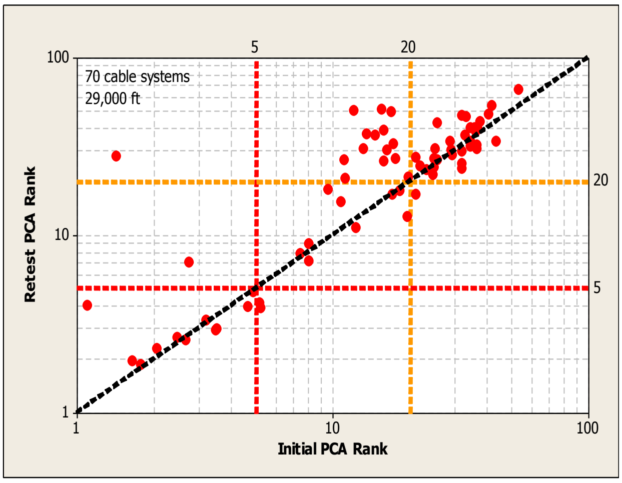

Figure 6: PCA Ranks at Initial Test and Repeat Test for all Tested Systems

Figure 7 shows an expanded view of the “No Action Required” class in Figure 6 (upper right corner) so that the movement within the class can be better observed. A portion of the movement within a class can be attributed to the different conditions at the repeat test (humidity and temperature) as well as differences in measurement equipment and changes in the condition of the system. As can be seen in Figure 4 below 80% PCA Rank small changes in the magnitude of the Principal Components can result in large changes in ranking.

The data in Figure 6 may also be segregated by host utility as shown in Figure 8.

It is interesting to note that several systems rose from the “Further Study” class to the “No Action Required” class. The improvements in assessment classes for such a large percentage of the population can be attributed to utility maintenance in the form of:

- Required (Tactical): replacement of one or two accessories (few).

- Planned (Strategic): replacement of accessories (> 25%).
- Fluid injection (Capital): generally include replacement of all accessories.

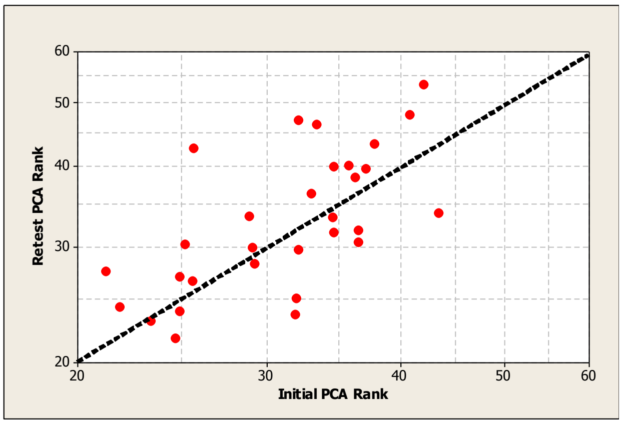

Figure 7: Systems Remaining in "No Action Required" Class – top right of Figure 6

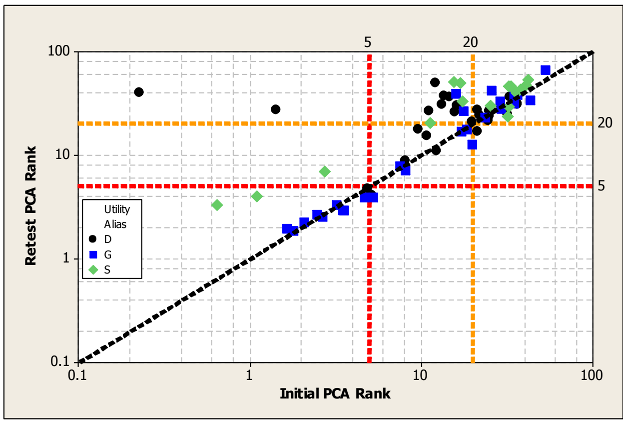

Figure 8: PCA Ranking Map with all CDFI Repeat Test Results segregated by Host Utility

Figure 9 shows the same data as Figure 8 with systems segregated by whether or not they received any of the three utility maintenance actions listed above. Systems that received maintenance saw a median change in PCA rank from 16.1 to 27.5. This is a larger change than was observed in the remaining systems that did not receive additional maintenance where the PCA rank changed from 21.6 to 23.8.

Clearly, the most dramatic improvements in PCA rank are the result of the maintenance actions performed by the utility. Of the 30 systems that most likely received maintenance, 76.7% displayed improvement in PCA rank while 23.3% showed degradation in PCA rank, though not necessarily a change in class ("Action Required" (AR), "Further Study" (FS), or "No Action Required" (NA)).

It is unclear how long the improvements in the maintained system population will last. The repeat test data in this section are somewhat limited in terms of time scale but these results do show the improvements last at least 2 years. These are direct system to system comparisons and are quite different from the more commonly reported population comparisons.

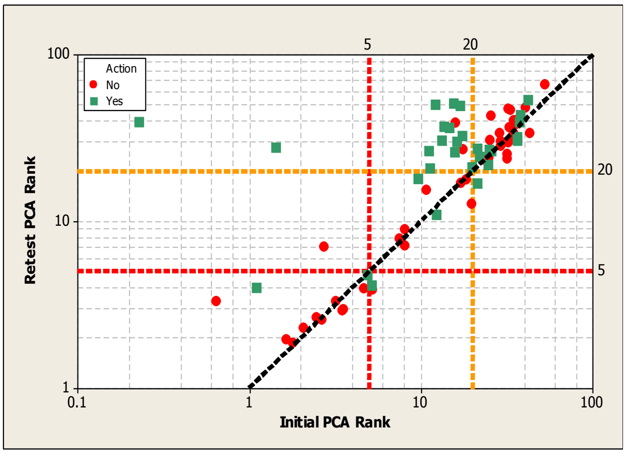

Figure 9: PCA Ranking Map with Systems Identified that Received Utility Maintenance (Action).

Table 3 shows a comparison of the movements of cable systems between classes of Figure 6. Clearly, the maintained systems improved (moved to a less degraded class) at a much higher rate than those that were left alone even though some improvement occurred in the non-maintained population as well. The vast majority of circuits that were not proactively maintained remained within their respective classes. This provides some guidance on the speed at which cable systems may move to a more degraded class and thus provides a time horizon for which a single test may be valid.

Table 3: Cable System Health Comparisons

Class Change	Non-Maintained		Maintained	
Down 2 Classes to Fail FS to Fail	0	3 (7%)	0	0
Down 1 Class to Fail AR to Fail	3		0	
Down 2 Classes NA to AR	0	1 (2%)	0	2 (6.7%)
Down 1 Class NA to FS or FS to AR	1		2	
No Change	36 (83%)		14 (46.7%)	
Up 1 Class AR to FS or FS to NA	3	3 (7%)	12	14 (46.7%)
Up 2 Classes AR to NA	0		2	

CONCLUSIONS

This paper has shown that considerable progress has been made in the practical implementation of a diagnostic data based Health Index. This is a notable and complimentary approach to the expert opinion based methodologies that are often used. A significant advantage to any data driven Health Index is the absence of “gaming” or “confirmation bias” seen in some opinion based methods. The PCA based approach provides an “unbiased” Health Index that is useful when considering trending or repeated tests for Tan δ diagnostic on medium voltage (MV) cable systems.

Condition assessment based on Tan δ criteria has evolved substantially over the past decade. The number of diagnostic features has increased. The multiple diagnostic features may be collated and analyzed to garner a data driven Health Index. The analyses have been formatted so that they may be readily used in the field to provide real-time guidance on the appropriate decisions that a user might take to proactively manage their cable system asset.

The use of a single set of percentiles for establishing levels enables a consistent and relatable set of criteria that can be used for all insulation types. For instance, Health Indices can be developed for cable systems with Paper or EPR-based insulations and they would be understood in the same manner as that for PE-based systems. This would avoid challenges due to common findings; for example, a negative Tip-Up and the rarity of large negative values on paper-based insulation systems.

The paper has also shown that the condition assessment of cable systems is a dynamic process, i.e. over time cable systems may improve or deteriorate at different rates. These changes or movements between assessment classes are due to a series of factors that include aging/degradation mechanisms, operating conditions, and possible maintenance/corrective actions by the utility. Specifically, for those cases in which an improved condition assessment is observed, the improvement can often be attributed to utility practices that include tactical, strategic, and capital replacement program policies.

Finally, the Health Index and its trend can provide valuable insight into the degradation mechanisms at work in different regions of a utility while also providing a means of quantifying improvements resulting from other proactive measures (rejuvenation, replacement, etc.).

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