

Medium Voltage Cable Health Index Integrating Diagnostic Data and Feeder Load for Reliability Assessment

Pande Putu Priyanithi Dharsania Negara^{1*}, Budi Sudiarto²

^{1,2}Department of Electrical Engineering, Faculty of Engineering, Universitas Indonesia, Indonesia

¹pande.putu31@ui.ac.id, ²budi.sudiarto@ui.ac.id

*Corresponding author, pande.putu31@ui.ac.id

Abstract — Reliable operation of medium-voltage (MV) distribution networks depends strongly on the condition of XLPE-insulated cable systems. However, existing diagnostic methods, including Partial Discharge (PD), Tan Delta (TD), and Very Low Frequency (VLF) testing, are typically interpreted in isolation, limiting their relevance to operational decision-making. This study develops a unified Health Index (HI) framework that integrates these three diagnostic parameters with feeder loading data under real field conditions. Using Min–Max normalization and dual weighting schemes, the model was applied to 33 cable segments in a tropical MV distribution network. HI values were statistically correlated with the System Average Interruption Duration Index (SAIDI) and Energy Not Supplied (ENS). Results show that the dielectric-oriented weighting scheme yields stronger correlation with SAIDI ($r = 0.967$, $p < 0.05$), while equal weighting enhances sensitivity to ENS. Although feeder loading contributes to degradation exposure, intrinsic insulation condition remains the primary determinant of health classification. High-risk segments are consistently identified under both schemes, confirming the structural robustness of the model. The proposed framework provides an empirically validated foundation for condition-based and risk-based asset management in MV distribution systems.

Keywords: Feeder loading, Health index, Medium voltage cable, Partial discharge, SAIDI.



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INTRODUCTION

Medium-voltage (MV) cables insulated with Cross-Linked Polyethylene (XLPE) play a crucial role in electric power distribution systems, serving as conduits for energy transmission from substations to distribution substations and ultimately to end-users. XLPE is preferred due to its excellent dielectric properties, resistance to high temperatures and harsh environments, and relatively long technical lifespan [1]. However, under real-world operational conditions involving load fluctuations, overvoltage events, extreme temperatures, and potential manufacturing or installation defects, XLPE cables remain susceptible to progressive degradation. One of the most significant degradation mechanisms is Partial Discharge (PD), which is typically triggered by microscopic voids within the insulation structure[1]. Repeated PD activity accelerates insulation material deterioration, reduces dielectric strength, and may eventually lead to complete cable failure [1], [2].

Early detection of cable degradation symptoms is essential for ensuring distribution system reliability. Various diagnostic testing methods have been developed, including Tan Delta (TD),

Very Low Frequency (VLF), and PD testing. PD testing at 0.1 Hz has been shown to be more sensitive in detecting defects at cable terminations compared to testing at the standard power frequency of 50 Hz [2]. This increased sensitivity is attributed to more stable charge accumulation at very low frequencies, which enabling more effective identification of internal defects. Meanwhile, research by [3] emphasized the importance of PD testing at cable joints, which are particularly vulnerable due to thermal stress and installation defects. The High-Frequency Current Transformer (HFCT) technique is employed to detect distinctive PD patterns as indicators of localized degradation [3]. In addition to PD, Tan Delta measurement is used to evaluate dielectric losses associated with insulation aging and moisture ingress, while VLF testing assesses the insulation withstand capability under controlled high-voltage stress conditions [1], [2].

Although several studies have investigated diagnostic testing methods individually, there remains limited comprehensive research on an integrative Health Index (HI) approach that systematically combines PD, TD, and VLF test results, particularly within the context of power distribution systems in Indonesia. The development of an HI model enables quantitative assessment of cable health condition and supports estimation of degradation severity. However, many existing approaches focus primarily on technical test interpretation without explicitly linking diagnostic results to operational loading conditions and system reliability indicators. Previous studies highlight the importance of integrating technical and operational data to evaluate system reliability [1], [2], yet they do not directly correlate Health Index values with reliability metrics such as SAIDI and Energy Not Supplied (ENS). Furthermore, the quantitative influence of feeder loading on insulation degradation remains insufficiently addressed in integrated HI modelling.

Based on diagnostic testing conducted by PT PLN (Persero) UP3 Majalaya in 2024 on 33 MV cable segments, most cables exhibited Tan Delta values greater than 0.01 and apparent PD magnitudes exceeding 500 pC, indicating insulation degradation consistent with previously described mechanisms [1], [2], [3]. Abnormal Phase-Resolved Partial Discharge (PRPD) patterns were identified at several joints, confirming the presence of localized defects as discussed in [3]. Moreover, feeders operating at loads exceeding 80% of nominal capacity showed accelerated degradation trends and frequent disturbance events. The highest disruption occurred in the second quarter of 2024, with ENS exceeding 15 MWh from a single 20 kV feeder. These conditions demonstrate the limitations of traditional time-based maintenance approaches in maintaining distribution system reliability under increasing operational stress.

To address these challenges, this study develops a quantitative Health Index model for medium-voltage XLPE cables based on integrated diagnostic data from PD, TD, and VLF testing. Two weighting schemes are evaluated to assess parameter sensitivity and classification robustness. The model incorporates feeder loading data to represent operational thermal stress and statistically examines the correlation between HI values and key reliability indicators, namely SAIDI and ENS. By integrating multi-parameter diagnostic assessment, operational loading analysis, and empirical reliability validation within a unified framework, this research enhances the practical application of Health Index modeling as a predictive and risk-based maintenance tool for distribution systems in Indonesia.

METHOD

This study employs a descriptive quantitative evaluative approach to numerically assess insulation degradation in medium voltage (MV) cables based on diagnostic parameters: Very Low Frequency (VLF), Tan Delta (TD), and Partial Discharge (PD). The methodological framework combines standardized field-testing procedures with quantitative scoring to develop a Health Index (HI) model and evaluate its relationship with feeder loading and reliability performance.

A. Research Location and Object

The research was conducted on 33 segments of 20 kV XLPE underground cables within the operational area of PT PLN (Persero) UP3 Majalaya. The cables comply with IEC 60502-2 requirements for rated voltage insulation systems [4].

B. Data Types and Sources

Primary data were obtained from field diagnostic tests (VLF, TD, PD) and feeder loading data from the SCADA system. Secondary data included fault history from the OMS, network topology, and technical standards such as IEEE 400-2012, IEEE 400.2, IEEE 400.3, IEC 60502-2, and IEC 60060-1.

C. Data Collection Procedure

The dataset includes Very Low Frequency (VLF) test results, Tan Delta (TD) measurements, Partial Discharge (PD) measurements, feeder loading data from SCADA, and disturbance and ENS records from OMS. The use of field diagnostic testing follows standardized guidelines including IEEE Std 400.2 for VLF testing [5], IEEE Std 400.3 for PD testing [6], and IEC 60060-1 for high-voltage testing procedures [7].

D. Data Processing and Normalization

VLF testing assesses insulation withstand capability under low-frequency stress conditions. IEEE Std 400.2 provides guidelines for field implementation [5]. Although VLF pass results indicate acceptable dielectric integrity, research indicates that withstand success does not eliminate localized PD defects [2], [6]. The integration of PD, TD, and VLF aligns with recommendations for multi-parameter diagnostic assessment in medium-voltage cable systems [8].

The diagnostic parameters used in this study, along with their measurement methods and normalization formulas, are summarized in Table 1. Tan Delta measurement evaluates dielectric dissipation factor and bulk insulation degradation. Elevated $\tan \delta$ values are associated with water tree development and aging in XLPE insulation systems [9], [10], [11]. Water tree initiation and progression mechanisms have been experimentally investigated in [10], supporting the interpretation of dielectric loss as an indicator of distributed degradation.

Table 1. Parameters

Parameter	Method	Normalization Formula
VLF Result	VLF	Pass = 0, Fail = 1
Tan Delta (TD)	TD	$x' = (x - x_{min}) / (x_{max} - x_{min})$
Partial Discharge	PD	pC scaled

PD testing was conducted to detect localized insulation defects such as voids and joint irregularities. The degradation mechanism of void-induced PD activity has been quantitatively analyzed in [2], while joint-related PD vulnerability has been emphasized in [1]. Cross-

correlation techniques for PD signal separation have been discussed in [12], highlighting the importance of accurate discharge identification. PD patterns were analyzed using Phase-Resolved Partial Discharge (PRPD) interpretation, consistent with defect modeling approaches described in [13] dan [14].

E. Health Index Formula

The Health Index (HI) is calculated as a weighted sum of normalized diagnostic parameters:

$$HI = w_1(TD) + w_2(VLF) + w_3(PD) \quad (1)$$

Two weighting schemes were evaluated, with weights assigned as follows: Option 1 applies TD weight of 0.4, VLF weight of 0.4, and PD weight of 0.2, emphasizing dielectric-oriented parameters. Option 2 applies equal weighting of 0.333 to each parameter.

The dual-weighting approach enables sensitivity analysis without employing machine learning or optimization algorithms such as those explored in [15] and [16], which are beyond the scope of this dataset.

Table 2. HI Classification

HI Range	Category
0.8 – 1.0	Excellent
0.6 – 0.8	Good
0.4 – 0.6	Alert
0.2 – 0.4	Poor
0.0 – 0.2	Very Poor

The resulting HI values are classified into five condition categories as presented in Table 2, ranging from Excellent to Very Poor. This classification supports maintenance prioritization consistent with asset management and reliability-centered maintenance principles discussed in [17] and techno-economic cable replacement strategies outlined in [18].

F. Health Index (HI) Model Validation

Model validation was performed through correlation analysis between HI and feeder loading, as well as between HI and reliability indicators, namely SAIDI and ENS, using Pearson and Spearman correlation coefficients to assess statistical relationships. This approach bridges diagnostic degradation assessment with system reliability impact, extending beyond purely technical evaluation frameworks commonly reported in [9], [11], and [19].

G. Study Limitation

The correlation analysis is based on a limited number of cable-related disturbance records. Therefore, statistical interpretation should be treated cautiously. The model applies static weighting and does not incorporate predictive machine learning frameworks such as those explored in [15] and [16]. However, within the available dataset, the approach provides a structured basis for condition-based and risk-based maintenance planning.

RESULT AND DISCUSSION

A. Interpretation of Diagnostic Results

The diagnostic results demonstrate that insulation degradation in the observed cable segments occurs in both localized and distributed forms. Elevated PD magnitudes exceeding 500 pC in

several segments indicate active defect sites consistent with void-induced degradation mechanisms described in [2] and [13]. High PD activity at joints aligns with findings in [3], where joint regions are identified as structurally vulnerable due to installation stress and field irregularities. The observed PRPD patterns correspond to defect characteristics discussed in [14], particularly in distinguishing internal void discharges from surface or corona-type discharges, confirming that localized insulation defects significantly contribute to degradation severity in specific cable segments.

Meanwhile, elevated Tan Delta values reflect increased dielectric dissipation associated with bulk insulation aging and water tree formation. Experimental investigations in [10] and field-based assessments in [9] and [11] confirm that moisture ingress and progressive water tree development increase dielectric loss and reduce insulation strength. Therefore, TD results in this study indicate distributed aging mechanisms rather than isolated defect activity.

VLF testing results show that most cable segments passed withstand testing. However, as noted in IEEE Std 400.2 [5] and discussed in [2], withstand success does not guarantee absence of incipient PD activity, which explains why certain segments classified as acceptable under VLF still exhibit significant PD or TD abnormalities. The integration of PD, TD, and VLF thus provides complementary diagnostic insight, consistent with the multi-parameter assessment recommendation in [8].

B. VLF Testing Results

The detailed VLF test results for all 33 cable segments are presented in Table 3. Out of 33 cable segments tested, 97% successfully passed the VLF test, indicating that the insulation integrity remains in good condition. One segment experienced a breakdown and requires further verification. All leakage currents were below the 15 mA threshold, in accordance with IEEE Std 400.2-2013.

Table 3. VLF Test Results (Success vs. Breakdown)

Segment	Phase	Voltage (kV)	RMS Voltage (kV)	RMS Current (mA)	Duration (min)	Result
GI - GD RTC (UCO)	L3	33.4 kV	25.1 kV	10.2 mA	03:00 min	Success
GI - GH DUTA (PDO)	L3	33.4 kV	25.1 kV	11.1 mA	03:00 min	Success
GI - GH DUTA (PDU)	L3	0.9 kV			00:02 min	Breakdown
GI - GH LEUWI (PLH)	L3	18.9 kV	25.2 kV	11.6 mA	02:00 min	Success
GI - GH LEUWI (PTH)	L3	4.0 kV	25.2 kV	11.7 mA	05:00 min	Success
GI - GH POLY (UPC)	L3	2.4 kV	25.1 kV	10.1 mA	03:00 min	Success
GI - GH POLY (UPK)	L3	1.4 kV	25.1 kV	10.2 mA	02:00 min	Success
KP KBDK - KABEL	L3	2.7 kV	25.1 kV	7.0 mA	05:00 min	Success
NAIK (RCBI)						
GI - GD ADX (SBM)	L1	0.1 kV	25.2 kV	11.5 mA	05:00 min	Success
GI - GD ANC (PSU)	L1	2.5 kV	25.1 kV	11.7 mA	05:00 min	Success
GI - GD PHA (PLM)	L1	4.5 kV	25.1 kV	5.7 mA	03:00 min	Success
GI - GD RTC (UCO)	L1	33.3 kV	25.1 kV	10.2 mA	03:00 min	Success
GI - GH DUTA (PDO)	L1	33.5 kV	25.1 kV	11.0 mA	03:00 min	Success
GI - GH DUTA (PDU)	L1	33.9 kV	25.1 kV	11.1 mA	03:00 min	Success
GI - GH LEUWI (PRH)	L1	1.3 kV	25.2 kV	11.5 mA	05:00 min	Success
GI - GH POLY (UPC)	L1	0.8 kV	25.1 kV	10.1 mA	03:00 min	Success
GI - GH POLY (UPK)	L1	0.8 kV	25.1 kV	10.2 mA	02:00 min	Success
KP KBDK - KABEL	L1	4.4 kV	25.1 kV	7.0 mA	05:00 min	Success
NAIK (RCBI)						
GI - GD ADX (SBM)	L2	1.5 kV	25.2 kV	11.5 mA	05:00 min	Success
GI - GD ANC (PSU)	L2	2.6 kV	25.1 kV	11.7 mA	05:00 min	Success
GI - GD PHA (PLM)	L2	3.0 kV	25.1 kV	5.7 mA	03:00 min	Success
GI - GD RTC (UCO)	L2	33.4 kV	25.1 kV	10.2 mA	03:00 min	Success
GI - GH DUTA (PDO)	L2	33.4 kV	25.1 kV	11.0 mA	03:00 min	Success
GI - GH DUTA (PDU)	L2	33.5 kV	25.1 kV	11.1 mA	03:00 min	Success

Segment	Phase	Voltage (kV)	RMS Voltage (kV)	RMS Current (mA)	Duration (min)	Result
GI - GH LEUWI (PLH)	L2	22.7 kV	25.2 kV	11.6 mA	03:00 min	Success
GI - GH LEUWI (PTH)	L2	2.0 kV	25.2 kV	11.8 mA	05:00 min	Success
GI - GH POLY (UPC)	L2	1.1 kV	25.1 kV	10.1 mA	03:00 min	Success
GI - GH POLY (UPK)	L2	1.7 kV	25.1 kV	10.2 mA	02:00 min	Success
KP KBDK - KABEL NAIK (RCBI)	L2	2.2 kV	25.1 kV	7.0 mA	05:00 min	Success
GI - GD ADX (SBM)	L3	1.6 kV	25.2 kV	11.5 mA	05:00 min	Success
GI - GD ANC (PSU)	L3	1.6 kV	25.1 kV	11.7 mA	05:00 min	Success
GI - GD KMFA (SKK)	L3	1.2 kV	25.1 kV	10.9 mA	05:00 min	Success
GI - GD PHA (PLM)	L3	3.1 kV	25.1 kV	5.7 mA	03:00 min	Success

C. Tan Delta Test Results

Table 4 presents the $\Delta \tan \delta$ distribution across all tested phases. Most segments had $\Delta \tan \delta$ values below 3, indicating good insulation condition. However, signs of degradation were observed in phase L2 of the LEUWI (PTH) and LEUWI (PLH) segments, with $\Delta \tan \delta$ values exceeding 10. High $\tan \delta$ values indicate potential thermal degradation and water treeing in the XLPE insulation.

Table 4. $\Delta \tan \delta$ Distribution per Phase

Segment	Phase	$\tan \delta_{0.5U0}$	$\tan \delta_{1.0U0}$	$\tan \delta_{1.5U0}$	$\Delta \tan \delta$	$\tan \delta_{Dev 1.0U0}$	Voltage (V)	Length (m)
GI-GH LEUWI (PLH)	L1	0	0	0	0	0	11.5	3,193
GI-GH LEUWI (PLH)	L2	2.2	5.8	14.6	12.4	0	11.5	3,193
GI-GH LEUWI (PLH)	L3	3.3	6	12.8	9.5	0	11.5	3,193
GI-GH LEUWI (PTH)	L1	2.1	3.2	5	2.9	0	11.5	3,155
GI-GH LEUWI (PTH)	L2	1.5	6	22.7	21.2	0	11.5	3,155
GI-GH LEUWI (PTH)	L3	3.2	5.6	12.4	9.2	0	11.5	3,155
GI-GH POLY (UPC)	L1	2	2.8	3.9	1.9	0	11.5	4,421
GI-GH POLY (UPC)	L2	2.1	2.7	3.5	1.4	0	11.5	4,421
GI-GH POLY (UPC)	L3	1.4	1.9	2.6	1.2	0	11.5	4,421
GI-GD ADX (SBM)	L1	1	1	1	0	0	11.5	4,566
GI-GD ADX (SBM)	L2	1	1	1	0	0	11.5	4,566
GI-GD ADX (SBM)	L3	1	1	1	0	0	11.5	4,566
GI-GD ANC (PSU)	L1	1	1	1	0	0	11.5	3,870
GI-GD ANC (PSU)	L2	1	1	1	0	0	11.5	3,870
GI-GD ANC (PSU)	L3	1	1	1	0	0	11.5	3,870
GI-GD KMFA (SKK)	L1	0	0	0	0	0	11.5	4,365
GI-GD KMFA (SKK)	L2	0	0	0	0	0	11.5	4,365
GI-GD KMFA (SKK)	L3	1	1	1.6	0.6	0	11.5	4,365
GI-GD PHA (PLM)	L1	1	1	1	0	0	11.5	1,180

Segment	Phase	$\tan\delta_{0.5U0}$	$\tan\delta_{1.0U0}$	$\tan\delta_{1.5U0}$	$\Delta\tan\delta$	$\tan\delta_{Dev_{1.0U0}}$	Voltage (V)	Length (m)
GI-GD PHA (PLM)	L2	1	1	1	0	0	11.5	1,180
GI-GD PHA (PLM)	L3	1	1	1	0	0	11.5	1,180
GI - GH POLY (UPK)	L1	1	1	1.2	0.2	0	11.5	4,441
GI - GH POLY (UPK)	L2	2	2.3	3.3	1.3	0	11.5	4,441
GI - GH POLY (UPK)	L3	1	1	1	0	0	11.5	4,441
GI - GH DUTA (PDU)	L1	1	1.3	2.6	1.6	0.05	11.5	6,025
GI - GH DUTA (PDU)	L2	1	1	1	0	0	11.5	6,025
GI - GH DUTA (PDU)	L3	12.4	0	0	0	0	11.5	6,025
GI - GH DUTA (PDO)	L1	1	1	1.5	0.5	0	11.5	5,986
GI - GH DUTA (PDO)	L2	1	1.4	3.6	2.6	0.07	11.5	5,986
GI - GH DUTA (PDO)	L3	1.5	2.5	3.7	2.2	0.05	11.5	5,986
GI - GD RTC (UCO)	L1	1	1.7	3.3	2.3	0	11.5	5,681
GI - GD RTC (UCO)	L2	1	1.1	2.1	1.1	0	11.5	5,681
GI - GD RTC (UCO)	L3	1	1.9	3.5	2.5	0.07	11.5	5,681
KP KBDK - KABEL NAIK (RCBI)	L1	1	1	1	0	0	11.5	1,481
KP KBDK - KABEL NAIK (RCBI)	L2	1	1	1	0	0	11.5	1,481
KP KBDK - KABEL NAIK (RCBI)	L3	1	1	1	0	0	11.5	1,481

D. Partial Discharge Results

The partial discharge measurement results for all cable segments are presented in Table 5. The RTC (UCO) and LEUWI (PTH) segments exhibited PD max values exceeding 20.000 pC. far above the critical threshold of 1.000 pC as defined by IEEE 400.3. High PD activity was detected even at nominal voltage (U_0). indicating serious localized insulation degradation.

Table 5. Partial Discharge Data

Segment	Phase	Disturbance	PD max_ U0	PD level_ U0	PD max_1.7 U0	PD level 1.7 U0
GI - GD PHA (PLM)	L1	1078	431	392	488	406
GI - GD PHA (PLM)	L2	1200	1592	450	1277	470
GI - GD PHA (PLM)	L3	1020	511	436	668	459
GI - GD RTC (UCO)	L1	1039	4075	1120	22776	2548
GI - GD RTC (UCO)	L2	1800	5178	1026	16318	1654
GI - GD RTC (UCO)	L3	1676	3315	1090	17161	1940
GI - GH DUTA (PDO)	L1	1022	539	466	531	473
GI - GH DUTA (PDO)	L2	1146	1078	523	922	531
GI - GH DUTA (PDO)	L3	918	568	448	1045	463
GI - GH LEUWI (PTH)	L1	1110	1762	1118	9346	1686
GI - GH LEUWI (PTH)	L2	3036	2519	1195	27513	3443
GI - GH LEUWI (PTH)	L3	1196	3556	1296	26712	4277

Segment	Phase	Disturbance	PD max_ U0	PD level_ U0	PD max_1.7 U0	PD level 1.7 U0
GI - GH POLY (UPC)	L1	1015	2883	279	1996	298
GI - GH POLY (UPC)	L2	1005	283	257	1218	271
GI - GH POLY (UPC)	L3	1023	302	280	1209	268
GI - GH POLY (UPK)	L1	1050	1204	1074	1163	1073
GI - GH POLY (UPK)	L2	1724	643	434	1655	568
GI - GH POLY (UPK)	L3	648	951	453	1877	725
KP KBDK - KABEL	L1	1051	2709	1085	2098	1283
NAIK (RCBI)						
KP KBDK - KABEL	L2	1741	1251	1091	2129	1123
NAIK (RCBI)						
KP KBDK - KABEL	L3	1859	1240	1164	2006	1154
NAIK (RCBI)						
GI - GD ADX (SBM)	L1	1023	1267	1139	1455	1146
GI - GD ADX (SBM)	L2	1004	1130	1059	1186	1086
GI - GD ADX (SBM)	L3	1011	1253	1137	1261	1111
GI - GD ANC (PSU)	L1	1006	263	232	6299	252
GI - GD ANC (PSU)	L2	1021	1063	218	1698	243
GI - GD ANC (PSU)	L3	1012	304	263	631	282
GI - GD ANA (MCC)	L1	1023	3401	642	7548	1708
GI - GD ANA (MCC)	L2	1048	0	0	5559	1119
GI - GD ANA (MCC)	L3	1021	0	0	12694	1554
GI - GH POLY (RPK)	L1	1097	593	510	796	533
GI - GH POLY (RPK)	L2	1230	509	465	2608	512
GI - GH POLY (RPK)	L3	1090	555	477	847	501
GI - GH POLY (RPM)	L1	959	755	643	781	629
GI - GH POLY (RPM)	L2	835	983	654	3548	1479
GI - GH POLY (RPM)	L3	931	789	679	817	691
GI - GD PKT (MLK)	L1	1057	1775	1019	1438	925
GI - GD PKT (MLK)	L2	906	1164	1064	1164	1088
GI - GD PKT (MLK)	L3	952	1164	1066	3783	1074
GI - GH POLY (RPC)	L1	1134	708	618	927	639
GI - GH POLY (RPC)	L2	1225	712	601	873	631
GI - GH POLY (RPC)	L3	1229	687	610	2241	651
GI - GD LLM (MTM)	L1	1006	549	474	1997	712
GI - GD LLM (MTM)	L2	1025	514	416	1530	900
GI - GD LLM (MTM)	L3	0	0	0	0	0
GI - GD TCS (RWM)	L1	1169	0	0	1257	1069
GI - GD TCS (RWM)	L2	1013	0	0	1163	995
GI - GD TCS (RWM)	L3	1051	0	0	1200	1009
GI - GH LEUWI (PLH)	L1	0	0	0	0	0
GI - GH LEUWI (PLH)	L2	1076	916	407	1929	518
GI - GH LEUWI (PLH)	L3	0	0	0	0	0
GI - GD KMFA (SKK)	L1	0	0	0	0	0
GI - GD KMFA (SKK)	L2	0	0	0	0	0
GI - GD KMFA (SKK)	L3	986	3501	478	3539	697
GI - GH DUTA (PDU)	L1	1022	388	198	732	238
GI - GH DUTA (PDU)	L2	972	721	211	1338	316

E. Health Index Analysis

Diagnostic integration reveals both localized and distributed degradation patterns. Elevated PD magnitudes align with void-induced mechanisms described in [2] and [13]. Increased TD values indicate progressive dielectric aging consistent with [9], [10], and [11]. Although most segments passed VLF testing, PD, and TD abnormalities confirm that withstand success does not eliminate incipient degradation [2], [5]. Feeder loading above 80% correlates with lower HI values, supporting thermal-aging mechanisms described in [20] and [21]. This validates inclusion of operational stress within the HI framework.

The HI distribution under Option 1 is illustrated in Figure 1. Weighting comparison shows structural stability in high-risk segment identification. Option 1 increases sensitivity to bulk

degradation, expanding the Alert category (74.2%). Option 2 redistributes classifications toward the Good category (45.2%), reducing parameter dominance. Correlation analysis confirms that segments classified as Poor or Very Poor contribute disproportionately to SAIDI and ENS. The HI therefore functions as a reliability-linked indicator rather than a purely descriptive metric.

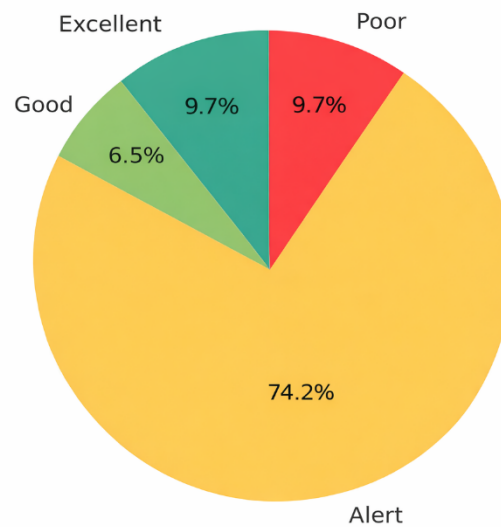


Figure 1. Status Distribution Chart Based on HI Option 1

The distribution under Option 2 is shown in Figure 2. Both schemes yield identical proportions in the Excellent category (9.7%). This consistency confirms structural robustness of the model identifying genuinely healthy assets, independent of weighting variation. From an asset management perspective, Option 1 aligns with risk-based maintenance prioritization, while Option 2 provides balanced baseline mapping. Weighting selection should reflect strategic maintenance objectives.

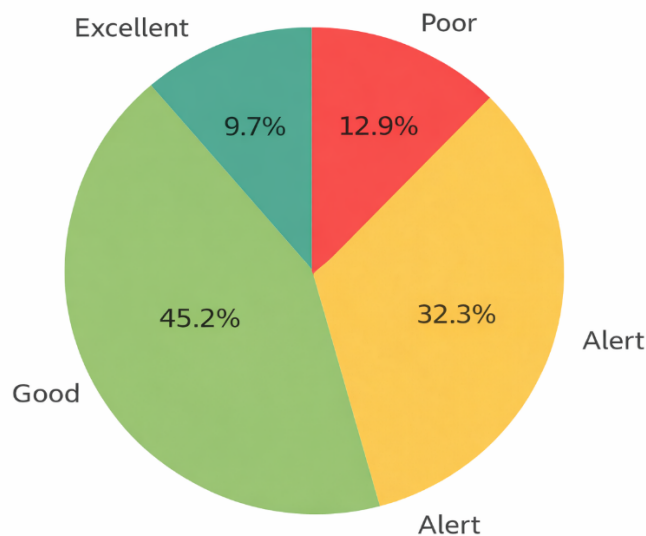


Figure 2. Status Distribution Chart Based on HI Option 2

F. Correlation Between Health Index and Feeder Load

Under Option 1, Pearson correlation is weak ($r = 0.096$, $p = 0.608$), indicating no significant

linear relationship. Spearman correlation ($\rho = 0.354$, $p = 0.051$) suggests only a marginal monotonic tendency. Scatter distribution shows high dispersion across loading ranges. High-loading feeders (>150 A) do not consistently exhibit lower HI, while some low-loading segments display moderate to low HI. Clustering confirms that classification is driven primarily by dielectric condition rather than operational load. Non-linear regression indicates a weak threshold-like pattern, but without strong statistical support. Overall, Option 1 reflects intrinsic insulation degradation rather than operational stress effects, as illustrated in Figure 3.

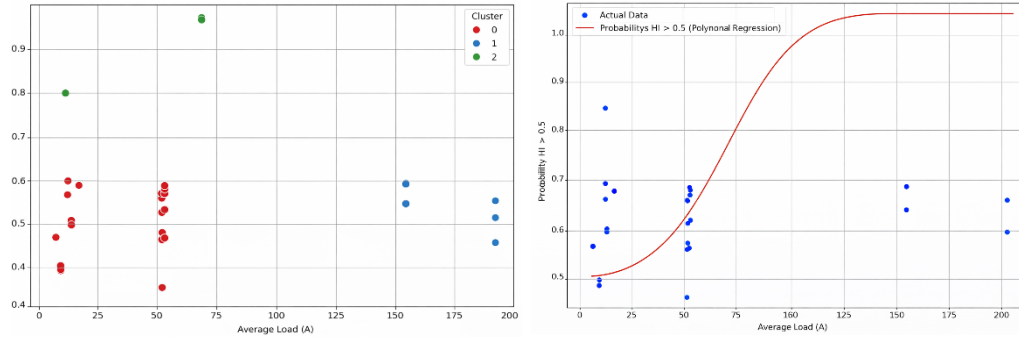


Figure 3. Clustering and Non-linear regression Option 1

Under Option 2, Pearson correlation remains weak ($r = 0.150$, $p = 0.420$), but Spearman correlation becomes statistically significant ($\rho = 0.356$, $p = 0.049$). This indicates a meaningful monotonic association between loading and HI. Scatter and clustering patterns show improved alignment between load intensity and HI grouping. Non-linear regression exhibits a clearer saturation trend: HI increases from low to moderate loading and stabilizes beyond approximately 100 A, suggesting an operational threshold effect. Option 2 therefore enhances sensitivity of HI to operational stress while maintaining structural stability, as shown in Figure 4.

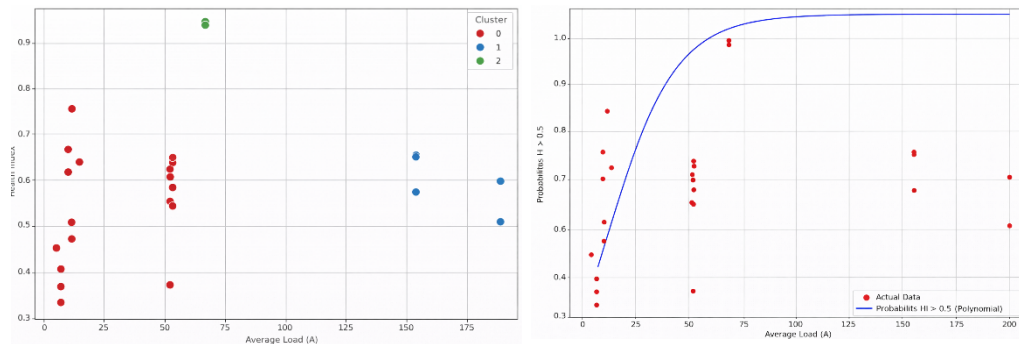


Figure 4. Clustering and Non-linear regression Option 2

The influence of feeder loading on HI is weighting-dependent. Option 1 emphasizes intrinsic dielectric degradation and minimizes operational sensitivity, while Option 2 strengthens statistical coupling between loading and HI. Importantly, neither scheme demonstrates strong linear dependence on loading alone. Feeder loading acts as a contributing factor, while insulation aging and joint condition likely exert greater influence. Weighting selection should align with maintenance strategy: conservative dielectric-focused monitoring (Option 1) or operational risk integration (Option 2).

G. Correlation Between Health Index and SAIDI/ENS

This section evaluates the relationship between the Health Index (HI) and reliability indicators.

namely SAIDI and ENS. to assess whether diagnostic-based condition classification reflects actual system performance.

Under Option 1, a very strong and statistically significant linear relationship is observed between HI and SAIDI (Pearson $r = 0.985$. $p = 0.0146$). The perfect monotonic correlation (Spearman $\rho = 1.000$. $p = 0.000$) indicates that segment ranking based on HI is fully consistent with SAIDI ordering. This result demonstrates that higher HI values correspond to lower outage duration per customer. Therefore, the dielectric-focused weighting effectively captures performance related to interruption duration. In contrast, the correlation between HI and ENS is strong ($r = 0.866$) but not statistically significant ($p = 0.1337$). While a monotonic tendency exists ($\rho = 0.800$), the absence of statistical significance suggests that energy-not-supplied is influenced by additional operational factors beyond insulation condition. Overall, Option 1 shows high sensitivity to service continuity metrics, particularly outage duration, but limited explanatory power for energy impact.

Under Option 2, HI demonstrates strong and statistically significant correlation with both reliability indicators. The relationship with SAIDI remains strong ($r = 0.967$. $p = 0.0330$), confirming consistency between HI classification and outage duration. Although slightly lower than Option 1, the association remains statistically meaningful. More notably, the correlation between HI and ENS becomes statistically significant. Pearson correlation reaches 0.908 ($p = 0.0917$), and Spearman correlation is perfect ($\rho = 1.000$. $p = 0.000$). This indicates that equal weighting enhances alignment between HI and energy-loss impact. These findings suggest that when PD influence is weighted equally, the Health Index better captures operational consequences reflected in ENS.

H. Technical Recommendations

Based on the diagnostic and reliability findings, Table 6 summarizes the recommended technical actions and implementation timeline. The strategic plan includes strengthening of jointing points, integration of the Health Index (HI) into the Asset Performance Management (APM) system, and the utilization of predictive models to prioritize cables based on HI, load, and fault history.

Table 6. Recommendations

Recommendation	Technical Action	Implementation
Cable replacement for GD RTC UCO	Replace the cable or use high-quality heat-shrink joints	Q3 2025
Jointing point audit on all feeders	Conduct PD & Tan Delta testing at all cable joints	Q2–Q3 2025
Load balancing for UPK/PLM feeders	Redistribute load using SCADA-based load mapping	Q4 2025
Integration of HI into APM	Include HI as an input in the Asset Performance Management System (APM)	2025–2026
Biannual HI evaluation	Re-test segments with HI < 0.6 using VLF & Tan Delta	Twice per year

CONCLUSION

This study proposed and empirically validated a multi-parameter Health Index (HI) model for medium-voltage XLPE cables by integrating Partial Discharge (PD), Tan Delta (TD), and Very Low Frequency (VLF) diagnostics with feeder loading data under real operational conditions. The findings demonstrate that the HI framework is structurally robust across two weighting schemes while remaining strategically adaptable. The dielectric-oriented scheme (Option 1)

exhibits stronger alignment with SAIDI, indicating high relevance for outage-duration prioritization. The balanced scheme (Option 2) enhances statistical coupling with ENS, improving representation of energy interruption impact. These results confirm that weighting selection directly influences operational sensitivity without compromising identification of high-risk segments. Correlation analysis further indicates that feeder loading acts as a contributing factor rather than a dominant determinant of cable health. Intrinsic insulation condition remains the primary driver of reliability performance, underscoring the necessity of integrating diagnostic data with operational metrics in condition assessment models. Although the dataset is limited to 33 segments within a defined operational area, the consistent alignment between HI classification and observed reliability indicators provides practical field validation. The model should therefore be interpreted as an operationally grounded framework rather than a universal predictive tool. Overall, this study advances Health Index modeling by linking diagnostic assessment, operational loading, and reliability performance within a unified and empirically tested structure. The proposed approach offers a practical foundation for condition-based and risk-based maintenance planning in medium-voltage distribution networks. Future research should expand dataset coverage, incorporate temporal degradation modeling, and explore adaptive weighting mechanisms to further enhance predictive capability and generalizability.

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BIOGRAPHIES OF AUTHORS



PANDE PUTU PRIYANITHI DHARSANIA NEGARA was born in Gianyar, Indonesia, on August 21, 1996. She completed her bachelor's degree in Electrical Engineering from Sanata Dharma University, Indonesia, in 2014, and her master's degree in Electrical Engineering from the University of Indonesia in 2025. Her research interests include Power Systems and Smart Grids.



BUDI SUDIARTO is a Full-Time Lecturer and Associate Professor at the Department of Electrical Engineering, Faculty of Engineering, Universitas Indonesia. He earned his Bachelor's degree (2001) and Master's degree (2005) in Electrical Engineering from the University of Indonesia. He later pursued his doctoral studies (Dr.-Ing.) in Mechanical Engineering at Universität Duisburg-Essen, Germany, and graduated in 2017. His main areas of expertise and research include high-voltage systems, electrical current and voltage measurements, renewable energy, and the development of modern electrical systems such as virtual power plants and photovoltaic generation. He actively publishes his research in both national and international journals and conferences.