Asset Management of MV Cables using Data Driven Health Indices for Water Treeing

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ABSTRACT

The underground distribution system makes up a significant portion of the distribution infrastructure (EEI) in the US. Most of the reported failures are associated with the accessories, which can easily (relative to the whole system) be addressed. However, the larger concern are the cables that; which as distributed devices, are more difficult and costly to address. This concern is amplified as cable from earlier generations still make up a large portion of the utility system. The main mode of failure, for EPR, HMWPE, WTRXLPE, and XLPE, is considered to be the conversion of water trees to electrical trees due to the modification of both the electrical strength and stress.

Luckily, water trees in EPR and PE-based insulations can be observed and measured thereby providing leading indicators to an Asset Management program so that appropriate actions may be taken. This work has developed a Health Index algorithm that is able to provide context to water tree studies and a data-driven (meta- data and water tree data) characterization.

KEYWORDS

Reliability, Water Trees, Health Indices, Extruded Cable

INTRODUCTION

The underground distribution system makes up approximately 18% - 24% of the distribution infrastructure (EEI) in the US [1]. This system is comprised of terminations / elbows, cable, and joints, which all contribute to the reported SAIDI and SAIFI data. The process of increasing the percentage of underground cables is seen as a way to improve reliability (Figure 1) [1, 2]. Most of the reported failures are associated with the accessories, which can easily (relative to the whole system) be addressed through replacement and diagnosis because they are discrete devices. However, the larger concern are cables [3, 4]; which as distributed devices, are more difficult and costly to address. This is especially concerning as cable from earlier generations still make up a large portion of the utility system.

Since the earliest days of extruded insulations and the discovery of water trees in PE (HMWPE, XLPE, and WTRXLPE) and EPR insulations, many utilities and laboratories have performed a large number of water tree inspections on extruded power cables returned from the field [5 – 15]. These examinations include both those which have failed in service and, very often, cohort lengths that have not failed. These studies were conducted in an effort to shed light on the processes that initiate and determine the rate of water tree growth. This work is influential as studies in 2004 and 2015 show that utility engineers place a premium on the cable reliability that they experience when determining which components to use on the systems that they design.

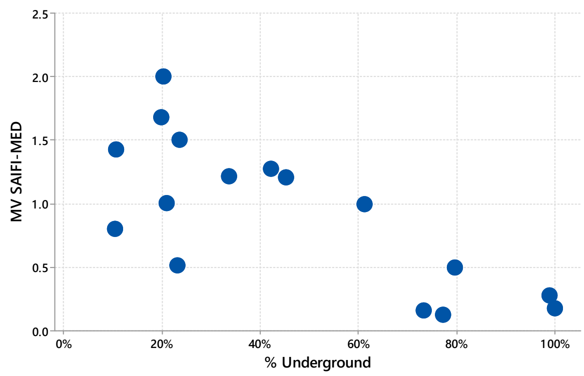

Figure 1 Impact of undergrounding on SAIFI – MED (Major Event Days) of selected countries

Generally, these studies are single or small group investigations and little consideration was given to consolidating the knowledge embedded in these analyses. Over the last few years, the authors have created a knowledge base from the many examinations (>450 investigations, 40 utilities, >5,000 trees) and used this repository to develop a fact-base (initial measured data and data developed more recently) to support the coming asset management challenges around the ageing cables within the distribution infrastructure. This is particularly useful for utilities

- Who proactively replace cables and wish to confirm that cables being extracted are near end of life
- Who extract samples upon failure and wish to assess the velocity of degradation and asset health

Health Indices are well suited to these tasks as they are commonly used to condense and summarize many quantitative and semi qualitative factors.

APPROACH

Sources of Data

Water tree inspections usually occur either after a service failure or to proactively identify potential tree formation.

- **After a service failure has occurred** – in these cases there is some level of damage around the failure site and invariably the initiator (often presumed to be the most stress enhancing water tree) is destroyed – thus the investigation focuses on the surrounding area whilst recognizing that the tree of most interest was already destroyed, and

- **After service for some time but prior to failure** – this is undertaken on a cable that has not failed, therefore any water trees which are present have yet to reach the critical size for conversion to electrical trees, and thus, the investigation focuses on the trees that may become critical in the future.

All methods used for the detection of water trees are in principle destructive and require either a) cutting of thin wafers or b) transparentization of cable insulation at elevated temperatures. The two methods are the wafer method and the hot oil method. A comparison of the two techniques is provided in Table 1.

Table 1: Wafer and Hot Oil Methods for Water tree Detection and Characterization

	Wafer Method	Hot Oil Method
Advantages	Can estimate radial length Permits photography	Very good at finding sites of water treeing Samples a large volume of material (much larger than inspected by wafers) Does not destroy trees in blind cutting
Disadvantages	Poor at finding sites of water treeing - investigates a small volume Misleading if “wrong” part is selected	Cannot estimate radial length of tree Photography difficult

Wafer Method

Thin wafers are cut from a short length (5 cm) of “selected” core using either a lathe or a microtome. These are then dyed (methylene blue or rhodamine) to provide contrast for the water trees within the matrix. The wafers are examined either by the naked eye or under a microscope to identify the trees (type, initiation point, number, etc). A suitable reticule in the microscope and calibration factor enables dimensions to be estimated.

Hot Oil Method

The outer semicon is removed from moderately long lengths of cable core (typically 25 cm). Multiple cores (5 to 10 core sections are not atypical) are placed in an oven or hot oil bath. Once the insulation temperature exceeds 105°C the crystallites in the insulation are molten and the insulation becomes clear rendering electrical and water trees visible. Contrast improves if the cores are soaked in water for some hours before the test. In practice, temperatures around 120°C provide a suitable margin for transparency during the cooling that occurs in examination. The application of silicone oil improves the detection as this matches the refractive index of the materials. Large or interesting trees are marked for wafering (radially or longitudinally is possible, though radial is the most common) to estimate the dimensions.

ANALYSIS

The collation of the water tree information includes the water tree data and the meta data for the cables from which they came, the disbursement of water trees may be summarised as:

- 45% failed in service / 55% condition assessment
- 33% jacket / 36% unjacketed / 31% unknown
- 50% neutral / 7% metal barrier / 43% unknown

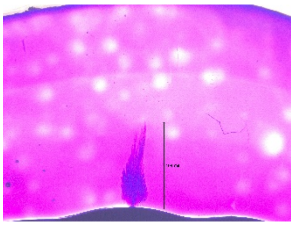

Figure 2: vented tree from a protrusion on the conductor shield

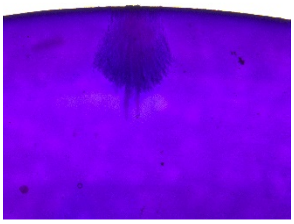

Figure 3: vented tree growing from the insulation shield

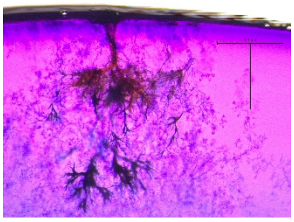

Figure 4: vented tree growing from the insulation shield with some electrical treeing

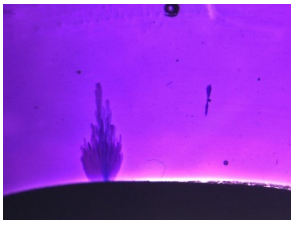

Figure 5: vented tree growing from protrusion on conductor shield and bow tie tree growing in insulation

Tree Data Summaries

The collated tree lengths can be used to determine the relevant tree lengths, including the longest of a failed sample which is assumed to have been destroyed in the fault. The next step is to construct summaries for suitable subsets. Figures 6 and 7 [16, 17] show the estimated longest tree length data segregated by the type of investigation (service of failure).

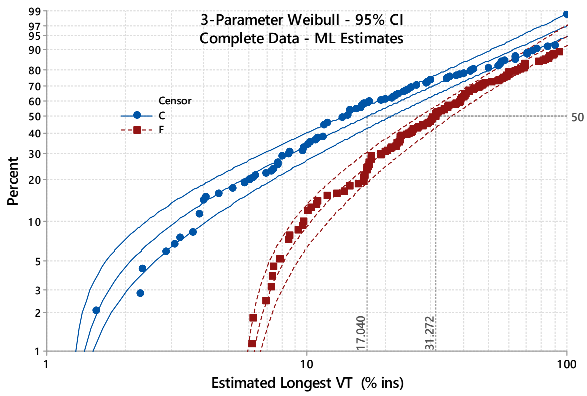

Figure 6 Estimated longest vented trees - failure in service (F) and survival (C)

As can be observed there is a separation of the centroids of the distributions but there is overlap between the tails (longest lengths). This overlap will be discussed later as it has important implications for data decision making. Moreover, it can be seen that the dimensions span the whole thickness of the cable insulations and the distributions are skewed. Thus, the authors prefer to summarise the findings in terms of the non-parametric descriptor, the median. Such descriptions are provided in Table 2.

Inspection of Figures 7 and 7 indicate that there are finite percentages shown for trees 100% through the insulation. This represents the fact that, although more likely to fail, cables do not automatically fail when a tree breaches the whole of the insulation. In fact 5% of the samplees (failed and condition assessment) had trees that fully breached the insulation. Furthermore in 25% of the cases where a cable failed in service, it was not possible to observe vented treeing. Thus clearly relating failure, tree length alone cannot provide the full picture.

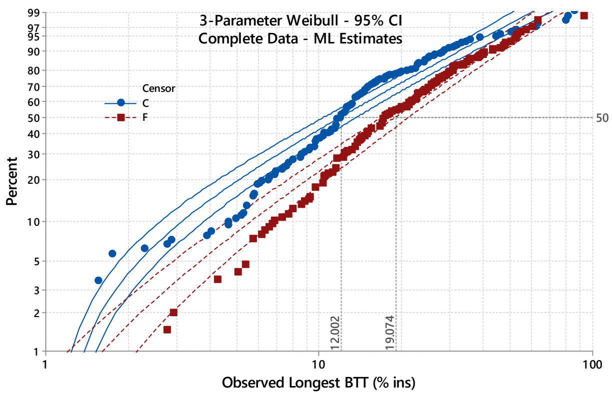

Figure 7 Distribution of longest bow tie trees, by fail in service (F) and condition assessment (C)

Finite Element Analysis

The impact of the tree lengths on the electrical stress can be assessed through finite element studies where a suitable tree model is analysed for different sizes within the divergent stress of a cable geometry. The stresses drive the rate of water tree growth and the initiation of the ultimate electrical tree. It is generally accepted that the water tree growth is slow and that electrical tree growth is fast. The likelihood that an electrical tree will initiate in either the high stress region in front of the water tree or in the low strength / low stress region within the water tree, will depend upon the water tree length. Thus, the ultimate mechanism of failure will depend upon water tree length. These studies provide further evidence that failure from water treeing is not a simple function of water tree length.

Meta Data Summaries

Almost all studies are undertaken also come with meta data such as age, type of study cable design, prior failure history, and alternate condition measures (condition of metallic neutral. To make optimal use of the cable design information, a summarisation scheme is required. Table 3 shows a suitable summarisation using generations of cable design. This provides a way to simply describe a complex evolution of designs and manufacturing.

Table 2: General descriptors (Median) for XLPE, HMWPE and WTRXLPE insulations

Condition	Insulation	Age	Longest BTT	Longest VT	Median of BTT	Median of VT	Density BTT	Density VT
		yrs	% insulation thickness				#/wafer	#/20 wafers
Condition Assessment	HMWPE	27	10.6	14.6	4.8	11.4	0.05	0.5
	WTRXLPE	11	5.9	11.5	5.8	11.5	0.05	0.0.5
	XLPE	21	12.9	17.0	8	11.4	0.1	0.8
Failure in Service	HMWPE	25	16.0	22.1	5.7	11.4	0.3	3
	WTRXLPE	16	10.4	14.2	6.9	8.2	0.05	1.7
	XLPE	24	19	33.3	7.7	20.6	0.2	3

Table 3: Major evolutionary elements in North American MV cable designs (excludes wall thickness)

Generation	Insulation	Semicon	Jacket	Barrier
1	HMPWE Non XL	C Tape	None	None
2		ThermoP		
3	XLPE or EPR	C Tape		
4		ThermoP		
5		ThermoS		
6			Jkt	
7	WTR XLPE or EPR			
8				Part WB
9				Full WB

The benefits of combining tree and meta data (age here) is shown in Figure 8 [18], where the median tree lengths are calculated, using the whole population, for selected age bins. This approach estimates the growth rate at selected cable ages. As can be observed, the growth is non linear and indicates that full thickness water trees should be anticipated for cables older than 35 years.

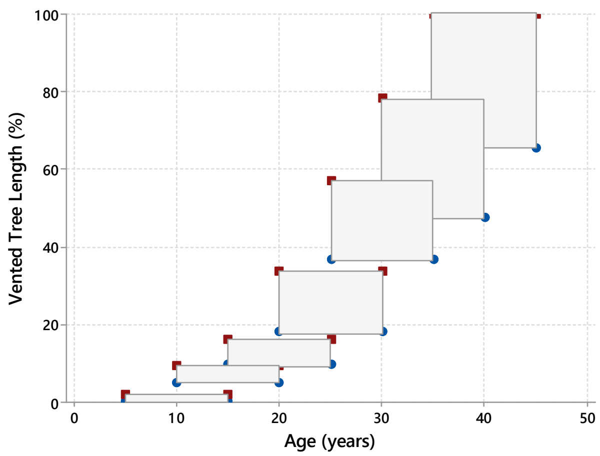

Figure 8: Evolution of median vented tree length (boxes = 90% Conf Int) for selected age ranges

DECISION MAKING

One of the goals for water tree analysis is to provide a way to consider a number of water tree factors / descriptors and infer whether the cable would be likely to fail and then provide an estimate of remaining life. To examine this need, an investigation assessed how useful the existing descriptors are at classifying water tree observations into two or more groups, in this case failed in service (F) and condition assessment (S). These meta data are available for all of these tree studies. Classically the length of the longest water tree has been considered sufficient to determine the likelihood of failure. The data collated in this work was sufficiently large to test how sufficient a descriptor is the longest water tree length. Analysis was then used to investigate how the different descriptors contribute to group separation. XLPE was selected for this analysis as it makes up the greatest number of segregated (F or S) cases. The results show:

- If the longest vented water tree length is considered then the classification is 40% accurate (i.e. if 100 failed samples are examined for tree length only 40 will be classed as failed)
- If the longest vented and bowtie water trees and their density are considered then the classification rate rises from 40% to 60% accurate
- Some methodologies use heuristics, such as number of water trees >50% of the insulation, to determine whether cables are at their end of life. Testing this model against the meta data, shows that this is accurate 49% of the time
- The use of cable age is little better as a means of decision making. Using the meta data collated here the age of the cable is 47% accurate in identifying cables that fail in service. This is particularly concerning as this is one of the primary means used by utilities to implement Asset Management

The median values for longest vented and bowtie water trees and their density are shown in Figure 9. The difference in the areas clearly show that the differences can be visualised on multiple dimensions of treeing. However to be practically useful it is important to be able to make such an assessment in a repeatable and robust manner. Additionally the representation in Figure 9 assumes that all of the features are equal weighted, in practice this is unlikely in that the maximum lengths carry a different weight to the tree density.

Figure 9: Radar Plot of Descriptors for Failed (blue) and Condition Assessment (red) (all insulations)

CABLE HEALTH INDEX

Although water tree data can provide a good description of the health of the insulation, it cannot capture all of the relevant information (cable design vintage (Table 2), number of previous failures, cable age, etc.). Thus, a more comprehensive decision tool would include these with the water tree data. One convenient way to combine the disparate "water tree" and "cable history" data is to use "principal component analysis" (PCA). This approach has proved to be very effective at combining different diagnostic features such as VLF Tan δ, Dissolved Gas Analysis (DGA) or Infra Red Thermography (IRT). The extension reported here is the first instance where meta data are combined with diagnostic features to determine health. The resulting results appear below for PC1, PC2, and PC3.

*PC(n) = a(n) * Longest vented tree length + b(n) * Median vented tree length + c(n) * Density of vented trees + d(n) * Longest bow tie tree length + e(n) * Median bow tie tree length – f(n) * Density of bow tie trees + g(n) * 1/Cable Generation + h(n)* Age + i(n)* Previous failures + j(n)*Neutral condition* Equation 1

In this work, the PCA method was applied to HMWPE, WTRXLPE, and XLPE insulations. A total of 310 cases are available with eight descriptors (Longest BTT % ins, Longest VT % ins, Density BTT (No/wafer), Density VT (No/20 wafers), Median BTT % ins, Median VT % ins, 1/Cable Generation, and Age). In the work reported here the impact of previous failures and condition of the metallic neutral have not been included. EPR cables grow water trees and can be treated in the same manner, but not within the same model as PE based insulations since the filled nature means that the density of trees are recorded at a different scale.

When undertaking PCA, all descriptors must be present for the analysis of each case. This requirement was satisfied for 108 cases for this set of descriptors. The contributions, or weights (values between -1 to 1), for each descriptor to each the first three principal components (PC1, PC2, PC3) are provided above. This was necessary to maintain a consistent "direction" for the features. In other words, the goal was to keep low numbers to mean "good" and high numbers to mean "less good". This scheme enables interpretation of the results and testing of the tool (i.e. if perceived bad numbers are inserted does the tool indicate a poor HI?).

It is important to note that the interpretation of principal components is semi-quantitative; however, patterns often emerge. This is not a concern here, as all previous approaches have been completely subjective and lacked the large collated database / structured analysis used here. Interpretations of the components appear below:

1. Most of the variance (37%) is covered by PC1 and this is a combination of the four water tree lengths (indicated by weights a, b, d, e). PC1 represents the combined impact of water tree lengths.
2. 18% of the variance is covered by PC2 and this is a combination of the two water tree densities (indicated by weights c, f). PC2 represents the combined impact of water tree density.
3. 15% of the variance is covered by PC3 and this (indicated by weights g, h) represents the cable generation and cable age.

The use of the principal components is additive in terms of the variance covered:

- PC1 covers 37% of the variance
- PC1 and PC2 cover 55% of the variance
- PC1, PC2, and PC3 cover 70% of the variance

After all of the components are calculated, combining them into a single Euclidean distance provides a single number for representing the Cable Health Index (CHI). This was done for these HMWPE/XLPE data, and is provided in as a cumulative probability function in Figure 10.

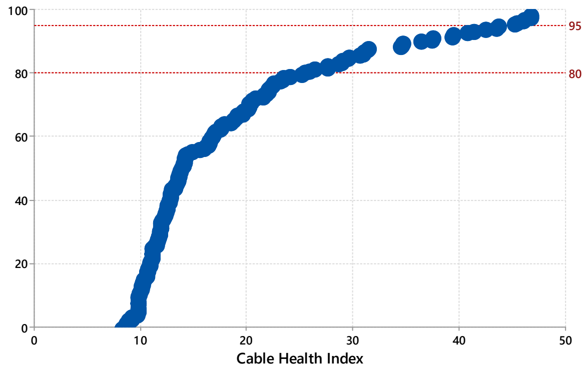

Figure 10 Cumulative probability of the Cable Health Index (calc from principal components) for PE based insulations – low CHI's represent good, high CHI's represent poor health

Furthermore, the percentile cut points can be used to establish robust assessment criteria, so that,

- Health indices > 45 may be categorized at the 95th percentile or above as **Action Required**
- Health indices > 25 and < 45 may be categorized between the 80th and 95th percentile as **Further Study Required**
- Health indices < 25 may be categorized below the 80th percentile as **No Action Required**

This method provides a consistent / unambiguous approach to decision making for cables found with water trees. There are a few other advantages

- If meta data are unavailable then the analysis can be completed based on the water tree data only using weights a through f. This is not to be recommended but can be necessary if details are not provided from the field
- As more data becomes available from sample returned from the field these can be fed back into the model to help refine the weights.

CASE STUDY

Table 4 Tree data for Case Study Cables

Ref	#452	#459
Longest VT	100	50
Longest BTT	36	13
Median VT	16	27
Median BTT	15	3
Density VT	6	0.7
Density BTT	0.02	0.6
CHI	35	23
CHI Context	90th percentile	80th percentile

To show how the Cable Health Index might be used consider the case of two 1970 vintage, generation 2, XLPE cables that were examined recently (Table 4).

There is extensive water treeing in these cables (gey rows of Table 4), however the context for the treeing is difficult to determine with the amount of data available. The Health Indices for these cables are provided in Table 5 (blue rows) along with the context, in terms of percentiles. Both cables are located within the Further Study Required region. If a prioritisation of resources had to be made then #452 would present the most concern due to its higher percentile.

CONCLUSIONS

Health Indices are well suited to these tasks as they are commonly used to condense and summarise many quantitative and semi qualitative factors.

The work reported focuses on how a collated fact base of water tree assessment was used in a diagnostic mode to:

1. Provide context to the outcomes of in-service diagnostic tests: water tree initiation, relative degrees of water treeing, etc.
2. Guide the selection of the appropriate diagnostic features to be included in assessments: limited usefulness of a single feature (age or longest vented water tree), the number of features required to describe water treeing, etc.
3. Develop a structure to estimate the health of the cable dielectric by addressing both water tree data and cable system meta data
4. Support the appropriate framing of the outcomes: how does water treeing relate to the chronological age; is it ageing slower or faster, how best to represent the results in context within a single utility and the industry

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GLOSSARY

BTT: Bow Tie Tree
CHI: Cable Health Index
MED: Major Event Day
PC : Principal Component
SAIDI: System Average Interruption Duration Index
SAIFI: System Average Interruption Frequency Index
ThermoP : Thermoplastic
ThermoS : Thermoset - crosslinked
VT: Vented Tree
WB: Water Block