A Study on Three Dimensional Assessment of the Aging Condition of Polymeric Medium Voltage Cables Applying Very Low Frequency(VLF) tanδ Diagnostic

WETS D'15 Workshop

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WETS D'15

Korea Electric Power Corporation (KEPCO)

Prologue

❖ Background

– As Power Grid becomes complicated and smart, and as customer & industrial facilities enhance, damage that customers feel and social loss cost from power failure increase.

– Maintenance policy for reasonable and optimum power facility is required based on scientific data analysis.

1st Generation of Facility Management

Time Based Management

• All replaced after certain time ⇒ excessive cost of maintenance

• Difficulty in preventing unexpected defect ⇒ lack of stability

2nd Generation of Facility Management

Condition Based Management

• Judging condition through diagnosis

• Securing grounds for investment to replace facility

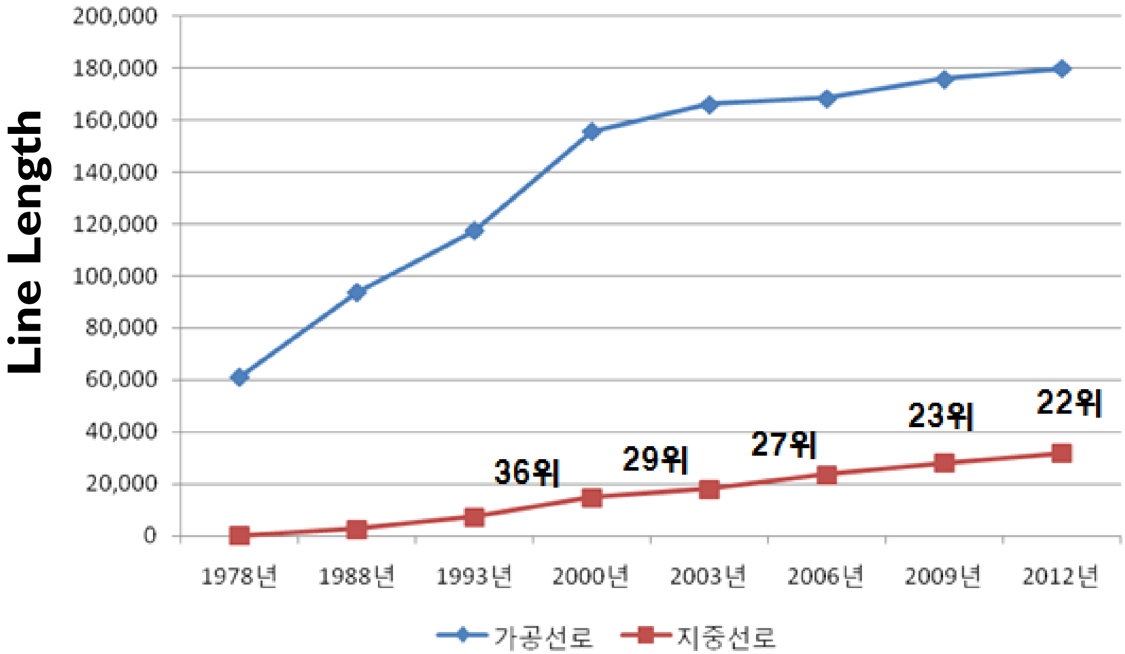
3rd Generation of Facility Management

Risk & Condition Based Management

• Decision-making method for operational limit is required to prevent defect.

• Change of paradigm by **risk-based state management technique, fusing maintenance technology and feasibility.**

❖ Growing Trend in Underground Distribution System



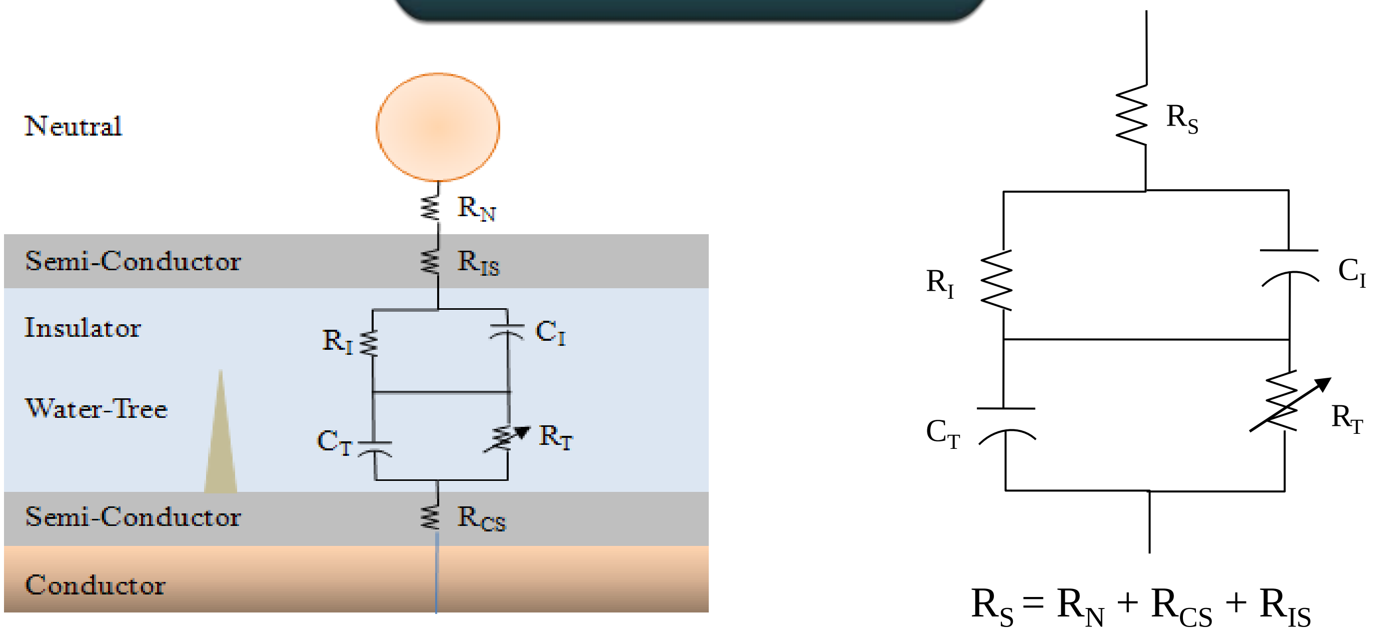
Processing Line / Underground Line

- As national competitiveness increases, the advanced infrastructure of **underground distribution system increases**.
- Rate of increase of underground distribution system in Korea is **about 6.6% in annual average**. In 2013, 31,907 c-km was installed.
- Meanwhile, processing facility showed rate of increase of 8% in annual average in 1990's; it dropped by 1% after 2003.
- In 2012, processing facility showed -0.6% of rate of increase ⇒ Substituted with underground distribution facility

❖ Equivalent Circuit of Water-tree

- Water-tree is expressed in change of capacitance C_T and resistance R_T
- **Level of water-tree generation is measured with size of charge** trapped in water-tree **(IRC method)**
- **Value of change in capacitance and resistance** by water-tree is **measured to measure level of water-tree generation (VLF tanδ method)**

Equivalent Circuit of Water-Tree Cable



$$R_S = R_N + R_{CS} + R_{IS}$$

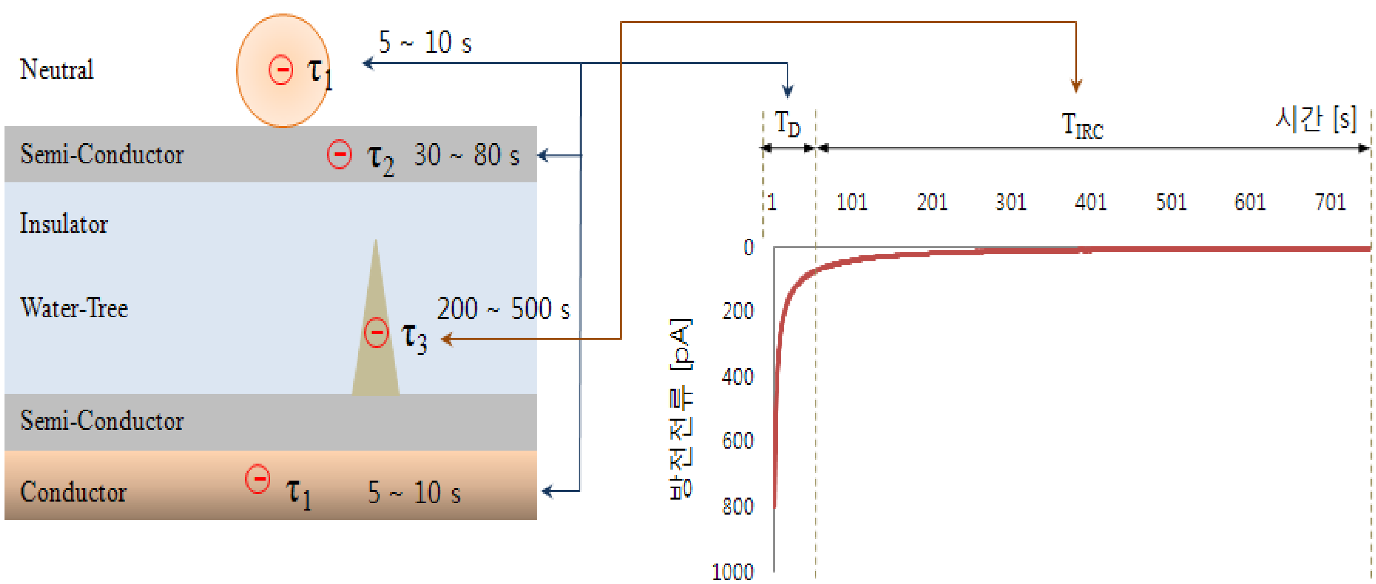
Diagnosis of Power Cable

1. IRC Diagnosis (Isothermal Relaxation Current)

❖ Principle of Measurement

- **After applying & charging core wire of cable, it is discharged in short period of time, and the quantity of remaining trapped charge is measured to determine condition of cable.**

Principle of IRC Diagnosis

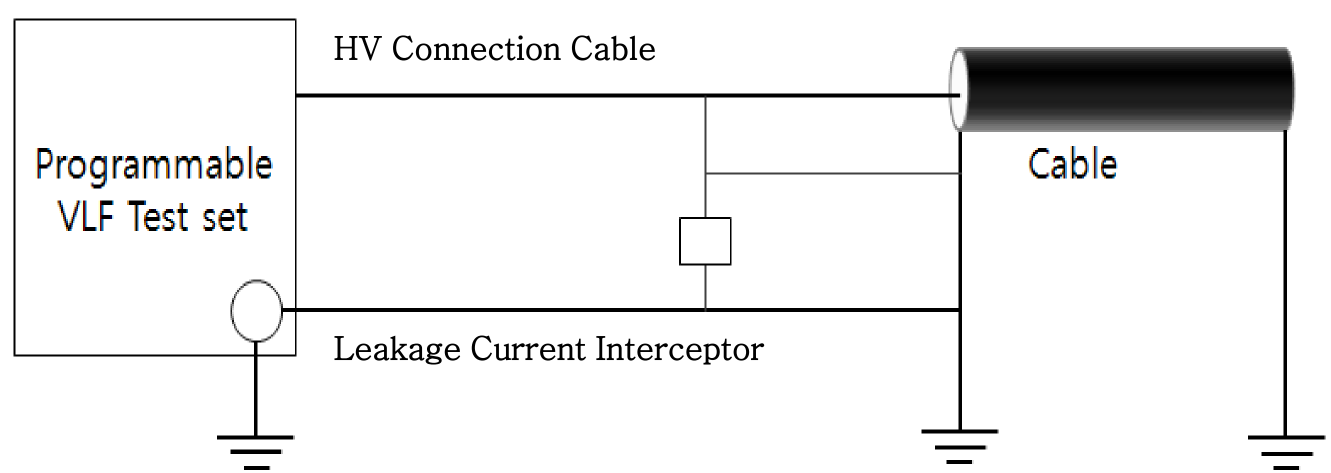


2. VLF tanδ Diagnosis (Very Low Frequency)

❖ Measuring Dissipation Factor (tanδ) using VLF(0.1Hz) Sine Waveform

- First used as monitoring degradation of extruded insulator cable in 1981
- Proven to have correlation with increase of dissipation factor for testing voltage of 0.1Hz and decrease of power frequency voltage breakdown (Bach et al.)

VLF(0.1Hz) Test set for Measurement of Dissipation Factor of Cable Insulator



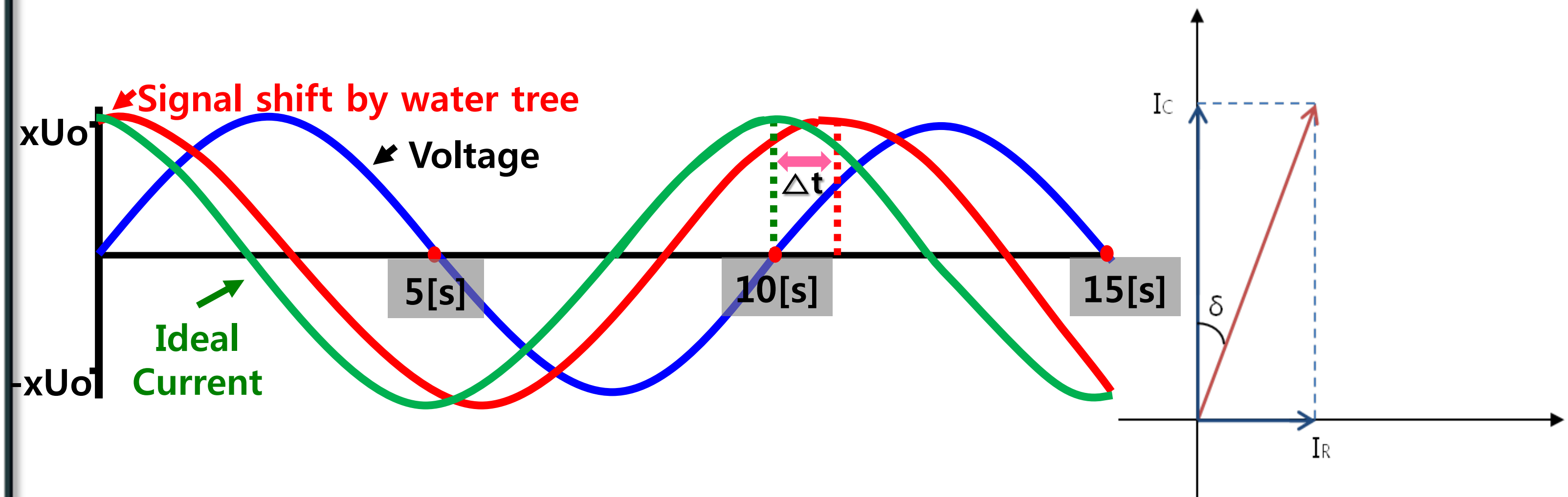
❖ Definition of Dissipation (tanδ)

- Measuring change in phase of voltage and current by applying power to cable

$$\tan\delta = \frac{I_R}{I_C} = \frac{true\ power}{reactive\ power} = \frac{V^2 / R}{V^2\ C} = \frac{1}{CR}$$

- In ideal cable with structure of Cylindrical Capacitance, **voltage and current have phase difference of 90°**
- In case of water-tree, change in phase angle with change of C and R components (90° - δ). **The dissipation factor is shown as tan δ**

Measurement of Cable Dissipation Factor using 0.1Hz Power



Phase difference: Voltage↔Current **Tanδ on Complex Plane**

3. Selection of Diagnosis: VLF tanδ

- **Reason: There are logical validity for easiness, quickness, and reliability to collect data and analyze types. It is possible to derive self-determination that is suitable for operational environment.**

Category	VLF	IRC
Collecting Data	Direct acquisition of Tanδ raw data	Quantified value by self-algorithm
Using Data	High reliability of data due to normalization of diagnostic conditions	Determined only with value suggested by equipment

- **IRC diagnosis is weak with limit of measurement distance (400m), long time required for measurement (3 hours), and outside noise.**

Features of VLF Diagnosis

- Time to measure is very short with testing voltage of 0.1Hz **(one data / 10 seconds)**
- Measurable with various testing voltage. 0.5, 1.0, 0.5U_0 are used in Korea (U_0 : basic phase voltage)
- **No side effect such as generation of space charge within insulator** because it uses alternating testing voltage.
  - ☞ IRC applies DC 1,000V as testing voltage (30min) ⇒ Inducement of polarization of high molecule
    ⇒ Generation of space charge
- But for accurate measurement, there should be no distortion of testing voltage waveform (true sine wave)

Result Analysis of Diagnosis & Development of Degradation Determination Tool

Definition of Measurement Factor for VLF tan δ

TD : the average of 8 of tanδ value

- VLF tanδ is measured dissipation of alternating voltage insulator
- tan δ is measured consecutively (6~8 times) and the arithmetic mean is set as TD. (※ Takes 10 seconds at a time)

  ☞ This study applied tan δ measured 8 times.

DTD : voltage stability of TD

- DTD is TD value for high applied voltage, deducted by TD value for low applied voltage; it shows voltage stability.
- As DTD is high, insulator is affected by applied voltage.

TDTS : time stability of 8 of tan δ value

- TDTS is standard deviation for 6~8 counts of tanδ value ⇒ $TDTS = \sqrt{\frac{\sum_{k=1}^{n}(x_k - m)^2}{n}}$
- It is factor to determine insulator tolerance during testing time for specific VLF testing voltage; it means time stability. (※ also marked as STDEV)

Trend of Criteria for VLF tan δ

International Trend

2001	2011	2013
IEEE Std. 400-2001 Provision of VLF tanδ criteria TD, DTD Only PE is regulated	**IEEE Std. 400 Draft 11** Provision of new criteria TDTS(TD Time Stability) Provision of standard such as XLPE, TR-XLPE, EP	**IEEE Std. 400.2-2012** Analysis of about 5,300 data collected from North American cable

National Trend

2010	2011 ~ 2012	2013 ~ 2014
Application of IEEE Std. 400-2001	**Acquisition of about 15,000 VLF tan δ Data from domestic XLPE cable**	**Development of degradation factor & establishment of Criteria** ⇒ **Contributed in IEEE TDEI Journal**

Change in tanδ by Cable Length

❖ **After VLF tanδ , VLF tanδ for sections by subdividing remaining phase (A, C phase) of cable with defect (B phase)**

⇒ It is difficult to determine defect, because TD shows dissipation factor of total cable, even though section with severe degradation is included.

Actual re-measured data for long-distance section (A phase)

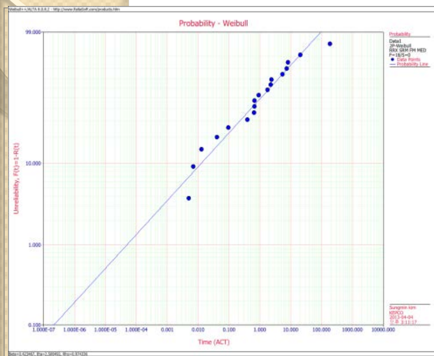
Measurement distance		TD at $0.5U_0$	TD at $1.0U_0$	TD at $1.5U_0$	DTD
3,696 m		0.242	0.250	0.298	0.056
Re-measurement after section separation	228 m	0.311	0.580	0.664	0.353
	1,840 m	1.033	2.838	4.966	3.933
	766 m	0.583	2.350	6.314	5.731
	1,074 m	0.256	0.258	0.338	0.082
	376 m	0.247	0.360	1.929	1.682
	366 m	0.274	0.456	0.731	0.457
	166 m	0.351	0.751	1.195	0.844
	191 m	16.211	20.119	30.476	14.265
	175 m	1.161	2.733	4.683	3.522

Actual re-measured data for long-distance section (C phase)

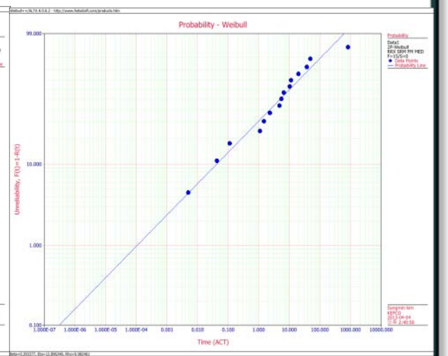
Measurement distance		TD at $0.5U_0$	TD at $1.0U_0$	TD at $1.5U_0$	DTD
3,696 m		0.237	0.260	0.294	0.057
Re-measurement after section separation	228 m	0.371	0.451	0.658	0.287
	1,840 m	0.232	0.250	0.284	0.052
	766 m	0.230	0.356	0.874	0.644
	1,074 m	0.284	0.424	0.403	0.119
	376 m	0.224	0.231	0.308	0.084
	366 m	0.360	0.550	0.729	0.369
	166 m	58.642	57.594	57.270	1.372
	191 m	1.318	2.565	3.646	2.328
	175 m	3.362	3.674	4.344	0.982

Tanδ Pattern

STDEV Weibull distribution for cable with defect



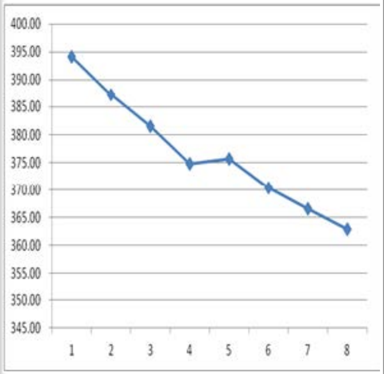
ⓐ $1.0U_0$



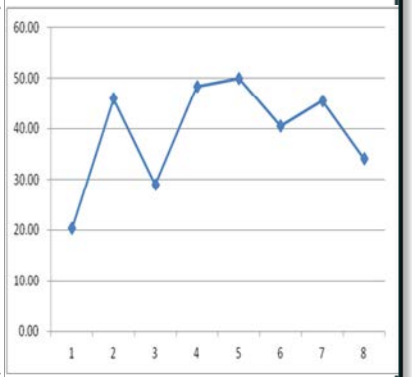
ⓑ $1.5U_0$ STDEV

- Defective cable adjusts to Weibull distribution,
- As testing voltage increases, scale parameter increases ⇒ tan δ increases

plotting trend of tanδ for time stability

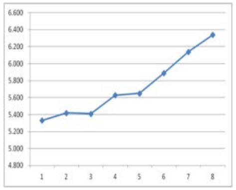
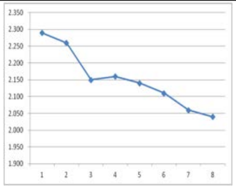
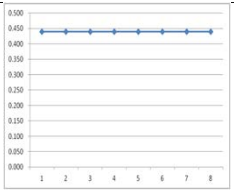
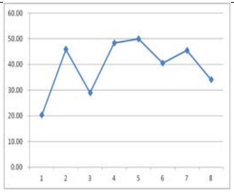


ⓐ Linear Trend



ⓑ Non-linear Trend

plotting trend & pattern of tanδ for time stability

Trend		Linear		Non-linear
Pattern	Positive	Negative	Constant	Oscillated
Shape				

Development of "Skirt," Time Stability Factor

1) In order to quantitatively divide linear and nonlinear trend for tanδ data, virtual line to connect the max and min values among 8 data (t_n) is generated

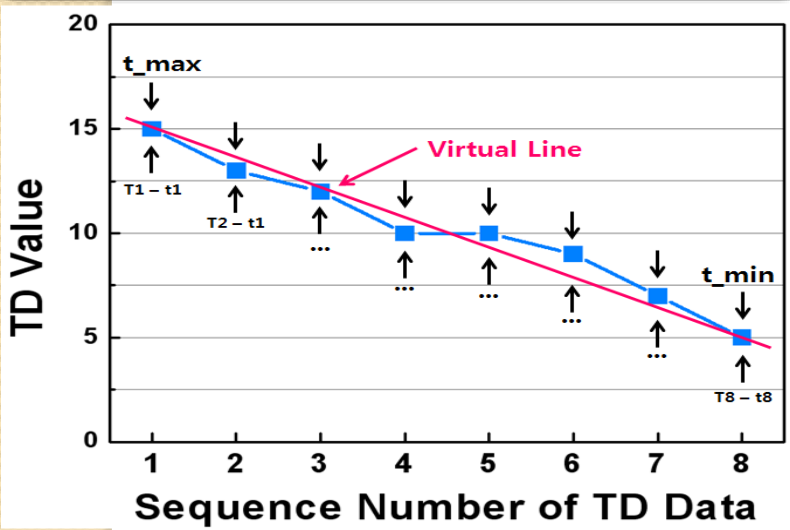
※ Skirt is the sign that occurs immediately before insulation breakdown of cable. Its size and level shall be expressed quantitatively.

$$Y = \frac{t_{max} - t_{min}}{N_{max} - N_{min}} X + A_0$$

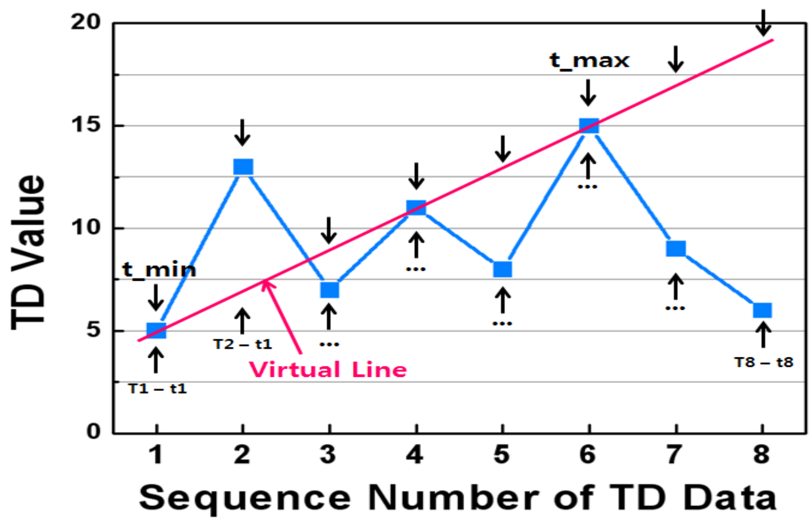
$$A_0 = T_i - \left(\frac{t_{max} - t_{min}}{N_{max} - N_{min}}\right) \times i$$

t_{max} : Max value from 8 actual tan δ,
t_{min} : Min value from 8 actual tan δ
N_{max} : Value of x-axis where t_{max} is
N_{min} : Value of x-axis where t_{min} is
A_0 : y-intercept of virtual line

Adjustment of virtual line for tanδ plots ⓐ Adjustment of linear trend



Adjustment of virtual line for tanδ plots ⓑ Adjustment of vibrating trend



2) Standard deviation for difference in virtual point and tanδ : $STDEV_{virtual}$

$$STDEV_{virtualline} = \sqrt{\frac{\sum_{k=1}^{n}(|T_k - t_k| - m)^2}{n}}$$

while, m : average of $|T_n - t_n|$

- To present the level of adjustment of actually measured tanδ and virtual line: **standard deviation for difference between virtual point T_n and tanδ measured value t_n** that are relevant to each sequence number.
- **As low the value of $STDEV_{virtual}$ is, it means high level of adjustment with virtual line. Large value of linear trend** $STDEV_{virtual}$ means that measured tanδ has irregular non-linear trend

3) Correction parameter : κ

$$\kappa = \frac{A_0}{Log(STDEV_{virtual} \times 10000)}$$

- **Defective cable shows high value of tanδ and low value of $STDEV_{virtual}$.**
- Because Tanδ and $STDEV_{virtual}$ shows conflicting quantitative value, **$STDEV_{virtual}$ is corrected for same tendency** (amplifying the size by 10,000 times and taking reciprocal of Log)

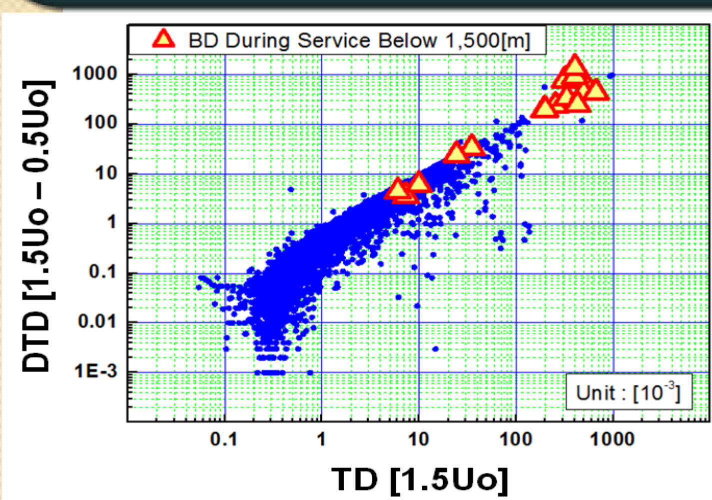
4) Derivation of Skirt

$$\mathit{Skirt} = \text{degree of slope} \times \kappa$$

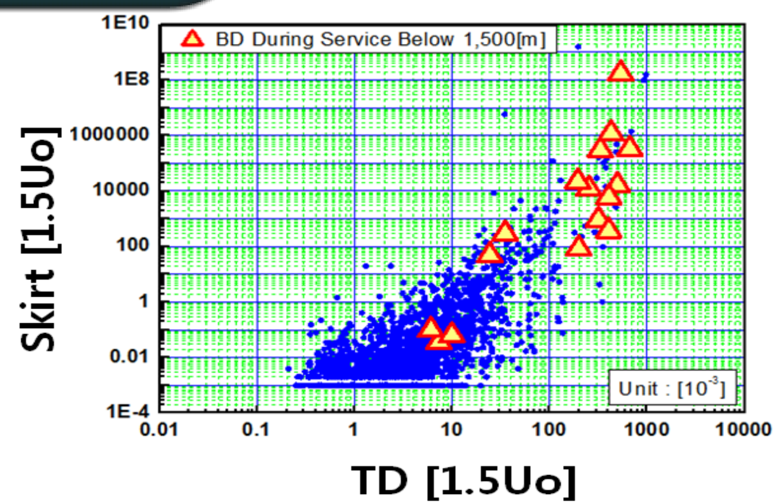
While, degree of slope = $(t_{max} - t_{min}) / (N_{max} - N_{min})$

1) Mathematical model that displays slope of tanδ as virtual line is presented.
2) Quantification of adjustment of virtual line and measured tanδ, using standard deviation
3) Presentation of correction parameter K, the mathematical model
4) **As composing quantitative value with slope of virtual line, invalid and valid value can be separated** by size and form of tanδ and measuring error.

Dispersed Distribution of TD vs. DTD, TD vs. Skirt



ⓐ TD vs. DTD (Voltage Stability)

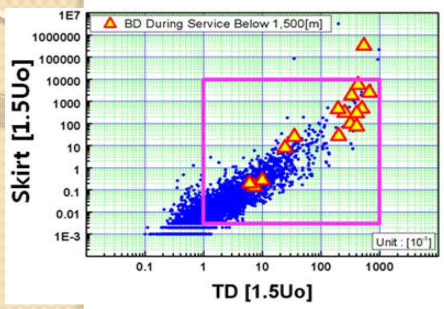


ⓑ TD vs. Skirt (Time Stability)

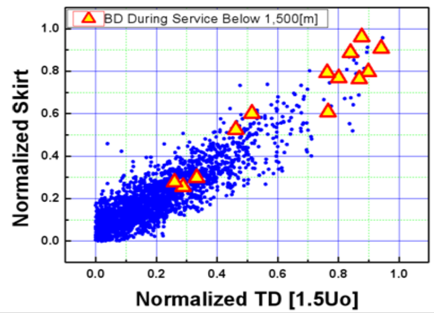
⇒ Triangles represent data for cable that showed defect after measuring tanδ

Development of Degradation Determination Tool using 3D Matrix

Normal Dispersed Distribution of TD vs. Skirt



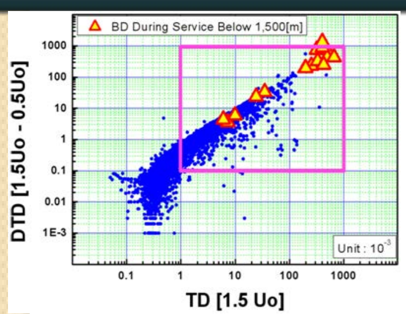
ⓐ TD vs. Skirt Distribution Graph



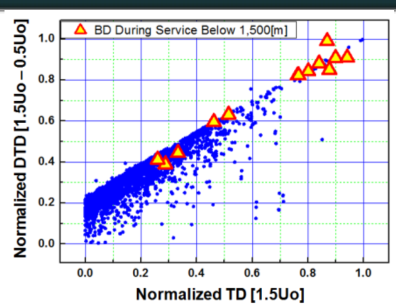
ⓑ TD vs. Skirt Normal Distribution

❖ Take logarithm of x- & y-axis that are marked in red line in ⓐ, and re-scale as 0~1; normal distribution graph is derived as ⓑ.

Normal Dispersed Distribution of TD vs. DTD



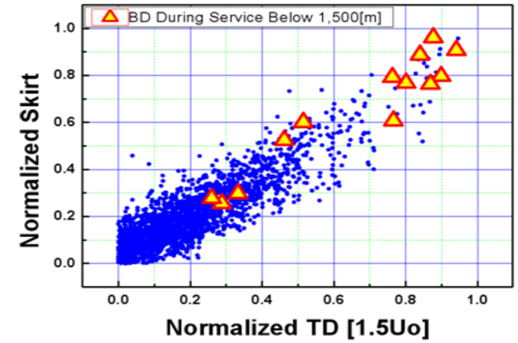
ⓐ TD vs. DTD Distribution Graph



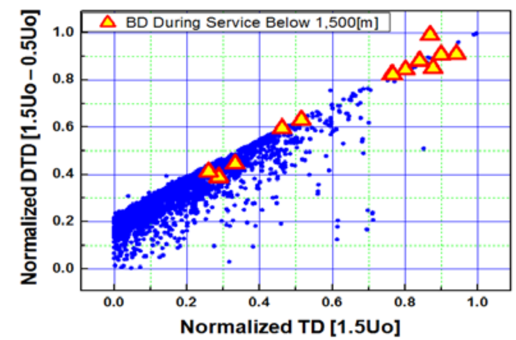
ⓑ TD vs. DTD Normal Distribution

❖ By taking the point at 1.0×10^{-3} of origin as unit coordinate with 0 possibility of defect, data meaningless to degradation determination can be eliminated.

Normal degradation factor distribution graph



ⓐ TD vs. Skirt Normal Distribution Graph



ⓑ TD vs. DTD Normal Distribution Graph

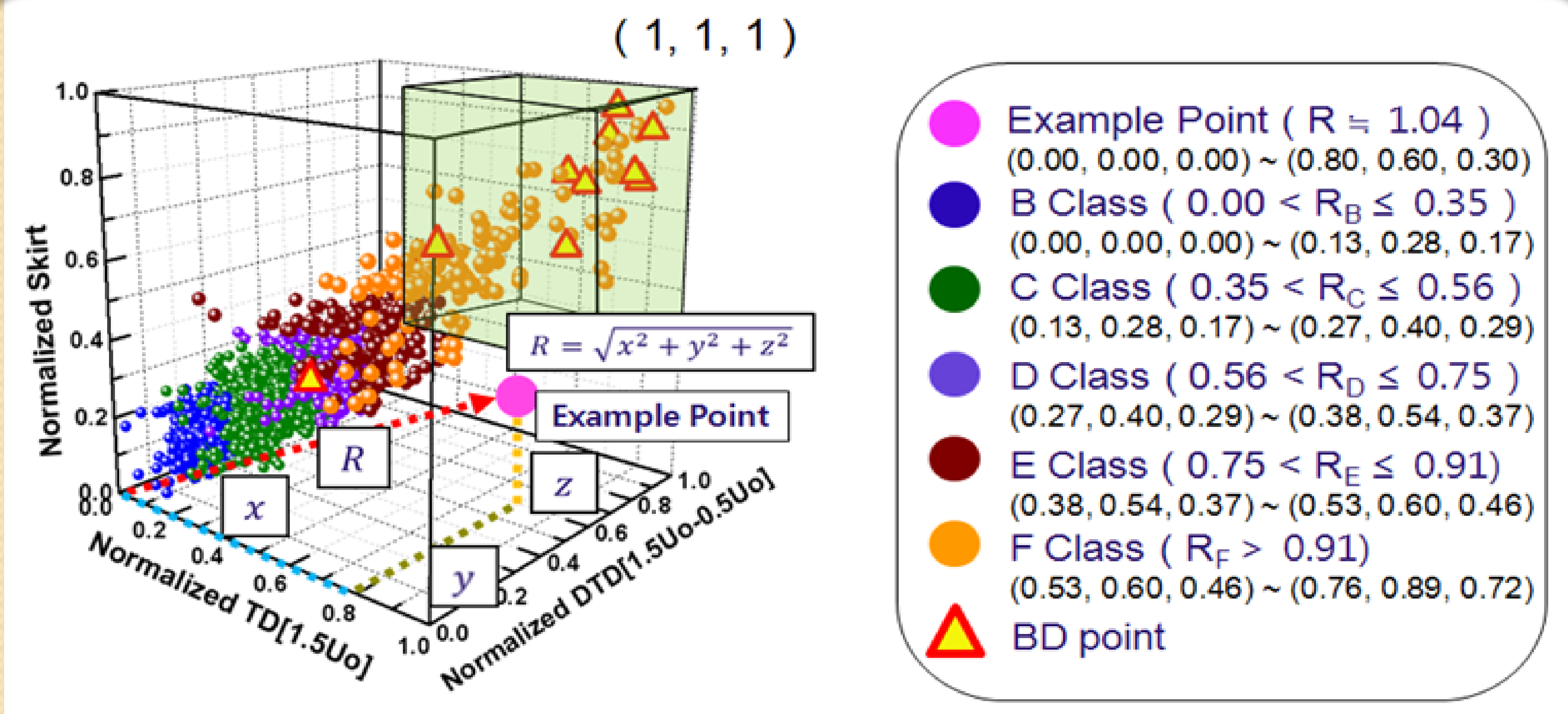
❖ Re-structure degradation factors as degradation distribution with same scale by normalization process

❖ Compare correlation between Skirt and DTD based on TD

Realization of 3D Matrix

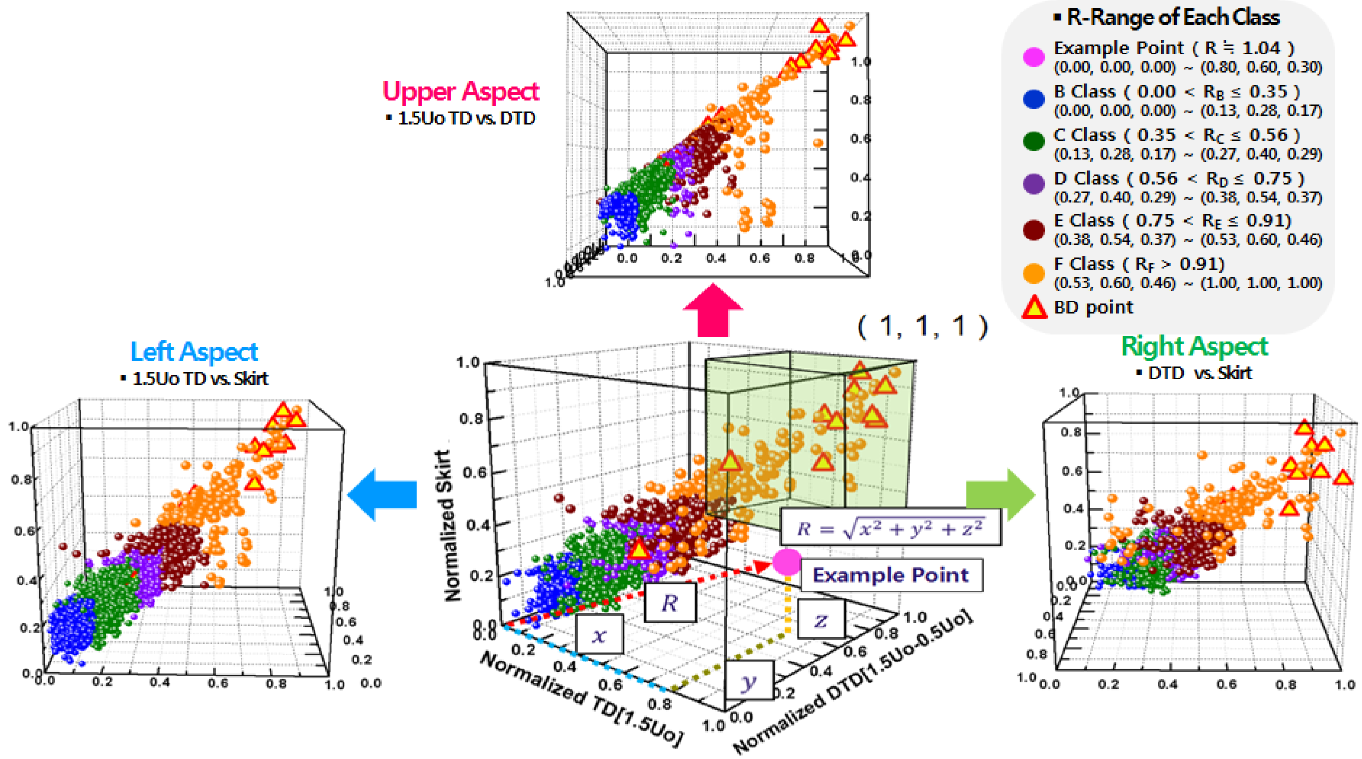
- Realization of 3D matrix by distributing normalized TD, DTD, and Skirt in 3-dimention
- Quantitative values of TD, DTD, and Skirt are displayed as fused position vector.
- Level of degradation is presented Scalar value of position vector.

※ Presented based on revision for criteria of IEEE in 2012 (IEEE Trans. on DEI , 2014)



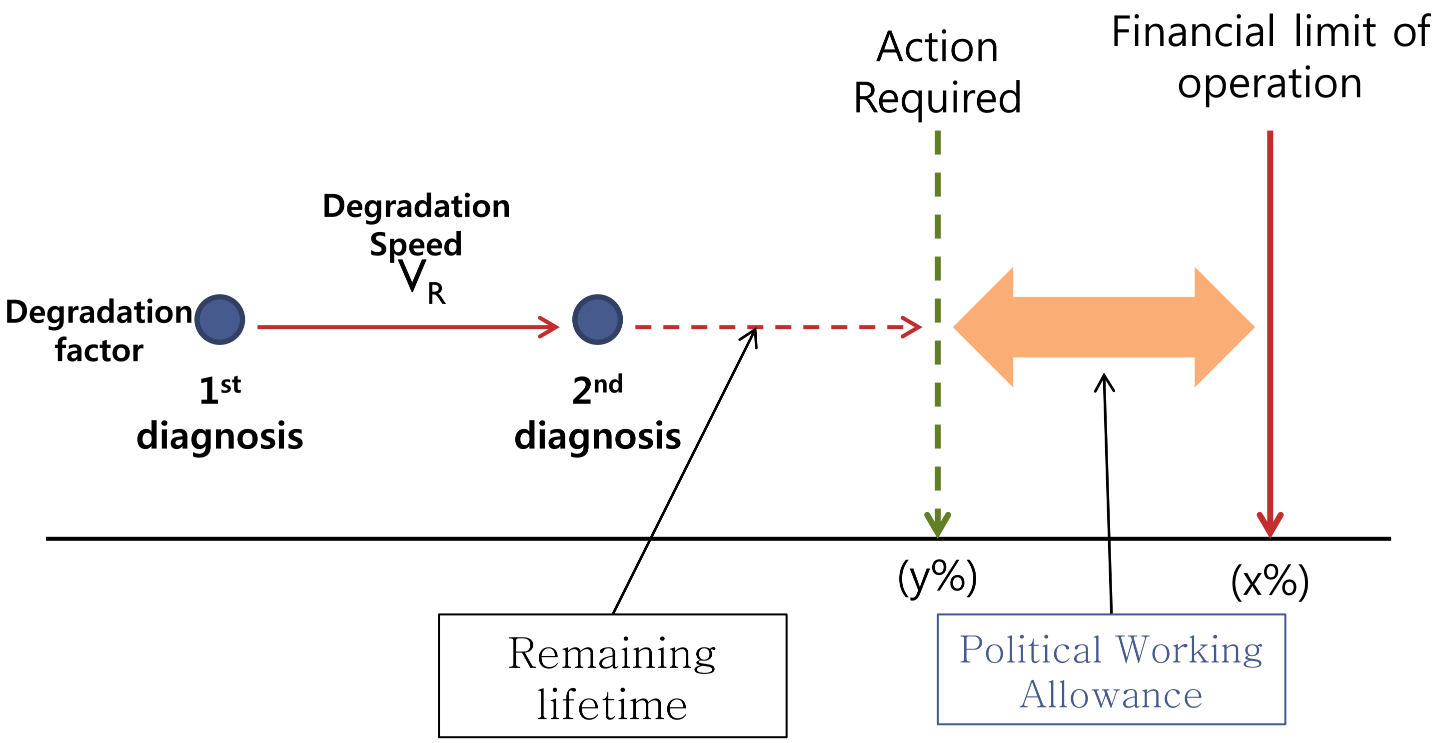
Why 3D Matrix?

Tracing degradation channel using 3D Matrix



1) By expanding and applying to other voltage Scale and type, limited domain is possible. (nuclear, National Railroad Admin, other than KEPCO)
2) Quantitative determination of current degradation of measured data using 3D Index
3) By tracing channel of position vector of the cable, ground to calculate remaining lifetime is provided.

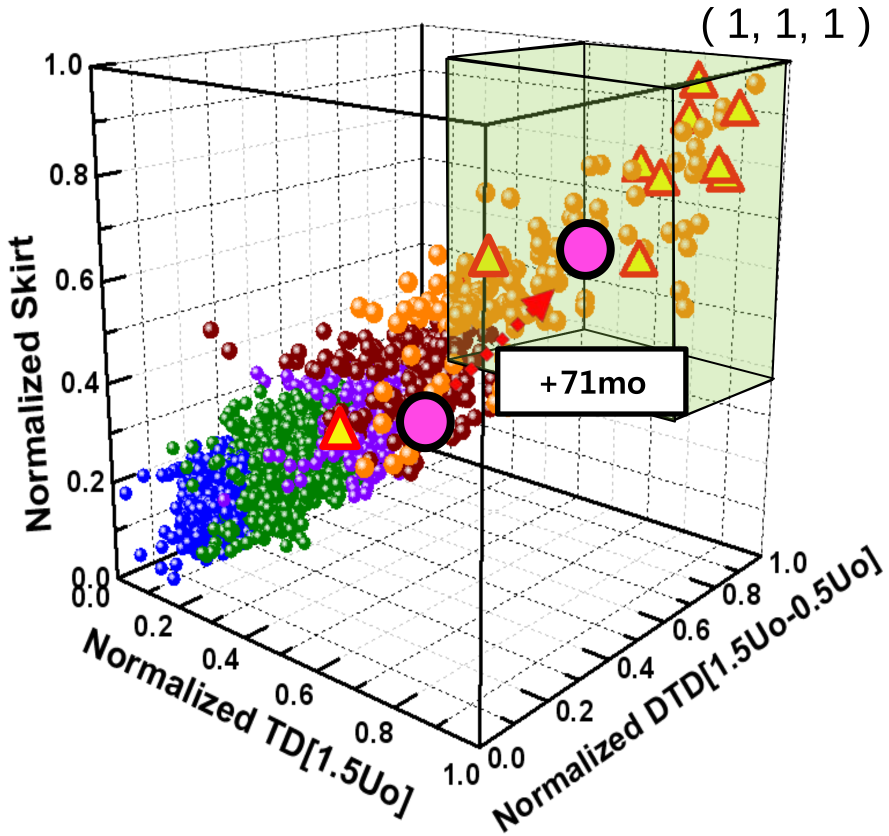
Cable Life Management



- To prevent defect, facility shall be replaced at point lower than financial limit of operation.
- "Working allowance" of "Defect Determination" point is politically determine for executing facility replacement.

Change of Index R

Application of Degradation Speed to 3D
(case 1)



Example

- Manufactured year: 1992
- Diagnosed year of VLF tan δ : 2013
- Distance based on result of diagnosis R = 0.79
- Degradation speed V_R=0.0082/month
- Time to reach Index R=1.382 = 71 months (estimated)

THANK YOU