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Methods and Experience of Diagnostic Testing to Support Asset Management of Feeder Type Cable Systems

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Outline

- Background
- Potential approaches
- Population based assessment principle
- Tan δ diagnostic features
- Combining diagnostic features - new approach
- Population based assessment - percentile Ranks
- Health index
- Case Study – Feeder Replacement Prioritization
- Takeaways

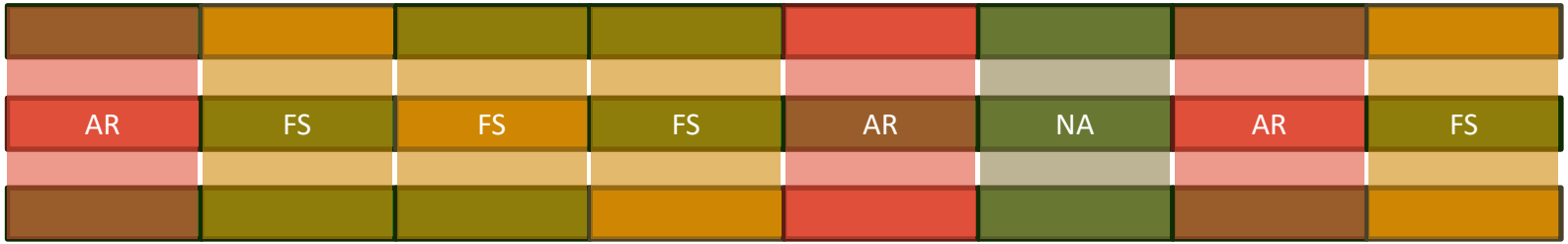
Background

- The documented VLF Tan δ criteria discussed to date only provides guidance at the “Single Phase” level

- It is increasingly common to test “Three Phase” systems (Feeders) a VLF Tan δ Health Assessment program – three phases diagnosed as they are treated jointly

Potential Approaches

- An obvious approach uses the current criteria is to simply take the worst assessment and apply this to the three phases

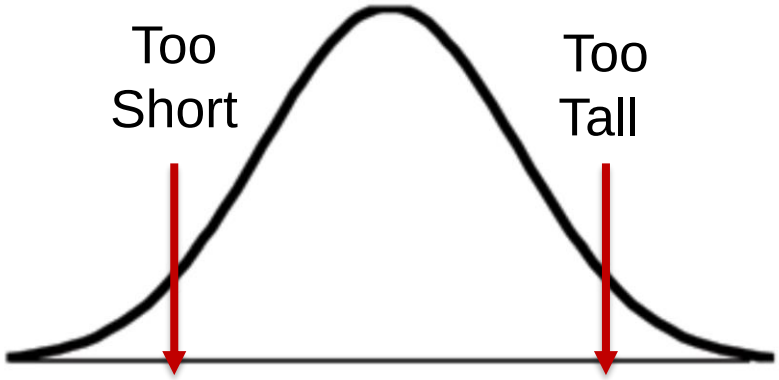


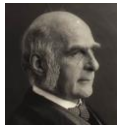
- However, this leads to
  - Higher than expected diagnoses of “Action Required” (14%) and “Further Study Advised” (35%)
  - Unused sources of information: phases expected to be similar

Population Based Assessment Principle

Population Height

From Disorder to Order

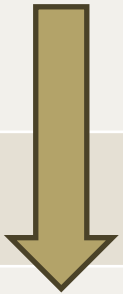




Sir Francis Galton (1822 - 1911): He was the first to apply statistical methods to the study of human differences

Recall – Single Phase Tan δ Features

	Feature	Individual Features	
IEEE 2024 CDFI 2016	**Tan δ Stability** Standard Deviation @ Uo	STD	Most Discerning
IEEE 2024 CDFI 2016	**Tip Up** Mean Tan δ @1.5Uo - Mean Tan δ @0.5Uo	TU	
CDFI 2016	**Tip Up of the Tip Up** Δ Tan δ 1.5Uo to Uo - Δ Tan δ Uo to 0.5Uo	TUTU	
IEEE 2024 CDFI 2016	**Tan δ** Mean Tan δ @ Uo	TD	Least Discerning



Simple Three Phase Tan δ Application

Feature	Individual Features		
	Phase A	Phase B	Phase C
Tan δ Stability	STD_A	STD_B	STD_C
Tip Up	TU_A	TU_B	TU_C
Tip Up of the Tip Up	$TUTU_A$	$TUTU_B$	$TUTU_C$
Mean Tan δ	TD_A	TD_B	TD_C

Three Phase Tan δ Diagnostic Features

Feature	Individual Features			Combined
	Phase A	Phase B	Phase C	**Feeder Level**
Tan δ Stability	STD_A	STD_B	STD_C	**Highest STD**
Tip Up	TU_A	TU_B	TU_C	**Highest TU**
Tip Up of the Tip Up	$TUTU_A$	$TUTU_B$	$TUTU_C$	**Highest TUTU**
Mean Tan δ	TD_A	TD_B	TD_C	**Highest TD**
	Similarities between Phases			
Mean Tan δ Range	TDRG			**TDRG**

Tan δ Diagnostic Feeder Features

Features used for condition assessment at the “Feeder” level:

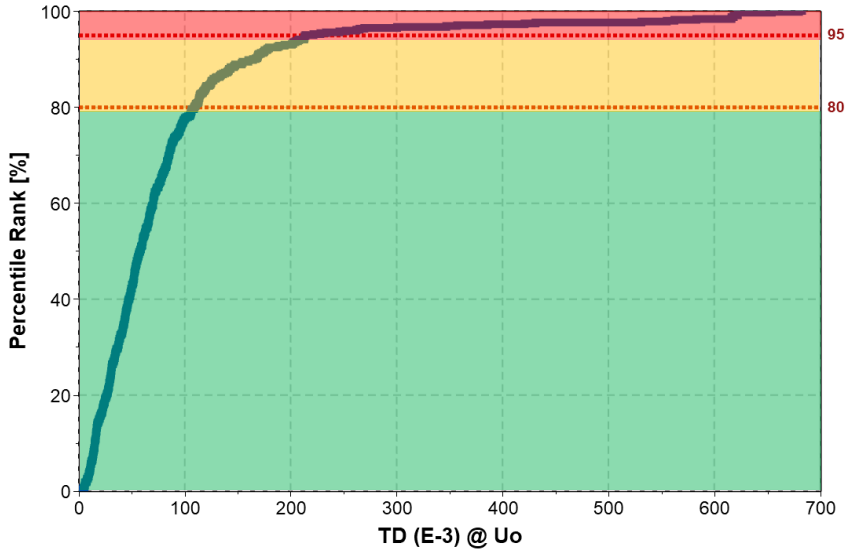
- **Maximum Phase Tan δ Stability (STD)** – The highest Tan δ stability of all three measured at U_0.
- **Poorest Phase Tip Up (TU)** – The highest Tip Up measured in any one of the three phases.
- **Poorest Phase TUTU** – The highest Tip Up of the Tip Up measured in any one of the phases.
- **Maximum Phase Mean Tan δ (TD)** – The highest mean Tan δ measured on any one of the three phases at U_0.
- **Mean Tan δ Range for Three Phases (TDRG)** – The difference between the highest mean Tan δ at U_0 and the mean lowest Tan δ at U_0.

Criteria Setting – basis used in IEEE400.2

- Limited information on actual field performance
- Pareto Principle – 20/80 rule
- Outlier Principle – 95th percentile
- Need to combine features:
  - Single value decomposition
  - Combining percentile ranks (NEW)
- Assessment outcomes:

- **No Action**
- **Further Study**
- **Action Required**

Example of Diagnostic Feature Percentile Rank



Tan δ Diagnostics – CDFI Criteria

Best ranking 80%

Middle ranking 15%

Poorest ranking 5%

Table 29: VLF Ta

These criteria CANNOT **data arc** **for all five**

Condition Assessment [E-3]	No Action Required	Further Study Advised	Action Required
Max Phase Stability for TD_{U_0} (standard deviation)	< 1.2	1.2 to 2.3	> 2.3
	and	or	
Tan δ Range for Three Phases (Max Mean TD_{U_0} –Min Mean TD_{U_0})	< 30	30 to 50	> 50
Poorest Phase Tip Up ($TD_{1.5U_0} - TD_{0.5U_0}$)	-45 to 24	-57 to -45 or 24 to 30	< -57 or > 30
	and	or	
Poorest Phase TuTu $\{(TD_{1.5U_0}–TD_{U_0}) - (TD_{U_0}–TD_{0.5U_0})\}$	< 16	16 to 23	> 23
	and	or	
Max Phase Mean TD_{U0}	< 170	170 to 210	> 210

Only PILC criteria is available

Courtesy: CME Wire & Cable

To be updated and expanded (insulation types) if data allows it

Overall Interpretation from Many Features

- Five features available for Feeder Cable diagnosis
- Need a straightforward and easily understood combination
- A parallel structure (exclusive OR) is used to combine features and estimate a Health Index at the “Feeder” level:
  - No transformation – probabilistic approach
  - All features have the same importance in statistical terms
  - Correlated with population-based condition assessment principles

$$\emptyset(x_1, x_2 \ldots, x_n) = 1 - (1 - x_1)(1 - x_2) \ldots (1 - xn) = \prod_{i=1}^{n} x_i$$

Combining Diagnostic Features – Health Index

Therefore, for condition assessment at the “Feeder” level with the five features:

$$Combined\ PR = 1 - (1 - PRST_D)(1 - PRTU)(1 - PRTUT_U)(1 - PRTD)(1 - PRTDRG)$$

Where PR is the Percentile Rank of the corresponding feature.

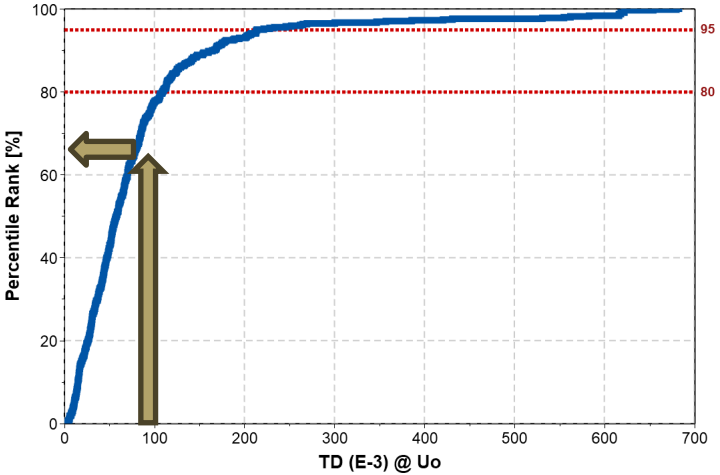
The Health Index is defined as:

$$Health\ Index = k(1 - Combined\ PR)$$

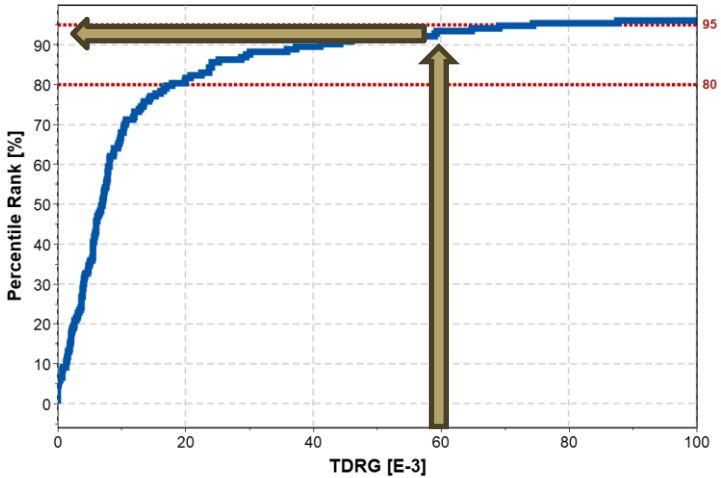
Where k is a correction factor to account for the compounded accumulation phenomena

Diagnostic Features – Percentile Ranks

PR_{TD}

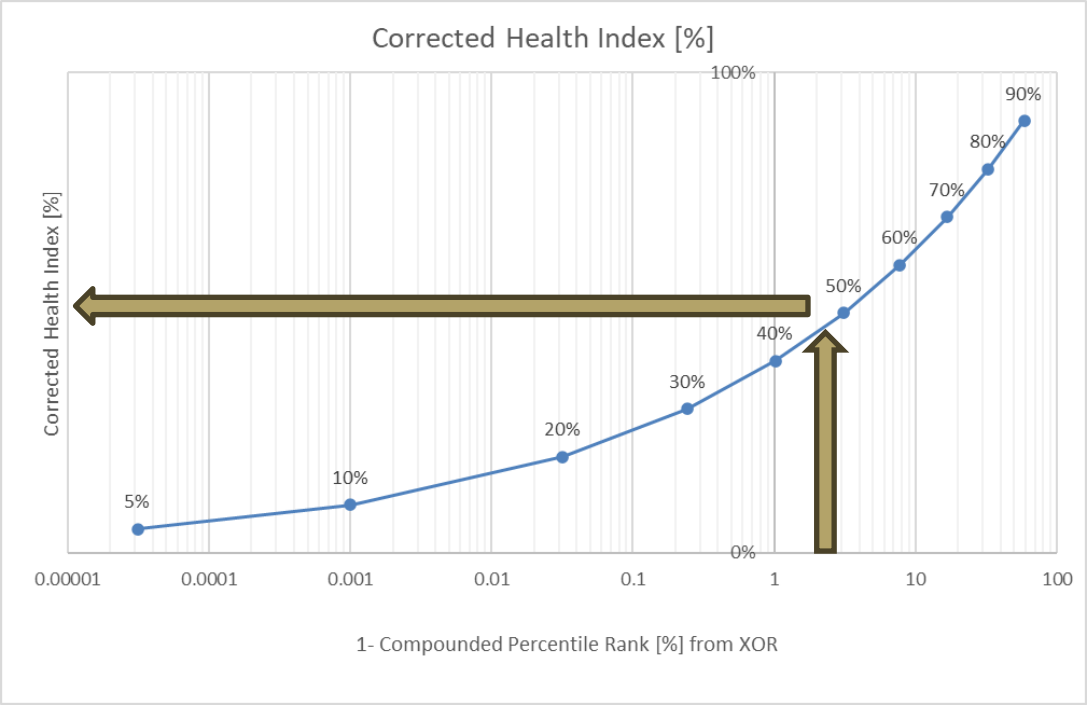


PR_{TDRG}



541 tests representing approximately 243 miles of active PILC cable system length

Assessment – Health Index Estimation



The corrected Health Index is computed considering all the features at the same percentile rank and establishing the corrected Health Index to be at the same rank level.

For example, if all the features are at the 20th percentile, the corresponding corrected Health Index is 80%

Case Study – Relative Feeder Replacement Priority

VLF Tan δ feeder test data:

No	Insulation	ID	Capacitance [nF]	Vn [kV]	Uo [kV]	TD (E-3) @0.5Uo	TD (E-3) @1Uo	TD (E-3) @1.5Uo	STD (E-3) @0.5Uo	STD (E-3) @1Uo	STD (E-3) @1.5Uo	Tip Up 1.5-0.5	TuTu (E-3)
1	PILC		117	15	12	20.40	21.23	25.38	0.2	0.3	0.9	4.98	3.32
2	PILC		122	15	12	13.44	9.99	8.17	0.1	0.0	0.0	-5.27	1.63
3	PILC		110	15	12	10.41	8.91	7.81	0.0	0.0	0.0	-2.60	0.40
4	PILC		52	15	12	56.95	53.60	49.79	0.0	0.2	0.3	-7.16	-0.46
5	PILC		55	15	12	76.39	66.06	62.08	0.1	0.3	0.2	-14.31	6.35
6	PILC		52	15	12	35.36	30.48	31.79	0.1	0.1	0.2	-3.57	6.19
7	PILC		112	15	12	8.80	7.77	7.04	0.0	0.0	0.0	-1.76	0.30
8	PILC		112	15	12	5.75	5.56	6.23	0.0	0.1	0.1	0.48	0.86
9	PILC		109	15	12	8.31	8.67	8.74	0.0	0.1	0.1	0.43	-0.29
10	PILC		50	15	12	42.92	42.87	42.33	0.1	0.1	0.0	-0.59	-0.49
11	PILC		51	15	12	28.35	23.62	21.21	0.2	0.4	0.3	-7.14	2.32
12	PILC		54	15	12	45.74	42.53	42.23	0.1	0.1	0.3	3.51	2.51
13	PILC		114	15	12	37.58	36.48	35.44	0.0	0.1	0.1	-2.14	-1.06
14	PILC		113	15	12	26.64	25.41	23.80	0.0	0.0	0.1	-2.84	-0.38
15	PILC		111	15	12	15.12	15.58	16.05	0.0	0.3	0.1	0.93	0.01
16	PILC		50	15	12	86.56	82.05	88.77	0.6	1.3	1.7	1.01	10.73
17	PILC		51	15	12	84.18	82.30	81.84	0.3	1.2	1.3	-2.34	1.42
18	PILC		53	15	12	79.44	71.40	69.48	0.3	0.7	0.2	-9.96	6.12
19	PILC		149	15	12	15.44	13.79	14.80	0.1	0.1	0.2	-0.64	2.66
20	PILC		148	15	12	19.61	18.05	16.86	0.0	0.0	0.2	-2.75	0.37
21	PILC		146	15	12	20.21	19.22	20.99	0.2	0.3	0.4	0.78	2.76
21	PILC		29	15	12	119.42	103.51	95.31	0.4	0.4	1.1	-24.11	7.71
21	PILC		28	15	12	65.33	55.57	51.13	0.4	0.4	0.8	-14.2	5.32
21	PILC		27	15	12	73.47	62.44	57.89	0.3	0.3	0.7	-15.58	6.48
21	PILC		29	15	12	100.04	80.54	73.84	0.6	0.5	1.2	-26.2	12.8
21	PILC		28	15	12	113.01	94.18	88.86	0.7	0.7	1.4	-24.15	13.51
21	PILC		32	15	12	74.86	61.36	57.31	0.6	0.6	1.3	-17.55	9.45
21	PILC		31	15	12	92.44	80.75	73.51	0.3	0.2	0.7	-18.93	4.45
21	PILC		29	15	12	96.88	79.05	73.29	0.7	0.7	1.2	-23.59	12.07
21	PILC		30	15	12	62.09	52.85	18.44	0.4	0.3	0.7	-43.65	-25.17

Measured Data

Calc Data

Case Study – Relative Priority Results

Feature Rank

Poorest STD	Range TD	Poorest TU	Poorest TUTU	Poorest TD	Compounded Rank	Health Index	Priority Rank	3-Phase Assessment	Individual Assessment
									Further Study
									Further Study
									Further Study
									Further Study
									Further Study
									Further Study
									Further Study
									Further Study
									Further Study
									Further Study

Takeaways

1. Single Phase methods cannot be directly applied to Three Phase systems
2. Simple heuristics are available for Three Phase Systems
3. Population based methods can provide condition assessment
4. New approach combines features using parallel structures
5. The Health Index can be used as a tool for prioritization