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CONDITIONAL INSULATION CONDITION TRIAGE WITH DEFERRED DECISIONS: AN ILLUSTRATIVE APPLICATION TO PARTIAL DISCHARGE MEASUREMENTS FROM THREE 35 KV XLPE CABLES IN ECUADOR

Eduardo David Guerrero Castillo[1], Maria José Verdezoto Cuenca, Xavier Alfonso Proaño Maldonado, Franklin Hernan Vásquez Teneda
Facultad de Ciencias de la Ingeniería y Aplicadas, Universidad Técnica de Cotopaxi, Latacunga, Ecuador.

ABSTRACT.
Off-line partial discharge (PD) measurements taken on three 35 kV XLPE single-core cables that were not new, before being put into service, are re-analysed. Discharge sites were located from the arrival times of direct and reflected pulses, discharge types were interpreted by the test operator from phase-resolved patterns, and apparent charge was recorded with a BAUR PD-TaD 62 coupler and BAUR SW4 software at up to four test voltages per cable; two of the twelve cable-voltage readings were not reported. The paper adds a deterministic ordinal triage rule with abstention: each reading receives one of four reference bands or a rejection output (missing, unresolved or invalid), and each cable receives its highest known band together with the counts of rejected pairs. The rule has no objective function, losses or costs and has not been validated. Its cut-offs (500, 1000 and 2500 pC) are taken from the original test report, which gives no verifiable source for them; its actions are defined in this study as provisional, so the bands are an illustrative convention, not a maintenance recommendation. Applied to the twelve pairs, the rule assigns 5 to the highest band, 4 to the lowest and one to an intermediate band, and leaves two as deferred decisions. L1 and L2 are prioritised for confirmatory inspection, whereas the decision on L3 is deferred. No post-test service outcomes are available, so no predictive performance is estimated. Under the CONDITIONAL assumption that the ±10 % uncertainty of IEC 60270 clause 9 applies, nine of the ten observed readings keep their band.
KEYWORDS: partial discharge; insulation condition triage; deferred decision; missing data; XLPE medium-voltage cable; time-domain reflectometry.
MSC: 90B25, 90B50, 62P30.
RESUMEN.
Se reanalizan mediciones de descargas parciales fuera de línea realizadas en tres cables monopolares XLPE de 35 kV, no nuevos, antes de su puesta en servicio. Las descargas se localizaron a partir de los tiempos de llegada del pulso directo y del reflejado, el tipo de descarga lo interpretó el operador del ensayo sobre los patrones resueltos en fase, y la carga aparente se registró con un acoplador BAUR PD-TaD 62 y el software BAUR SW4 en hasta cuatro niveles de tensión por cable; dos de las doce lecturas cable-nivel no fueron reportadas. El artículo añade una regla de triaje ordinal y determinista con abstención: cada lectura recibe una de cuatro bandas de referencia o una salida de rechazo (ausente, no resuelta o inválida), y cada cable recibe su máxima banda conocida junto con el recuento de pares rechazados. La regla no tiene función objetivo, pérdidas ni costes y no ha sido validada. Sus cortes (500, 1000 y 2500 pC) se toman del informe original de los ensayos, que no indica una fuente verificable; sus acciones se definen en este estudio como provisionales, de modo que las bandas son una convención ilustrativa y no una recomendación de mantenimiento. Aplicada a los doce pares, la regla asigna 5 a la banda superior, 4 a la inferior y uno a una banda intermedia, y deja dos como decisión diferida. La L1 y la L2 se priorizan para inspección confirmatoria, mientras que la decisión sobre la L3 queda diferida. No se dispone de resultados posteriores de servicio, de modo que no se estima capacidad predictiva. Bajo el supuesto CONDICIONADO de que rige la incertidumbre de ±10 % de la cláusula 9 de IEC 60270, nueve de las diez lecturas observadas conservan su banda.
PALABRAS CLAVE: descargas parciales; triaje del estado del aislamiento; decisión diferida; datos ausentes; cable de media tensión XLPE; reflectometría en el dominio del tiempo.

1. INTRODUCTION

Partial discharge (PD) measurements are also carried out in the field, in particular during commissioning and entry-into-service tests of cables and electrical equipment, because they allow early detection of insulation defects that could lead to failures and supply interruptions [14].

This article deals with field PD tests on 35 kV XLPE cables before entry into service. Unlike very-low-frequency

[1]Corresponding author:eduardo.guerrero6155@utc.edu.ec.

(VLF) tests described in IEEE 400.2-2013 [9, 20], which are resolved with a pass/fail criterion, PD tests measure the apparent charge of the discharges and allow their origin to be located along the cable. Detecting a defect does not by itself guarantee continuity of supply: that is provided by the maintenance action decided on the basis of the finding.

This article derives from the degree work of Guerrero Castillo and Verdezoto Cuenca, supervised by Proaño Maldonado at Universidad Técnica de Cotopaxi [7]. The measurements, data tables and figures analysed here are taken from the original test report, which derives from that thesis; the thesis presents the same pulse and charge values with different table and figure numbering. What this article adds is the step that goes from the measured charge to the maintenance action: a triage rule with abstention that applies four reference bands to the twelve cable-level pairs, treats unreported or unresolved readings as a deferred decision, checks the published totals, and examines the sensitivity of the assignment and its resolution under IEC 60270 uncertainty. No measurement has been repeated or modified.

Section 2 summarises the background; Section 3, the measurement procedure and the reference bands; Section 4 formulates the triage rule; Section 5 presents the three cases; Section 6 assigns the bands; Section 7 examines sensitivity; Section 8 states the limitations; and Section 9 gives the conclusions.

2. STATE OF THE ART

PD is a measurable indicator of the progression of insulation defects: over time they erode the damaged zones and can lead to failure. In the factory they are measured off-line in acceptance tests under international standards [8]; in the field they are repeated before entry into service, because installation can damage splices and terminations even if the cable has passed the factory test [17]. Periodic measurements also allow the trend of insulation condition to be tracked.

2.1 Standards

The reference standards are IEC 60270 and the IEEE 400.3 guide. IEC 60270 defines partial discharge as a localised electrical discharge that only partially bridges the insulation between conductors and that may or may not occur adjacent to a conductor (clause 3.1) [12]. The IEEE 400.3-2022 guide deals with field PD diagnostic testing of shielded cable systems [10]; its text could not be consulted, so this article does not attribute any clause to it.

2.2 Types of partial discharge by origin

By origin, PD is classified as internal, surface, and corona-effect [6, 23]. Internal discharges occur in cavities, bubbles or imperfections in the dielectric, often originating in manufacturing [11]. Surface discharges appear when the electric field has a component parallel to the dielectric surface, as in cable terminations and splices [15]. Corona-effect discharges are due to ionisation of the air around a point under voltage, typically at air-insulated termination points, and in alternating current they often appear only in the negative half-cycle. Table 1 summarises causes and types of PD by defect location in terminations, cables and splices [1].

Terminations		
Cause	**Effect**	**PD type**
Dirt accumulation, oxidation	Discharges on the surface	Surface PD
Assembly problems, manufacturing problems	Partial discharges within the insulation	Internal PD
Cables		
Cracks, air bubbles, dirt	PD, minor insulation damage	Internal PD
Electrical treeing	PD, small insulation breakdown	Internal PD
Splices		
Installation problems, manufacturing problems, ageing	PD, minor insulation damage	Internal PD
Humidity	PD, small insulation breakdown between conductor and screen	Surface PD

Table 1: Type of partial discharge by defect location

3. MEASUREMENT METHODOLOGY

Off-line PD measurements were carried out with a 0.1 Hz VLF source (VIOLA TD) and a capacitive coupler (PD-TaD 62), to obtain the maximum apparent charge in pC and the pulse count per voltage level. The test campaign also intended to obtain inception and extinction voltages; the available record does not report the extinction voltage, and the inception voltage of L1 cannot be determined (Section 6), so that objective is withdrawn.

Location is based on time-domain reflectometry (TDR), which in this context denotes two distinct procedures. In conventional fault-location TDR, the instrument injects a low-voltage pulse and the distance to an impedance change is obtained from the time between emission and reflection [3]. In PD location, the pulse is generated by the discharge itself and the coupler records the direct pulse and its reflection at the remote end; the time difference, multiplied by the parameter h = v/2, locates the source along the cable. This geometry is formulated in equation (3) as our own derivation from the relationship between time, velocity and distance, and is not attributed to a clause of IEEE 400.3.

In conventional TDR the instrument records variations of the line's characteristic impedance, which is a property of the conductor-shield pair and not a difference between their two impedances, and measures the round-trip time of the pulse to the discontinuity [18]. The reflection coefficient at the discontinuity is [5]:

$$r = \frac{Z_p - Z_{L1}}{Z_p + Z_{L1}} \tag{1}$$

where:

Z_p= Impedance at the discontinuity point (load), [Ω].

Z_{L1}= Characteristic impedance of the line, a property of the conductor-shield pair as a whole, [Ω].

3.1 Mathematical model for cable fault location (TDR)

Equation (2) is the generalised model with which the instrument calculates the distance to an impedance variation along the conductor [22].

$$L = v * \frac{t_d}{2} = c * \frac{1}{PF} * \frac{t_d}{2} = c * \frac{V_0P}{100} * \frac{t_d}{2} \tag{2}$$

where:

L = Distance to the impedance irregularity, [m]

v = propagation velocity of the electromagnetic wave in the line, [$^{m}/_{\mu s}$];

PF = propagation factor, $^{c}/_{v}$

V_0P = relative propagation velocity, $(^{v}/_{c}) * 100\%$

t_d = measured time delay of the reflected signal, [μs];

c = speed of light, equal to 299.8 [$^{m}/_{\mu s}$]

The instrument introduces this calculation through a single parameter, h = v/2, with which the distance is obtained as L = h·td. The value of 81 m/µs recorded for the three cables is that parameter h, not the physical velocity v, which works out to 162 m/µs (Section 8).

For a partial discharge, the pulse originates at the defect, located at a distance x from the end where the coupler is connected, and travels toward both ends. The coupler first records the direct pulse, which travels x, and then its reflection at the remote end, which travels L − x to that end and L back. The arrival-time difference between the two is Δt = 2(L − x)/v, from which:

$$x = L - h \cdot \Delta t \tag{3}$$

with L the cable length and h = v/2. Equation (3) locates the discharges in the linear PD profiles of Section 5. The end from which measurement was taken was not recorded (Section 8); x is understood as measured from the coupler end.

The test procedure (Figure 1) applies the voltage with a VLF source, which reduces stress on the insulation, and measures the signals with a capacitive coupler. It also includes a system calibration and a noise measurement before the test, and a record of the discharges along the cable with TDR location. The execution and adequacy of that calibration and that noise measurement cannot be verified, because the certificate, the background noise level, the filters and the test records are not available (Section 8).

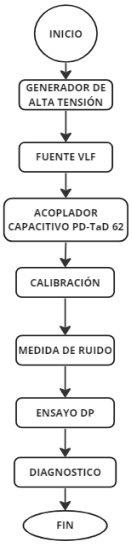


Figure 1: Simplified diagram of PD location

3.2 Equipment connection

The equipment used is shown in Figure 2, where:

1= PD Calibrators

2= PD-TaD 62 (Capacitive coupler)

3= VIOLA TD

4= BAUR SW4 software

5=Common equipment power outlet

Before the test the equipment was calibrated to IEC 60270 with the PD calibrators, which inject a known reference charge at the measurement point. That calibration fixes the system's charge reference; it is a necessary condition for interpreting readings in pC, but it does not by itself bound the measurement uncertainty, which is not documented.

The calibrator connection is shown in Figure 3. The original test report declares an injected charge of 5 pC to 10 pC, below the lowest setting of the calibrators listed in the system's datasheet: the CAL1B starts at 0.1 nC = 100 pC and the CAL1E at 0.5 nC = 500 pC [2]; the discrepancy is not resolved (Section 8).



Figure 2: Equipment for PD analysis

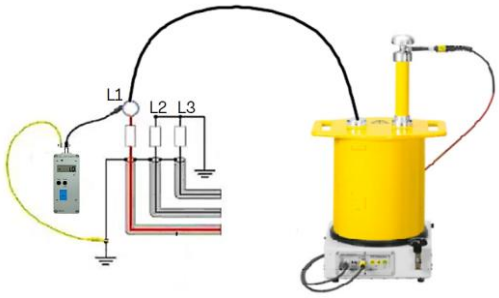


Figure 3: PD Calibrators calibration equipment

For partial discharge measurement, the connection shown in Figure 4 must be taken into account.

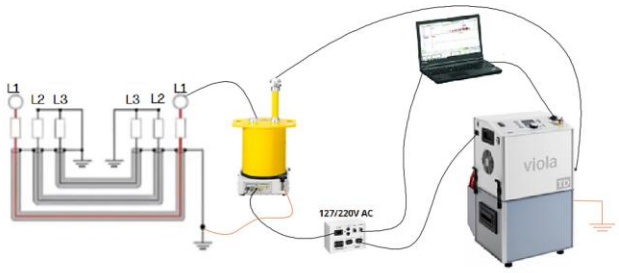


Figure 4: Measurement circuit for PD.

3.3 Apparent-charge reference bands

To order the reading of the measured charges, four apparent-charge bands are adopted (Table 2). These are conditioned reference bands: they do not constitute a normative acceptance criterion, but a conditioned illustrative convention whose application to a specific installation would require contrasting its cut-offs and actions against applicable standards, the cables' service history, and expert judgement.

Band	Maximum apparent charge [pC]	Associated provisional action
I	less than 500	Low provisional priority: no action derived from the test
II	from 500 to less than 1000	Provisional monitoring: repeat the measurement
III	from 1000 to less than 2500	Confirmatory inspection: pre-location of the source
IV	2500 or more	Priority confirmatory inspection of conductor and terminations

Table 2: Apparent-charge reference bands. Only the 500, 1000 and 2500 pC cut-offs are kept from the original test report; the boundaries (intervals closed at the bottom and open at the top) and the provisional actions were defined for this study and do not constitute a maintenance recommendation.

The original test report warned that these values are for reference only and that the final interpretation must include the operator's experience.

4. TRIAGE RULE WITH DEFERRED DECISION

4.1 Reference bands and boundary convention

The original test report's table had four rows, «0 to 500», «500 to 1000», «1000 to 2500» and «> 2500» pC, with actions ranging from requiring none to locating the source and repairing immediately, and its text rated readings as acceptable, «not acceptable», «high» risk or «very high» risk. Its conclusions, however, reduced the cables to two states, acceptable or at risk, and did not consistently operationalise the intermediate bands. This work keeps only the cut-offs from that table: it redefines the boundaries with its own convention and replaces the actions with provisional ones (Table 2), so that the intermediate bands receive an explicit action.

The cut-offs come from the original test report, which reproduced them without indicating a verifiable source: they do not come from a consulted standard and have not been validated against expert criteria or service data, which is why the actions are provisional. The analysis is revisable if contrasting it against applicable standards, service history, or expert judgement led to different cut-offs or actions. The same absolute cut-offs in pC are applied at the four voltage levels, as the source protocol did, even though apparent charge grows with voltage: the cut-off is more permissive at 0.5 U0 and stricter at 1.5 U0. Voltage-level-dependent cut-offs, or a rule based on the trend of charge with U/U0, are reasonable alternatives that have not been evaluated (Section 8).

The boundaries are defined with our own operational convention: intervals closed at the bottom and open at the top, so that the partition covers every valid charge without overlaps. At 2500 pC this convention assigns the upper band, the more conservative of the two possible choices. None of the ten measurements with data falls exactly on a cut-off, so the convention does not alter any result of this study.

A category the table does not provide for is added: the deferred decision. An empty cell is not converted to zero, because the original record does not allow distinguishing between a test not performed, data not reported, absence of detection, and a value below the detection limit; those cells receive no band. A reported entry that is not a real, finite, non-negative number is invalid and is rejected for a different reason.

It is a triage rule, not a predictive model: it has not been fitted to training data, its accuracy is not estimated, and it is not credited with any ability to anticipate failures, because the three cables have no subsequent service outcomes. Its function is to make explicit and auditable the step from a measured charge to a provisional action.

4.2 Formalisation as a triage rule with abstention

Let q_{ij} be the maximum apparent charge recorded on cable i at voltage level j, with cut-offs $t_0 = 0 < t_1 = 500 < t_2 = 1000 < t_3 = 2500 < t_4 = \infty$ pC. A reported entry is a valid charge if it is a real, finite, non-negative number, that is, if $q_{ij} \in [0, \infty)$. The nominal band of a valid charge q is:

$$b(q) = k \text{ si } t_{k-1} \leq q < t_k,\ k = 1, \ldots, 4 \tag{4}$$

For a valid charge, let $u_{ij} \geq 0$ be the uncertainty half-width attributed to the reading, and $I_{ij} = [max(0, q_{ij} - u_{ij}), q_{ij} + u_{ij}]$ its interval; for a missing or invalid entry the interval is not defined. Given u_{ij}, the triage assigns each pair a band or one of three abstention outputs, which are not bands and are not aggregated among themselves; the output depends on the charge and on the assumed uncertainty, which is why it is written $\tau(q_{ij}, u_{ij})$:

$$\tau(q_{ij}, u_{ij}) = \begin{cases} D_M \text{ si } q_{ij} \text{ no reportado} \\ R \text{ si } q_{ij} \text{ reportado y } q_{ij} \notin [0, \infty) \\ B_{b(q_{ij})} \text{ si } q_{ij} \in [0, \infty) \text{ y } b(max(0, q_{ij} - u_{ij})) = b(q_{ij} + u_{ij}) \\ D_U \text{ si } q_{ij} \in [0, \infty) \text{ y } I_{ij} \text{ interseca más de una banda} \end{cases} \tag{5}$$

With $u_{ij} = 0$ the interval reduces to a point and $\tau(q_{ij}, 0)$ returns the nominal band (Section 6.4); with $u_{ij} = 0{,}10 \cdot q_{ij}$, $\tau(q_{ij}, 0{,}10 \cdot q_{ij})$ it returns that of the conditioned analysis (Section 7.2), in which the same L3 reading at 1.5 U0 goes from B_1 to D_U. A value lying exactly on a cut-off receives the upper band and only becomes D_U if its interval intersects more than one band, so that, for each u_{ij}, the four outputs are mutually exclusive. D_M signals missing information, D_U a valid reading whose band is not determined under the assumed uncertainty, and R an invalid entry. Each output carries a provisional action: that of Table 2 for the bands; retrieve the record or repeat the measurement for D_M; reduce the uncertainty or repeat the test for D_U, and correct the record for R. The result per cable, for a given uncertainty, is a four-component vector:

This distinction between the four outputs replicates, in a concrete case, the separation between types of indeterminacy proposed by typed indeterminacy engineering [4, 16]: absence is a form of ignorance removable by the same type of evidence (retrieving the record), the undetermined-band output is indeterminacy removable by a different premise (reducing the assumed uncertainty, not obtaining more data of the same type), and the invalid entry is a data-quality defect closer to falsity than to ignorance [19] — hence each one receives a different provisional action instead of a single catch-all rule.$u_{ij} = 0\tau(q_{ij}, 0)u_{ij} = 0{,}10 \cdot q_{ij}\tau(q_{ij}, 0{,}10 \cdot q_{ij})B_1 D_U D_U u_{ij} D_M D_U R D_M D_U R$

$$\Delta_i = (\beta_i, n_{M,i}, n_{U,i}, n_{R,i}),\ \beta_i = max\{\, b(q_{ij}) : \tau(q_{ij}, u_{ij}) \in B \,\},\ max\, \emptyset \coloneqq \emptyset \tag{6}$$

where B is the set of the four bands; β_i is the highest known band of the cable, with the null state $\emptyset$ when no pair has a band, and $n_{M,i}$, $n_{U,i}$ and $n_{R,i}$ count the cable's pairs in D_M, D_U and R. The decision rule for the cable is explicit. (i) If $\beta_i = B_4$, the cable is prioritised for confirmatory inspection even if there are deferred or rejected pairs, because no additional data or correction could lower that action; the pairs in R remain flagged to correct the record. (ii) If $\beta_i \neq B_4$, including the null state, and some pair in D_M, D_U or R could raise the action once resolved, the decision on the cable is deferred; a pair in D_U does not defer it if the band at the upper end of its interval does not exceed β_i. (iii) In all other cases, the decision is that of β_i. It is an ordinal, deterministic rule with abstention, not a decision model: it has no objective function, losses, preferences or costs associated with the actions, because the study does not have them, and it has not been validated against subsequent service outcomes or an independent panel of specialists; both are noted as future work in Section 8.

4.3 From the cable-level pair to the decision on the cable

Bands are assigned to each cable-level pair and the step to the cable is the rule of equation (6). L1 has Δ = (B4, 1, 0, 0): its highest known band is the upper one and the missing 0.5 U0 level could not lower the action, so it is prioritised for confirmatory inspection of the conductor and terminations. L2 has Δ = (B4, 0, 0, 0) and is prioritised equally. L3 has Δ = (B1, 1, 0, 0) with u = 0 and Δ = (B1, 1, 1, 0) under the conditioned uncertainty: it lacks the 0.5 U0 measurement and its 1.5 U0 reading, 11.3 pC from the cut-off, is not resolved; either one could raise the action. The decision on L3 therefore remains deferred, not concluded as B1. Taking the highest band is the most conservative criterion, because

the highest test level interrogates the insulation under the least favourable condition.

As a sensitivity check, a stricter rule was applied: prioritise the cable only if the upper band appears at two consecutive voltage levels. The decisions do not change: L1 shows the upper band at 1.0, 1.2 and 1.5 U0 and L2 at 1.2 and 1.5 U0, while L3 does not reach it at any level and its decision remains deferred. This check does not cover the alternatives of voltage-level-dependent cut-offs or a trend rule with U/U0.

The reverse reading is not valid: not triggering the upper band does not equate to not needing review. That L3 shows no activity in the upper band at the three measured levels does not imply it is fit to enter service; what is indicated is to complete the 0.5 U0 measurement and repeat the 1.5 U0 one with the system's uncertainty documented, and only then decide.

5. CASE STUDIES

Of the six cables tested in a 1.1 km three-phase set, three cases with discharge activity were selected [7]. They are 35 kV XLPE single-core cables, not new, tested before entry into service. Their characteristics are summarised in Table 3, and the confirmed pulses and the maximum apparent charge recorded by the BAUR SW4 software over the total length of each cable, in Table 4.

Characteristic	**L1**	**L2**	**L3**
Rated voltage [kV]	35	35	35
Insulation	XLPE	XLPE	XLPE
Length [m]	556	538	544
Equipment location parameter, h = v/2 [m/µs]	81	81	81
Number of phases	1	1	1
Sheath properties	PVC	PVC	PVC
Gauge according to the original test report	750 MCM	750 MCM	not stated
Gauge according to the thesis [7]	500 MCM	500 MCM	500 MCM

Table 3: Characteristics of cables L1, L2 and L3. The gauge is transcribed from both sources because they differ: the original test report states 750 MCM for L1 and L2 and does not state it for L3; the thesis [7] states 500 MCM for all three.

Voltage level	**L1 (0-556 m)**		**L2 (0-538 m)**		**L3 (0-544 m)**	
	Confirmed PD	**Max. charge [pC]**	**Confirmed PD**	**Max. charge [pC]**	**Confirmed PD**	**Max. charge [pC]**
0.5 U0 / 10.1 kV			152	142.9		
1.0 U0 / 20.2 kV	396	3456.6	305	1295.9	1	208.7
1.2 U0 / 24.3 kV	562	3519.1	439	3530.6	6	207
1.5 U0 / 30.3 kV	793	3552.1	755	3755.1	72	488.7
Printed PD sum / Max. charge	**1751**	**3552.1**	**1651**	**3755.1**	**79**	**488.7**

Table 4: Confirmed pulses (confirmed PD) and maximum apparent charge over the total length of each cable. Empty cells are empty in the original test report; the last row reproduces the printed «Sum PD» and «Max. Charge».

5.1 Case study on L1

The maximum test voltage was 1.5 U0 and the duration 15 min, values the original test report justified by the cables not being new and attributed to IEEE 400.3-2022; since that guide could not be consulted, they are presented here as parameters of the protocol applied, without normative attribution.
Figure 5 shows the voltage steps, from 0.5 U0 to 1.5 U0. According to the original test report, each level consists of 6 measurement periods; the source cited for that figure does not contain it, so it is presented as a protocol parameter. Six periods at 0.1 Hz are 60 s per level and 4 min spent across the four levels; the remainder of the declared 15 min (ramps, stabilisation and recording) is not broken down (Section 8).

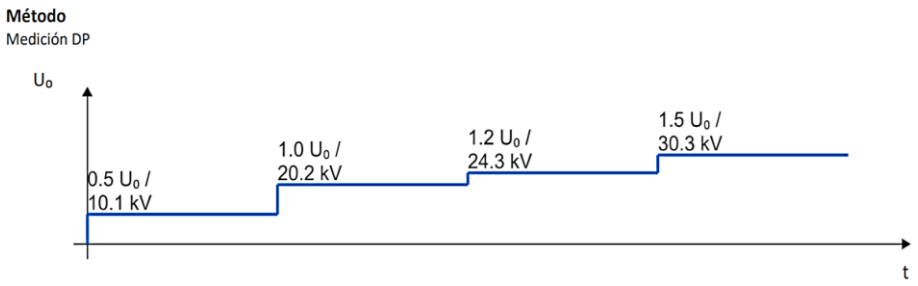


Figure 5: Ramp-up measurement stage

In L1, 556 m long, the total length and the 0 m to 10 m and 548 m to 556 m stretches were examined; Figure 6 shows the PD level along the cable.

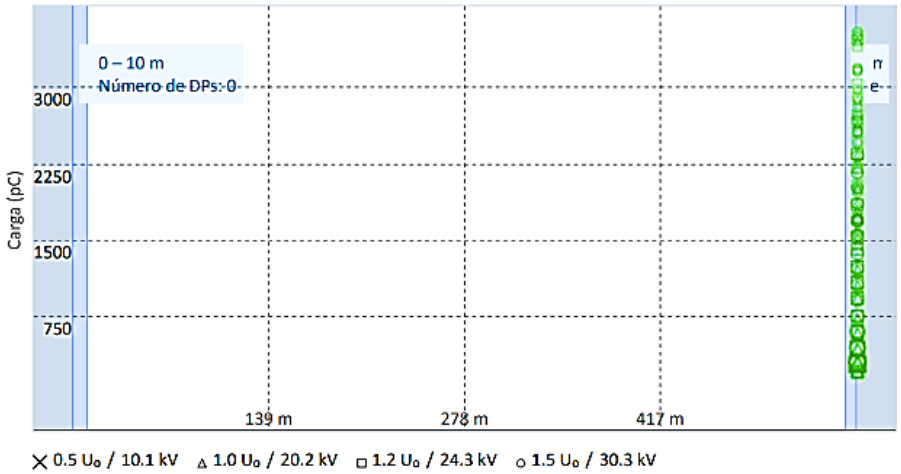


Figure 6: L1 linear PD level

Figure 6 detects discharges in the 548 m to 556 m stretch, that is, at the termination; between 0 m and 10 m no activity is observed.

5.2 Case study on L2

In this case three distances are examined: the total length, from 0 to 538 m; the initial stretch, from 0 to 5 m; and the final stretch, from 531 to 538 m.

Over the total length of L2 the sum of confirmed pulses is 1651 and the maximum charge is 3755.1 pC (Table 4). Under equal test conditions, a higher count indicates more discharge activity, but it is not by itself a probability of failure.

The 0 to 5 m stretch gathers 470 pulses (Table 5), fewer than the 531 to 538 m stretch (Table 6).

Figure 7 shows in green the PD located between 0 and 5 m and between 531 and 538 m. The two stretches together gather 1634 of the 1651 pulses confirmed over the total length: 470 in the initial stretch and 1164 in the final one. The remaining 17, which are 6, 4, 3 and 4 by voltage level from 0.5 to 1.5 U0, 1.0% of the total, are recorded outside both stretches. Activity is concentrated at the terminations, but is not exclusive to them, and those 17 pulses were not located.

Zone (0-5 m)	Confirmed PD	Max. Charge [pC]
0.5 U0 / 10.1 kV	134	122.4
1.0 U0 / 20.2 kV	134	132.7
1.2 U0 / 24.3 kV	90	173.5
1.5 U0 / 30.3 kV	112	244.9
	PD sum: 470	**Max. Charge [pC]: 244.9**

Table 5: PD data in the 0 to 5 m stretch of L2

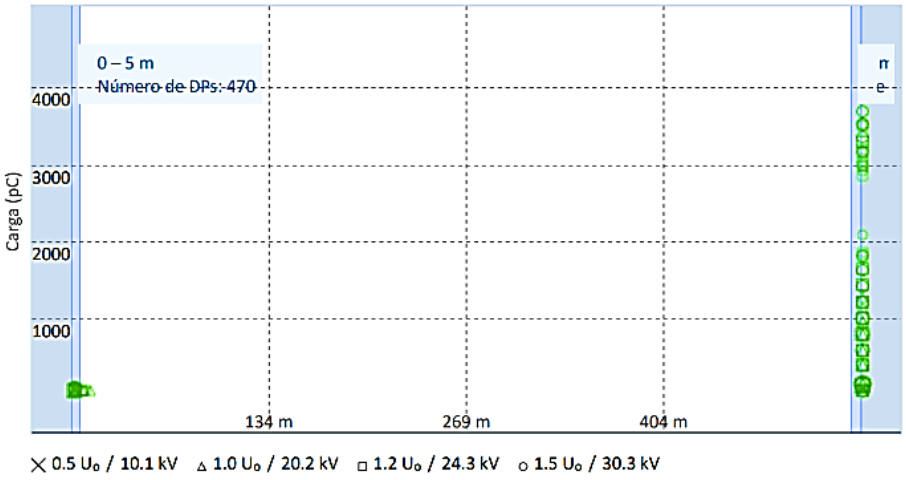


Figure 7: L2 linear PD level

Zone (531-538 m)	Confirmed PD	Max. Charge [pC]
0.5 U0 / 10.1 kV	12	142.9
1.0 U0 / 20.2 kV	167	1295.9
1.2 U0 / 24.3 kV	346	3530.6
1.5 U0 / 30.3 kV	639	3755.1
	PD sum: 1164	**Max. Charge [pC]: 3755.1**

Table 6: PD data in the 531 to 538 m stretch of L2

5.3 Case study on L3

In the 0 to 7 m stretch no discharges are observed; PD is located in the 537 m to 544 m stretch, at the termination point (Figure 8). With the reference bands, that activity falls in the lower band, of low provisional priority; it does not follow from this that the installation is free of risk.

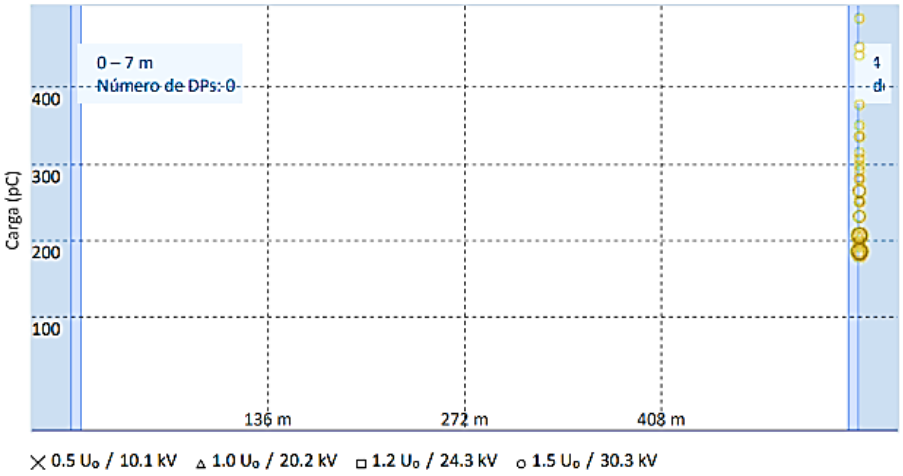


Figure 8: L3 linear PD level

In L3 the sum of pulses is 79 and the maximum charge is 488.7 pC (Table 4). With the bands of Table 2 the three reported readings fall in the lower band; even so, the decision on L3 remains deferred (Section 4.3), because the 0.5 U0 reading is missing and the 1.5 U0 one is 11.3 pC from the cut-off.

6. ANALYSIS OF RESULTS

6.1 Analysis Case study on L1

In L1 (Figure 9) the affected stretch runs from 548 m to 556 m. The test operator interpreted the pattern as consistent with an internal PD, taking as evidence the presence of discharges in both half-cycles. That evidence is necessary but not sufficient: the interpretation was made on the BAUR SW4 phase-resolved patterns, without quantitative criteria, without documented noise filtering, and without independent contrast. The band assignment does not depend on it. The original test report placed L1's inception voltage (PDIV) at 10.1 kV, but the 0.5 U0 / 10.1 kV row of Table 4 is empty and an empty cell does not inform on that voltage: L1's PDIV cannot be determined from what is published.

L1's charges at 1.0, 1.2 and 1.5 U0, of 3456.6, 3519.1 and 3552.1 pC (Table 4), all fall in the upper band, for which Table 2 provides for priority confirmatory inspection. The cable's maximum apparent charge, 3552.1 pC at 1.5 U0, is a maximum, not a sum.

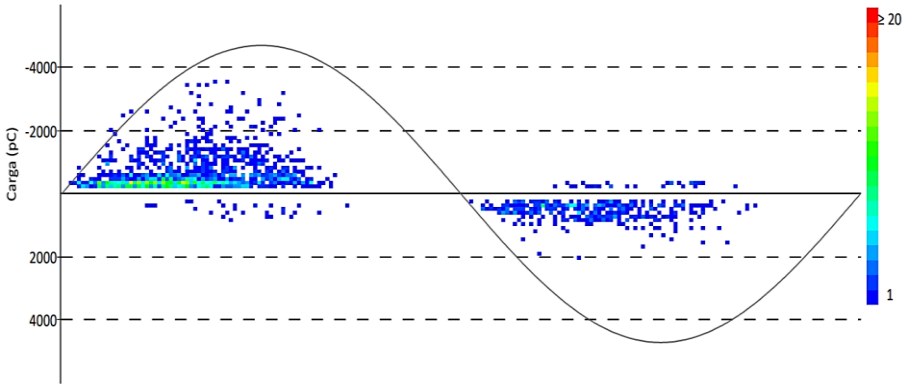


Figure 9: PD of the 548 m to 556 m segment (L1)

6.2 Analysis Case study on L2

The test operator attributed the pattern of the 0 to 5 m stretch (Figure 10) to noise, which they associated with the termination point or with the ramp voltage variation, and interpreted it as not associated with the insulation. This is an operator hypothesis with no records, filters or quantitative criteria to support it; the thesis [7] attributed it to IEEE 400.3-2022, an attribution that has not been verified.

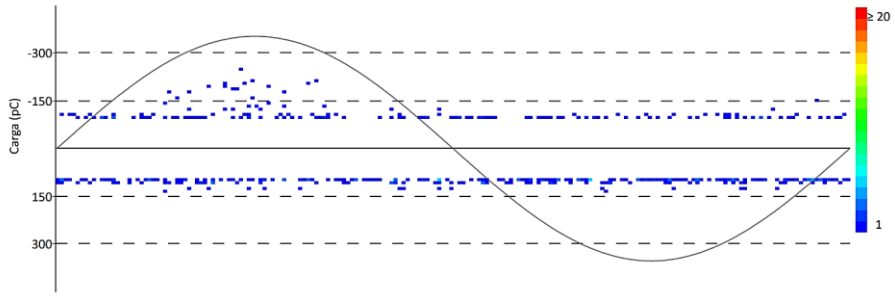


Figure 10: PD analysis chart for the 0–5 m segment (L2)

In the 531 to 538 m stretch (Figure 11) the operator attributed the pattern to corona effect, while in L3 a pattern also attributed to corona is described as having no action on the insulation. These are different stretches and both readings could be compatible, but neither is supported by documented grounds, and the band assignment does not depend on them. The original test report refers to [21] for the reference patterns; that work deals with locating discharges in cable terminations by waveform analysis, and it has not been verified that it contains the pattern classification applied.

In that stretch the charge grows with voltage (Table 6): at 0.5 U0 it is 142.9 pC, in the lower band; at 1.0 U0, 1295.9 pC, in the intermediate band B3, for confirmatory inspection with source pre-location; at 1.2 and 1.5 U0, 3530.6 and 3755.1 pC, in the upper band B4, for priority confirmatory inspection.

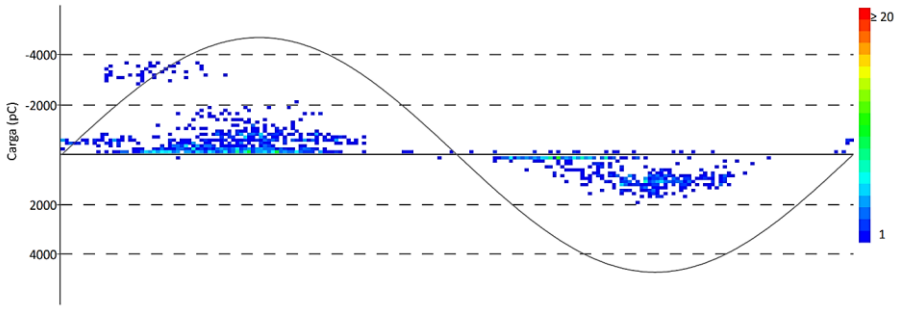


Figure 11: PD of the 531–538 m segment (L2)

6.3 Analysis Case study on L3

In L3 (Figure 12) the operator attributed the pattern to corona effect, which they associated with a termination point close to or in contact with a metallic part, and described it as having no action on the insulation; this is an operator hypothesis that has not been verified. The three measured readings fall in the lower band, but the highest, 488.7 pC at 1.5 U0, is 11.3 pC from the cut-off, and under the conditioned analysis of Section 7.2 its interval would cross that boundary; furthermore, the 0.5 U0 level is not reported. The defensible conclusion is not that L3 requires no action, but that it does not trigger the upper band at the measured levels and that its most demanding case remains unresolved.

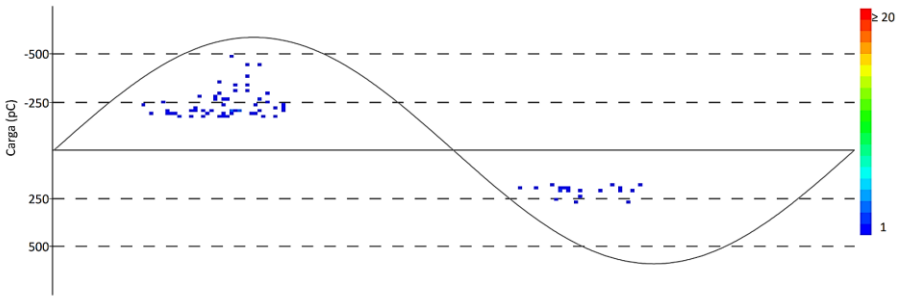


Figure 12: PD analysis in the 537–544 m segment (L3)

6.4 Band assignment and arithmetic check

Of the 12 pairs, 10 receive a band and 2 remain in deferred decision for lack of data (Table 7): the assignment coverage is 83.3%. That figure states what fraction of the measurements receives an associated provisional action. It is not an accuracy, it is not a confidence, and it does not constitute validation of anything: without subsequent service outcomes there is no criterion against which to measure any correctness.

There is also a precondition to any comparison against absolute thresholds that was not documented: whether the charges were corrected for pulse attenuation along the cable, from which end they were measured, and with what factor. Without that information the charges are comparable with one another within the same test, but their comparison against Table 2 remains conditioned.

Cable	Level	Confirmed pulses	Max. apparent charge [pC]	Source table	Assigned band
L1	0.5 U0	not reported	not reported	Table 4	No band: datum not reported
L1	1.0 U0	396	3456.6	Table 4	B4 Priority inspection
L1	1.2 U0	562	3519.1	Table 4	B4 Priority inspection
L1	1.5 U0	793	3552.1	Table 4	B4 Priority inspection
L2	0.5 U0	152	142.9	Table 4	B1 Low priority
L2	1.0 U0	305	1295.9	Table 4	B3 Confirmatory inspection
L2	1.2 U0	439	3530.6	Table 4	B4 Priority inspection
L2	1.5 U0	755	3755.1	Table 4	B4 Priority inspection
L3	0.5 U0	not reported	not reported	Table 4	No band: datum not reported
L3	1.0 U0	1	208.7	Table 4	B1 Low priority
L3	1.2 U0	6	207.0	Table 4	B1 Low priority
L3	1.5 U0	72	488.7	Table 4	B1 Low priority

Table 7: Band assignment for the twelve cable-level pairs. «Not reported» flags empty cells in the source and is not equivalent to absence of discharges**.**

The two pairs without a band are so because information is missing, not because of intermediate severity. If the level was not tested or the datum was not transcribed, no band can be deduced at all. If nothing was detected or the reading fell below the detection limit, the charge could only be bounded by the setup's actual detection limit, which depends on noise, length and attenuation and is not documented; the 1 pC to 100 nC range with 0.1 pC resolution from the datasheet [2] is an instrument specification, not that limit. In all four situations the cell is still not a zero, and the pair is kept as a deferred decision, which the original record or repeating the measurement would resolve.

In L1 the three known readings are in the upper band, so the missing level would not change the decision. In L3 this is not the case: its known readings are in the lower band, and if the missing measurement existed and turned out high, the assessment could change. The decision on L3 therefore depends on information that is not available.

The «Sum PD» printed at the foot of each source table is a sum of confirmed pulses, and «Max. Charge» is the maximum of the charge column, not its sum; the original text treated them as a single quantity. Both have been verified (Table 8).

Cable	Table	Printed pulse sum	Sum of rows with data	Printed max. charge [pC]	Rows without data
L1	Table 4	1751	1751	3552.1	1
L2	Table 4	1651	1651	3755.1	0
L3	Table 4	79	79	488.7	1

Table 8: Check of the printed totals. The pulse sums match the rows with data; in L1 and L3 the empty 0.5 U0 row contributes nothing to the total, which is compatible with either no discharges being detected or that level being left out of the count.

7. SENSITIVITY ANALYSIS

7.1 Stability of the assignment

The effect of moving the reading with fixed thresholds, and that of moving a threshold with the readings intact, are examined separately.

Each reading was perturbed by ±1%, ±2% and ±5%, illustrative gradations, and by ±10%, the uncertainty IEC 60270 declares (Section 7.2). With ±1% and ±2% the ten readings keep their band; with ±5% and ±10% only L3 at 1.5 U0 changes, moving from the lower band to the watch band. This is the tightest case: 488.7 pC against a 500 pC cut-off, 11.3 pC of margin, equivalent to a relative increase of 2.312% over the reading itself. The five upper-band readings are far from their cut-off.

The cut-offs must keep their order, $0 < t_1 < t_2 < t_3$, so each one can only shift between its neighbours. Since the lower end of each band is closed, lowering a cut-off until it REACHES a reading already changes its band, whereas raising it requires crossing it, that is, a strictly larger shift (Table 9).

Cut-off [pC]	Admissible margin [pC]	Lower it [pC]	Raise it [pC]
500	(0 ; 1000)	11.3 (reach, L3 1.5 U0)	no change before reaching the neighbouring cut-off (1000 pC)
1000	(500 ; 2500)	no change before reaching the neighbouring cut-off (500 pC)	> 295.9 (cross, L2 1.0 U0)
2500	(1000 ; ∞)	1204.1 (reach, L2 1.0 U0)	> 956.6 (cross, L1 1.0 U0)

Table 9: Effect of shifting ONE cut-off with the readings and the other two cut-offs intact, under the restriction $0 < t_1 < t_2 < t_3$. When raising, the indicated shift is a strict lower bound.

The 500pC cut-off is the most fragile from below: lowering it by 11.3 pC is enough for L3 at 1.5 U0 to move to the watch band, whereas moving it upward it reaches its neighbour without changing anything. The 1000 pC cut-off behaves the other way round, and the 2500 pC one has slack in both directions.

7.2 Analysis conditioned on conformity with IEC 60270

It remains to be seen whether an 11.3 pC deviation is plausible. Clause 9 of IEC 60270:2000, «Measuring uncertainty and sensitivity», states that the apparent-charge measurement, «using a measuring system in accordance with the provisions of this standard and calibrated in accordance with the provisions of clauses 5 and 7, is considered to have a measuring uncertainty of ±10% or ±1 pC, whichever is the greater» [12]. The text was checked in the third edition, of 2000; in its amendment 1, of 2015, also in force until June 2025, that clause has not been consulted. The fourth edition, IEC 60270:2025, replaces both from June 2025 [13].

The figure is not unconditional: it applies to a measuring system that conforms to the standard and is calibrated per its clauses 5 and 7, which include calibrator checks and recommended traceability to national standards.

The original test report declares that the equipment «is calibrated in accordance with IEC 60270», with a charge of 5 to 10 pC. That is a declaration of having calibrated, not a conformity record: the certificate, the calibrator's traceability and the verification of the measuring system are not available, and the declared charge is below the lowest setting of the calibrators in the datasheet [2]. The thesis [7] refers to a calibration certificate in its Annex 1, which does not appear in the deposited version. With that evidence it cannot be stated that the test uncertainty is ±10%.

That is why Table 10 is a CONDITIONED analysis: it shows what would happen if the test met those conditions, not the instrumental uncertainty of these measurements, and no confidence level is assigned to it.

The same clause warns that the magnitude and repetition rate of the discharges depend on the voltage application time,

and that «it can be difficult to confirm PD test data by repeating tests».

Cable	Level	Charge [pC]	Uncert. [pC]	Min. [pC]	Max. [pC]	Band	Resolvable?
L1	1.0 U0	3456.6	345.66	3110.94	3802.26	B4 Priority inspection	yes
L1	1.2 U0	3519.1	351.91	3167.19	3871.01	B4 Priority inspection	yes
L1	1.5 U0	3552.1	355.21	3196.89	3907.31	B4 Priority inspection	yes
L2	0.5 U0	142.9	14.29	128.61	157.19	B1 Low priority	yes
L2	1.0 U0	1295.9	129.59	1166.31	1425.49	B3 Confirmatory inspection	yes
L2	1.2 U0	3530.6	353.06	3177.54	3883.66	B4 Priority inspection	yes
L2	1.5 U0	3755.1	375.51	3379.59	4130.61	B4 Priority inspection	yes
L3	1.0 U0	208.7	20.87	187.83	229.57	B1 Low priority	yes
L3	1.2 U0	207.0	20.70	186.30	227.70	B1 Low priority	yes
L3	1.5 U0	488.7	48.87	439.83	537.57	B1 Low priority	NO

Table 10: Analysis CONDITIONED on the test meeting the IEC 60270 conformity and calibration conditions [12]. «NO» means that the ±10% interval would cross a cut-off point; it is not the confirmed instrumental uncertainty of these measurements.

Coverage and stability have different denominators. Assignment coverage is 10 out of 12 cable-level pairs; stability under the adopted interval is 9 out of 10 observed readings, 90.0%, and can only be calculated over those with data. Their denominators are not interchangeable.

Under that assumption, the five upper-band readings would remain above 2500 pC, and those of L2 at 0.5 U0 and L3 at 1.0 and 1.2 U0, below 500 pC throughout their interval; the exception is L3 at 1.5 U0, whose interval would cross the 500 pC cut-off.

Even granting the unaccredited conformity, that reading would not allow deciding between «low provisional priority» and «provisional watch»; without it, the real uncertainty is unknown and could be larger. In both scenarios what is indicated is to repeat the measurement and document the system's uncertainty.

8. LIMITATIONS

This work is an exploratory case study. It is three cables selected for showing discharge activity, with measurements reported at four voltage levels for L2 and at three for L1 and L3, whose 0.5 U0 level is not available, and with no subsequent service outcomes. Three limits follow from this. There is no estimable predictive capacity, because no failure labels exist against which to contrast the triage. Closing this gap requires a minimal follow-up set: for each cable and measured voltage level, recording whether a failure occurred within a service horizon defined in advance, so that the band assigned by the triage rule can be contrasted against that outcome and not merely described. There is no representative sample, because the cables were chosen precisely for being relevant. And there is no certification of fitness for service: the rule orders maintenance attention, it does not authorise entry into operation.

Five elements remain undocumented in the available sources and are flagged as such. The first is the basis of Table 2: its cut-offs and actions have not been contrasted against applicable standards, service history, or expert judgement, so the bands are a conditioned convention and do not by themselves ground fitness-for-service or repair decisions. The second, the meaning of the empty 0.5 U0 cells. The third, the normative backing for 1.5 U0 and 15 minutes: the original test report attributed them to IEEE 400.3-2022, an attribution that could not be verified because the guide's text is not open access; nor is the breakdown of the 15 minutes available. The fourth, attenuation: it is not stated whether the charges were corrected, from which end they were measured, or with what factor. The fifth is evidence of conformity with IEC 60270: the declaration of having calibrated is available, but not the certificate, the traceability, or the system's verification, and the declared calibration charge is incompatible with the calibrators in the datasheet; that is why Table 10 is a conditioned analysis.

A sixth matter has indeed been settled with manufacturer documentation. The value of 81 m/µs that the equipment report labelled as propagation velocity is the location parameter h = v/2, as Table 3 now calls it: the datasheet of the BAUR PD-TaD 62 coupler expresses its location range «at v/2 = 80 m/µs» and sets the parameter's adjustable range at 50 to 120 m/µs [2]. The implied velocity is v = 162 m/µs, to which an effective permittivity of $(299.8/162)^2 = 3.42$ corresponds. The published distances are thus obtained with the parameter the instrument expects.

The rule has not been compared against reasonable alternatives, such as voltage-level-dependent cut-offs or a rule based on the trend of charge with U/U0, which the two-consecutive-levels check (Section 4.3) does not cover. No

costs or consequences have been assigned to the actions, nor has the rule been contrasted with an independent panel of specialists, and there is no validation against service outcomes either; the three extensions remain as future work.

Finally, the test's reproducibility is limited by what is not available in the available sources: the date of each test, the service history of each cable, the exact duration of each voltage level and the number of cycles applied, the ramp profile, the background noise level and the filters used, the setup's effective detection threshold, the end from which measurement was taken, the attenuation correction, the calibrator model and its certificate. Without that data the measurements are comparable with one another within the same test, but not reproducible by a third party, and the conclusions must be read with that restriction.

9. CONCLUSIONS AND RECOMMENDATIONS

Applying field PD tests to three 35 kV XLPE single-core cables made it possible to describe and prioritise the cases studied. Reflectometry locates the origin of the pulses along the cable; the discharge type does not come from reflectometry but from the interpretation of the phase-resolved patterns, subject to the operator's judgement.

In L1 activity is located in the 548 m to 556 m stretch and is consistent with a source at the cable termination, with a pattern consistent with an internal discharge according to the operator's interpretation. In L2 it is concentrated between 531 m and 538 m, with 1164 of the 1651 pulses, 470 in the 0 to 5 m stretch, and 17 (1.0%) outside both stretches; the operator interpreted the pattern as internal discharge mixed with corona and associated it with contact with external surfaces, a hypothesis that could not be contrasted.

L1 and L2 fell in the upper band of Table 2, at 3552.1 pC and 3755.1 pC. Those bands are the conditioned convention taken from the original test report, not a criterion from IEEE 400.3-2022 or any other standard consulted, and they order maintenance attention without estimating risk over the cables' service life.

The activity of L1 and L2 is consistent with sources located at the termination points, which according to the original test report had been the subject of splices. That report proposed cutting out the damaged parts, making new splices, or re-rating the cables; the measurement does not demonstrate material damage nor allow choosing among those interventions, which remain proposals subject to an inspection confirming the defect's type, extent, and cause.

In L3 the maximum charge of 488.7 pC falls in the lower band at the three measured levels, but the decision remains deferred by the rule of equation (6): the 0.5 U0 measurement is missing, and the 1.5 U0 reading, 11.3 pC from the 500 pC cut-off, is not resolved under the adopted uncertainty. What is indicated is to complete and repeat those measurements before deciding on its entry into service and, as a maintenance practice and not as a prescription of the bands, to repeat the measurement at the frequency the operator's maintenance plan sets.

The tests were carried out in the Ecuadorian Amazon region. This study did not record or analyse humidity or ambient temperature, so no effect on the measurements can be attributed to them. Measuring those variables and contrasting their influence, which has not been established here, remains an open line of work.

The triage rule with abstention distinguishes what the source conclusions reduced to acceptable or at risk: 5 readings in the upper band and 4 in the lower one; one, L2 at 1.0 U0, in an intermediate band with its own provisional action; and two without data, declared deferred instead of assumed safe. It is recommended to complete the 0.5 U0 measurement on L1 and L3, document the equipment's uncertainty and the treatment of attenuation, and adopt a four-state structure only after calibrating its cut-offs and actions against applicable standards, service history, and expert judgement, comparing it with voltage-level-dependent cut-offs and with a trend rule based on U/U0.

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