

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Influence of materials and fabrication process in partial discharges in medium and high voltage underground cables

Maria Isabel Saraiva de Almeida



Mestrado em Engenharia Eletrotécnica e de Computadores

Supervisor: Prof. Bernardo Marques Amaral Silva

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Resumo

Esta dissertação tem como objetivo investigar as descargas parciais em cabos subterrâneos AC de Média e Alta Tensão (MT e AT), e como estas são influenciadas pela seleção de matérias-primas e pelo processo de fabrico, visando aumentar a fiabilidade e durabilidade das redes elétricas.

As descargas parciais (DP) constituem uma das principais causas de degradação prematura e falha catastrófica em sistemas subterrâneos de cabos de Média e Alta Tensão (MT e AT). Dada a sua natureza de crescimento lento e difícil deteção, quer em fábrica quer após instalação, estas descargas podem levar à destruição total do cabo e do equipamento adjacente, resultando em interrupções graves no fornecimento de energia e em custos de reparação consideráveis.

O foco desta dissertação reside na compreensão de como a natureza das matérias-primas e as especificidades do processo de fabrico condicionam a atividade dielétrica. Para tal, é efetuada uma análise retrospectiva da base de dados de qualidade de produção da fábrica, ao longo de uma janela contínua de 17 meses (janeiro de 2025 a maio de 2026). São identificados os parâmetros críticos do processo que conduzem à criação de defeitos, e estabelece-se uma correspondência entre esses defeitos e os mecanismos físicos de descarga parcial. O estudo explora ainda o comportamento destas descargas em diferentes níveis de tensão, correlacionando a integridade do cabo desde o processo de fabrico até ao produto final. O potencial de materiais isolantes mais sustentáveis, como o polipropileno termoplástico (PP), é discutido a nível teórico como complemento aos materiais tradicionais XLPE e EPR, não tendo sido possível incluí-lo na análise quantitativa devido ao volume de produção insuficiente durante o período em estudo.

A metodologia desta dissertação combina esta análise retrospectiva com uma fase experimental conduzida de acordo com as normas IEC 60502-2 (MT), IEC 60840 (até 150 kV inclusive) e IEC 62067 (acima de 150 kV até 550 kV), no âmbito da qual são realizados ensaios de tensão e de descargas parciais segundo a IEC 60270. O estudo estende-se a um caso prático de ensaios de aceitação em fábrica (FAT) em acessórios de sistemas de linhas de AT, como terminais e uniões, que constituem pontos vulneráveis e propensos a este fenómeno.

Os resultados obtidos permitem estabelecer uma correlação entre o nível de descargas parciais e a combinação de matérias-primas, parâmetros de processo e estado mecânico dos equipamentos de fabrico, identificando as condições que minimizam a ocorrência deste fenómeno no cabo. Com base nestas conclusões, é proposto um plano de medidas corretivas e preventivas, priorizado segundo a frequência e a severidade dos defeitos identificados, bem como recomendações técnicas e boas práticas de controlo de processo, com vista a otimizar a qualidade dielétrica e a vida útil dos sistemas elétricos de energia.

Palavras-chave: Descargas Parciais, Cabos Subterrâneos, XLPE, EPR, Média Tensão, Alta Tensão, Processos de Fabrico, Análise de Causa-Raiz, Sustentabilidade

Abstract

This dissertation aims to investigate partial discharges in Medium and High Voltage (MV and HV) AC underground cables, and how they are influenced by the selection of raw materials and the manufacturing process, with the objective of increasing the reliability and durability of electrical grids.

Partial discharges (PD) constitute one of the primary causes of premature degradation and catastrophic failure in Medium and High Voltage (MV and HV) underground cable systems. Given their slow-growing nature and difficult detection, both in the factory and after installation, these discharges can lead to the total destruction of the cable and adjacent equipment, resulting in severe power supply interruptions and considerable repair costs.

The focus of this dissertation lies in understanding how the nature of raw materials and the specifics of the manufacturing process condition dielectric activity. To this end, a retrospective analysis of the factory's production quality database is carried out over a continuous 17-month window (January 2025 to May 2026). The critical process parameters that lead to defect creation are identified, and a correspondence is established between these defects and the physical mechanisms of partial discharge. The study further explores the behavior of these discharges across different voltage levels, correlating cable integrity from the manufacturing process to the final product. The potential of more sustainable insulating materials, such as thermoplastic polypropylene (PP), is discussed at a theoretical level as a complement to traditional XLPE and EPR materials, though it was not possible to include it in the quantitative analysis due to insufficient production volume during the period under study.

The methodology of this dissertation combines this retrospective analysis with an experimental phase conducted in accordance with standards IEC 60502-2 (MV), IEC 60840 (up to 150 kV inclusive), and IEC 62067 (above 150 kV up to 550 kV), under which voltage and partial discharge tests are performed according to IEC 60270. The study extends to a practical case of factory acceptance testing (FAT) on HV line system accessories, such as terminations and joints, which constitute vulnerable points prone to this phenomenon.

The results obtained allow for the establishment of a correlation between the partial discharge level and the combination of raw materials, process parameters, and the mechanical condition of the manufacturing equipment, identifying the conditions that minimize the occurrence of this phenomenon in the cable. Based on these conclusions, a plan of corrective and preventive measures is proposed, prioritized according to the frequency and severity of the identified defects, as well as technical recommendations and process control best practices, aiming to optimize the dielectric quality and service life of electrical power systems.

Keywords: Partial Discharges, Underground Cables, XLPE, EPR, Medium Voltage, High Voltage, Manufacturing Processes, Root-Cause Analysis, Sustainability

UN Sustainable Development Goals

The United Nations Sustainable Development Goals (SDGs) provide a global framework to achieve a better and more sustainable future for all. It includes 17 goals to address the world's most pressing challenges, including poverty, inequality, climate change, environmental degradation, peace, and justice. These dissertation is aligned with the following Sustainable Development Goals:

SDG 7 Ensure access to affordable, reliable, sustainable and modern energy for all. [1]

SDG 8 Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all. [1]

SDG 9 Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. [1]

SDG 11 Make cities and human settlements inclusive, safe, resilient and sustainable. [1]

SDG 12 Ensure sustainable consumption and production patterns. [1]

SDG 13 Take urgent action to combat climate change and its impacts. [1]

SDG 17 Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development. [1]

SDG	Target	Contribution	Performance Indicators and Metrics
7	7.2	Enhancing the reliability of underground power cables through PD analysis facilitates the expansion of modern and sustainable energy infrastructure.	Percentage reduction in grid downtime/outages caused by cable insulation failure. [1]
8	8.2	Promoting technological upgrading and innovation by researching advanced insulation materials (PP) to achieve higher levels of economic productivity in the energy sector.	Increase in manufacturing efficiency and reduction in material rejection rates during production. [1]
	8.8	Reducing the risk of catastrophic cable failures and electrical accidents ensures a safer working environment for maintenance crews and utility workers.	Reduction in occupational hazards and injury frequency related to grid maintenance. [1]
9	9.4	Upgrading manufacturing processes and adopting sustainable materials promotes greater resource-use efficiency and cleaner industrial adoption.	Comparative dielectric strength and PD inception voltage levels between traditional and new materials. [1]
11	11.6	Improving the efficiency of urban power distribution reduces the environmental footprint of cities by minimizing the waste and pollution caused by frequent infrastructure replacement.	Reduction in per capita environmental impact of municipal energy infrastructure. [1]
13	13.1	Building more resilient electrical grids reduces the vulnerability of energy systems to climate-related hazards and prevents catastrophic environmental damage from failures.	Increase in insulation resilience metrics and cable service life expectancy. [1]
17	17.6	Contributing to the global knowledge base on clean energy technology and advanced materials through scientific research and technical collaboration.	Number of international standards (e.g., IEC 60270) applied and research data shared for technological transfer. [1]

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Isabel Almeida

“We cannot reason ourselves out of our basic irrationality. All we can do is learn the art of being irrational in a reasonable way”

Aldous Huxley, *Island*

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List of Acronyms

AC	Alternating Current
ANN	Artificial Neural Networks
APF	After-Production Failure (internal quality return category)
AT	Alta Tensão (High Voltage)
BL	Cableator machine (Bobinadora/Leira designation)
CBM	Condition-Based Maintenance
CB	Cabling machine designation (internal)
CCV	Catenary Continuous Vulcanisation (tube)
CNN	Convolutional Neural Networks
CT	Computed Tomography
CTE	Coefficient of Thermal Expansion
CV	Continuous Vulcanisation (tube)
DAC	Damped AC
DAS	Distributed Acoustic Sensing
DC	Direct Current
DCP	Dicumyl Peroxide
DDX	Partial Discharge Analyser model (Haefely Test AG DDX 9121b)
DFA	Detrended Fluctuation Analysis
DL	Deep Learning
DP	Descargas Parciais (Partial Discharges)
DSO	Distribution System Operator
DTS	Distributed Temperature Sensing
DTD	Differential Tan Delta
EHV	Extra-High Voltage
EMI	Electromagnetic Interference
EMTR	Electromagnetic Time Reversal
EP	Extrusion line designation (machine designation, internal)
EPDM	Ethylene Propylene Diene Monomer
EPR	Ethylene Propylene Rubber
FAT	Factory Acceptance Test
FEM	Finite Element Method
FPD	Floating Potential Discharge
GIS	Gas-Insulated Switchgear
GT	Cable Transfer Group (machine designation)
HDPE	High-Density Polyethylene
HFCT	High Frequency Current Transformer
HI	Health Index
HPTE	High-Performance Thermoplastic Elastomer

HV	High Voltage
HVDC	High Voltage Direct Current
IQR	Interquartile Range
KPI	Key Performance Indicator
KW	Keyword (defect classification flag)
LDPE	Low Density Polyethylene
LV	Low Voltage
ML	Machine Learning
MPD	Multi-Phase Partial Discharge (OMICRON MPD 600 instrument)
MT	Média Tensão (Medium Voltage)
MV	Medium Voltage
NCF	Non-Conformity Frequency
OD	Outer Diameter
PD	Partial Discharge
PDEV	Partial Discharge Extinction Voltage
PDIV	Partial Discharge Inception Voltage
PMIS	Production Management Information System
PP	Polypropylene
PRPD	Phase-Resolved Partial Discharge
PVC	Polyvinyl Chloride
QA	Quality Assurance
QMS	Quality Management System
RC	Rogowski Coil
RMS	Root Mean Square
RNN	Recurrent Neural Networks
RR	Rate Ratio
SCADA	Supervisory Control and Data Acquisition
SCE	Semi-Conductor Exterior (screen defect category)
SCI	Semi-Conductor Interior (screen defect category)
SDG	Sustainable Development Goal
SEF	Stress Enhancement Factor
SNR	Signal-to-Noise Ratio
SPC	Statistical Process Control
SVM	Support Vector Machines
TDR	Time Domain Reflectometry
TEM	Transmission Electron Microscopy
TOF	Time-of-Flight
TR-XLPE	Tree-Retardant Cross-Linked Polyethylene
TSO	Transmission System Operator
UHF	Ultra-High Frequency
VLF	Very Low Frequency
VPIS	Voltage Presence Indicating System
XLPE	Cross-Linked Polyethylene
XRD	X-Ray Diffraction

Chapter 1

Introduction

1.1 Context and Motivation

The global energy transition has fundamentally intensified the demand for Medium Voltage (MV) and High Voltage (HV) underground cable systems. This shift is characterised not only by an increase in infrastructure volume but also by a transition toward more sustainable and high performance dielectric materials. While Cross-linked Polyethylene (XLPE) and Ethylene Propylene Rubber (EPR) remain the predominant industry standards, there is a growing integration of thermoplastic alternatives, such as Polypropylene (PP) blends, which offer enhanced recyclability and higher operating temperatures [2, 3].

This dissertation was established within the industrial framework of **Cabelte, Cabos Elétricos S.A.**, a Portuguese cable manufacturer with a production portfolio spanning from Low Voltage (400 V) to Extra High Voltage (275 kV) underground cables. In such a high output environment, the primary challenge lies in bridging the gap between theoretical material science and large scale manufacturing.



Figure 1.1: Cabelte Logo

The motivation for this research is rooted in both operational excellence and network safety. From an industrial perspective, minimising PD related defects is essential to reducing scrap rates and optimising production costs. From a technical standpoint, localised insulation failures caused by PD present a significant risk to the reliability of the power grid, potentially leading to catastrophic breakdowns [4] and costly emergency repairs [5].

Working within an active industrial setting allowed for a comprehensive characterisation of the variables leading to PD—ranging from unintended material contamination during compounding to detection during rigorous Quality Assurance (QA) protocols [6].

1.2 Problem Statement, Research Questions, and Objectives

The operational reliability of Medium Voltage (MV) and High Voltage (HV) underground cables is significantly compromised by Partial Discharges (PD). These localised dielectric breakdowns gradually erode the insulation matrix, ultimately leading to catastrophic electrical failure [7]. A critical challenge in cable manufacturing is the inherent vulnerability introduced during the manufacturing process; factors such as material impurities, poor additive dispersion, and inconsistencies in the extrusion process create micro-voids and semiconductive screen protrusions which serve as precursors to PD [6, 8].

These defects act as points of electrical stress concentration, a vulnerability further compounded by diagnostic uncertainties. Consequently, there is a critical need to optimise manufacturing parameters and understanding of the PD origin to ensure long term insulation integrity. To address these challenges, this research seeks to answer the following research questions:

- How do specific variations in insulating materials and manufacturing parameters influence the creation of PD inducing defects?
- What process optimisation measures can be implemented within the industrial environment to minimise the occurrence of defects?
- How does the relationship between voltage gradients and Partial Discharge values vary across different defect typologies? [9, 10]

The overarching goal of this dissertation is to investigate the influence of insulating materials and critical manufacturing parameters on the occurrence of PD in MV/HV cables and to identify ways to improve the manufacturing process. This includes a comparative evaluation of the technical performance of sustainable materials, such as Polypropylene (PP), against traditional benchmarks like XLPE and EPR [11, 12]. To achieve this, the following specific objectives have been identified:

- **Analyze** the influence of specific manufacturing defects on PD occurrence in XLPE and EPR [10, 13].
- **Correlate** the operational relationship between voltage gradients and Phase Resolved Partial Discharge (PRPD) patterns and values across distinct defect combinations to establish a diagnostic baseline [14, 15].
- **Propose** technical recommendations for manufacturing process control [3, 4].

By fulfilling these objectives, this dissertation contributes to the reduction of PD related defects during production, thereby mitigating the risk of in-service cable breakdown and enhancing the long term reliability of the power network.

1.3 Scope and Limitations

The scope of this dissertation is centered on the investigation of Partial Discharge (PD) phenomena within Medium Voltage (MV) and High Voltage (HV) underground cable systems, specifically focusing on the manufacturing and testing range of 1 kV to 275 kV. A core component of this work is the comparative analysis between established thermoset materials (XLPE and EPR). Low Voltage cables were not considered since the PD levels in these systems are typically negligible and do not present a significant reliability concern.

The study initially intended to include a quantitative comparison of PD behaviour across three insulation systems: XLPE, EPR, and thermoplastic polypropylene (PP). However, the availability of PP-based cable samples was limited, owing to low demand for cables of this type within the scope of the research. Accordingly, the quantitative results and statistical analyses presented in Chapter 4 and 5 are limited to XLPE and EPR cables. The discussion of PP's manufacturing sensitivities, dielectric properties, and potential defect profile is retained in Chapter 2 as theoretical groundwork, and the corrective measures proposed in Chapter 4 (Section 4.10) explicitly identify the process conditions that will require monitoring when PP production scales. A comparative PP analysis is identified as a priority direction for future research in Chapter 6.

The work encompasses the entire manufacturing cycle, from material compounding and extrusion to final assembly—identifying the genesis of structural defects such as micro-voids, contaminants, and semiconductive screen protrusions [5, 8]. From a diagnostic perspective, the study evaluates the efficacy of established electrical testing standards [7, 16]. This includes an attempt to characterise Phase Resolved Partial Discharge (PRPD) patterns, with the aim of establishing a library of correlations between specific manufacturing flaws and their resulting electrical signatures [17].

The research is inherently constrained by the practicalities of industrial production and material availability. The experimental phase is dependent on active production cycles, meaning the investigation is limited to the specific cable typologies, voltage ratings, and material grades available on the factory floor during the data collection period. This constraint extends to the testing of emerging materials. Finally, the inherent electromagnetic noise of a heavy industrial environment may restrict the detection of very low magnitude PD pulses.

1.4 Approach

The research adopts a dual track approach that bridges industrial production analytics with standardised testing. The first track focuses on the retrospective analysis of manufacturing defect records accumulated at Cabelte, Cabos Eléctricos S.A. between January 2025 and May 2026, enabling a statistically grounded characterisation of defect occurrence, machine attribution, and their relationship to partial discharge risk. The second track draws on the results of factory tests conducted in compliance with IEC 60270 and the relevant cable standards [7, 18, 19], anchoring the defect analysis in measurable dielectric performance outcomes. Together, these tracks allow the

investigation to move from observed defects in production to their electrical consequences in the finished cable.

Rather than treating manufacturing quality and electrical testing as separate domains, this work explicitly correlates them: defect types identified in the production database are mapped onto the partial discharge mechanisms established in the theoretical framework of Chapter 2, and the PD measurements obtained during testing.

From a materials perspective, the study examines how the different manufacturing sensitivities of XLPE and EPR — the two dominant insulation systems in the factory's production portfolio during the study period — contribute to distinct defect profiles and PD intensities. The potential of thermoplastic polypropylene (PP) as a sustainable alternative is evaluated theoretically: the analysis identifies the process conditions and defect types most relevant to PP's introduction, providing a diagnostic baseline for future production campaigns. The overall approach is described in further detail in Section 1.5 and operationalised through the nine phase methodology presented in Chapter 3.

1.5 Dissertation Structure

This dissertation is organised into six chapters, systematically progressing from a theoretical foundation to industrial application and results analysis:

Chapter 1 Establishes the research context and motivation, defines the problem statement and objectives, and outlines the scope and limitations of the work.

Chapter 2 Provides the essential theoretical framework regarding dielectric physics, the mechanisms of partial discharge, and the properties of high voltage insulating materials. It also presents the mechanisms of the defects that can lead to PD, and critically examines current research in the field, focusing on the latest developments in sustainable thermoplastic compounds and diagnostic methodologies, in order to identify the research gap this work aims to fill.

Chapter 3 Details the experimental protocols and data collection strategies implemented at Cabelte, Cabos Eléctricos S.A., including the characterisation of specific manufacturing defects and the utilised detection techniques.

Chapter 4 Presents a comprehensive evaluation of the factory data, including defect rates by category, machine, and voltage level, distinguishing defects that directly cause PD from those that later lead to it, together with the corrective measures proposed to prevent them (with a 2025 vs. 2026 comparison). It also includes the partial discharge testing data and the corresponding PRPD graphs.

Chapter 5 Presents a practical case study of Factory Acceptance Testing (FAT) conducted on 220 kV cable accessories, including body joint and stress cone tests performed in compliance with IEC 62067 [20]. The chapter includes analysis of PD pattern interpretation in an industrial noise environment and discusses the implications of the FAT results for the production quality findings of Chapter 4.

Chapter 6 Summarises the main contributions of the research, evaluates the fulfilment of the initial objectives, and proposes directions for future investigations to extend the lifespan of MV/HV cable systems.

DISCLAIMER: I acknowledge the use of AI assisted tools (specifically Gemini and Claude) during the technical and editorial execution of this dissertation. Their use was strictly limited to two functions: technical coding, namely the writing and formatting of data visualisation scripts, and text enhancement, namely grammar refinement and copy editing. Crucially, no AI tool was involved in data generation or substantive analysis. All ideas, research frameworks, data interpretations, and conclusions are entirely original and represent my independent work, who accepts full responsibility for the academic integrity of this dissertation.

Chapter 2

Background and Fundamental Aspects

2.1 History and Evolution of Underground Power Cables

The history of power cables spans over two centuries, evolving from early primitive insulation to modern polymeric and recyclable technologies [4, 21]. The transition from oil impregnated paper to synthetic polymers marked a significant shift toward higher operational temperatures, simplified maintenance, and increased dielectric reliability. Critically, this shift also introduced a new class of manufacturing origin failure modes (degassing inadequacy, extrusion voids, and compound contamination) that did not exist in paper oil technology. Understanding the physical mechanisms behind these failures and their signatures in factory acceptance testing is the analytical foundation of this dissertation.

Table 2.1: Historical milestones in the evolution of power cable insulation.

Year	Milestone
1812	• First recorded use of insulated wires (rubber-varnish) for detonating mines in Russia [22].
1837–1850	• Invention of the telegraph and the first subsea telegraph cable (Dover–Calais, 1850) [21, 22].
1880s	• Edison introduces early rubber insulated power cables (Pearl Street, 1882) [22].
1890	• Ferranti pioneers the first modern high voltage cable (10 kV) using impregnated paper insulation [21, 22].

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Table (continued)

Year	Milestone
1903	Discovery of Polyvinyl Chloride (PVC) [22].
1917	Pirelli perfects fluid impregnated paper insulation; pressurized cables follow in 1925 [22].
1930s–1940s	Polyethylene developed; first cable use in 1942 [22, 23]. Butyl rubber commercialized in 1944.
1955–1962	Development and commercialization of Ethylene Propylene Rubber (EPR) [12, 22].
1963	Cross-linked Polyethylene (XLPE) invented, enabling higher thermal ratings [22, 23].
1968–1970s	XLPE adopted for medium-voltage cables; triple extrusion mitigates water treeing [21, 22].
1980s–1991	Polymeric cables dominate; XLPE exceeds 90% of new installations in Japan [22].
1999	First commercial HVDC XLPE cable installed (Gotland, Sweden) [22].
2000s	Extruded HVDC cables reach 525 to 640 kV [22]; standardized partial discharge monitoring [7].
2006–Present	Recyclable insulation technologies: P-Laser (HPTE) and PP-based cables [3, 22].

2.2 Cable Structure and Layer Functionality

The typical construction of a MV/HV cable includes the following layers, presented from the centre outward [18, 24].

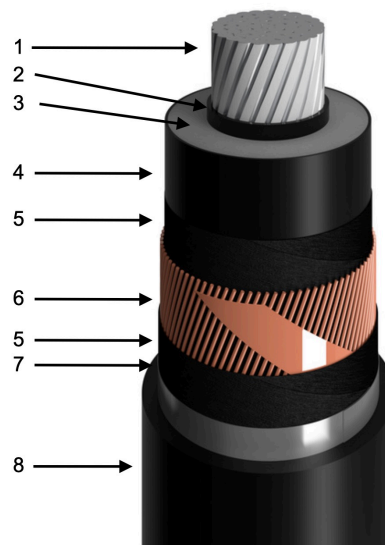


Figure 2.1: Cross-sectional structure of a MV/HV extruded cable.

- **1. Conductor:** The central core carries the electrical current. Made of aluminium or copper, it can be solid or stranded [6]. For cross-sections exceeding 1200 mm^2 , a Milliken segmented design is used to minimise skin effect and proximity effect losses [25].
- **2. Conductor Screen:** The conductor screen is a thin semiconductive layer that smooths the electric field and prevents partial discharge at the conductor interface [6, 26]. The conductor screen, the insulation, and the insulation screen are applied simultaneously via simultaneous triple extrusion through a triple-layer crosshead, ensuring smooth, void free interfaces [6].
- **3. Insulation:** The insulation is the primary dielectric layer; common materials include XLPE and EPR [4, 12], or more recently PP blends [12, 27].
- **4. Insulation Screen:** The insulation screen is a second semiconductive layer that guarantees a uniform electric field and prevents stress concentration at the insulation outer surface [6, 21].
- **5. Water Blocking Tape:** Prevents radial moisture ingress by swelling on contact with water [25]. More than one tape layer may be present, as shown in Figure 2.1.
- **6. Metallic Screen/Sheath:** Confines the electric field and carries fault currents to earth [19, 24]. Made from copper or aluminium wires, or an aluminium/copper tube.
- **7. Bedding and Armour (MV) / Al Tape (HV):** Provides mechanical protection against crushing or impact [24, 25]. MV cables typically use bedding and armour; HV cables use an aluminium polymer (Al/PE) tape, which additionally provides longitudinal water blocking.
- **8. Outer Sheath:** The outermost layer, typically polyethylene (PE) or high density polyethylene (HDPE), protects against moisture, chemicals, and fire/flame [25, 28]. Most cables include a semiconductive layer over the outer sheath, applied during extrusion.

2.3 Dielectric Integrity and Manufacturing Physics

The dielectric strength of a cable's insulation is fundamentally rooted in its molecular architecture and crystalline structure, which physically restrict the movement of charge carriers and prevent electron avalanches under high electric fields. During the manufacturing phase, this inherent strength is built, secured, and refined through several highly controlled processing steps centred on the **Continuous Vulcanisation (CV) Line** and its catenary variant, the **Catenary Continuous Vulcanisation (CCV) Line**.

2.3.1 Conductor Manufacturing

Power cable conductor manufacturing begins with **wire drawing**, where raw high conductivity copper or aluminium rods are pulled through progressively smaller tungsten carbide dies. The resulting wires undergo **stranding**, where individual strands are twisted into concentric layers to achieve the required ampacity. Finally, the assembly undergoes **compaction** through a compacting die, which flattens the outer wire surfaces and minimises interstitial voids, reducing the overall cable diameter and the volume of insulation required.

For systems requiring cross-sectional areas of 1200 mm² and over, standard circular stranded conductors become inefficient due to the electromagnetic **skin effect** and **proximity effect**, which force AC current to flow primarily through the outer periphery of the core, significantly increasing effective resistance. To mitigate these losses, manufacturers employ the segmented **Milliken conductor** design [25, 29].

To ensure the conductor remains longitudinally watertight, **hydro expansive water blocking tapes** or hygroscopic swellable powders are inserted between the wire strands during stranding [25]. In the event of a sheath breach, these materials absorb ingressing moisture and swell into a high viscosity gel that fills the microscopic interstrand gaps, preventing longitudinal water migration along the conductor.

2.3.2 Conductor Preparation and Triple Extrusion

The metallic conductor is commonly **pre heated** before entering the extrusion crosshead to eliminate the drastic temperature drop that occurs when molten polymer contacts cold metal. Without pre heating, the innermost semiconducting layer shrinks rapidly, generating interface delamination or microscopic gaps that become critical nucleation sites for partial discharge activity [8].

The process then relies on **Simultaneous Triple Extrusion**, in which the inner semiconducting screen, the main polymeric insulation, and the outer semiconducting screen are deposited onto the conductor in a single pass through a triple layer crosshead. Extruding all three layers simultaneously ensures perfectly smooth, void free interfaces; the semiconducting screens smooth the rough surface of the stranded conductor, suppressing the localised electric field concentrations that would otherwise initiate early dielectric breakdown or partial discharges [6, 8].

2.3.3 Vulcanisation and Cross linking Chemistry

For thermosetting materials such as XLPE and EPR, high temperature dielectric performance depends on the chemical cross linking process.

Two types of extruder lines fall within the scope of this work: continuous vulcanisation lines (CV) and catenary continuous vulcanisation lines (CCV). These differ in several respects, the principal one being that CV lines are cured by a silane reaction at 170 to 180 °C, while CCV lines are cured by a peroxide reaction at approximately 120 °C, both under a dry nitrogen atmosphere. Chemical initiators decompose into free radicals that link linear polymer chains into a robust three dimensional molecular network. This network prevents chain slipping under thermal stress, allowing the insulation to maintain structural integrity and dielectric strength up to 90°C during continuous operation and 250°C under short circuit conditions.

The chemistry and process implications differ between material systems. In XLPE, the peroxide initiated reaction releases volatile by products, primarily methane (CH₄). To prevent these expanding gases from forming internal voids, elevated pressure is strictly maintained throughout the CV tube. EPR follows a broadly similar thermal curing sequence; because its compound is mechanically reinforced by inorganic mineral fillers, it provides sufficient internal resistance to manage moderate cure pressures. The primary by products of EPR vulcanisation are sulphur and sulphur bearing compounds that evolve as sulphur donor curing agents decompose under heat [5, 30].

In both cases, the dry nitrogen atmosphere inside the CV tube serves a critical function beyond inert pressure maintenance: it excludes ambient moisture. If water vapour enters the vulcanisation zone, it is absorbed into the hot polymer matrix and subsequently vaporises upon rapid cooling, forming steam micro voids that act as permanent field stress multipliers and nucleation sites for internal partial discharges [5].

2.3.4 Cooling Rate and Crystallisation Dynamics

As the hot cable exits the vulcanisation phase, it enters a carefully controlled cooling process that governs the polymer's partial crystallisation. The resulting dielectric strength is highly dependent on the degree of crystallinity and the formation of microstructures such as lamellae and **spherulites** [2, 23]. Higher crystallinity improves dielectric performance by minimising free volume and tightening molecular packing, which shortens the mean free path of electrons and makes it significantly harder to initiate impact ionisation breakdown.

If the semi crystalline polymer is cooled too rapidly, it develops large, irregular spherulites with weak, low density boundaries. These interspherulitic regions allow electrons to accelerate easily under localised electric fields, promoting impact ionisation and water treeing. Conversely, a gradual, controlled thermal transition promotes a fine grained crystalline structure with smaller, more uniform spherulites that maximise resistance to electron bombardment [2, 23].

Due to the thickness of HV cable insulation walls, a **radial inhomogeneity** in crystalline structure inevitably arises [23, 31]: the inner and outer layers, being closest to thermal boundaries,

cool faster than the mid wall region. This structural gradient must be managed through controlled cooling protocols to ensure uniform electrical properties across the insulation cross section. Electron avalanches and partial discharges preferentially propagate through the lower density **amorphous regions** between spherulites; optimising crystallisation therefore reduces the volume of these propagation pathways and prevents the concentration of cross linking by products at spherulite boundaries, which would otherwise act as PD initiation sites. For PP cables, which bypass chemical cross linking entirely, the precise regulation of crystallisation during cooling is the primary source of dielectric strength [2, 12]. In next generation PP systems, specialised cooling protocols induce **β type crystals** [2, 3], which serve as deep charge traps that suppress space charge mobility and significantly enhance breakdown strength.

2.3.5 Real Time In Line Diagnostics in the CV Line

To ensure insulation integrity over long production lengths, the industry is transitioning from destructive sampling toward real time, in line diagnostics within the CV line. **Ultrasonic pulse echo analysis** monitors XLPE cross linking non invasively by measuring shifts in acoustic velocity and attenuation (α). Complementing this, automated water bath scanning detects internal micro voids and fissures down to 100 μm , pre empting potential PD inception sites before the cable leaves the line [32].

X-ray techniques, including Computed Tomography (CT) and X-ray Diffraction (XRD), extend this capability to three dimensional visualisation of electrical trees and quantification of microstructural crystallinity. Because these methods excel at static structural forensics rather than dynamic fault tracking, they are paired with electrical PD measurements to capture transient defects that X-ray imaging alone would miss. At the outermost layer, in line industrial spark testing identifies external insulation breaks along the cable surface [32, 33]; this is distinct from laboratory spark gaps, which function as hardware protection against transient overvoltages.

A further degradation risk concerns contamination of the semiconducting screen. If this region absorbs organic liquids such as oil or gasoline, its electrical resistivity rises sharply, concentrating electrical stress at the metallic neutral wires and triggering partial discharges at the interface between the metallic screen and the underlying semiconducting layer.

2.3.6 Degassing and Compound Purity

Following cross linking, the cable core must undergo **degassing** to achieve its theoretical dielectric strength. The peroxide curing of XLPE generates volatile by products including methane (CH_4), acetophenone, and cumyl alcohol. Because methane gas pockets have a substantially lower dielectric strength than the solid polymer, immediate testing or energisation causes partial discharges to initiate within these cavities. To restore dielectric integrity, the cable is placed in heated chambers at approximately 70°C for several days to weeks, allowing trapped gases to diffuse out of the insulation bulk. For EPR, a dedicated degassing period is similarly required to remove sulphur bearing vulcanisation by products, though the duration is substantially shorter owing to the higher

diffusivity of these species through the filled elastomeric matrix [5, 30]. If retained, these species migrate to the insulation and semiconductor boundary over time, altering local surface resistivity and establishing conditions favourable for interfacial partial discharge.

Complementing degassing, maintaining absolute **compound purity** is essential for HV cables operating under elevated stress. Manufacturers employ ultra clean compounds produced using filtration meshes as fine as 50 μm [5, 6], combined with closed material handling systems and clean room extrusion environments. Microscopic contaminants, such as metallic dust or cellulose fibres act as localised electric field stress multipliers; their exclusion is a fundamental prerequisite for preserving the polymer's inherent dielectric strength.

This purity requirement makes product changeovers a particularly high risk operation. Switching production from MV to HV cables introduces a significant contamination hazard: MV insulation compounds are manufactured to lower purity standards, and any residual material left in the extrusion barrel acts as a contaminant once HV grade compound is introduced. Even when all other extrusion parameters are within specification, such impurities can cause premature insulation failure, making changeover events a primary focus of defect analysis in HV cable manufacturing.

2.4 Insulation Materials

2.4.1 XLPE

XLPE remains the most widely utilised insulation material for underground cables due to its exceptional dielectric strength, low dissipation factor, and robust thermo mechanical properties [6, 34]. It is produced by cross linking Low Density Polyethylene (LDPE) polymer chains, typically by compounding LDPE with an organic peroxide such as dicumyl peroxide (DCP) and subjecting the mixture to high heat and pressure [8]. The peroxide decomposes into free radicals that facilitate the formation of a three dimensional covalent network, transforming the material from a thermoplastic melt into a permanent thermoset. This 3D network prevents molecular chain slipping at elevated temperatures, allowing XLPE to operate continuously at 90°C and withstand short circuit transients up to 250°C [4, 23].

Despite its dominance, XLPE presents several environmental and manufacturing challenges inherent to its thermoset nature. Being non recyclable [3, 34], the cross linking process generates volatile by products that must be removed through a time consuming and energy intensive degassing process [5, 8], a necessary step to prevent void formation, which is a precursor to partial discharge [5]. Beyond manufacturing constraints, XLPE is susceptible to water treeing, a degradation phenomenon occurring in the presence of moisture and electric fields [4, 35]. Its application in extra high voltage (EHV) grids is further limited by space charge accumulation and susceptibility to electrical treeing [36].

These limitations have driven targeted material and process innovations. Tree-Retardant XLPE (TR-XLPE) was developed using specific additives, most notably hydrophilic molecular clusters that prevent water condensation in electro oxidised regions, halting tree propagation in submarine

or high humidity environments and demonstrating superior dielectric strength retention under ageing conditions [4, 23]. On the manufacturing side, polyethylene resins with increased terminal unsaturation (vinyl content) enable full cross-linking cure with reduced peroxide initiators, yielding a scorch retardant XLPE grade that cuts mandatory degassing time by over 70% [4]. Ultra clean manufacturing protocols employing clean room standards and filtration now remove sub 50 μm contaminants during extrusion, eliminating precursors to electrical treeing [36].

2.4.2 Ethylene Propylene Rubber (EPR)

Ethylene Propylene Rubber (EPR) is an amorphous, elastomeric thermosetting copolymer heavily compounded with inorganic mineral fillers, such as kaolin clay, talc, and silica, that constitute roughly 50% of its insulation volume [4]. This elastomeric matrix maintains excellent flexibility at low temperatures and provides superior resistance to mechanical stress and moisture ingress, making EPR the standard choice for submarine links, mining equipment, and flood prone environments [30].

Unlike semi crystalline XLPE, EPR's dielectric integrity is governed by filler dispersion quality rather than crystallisation dynamics [30, 37]: while optimal loading (≈ 35 to 45 wt%) physically blocks electrical tree propagation, agglomerated filler clusters or concentrations exceeding ≈ 50 wt% create localised permittivity mismatches that amplify the electric field and lower the partial discharge inception voltage (PDIV) [30]. Because EPR's dominant PD risk defects originate during raw material compounding rather than extrusion, incoming compound quality control via transmission electron microscopy (TEM) represents the critical process control point.

This filler driven behaviour also shapes EPR's comparative electrical performance against XLPE. For equivalent geometries, EPR cables typically exhibit a lower PDIV than XLPE, as EPR's higher permittivity ($\epsilon_r \approx 2.8$ versus 2.3 for XLPE) concentrates the local electric field more intensely around any insulation voids or protrusions [30, 38]. Conversely, the absence of crystalline lamellae boundaries removes the primary nucleation sites for electro oxidised channels, making EPR intrinsically more resistant to water treeing and partial discharge erosion over long service lives in high humidity environments [23, 38].

The high filler content that governs EPR's electrical behaviour also defines its manufacturing challenges. Elevated melt viscosity drives excessive shear heating in the extruder barrel and raises the risk of material scorch, requiring tighter barrel temperature regulation and shorter maximum residence times than XLPE [23]. Current research focuses on partial replacement of conventional kaolin fillers with nano scale surface treated silica or magnesium oxide particles, which maintain treeing resistance at lower loading fractions (< 10 wt%) while reducing the permittivity penalty [23]. For HVDC applications, EPR formulations specifically designed to minimise space charge accumulation have been developed and characterised, with several now available for ratings up to ± 525 kV [38].

2.4.3 Polypropylene (PP)

Polypropylene (PP) is a semi crystalline thermoplastic polymer that has recently gained traction as a potential successor to thermosetting insulation in high voltage applications. Unlike XLPE and EPR, PP requires no chemical cross linking to maintain structural integrity at elevated temperatures, instead relying on an intrinsically high melting point of 160 to 165°C [2, 12]. As a thermoplastic, its molecular chains are held together by intermolecular forces that can be overcome with heat, allowing the material to be melted, reshaped, and fully recycled at end of service life, a fundamental advantage over thermoset insulations.

This recyclability comes with a shift in manufacturing logic: because no peroxide initiators are used, PP cables generate neither methane nor sulphur by products, bypassing the degassing phase entirely and reducing greenhouse gas emissions by 20 to 34% compared to conventional XLPE production [12, 39]. The manufacturing focus shifts instead to thermal morphology control. During cooling, polymer chains fold into lamellae that organise into spherical structures known as spherulites; the amorphous boundaries between these spherulites represent the primary pathway for dielectric breakdown, making the size and distribution of crystalline regions the principal determinant of insulation quality [2, 12]. Controlled cooling protocols are therefore the critical process variable for PP, occupying the role that degassing and compound purity play for XLPE and EPR respectively.

To replicate the mechanical flexibility of XLPE without sacrificing these advantages, High Performance Thermoplastic Elastomers (HPTE), such as *P-Laser*, blend the PP matrix with polyolefin elastomers, sustaining continuous operating temperatures of 110°C [2, 3, 40, 41]. For HVDC applications specifically, the absence of polar cross-linking by products significantly reduces space charge accumulation, preventing the field enhancement that underlies DC failure in XLPE systems [11].

2.5 Physics of Partial Discharges

2.5.1 Classification and Inception Conditions

Partial Discharges (PD) are defined by IEC 60270 [7] as a “localised electrical discharge that only partially bridges the insulation between conductors”. These discharges emerge as pulses with durations much less than 1 μ s and serve as a reliable indicator of potential insulation failures [16].

For a partial discharge to occur, two conditions must be satisfied simultaneously: the local electric field must exceed the inception field of the medium (typically gas in a void), and a seed electron must be available to trigger the initial Townsend avalanche [10, 42]. Since gas in a void has lower permittivity ($\epsilon \approx 1$) than solid insulation ($\epsilon \approx 2.3$ for XLPE), the field inside the void is enhanced relative to the macroscopic field [9, 10].

They are categorised based on their physical location within the insulation system and the specific ionisation mechanism involved; in the context of MV and HV underground cables, each

category presents a different risk level and exhibits unique signatures in Phase Resolved Partial Discharge (PRPD) patterns.

2.5.2 Electric Field Distribution and Enhancement

In a cylindrical cable, the electric field $E(r)$ reaches its maximum at the conductor interface ($r = r_i$), described by [9, 10]:

$$E(r) = \frac{U}{r \cdot \ln(r_o/r_i)} \quad (2.1)$$

When a gaseous void is present, the internal field E_{cav} is enhanced due to dielectric mismatch. For a spherical cavity in XLPE ($\epsilon_{\text{ins}} \approx 2.3$), applying continuity of the electric displacement field ($\vec{D}$) at the boundary gives:

$$E_{\text{cav}} = \frac{3\epsilon_{\text{ins}}}{2\epsilon_{\text{ins}} + \epsilon_{\text{cav}}} E_0 \quad (2.2)$$

where E_0 is the macroscopic field. This concentration explains why gas inside a void reaches its breakdown threshold long before the surrounding solid insulation.

2.5.3 Gas Breakdown and the ABC Capacitive Model

The breakdown voltage V_b within a void follows **Paschen's Law**, relating pressure (p) and gap distance (d):

$$V_b = \frac{B \cdot p \cdot d}{\ln(A \cdot p \cdot d) - \ln[\ln(1 + 1/\gamma)]} \quad (2.3)$$

To model PD events externally, IEC 60270 [7] uses the **ABC model**, where C_c represents the void capacitance, C_b the series insulation capacitance, and C_a the bulk healthy material capacitance [43]. The measurable **apparent charge** (q) is:

$$q = C_b \cdot \Delta V_c \quad (2.4)$$

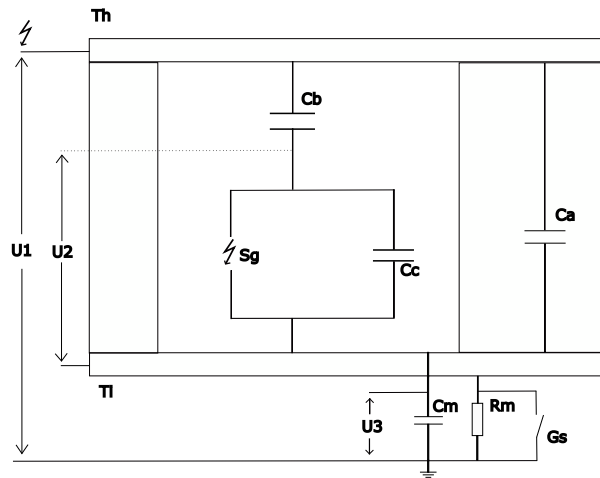


Figure 2.2: ABC capacitive model of a void embedded in cable insulation.

Table 2.2: Nomenclature of electrical parameters for the PD testing circuit.

Symbol	Element	Description
U_1	Applied Voltage	RMS value of the test voltage applied to the circuit.
U_2	PD Source Voltage	Instantaneous voltage drop across the local discharge site.
U_3	Measuring Voltage	Voltage pulse detected across the measuring impedance.
T_l	LV Terminal	Low voltage/earth connection point of the test object.
T_h	HV Terminal	High voltage connection point of the test object.
S_g	Spark Gap	Protective device to bypass overvoltages during breakdown.
G_s	Grounding Switch	Safety switch used to earth the system after the test.
R_m	Measuring Resistor	Resistive component of the quadrupole measuring impedance.
C_m	Measuring Capacitor	Capacitive component of the quadrupole measuring impedance.
C_c	Coupling Capacitance	Internal capacitance of the specific void or defect site.
C_b	Stray Capacitance	Total parasitic/stray capacitance of the laboratory setup.
C_a	Apparent Capacitance	Virtual capacitance representing the total test object charge.

2.5.4 Influencing Factors on PD Behaviour

2.5.4.1 Electrical Stress

PD activity increases with applied voltage magnitude, as higher fields raise the electron generation rate [7]. Transient waveforms, such as lightning or switching impulses, can initiate PD in defects that remain dormant under normal AC conditions [16]; the peak impulse voltage is more influential than impulse shape [4]. At higher test frequencies, PD pulse counts increase because the voltage exceeds the inception threshold more frequently per unit time, while at very low frequencies, wall charges have more time to decay between cycles, altering the field distribution for subsequent discharges [44]. Under DC, field distribution is governed by conductivity rather than permittivity [4, 39], yielding much lower PD repetition rates and different discharge patterns compared to AC. Voltage harmonics and distortion further accelerate field enhancement and cumulative PD activity [23].

2.5.4.2 Physical Characteristics of Defects

Defect geometry and location within the insulation are critical determinants of electric field enhancement and resulting PD severity [9, 10]. Larger voids produce discharges with higher apparent charge magnitudes; cylindrical and rectangular voids exhibit higher maximum stress than spherical ones [10]. Because the coaxial cable field is non uniform highest near the conductor, lowest near the sheath, where a void near the conductor is subjected to significantly higher electrical stress than an equivalent void near the outer screen [9]. As PD activity persists, conductive by products accumulate on void walls, increasing surface conductivity and altering the charge

neutralisation rate. This can trigger a transition from high energy streamer like discharges to diffuse, low energy Townsend like events, or lead to PD evanescence [44, 45].

2.5.4.3 Environmental and Thermal Factors

Rising temperatures increase insulation conductivity in XLPE and EPR, altering the resistive field distribution and potentially lowering breakdown strength [6, 39]. In loaded cables, radial temperature gradients cause variations in permittivity that modify the internal electric field distribution. For gas filled voids, elevated temperature increases internal gas pressure; by Paschen's Law, this typically raises the breakdown voltage required to initiate PD [10], though in some materials higher temperatures can facilitate electron emission and paradoxically lower inception voltage [4]. Repeated thermal cycling induces mechanical stress that can cause delamination or void formation at interfaces [35]. In cable accessories, low interfacial pressure can drastically reduce PDIV [10]. Moisture ingress increases surface conductivity at defect sites, particularly in joints and terminations, lowering PDIV and promoting surface tracking [30, 35].

2.6 Types of Partial Discharges

2.6.1 Internal Partial Discharges

Internal partial discharges represent the most hazardous failure precursor in power distribution networks, occurring within microscopic voids, gas filled cavities, or structural fissures created during the extrusion process due to differential cooling and polymer shrinkage, or through entrapment of volatile cross linking by products such as methane [9]. The primary driver is the **dielectric mismatch** between the trapped gas ($\epsilon_r \approx 1$) and the surrounding solid polymer ($\epsilon_r \approx 2.3$ for XLPE).

Internal PDs are often described as “silent defects” because their enclosed nature provides no visual, audible, or olfactory warning prior to failure. They are nevertheless exceptionally destructive: continuous ion bombardment, localised thermal spikes, and chemically aggressive by products progressively erode the cavity walls, serving as the primary initiation point for **electrical trees**, which are hollow, carbonised branching channels that bridge the insulation wall. The magnitude and severity of the discharge are dictated by void geometry and position within the cable's coaxial field; voids adjacent to the conductor exhibit significantly higher discharge energies than those near the outer semiconducting screen [10].

2.6.2 Surface Discharges and Tracking

Surface discharges occur at the interface between distinct dielectric materials when the tangential electric field component exceeds the localised dielectric strength of the surrounding medium [30, 46]. They are most prevalent in cable accessories, such as joints and terminations, where field control is inherently more complex than in the cable bulk. Common initiation sites include air gaps between the stress cone and main insulation, knife cuts or scratches on the cable core, and mispositioned pre-moulded components [46, 47]. Moisture, saline dust, pollutants, and metallic

particulates intensify discharge activity by increasing surface conductivity. Unlike silent internal defects, surface PD is often detectable through crackling sounds, ozone odour, or visible carbonised marks; however, sustained activity leads to cleavage of C–H bonds, severe surface erosion, and ultimately **tracking**, which is permanent conductive carbonised paths that trigger surface flashover or initiate a secondary internal electrical tree, both resulting in catastrophic failure [44].

Modern diagnostic research emphasises that tracking behaviour is strongly dependent on the quality of dielectric grease and the mechanical pressure sustained across the XLPE and elastomer interface in accessories. Advanced diagnostic strategies leverage the asymmetry and pulse width variation of surface PRPD patterns to distinguish surface defects from internal voids, enabling targeted intervention before tracking causes irreversible joint failure [24].

2.6.3 Corona Discharges

Protrusions, sharp metallic points on the conductor, irregularities in the semiconducting screens, or conductive contaminants in the dielectric, serve as sites of extreme electric field concentration [44]. The “sharp factor” (height to radius ratio) dictates the Stress Enhancement Factor (SEF), with high SEF values facilitating localised ionisation and electrical tree initiation. When sharp edges such as “semicon feathers” (triangular remnants from semiconducting layer stripping) are exposed to air at cable terminations, they ignite **corona discharges** [48], single electrode discharges in gaseous media characterised by ionisation of air molecules under extreme localised field gradients. While corona is less immediately destructive than internal PD, it causes continuous energy dissipation and generates corrosive ozone (O_3) and nitrogen oxides (NO_x) that degrade nearby components.

A significant dynamic behaviour of sharp protrusions is the “burn off” or self recovery effect, where sustained discharge activity physically erodes the protrusion apex, temporarily rounding the tip and counterintuitively reducing PD activity even as applied voltage increases [44]. Protrusions also facilitate **space charge injection** into the bulk insulation: at sub millimetre scales, the localised tip field bypasses potential barriers at the metal polymer interface, injecting charge packets into the XLPE or EPR bulk that distort the internal field distribution and reduce long term dielectric strength. Modern diagnostic systems use rise time differences between positive and negative corona pulses to distinguish these external events from internal bulk defects [24].

To mitigate corona at cable terminations, high voltage terminals use geometric grading components such as corona rings or toruses. By artificially increasing the effective radius of curvature at the terminal, these components reduce the localised field ($E_{\max} \propto 1/R$), suppressing ionisation and the associated chemical degradation.

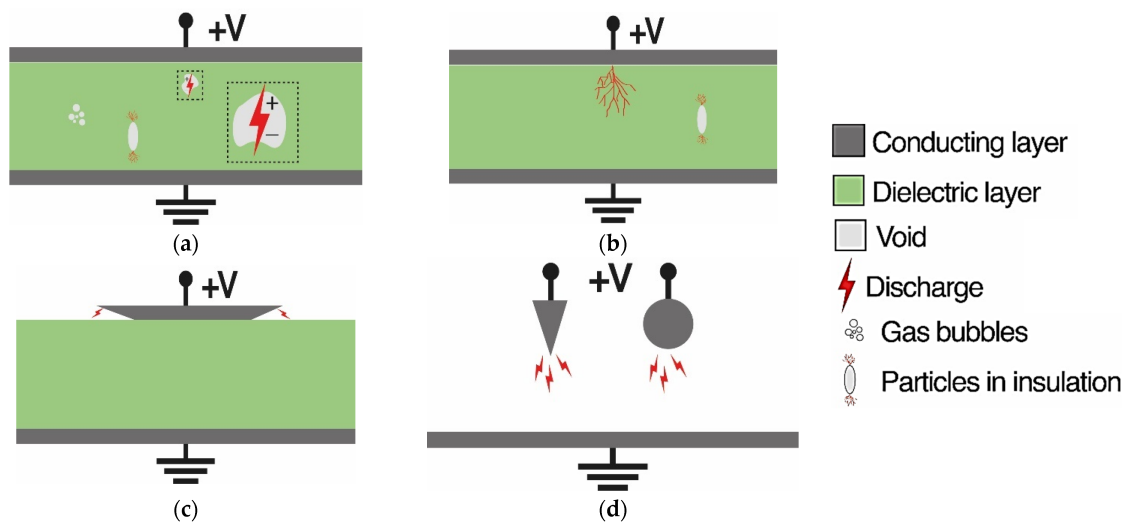


Figure 2.3: Classification of partial discharge types by physical mechanism [47] (a) Internal PD (b) Treeing (c) Surface PD (d) Corona PD

2.6.4 Floating Potential Discharges and Surface Metallic Contaminants

Floating potential discharges (FPDs) occur when a conductive metallic element, such as a structural fastener, a field grading shield, or the Al/PE tape, is electrically isolated within an insulation system. Lacking a galvanic connection to either the HV conductor or earth, the object assumes a potential governed by the capacitive coupling of the surrounding dielectric, establishing a capacitive divider network that continuously charges and discharges across a microscopic gap [16, 47]. As the small gap between the floating object and the adjacent conductor exceeds the local breakdown strength with each half cycle, a spark momentarily equalises the potential before the object returns to an isolated state, producing a high frequency sequence of pulses. FPDs are recognised in diagnostic measurements by their exceptionally high pulse repetition rates, large apparent charge magnitudes reflecting the significant energy transfer in discharging a metallic body, and a characteristic rise time of 1 to 15 ns [24, 47]. Under AC stress, inception typically occurs in the 4 to 5 kV range [24]; under DC, the inception voltage exhibits higher variance and a drastically reduced repetition rate as the charging mechanism shifts from capacitive displacement to resistive field distribution.

A specialised and hazardous subset of this category involves a metallic contaminant adherent to the surface of a solid insulator. This creates extreme field enhancement at the **triple-junction**, the boundary where metal, solid dielectric, and ambient gas meet. Unlike bulk FPDs, isolated surface particles generate signals of extremely low magnitude, often below 5 pC [7, 47], making them difficult to detect via conventional IEC 60270 methods. Despite their low apparent charge, sustained ion bombardment and chemical erosion of the polymer surface eventually initiate conductive tracking or electrical tree growth, making surface metallic particles a silent but equally lethal long term threat to dielectric integrity.

2.7 Sensing Technologies

Detecting the discharge families described above requires instrumentation matched to each mechanism's electrical and physical signature. The literature distinguishes between conventional sensors, compliant with IEC 60270 [7], and unconventional sensors optimised for field use and noise rejection [7, 16].

2.7.1 Capacitive Coupling: IEC 60270

Capacitive couplers (C_k) represent the industrial benchmark for PD detection under IEC 60270 [7], as shown in Figure 2.4. Functioning as high pass filters within a capacitive divider network, they exploit frequency dependent impedance to extract high frequency PD transients while blocking the 50/60 Hz power voltage [16]. System sensitivity is governed by the ratio between C_k and the test object capacitance (C_{DUT}), requiring proportionally larger couplers for high capacitance loads to maintain an adequate signal to noise ratio.

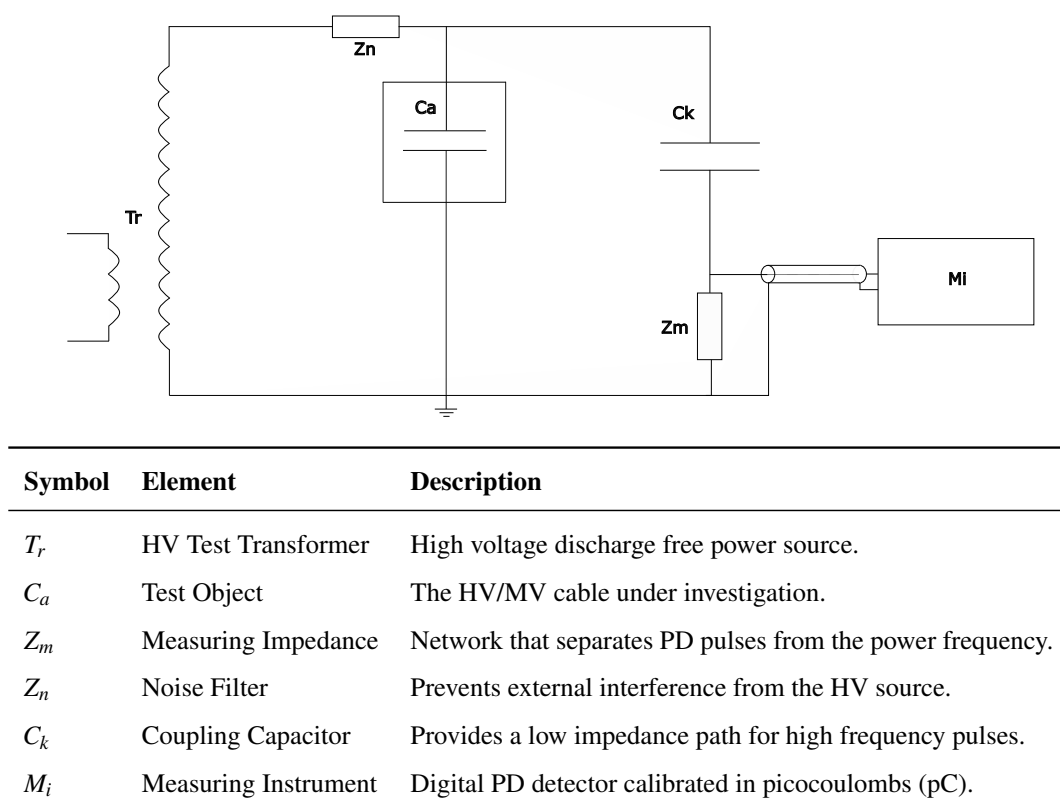


Figure 2.4: Testing circuit according to IEC 60270 [7].

Beyond offline diagnostics, capacitive sensing is increasingly integrated into online monitoring systems, where sensors interfaced with existing Voltage Presence Indicating Systems (VPIS) allow surveillance without requiring outages [47]. These sensors also provide the essential phase

reference for PRPD analysis. Despite their high sensitivity (<5 pC), capacitive couplers require direct galvanic connections, introducing installation challenges, and signal attenuation through semi conductive layers in cable integrated designs necessitates digital compensation.

2.7.2 Inductive Sensors: HFCT and Rogowski Coils

Inductive sensors utilise electromagnetic coupling to capture transient magnetic fields from propagating PD pulses along a cable's grounding or shield path. High Frequency Current Transformers (HFCTs) employ high permeability toroidal ferrite cores to translate time varying magnetic flux into a proportional electromotive force [24, 47]. Their split core structure allows non intrusive mounting, while a bandwidth of 30 kHz to 100 MHz captures nanosecond scale transients. Synchronised arrays enable polarity recognition for external noise rejection. Their primary constraint is magnetic saturation from power frequency currents, which degrades core permeability and necessitates electrostatic shielding.

Rogowski Coils are air cored sensors that measure the current time derivative (di/dt) using a helical winding geometry that responds exclusively to azimuthal flux, rejecting external electromagnetic noise [24]. The air core design provides complete immunity to magnetic saturation, ensuring high linearity up to 1 GHz. Because the output voltage is proportional to di/dt ($V_{out} = M \cdot di/dt$), an integrator circuit is required to reconstruct the PD waveform. Modern PCB based iterations implement precision printed traces to maximise geometric uniformity and frequency stability [49].

2.7.3 Non Conventional and Radiometric Methods

Non conventional methods leverage secondary physical indicators of PD, electromagnetic radiation, acoustic pressure waves, and light emission, which are offering inherent immunity to low-frequency electromagnetic interference (EMI). Ultra-High-Frequency (UHF) sensors detect EM signals emitted during picosecond-scale PD transients in the 300 MHz to 3 GHz band, achieving a high signal-to-noise ratio by bypassing low-frequency noise and corona [24, 47]. Wave attenuation from metallic cable shielding typically limits UHF use to accessories where dielectric windows permit sensor integration; wave reflections also prevent direct calibration to apparent charge in pC.

Acoustic detection captures mechanical pressure waves (20 kHz to 1 MHz) generated by localised dielectric vaporisation at the fault site [47, 49]. Its principal advantage is precision PD source localisation using Time of Flight (TOF) or Time Difference of Arrival (TDOA) algorithms. However, significant attenuation and scattering within solid dielectrics such as XLPE and EPR restrict its application to switchgear and transformer tanks rather than continuous cable monitoring.

Optical sensing captures photons emitted during ionisation across the UV and infrared spectra, though it is generally limited to transparent media. State of the art systems have transitioned toward **Distributed Acoustic Sensing (DAS)**, which uses Rayleigh backscattering in standard optical fibres to transform the entire cable into a continuous sensing array, enabling real time PD localisation across submarine and underground transmission networks [4, 17].

2.8 Operational Thresholds and the PDIV/PDEV Hysteresis Gap

Three voltage thresholds govern PD testing protocols [50]: the **PD test voltage**, at which the specimen must remain below a defined apparent charge threshold; the **PD Inception Voltage (PDIV)**, the voltage at which repetitive PD pulses first exceed that threshold as voltage is raised from a zero discharge baseline; and the **PD Extinction Voltage (PDEV)**, the voltage at which pulses drop back below the threshold as voltage is subsequently reduced from an active discharging state. The specified magnitude threshold should be twice the background noise level [51] and no greater than 10 pC per IEC 60840 [19] and IEC 62067 [20], though lower values may be required by client specifications or national grid requisitions.

Neither threshold is a fixed material constant. Both are statistical quantities, and the gap between them is a direct consequence of how a discharge channel sustains itself once ignited.

2.8.1 Why PDIV Is a Statistical, Not a Deterministic, Threshold

Reaching the inception field E_{inc} is a necessary but not sufficient condition for a discharge to occur: a seed electron must also be present to trigger the initial Townsend avalanche. In a virgin defect, where no prior discharge has taken place, seed electrons arise only from background cosmic radiation or random detrapping from the cavity walls. Because this rate is low, the voltage applied to the specimen can rise measurably above the theoretical inception field before a seed electron happens to arrive, an effect known as **gap over-voltage**. This is why PDIV measurements scatter across repeated tests on nominally identical defects, and why factory and laboratory protocols mandate a slow voltage ramp: a fast ramp gives the random seed-electron process less time to act, pushing the measured PDIV artificially higher. The effect is also frequency dependent, since a faster rate of voltage change (dV/dt) shortens the window in which a seed electron can appear during the stress peak, again biasing the measured PDIV upward.

Once a defect has discharged for the first time, this picture changes. Surface charge deposited on the cavity wall by the first avalanche becomes a standing source of initiatory electrons through subsequent field emission, a **memory effect** that removes most of the randomness from later discharges and stabilises the pattern of activity that follows.

2.8.2 The Extinction Mechanism and the Resulting Hysteresis Gap

A discharge pulse is brief as it subsides within nanoseconds, as positive and negative ions generated by the avalanche deposit on the cavity walls and build a local field (E_q) that opposes the externally applied field (E_c). Once the net field falls below the extinction field E_{ext} , the avalanche is starved of energy and stops. Because the discharge process has already created its own population of seed electrons through this same ionisation and surface charge deposition, a defect that is already active can be sustained at a field intensity below the one originally required to ignite it from rest. This is the physical origin of the gap between the two thresholds:

$$\Delta V_{\text{hysteresis}} = V_{\text{PDIV}} - V_{\text{PDEV}} \quad (2.5)$$

PDEV is consistently lower than PDIV, though the precise size of the gap is defect and condition dependent and has been reported across a fairly wide range, from roughly 10% to 50% [7, 10, 42, 46].

The gap is not static over the life of a defect. As insulation ages and an electrical tree begins to form, chemical by products such as oxalic and nitric acids accumulate on the channel walls, raising their conductivity and making charge detrapping progressively easier. Both PDIV and PDEV fall as a result, the statistical time lag shrinks, and the defect produces a higher pulse repetition rate per power cycle and dissipates more cumulative energy, a pattern consistent with a defect approaching terminal failure rather than stabilising.

2.9 Evanescence

In the field of high voltage cable diagnostics, **PD Evanescence** represents one of the most critical challenges to asset reliability. It is defined as the temporary disappearance or substantial diminution of partial discharge signals despite the presence of an active, progressive insulation defect, a deceptive diagnostic trap where a cable may be erroneously classified as healthy during a periodic test, only to suffer catastrophic dielectric breakdown shortly thereafter. This masking effect is not a sign of self healing, but a complex physical state driven by two distinct mechanisms [13, 45].

2.9.1 Chemistry Driven Masking: Surface Shielding and Discharge Kinetics

The internal chemistry of a void evolves rapidly under sustained partial discharge activity. High energy electron avalanches and localised plasma reactions cleave the polymer chains, interacting with trapped moisture to produce corrosive acids, most notably oxalic and nitric acids, which precipitate on the cavity walls as a semi conductive liquid film or crystalline layer [44]. As this layer grows, it acts as a Faraday like electrical shield, neutralising the internal electric field and preventing the potential difference across the cavity from reaching the PDIV, effectively silencing the discharge pulses.

Concurrently, the same surface conductivity increase alters the charge neutralisation rate within the void, triggering a transition from high energy streamer like discharges to diffuse, low energy Townsend like events [44]. This shift further reduces detectable signal amplitude, compounding the masking effect. The silence, however, is not benign: the now conductive defect sustains a continuous leakage current across the site, inducing intense localised Joule heating that accelerates carbonisation and thermal degradation. A virgin cavity, which initially exhibits a PDIV approximately 5% above the theoretical Paschen limit [10] progressively lowers its inception threshold toward the Paschen curve before ultimately crossing into full evanescence. If degradation advances into an electrical tree, both PDIV and PDEV decrease as branching channels expand, driving a higher pulse repetition rate per cycle as the system approaches terminal breakdown [13].

2.9.2 Thermodynamic and Load Induced Masking

The second masking mechanism is governed by the cable's operational thermal state. When a cable carries a high electrical load, Joule heating raises the temperature of gas trapped within a constant volume void, producing a proportional increase in internal pressure. By Paschen's Law, this elevated pressure shifts the breakdown requirement to a higher point on the Paschen curve, paradoxically raising the PDIV under operating conditions [10, 46]. A defect that discharges readily during a standard offline test on a cold, de energised cable may therefore become completely inactive and undetectable under full load, a direct inversion of the intuitive expectation that higher stress reveals more defects.

The inverse trap exists during cooldown. In cable accessories, contraction following high load operation induces thermomechanical stress across multi material interfaces with mismatched coefficients of thermal expansion. This can open new microscopic air gaps and trigger severe PD activity that was physically absent during the high temperature operational state, meaning that a test conducted immediately after load removal may capture transient activity that neither preceded nor will follow the test window. Beyond external load factors, the physical act of discharging itself can induce transient extinction: the rapid generation of gaseous by products during active PD causes a localised pressure spike within the void, temporarily suppressing further activity until the gases permeate the surrounding polymer bulk and pressure normalises [13, 45].

These two masking mechanisms, chemical shielding and thermodynamic suppression, can operate simultaneously and reinforce one another. A single point in time diagnostic test may therefore fail to reflect the true condition of the insulation regardless of its sensitivity. The absence of a PD signal is not evidence of a defect free cable, but only evidence that no defect crossed its inception threshold under the specific thermal and electrical conditions present at the moment of measurement. Capturing the episodic, fluctuating nature of evanescent activity requires continuous online monitoring capable of sampling across varied load states and extended time windows.

2.10 Degradation and Failure Mechanisms

Insulation does not normally fail from a single stressor acting alone. Thermal, electrical, ambient, and mechanical stresses cross couple in service, and their combined action is consistently more severe than any one factor would produce in isolation [4, 37]. Mechanical yielding or cyclic thermo mechanical expansion creates physical micro voids at material interfaces, converting a structural defect into a high field ignition site that facilitates electrical breakdown at much lower global voltage levels. Thermal and electrical stress interact through the same mechanism described by thermodynamic ageing theory [37]: heat supplies the free energy electrons need to overcome potential barriers, while electrical stress simultaneously lowers those barriers, and the two effects together accelerate space charge accumulation in deep traps created by thermo oxidation. Once a discharge initiates under this combined stress, a self reinforcing cycle follows: localised heating and chemically aggressive by products such as ozone and nitrogen oxides corrode the surrounding

polymer, enlarge the defect, and create still more favourable conditions for further discharge activity, until the insulation system cascades toward failure.

The long term degradation of polymeric insulation under this combined stress is governed by the evolution of tree like structures within the dielectric bulk. While water treeing and electrical treeing share a branching morphology, they represent fundamentally different physical and chemical processes: one remains undetectable by conventional PD measurements, while the other is the immediate precursor to catastrophic dielectric breakdown.

2.10.1 Water Treeing: The Electro Chemical Precursor

Water treeing is a slow growing, self propagating pattern of electro oxidation that occurs under the combined influence of an alternating electric field and moisture ingress. Unlike electrical trees, water trees are diffuse regions of moisture filled microcavities, connected by extremely fine electro oxidised tracks. Initiation is often driven by **dielectrophoresis**, where water molecules migrate into regions of high electrical stress [52].

Water trees are categorised into two typologies:

- **Bow-tie Trees:** Initiate from internal defects such as impurities or voids within the bulk, propagating outward in two opposite directions along field lines. They reach a limited length and are considered less immediately critical.
- **Vented Trees:** Originate at the interface between semi conductive screens and the clean dielectric, with a continuous moisture supply. They grow continuously and can penetrate the entire insulation wall, making them significantly more detrimental.

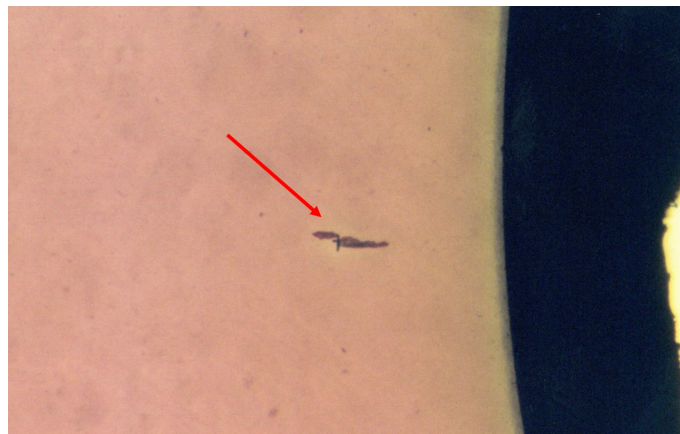


Figure 2.5: Bow-tie water tree 350 μm long (indicated by the red arrow) approximately 6% of the insulation thickness [52]



Figure 2.6: Vented water tree $120\ \mu\text{m}$ long (indicated by the red arrow) approximately 2% of the insulation thickness [52]

From a diagnostic perspective, **water trees do not generate PD activity** because the micro voids are filled with liquid water rather than gas; they cannot therefore be detected by HFCT or IEC 60270 [7] methods. However, their presence significantly increases dielectric loss ($\tan \delta$), relative permittivity, and localised conductivity, while drastically lowering the overall breakdown strength of the system.

2.10.2 Electrical Treeing: The Terminal Phase

Electrical trees occur when localised electrical stress exceeds the intrinsic dielectric strength of the polymer, typically at sites of severe stress enhancement such as sharp semi conductive protrusions, metallic contaminants, or voids. In contrast to water trees, electrical trees consist of **hollow, gas filled, often carbonised microscopic branching channels** that physically and chemically destroy the polymer matrix. Their formation is driven by internal partial discharges igniting within the gas filled channels, releasing heat, UV radiation, and high energy ions that erode the channel walls and force the tree to expand. Growth follows three phases:

1. **Inception (Incubation):** Latent degradation driven by space charge accumulation and Maxwell stress weakening the polymer bonds.
2. **Propagation:** The branching phase, exhibiting fast or stagnant growth depending on the fractal nature of the channels.
3. **Rapid Breakdown (Runaway):** A channel bridges the electrode gap, causing total short circuit failure.

Lower fields produce sparse “branch type” trees; higher stresses produce dense “bush type” trees. The **fractal dimension** (d_f) quantifies this morphological difference: branch type trees exhibit d_f of 1.2 to 1.8, while bush type trees yield d_f of 2.4 to 3.0 [37, 44]. According to the **Discharge Avalanche Model** [37], bush type trees cause more extensive volumetric damage despite slower linear propagation. This evolution can be monitored through Detrended Fluctuation Analysis

(DFA) of PD pulse sequences [45]: as tree complexity increases, the fractal scaling index of PD amplitude decreases, serving as a critical indicator of approaching terminal instability. Once initiated, electrical trees can cause complete cable failure in minutes to weeks.



Figure 2.7: Electrical tree directed toward the insulation screen, indicating breakdown initiated from a bow tie tree or from the conductor screen [52]

2.10.3 The Transition: Water Tree to Electrical Tree

While a water tree may exist for decades without causing failure, it acts as a massive stress enhancer. If a water tree sufficiently alters the localised stress distribution, or if a transient overvoltage (switching surge or lightning strike) is applied, the intense field at the sharp tip of the moisture filled water tree can ignite a gas discharge [44]. As the liquid filled micro voids at the tip are converted into hollow, gas filled channels, **partial discharge activity actively ignites**. This transition converts a silent defect into an active, self propagating electrical tree that rapidly drives the cable toward irreversible electrical breakdown. Water trees slowly weaken the dielectric integrity; the subsequent electrical tree delivers the final, fatal blow.

2.11 Manufacturing Defect Taxonomy

Every defect type described below has a traceable origin in a specific manufacturing process step. Understanding this mapping is essential for interpreting factory acceptance test results: a PD flag, or its absence, is only diagnostically meaningful when read against the process conditions that preceded it. While most manufacturing defects are not immediate partial discharges, they serve as precursor sites that eventually facilitate PD activity once the PDIV is exceeded under service or test conditions. The subsections that follow are ordered by process sequence, from conductor construction through to final screen and mechanical layers.

2.11.1 Defects in Conductor Construction

Conductors are rendered longitudinally watertight by filling inter strand gaps with hygroscopic water blocking compounds [25]. If this step is deficient, moisture ingress travels freely along the conductor, providing a continuous reservoir that promotes vented water tree growth from the inner semi conductive screen into the primary insulation. Water blocking powders containing sodium can themselves introduce defects by accelerating conductor screen degradation under humid conditions. If the conductor is not watertight, moisture and dissolved minerals cause metallic oxidation and corrosion, releasing gases such as hydrogen (H_2) and generating oxide layers that disrupt the smooth conductor semiconductor interface, causing delamination and creating gas filled voids where internal partial discharges can ignite.

2.11.2 Internal Voids and Micro cavities from Extrusion

Gaseous voids and micro cavities within the insulation bulk are primarily consequences of inconsistencies during compounding and triple extrusion [8–10]. Poor dispersion of additives during mixing creates interphase stratification and microscopic gaps at material boundaries that become primary internal PD sites under high AC field gradients. The triple extrusion process itself is highly sensitive to temperature and pressure fluctuations: any melt flow instability can cause delamination or the formation of protrusions, which are sharp conductive needles jutting into the dielectric that cause massive localised field enhancements. In HV systems, where average electrical stress is inherently higher, even small protrusions significantly accelerate electrical tree formation.

2.11.3 Scorch and Amber Formation

In XLPE extrusion, “scorch” refers to the premature and uncontrolled cross linking of the polymer melt within the extruder barrel. If the localised temperature exceeds the peroxide’s activation energy before the material enters the CV tube, or if residence time is excessive, the cross linking agents decompose in the melt. This produces pre crosslinked particles or high viscosity gel like substances known as **ambers**. While most ambers are captured by filter screens, leading to increased head pressure and altered rheological properties, which microscopic gel particles can pass through. Once embedded in the primary insulation, these pre cured ambers become permanent structural defects that concentrate the electric field and compromise dielectric integrity [5, 6, 8].

2.11.4 Thermal Gradient and Crystallisation Defects

In thick walled MV and HV cables, the metallic conductor’s high thermal conductivity combined with external cooling at the outer surface causes the insulation layers to solidify at non uniform rates across the radius [23]. This thermal mismatch restricts molecular chain arrangement at the boundaries, producing smaller spherulites and lower crystallinity in the inner and outer layers compared to the mid wall region. As the polymer solidifies and undergoes uneven shrinkage,

residual thermo mechanical stresses are locked into the dielectric bulk, potentially opening micro cavities or structural micro cracks that become PD initiation sites.

2.11.5 Inadequate Degassing and Dielectric Integrity

The peroxide cross linking reaction in XLPE inherently generates volatile by products. Inadequate degassing represents a dual threat: trapped methane can expand into gas filled cavities providing a medium for internal PD, and residual polar by products, such as acetophenone and cumyl alcohol, increase dielectric loss ($\tan \delta$) [5, 53]. Elevated $\tan \delta$ leads to increased dielectric heating, which accelerates thermal and electrical ageing and reduces service life. If sulphur bearing EPR by products are similarly retained, they migrate to the insulation and semiconductor boundary over time, altering surface resistivity and establishing conditions favourable for interfacial partial discharge.

2.11.6 Advanced Extrusion Anomalies

Beyond void formation, the extrusion process can introduce complex structural anomalies. An improperly maintained crosshead can create a “weld line” at the point where molten polymer rejoins after wrapping around the mandrel [6, 8]. This serves as a permanent structural and dielectric weak point. Inhomogeneous molecular chain orientation from uneven extrusion shear forces results in spatial anisotropy, causing mechanical and electrical properties to fluctuate throughout the dielectric bulk.

2.11.7 Thermomechanical Incompatibility and Delamination in Accessories

The reliability of cable accessories (joints and terminations) is fundamentally challenged by the mismatch in coefficients of thermal expansion between XLPE insulation and rubber based accessory bodies. During cyclic loading, Joule heating induces volumetric expansion and contraction across the dielectric layers. If the accessory is improperly sized or if material relaxation occurs, the resulting thermomechanical stress can exceed the interfacial pressure, forming air filled cavities and causing macroscopic delamination. These gaps are particularly dangerous during cooldown after peak load, as differential contraction may migrate lubricants such as silicone grease and leave a low permittivity gas filled void. Such voids locally magnify the electric field, readily initiating PD and surface tracking along the weakened boundary.

2.11.8 Defects in the Metallic Screen

Defects in the copper or aluminium wire screen compromise its ability to equalise the electric field and carry fault currents. Incorrect wire count or diameter, or poorly monitored application, prevents uniform field distribution and creates localised electrical stress. An undersized screen results in approximately 10 to 15% additional energy losses [6], significant sheath heating, and potential burnout. Insufficient electrical contact between the screen and the outer semi conductive layer

ignites partial discharges. Direct galvanic contact between copper and aluminium components without bi metallic connectors causes rapid galvanic corrosion. Closed loop metallic configurations can also induce circulating currents from electromagnetic interference by neighbouring cables, causing severe overheating.

2.11.9 Defects in the Al/PE Tape

The Al/PE tape is designed as a radial moisture barrier, but thermo mechanical stress during thermal cycling can cause wrinkles at the tape's overlapping extremities. Inadequately degassed cables are particularly susceptible: expanding trapped gases generate internal pressure that distorts or ruptures the foil. When tape segments detach and lose electrical contact with the metallic screen, a **floating potential** is established [47, 54]. This behaves as a capacitive voltage divider that continuously charges under the alternating electric field; because the physical gap is extremely small, the potential rapidly exceeds the local dielectric strength, causing high amplitude, high pulse count partial discharge activity. Left unmitigated, this high energy arcing ablates surrounding layers and eventually attacks the primary insulation.

2.11.10 Solid and Metallic Inclusions

Metallic and solid inclusions arise from inadequate cleanliness during compounding or from impurities bypassing extruder filter screens. Their conductivity and permittivity differ fundamentally from the surrounding insulation, causing the electric field to distort and concentrate around them. Over time, this stress concentration drives dendritic growth of microscopic cavities, initiating an electrical tree and eventual catastrophic failure. If the semiconducting screen is contaminated by organic liquids such as oil or gasoline [6], its electrical resistivity increases drastically, concentrating stress at the metallic neutral wires and triggering partial discharges between the metallic screen and the underlying semiconducting layer.

2.12 Summary and Concluding Remarks

Summary: Comparing the Theoretical Strands

Four strands of theory have been assembled: cable construction and manufacturing physics; the physics, classification, and detection of partial discharges; PDIV/PDEV threshold behaviour; and long term degradation pathways together with the manufacturing defect taxonomy. Together they support one conclusion: a PD measurement is only meaningful when read against the manufacturing step that produced the defect it detects. The four PD families (internal, surface, corona, floating potential) each point to a different stage of manufacturing or assembly, which is what gives physical meaning to the non conformity categories tracked in the production database later in this dissertation. PDIV, PDEV, and evanescence show that a clean test result is a bounded claim — valid only at that voltage and in that test window — not proof of a void free cable. Water and electrical treeing represent the slow and fast failure pathways respectively, with the defect taxonomy as the

bridge between them: a manufacturing stage void or protrusion is the seed from which either tree subsequently grows in service. Because the production dataset analysed later is overwhelmingly XLPE, the materials discussion (XLPE, EPR, PP) is retained as theoretical groundwork rather than as the basis for an empirical comparison.

2.12.1 Research gap

Existing literature splits into mechanism level PD studies (small sample, lab based, tied to one defect geometry) and process level industrial studies (plant wide non conformity rates, rarely traced back to a specific mechanism or asset). Few studies connect the two. This dissertation fills that gap by applying the manufacturing defect taxonomy and six PD risk criteria developed here to 17 months of real factory data across eight production lines and the full MV/HV range, then cross checking the resulting root causes against PRPD waveforms and an independent FAT case study — producing corrective actions traceable to physical mechanisms rather than bare statistics. The PP comparison could not be completed empirically and is reported as a boundary of the study, not a gap it claims to close.

2.12.2 Why the theory matters going forward

First, the defect taxonomy gives physical grounding to the six PD risk criteria used in the methodology and to every root cause narrative built in the results chapter. Second, PDIV/PDEV hysteresis and evanescence mean the near zero HV PD rate and the two accessory PASS verdicts later in the dissertation are evidence of genuine process control under test conditions — not proof of zero defects — a distinction carried through to the limitations discussion. Third, the PRPD signatures examined later offer a smaller, confirmatory check against the theory here, but remain secondary to the production non conformity data, which is the dissertation's primary evidence base throughout.

Chapter 3

Methodology

3.1 Introduction

This chapter explores how the causes of manufacturing non conformities were investigated on MV and HV cables at Cabelte, Cabos Elétricos S.A., over a 17 month window (Jan 2025 – May 2026). The approach combines four elements: attributing every defect to the machine that produced it, normalising that attribution across several axes so comparisons are fair, mining the free text descriptions left by operators, and reading the digital phase resolved partial discharge (PRPD) waveforms captured during factory testing. Together, these elements are intended not merely to describe what went wrong, but to identify why, in a manner that can be independently verified, and to indicate maintenance and process changes warranted by the evidence.

The defect data are processed through three complementary metrics. The first, Non Conformity Frequency (NCF), captures baseline rates across five different denominators. The second restricts the analysis to the primary insulation extruders, excluding the noise introduced by downstream sheathing and winding steps. The third cross tabulates machine and voltage class jointly, so that product specific effects are not averaged away. Each of these metrics feeds directly into a specific figure or table in Chapter 4 and the equations below define exactly the quantities used to produce them.

Metric 1 — Non Conformity Frequency (NCF)

Five variants of this metric are used, each normalising against a different denominator according to the question under consideration.

- (i) *Per-machine defect rate — feeds the performance tracking in Figure 4.1 (Section 4.2); full mathematical values are compiled in Appendix A, Table A.1.*

This metric expresses the share of a given machine’s own output that carries a recorded non conformity. Normalising against the machine’s own production, rather than the plant’s, permits a fair comparison between a low volume speciality line and a high volume primary extruder:

$$\text{Machine NCF}_m^{(i)} (\%) = \frac{D_m}{P_m} \times 100 \quad (3.1)$$

where:

- D_m = Cable metres with defects logged on machine m
- P_m = Total cable metres produced by machine m

(ii) *Machine contribution to total produced metres — feeds the headline facility metrics in the left panel of Figure 4.2 (Section 4.2); full values are compiled in Appendix A, Table A.4.*

Here the denominator changes to the whole plant's output, which addresses a different question: not the reliability of an individual machine, but the proportion of the factory's overall non conformance rate attributable to it.

$$\text{Machine NCF}_m^{(ii)} (\%) = \frac{D_m}{P_{\text{total}}} \times 100 \quad (3.2)$$

where:

- D_m = Cable metres with defects logged on machine m
- P_{total} = Total cable metres produced across all plant assets

(iii) *Machine share of total defect metres — feeds the volume tracking in the right panel of Figure 4.2 (Section 4.2); full values are compiled in Appendix A, Table A.22 and Table A.24.*

This third variant identifies which machines account for the largest share of physically scrapped material, independent of their overall production volume.

$$\text{Machine NCF}_m^{(iii)} (\%) = \frac{D_m}{D_{\text{total}}} \times 100 \quad (3.3)$$

where:

- D_m = Cable metres with defects logged on machine m
- D_{total} = Total defective cable metres recorded plant wide

(iv) *Defect category share of total defect metres — feeds the spatial scale tracking in Figure 4.5 (Section 4.3); full values are compiled in Appendix A, Table A.11.*

This metric measures the proportion of total scrapped length attributable to a given category of defect (electrical, structural, sheath).

$$\text{Category NCF}_c^{(iv)} (\%) = \frac{L_c}{D_{\text{total}}} \times 100 \quad (3.4)$$

where:

- L_c = Cable metres carrying defect category c
- D_{total} = Total defective cable metres recorded plant wide

(v) *Defect category global production impact — feeds the divergence analysis in Figure 4.4 (Section 4.3); the comprehensive breakdown is compiled in Appendix A, Table A.10.*

Finally, normalising a category's length against the entire plant's output produces a baseline unaffected by uneven period of 2025 vs 2026.

$$\text{Category NCF}_c^{(v)} (\%) = \frac{L_c}{P_{\text{total}}} \times 100 \quad (3.5)$$

where:

- L_c = Cable metres carrying defect category c
- P_{total} = Total cable metres produced across all plant assets

Metric 2 — Extruder Filtered Voltage Non Conformity Frequency (NCF_v)

To examine how defect rates vary by voltage rating without distortion from sheathing, winding, or logistics records, this metric is restricted to the four primary insulation extruders, **EP100**, **EP102**, **EP23**, and **EP08**, as these are the only lines on which the voltage class assignment reflects the insulation itself rather than a downstream process. For a given voltage class v :

$$\text{Voltage NCF}_v^{(i)} (\%) = \frac{\sum_{m \in \mathcal{E}} D_{m,v}}{\sum_{m \in \mathcal{E}} M_{m,v}} \times 100 \quad (3.6)$$

where:

- $\mathcal{E} = \{\text{EP100}, \text{EP102}, \text{EP23}, \text{EP08}\}$
- $D_{m,v}$ = Defect metres at voltage v on machine m
- $M_{m,v}$ = Total metres produced at voltage v on machine m

This metric underlies the comparative internal rate curves in Figure 4.6 (Section 4.4); the full datasets are in Appendix A, Table A.12

The following two variants of this metric express, respectively, the global impact and the global share of this machine group's defect metres: the first normalises the group's defect metres against total plant production, while the second normalises them against the plant's total defective metres.

$$\text{Voltage NCF}_v^{(ii)} (\%) = \frac{\sum_{m \in \mathcal{E}} D_{m,v}}{\sum_{m \in \mathcal{E}} M_{m,\mathcal{E}}} \times 100 \quad (3.7)$$

where:

- $\mathcal{E} = \{\mathbf{EP100}, \mathbf{EP102}, \mathbf{EP23}, \mathbf{EP08}\}$
- $D_{m,v}$ = Defect metres at voltage v on machine $m \in \mathcal{E}$
- $M_{m,\mathcal{E}}$ = Total metres produced by machine m in $\mathcal{E}$

and

$$\text{Voltage NCF}_v^{(iii)} (\%) = \frac{\sum_{m \in \mathcal{E}} D_{m,v}}{D_{\text{total},\mathcal{E}}} \times 100 \quad (3.8)$$

where:

- $\mathcal{E} = \{\mathbf{EP100}, \mathbf{EP102}, \mathbf{EP23}, \mathbf{EP08}\}$
- $D_{m,v}$ = Defect metres at voltage v on machine $m \in \mathcal{E}$
- $D_{\text{total},\mathcal{E}}$ = Total metres with defect produced by all machines in $\mathcal{E}$

Metric 3 — Machine Attributed Voltage Non Conformity Frequency

A further consideration is pooling machines and voltage classes together prior to normalisation can obscure product specific effects behind a single denominator. To address this, the second metric calculates joint machine $\times$ voltage profiles directly, before aggregation. Two variants are used in Chapter 4.

(i) *Machine $\times$ voltage joint share of total defect metres — feeds the cell densities of the machine product distribution heat map in Figure 4.9 (Section 4.4).*

For a specific machine m and voltage class v , this metric tracks that cell's defective volume against the plant wide total, allowing a change in a product's overall quality to be traced to the specific asset responsible:

$$\text{Voltage NCF}_{m,v}^{(i)} (\%) = \frac{D_{m,v}}{D_{\text{total}}} \times 100 \quad (3.9)$$

where:

- $D_{m,v}$ = Defect metres at voltage v on machine m
- D_{total} = Total defective cable metres recorded plant wide

(ii) *Defect category share within a voltage class — feeds the product fault cross tabulations evaluated alongside the voltage band defect mode comparison in Section 4.4; the complete joint matrix is compiled in Appendix A*

The final variant narrows the focus further, to a single defect category within a single voltage class, again expressed as a share of the plant wide defective total:

$$\text{Voltage NCF}_{v,c}^{(ii)} (\%) = \frac{\sum_m D_{m,v,c}}{D_{\text{total}}} \times 100 \quad (3.10)$$

where:

- $D_{m,v,c}$ = Defect metres for category c at voltage v on machine m
- D_{total} = Total defective cable metres recorded plant wide

3.2 Research Design and Overall Approach

The investigation proceeds from database extraction through wave mechanics diagnostics to a long term quality plan. Quantitatively, the analysis focuses on period to period rate shifts, percentage point share comparisons, and apparent charge percentiles; qualitatively, structured text screening and the insulation physics reviewed in Chapter 2 are used to interpret the observed numerical trends.

To maintain alignment between these two strands, the work is organised into nine sequential phases, each producing a specific figure or table in the results chapter rather than a free standing analysis. Tables 3.1 and 3.3 set out this structure in full.

Table 3.1: Analytical framework: Defect distribution and profiling (Phases 1 to 5).

Ph.	Title	Primary output	References
1	Defect by Machine	Normalized performance dot plots tracking NCF per asset class across 2025 and 2026 (Metrics 1(i)–1(iii)).	section 4.2 and figs. 4.1 and 4.2
2	Defect by Category	Typology composition tracking shifting profiles by macro family, normalized production impact, and physical defect metre share (Metrics 1(iv)–1(v)).	section 4.3 and figs. 4.3 and 4.5
3	Defect by Voltage	Internal defect rates per voltage class (Metric 2); machine $\times$ voltage heat maps and category $\times$ voltage shares (Metric 3).	section 4.4 and figs. 4.6 and 4.9
4	Root-Cause & Critical Defects	Operational performance breakdown; structured description screening isolating physical PD risk indicators in operator comments.	section 4.5 and tables 4.1 and 4.3
5	Temporal & PD Risk Profiles	Defect type percentage point divergence analysis; rate ratios (RR) for macro categories; spatial defect position profiles along reel length.	section 4.6 and figs. 4.11 and 4.14

Table 3.3: Analytical framework: Causal diagnosis and mitigation (Phases 6 to 9).

Ph.	Title	Primary output	References
6	PD Intensity Analysis	PD charge (Q , pC) median distributions and outlier profiles stratified by voltage class, machine, and reel position.	section 4.7 and fig. 4.15
7	PRPD Pattern Recog.	Classification matrix of wave signatures across factory acceptance tests, separating structural voids/tracking from external lab artefacts.	—
8	Root Cause Synthesis	Integrated causal model linking machine maintenance cycles, defect typologies, and PD signatures into distinct failure mechanisms.	section 3.12
9	Corrective Measures	Risk prioritized framework matrix mapping equipment overhauls and process modifications with associated tracking KPIs.	section 3.13

The comparison between 2025 and 2026 it is carried through all nine phases. Phase 4.2 presents each machine’s two annual rates side by side; Phase 4.4 repeats the exercise for product assignment; and Phase 4.6 places this comparison on a consistent quantitative footing applied uniformly across categories, machines, and voltage classes. The objective throughout is to pair every observed change with a measure of its size and direction, read alongside the mechanistic evidence needed to judge whether it is genuine. Phases 4.9 and 4.10 do not introduce further raw data metrics: they re use the outputs of Phases 4.2 to 4.8 as inputs, first to establish which candidate causal mechanisms are adequately supported by the evidence (Phase 4.9), and then to convert that synthesis into a prioritised, traceable corrective programme (Phase 4.10).

3.3 Data Sources and Extraction

3.3.1 Industrial Context and Source Systems

The data originate from two systems: the facility’s Production Management Information System (PMIS) and its Quality Management System (QMS). The PMIS holds processing parameters, design specifications, asset tracking flags, raw material lot numbers, and line run times. The QMS holds the post production inspection logs, non conformance reports, standardised category codes, free text operator comments, and the final high voltage laboratory accept/reject readings, including the raw apparent charge magnitudes (Q , in picocoulombs) recorded under standard high voltage measurement practice [7, 33].

3.3.2 Database Construction and Quality Checks

Records from both systems were joined into a single relational database using the manufacturing order number and batch identifier shared between them. Each resulting record carries the production

order code, the processing asset, the defect classification, the free text description, a timestamp, the shift team, and the high voltage laboratory result, where available.

Before any statistical work began, the merged data underwent three checks:

- **Completeness validation:** flagging records with missing core fields, with no machine identifier, no voltage rating, no defect classification.
- **Structural consistency auditing:** cross-checking the operator logged voltage class against the original order specification, to identify data entry errors.
- **Physical plausibility screening:** confirming that partial discharge readings fell within physically realistic bounds for the insulation material in question.

Records with unrecoverable gaps were removed from the quantitative pool, and the share of the population affected was tracked as a check against selection bias. Duplicate or secondary derived entries were also removed, so that every remaining record represents one independent non conformance event.

3.4 Data Filtering and Scope Delimitation

The dataset was narrowed to medium and high voltage cable runs using cross-linked polyethylene (XLPE) or ethylene propylene rubber (EPR) insulation. Low voltage products ($U_0 \leq 1$ kV) were excluded, since partial discharge is not a primary failure mode at that rating. Polypropylene (PP) is discussed on theoretical grounds in Chapter 2; the production volume required to evaluate it empirically alongside XLPE and EPR was not available during the study window, and that comparison is therefore proposed as future work.

3.5 Phase 1 — Defect Distribution by Machine

3.5.1 Classification Framework

Every validated non conformance event was attributed to the specific machine that processed the cable core, with machine identifiers cross checked against the PMIS order tracking flags to resolve ambiguous cases. The resulting record covers every line that produced a quality deviation during the study window: extrusion crossheads, cabling cages, armouring lines, and the transport and logistics stages.

A distinction maintained throughout this work is between the primary insulation extruders (the triple-crosshead lines EP102, EP08, EP23, and EP100) and the downstream sheathing lines (EP101 and EP05). Since the sheathing lines never contact the insulation itself, any electrical defect attributed to them necessarily originates upstream and is detected only once the finished reel reaches final testing.

3.5.2 Frequency Analysis by Machine

Machine performance is evaluated through three normalised views, each addressing a distinct question:

Per Machine Defect Rate — $\text{NCF}_m^{(i)}$: A machine's non conforming output as a share of its own production volume (Equation 3.1). Because it corrects for throughput, this metric permits a fair comparison between a high volume primary line and a low volume speciality asset, and is the quantity tracked over time by the dot plot in Figure 4.1.

Machine Facility Wide Output Contribution — $\text{NCF}_m^{(ii)}$: A single asset's defective metres as a share of the entire plant's output (Equation 3.2). This metric addresses the question most relevant to plant management: not the reliability of a machine in isolation, but its contribution to the factory's overall non conformance rate (Figure 4.2, left panel).

Machine Global Scrap Share — $\text{NCF}_m^{(iii)}$: An asset's non conforming metres as a share of the total defective volume across the plant (Equation 3.3). Weighting by physical scrap volume identifies a different set of contributing assets than the rate alone (Figure 4.2, right panel).

3.6 Phase 2 — Defect Distribution by Category

3.6.1 Classification Framework

Defects are organised on three nested levels where each one is the unit of analysis for a different part of Chapter 4. The QMS maintains more than thirty standardised category **codes**, separating dielectric strength failures, partial discharge rejections, and semiconductor flaws from structural issues such as eccentricity, insulation thinning, jacket blemishes, tape wrinkles, and handling scuffs. These codes are consolidated into a smaller set of named defect **categories** (e.g. Dielectric Strength, Partial Discharges, Sheath Appearance, Poorly Guided Cable, Water Marks) by grouping sub codes that describe the same physical failure mode at different levels of detail; this is the level at which the category level detail in Section 4.3, and the apparent charge statistics in Section 4.7 all operate, and a category's reported RR is therefore a **consolidated** figure across every sub code mapped to it. Finally, for the macro level view, these same categories are pooled further into three families — Electrical, Sheath & Structural, and Other, shown in Figure 4.3.

3.6.2 Frequency Analysis by Category

The normalisation logic used for machines is applied here, adapted to the question of how the defect hierarchy is shifting over time:

Proportional Category Share: The proportion of the total non conformance population accounted for by each category within each annual window (Figure 4.3). As a proportion rather than a rate, this metric shows structural shifts in the quality burden independent of the absolute baseline.

Defect Category Global Production Impact — $\text{NCF}_c^{(v)}$: A category's length as a share of the plant's total output (Equation 3.5). Normalising against total output, rather than only the defective subset, removes the distortion that would otherwise arise from the unequal observation lengths of 2025 and 2026, and indicates whether a category's apparent rise or fall represents a genuine process shift or an artefact of the calendar (Figure 4.4).

Defect Category Scrap Volume Share — $\text{NCF}_c^{(iv)}$: A category's length as a share of the plant's total defect metres (Equation 3.4), indicating each category's relative contribution to total scrapped length within the study scope, as shown in Figure 4.5

3.7 Phase 3 — Defect Distribution by Voltage Level

3.7.1 Scope and Layered Analysis

Whether a cable's voltage rating predicts its likelihood of carrying a non conformity is examined in three layers:

Layer 1 — Population Proportional Profiles: An examination of how macro category proportions vary across voltage bands. This layer operates on classification frequencies and is reported as a direct comparison of percentage shares across bands (Section 3.7).

Layer 2 — Core Extruder Voltage NCF: Volume normalised defect rates by voltage class, restricted to the four primary extrusion lines EP100, EP102, EP23, and EP08 (Metric 2, Equation 3.6). Restricting the dataset in this way keeps the resulting rates representative of insulation processing quality specifically, rather than diluted by downstream noise (Figure 4.6) [18, 19].

Layer 3 — Multi Variable Joint Share Matrices: Plant wide voltage defect shares, constructed by cross tabulating individual asset contributions (Metric 3). The machine $\times$ voltage joint share (Equation 3.9) supplies the cell densities behind the heat map in Figure 4.9, while the defect category $\times$ voltage share (Equation 3.10) indicates how different fault types are distributed across the voltage rates; the full data are presented in the heat map in Figure 4.10.

3.8 Phase 4 — Root Cause Analysis and Critical Defect Identification

3.8.1 Cause–Effect Mapping by Machine

For every high priority asset identified in the Phase 4.2 curves, a cause and effect matrix was constructed, with the results reported in Section 4.5. Each causal link was verified against the free text operator comments in the QMS and against the polymer degradation mechanisms reviewed in Chapter 2, so that the process vulnerabilities identified are grounded in verified physics rather than statistical association alone.

The analysis covers five equipment classes: the triple pass crosshead extruders (EP), the take up systems (GT), the cabling lines (BL/CB), the armouring cages (AR), and manual floor tasks (MAN). For each, Table 4.1 reports NCF evolution, the dominant fault categories, the verified root causes, and the primary voltage classes involved.

3.8.2 Systematic Description Screening

Because standardised database codes inevitably flatten some nuance, a structured text mining script was run across every free text description field in the QMS, identifying physical indicators of structural anomalies, parameter drift, or partial discharge risk not captured by the coded categories alone (Table 4.3).

The script searched for specific terminology: phrases indicating that a fault ran the length of the reel, comments referring to the semiconductor boundary zones, descriptions of surface roughness, mentions of scorching or carbonaceous contamination, and language matching the six partial discharge risk criteria defined in Phase 3.9 below. Matching records were extracted and tabulated alongside their machine attribution and the corresponding risk criterion.

3.9 Phase 5 — Temporal Comparison and PD Risk Defect Identification

Phase 4.6 performs two complementary analyses on the same underlying data: it quantifies how rates shifted between the two periods, and it isolates the specific structural defects carrying the highest partial discharge risk. These analyses are conducted jointly by design, as doing so connects a statistically confirmed change to a physical explanation for that change, rather than treating the two as independent.

3.9.1 Keyword Flag Analysis

Every record in the standardised window was scanned against a fixed list of keywords spanning 18 quality categories, grouped into four families: Electrical & Insulation (burn marks, PD activity, dielectric punctures, semiconductor deviations), Outer Sheath & Mechanical (surface blemishes, blisters, scoring, water marks, creases, scorched jackets), Component & Tape (laminar shifts, water swellable tape issues, shielding variations), and Bobbin & Structure (flange damage, tie rod

issues, misguided layers). The number of keyword flags triggered per record provides a simple measure of the complexity of a given failure, and of whether that complexity changed over time.

3.9.2 PD Risk Defect Criteria

Drawing on the polymer physics reviewed in Chapter 2 and on international high voltage testing guidance [7, 50], six processing flaws were defined in advance as the primary drivers of partial discharge activity. Any record matching one of these criteria was assigned to a dedicated PD Risk Defect Population sub dataset, used subsequently for the intensity and waveform analysis:

- **(a) Insulation Voids and Gas Inclusions:** Microscopic cavities inside the main insulation caused by crosshead pressure drops, uneven cooling rates, or trapped volatile gases from cross linking reactions [5, 53, 55, 56].
- **(b) Interface Protrusions:** Conductive irregularities at the semiconductor boundaries caused by die lip wear, forcing screen compound to bleed into the active insulation and creating intense electric field concentrations [57, 58].
- **(c) Material Contamination:** Conductive or non conductive inclusions embedded within the polymer bulk, tracing to filter mesh erosion or crosshead cross-contamination during compound changeovers [59, 60].
- **(d) Insulation Eccentricity:** Non-uniform wall thickness across the cable cross section, reducing the dielectric distance and concentrating electrical stress at the thinnest point [18, 19].
- **(e) Semiconductive Screen Roughness:** Structural irregularities along the screen interfaces that disrupt the potential fields and initiate local air ionization [6, 57].
- **(f) Moisture Barrier Tape Anomalies:** Creases, wrinkles, or overlap gaps within the Al/PE laminate foil, creating ungrounded spaces that discharge repeatedly under AC stress [19].

3.9.3 Rate Ratio Comparison of Temporal Trends

To compare how often a given category, machine, or voltage class produced a defect between the two periods under study, the same normalised rate logic introduced for Metrics 1 and 2 (Section 3.5) is reused directly: each period $k \in \{1, 2\}$ is summarised by an event count x_k (or defect metres) over an exposure T_k (cable metres produced, for the relevant asset or category, in that period), giving a rate $\hat{\lambda}_k = x_k/T_k$. Two exposure bases are used depending on the underlying data source: for the category, machine, and voltage level NCF comparisons in Sections 4.2–4.5, T_k is cable metres produced and x_k is defect metres logged. For the machine and category level RR discussed in Section 4.6.2 and in Table A.26, Appendix A, x_k and T_k are instead drawn from the keyword flagged description mining sub dataset (Section 3.9.1): x_k is the count of free text records matching a PD risk criterion, and T_k is the total count of production records for that machine in the period.

The two are not interchangeable and are reported separately for this reason. Because each rate is independently normalised by its own period’s production volume, the comparison is made directly between the full 2025 calendar year and the January to May 2026 partial year, without truncating 2025 down to a matching five month window: the metres produced denominator, not an artificially shortened time window, is what makes the two periods comparable. The rate ratio between the two periods is:

$$RR = \frac{\hat{\lambda}_2}{\hat{\lambda}_1} = \frac{x_2/T_2}{x_1/T_1} \quad (3.11)$$

An RR below 1 indicates the rate fell between the two periods; an RR above 1 indicates it rose. This is the same RR reported throughout Appendix A (e.g. Tables A.1, A.10, and A.13) and in Chapters 4 and 6: a single, consistent definition is used everywhere a temporal rate ratio is reported in this dissertation, rather than a separate calculation for the headline tables and another for the in chapter discussion.

Alongside the rate ratio, every comparison in this dissertation also reports the corresponding shift in **occurrence share**: the percentage of the period’s total records (or, where stated, total defect metres) attributable to a given category, machine, or voltage class. For a given item c in period k , with $n_k(c)$ the count (or defect metres) attributed to c and N_k the period total:

$$\text{Share}_k(c) = \frac{n_k(c)}{N_k} \times 100, \quad \Delta_{pp}(c) = \text{Share}_2(c) - \text{Share}_1(c) \quad (3.12)$$

Δ_{pp} is reported in percentage points (pp), and is deliberately distinct from RR: RR compares an item’s **rate** against its own exposure in each period (Equation 3.11), whereas Δ_{pp} compares an item’s **share of the whole** between the two periods. The two can, and sometimes do, point in different directions for the same item; a category’s share of total defects can rise even while its underlying rate is roughly flat. Both are reported together for this reason, as RR isolates whether an item’s own behaviour changed, while Δ_{pp} shows how that change reshaped the plant’s overall defect composition. Consistent with the chapter’s normalisation convention, only the resulting $\hat{\lambda}_k$ and RR are reported in Chapters 4 and 6 — the underlying counts x_k and exposures T_k are not disclosed.

3.9.4 Defect Localisation Along the Cable Reel

When the quality log includes a distance value, that figure locates the defect at a specific point along the physical length of the reel, making it possible to separate start of run transients, end of run drift, and faults that run continuously (Figure 4.14). Table 3.6 sets out the engineering interpretation associated with each spatial pattern, and the corrective action it indicates.

Defect position pattern	Engineering interpretation	Corrective measure category
Clustered at reel exterior end	Start up transient: thermal warm up gradient in die, residual compound from preceding campaign, extruder speed pressure control not yet at steady state	Extend pre run purge length; revise start up temperature ramp protocol
Clustered at reel interior end	End of run drift: thermal fatigue, compound depletion, die gap opening with progressive wear	Reduce maximum reel length before scheduled tooling inspection
Uniform distribution across reel	Chronic process condition: worn tooling, continuous filtration inadequacy, steady state parameter drift	Scheduled tooling replacement; filter mesh upgrade
Multiple mid reel clusters	Intermittent cause: periodic line speed deviation, material inhomogeneity in compound batch	Review compound batch homogeneity; install line speed deviation alarm

Table 3.6: Defect position patterns, engineering interpretations, and corrective measure categories.

3.10 Phase 6 — Partial Discharge Intensity Analysis

3.10.1 Data Extraction and Linkage

High voltage laboratory test logs were extracted from the quality database and matched to production runs using manufacturing order references and lot numbers. For every record in the PD Risk Defect Population, the apparent charge value (Q , in pC) was extracted from the free text description fields via regular-expression parsing, since the legacy database stores these values as comments rather than structured numeric fields.

3.10.2 Analysis by Voltage Level

Partial discharge distributions are broken down by voltage class, since MV and HV designs are governed by different testing standards [18] and dedicated alternative high voltage specifications [19, 20].

3.10.3 Analysis by Manufacturing Unit and Cable Position

The same charge statistics are then broken down by primary extrusion line and by reel position, assessing whether the lines with the highest defect frequencies also produce the most severe discharges, or whether any apparent severity gradient is merely a logging artefact. The distinction is operationally significant: frequent low-energy discharges indicate a different root cause, such as minor screen roughness, than rare but high-energy events, which are more indicative of large voids or material impurities.

3.11 Phase 7 — PRPD Analysis and Pattern Recognition

3.11.1 Overview

Phase resolved partial discharge (PRPD) analysis maps each discharge pulse to the phase angle of the applied AC wave at the moment it occurred, enabling inference of the physical nature of the underlying defect [7]. Phase 4.8 analyses the raw instrumentation charts produced by the factory's digital monitoring units, matching observed signatures to the defect types already identified in Phases 4.4 and 4.6. As the central servers do not retain raw waveform data, the original files were retrieved directly from the laboratory workstation; nine cable body records, spanning the 36 kV and 76 kV ratings, were evaluated by this method. Data retrieval was performed using the MPD 600 instrument, with subsequent analysis carried out in OMICRON's MPD Suite software.

3.11.2 Internal Discharges — Insulation Voids

Inside a gas filled cavity, ionisation is governed by the rate of voltage change (dv/dt) rather than the instantaneous voltage level, which is why discharge activity tends to concentrate on the rising edges of both half cycles. The result is a symmetric, bilateral "rabbit ear" PRPD distribution, clustered tightly in the 0° to 90° and 180° to 270° phase windows [50, 61, 62]. As the void's walls degrade and carbonise under sustained stress, this symmetric pattern gradually spreads across the phase axis [21].

3.11.3 Surface and Interface Discharges

Electron tracking along the internal semiconductor boundaries behaves differently: the semi conductive interface layer acts as a capacitive grid, retaining charge before surface breakdown occurs, which delays the peak pulse density past the voltage maxima and shifts the clusters into the declining quadrants (90° to 180° and 270° to 360°) [50, 63]. If sustained stress eventually produces irreversible carbon tracks along the interface, this orderly phase sorting breaks down into a chaotic, full cycle distribution that saturates the instrument's measurement range [10, 64].

3.11.4 External Corona and Switching Noise Artefacts

Corona in the surrounding laboratory air, generated around sharp metal clips or connection leads, concentrates instead at the absolute voltage peaks (90° and 270°), producing fine vertical "comb" columns with limited charge variation and a marked negative half cycle bias at inception [48, 50]. A separate artefact arises from high frequency electronic noise generated by heavy machinery elsewhere on the shared plant grid, appearing as steady vertical lines at fixed harmonic spacing, independent of the voltage wave's phase [24]. Both must be identified and screened out, to avoid rejecting a sound cable reel for an incorrect reason.

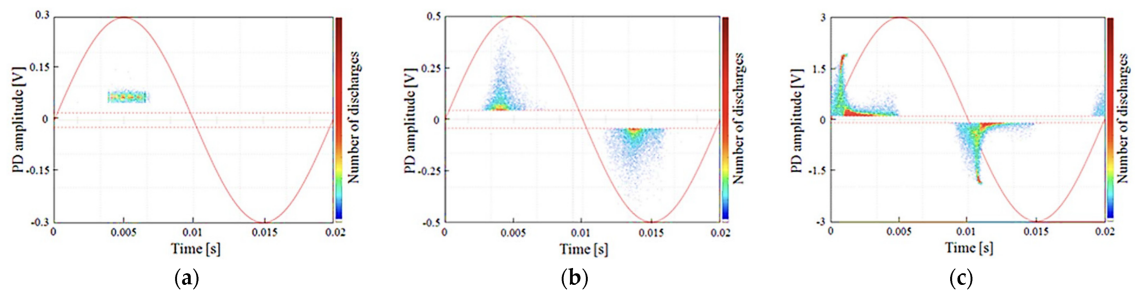


Figure 3.1: Different types of PD graphs [47] (a) Corona discharges (b) Surface discharges (c) Internal discharges.

3.12 Phase 8 — Root Cause Synthesis

Phases 4.2 to 4.8 each isolate one slice of the evidence: which assets and voltage classes carry the non conformity burden (Phases 4.2 to 4.4), which physical mechanisms are responsible (Phase 4.5), whether the observed period to period changes are statistically genuine (Phase 4.6), how severe the resulting discharges are (Phase 4.7), and which PRPD signature each mechanism produces in factory testing (Phase 4.8). Phase 4.9 collects no new data; it cross references these seven outputs to decide which candidate root causes are adequately supported, folding the surviving causes into a small number of integrated findings.

3.12.1 Convergence Criteria

A candidate root cause is treated as established, rather than merely suggestive, only where it satisfies at least one of the following two independent lines of evidence:

1. **Rate ratio confirmation (Phase 4.6):** the affected category, machine, or voltage class shows a rate ratio departing substantially from 1 (in practice, $RR \leq 0.7$ or $RR \geq 1.3$ in this study), large enough that the change is unlikely to reflect ordinary period to period variation, even though no formal significance test is applied.
2. **Mechanistic confirmation (Phase 4.5):** the cause effect matrix links the change to a specific, physically grounded process deviation (die wear, contamination, thermal drift) rather than to an unexplained correlation, with that physical pathway traceable to the theory in Chapter 2.

Findings supported by both lines of evidence are reported as confirmed causal mechanisms; findings supported by only one are reported as directional evidence requiring further monitoring rather than immediate corrective action. This distinction is what separates, for example, EP101's sheath deterioration (a substantial rate ratio shift in Phase 4.6 and a mechanistic trace in Phase 4.5) from the EP102/EP08 PD risk findings (supported by both criteria).

3.12.2 Two Tier Frequency Severity Model

A second function of Phase 4.9 is to test whether the mechanisms governing how **often** a defect occurs are the same as those governing how **severe** it is, by cross tabulating each asset's Phase sections 4.2 and 4.6 occurrence rate trend against its Phase 4.7 apparent charge trend. Where the two move together, a single root cause explains both. Where they diverge — for example, when a machine's defect frequency falls sharply after a tooling intervention while its mean discharge magnitude remains elevated — this is treated as evidence that frequency and severity are governed by distinct mechanisms, and the corrective programme in Phase 4.10 is structured accordingly.

3.13 Phase 9 — Corrective and Preventive Measures

Phase 4.10 converts the Phase 4.9 synthesis into a prioritised, traceable action plan: every measure traces back to a specific finding from Phases sections 4.2 and 4.9, via a scoring procedure for prioritisation and a fixed reporting format for traceability.

3.13.1 Risk Prioritisation Scoring

Each non conformity cluster identified in Phase 4.9, typically a single asset or a small group of related assets, is scored against three criteria, balanced jointly rather than ranked lexicographically:

- **Failure frequency:** the asset's NCF level and its Phase 4.6 rate of change (Equation 3.1).
- **Risk severity:** whether the affected category carries confirmed PD risk (Phase 4.6 criteria (a) to (f)) and, where applicable, Phase 4.7's apparent-charge distribution for that asset or voltage class.
- **Engineering deployment effort:** whether the corrective action can be implemented through existing maintenance windows at no capital cost, or requires equipment procurement, line downtime, or a planned shutdown.

Clusters scoring highly on both frequency and severity, with low deployment effort, are assigned the highest priority tier; clusters that show a substantial rate ratio shift but address a single, contained risk are assigned a monitoring only tier rather than an immediate action tier. This scoring is applied across four parallel tracks, separating the plant's distinct risk families so that an asset is never compared against a mechanistically unrelated one: a PD risk track for the primary insulation extruders, a sheath defect track for the downstream jacketing and winding lines, a mechanical handling track for HV reel logistics, and a monitoring track for findings not yet sufficiently confirmed to warrant immediate intervention.

3.13.2 Traceable Reporting Format

The output of this scoring is reported in two linked tables. The first records, for every cluster, the priority tier, the supporting Phase sections 4.2 and 4.9 evidence, and the recommended action

in narrative form. The second restates the same clusters as a numbered action plan, with each measure mapped explicitly to the asset(s) it targets, the PD risk criterion or defect category it addresses, and a measurable key performance indicator (KPI) expressed in the same normalised units used throughout this chapter (an NCF reduction target, a contamination event count, or a detection capability outcome). This shared unit of measurement is deliberate: it allows the post implementation monitoring proposed in Chapter 6 to re apply the identical Phase 4.2 and Phase 4.6 metrics to the same assets after the corrective measures are deployed, so that whether a measure worked can be checked with the same rate ratio comparison used to identify the problem, rather than assessed qualitatively.

A second, longer horizon set of infrastructure measures, covering wire drawing lubricant chemistry, MV/HV changeover protocols, purging agents, tape guide and die hardware, and a full planned shutdown line overhaul, is reported separately, since these address PD risk criteria at the level of plant wide infrastructure rather than a single asset's maintenance schedule. Each is nonetheless traced back to the specific PD risk criterion (a) to (f) it is designed to remove, preserving the same evidence chain from defect mechanism to corrective action.

3.14 Summary

This chapter has set out the pipeline used to convert the 17 month MV/HV quality dataset into the results presented in Chapter 4, normalised throughout so that no aspect of the comparison between 2025 and 2026 reflects an artefact of unequal volumes or observation windows.

This pipeline implements the nine phases directly: it produces the performance dot plots tracking each asset over time (Phase 4.2), drives the percentage point divergence analysis across category typologies (Phase 4.3), and constructs the product susceptibility profiles by voltage class (Phase 4.4). It structures the cause effect matrices and keyword text mining used to parse operator comments (Phase 4.5), governs the rate ratio comparison between the full 2025 calendar year and the January to May 2026 partial year across categories, machines, and voltage classes, and the spatial defect position profiling along the reel (Phase 4.6), and produces the apparent charge severity boxplots (Phase 4.7) and the PRPD based separation of structural voids and interface tracking from laboratory artefacts (Phase 4.8). The final two phases close the loop: Phase 4.9 cross checks every candidate root cause against the rate ratio, mechanistic, and PRPD signature criteria established by Phases sections 4.2 and 4.8, and Phase 4.10 converts the surviving causes into the prioritised, KPI tracked corrective programme reported in Chapter 4 and revisited in Chapter 6's limitations and future work.

Every causal claim and every corrective measure proposed in the chapters that follow rests on this evidentiary foundation, rather than on visual inspection of a chart alone.

Chapter 4

Results and Discussion

4.1 Dataset Overview

This chapter presents the results of the non conformance defect analysis conducted on the MV and HV cable production lines at Cabelte, from January 2025 up to May 2026. The analysis is structured into nine sequential phases, each addressing a progressively deeper level of the defect causal hierarchy: from aggregate machine load through voltage class attribution, root cause identification, and temporal rate comparison, to partial discharge intensity and pattern resolved waveform classification.

The quantitative analysis is restricted to XLPE and EPR insulated cables. Polypropylene (PP) insulation did not reach sufficient production volume during the study period to support a statistically valid quantitative comparison. Theoretical PP properties relevant to partial discharge risk are discussed in Section 2.4.3; an empirical comparison is proposed as future work in Chapter 6.

4.2 Phase 1 — Defect Distribution by Machine

Phase 1 addresses a foundational question: which machines are responsible for the plant’s non conformance burden, and was there a shift between 2025 and 2026? Three normalisation views are used in sequence to disentangle these effects, with full numerical tables available in Table A.1, Table A.4, and Table A.1 of Appendix A.

4.2.1 Per Machine Defect Rate

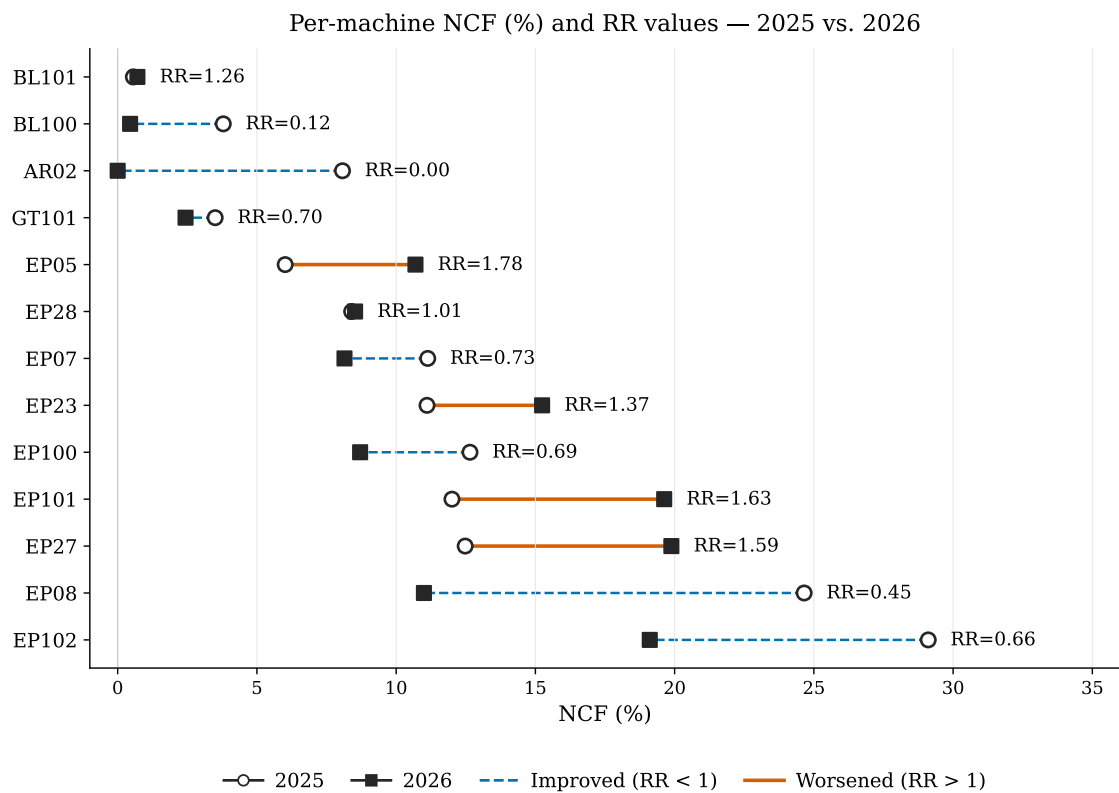


Figure 4.1: Per machine non conformity frequency (NCF, %) with RR values — 2025 vs. Jan – May 2026. Numerical values in Table A.1, Appendix A

Within this group, EP102 and EP08 are horizontal continuous vulcanisation (CV) lines, cured by a silane reaction at 170 to 180 °C, and run almost exclusively MV product. EP23 and EP100 are catenary continuous vulcanisation (CCV) lines, cured by a peroxide reaction at approximately 120 °C; EP23 predominantly runs MV product with occasional HV campaigns, while EP100 predominantly runs HV product with occasional MV campaigns. EP101 and EP05, by contrast, are downstream sheathing lines: they receive an already insulated core and apply only the outer jacket (EP101 can additionally apply the Al/PE moisture barrier tape). Because EP101 and EP05 never contact the insulation itself, any electrical (PD, dielectric strength) defect attributed to them in fact originates upstream and is detected only when their finished reel reaches testing.

Table A.1, which underlies Figure 4.1, reveals a two tier structure among the insulation extrusion assets. In 2025, EP102 and EP08 are distinguished from all other machines at 29.11,% and 24.65,% respectively. Below them, EP101, EP100, EP23, and EP05 cluster in the 6 to 13,% band. In 2026, EP102 still leads the group but with a markedly lower NCF of 19.11%, a fall of almost 10 percentage points, while EP101 has risen to 19.62%, narrowing the gap between the two machines considerably. The RR values are equally informative here, distinguishing machines whose condition genuinely improved from those whose condition worsened: EP08 and EP102 show the largest

improvements, while EP05, EP101, and EP23 show a deterioration in their underlying rate. These worsening trends are examined in detail throughout the remainder of this chapter.

EP102’s leading position. First, EP102’s die head showed progressive wear over 2025: a worn die lip produces an irregular melt flow front that intermittently pushes semiconductor screen compound into the XLPE boundary layer, forming conductive protrusions at the SCI/SCE–insulation interface (PD risk criterion b) [57, 58]. These protrusions concentrate the local electric field, lowering the PDIV below the IEC test threshold.

Second, residual moisture from the conductor drawing emulsion migrates into the freshly extruded inner semiconductor layer as vapour during conductor preheat, nucleating micro voids at the conductor–semiconductor interface (criterion a); this mechanism, common to EP102 and EP08, is examined in full in Section 4.5.

Third, because EP102 runs a highly diverse product mix spanning a wide range of insulation thicknesses, each changeover to a different wall thickness requires re tuning crosshead pressure and line speed to the new cross section; an imperfect re tuning leaves the first metres of the new thickness run with boundary irregularities or uneven cure depth. These three mechanisms reinforce one another: a protrusion at the semiconductor boundary, surrounded by moisture induced micro voids, on cable produced during an imperfectly re tuned changeover, presents a combined field concentration substantially more severe than any single defect mechanism alone.

EP08’s comparable severity and subsequent improvement. EP08’s 2025 profile was dominated by insulation failures. Four concurrent process deviations were identified in section 4.5: cooling rate inconsistency across the water quench trough; periodic line speed deviations; crosshead core misalignment accumulating eccentricity; and a conductor preheat deficit that left a radial temperature gradient in the insulation at the onset of cross linking. EP08 is also affected by the same conductor moisture mechanism identified on EP102 (section 4.5), though with comparatively smaller impact.

Each thickness changeover is itself a re tuning event, and a process already prone to cooling rate and line speed drift is more likely to leave that re tuning incomplete. Each deviation alone produces a marginal reduction in quality; in combination they produced a 24.65% NCF. The end 2025 maintenance intervention on EP08 addressed all four simultaneously — die replacement, crosshead realignment, cooling trough flow rate recalibration, and preheat element service — and the 2026 rate fell to 10.99% ($RR = 0.446$). This mechanistic explanation for the improvement is significant: it confirms that the maintenance programme correctly targeted the causal root causes, rather than merely coinciding with a production volume change.

EP101’s divergent trajectory. EP101 deteriorated from 12.00 % to 19.63 % ($RR = 1.635$). EP101’s dominant defects in 2026 are sheath appearance (35.9 %) and structural/tape anomalies (17.3 % bobbin/structural), not electrical failures, consistent with its role as a jacket and tape application line.

The root cause is Al/PE tape winding guide wear: as the tensioning rollers wear, the laminate tape is laid with inconsistent tension, producing wrinkles along the tape overlap seam. A wrinkled Al/PE tape creates a small air gap at a floating potential between the insulation surface and the copper/aluminium screen beneath it, which is a geometry that discharges repeatedly under AC stress (criterion f). Because this is a mechanical winding guide problem rather than an insulation extrusion problem, the corrective response differs accordingly: in wear cycle terms, EP101 in 2026 is overdue for the equivalent of a tooling replacement intervention, applied to its tape guide hardware rather than to a crosshead die.

The disproportionate significance of EP23's rising rate. EP23's numbers are moderate (11.11 % $\rightarrow$ 15.24 %), but context changes their interpretation: EP23 is dedicated almost entirely to 8.7/15 kV production. Phase 4 identified a compound filtration bypass as the likely mechanism: a degraded filter mesh in the extruder crosshead allows sub micron carbonaceous particles from the compound batch to pass through and embed in the XLPE insulation (criterion c) [59, 60]. These particles act as electric field stress risers at the molecular scale, lowering the local partial discharge inception voltage (PDIV) below the FAT test threshold. Because the contamination source (a failing filter mesh) operates continuously rather than episodically, every metre produced on EP23 after the mesh begins to degrade carries an elevated contamination risk, which accounts for the steady rise of the rate across the reporting period rather than an isolated spike.

4.2.2 Facility Level Contribution and Defect Metre Share

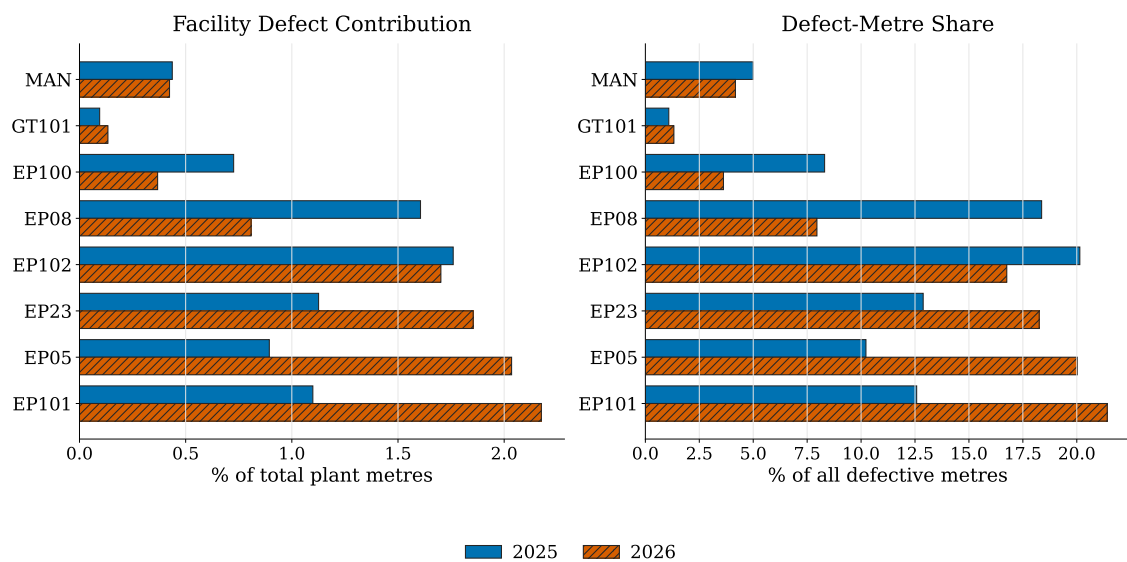


Figure 4.2: Facility defect contribution (% of total plant defect metres, left panel) and defect metre share (% of all defective metres, right panel). Full numerical tables in Appendix A (Tables A.4 and A.1).

The second and third normalisation views (Figure 4.2) add two dimensions that the per machine NCF rate cannot supply.

The facility defect contribution (left panel) weights each machine by its share of total plant output, converting the per machine rate into the question most relevant to the headline quality metric: what proportion of every metre the factory ships is affected by a given line? The 1.4 percentage point rise in the plant wide NCF between 2025 and 2026 (8.74 % to 10.16 %) is not distributed uniformly. EP08 and EP100 contributed to a reduction in the rate; EP101, EP05, and EP23 contributed to an increase by a larger combined margin. The factory's headline quality figure worsened not because quality deteriorated broadly, but because the improvement on the maintained machines was more than offset by machines not yet maintained. This distinction is material to how the 2026 result should be communicated: the underlying process capability of the maintained assets improved; the scheduled maintenance coverage was simply incomplete. As established in Phase 2 and Phase 5, this rise is itself largely a symptom of the redistribution of the defect burden toward the downstream sheathing and cabling lines rather than evidence against the extruders' improvement; the more diagnostic measure of process control on the insulation side is therefore the extruder restricted rate reported in Section 4.11

The defect metre share (right panel) weights each machine by its defective metres as a proportion of the total defective metres recorded across all machines. The near doubling of EP05's share (10.23 % to 20.03 %) is the most pronounced movement in this view. EP05's doubling in defect metre share, accompanied by only a moderate rise in NCF rate, confirms that its 2026 events were predominantly of the long running, drifting parameter type, which is economically the most damaging category of failure. EP101 followed the same trend as EP05, with its defect metre share nearly doubling (12.58% in 2025 to 21.41% in 2026); here, as previously explained, the main contributor is the Al/PE tape winding issue.

4.3 Phase 2 — Defect Distribution by Category

Phase 2 examines what type of defects they generate, and whether the mix changed between the two periods. This distinction is essential, as electrical insulation failures trace to the CV extrusion stage and require process temperature and die condition interventions; sheath and mechanical failures trace to the downstream jacketing and reeling stage and require a different set of tooling and tension controls, which helps determine the most appropriate maintenance protocol.

4.3.1 How the Defect Hierarchy Shifted

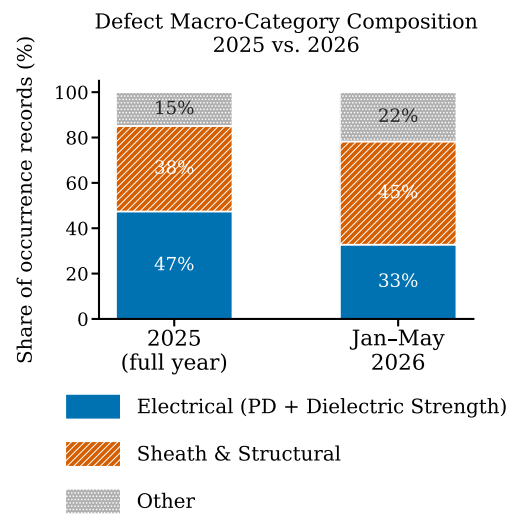


Figure 4.3: Defect macro category composition — 2025 vs 2026

Figure 4.3 represents the shift across three categories. In 2025, electrical defects accounted for approximately 47 % of all records; by Jan – May 2026 that proportion had fallen to under 33 %. The sheath and structural category rose from approximately 38 % to 45 %, while the Others category rose from 15 % to 22 %.

The machines that drove the 2025 electrical dominance, EP08 and EP100, received end 2025 maintenance. Their improvement specifically removed electrical defect records from the 2026 tally. The machines that deteriorated in 2026, EP101 and EP05, exhibit failure modes concentrated in the sheath and structural family. The hierarchy inversion does not, therefore, represent a genuine quality improvement at the category level: it is a mechanical consequence of which machines were and were not targeted by maintenance. The factory redistributed the burden from electrical to sheath failures.

4.3.2 Category Level Detail

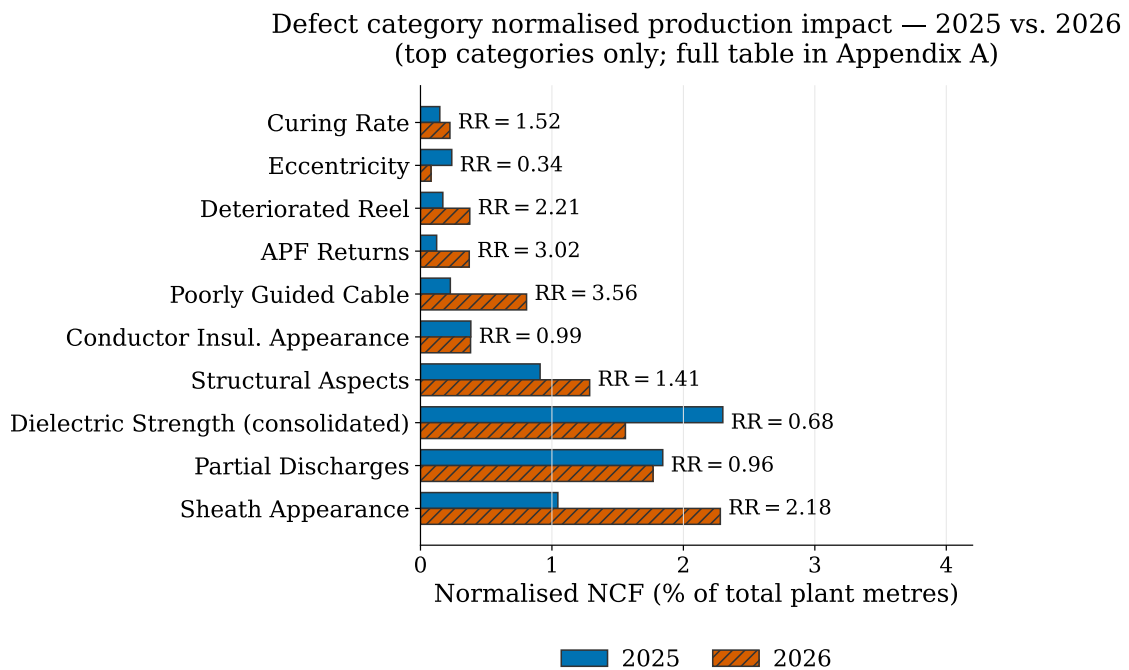


Figure 4.4: Top defect categories by normalised production impact — 2025 vs. Jan–May 2026. Remaining categories together account for <3 % in both years. RR values annotated. Complete information at Table A.10, Appendix A.

Figure 4.4 presents the individual categories driving the macro shift, normalised against total plant output to render the two periods directly comparable despite their different durations.

Dielectric Strength declined most substantially (consolidated $RR = 0.678$ across all sub codes). This is the direct outcome of the EP08 and EP100 maintenance: both machines had Dielectric Strength as their largest single defect category, so their improvement removed a disproportionate share of those records from the count. Partial Discharges also declined, but only modestly ($RR = 0.960$); PD events can lead to Dielectric Strength failures (electrical breakdown).

Sheath Appearance more than doubled ($RR = 2.183$), and Poorly Guided Cable nearly tripled ($RR = 3.555$). Both increases are mechanically explained by the deterioration of EP101 and EP05. Water Marks emerged from a near zero baseline ($RR = 3.125$): this defect forms when cold cooling water contacts the freshly extruded jacket compound, creating localised thermal shock marks on the surface. Its appearance reflects a process condition on the cooling trough (a temperature differential between trough water and jacket compound exit temperature) that is independent of the extrusion crosshead and therefore unaffected by the maintenance interventions applied in 2025. Water marks defects occur predominantly on EP05, where the thermal shock between the cold cooling water and the hot sheath layer creates surface marks that act as localised protrusions, promoting surface and corona discharge and forming weak points that can progress to full dielectric breakdown.

Misguided cable occurs when the take up reel’s traverse mechanism fails to layer cable evenly, causing runs to overlap or accumulate on one section of the drum. This is a mechanical symptom of either traverse mechanism wear or reel speed synchronisation drift. Its near tripling in 2026 corresponds to the increased production on EP101 and EP05, lines that handle the longest reels in the plant and where a traverse deviation produces the greatest defect metre length before detection. The connection to the reel handling infrastructure is developed further in Phase 3’s voltage class analysis.

4.3.3 Category defect by total meters with defect (all machines)

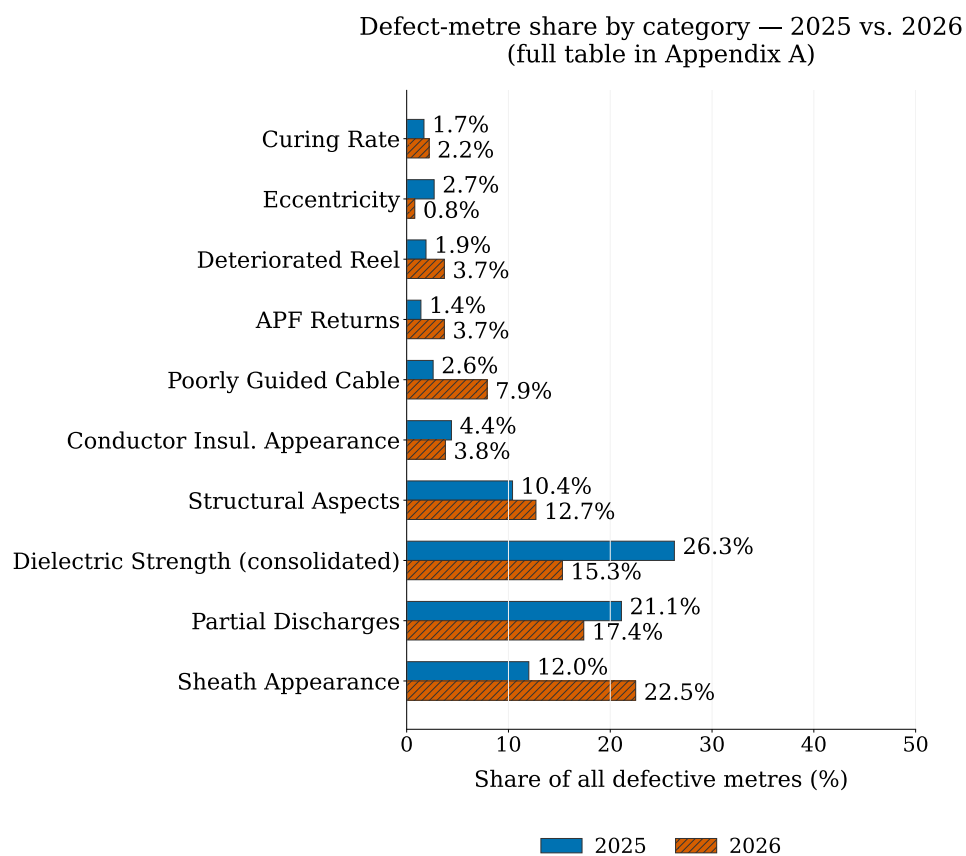


Figure 4.5: Defect metre share by category — 2025 vs. Jan–May 2026, as a percentage of all defective metres. Full table in Table A.11, Appendix A.

Figure 4.5 weights each category by its defect metres as a proportion of the total defect metres recorded across all machines.

Dielectric Strength’s defect metre share fell from 26.3 % to 15.3 %, which is a larger proportional decline than its occurrence count decline reported above. This is consistent with the EP08/EP100 maintenance mechanism described in Section 4.2: die replacement and crosshead realignment do not only reduce how often a protrusion or void event occurs.

Sheath Appearance shows the opposite pattern. Its defect metre share nearly doubled, from 11.96% to 22.45%, a larger increase than its occurrence based rise reported above. This indicates that EP101 and EP05's deteriorating winding guide and traverse mechanisms are not only triggering more sheath appearance events, but are producing longer ones as well — consistent with the traverse wear mechanism discussed above, in which a synchronisation drift persists and accumulates length until an operator intervenes.

Poorly Guided Cable follows the same pattern as Sheath Appearance, tripling from 2.59 % to 7.94 % of defective metres, reinforcing that this is a sustained mechanical condition on EP101 and EP05. Structural Aspects (10.41 % → 12.67 %), APF Returns (1.40 % → 3.65 %), and Deteriorated Reel (1.95 % → 3.69 %) all rose moderately, while Eccentricity fell (2.72 % → 0.79 %) and Conductor Insulation Appearance declined slightly (4.39 % → 3.75 %), broadly tracking the same machine level trends already established above.

Note: in 2026, following the issues identified in 2025, a more rigorous QA control regime was put into action. This heightened scrutiny can itself contribute to the appearance of categories at near zero share in 2025 and to higher recorded shares for several non electrical defects in 2026, independent of any underlying change in the physical defect generation rate.

4.4 Phase 3 — Defect Distribution by Voltage Level

Phase 3 examines whether a product's electrical specification determines its susceptibility to non conformance. A straightforward expectation might be that higher voltage cables, processed under tighter controls, would show fewer defects; the evidence is more nuanced. The internal defect rate depends on both the product's inherent process difficulty and the specific condition of the machine running that campaign. Phase 3 disentangles these two effects and quantifies which voltage classes are the primary drivers of the factory's quality burden. Full numerical tables are in Appendix A (Table A.12).

4.4.1 Internal Defect Rate by Voltage Rating

Figure 4.6 indicates a structured gradient rather than random variation: internal defect rates generally rise with voltage rating within the MV band, before falling sharply at HV.

The increasing difficulty of higher MV ratings. The IEC mandates progressively thicker insulation walls as design voltage increases [18, 19]. Each additional millimetre of wall depth requires a proportionally longer CV tube residence time to achieve complete and uniform cross linking throughout the wall thickness, and tighter temperature control, because a thicker cross section sustains steeper radial temperature gradients during the quench and leaves the interior of the wall more susceptible to incomplete cure if the CV tube setpoints drift. If any of these parameters approaches its borderline value, a non conforming section is substantially more likely to result at 20 kV than at 11 kV for a given machine state. This reflects the physics of thick wall XLPE rather than a failure of process discipline.

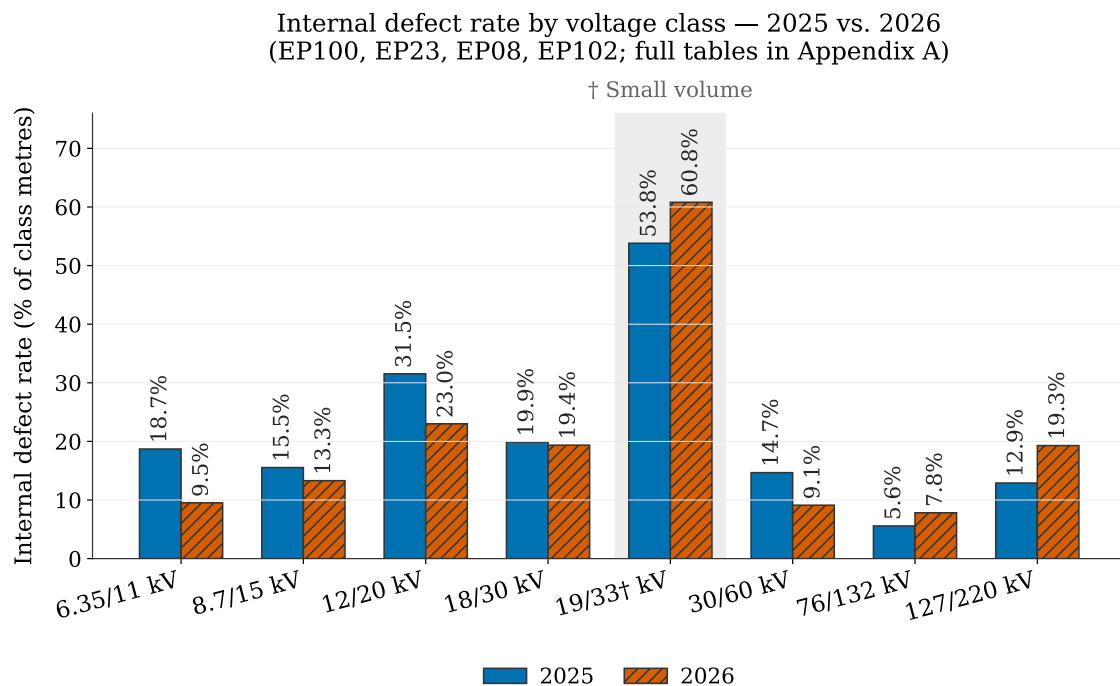


Figure 4.6: Internal defect rate (% of metres produced at each voltage level) for EP100, EP23, EP08, and EP102 for 2025 and 2026. Marked † are rates not statistically stable; interpret with caution. Full tables in Appendix A.

Interpreting the 19/33 kV rate of 53.81 % in 2025. This class produced only 71,220 m from two EP102 campaigns, such that a small number of defective reels drives the percentage to an extreme value. The underlying root cause is the same as EP102’s overall NCF, applied to a product that demands even stricter insulation wall tolerances. The 19/33 kV rate is therefore a signal regarding EP102’s process condition, rather than evidence that this voltage class is categorically unmanufacturable.

The lower rates of HV classes (76/132 kV, 127/220 kV) relative to upper MV despite thicker insulation. This result may appear counterintuitive, since thicker walls are generally more difficult to process. The explanation lies in the different process regime mandated by [19].

Before each HV campaign, the extrusion cell is physically isolated from the main production floor; air filtration is upgraded with positive pressure exclusion of ambient particulates, compound filtration meshes are upgraded and pressure tested for integrity; line speed is reduced to allow longer CV tube residence and more conservative thermal control; and a mandatory purge flushes any MV grade compound residue from the crosshead. These process disciplines, applied specifically ahead of HV campaigns, suppress the four most common void and contamination formation mechanisms simultaneously. This is consistent with the voltage band defect mode comparison in Section 4.4.1, which shows the same pattern directly in the percentage point shares.

Improvement between 2025 and 2026. The 8.7/15 kV class improved from 15.54 % to 13.30 %, driven primarily by EP08’s maintenance and partially offset by EP23’s persistent filtration degradation at the same voltage rating. The 12/20 kV class improved from 31.54 % to 23.00 %, driven by EP102, the dominant producer of that class (RR = 0.656), with a secondary contribution from EP08. Several small volume classes (19/33 kV, 35 kV, 26/45 kV) show extreme 2026 rates that carry no statistical weight: a production run of 3,450 to 5,763 m means that any single reel rejection produces a rate above 50 %.

Figure 4.7 and 4.8 complement the within class internal rates of Figure 4.6 by placing each voltage class’s contribution in a plant wide context: the Figure 4.8 reports each class’s share of total plant production metres, while the Figure 4.7 reports its share of total plant defect metres. For every voltage class shown, the defect metre share substantially exceeds the production metre share, confirming that the four primary extrusion lines are jointly responsible for a disproportionate fraction of the plant’s defective output relative to the volume they produce.

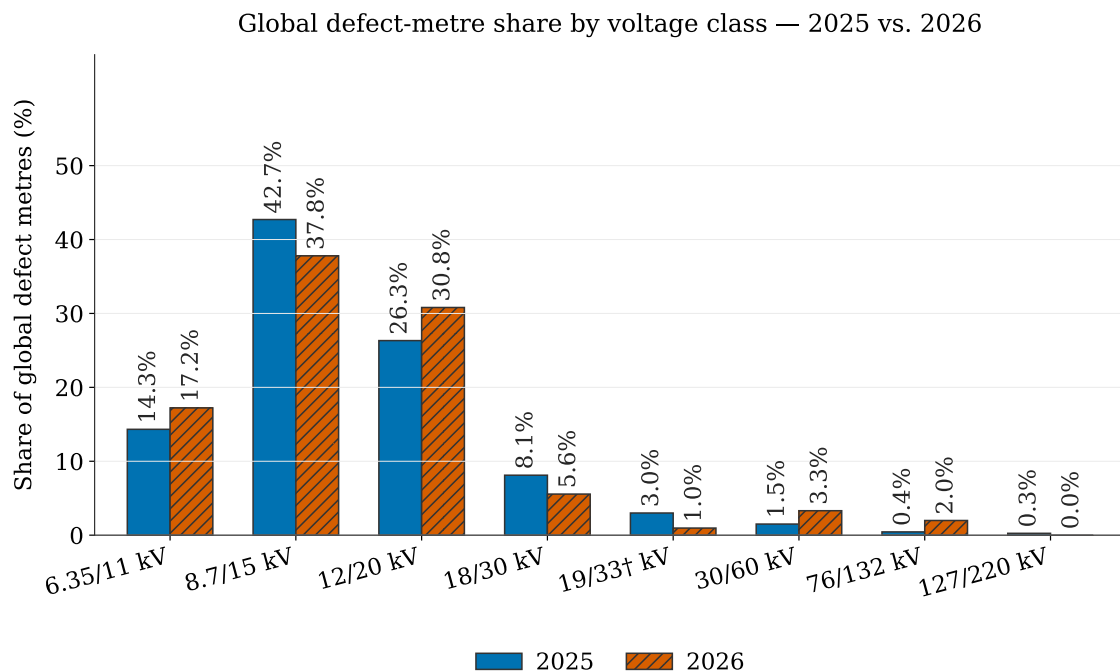


Figure 4.7: Defect rate (% of metres produced at each voltage level) for EP100, EP23, EP08, and EP102, compared to total meters with defect and total meters produced.

The two highest volume classes, 8.7/15,kV and 12/20,kV, dominate both panels in both years, together accounting for the majority of this group’s production and defect metres — the metre weighted confirmation of the EP23/EP08 and EP102 dominance established in the machine voltage attribution discussed below. Between 2025 and 2026, however, the two classes diverge. 8.7/15,kV’s defect metre share fell from 42.7% to 37.8%, tracking its declining production share (7.8% to 5.3,%) and consistent with EP08’s maintenance driven improvement. 12/20,kV’s defect metre share instead rose, from 26.3% to 30.8%, even as its production share fell slightly (4.8% to 4.3%) —

indicating that EP102 remains the single largest contributor to the plant's defect metre total, and proportionally more so in 2026 than in 2025, despite the modest improvement already noted in EP102's own internal rate.

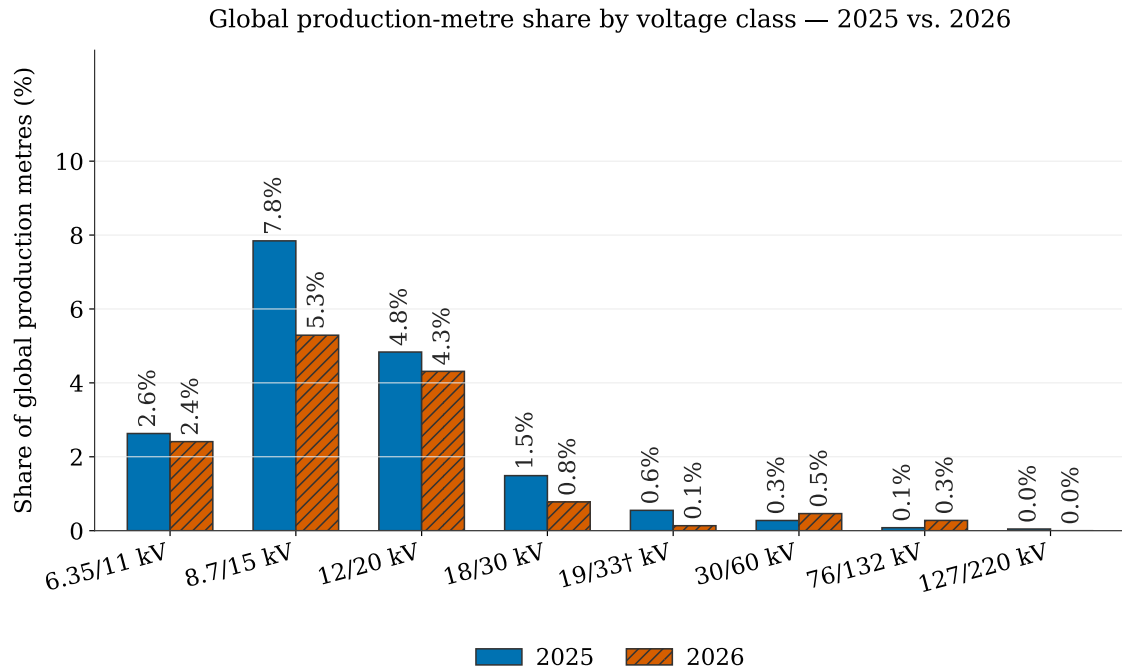


Figure 4.8: Defect rate (% of metres produced at each voltage level) for EP100, EP23, EP08, and EP102, compared to total meters with defect and total meters produced.

18/30,kV and 19/33,kV both show a marked decline in defect metre share (8.1% to 5.6%, and 3.0% to 1.0% respectively), consistent with the EP100 improvement already linked to these upper MV ratings. At the opposite end of the distribution, the HV adjacent classes 30/60,kV and 76/132,kV both show a rise in defect metre share between the two periods (1.5% to 3.3%, and 0.4% to 2.0% respectively) despite their minimal production volume. While the absolute metres involved remain small, this upward trend is consistent with the emerging HV reel handling concern identified in Phases 5 and 6, and supports treating HV quality as an area requiring continued monitoring rather than one that can be assumed safe on the strength of its low internal rate alone.

4.4.2 Machine Voltage Attribution

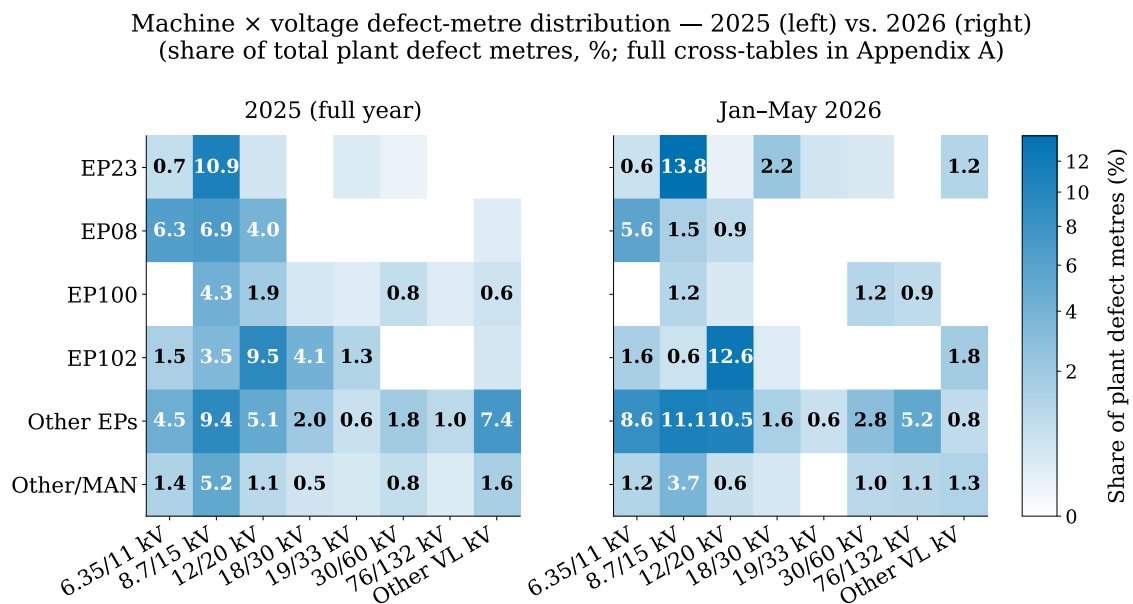


Figure 4.9: Machine × voltage defect metre heat maps — share of total plant defect metres (%). Left: 2025 (full year); right: Jan–May 2026. Cell colour scales with share; white = zero. Full cross tables in Tables A.18 and A.20, Appendix A.

The heat maps (Figure 4.9) render the machine product pairing directly visible. Each machine displays a characteristic column profile reflecting its campaign assignment: EP23 and EP08 dominate the 8.7/15 kV column, EP102 dominates 12/20 kV, and EP100’s contribution is concentrated at the HV ratings (30/60 kV, 76/132 kV, 127/220 kV), consistent with its role as the plant’s predominant HV producer.

This structure indicates why the voltage class rates in Figure 4.6 are substantially driven by machine process states rather than product specifications. The 8.7/15 kV internal rate is partly inherent (wall thickness and CV tube conditioning requirements) and partly a function of EP23’s filtration condition and EP08’s die wear. When EP08 improved between 2025 and 2026, the 8.7/15 kV internal rate improved correspondingly, not because the cable specification changed but because the primary machine producing that class improved. The heat map renders this coupling explicit: the 2026 right panel shows EP08’s 8.7/15 kV cell decreasing from 6.87 pp to 1.51 pp, while EP23’s cell at the same voltage grew from 10.92 pp to 13.77 pp. The class’s net improvement is therefore EP08’s gain partially offset by EP23’s persistent possible filtration degradation.

Two structural changes from 2025 to 2026 are evident in the right panel. First, EP23 acquires a new 18/30 kV cell (2.24 pp, absent in 2025): EP23 ran its first 18/30 kV campaign under conditions where its contamination problem was already established, producing a defect rate at that voltage consistent with its general NCF trajectory. Second, the Other EPs row at 8.7/15 kV and 12/20 kV expanded substantially, driven by EP101 and EP05 taking on additional production volume at those classes.

4.4.3 Defect Category Voltage Attribution

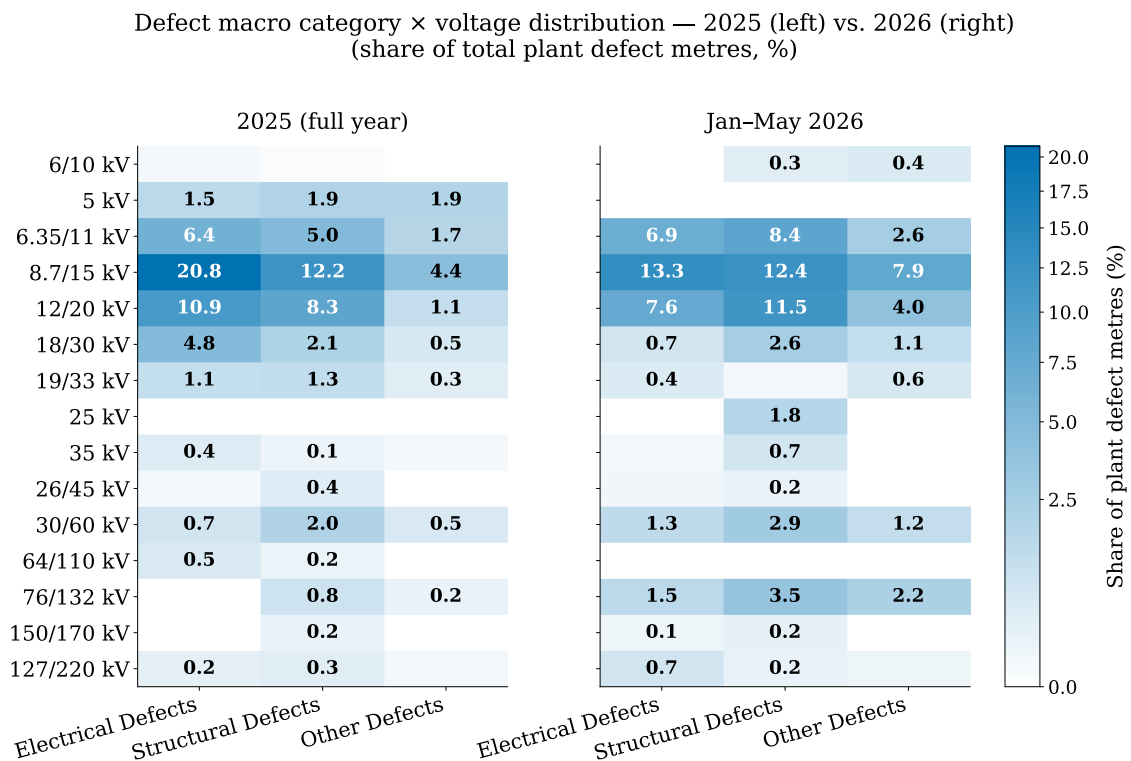


Figure 4.10: Defect category × voltage heat maps — share of total plant defect metres (%), by macro category (Electrical, Structural, Other). Left: 2025 (full year); right: Jan–May 2026. Cell colour scales with share; white = zero. Full cross tables in Tables A.22 and A.24, Appendix A.

Where Figure 4.9 cross tabulates machine against voltage class, Figure 4.10 cross tabulates the three macro defect categories (Electrical, Structural, Other) against voltage class, revealing which type of failure dominates each rating rather than which machine produces it.

In 2025, Electrical defects are overwhelmingly concentrated at 8.7/15 kV (20.82 pp of all plant defect metres) and, to a lesser extent, 12/20 kV (10.85 pp) are together the two largest cells in the entire matrix, and a direct echo of Figure 4.9, where EP23, EP08, and EP102 dominate exactly these same two voltage classes. By Jan–May 2026, the 8.7/15 kV Electrical cell fell to 13.31 pp and the 12/20 kV cell fell to 7.58 pp, the metre level signature of the EP08 maintenance intervention already identified in Sections 4.2 and 4.4.

Structural defects show the opposite trajectory across almost every voltage class. At 6.35/11 kV, the Structural share rose from 4.96 pp to 8.40 pp; at 12/20 kV it rose from 8.26 pp to 11.47 pp; and at 18/30 kV it rose from 2.10 pp to 2.61 pp. This is the metre weighted confirmation of the machine level finding that EP101 and EP05 absorbed additional production volume across multiple voltage, and that this volume carried with it a structural, rather than electrical, failure signature.

The 76/132 kV column is the clearest illustration of the HV reel handling concern raised in Section 4.4: every category at this rating grew between the two periods (Electrical 0.00 pp → 1.49 pp;

Structural 0.79 pp → 3.54 pp; Other 0.17 pp → 2.21 pp), with the Structural and Other cells growing fastest. Because the Electrical share at 76/132 kV remains the smallest of the three even after the increase, this confirms that the deterioration at this rating is predominantly mechanical (reel handling and sheath damage) rather than a degradation in dielectric performance, consistent with the absence of any partial discharge flagged test at the 76/132 kV rating reported in Section 4.11.

4.5 Phase 4 — Root Cause Analysis and Critical Defect Identification

Table 4.1: Root cause analysis and NCF evolution across extrusion lines (2025 vs. Jan–May 2026).

Machine	NCF 2025 (%)	NCF 2026 (%)	Primary defect types	Root causes	Voltage
EP102	29.107	19.107	Dielectric strength; PD	Die head wear; moisture ingress from emulsion based wire drawing lubricant; insulation thickness changeover re tuning	MV
EP08	24.651	10.997	Dielectric strength; constructive aspects; PD	Cooling rate inconsistency; crosshead alignment drift; conductor pre heat deficit; insulation thickness changeover re tuning	MV
EP05	6.015	10.693	Sheath appearance; PD	Jacketing die wear; cooling trough thermal instability	MV
EP101	12.004	19.625	Sheath appearance; structural aspects; PD	Outer sheath protrusions; worn Al/PE tape winding guides	MV/HV
EP23	11.108	15.241	Dielectric strength	Compound filtration bypass; ambient contamination (clean-room breach)	MV/HV
EP100	12.651	8.706	PD; Dielectric strength	Melt temperature variation; CCV tube temperature gradient across thick insulation wall; crosshead pressure oscillation	HV/MV

The root causes in Tables 4.1 fall into five mechanistic families, each producing a distinct defect signature in the QMS record.

Process parameter variation. EP08 and EP100 exhibit defects traceable to continuous state process deviations: temperatures, line speeds, or pressures that depart from their set points and subsequently drift back gradually. The distinguishing feature is that these defects tend to cluster at the start of production runs (extruder warm up) and become less frequent as the run reaches steady state, a spatial pattern confirmed in Phase 5's cable position analysis. EP08's crosshead misalignment produced eccentricity that varied with die pressure; EP100's melt temperature variation created radial cross linking gradients in its peroxide cured CCV tube. EP05 exhibits thermal drift in the jacketing die and cooling trough. All three machines responded well to maintenance because the underlying mechanism in each case (drift from set point) could be corrected by mechanical service and recalibration.

Progressive tooling degradation. EP102 and EP08 share a die wear mechanism, consistent with their being the same type of asset. Die wear is a cumulative process: as the die lip gradually erodes, the melt flow front becomes increasingly irregular, and the frequency of semiconductor protrusion events increases monotonically [58]. Therefore, NCF rises progressively between maintenance interventions and falls sharply after each die replacement, a sawtooth pattern predictable from wear rates. EP102's higher NCF relative to EP08 reflects either a more aggressive wear regime (higher throughput, harder compound, greater product mix variability) or a longer interval since its last die replacement.

Material contamination. EP23 and EP102 both exhibit contamination driven defects whose character is episodic rather than gradual: a filtration bypass event or compound changeover residue introduces a batch of contaminated insulation into production [60], which can occur at any point in a campaign. The QMS description database confirms this: the "scorched/carbonaceous appearance" theme accounts for approximately a third of the records flagged across these five themes, concentrated on EP102 and EP23 (Table 4.3), with their temporal distribution showing no relationship to campaign start or end. This family is the most difficult to detect, because the defects are not visible to the operator until electrical testing, and the severity of each contamination event depends on particle size and concentration.

The cross contamination risk merits particular attention. Standard MV formulations are processed under less stringent purity controls than HV compounds. Any residual MV insulation material left in the extruder crosshead cavity during a campaign transition to HV introduces conducting or non conducting inclusions into the new insulation layer. Even a small quantity of MV compound residue, blended into the first metres of an HV run, can produce several thousand metres of cable with elevated inclusion content, all of which must be scrapped once the electrical test results are obtained. Measure II (Section 4.10) directly addresses this by mandating a full reel purge and engineer sign off at every MV to HV changeover, applying to EP100.

Cure chemistry vulnerability. The plant's two insulation extrusion architectures use different cure chemistries with different sensitivities. EP102 and EP08, the horizontal CV lines, cure via a silane condensation reaction at 170–180 °C. EP23 and EP100, the catenary (CCV) lines, cure via a peroxide initiated reaction at approximately 120 °C [5, 55]. The lower CCV temperature reduces the cross linking reaction rate: a CCV cable requires a proportionally longer residence time in the curing zone to reach the same degree of cure as a silane cured CV cable. If production scheduling shortens this residence time on EP23 or EP100, the insulation exits the curing zone partially cured, with amorphous polymer regions of lower dielectric strength that increase the probability of defect formation. This is a distinct vulnerability from the die wear and product variety mechanisms that dominate EP102 and EP08: it is a cure chemistry risk specific to the slower peroxide reaction, rather than a tooling risk. The heating chambers in which any subsequent thermal conditioning of the insulation occurs downstream of the CV/CCV tube constitute separate equipment and fall outside the scope of this study; process condition data for those stages are therefore not available for direct analysis.

Conductor moisture ingress. Related to the extrusion architecture differences described above, a fifth mechanism affects cables across all voltage levels: moisture left by the emulsion used during conductor drawing on the copper/aluminium core. On cables passing through EP102 and EP08 — horizontal lines that operate at a higher process temperature — water trapped in the interstices of the conductor strands evaporates into steam, which then migrates into the semiconductor or insulation layer. This produces voids within the insulation (a source of internal partial discharge) and protrusions in the semiconductor layer (a source of surface partial discharge). Where the trapped water does not evaporate, it can instead lead to oxidation of the conductor.

4.6 Phase 5 — Temporal Comparison and PD Risk Defect Identification

Because standardised database codes inevitably flatten some nuance, a structured text mining script was run across every free text description field in the QMS, identifying physical indicators of structural anomalies, parameter drift, or partial discharge risk not captured by the coded categories alone (Table 4.3).

Table 4.3: Critical description themes identified in the MV/HV defect database.

Description theme	Top machines	Criticality indicator	PD risk criterion
<i>“Along the entire length / throughout the reel”</i>	EP05, EP101, EP23	Full reel systematic failure; chronic, non transient process condition (worn tooling, contaminated compound batch, continuous filtration inadequacy)	(a), (c)
<i>Wrinkled / creased Al/PE tape</i>	EP101	Al/PE tape wrinkle creates a capacitively charged gap; concentration on EP101 links to worn tape winding guides	(f)
<i>Roughness / screen like appearance on semiconductor</i>	EP102, EP23, EP101	Irregular semiconductor surface raises tangential field component; primary mechanism for surface discharge PRPD patterns (Cases 5 to 7, Section 4.8.3)	(b), (e)
<i>“Permanent indentation”</i>	EP05, EP101	Flat spot at HV ratings creates localised wall thinning; associated with caterpillar wear documented in Measure V	(d)
<i>Scorched material / carbonaceous appearance</i>	EP102, EP23	Carbonaceous residue in insulation bulk; scorch or contamination from preceding compound campaign	(c)

The script searched for specific terminology: phrases indicating that a fault ran the length of the reel, comments referring to the semiconductor boundary zones, descriptions of surface roughness, mentions of scorching or carbonaceous contamination, and language matching the six partial discharge risk criteria. Matching records were extracted and tabulated alongside their machine attribution and the corresponding risk criterion.

Phase 5 applies a quantitative comparison to the question raised qualitatively by Phases 1 to 4: how large were the changes between 2025 and 2026? The comparison is made using the rate ratio (RR, Section 3.9.3) to express the size and direction of each change on a consistent scale. Because the RR operates inherently on rates, a category, machine, or voltage class that simply ran more or less volume in one period is not mistaken for one whose underlying defect generation rate genuinely changed.

4.6.1 Defect Category Shifts

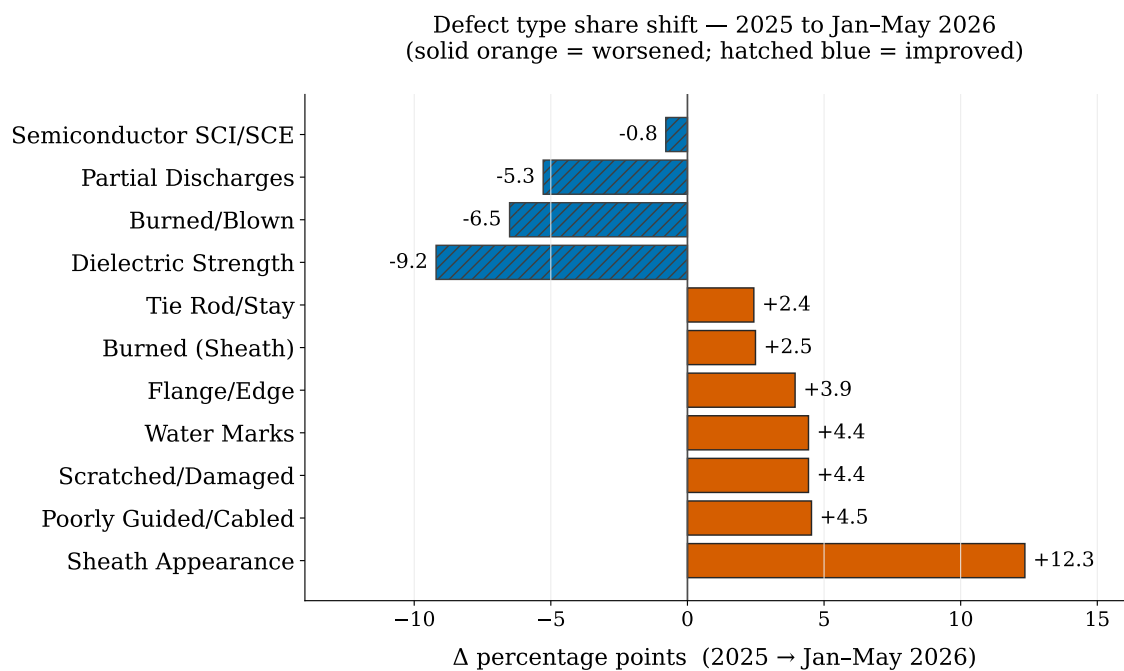


Figure 4.11: Defect type percentage point change — 2025 to Jan–May 2026. Categories sorted by absolute magnitude of change. Full share table in Table A.26, Appendix A.

Figure 4.11 converts the Phase 2 directional findings into measured magnitudes for the 2025 vs 2026 comparison. The three electrical categories (Dielectric Strength -9.2 pp, Burned/Blown -6.5 pp, Partial Discharges -5.3 pp) account for the largest improvements. Among the categories that worsened, Sheath Appearance ($+12.4$ pp) substantially exceeds all others, followed by Poorly Guided/Cabled ($+4.5$ pp), Flange/Edge ($+3.9$ pp), and Scratched/Damaged ($+4.4$ pp).

The 12.4 percentage point increase in Sheath Appearance. This figure represents EP101’s and EP05’s combined contribution to the 2026 reporting period. Both machines had already begun their deterioration trajectory within the 2025 window, but by January May 2026 had accumulated 8 18 additional months of unremediated die and guide wear. In addition, EP101 absorbed additional production volume as more cable passing through a deteriorating winding guide mechanism produces more sheath wrinkle events.

The emergence of Water Marks from a near zero baseline. Water Marks occur when the cooling trough delivers water that is significantly colder than the freshly extruded jacket compound. The thermal shock causes localised surface stress marking without dimensional change. The mechanism’s emergence in 2026 traces to EP05’s MV production runs, which experienced overcooling in the cooling process.

4.6.2 Machine Distribution Shift

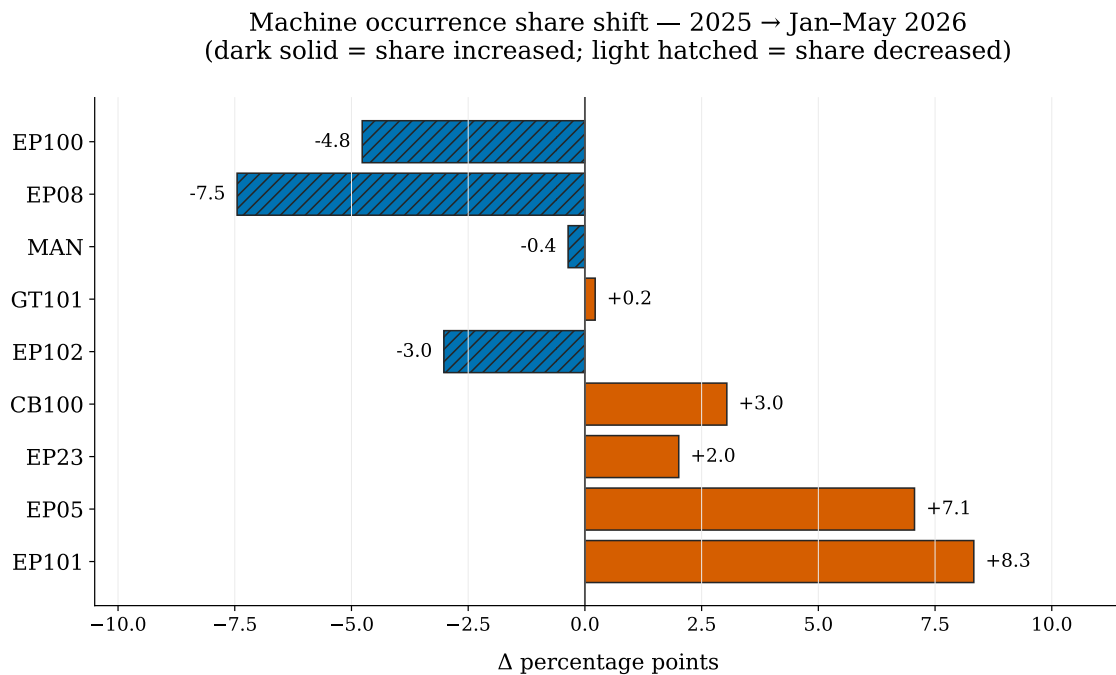


Figure 4.12: Machine occurrence share shift (2025 vs. Jan–May 2026), with Δ pp labels. Machines with $|\Delta| < 0.5$ pp omitted for clarity; full table in Table A.28, Appendix A.

Figure 4.12 presents the redistribution of the defect burden across the fleet. EP101's increase (+8.3 pp) and EP05's increase (+7.1 pp) track the same direction as their rate ratios above, as do EP08's decrease (−7.5 pp) and EP100's decrease (−4.8 pp). The plant level stability (total records broadly flat between the two windows) masks this internal restructuring.

CB100's emergence from near zero to 3.10% (+3.0,pp) reflects a different mechanism: CB100 was brought into heavy use for a new 76/132,kV cabling campaign in early 2026. This sudden increase in usage typically produces above-average sheath and scratch defects, since guide surfaces that have sat idle accumulate contamination and require a running in period. CB100's defect profile (Sheath Appearance 91.3 %, Scratched/Damaged 91.3 %) is consistent with this explanation; the defect types are mechanical and surface related, with no electrical failures observed. CB100's inclusion in the monitoring matrix (Track B, Section 4.10) ensures the rate is tracked through its settling period.

4.6.3 Voltage Class Redistribution

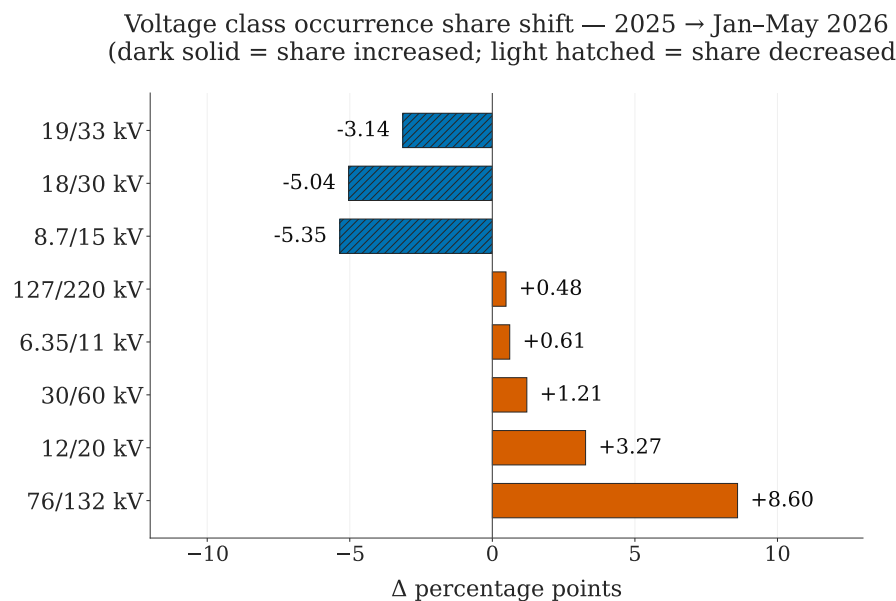


Figure 4.13: Voltage class occurrence share shift (Δ pp) — 2025 vs Jan May 2026. Full table in Table A.31, Appendix A

The most structurally significant shift (Figure 4.13) is the rise of the 76/132 kV class from 3.0 % to 11.59 % of the occurrence share (+8.6 pp). The composition of those 2026 HV records is informative: Sheath Appearance (30.6 %), Poorly Guided/Cabled (17.1 %), and Scratched/Damaged are the dominant types, while Dielectric Strength accounts for only 10.6 %.

The 76/132 kV class surge originates not from insulation quality degradation but from a production volume increase at that rating driven by new customer orders. More 76/132 kV reels produce more opportunities for mechanical non conformances, including sheath marking, reel handling damage, and tape anomalies, which accompany the handling of the heaviest reels in the plant. The 76/132 kV defect profile is dominated by post extrusion events, consistent with GT101 and reel transfer. This finding is significant for prioritisation: HV electrical quality is not deteriorating; the reel infrastructure handling HV products has not kept pace with production volume.

The 8.7/15 kV and 18/30 kV classes declined (−5.4 pp and −5.0 pp respectively), consistent with the documented improvement of EP08 and EP100 on the machines that dominate those ratings.

Read as a set, these ratios separate cleanly into two groups. Dielectric Strength (RR = 0.623), Burned/Blown (RR = 0.668), Partial Discharges (RR = 0.739), Semiconductor SCI/SCE (RR = 0.764), EP08, and EP100 all show a clear, substantial reduction (RR well below 1), and each is directly traceable to the documented end of 2025 maintenance interventions on EP08 and EP100 described above the magnitude of the change and the mechanistic explanation point the same direction, which is the basis for treating these as genuine improvements rather than incidental fluctuation. Sheath Appearance (RR = 1.457) and EP05 show an equally clear increase, again

with a specific, independently documented mechanism (worn winding guides, absorbed production volume).

EP101's description-mining RR of 1.490 drawn from the free text keyword analysis, rather than the metres based NCF used in Phases 1 and 4, which points in the same direction and now sits close in magnitude to the metres based RR of 1.635 reported there, offering independent corroboration from a second data source rather than a repeat of the same measurement. The sheath related deterioration on EP101 is consistent with a genuine process trend, and the mechanistic explanation (worn tape winding guides, absorbing additional volume as EP08 cleared its backlog) accounts for the magnitude of the effect, which is now broadly comparable to the step changes observed on the lines that had already received tooling overhauls.

EP102 is a machine where the two evidence sources agree on direction but differ in magnitude: the metres based NCF shows a substantial improvement (RR = 0.656, Phase 1), while the description mining RR shows a more modest improvement (RR = 0.834). Since the metres based figure reflects the physical volume of defective product while the description mining figure reflects how often a PD risk keyword pattern is flagged per production record, this gap suggests that EP102's 2026 defects are markedly fewer in total length, but the remaining defects are still flagged with a PD risk linguistic signature close to their previous rate, consistent with a smaller number of residual, persistent issues rather than a uniform improvement across all defect types. This is consistent with the emulsion moisture and die wear mechanisms identified in Section 4.5: even as the most severe protrusion events are eliminated by partial die replacement, occasional moisture related micro voids and minor semiconductor interface irregularities continue to be logged at a similar rate.

4.7 Phase 6 — Partial Discharge Intensity Analysis

4.7.1 Defect Position Along the Production Reel

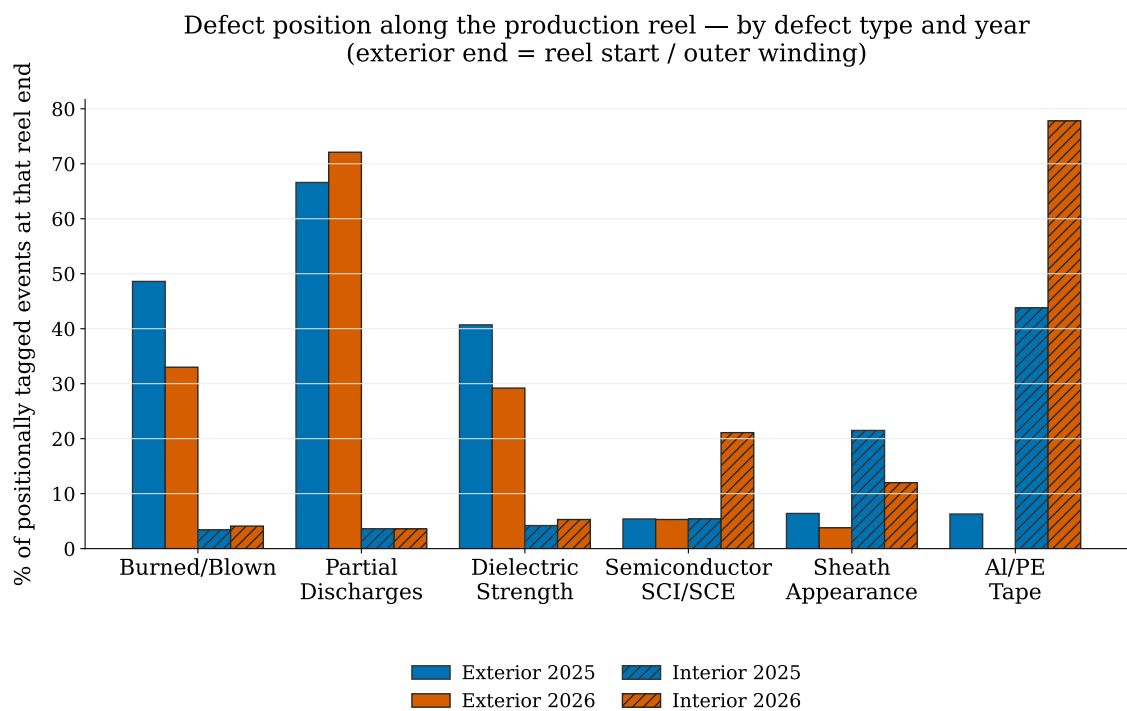


Figure 4.14: Cable position of defect occurrence — exterior end % (outer reel end, wound last) vs. interior end % (inner reel end, wound first), by defect type and year. Bars above the centreline: predominantly exterior. Bars below: predominantly interior. Full table in Table A.34, Appendix A.

Figure 4.14 encodes a dimension of defect formation that occurrence counts alone cannot supply: the location along the reel at which the defect forms. This constitutes a spatial fingerprint of the formation mechanism. This spatial dimension is placed first in this phase because it directly conditions how the apparent charge severity results below should be read: a defect's position along the reel reflects when, during the run, the discharge causing flaw formed, while its apparent charge (discussed next) reflects how energetically it discharges once formed.

The exterior reel end corresponds to the start of the production run, the first metres wound onto the drum. Three concurrent mechanisms generate peak defect risk at the beginning of the run:

1. The extrusion die body retains thermal inertia even after the extruder reaches its set point temperature; during the first 200 to 500 m, radial temperature gradients across the die generate non uniform melt viscosity and irregular semiconductor XLPE boundary geometry;
2. The crosshead cavity contains residual compound from the previous campaign batch, which blends into the first metres of the new run, producing a transition zone with unpredictable electrical properties;

3. The extruder screw speed regulator, melt pressure feedback, and line speed control loops overshoot and undershoot around their set points until the run stabilises, creating periodic die pressure oscillations that produce protrusion events.

All three mechanisms concentrate defect formation at the start of the reel and diminish as the run reaches steady state. The slight increase in PD median distance from reel start (502 m → 600 m in 2026) is consistent with improved start up purge protocols extending the clean running transition.

The interior reel end is wound first, ending on the inside of the full reel. As cable accumulates on the drum, the layers already wound bear the weight of all subsequent layers. At 76/132 kV reel weights, the compressive loading on the inner layers is substantial. The outer jacket, still at slightly elevated temperature from the cooling trough, deforms slightly under this load, creating the permanent indentations, flat spots, and tape wrinkles characteristic of the “interior biased” defect types. The Al/PE tape pattern (43.8 % interior in 2025, 77.8 % in 2026) is particularly notable: the tape’s metallic foil has no elastic recovery and retains any deformation sustained while warm. Reel weight management, limiting take up speed as the reel approaches its weight limit, directly addresses this mechanism.

4.7.2 Partial Discharge Intensity

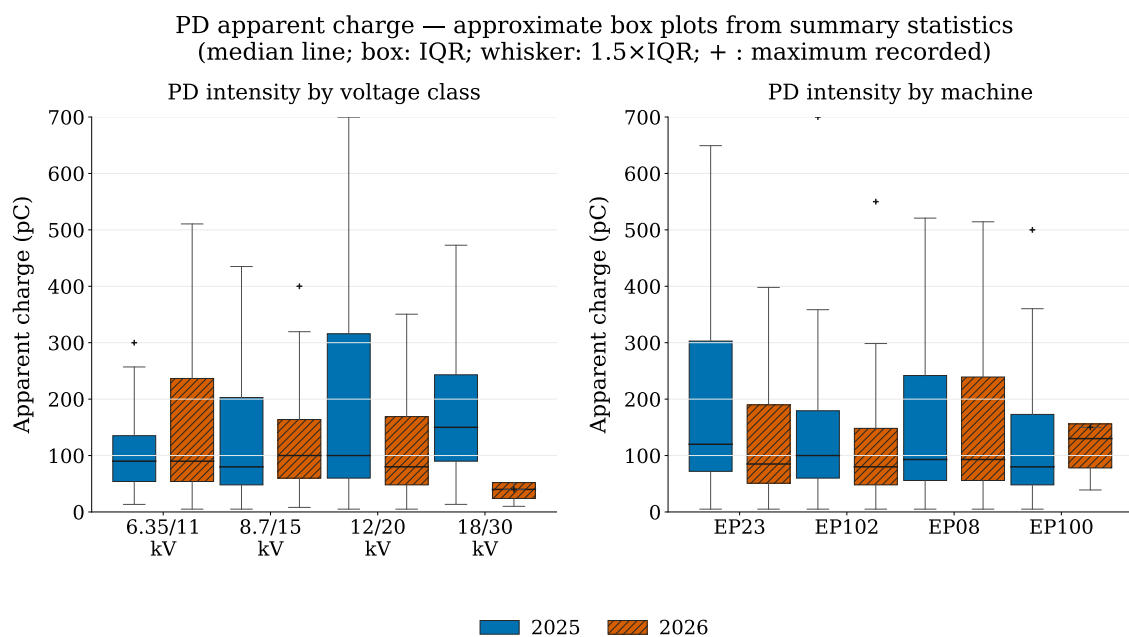


Figure 4.15: PD apparent charge distribution — 2025 vs. 2026. Left: by voltage class. Right: by primary extrusion machine. Box: IQR; whisker: $1.5 \times \text{IQR}$; dots: outliers. Full statistics in Tables A.36 and A.37, Appendix A.

The box plots (Figure 4.15) add a severity dimension that occurrence counts cannot provide: when a PD event occurs, its energetic magnitude.

The combined frequency and charge improvement of the 12/20 kV class. Both EP08 and EP100 dominate 12/20 kV production. Their maintenance reduced the frequency of defect forming events (reflected in the lower NCF rates of Phase 1) and also reduced the severity of each event by eliminating the most severe die wear protrusions. This accounts for the decline in both the median pC and the proportion exceeding 200 pC for this class.

EP08’s retention of the highest mean charge in 2026 (184 pC) despite improved NCF. In addition, the compound filtration upgrade on EP08 (part of Measure VII, Section 4.10.1) had not yet been fully deployed at the time of the 2026 data collection. The practical consequence is that maintenance reduced defect frequency (NCF) substantially, as the replacement die eliminated the highest frequency large protrusions, but has not yet reduced defect severity (mean pC) to the same degree, because the contamination and filtration conditions that determine event energy had not yet been fully addressed.

The worsening of charge in the 6.35/11 kV class (mean 104 → 182 pC). The primary contributor to the 6.35/11 kV class changed between the two periods: the “Other EPs” group (EP101, EP05) increased its share of 6.35/11 kV production as EP08’s schedule opened up. These machines generate sheath type defects rather than void type defects, but when they do produce electrical events, their compound batch quality is less tightly controlled than that of the primary extrusion machines, resulting in larger contamination inclusions and higher apparent charge when PD does occur.

Extending the analysis to the full 17 month tracking window enables an examination of the severity of partial discharge events when they occur, rather than a count of their occurrence alone. The proportion of records containing parseable apparent charge data increased between the two periods, from 8.4 % to 12.7 %. This shift does not indicate a sudden increase in insulation damage; rather, it reflects improved shop floor discipline, as testing operators became more diligent in recording exact pC values in the quality management system.

Table 4.5: Partial Discharge (PD) intensity summary analysis by cable position (2025 vs. 2026).

Position	2025				2026				Trend
	Mean (pC)	Med. (pC)	Max (pC)	% >200	Mean (pC)	Med. (pC)	Max (pC)	% >200	
Outer end	148	90	800	17.0	144	85	900	14.5	↓
No reference	284	120	2000	22.2	138	83	500	13.6	↓

A notable pattern emerges from Panel C. Records that lack a physical position reference consistently display the highest mean charge values (284 pC in 2025). This indicates a systematic bias in the logging procedure: when a cable under test exhibits intense, critical discharge activity, testing operators bypass standardised logging steps in order to escalate the failure immediately to a senior quality engineer. Consequently, the test entry is locked and archived before the exact

spatial coordinates can be documented. Standardising real time positional logging (Measure 7) is necessary to eliminate this information loss and clarify the true spatial distribution of severe discharges.

4.8 Phase 7 — PRPD Analysis and Pattern Recognition

To examine the underlying physics of these insulation failures, phase resolved partial discharge (PRPD) wave patterns were examined across a sequence of factory acceptance tests. Surface type discharge signatures, which are typically associated with jointing workmanship issues on active networks, must instead be interpreted here as structural layer imperfections embedded directly within the cable body, specifically along the boundaries separating the extruded semiconductor screens from the core XLPE matrix.

The cable tests presented in this chapter are all HV cables. MV cable acceptance tests are not presented here because the PD measurement software used on the MV test bay does not generate the phase resolved PRPD waveform plot used throughout this section; it reports only the integrated apparent charge value, not its phase angle distribution. The HV test bay's PD instrumentation produces the full waveform, which is why the PRPD case studies below are drawn exclusively from HV cable acceptance tests.

By relating these wave distributions to the previously established risk categories (Section 4.6) and severity trends (Section 4.7), individual electrical fingerprints are sorted into four operational groups: internal polymer voids, external laboratory corona, semiconductor boundary tracking, and factory wide electronic switching noise.

4.8.1 Reference Case: Healthy Cable — Background Noise

4.8.1.1 Case 1 — Approved: No Partial Discharge Activity

Table 4.6: Electrical Insulation and Partial Discharge Test Parameters Summary

Parameter Group	Specifications and Test Values
Test Reference	Ens_AT\OF_787572\2502-75_191218_101744
Cable Class	36 kV XLPE, $U_0 = 36$ kV
Test Conditions	54.28 kV RMS ($1.5 \times U_0$), 36 min duration (stable)
Standard	IEC 60840
PD Metric (Q_{IEC})	960.3 fC (0.96 pC)
PD Pulse Rate	0 pulses/s
Noise Pattern	Uniform background noise
VERDICT	APPROVED : No PD activity detected

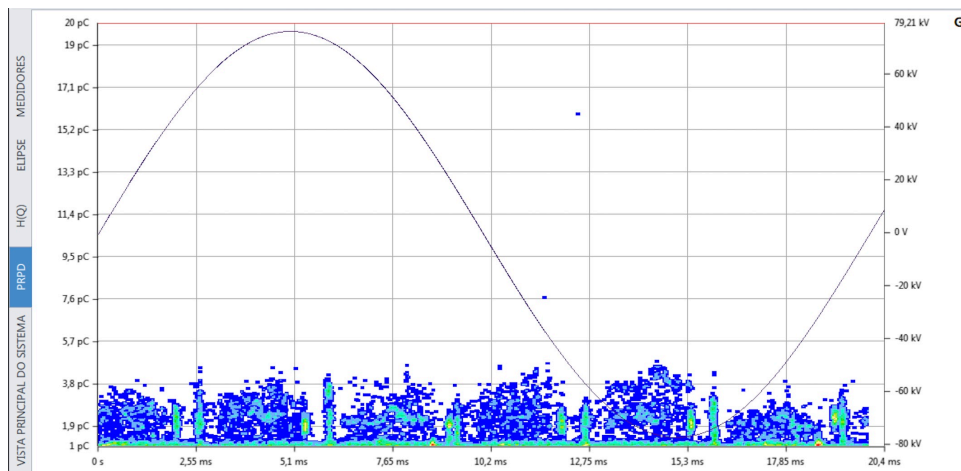


Figure 4.16: PRPD plot: healthy 36 kV cable, APPROVED.

The baseline trace shows a clean profile across the entire phase cycle. The recorded signal points scatter uniformly across the 20.4 ms power cycle with no tracking relationship to the voltage sinusoid, characteristic of basic instrumental noise. The calculated apparent charge (0.96 pC) remains well within the 10 pC acceptance threshold defined by industry testing standards. The isolated discharge burst at the end of the timeline is a normal instrumental transient produced by the opening of the high voltage circuit breaker.

4.8.2 Internal Void Discharges (PD Risk Criterion a)

Internal void defects arise from entrapped gas pockets within the main cross linked polyethylene insulation bulk. These form when volatile cross linking by products cannot escape, during localised thermal contraction under irregular water trough cooling, or as a result of rapid extrusion melt pressure drops.

4.8.2.1 Case 2 — Internal Void: Early Stage (6 pC, initial ionisation)

Table 4.7: Electrical Insulation and Partial Discharge Test Parameters Summary

Parameter Group	Specifications and Test Values
Test Reference	895222-1-L326F-21_240211_081838
Cable Class	76 kV XLPE, $U_0 = 76$ kV
Test Conditions	107.4 kV (PDIV); peak reached 126.7 kV
Standard	IEC 60840
PD Metric (Q_{IEC})	6.083 pC (Accept. limit: 10 pC)
PD Inception (PDIV)	107.4 kV
PD Pulse Rate	1.124 pulses/s
Noise Pattern	Bilateral symmetric cloud with rising edges
VERDICT	REPROVED : PD inception below normative threshold

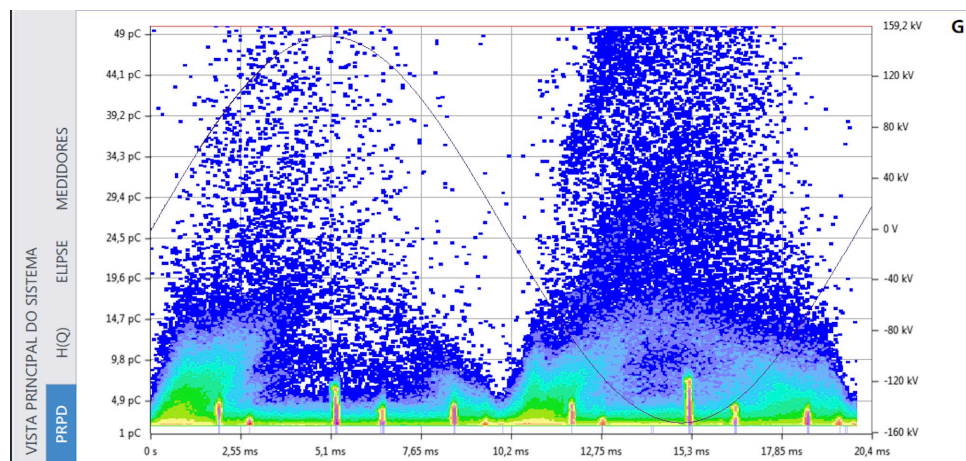


Figure 4.17: PRPD plot: internal void discharge, early stage

This pattern displays two distinct, highly symmetrical, rounded pulse clusters aligned with the rising quadrants of both half cycles, the characteristic "rabbit ear" signature of localised internal gas gap breakdown [10, 42]. The clear positive to negative symmetry indicates that the void is nested symmetrically within the polymer bulk, isolated from either screen interface. Although the total charge magnitude (6.083 pC) nominally satisfies the baseline 10 pC threshold, the cable is classified as REPROVED, because the discharge inception voltage (PDIV) occurs at 107.4 kV, below the normative insulation safety margins. This represents an unacceptable long term breakdown risk under operational switching transients.

This bulk void pattern provides direct spatial confirmation of the volatile cross linking by product trapping (melt temperature variation and a CCV tube temperature gradient across the thick

HV insulation wall) identified during the Phase 4 review of line EP100, the plant’s predominant HV producer.

4.8.3 Surface and Interface Discharges at the Semiconductor Screen

Pulse activity the post peak phase angles indicates electron tracking directly along the internal interface layers [63]. Three distinct tooling errors can produce this structural condition:

- 1. **Semiconductor screen protrusions (criterion b):** Worn semiconductive compound bleeds outward, introducing irregular, conductive micro needles into the main polymer [58]. This distorts the local electric field and delays the discharge timing, shifting the pulse clusters past the voltage peaks.
- 2. **Layer boundary delamination (criteria a and e):** Microscopic separation gaps along the extruded boundary layer, caused by rapid crosshead thermal contraction or shear stresses, initiate surface type carbon tracking.
- 3. **Screen surface roughness (criterion e):** Structural imperfections along the semiconductive screen alter local electric field profiles, initiating interface tracking prior to bulk breakdown.

Correcting these issues requires mechanical intervention: crosshead concentricity must be restored, extrusion melt temperatures stabilised, and worn die heads replaced on the responsible asset.

4.8.3.1 Case 3 — Surface Discharge: Early Stage (3.5 pC, onset at 28 min)

Table 4.8: Electrical Insulation and Partial Discharge Test Parameters Summary

Parameter Group	Specifications and Test Values
Test Reference	2507-13_787572_200217_154956
Cable Class	36 kV, $U_0 = 36$ kV
Test Conditions	53.88 kV RMS ($1.5 \times U_0$), 40 min duration (Onset at ≈ 28 min)
PD Metric (Q_{IEC})	3.495 pC (Peak pulses: 20to 50 pC)
PD Inception/Extinction	PDIV: 54.47 kV PDEV: 54.04 kV
PD Pulse Rate	Elevated profile (accumulated)
Noise Pattern	Post peak bilateral clouds; 5.1 to 7.65 ms and 15.3 to 17.85 ms
VERDICT	REPROVED: Surface discharge, onset at 28 min

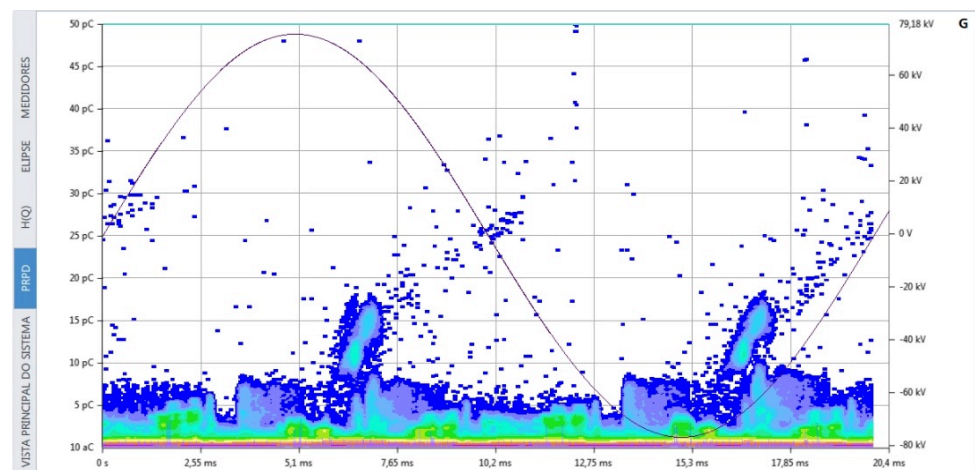


Figure 4.18: PRPD plot: cable surface discharge, early stage.

Here, the pulse clouds are visibly shifted along the phase axis into the declining voltage quadrants. This post peak displacement is the characteristic indicator of an interface tracking condition: the semi conductive layer boundary acts as a capacitive grid, retaining charge until a localised breakdown threshold is reached. The asymmetric cloud forms between 90° and 140° on the positive wave, mirrored between 270° and 320° . The defect remained undetected until 28 minutes into the test hold. This temporal delay indicates a significant vulnerability: sustained electrical stress drives localised thermal runaway around an extrusion defect, such that a shortened test profile would have failed to detect this latent structural flaw.

4.8.3.2 Case 4 — Surface Discharge: Severe Stage (9.942 pC, near dielectric collapse)

Table 4.9: Electrical Insulation and Partial Discharge Test Parameters Summary

Parameter Group	Specifications and Test Values
Test Reference	2506-30_787572_200218_125051
Cable Class	36 kV, $U_0 = 36$ kV
Test Conditions	54.46 kV RMS ($1.5 \times U_0$), >41 min duration
PD Metric (Q_{IEC})	9.942 pC (at 10 pC ceiling)
PD Pulse Rate	47,748 pulses/s
Trend Dynamics	Stable high level until 39 min; followed by exponential growth
Noise Pattern	Chaotic full cycle saturation; geometric definition lost
VERDICT	REPROVED CRITICAL : Dielectric collapse at 39 min; runaway

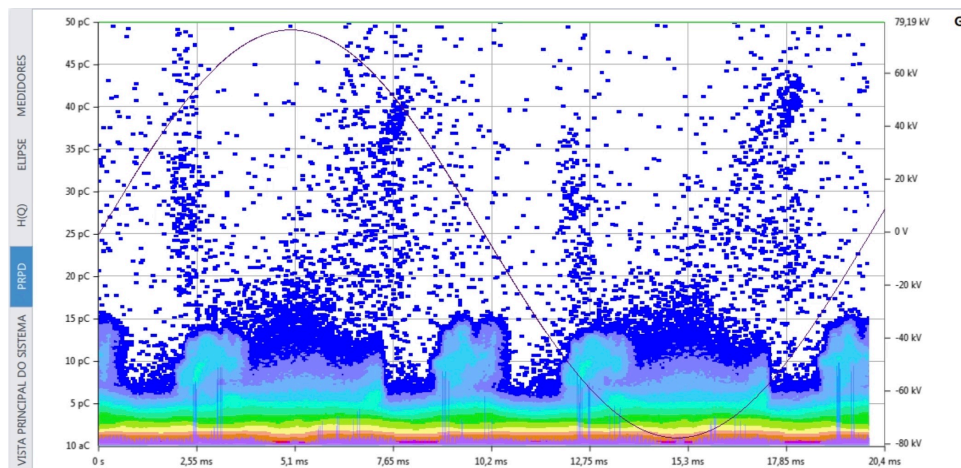


Figure 4.19: PRPD plot: cable surface discharge, severe stage.

In this case, the structured phase clouds have dissolved into a dense, chaotic scatter across the full 360° sinusoid, saturating the upper bounds of the instrumentation window. This loss of phase definition indicates that the internal semi conductive interface has carbonised thoroughly. The resulting conductive track permitted random, low energy arcing at any point in the voltage wave. The system recorded high, steady activity for 39 minutes before localised heat triggered an exponential increase in pulse rate. This reel section was entering structural thermal collapse and required immediate quarantine.

4.8.4 External Corona Discharges — Test Circuit Artefacts

Corona originates in the ambient laboratory air, occurring around sharp exposed metal clips or instrumentation leads rather than within the core insulation matrix. Correct identification of these signals is necessary to avoid the unwarranted rejection of sound production reels.

4.8.4.1 Case 5 — External Corona: Comb Pattern at Low U_0 Level

Table 4.10: Electrical Insulation and Partial Discharge Test Parameters Summary

Parameter Group	Specifications and Test Values
Test Reference	Ens_AT\OF_787572\2502-75_2_191218_120603
Cable Class	36 kV, $U_0 = 36$ kV
Test Conditions	63.12 kV RMS; PDIV triggered at 50.55 kV
PD Metric (Q_{IEC})	1.225 pC (Peak pulses: up to 19 pC)
PD Inception (PDIV)	50.55 kV
PD Pulse Rate	22.68 pulses/s
Noise Pattern	Comb columns at $\pm 90^\circ/\pm 270^\circ$; negative dominant
VERDICT	REPROVED (artefact) — cable body intact; external corona at connections

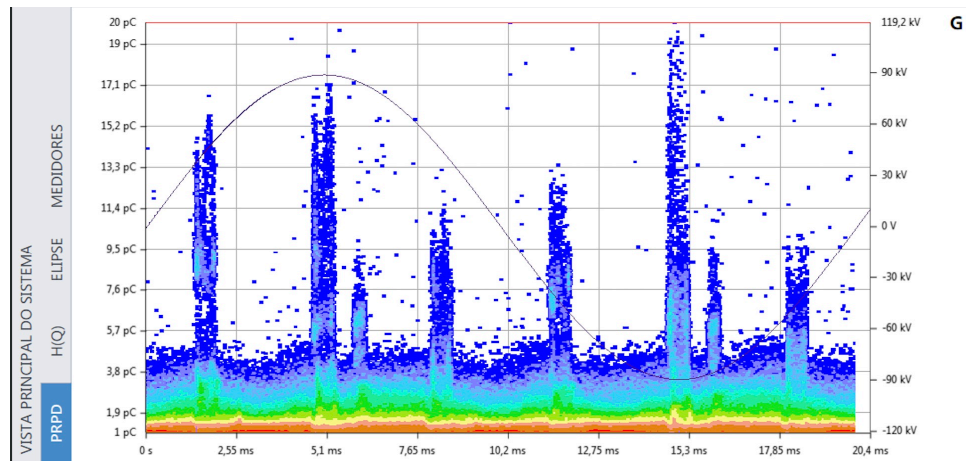


Figure 4.20: PRPD plot: external corona, comb pattern.

The sharp, needle like vertical alignments centred precisely at the sinusoids' maximum peaks, exhibiting a marked negative half cycle dominance, reproduce the characteristic Trichel pulse behaviour of air ionisation around a sharp metal edge [65]. The low pulse frequency (22.68 pulses/s) and the close correspondence of the inception voltage to atmospheric breakdown parameters confirm that the active cable core is sound. Corrective action requires no mechanical downtime; the testing bay requires only that exposed lead connections be shrouded with conductive corona shielding spheres prior to retesting.

4.8.4.2 Case 6 — External Corona at $1.73 \times U_0$

Table 4.11: Electrical Insulation and Partial Discharge Test Parameters Summary

Parameter Group	Specifications and Test Values
Test Reference	Ens_AT\REPSOL\2501-66_200123_153455
Cable Class	76 kV, $U_0 = 76$ kV
Test Conditions	131.6 kV RMS ($\approx 1.73 \times U_0$), >1 h 7 min duration
PD Metric (Q_{IEC})	Peak pulses: up to 12 pC
PD Inception (PDIV)	131.8 kV
Noise Pattern	Four narrow columns at $\pm 90^\circ/\pm 270^\circ$
VERDICT	REPROVED (artefact) : external corona; cable insulation intact

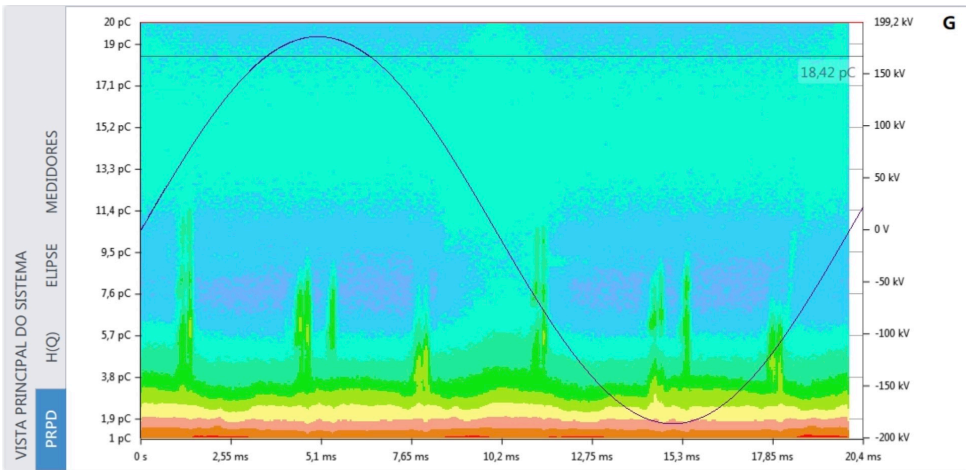


Figure 4.21: PRPD plot: external corona at $1.73 \times U_0$.

The presence of four fine, isolated vertical columns tracking precisely with the voltage maxima, and showing no activity along the zero crossing axes, confirms an ambient air gap problem. Because the inception voltage level (131.8 kV) corresponds closely to the maximum voltage step, ionisation occurs only when the laboratory air is brought to its limit, leaving the core insulation structural layers unaffected.

4.8.5 Electronic Switching Noise — Test Environment Artefacts

Industrial switching noise originates from heavy machinery operating elsewhere on the plant floor. It manifests as solid, unvarying vertical bars locked to fixed power grid harmonics, retaining their shape regardless of changes to the cable’s test voltage.

4.8.5.1 Case 7 — Massive Switching Noise Masking (step-change at 15 min)

Table 4.12: Electrical Insulation and Partial Discharge Test Parameters Summary

Parameter Group	Specifications and Test Values
Test Reference	OF_756682_C10_190426_114829_115852
Cable Class	36 kV, $U_0 = 36$ kV
Test Conditions	53.72 kV RMS ($1.5 \times U_0$), 32 min duration
PD Metric (Q_{IEC})	4.824 pC (noise-driven)
PD Inception/Extinction	PDIV: 54.47 kV PDEV: 52.95 kV
PD Pulse Rate	2,758 pulses/s
Noise Onset Dynamics	Step-change onset at 15 min (facility grid harmonic noise)
Noise Pattern	Six dense comb columns; sinusoid-independent; 20 pC ceiling
VERDICT	REPROVED (environment) : cable sound; external grid noise injected

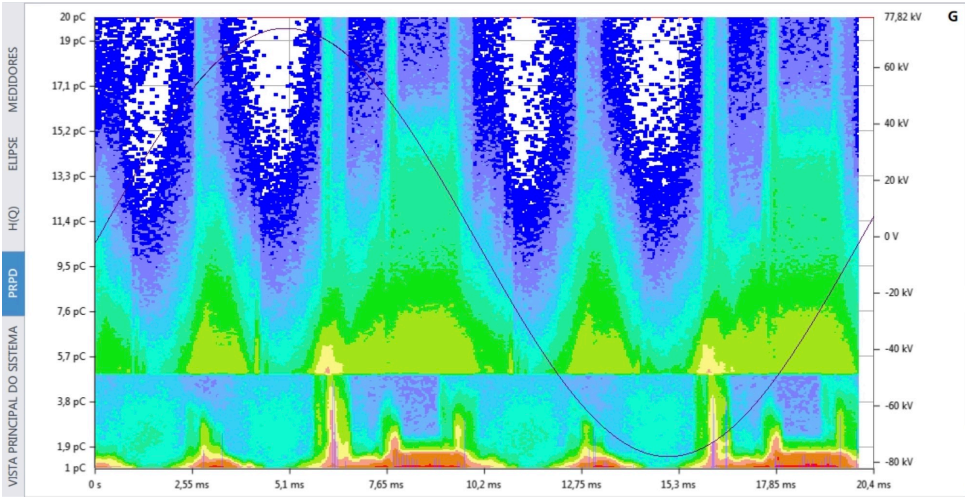


Figure 4.22: PRPD plot: massive switching noise

The wave pattern is obscured entirely by six dense vertical bars that disregard the phase curvature of the voltage sinusoid. This profile is a characteristic signature of heavy solid state switching noise entering the test loop from the shared facility grid. The diagnostic window remained clean for the first 14 minutes of the run, confirming that the core insulation was stable. The sharp step change at the 15 minute mark coincides with heavy industrial machinery cycling on elsewhere in the plant. The underlying cable insulation is sound.

4.8.5.2 Case 8 — Noise and Real Flaw Superposition

Table 4.13: Electrical Insulation and Partial Discharge Test Parameters Summary

Parameter Group	Specifications and Test Values
Test Reference	OF_756682_C11_noise_corona
Cable Class	36 kV, $U_0 = 36$ kV
Test Conditions	53.48 kV RMS ($1.5 \times U_0$), 32 min 28 s duration
PD Metric (Q_{IEC})	8.708 pC (Noise-driven; peak columns up to 20 pC)
PD Inception (PDIV)	53.35 kV
PD Pulse Rate	21.69 pulses/s (Accumulated: $> 9.6 \times 10^6$ pulses)
Noise Pattern	Base V pattern columns + prominent tracking at 7.65 ms and 17.85 ms
VERDICT	REPROVED : External corona and electronic switching noise

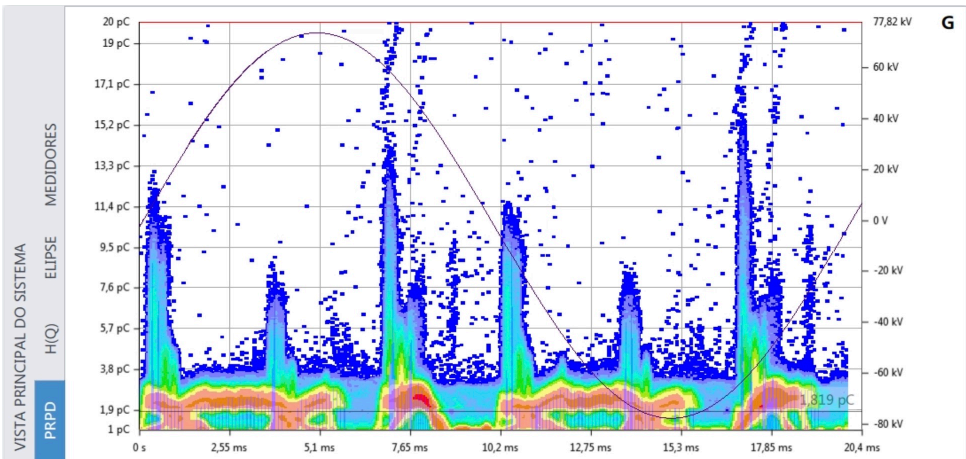


Figure 4.23: Case 8: facility noise + real boundary discharge. $Q = 8.708$ pC; PDIV = 53.35 kV.

Cable run C11 presents a complex diagnostic case: a genuine boundary layer discharge is superimposed on heavy plant grid noise. While the typical grid harmonic lines form the background matrix, two specific vertical bands located at post peak angles (7.65 ms and 17.85 ms) accumulate a disproportionately high pulse density, extending to approximately 20 pC. Because these columns are displaced from the standard power line harmonic frequencies, they indicate an active partial discharge along the cable’s internal semiconductive interface, distinguishable from the surrounding ambient noise floor.

4.8.6 Summary of PRPD Pattern Analysis

Table 4.14: PRPD pattern types identified across the evaluated factory acceptance test records.

Pattern type	Phase distribution	Key features	Crit.	Verdict / disposition
Background noise (healthy)	Uniform, all phases	No phase synchronism; $Q < 1$ pC; flat trend	None	APPROVED – cable intact
Internal void – early	Bilateral, rising edges $0^\circ\text{--}90^\circ/180^\circ\text{--}270^\circ$	Rabbit-ear cloud; $Q \approx 6$ pC; PDIV below normative threshold	(a)	REPROVED – PDIV below withstand; latent service risk
Surface discharge – early	Post-peak bilateral, $90^\circ\text{--}140^\circ/270^\circ\text{--}320^\circ$	Dense post-peak clouds; onset 28 min; capacitive grid charge retention	(b),(e)	REPROVED – interface tracking; extrusion correction required
Surface discharge – severe	Chaotic, full-cycle, ceiling-saturated	Geometric definition lost; $Q \approx 10$ pC; carbonised track arcing; exponential growth	(b),(e)	REPROVED CRITICAL – interface collapse; immediate quarantine
External corona (low level)	Narrow columns at $\pm 90^\circ/\pm 270^\circ$	Comb columns; negative dominant; $Q_{\text{mean}} < 2$ pC; low pulse rate	None (artefact)	REPROVED (artefact) – corona-shield connections; retest
External corona (high level)	Four narrow columns at $\pm 90^\circ/\pm 270^\circ$	Ionisation at $1.73 \times U_0$; peak pulses up to 12 pC; ambient air gap problem	None (artefact)	REPROVED (artefact) – shield connections; body intact
Electronic switching noise	Uniform comb, fixed harmonic spacing	Sinusoid independent; step change onset at 15 min; thousands of pulses/s	None (environment)	REPROVED (artefact) – gating filters; retest off-peak
Noise + corona superposition	Comb base plus post-peak columns	Columns at 7.65 ms and 17.85 ms exceed noise floor; $Q \approx 8.7$ pC; edge of test PDIV	None (artefact)	REPROVED – suppress grid noise; shield exposed sharp metal connections

This review yields four practical operational conclusions for factory testing protocols:

The laboratory diagnostics are reliable: every run affected by genuine internal gas cavities (Case 2) or physical layer boundary tracking (Cases 3, 4, and 7) was correctly identified and flagged as REPROVED by the monitoring platform.

Ambient testing loop conditions frequently produce false positives: Cases 5 and 6 arise from external corona at connection clips, while Cases 8 and 9 are substantially affected by facility grid noise [66].

A test hold of at least 30 minutes is necessary: both critical interface tracking failures (Cases 3 and 4) remained undetected until 28 to 32 minutes into their hold windows. Accelerating or shortening this testing protocol would allow serious latent defects to enter service undetected.

Inception voltage steps clearly distinguish bulk anomalies from interface flaws. The internal void profile (Case 2) required an overvoltage step to 107.4 kV to ignite within a 76 kV cable, whereas early stage interface tracking (Cases 3 and 4) broke down at 54 to 55 kV, at the baseline $1.5 \times U_0$ testing threshold. This confirms physically that gas pockets nested within the bulk insulation require substantially higher electric field stresses to ignite than layer variations or semiconductor screen protrusions.

4.9 Phase 8 — Root-Cause Synthesis

The trends presented in Section 4.6 indicate an important distinction: the factory is not experiencing a uniform decline in product quality, but two distinct and separate mechanical trends. Extrusion insulation controls have improved substantially. Serious electrical failures, including dielectric breakdowns ($RR = 0.623$) and material burning conditions ($RR = 0.668$), declined substantially in 2026. This improvement is driven entirely by the overhaul of lines EP08 and EP100 executed at the end of 2025, which reduced their defect rates substantially ($RR = 0.475$ and 0.450).

Conversely, outer jacketing and material handling flaws increased substantially ($RR = 1.457$). This identifies clear vulnerabilities on lines EP101 and EP05 ($RR = 1.490$ and 1.553), driven primarily by worn laminate feeds (addressed by Measure IV) and wire drawing lubricant contamination (Measure I). These lines are now the highest priority targets for the next maintenance window.

These findings allow for an evaluation of three central questions: which assets pose the greatest risk to insulation integrity, why HV production profiles differ fundamentally from MV runs, and how shop floor processing errors translate into high pC test rejections.

Finding 1: The primary driver of PD rejections is the combination of crosshead flow instability and inadequate polymer vulcanisation across EP100, EP08, EP23 and EP102. These four primary assets generate the majority of the active defect database, returning the highest net PD risk profiles. Their dominant failures, dielectric strength breakdowns and PD rejections, map directly to the insulation risk criteria (a) and (b) for micro void nesting and screen interface protrusions. The PRPD data substantiate this causal link: Case 2 (bilateral rising edge clouds) corresponds to the vulcanisation tracking anomalies identified on EP100, while Cases 3 to 4 (delayed post peak clouds) correspond to the screen surface roughness and die erosion profiles of EP08 and EP23.

Worn tooling is the principal root cause of both failure modes, providing the core justification for Measure 1.

Finding 2: The PD record for HV cables reflects the impact of process discipline, not an inherent absence of material risk. HV production operates under mandatory cleanroom protocols and conservative line speeds, which effectively suppress PD inducing defects below test thresholds. This is supported by the low HV non conformance rate and the voltage band defect mode comparison, which shows HV's Electrical share well below the plant wide average. However, the substantial 76/132 kV handling surge (with the monthly rate more than doubling between the two periods) and the corresponding shift in the GT101 reel logistics profile indicate that HV quality cannot be assumed and requires continuous monitoring, particularly on EP101.

Finding 3: The factory's quality trajectory is differentiated by machine, rather than uniform across the floor. While insulation reliability improved substantially in early 2026, outer jacket appearance issues ($RR = 1.457$) and localised water marks increased. At the machine level, lines EP08 and EP100 responded effectively to their end 2025 overhauls, while lines EP101 and EP05 deteriorated. This performance differentiation indicates that the targeted maintenance approach is effective, and that equivalent die overhauls and sensor recalibrations should now be extended to the deteriorating sheathing lines.

These three findings converge on a structural conclusion: processing defects do not arise independently of one another. Parameter drift and tool erosion determine how frequently defects occur, while raw material contamination determines how severely they fail. A micro void formed by a pressure drop in a clean crosshead remains small and manageable; the same pressure drop occurring in the presence of carbonaceous residue produces a severe, field concentrating defect. This coupling implies that die wear and compound cleanliness must be addressed concurrently. The temporal data support this: the end 2025 overhaul on line EP08 reduced its total defect rate by roughly half ($RR = 0.475$), yet its average discharge magnitude remained high (184 pC), because the compound filtration upgrade (Measure 6) and extended vulcanisation steps (Measure 5) had not yet been deployed. A two tier strategy, reducing failure frequency through machine specific overhauls while reducing failure severity through plant wide compound management, is therefore required to achieve comprehensive quality control.

4.10 Phase 9 — Corrective and Preventive Measures

Combining the Phase 8 root cause synthesis with a risk prioritisation framework, balancing failure frequency, insulation risk severity (Phase 5 tracking), and engineering deployment effort, a corrective priority matrix (Tables 4.16 and 4.18) and a strategic action roadmap (Table 4.20) were established. Each process refinement targets a verified production vulnerability.

Table 4.16: Corrective priority framework matrix — Part 1: Electrical and Insulation Risks (Tracks A and B).

Track	Target	Problem	Evidence	Priority	Action
A – PD Risk	EP102	PD occurrence rate shows a partial reduction (RR = 0.834) but EP102 still dominates plant wide PD rejections in 2026; semiconductor screen boundary protrusions are confirmed by Phase 7.	Phase 6 intensity logs show the highest sustained discharge volumes; high incidence of semiconductor screen comments flagged during Phase 4 text screening.	HIGHEST	Maintain current operating controls; execute immediate intervention for residual die head wear.
A – PD Risk	EP23	PD rate rose (RR = 1.177), causing its share of plant wide PD rejections to expand; stands out as the only primary extruder with a worsening PD trend.	The 6.35/11 kV rating represents the only worsening PD voltage band, traced directly to EP23 crosshead filter degradation (Phase 4).	HIGHEST – NEW	Launch immediate line audit: inspect die alignment, crosshead concentricity, and execute an immediate compound filter mesh upgrade.
A – PD Risk	EP08 / EP100	Both lines secured a substantial quality improvement (RR = 0.475 and 0.450).	The rate ratio comparison confirms the end 2025 overhauls were effective; their combined share of plant failures decreased substantially.	HIGH	Maintain current maintenance parameters. Schedule the next maintenance cycle before tool wear resumes.
B – Sheath	EP101 / EP05	EP101 defect rates rose by approximately 26 % and EP05 by nearly 60 %; both assets display a high density of jacket and mechanical flaws with no electrical failures.	Combined 2026 profile reveals an elevated density of physical flaws; Water Marks and Burned Sheath emerged as new risks; structural root causes are distinct from insulation flaws.	HIGH	Execute a sheathing die alignment audit and a full barrel temperature control check.
B – Sheath	CB100	Exhibited a sharp relative increase in surface defects in early 2026 compared to a near zero baseline across all of 2025; failures are confined to Sheath and Scratched/Damaged tags.	Directly corresponds to the reactivation of the cabling asset for a major new campaign; guide surface scoring and uneven die clearances are typical during campaign start up.	HIGH	Inspect all cabling dies and guide surfaces; audit and verify the formal campaign restart protocol.

Table 4.18: Corrective priority framework matrix — Part 2: Heavy Mechanical Risks and Quality Monitoring (Tracks C and D).

Track	Target	Problem	Evidence	Priority	Action
C – HV Mech	GT101 / Logistics	Logistical tie rod failures emerged prominently; surface flat spotting appeared on 76/132 kV reels, which are the heaviest in the plant.	The steady weight increase from expanded 76/132 kV production volumes is the principal driver (with the monthly rate more than doubling between the two periods).	HIGH	Conduct a comprehensive review of the 76/132 kV reel handling protocol; inspect all GT101 guide roller surfaces.
D – Monitor	76/132 kV Burned	Burned/Blown tags at the 76/132 kV rating increased noticeably; individual record auditing is required to separate external jacket heat scoring from core insulation failures.	Proportional increase in sub category entries at the 76/132 kV level; engineering indicators point to external jacket thermal damage rather than core electrical breakdown.	MEDIUM	Audit and verify raw burn entry classifications; separate external jacket and core insulation sub categories within QMS codes.
D – Monitor	6.35/11 kV PD band	Stands out as the only worsening PD voltage rating (RR = 1.24), tied directly to EP23 filter mesh erosion.	Expected to resolve following deployment of Track A filtration updates on line EP23.	MEDIUM	Monitor the 6.35/11 kV rating's discharge behaviour following EP23 filtration overhauls.

Table 4.20: Strategic action plan and corrective measures for quality optimisation and PD risk mitigation.

P	Measure	Category	Machine(s)	KPI
1	Revised maintenance and die wear protocol; reduce calibration interval	Maintenance	EP102, EP08, EP23, EP100	Dielectric NCF ↓20 %
2	Formalised MV→HV changeover cleaning; purge ≥one full reel	Cleanliness	EP100	Zero contamination events
3	Adjust CV tube temperature profile; online thermocouple ($\pm 1^\circ\text{C}$)	Process	EP08, EP102	Void type rate ↓20 %
4	Ultrasonic water bath scan before reel take-up [32, 67]	Inspection	EP101, EP05	Early void detection
6	Upgrade compound filter mesh on EP23	Cleanliness	EP23	Contam. NCF ↓30 %
7	Introduce tan delta monitoring as supplementary FAT [68]	Testing	All machines	Latent PD detection

The top two initiatives are classified as high criticality actions, as they address the two processing variables responsible for the most frequent and severe insulation breakdowns: mechanical crosshead wear on high volume extruders, and compound cross contamination during campaign swaps. Both measures can be incorporated directly into current maintenance schedules without requiring significant capital expenditure. Measures 3 through 6 refine processing temperatures and filtration screens, and are expected to produce measurable benefits within one to two quarters. Measures 7 and 8 optimise the laboratory testing loops to detect latent defects before they leave the factory floor.

4.10.1 Process, Equipment, and Infrastructure Improvement Measures Implemented or Planned

Measure I — Transition from Emulsion-Based to Oil Based Conductor Wire Drawing Lubricants: The core wire drawing lines currently operate with water emulsion lubricants. This fluid routinely leaves residual moisture trapped between the tightly wound strands of the raw conductor. When this conductor is preheated immediately before the crosshead, the trapped moisture vaporises. Unable to escape, this vapour migrates directly into the freshly extruded inner semiconductor screen, creating dense nests of micro voids (criterion a) [56, 69]. This residual water also oxidises copper and aluminium surfaces, which degrades the hydro expansive water blocking tapes and releases additional volatile by products. The plant is actively transitioning to dry, oil based lubricants to eliminate this moisture pathway and prevent void formation at the conductor interface.

Measure II — Enhanced Purging Protocols during MV to HV Campaign Transitions: This measure formalises the full reel purge and engineer sign off requirement at every MV to HV changeover described above, with particular application to EP100.

Measure III — Transition to Inert Purging Agents for Extruder Cleaning: Standard commercial cleaning compounds frequently leave behind baked carbonaceous flakes or hydrocarbon film residues inside the crosshead channels (criterion c) [59]. To address this, the plant is transitioning to chemically inert purging compounds that disintegrate cleanly at standard extrusion melt temperatures, ensuring that the cleaning process itself does not introduce impurities into the line.

Measure IV — Mechanical Upgrades for Aluminium Tape Winding Guides and Outer Jacket Extrusion Dies: Failures associated with metal laminate tape increased as a proportion of total defects between 2025 and the 2026 window ($RR = 2.532$), driven by worn tensioning rollers that crease the foil or create uneven overlaps, leading to floating potential arcs under AC stress (criterion f). High stability tape laying modules equipped with automated overlap sensors have been procured, and are being paired with an outer jacket die overhaul to eliminate surface appearance flaws.

Measure V — Component Replacement: Line Caterpillar Extractors and Drive Motor Inverters: Mechanical wear within the vulcanisation line's caterpillar extractors and motor inverters introduces minor, periodic line speed variations. These micro jerks cause periodic wall eccentricity (criterion d) and localised void nests. A targeted replacement programme for high priority caterpillar tracks and drive inverters has been initiated, prioritising the units feeding lines EP102 and EP08.

Measure VI — Installation of a Hot Water Recirculation Loop to Eliminate Cooling Water Marks: Surface water marks on the outer protective jacket increased substantially in early 2026 ($RR = 11.575$). These occur when cold municipal water contacts the heated extruded jacket compound, creating localised cosmetic stress cracks due to thermal shock. A hot water recirculation loop is being installed at the entrance of the cooling trough to reduce this temperature differential.

Measure VII — Full Extrusion Line Overhaul during Planned Shutdown: A comprehensive mechanical overhaul of lines EP102, EP08, and EP23 is planned during the upcoming annual plant shutdown. This intervention includes replacement of aged extrusion dies and triple crosshead cores, renewal of all vulcanisation tube thermal sensors, rebuilding of the caterpillar pull mechanics, and auditing of all automated instrument loops.

The combined deployment of Measures I through VII addresses the three core problem areas identified in this study: process parameter instability (Measures V and VII), physical tool degradation (Measures IV and VII), and material contamination (Measures I, II, and III).

4.11 Summary and Conclusions

This chapter has evaluated the quality dataset spanning the full calendar year 2025 and January to May 2026. By processing these records through a structured, nine phase analytical framework, combining descriptive text filtering, rate ratio comparisons, percentage point share comparisons, apparent charge intensity statistics, and PRPD waveform diagnostics, a comprehensive view of the plant's manufacturing quality has been developed. Six central conclusions emerge from this study.

Conclusion 1 — Extrusion parameter drift and incomplete vulcanization and emulsion related issues are the dominant causal drivers of partial discharge risk, and the PRPD case studies confirm that the same mechanisms operate on the HV capable lines. The two highest NCF assets, lines EP102 (29.11% in 2025) and EP08 (24.65%), account for a substantial share of the factory's total defect database and exhibit the most critical PD risk concentrations. Both are MV dedicated lines, and their primary failure modes stem from two simultaneous mechanical variations: progressive crosshead die erosion, distorting the boundary between the semiconductor and the insulation, and insufficient CV tube residence time, trapping volatile by products as micro voids. A significant contributing factor here is moisture trapped from the wire drawing emulsion, the mechanism explained previously, which also creates micro voids in the semiconductor layer or within the insulation itself.

Because all PRPD waveform case studies in Section 4.8 were captured on HV cable acceptance tests (Section 4.8), the individual waveform patterns trace not to EP102/EP08 but to the HV capable lines that share the same underlying mechanisms. The post peak surface discharge PRPD patterns observed in Cases 5 to 7 are consistent with the interface protrusions (criterion b) and surface roughness (criterion e) identified on EP23 in Table 4.3, which, although predominantly an MV asset, is HV capable and shares EP102's contamination driven roughness mechanism. The symmetric, rising edge rabbit ear signature seen in Case 2 is consistent with the melt temperature variation and CCV tube temperature gradient identified on EP100, the plant's predominant HV producer, which traps volatile cross linking by products as dense micro void networks (criterion a) under the longer cure cycle required by thick HV insulation walls. These combined flaws lower the localised inception voltage (PDIV), causing reels to fail factory acceptance criteria despite meeting basic dimensional tolerances, regardless of whether the producing line is nominally classified as MV or HV.

Conclusion 2 — The plant achieved a genuine, statistically verified improvement in electrical insulation reliability, but this improvement was confined to maintained lines and was not shared across the entire extrusion fleet. Across the plant's four primary insulation extruders (EP102, EP08, EP23, EP100), the non conformance rate fell from 18.37% to 14.00% (RR = 0.762). The plant wide figure across all production lines moved in the opposite direction over the same period (8.74% to 10.16%, Section 4.2.2); read alongside Phase 2's category mix inversion and Phase 5's machine share redistribution, this divergence is consistent with — not contradictory to —

the extruder level improvement: it reflects defects shifting toward the downstream sheathing and cabling lines, not a reversal of the gains made on the insulation extrusion side. At the category level, the principal electrical defect categories declined substantially: Dielectric Strength fell with an $RR = 0.623$ and Burned/Blown material issues with an $RR = 0.668$. This result is directly attributable to the targeted overhauls executed on lines EP08 and EP100 ($RR = 0.475$ and 0.450).

Lines EP101 and EP05, however, deteriorated over the same period ($RR = 1.490$ and 1.553). This divergence demonstrates that quality is driven by machine specific overhauls rather than plant wide operational improvements. The maintenance protocols that improved line EP08 should now be extended to the deteriorating jacketing lines.

Conclusion 3 — Partial discharge severity is governed by plant wide material cleanliness, whereas discharge frequency is governed by machine specific tooling wear. The median apparent charge values for the four primary extrusion lines fall within a narrow 50 pC window (80 to 130 pC), despite substantial differences in overall failure frequencies and mechanical designs. Similarly, the elevated discharge mean observed in the 18/30 kV rating (186.5 pC in 2025) is an inherent material consequence of thick walled extrusion, which requires long vulcanisation times and generates elevated chemical by products.

This distinction indicates a two tier strategy: machine specific die overhauls should be used to reduce the frequency of defects, while plant wide filter mesh upgrades and changeover purge rules should be used to reduce their physical severity. These two approaches are not interchangeable.

Conclusion 4 — While electrical defect quality improved, a simultaneous and substantial degradation in mechanical protective sheathing occurred, driven by different assets and different failure mechanisms. Sheath defects increased with an $RR = 1.457$. Three failure modes that were largely absent in 2025 emerged in early 2026: thermal shock Water Marks, Poorly Guided Cable ($RR = 3.555$), and structural Tie Rod failures. These issues are concentrated on lines EP101, EP05, CB100, and GT101, assets that were not addressed during the 2025 maintenance programme.

These surface anomalies are not dielectrically benign: torn jackets permit moisture ingress that triggers water tree degradation in service, screen ripples cause the interface tracking confirmed in the PRPD analysis, and misguided winding creates wall eccentricity that thins the insulation at its most vulnerable point.

Conclusion 5 — Mapping the spatial distribution of defects along the production reel yields process intelligence that simple pass/fail counts do not capture. Partial discharge rejections display a pronounced 66.6 % bias toward the start of the production run, at the reel's exterior end. Three mechanisms account for this trend: crosshead thermal gradients prior to die body equilibrium, residual compound from the previous campaign blending into the new polymer layer, and pressure control loops oscillating before reaching steady state.

All three mechanisms are concentrated at the start of the run and diminish as production advances. Conversely, sheathing and metal tape defects are heavily biased toward the interior end (aluminium tape displays a 61.8 % interior concentration), implicating the cumulative weight of compounding reel layers as the primary driver of jacket deformation. These spatial signatures function as a process diagnostic, indicating when and where a defect formed during the extrusion run.

Conclusion 6 — High voltage cable runs exhibit structurally superior electrical performance relative to medium voltage lines, but face a rising logistical reel handling risk that requires correction. HV cables recorded only a small number of partial discharge flagged tests throughout the 17 month study, all of them confined to the 30/60 kV class on EP100 and EP23, with apparent charge readings as high as 500 pC where the 76/132 kV and 127/220 kV ratings recorded none. This demonstrates that the cleanroom protocols and manufacturing controls applied to HV lines are highly, but not yet completely, effective. The voltage band defect mode comparison shows a more nuanced pattern: HV's Electrical share of total plant defect metres rose from 1.516 % in 2025 to 3.698 % in 2026 — a higher absolute share despite the stricter process controls applied to HV campaigns, and worth continued attention even though HV production volume also increased over the same period. HV's Structural and Other shares grew by a larger margin over the same window (Structural: 3.834 % → 6.961 %; Other: 0.704 % → 3.463 %), confirming that the majority of HV's growing defect footprint remains mechanical rather than electrical in nature, consistent with the surface defect discussion that follows.

However, the 76/132 kV rating simultaneously exhibited the largest relative increase in surface defects across the plant (with its monthly rate more than doubling), centred on the heavy transport rollers of unit GT101. High voltage reels are the heaviest units in the inventory; this cluster of flat spotting flaws and tie rod failures indicates that the material handling infrastructure has not kept pace with rising HV production volumes. Mechanical jacket damage opens moisture paths that promote long term water tree degradation, a latent flaw that passes factory acceptance testing but can cause premature insulation failure in service.

Overall Conclusion. The factory is progressing in the correct direction with respect to core electrical insulation quality, supported by verified reductions in the two most significant failure categories and confirmed improvements on two primary assets. The mechanical adjustments responsible for this improvement, die wear control and vulcanisation tube temperature management on lines EP08 and EP100, are well established and can be extended to the remainder of the production floor.

Chapter 5

Practical Case Study: Factory Acceptance Test (FAT) of Cable Accessories

5.1 Cable Accessories: Terminations and Joints

While the termination and joint bulk pieces are manufactured under highly controlled factory conditions, their assembly is typically in the field, making them the most vulnerable components of a power network. Although both are designed to manage localized electrical stress, their distinct operational roles and geometric configurations make them susceptible to specific, localized defects that act as primary sites for partial discharge (PD) inception.

5.1.1 Cable Terminations and Stress Management

Terminations serve as the critical transition point where an insulated, shielded power cable connects to uninsulated system components, such as busbars, transformers or overhead lines. The primary engineering challenge in a termination is the abrupt truncation of the cable's grounded semi-conductive shield. This discontinuity creates a massive concentration of the radial and longitudinal electric fields at the cut-back point. To mitigate this, terminations rely on stress control components, such as stress cones or high-permittivity tubes, to grade the potential gradient and smooth the transition [46, 47].

Defects in terminations primarily revolve around the failure to properly manage this interfacial stress or the interaction with the external environment. Cut-back defects occur at the precise boundary where the outer semi-conductive layer is removed; poor preparation here can leave behind protrusions, rough irregularities, or microscopic voids.

Furthermore, the misalignment or omission of the stress cone during assembly is a notorious workmanship error that leaves the insulation subjected to unmitigated tangential stress. Because terminations interface with ambient air or gas-insulated switchgear (GIS), they are also highly

prone to corona discharges at the cable lug or terminal hardware [48]. Sharp edges on projecting bolts or unpolished connectors can ionize the surrounding air, leading to continuous energy loss and chemical degradation of the housing.

Additionally, if the outer non-tracking surface of the termination becomes contaminated by moisture, dust, or industrial pollutants, surface tracking can initiate, progressively eroding the external housing until a flashover occurs [35, 44].

5.1.2 Cable Joints and Workmanship Sensitivity

Unlike terminations, cable joints must completely rebuild the cable's multi-layered structure to join two separate lengths. This complex process involves re-establishing the electrical continuity of the conductor, the semi-conductive screens, the primary insulation, and the protective metallic and outer jackets. Because this intricate assembly is performed in the field—often within restricted environments like trenches or manholes—joints are heavily plagued by workmanship-related defects.

One of the most critical internal defects in joints involves connector burrs and sharp edges on the metallic ferrule. If the installer fails to perfectly polish the connector after crimping or welding, metallic protrusions act as massive stress enhancers that immediately ignite internal PD [46]. Similarly, cutting errors during the stripping of the semi-conductive layer are a major cause of failure. These include tram lines (longitudinal grooves) or ring cuts (circumferential trenches) sliced into the underlying XLPE insulation [46, 47]. Even a small semicon feather, a triangular remnant of the semi-conductive screen left on the clean insulation—creates a severe point of field concentration.

Furthermore, interfacial gaps and voids are a frequent root cause of discharge in joints [46]. Premolded joint bodies must achieve an interference fit over the cable insulation; if silicone grease is applied inadequately or if air is trapped during the sliding of the joint body, microscopic voids form at the interface. These are often compounded by trapped contaminants, such as metallic particles or conductive sandpaper debris sealed inside the joint during the assembly process. Finally, if the joint's outer protective jacket is poorly sealed, moisture ingress can occur [35]. When pressurized groundwater penetrates the interface between the XLPE and the rubber joint body, it initiates severe interfacial tracking, which eventually leads to a catastrophic thermal-dielectric failure of the splice.

5.2 FAT procedure

The Factory Acceptance Tests (FAT) described in this chapter were conducted in compliance with IEC 62067 [20] for the 220 kV system under test. The FAT sequence comprised two consecutive stages: a high-voltage test at the specified overvoltage level for a duration of 30 minutes, applied gradually from zero to prevent transient stress; and the partial discharge test, performed during 15 seconds at a voltage of 190 kV, conducted after the voltage test to ensure the test voltage had fully stabilised prior to PD acquisition. The acceptance criterion for partial discharge was a charge magnitude not exceeding 5 pC at the test voltage, in accordance with the normative IEC 62067 [20]

and the test circuit according with IEC 60270 [7]. Table 5.1 summarises the test parameters applied to each accessory.

Table 5.1: Summary of testing parameters and results for Body Joint and Stress Cone accessories.

Parameter	Body Joint	Stress Cone	Standard	Acceptance
Rated voltage U_0	127/220 kV	127/220 kV	IEC 62067	—
Voltage test	318 kV (1.45 U_0)	318 kV (1.45 U_0)	IEC 62067 Cl. 12.3	No breakdown
Voltage test duration	30 min	30 min	IEC 62067	No breakdown
PD test voltage	190 kV	190 kV	IEC 62067	—
PD duration	15 sec	15 sec	IEC 62067	—
PD acceptance limit	≤ 5 pC	≤ 5 pC	IEC 62067	PASS if ≤ 5 pC
Test temperature	Ambient	Ambient	IEC 62067	—
Result — withstand	PASS	PASS	—	—
Result — PD	PASS	PASS	—	—

5.3 Body joint testing

5.3.1 Test preparation

Prior to testing, the 220 kV body joint sample was thoroughly cleaned to remove any surface contamination, dust, or residual moisture. Moisture removal is particularly critical in high-voltage testing: surface condensation on the insulating housing reduces its surface resistivity, creates conductive paths that distort the electric field at the semiconductor cut-back region, and generates spurious discharge pulses that are electrically indistinguishable from genuine PD activity within the accessory. Ambient temperature was recorded and confirmed within the range specified by [20] prior to commencing the voltage ramp. A representative image of the body joint sample prepared for testing is shown in Figure 5.1.

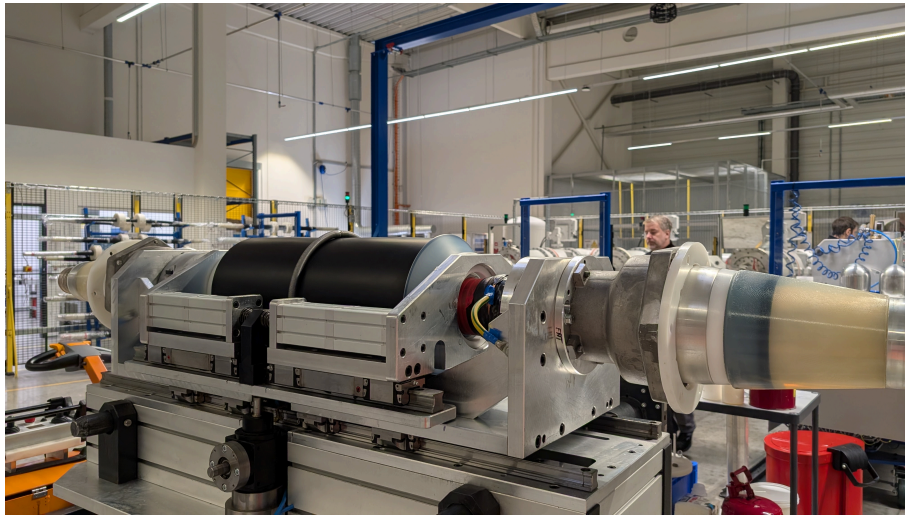


Figure 5.1: 220kV body joint sample prepared for factory acceptance testing

5.3.2 Test circuit and procedure

The test circuit was assembled in accordance with IEC 62067 [20] and IEC 60270 [7], the high-voltage transformer was connected on one side through a GIS system to the cable sample, which passes through the body joint; the opposite end was connected through a second GIS enclosure, completing the test loop. This circuit geometry, shown in Figure 5.2, minimises external electromagnetic interference by enclosing all high-voltage conductors within grounded metallic enclosures except at the accessory under test.

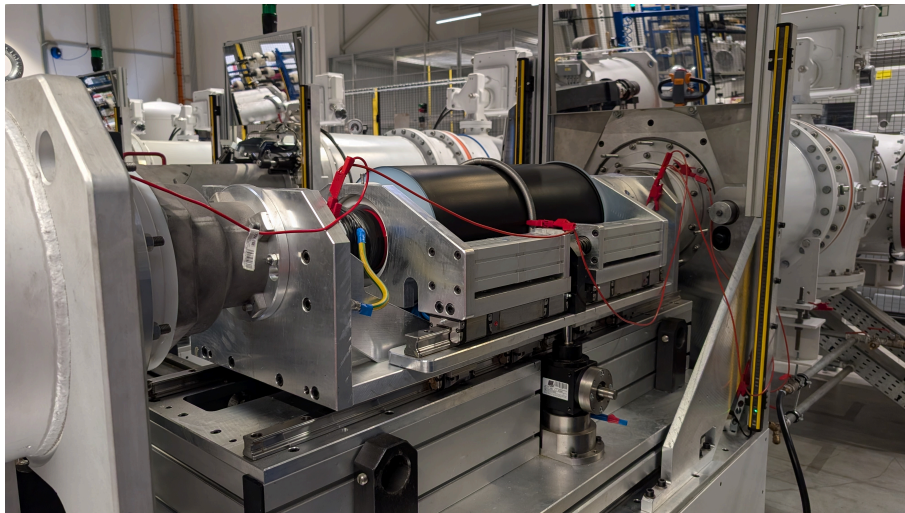


Figure 5.2: Test circuit for the 220kV body joint FAT — GIS connections on both sides

Figure 5.3 shows the test-circuit schematic as displayed by the partial discharge measurement software, indicating the applied voltage along with the other monitored test parameters.

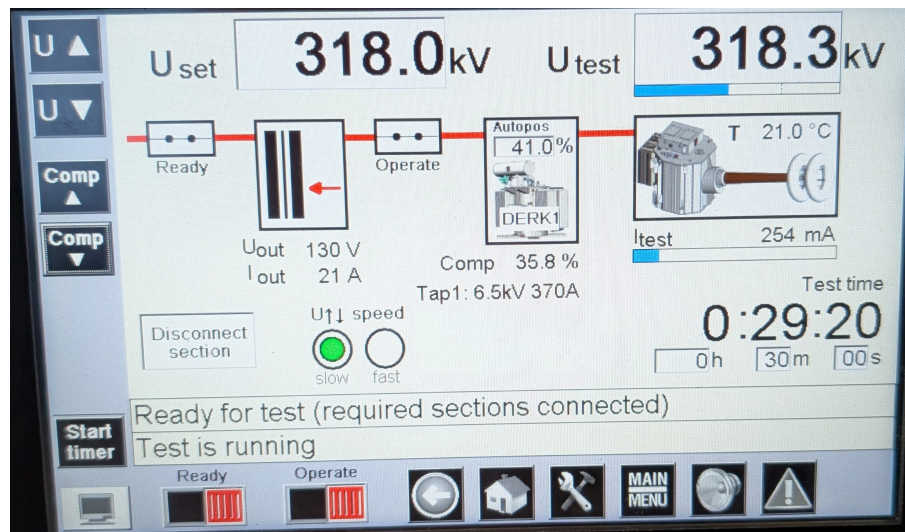


Figure 5.3: MPD instrument display showing test parameters for the body joint

The test proceeded in two stages. First, a voltage test was conducted at $U_0 \times 2.5 = 318 \text{ kV RMS}$ for 30 minutes. The voltage was raised gradually from zero to 318 kV to avoid the generation of steep-fronted transients (DIRAC pulses) that could cause mechanical shock to the accessory body and produce a false dielectric event [70]. After the withstand phase, the voltage was held stable for 10 minutes before the partial discharge measurement commenced. This stabilisation interval is essential: PD testing is not performed simultaneously with or immediately after voltage application because the cable's dielectric capacitance and the accessory's contact pressure are still equilibrating, and the resulting apparent charge readings would not reflect the steady-state dielectric condition of the insulation.

5.3.3 PD measurement results and diagnostic commentary

The partial discharge test was then conducted for 15 seconds at 190 kV AC. The PD trace recorded during this window is shown in Figure 5.4. Throughout the steady measurement window, the apparent charge remained below the 5 pC acceptance criterion specified by the IEC 62067 [20], and the PD pattern showed no synchronised activity, confirming the absence of genuine partial discharge activity within the joint body.

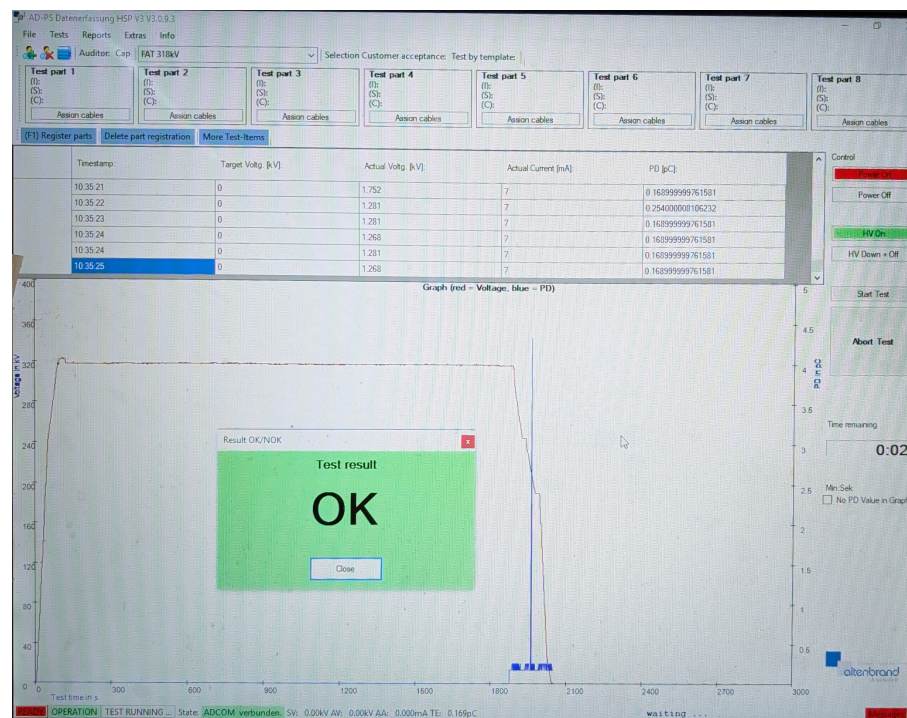


Figure 5.4: PD plot and charge trend recorded during the 220kV body joint PD measurement

The PD trace warrants specific analytical commentary regarding a transient episode visible during the measurement window. A brief cluster of scattered apparent PD pulses with elevated charge values appeared at one point in the test. This episode arose from mechanical vibration generated by production activity on the adjacent factory floor, which was transmitted acoustically to the test bay and induced electromagnetic coupling into the measurement circuit. Four characteristics of this cluster collectively identify it as an external noise artefact rather than genuine internal discharge activity [66]:

1. **Temporal correlation:** the pulse cluster was precisely coincident with an audible noise event from the factory floor, rather than occurring at a random or continuous rate.
2. **Symmetry:** the pulses were symmetrically distributed across both half-cycles of the applied voltage, whereas genuine protrusion- or void-induced discharges in a 220 kV cable at this test voltage would be expected to exhibit the asymmetric, post-peak bilateral pattern shown in Figure 5.4.
3. **Transience:** the cluster was entirely absent from the remainder of the 30-minute voltage test, during which background PD levels were continuously monitored. Genuine PD originating from a structural defect would be expected to persist throughout the test, or to worsen over time, as documented in Cases 5–8 of Section 4.8.
4. **Charge level:** the underlying apparent charge for the joint itself remained below 5 pC throughout, satisfying the IEC 62067 acceptance criterion. The noise episode did not affect the final Q_{IEC} value.

This observation reinforces a finding from the cable body PD analysis from Section 4.8: peak charge magnitude alone is insufficient as the primary diagnostic parameter in an industrial FAT environment; PD pattern shape, phase distribution, and temporal behaviour are essential complementary criteria. The practical recommendation arising from this episode is the scheduling of FAT tests during periods of low production activity.

The body joint **PASSED** the factory acceptance test at 220 kV ($U_0/U = 127/220$ kV): withstand at 318 kV for 30 minutes without breakdown, and PD charge below 5 pC throughout the measurement window.

5.4 Stress-cone testing

The stress cone followed the same overall test procedure as the body joint, with one notable addition: prior to testing, the sample was placed in a heating chamber to bring it to the temperature required by the standard. The test circuit was likewise similar to that used for the body joint, with the only difference occurring at the far end of the loop. While the transformer-side connection remained unchanged (a GIS system), the opposite end was configured to simulate an open-air termination, representative of a termination typical in-service connection at the end of an overhead line.

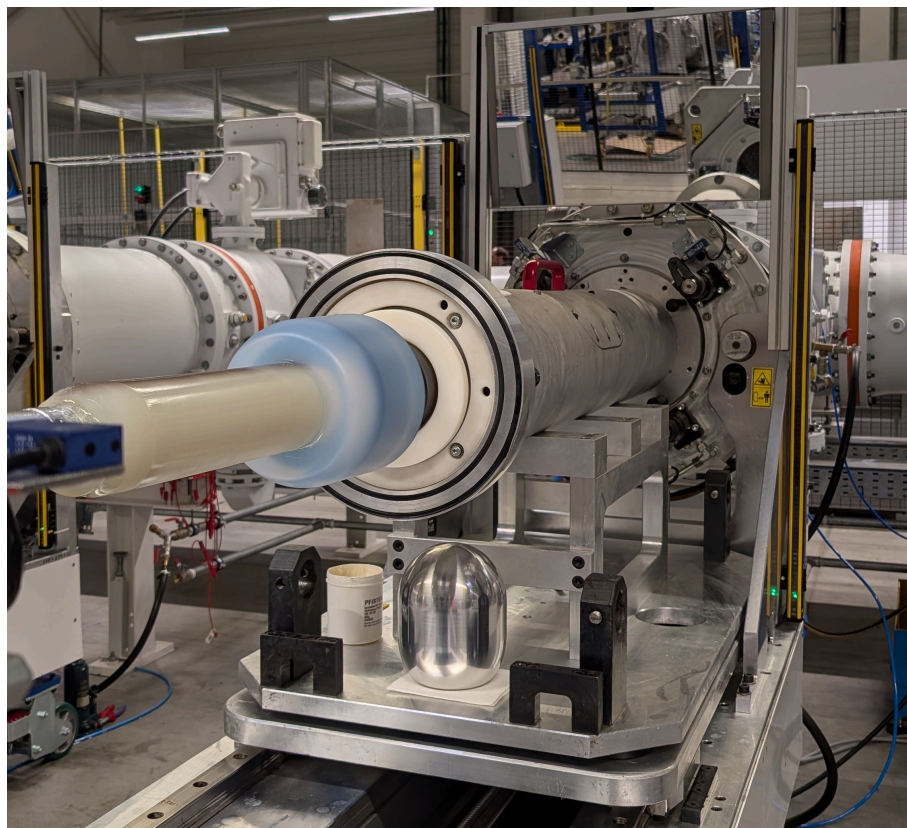


Figure 5.5: 220kV stress cone installed in the circuit

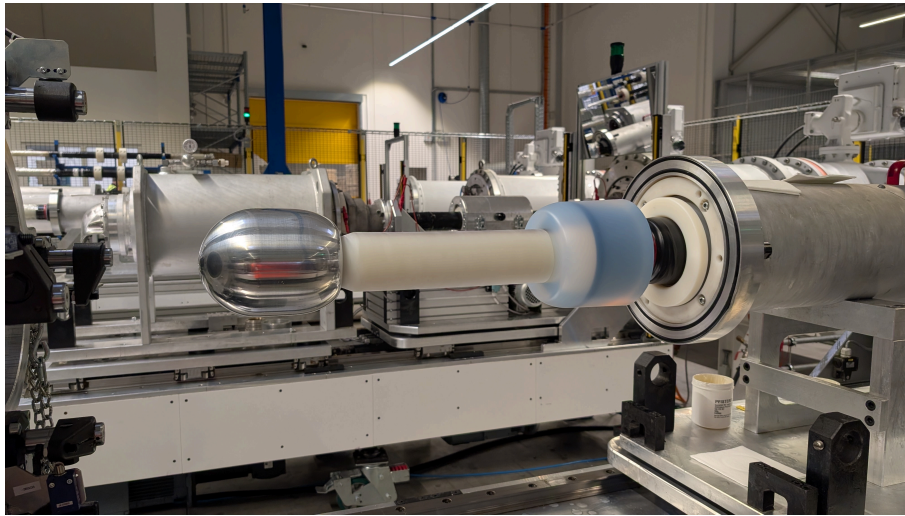


Figure 5.6: 220kV stress cone FAT test circuit — termination end simulating an open air connection

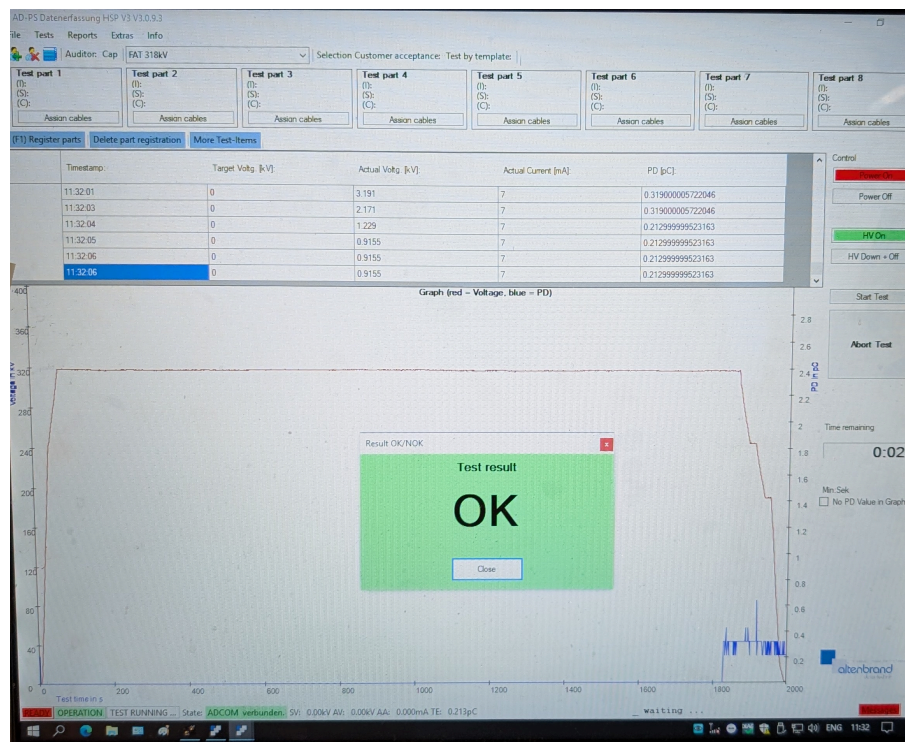


Figure 5.7: PD plot and charge trend recorded during the 220 kV stress cone PD measurement

The stress cone also **PASSED** the factory acceptance test at 220 kV ($U_0/U = 127/220$ kV): withstand at 318 kV for 30 minutes without breakdown, and PD charge below 5 pC throughout the measurement window.

5.5 Conclusion

The successful FAT results for both the 220 kV body joint and the stress cone provide direct validation of the manufacturing quality of the cable accessories tested. This is significant because, in the final on-site assembly of high-voltage cable systems, the accessory connection points represent the weakest links in the network and can compromise the integrity of the entire line if improperly manufactured or installed. The example of accessory testing presented here underscores the importance of rigorous manufacturing standards: both accessories and cables must meet equally high quality requirements, free of defects, for the system as a whole to operate reliably.

Table 5.3: Detailed test parameters and results for high-voltage accessory factory acceptance tests.

Test item	Applicable standard	Test voltage	Dur.	PD threshold	Result
Body joint — with-stand test	IEC 62067 [20], Cl. 12.3	$U_0 \times 2.5 = 318 \text{ kV}$	30 min	No breakdown	PASS
Body joint — PD measurement	IEC 60270 [7] IEC 62067 [20]	190 kV AC	15 sec	$\leq 5 \text{ pC}$	PASS
Stress cone — with-stand test	IEC 62067 [20], Cl. 12.3	$U_0 \times 2.5 = 318 \text{ kV}$	30 min	No breakdown	PASS
Stress cone — PD measurement	IEC 60270 [7]; IEC 62067 [20]	190 kV AC	15 sec	$\leq 5 \text{ pC}$	PASS
Test temp. — stress cone	IEC 62067 [20], Cl. 12.3	N/A	Pre-cond.	Temp $\geq 95^\circ\text{C}$	Compl.

Chapter 6

Conclusion and Future Work

6.1 Summary and Fulfilment of Objectives

This dissertation examined how insulating material characteristics and manufacturing process conditions influence partial discharge (PD) activity in medium voltage (MV) and high voltage (HV) underground AC cables produced at Cabelte, Cabos Elétricos S.A. Two complementary investigative tracks were employed: a retrospective analysis of the plant's production quality database over a continuous 17 month window (January 2025 to May 2026), and a case study of factory acceptance testing (FAT) on high voltage cable accessories. Together, these tracks enabled the investigation to proceed from manufacturing deviations recorded on the shop floor to their electrical consequences in the finished cable, in accordance with the research questions and objectives defined for this work.

The specific engineering objectives were met. The influence of processing anomalies on partial discharge inception was quantified at machine, voltage class, and defect typology resolution. Digital phase resolved partial discharge (PRPD) wave profiles were classified and linked to specific manufacturing root causes, establishing a verified correspondence between process level failure modes and their electrical signatures. A corrective framework balancing machine overhauls, process adjustments, and plant wide material controls was also developed, intended to guide the plant's reliability programme.

One analytical limitation should be stated explicitly: polypropylene (PP) production volume during the study period was insufficient to support a statistically stable comparison alongside cross-linked polyethylene (XLPE) and ethylene propylene rubber (EPR). PP is therefore discussed on theoretical grounds, with the empirical comparison proposed as future work.

6.2 Responses to Research Questions

Research Question 1 — How do specific variations in insulating materials and manufacturing parameters influence the creation of PD inducing defects?

The results identify thermo mechanical and flow instabilities during extrusion and continuous vulcanisation as the predominant source of PD vulnerability. EP102 and EP08 are the principal

contributors to the historical defect burden, with normalised non conformity frequencies of 29.11 % and 24.65 % respectively in the baseline window. Three process deviations were found to operate concurrently on these lines: progressive die head lip wear, which deforms the melt flow front and creates conductive protrusions along the semiconductor screen interface (PD risk criterion b); line speed and water quench cooling instabilities, which induce radial thermal gradients and localised micro void nesting in the polymer bulk (criterion a); and residual emulsion lubricant from wire drawing, which vaporises under preheating and nucleates moisture induced micro cavities at the conductor boundary (criterion a). Each of these mechanisms is connected to PD risk microstructure formation through the physical pathways established in Chapter 2 [5, 6, 10].

XLPE and EPR also exhibit structurally distinct failure modes. The XLPE dominant upper MV classes (12/20 kV and 18/30 kV) are the most sensitive to gas pocket retention and degassing adequacy: any lapse in the mandatory post extrusion thermal conditioning traps volatile peroxide cross linking by products, such as methane and acetophenone, as high stress gas cavities in the bulk. EPR dominant classes, such as the 6.35/11 kV rating, exhibit different behaviour: their failure modes are constructive and dimensional rather than bulk electrical, reflecting EPR's sensitivity to filler dispersion homogeneity, in which agglomerated filler produces surface roughness and geometric deformation rather than clean voids [23, 30].

The clearest evidence for this dynamic is the inversion of the macro category mix between the two reporting periods: electrical defects fell from approximately 47 % to under 33 % of all records, while sheath and structural flaws rose to 45 %. This shift does not indicate a general deterioration in quality; rather, it tracks the mechanical condition of individual assets, confirming that the relationship between material processing and PD risk must be examined at that level of detail rather than as a single plant wide figure.

Research Question 2 — What process optimisation measures can be implemented within the industrial environment to minimise the occurrence of structural defects?

The corrective measures developed in this work correspond directly to the process variations, tooling degradation cycles, and contamination pathways identified during the study, rather than constituting generic best practice recommendations. The two highest priority initiatives require no capital expenditure: a shortened, revised die wear inspection protocol for EP102 and EP08 (Measure 1), and a formal MV to HV transition protocol requiring a purge of at least one full reel volume plus a cross sectional visual check before logging resumes (Measure 2). Together, these two procedural changes target the crosshead flow instability and the cross contamination risk responsible for most of the high consequence PD risk defects identified in this study.

A second tier of measures addresses gradual, continuous state drift rather than acute events: retuning the CV tube thermal zones on EP08 (Measure 3), adding ultrasonic water bath scanning on EP102 for earlier void detection (Measure 4), extending the thermal degassing loop on EP100 (Measure 5), and upgrading the crosshead filtration mesh on EP23 (Measure 6). Measures 7

addresses the laboratory side, improving diagnostic sensitivity against the ambient noise discussed in Chapter 5.

These measures accompany seven longer term infrastructure changes the facility has begun implementing or scheduling: substitution of water emulsion with dry oil based wire drawing lubricant, to eliminate the moisture vapour migration pathway (Measure I); stricter MV to HV cleaning boundaries (Measure II); inert purging agents to prevent carbonaceous buildup (Measure III); mechanical overhaul of the aluminium tape winding guides, to eliminate the floating potential wrinkling caused by worn rollers (Measure IV); replacement of caterpillar extractors and drive inverters, to remove the line speed micro jerks responsible for eccentricity (Measure V); installation of a hot water cooling trough loop, to prevent thermal shock water marks (Measure VI); and a full line revamp of EP102, EP08, and EP23 during a planned shutdown (Measure VII).

The temporal comparison substantiates this plan with measured evidence. Across the plant's four primary insulation extruders, the non conformance rate fell from 18.37% to 14.00% ($RR = 0.762$), driven primarily by the completed turnarounds on EP08 and EP100 ($RR = 0.475$ and 0.450). At the category level, the electrical failure modes most directly associated with these interventions also declined substantially: dielectric breakdowns ($RR = 0.623$) and burn conditions ($RR = 0.668$). This is consistent with the tooling and thermal interventions producing their intended effect, rather than coinciding with an unrelated change in production mix.

Research Question 3 — How does the relationship between voltage gradients and Partial Discharge values vary across different defect typologies?

The intensity analysis and the PRPD waveform classification converge on the same conclusion: the relationship between electric field gradient and partial discharge values depends on the geometry of the defect, not on voltage class alone.

At the voltage class level. The 18/30 kV class exhibits an elevated mean charge magnitude (186.5 pC in 2025), substantially above the lower voltage MV runs. This is consistent with the physics of thick walled insulation: a thicker wall sustains steeper internal radial temperature gradients during processing and requires a proportionally larger volume of peroxide compound per unit length, which raises the density of volatile cross linking gas pockets and the local field enhancement across the bulk [5, 53]. Under test, these bulk anomalies produce the energetic discharge pulses recorded up to 2,000 pC.

By contrast, the QMS database recorded only a small number of partial discharge flagged HV events, all confined to the 30/60 kV class; the 76/132 kV and 127/220 kV ratings recorded none. Separately, the single FAT case study in Chapter 5 recorded no partial discharge exceedance on either HV accessory tested. Together these results are consistent with the stricter cleanroom isolation and cleanliness controls applied to HV campaigns, while showing that HV's strong electrical performance is not yet absolute. The voltage band defect mode comparison supports this distinction directly: HV's share of total plant defect metres attributable to Electrical causes rose from 1.516 % in 2025 to 3.698 % in 2026, while its Structural share rose by a larger margin over

the same window (3.834 % $\rightarrow$ 6.961 %), indicating that HV non conformities remain dominated by downstream mechanical jacket and reeling issues rather than core electrical insulation failure, even as both shares grew alongside rising HV production volume.

At the defect typology level. The PRPD classification indicates that the geometry of a flaw determines both its phase distribution and its inception threshold. Internal bulk voids (Case 2, criterion a) produce a symmetric, rounded "rabbit ear" pulse cloud on the rising edges of both half cycles (0° to 90° and 180° to 270°), igniting under a comparatively modest overvoltage step (PDIV = 107.4 kV for a 76 kV cable), consistent with the Paschen ionisation threshold for an enclosed gas cavity [10, 42].

Surface and interface defects along the semiconductor screen (Cases 5 and 7, criteria b and e) exhibit different behaviour: the pulse cloud is asymmetric and phase delayed, shifted past the voltage peaks into the declining quadrants (90° to 140° and 270° to 320°), consistent with capacitive charge retention at the semiconductive interface. These boundary flaws further divide into two distinct behaviours: an acute, low PDIV cluster (54 to 55 kV, at the baseline $1.5 \times U_0$ test threshold) traced to sharp die wear protrusions concentrating the local field, and a higher PDIV cluster (70 to 90 kV) traced to milder screen roughness, requiring greater activation energy to ignite [10, 42].

One further pattern merits attention. Median apparent charge across the primary assets falls within a narrow 50 pC band (80 to 130 pC), regardless of which machine produced the cable. Read alongside the machine specific defect frequencies, this suggests that discharge *severity* is largely a plant wide material property governed by overall compound quality, whereas discharge *frequency* is genuinely machine specific and governed by local tool wear. The 220 kV factory acceptance case study in Chapter 5 is consistent with this picture: both the joint and the stress cone cleared the acceptance limit (≤ 5 pC at 318 kV), confirming that zero PD performance is achievable under adequate process control.

6.3 Main Contributions

This dissertation makes five contributions to the practice of medium and high voltage cable quality engineering and partial discharge diagnostics:

1. **A normalised, machine level defect attribution framework.** A method of attributing defects independent of raw counts and throughput, applied consistently across the 17 month window. The dependency between defect category and voltage rating is demonstrated directly by the voltage band defect mode comparison, which shows HV's Electrical and Structural defect metre shares moving in different directions and at different rates than the plant wide average, providing a normalised basis for the relationship between product geometry and defect distribution.
2. **An integrated frequency severity quality model.** The finding that the lines with the highest non conformance frequency are also, empirically, the lines producing the highest energy

discharges at FAT, while the median apparent charge across all primary assets remains within a narrow 50 pC band. Taken together, this indicates a two tier corrective strategy: tool wear governs how *often* defects occur, while material purity governs how *severe* they are.

3. **A cable body PRPD diagnostic reference library.** A classification of digital FAT records into distinct pattern families: internal voids, external laboratory corona, semiconductor interface tracking, and electronic grid noise, constructed by mapping phase angle distributions and inception voltage steps for cable body runs. This provides a reference point for distinguishing genuine processing defects from ambient laboratory artefacts.
4. **A split trend temporal monitoring methodology.** A reproducible rate ratio approach applied consistently across categories, machines, and voltage classes. This method revealed a result that an aggregate plant quality figure would have obscured entirely: a substantial improvement in dielectric reliability ($RR = 0.623$) occurring concurrently with a substantial degradation in downstream sheathing quality ($RR = 1.457$).
5. **A prioritised action plan.** An eight part corrective framework and roadmap connecting specific mechanical, filtration, and process changes to the verified root causes and asset classes identified in this study, intended as the operational baseline against which post implementation monitoring can be measured.

6.4 Limitations

Several constraints in this work should be stated explicitly. The analysis is entirely retrospective, and its accuracy is bounded by the consistency with which individual operators logged events across shifts. The structured keyword and description mining screen mitigates this concern but cannot fully eliminate inter rater variability in how a given defect was described. Attribution to a specific asset also required inferential judgement in cases where a continuous run failure was identified only at a downstream laboratory bay, introducing minor uncertainty concentrated in the lines with the smallest relative defect shares.

The January to May 2026 window is short and overlaps with the plant's seasonal maintenance shutdown, and should therefore not be interpreted as representative of a full production year. The high voltage laboratory results are similarly bounded by the test voltage applied: a defect with an ignition threshold above that voltage remains latent, and the zero PD result for HV production should be interpreted as evidence of effective process control under the test conditions used, rather than proof of the absence of any sub threshold flaw.

A further limitation concerns positional data: the most severe, highest criticality discharges were disproportionately likely to lack a recorded reel distance, as they were escalated to engineering before the position could be logged. This prevents a complete spatial correlation between discharge energy and reel position. Finally, polypropylene could not be evaluated empirically within the study window, and its treatment in this work therefore remains theoretical.

6.5 Future Work

Five directions follow from the root cause synthesis and the limitations identified above:

1. **Empirical polypropylene comparison (RQ1 and RQ3).** A dedicated data collection effort during a polypropylene production run of sufficient volume to support a statistically stable NCF comparison with XLPE and EPR under matched manufacturing conditions. This would directly test whether eliminating the cross linking peroxide reaction also removes the bulk void formation pathway, and whether PP's crystalline morphology introduces a different mode of field concentration.
2. **Longitudinal validation and control charting (RQ2).** Extension of the retrospective analysis across further production quarters to conduct a formal before/after evaluation of the seven corrective measures already underway. Statistical process control charting would establish whether the overhauls stabilise the lines over time, with particular attention to the outer jacket and semiconductor screen categories that continued to degrade at the end of this study's window.
3. **Upstream precursor detection and in line scanning (RQ2 and RQ3).** A feasibility study on integrating 100 μm ultrasonic water bath scanners and continuous online tan delta monitoring directly into the continuous vulcanisation line [32, 68], to evaluate the cost and benefit of detecting defects before reel take up relative to the current practice of detection in the downstream laboratory.
4. **An automated PRPD diagnostic library (RQ3).** Use of the classified cable body PRPD records from this study as a labelled training set for a pattern recognition algorithm, with the aim of constructing a factory specific fingerprint library capable of distinguishing genuine bulk voids and interface tracking from external corona and grid noise automatically, thereby accelerating quality disposition.
5. **Long term in service reliability validation (RQ1 and RQ3).** A field monitoring programme following cable produced into service, using Very Low Frequency (VLF) or Damped AC (DAC) diagnostic testing one to five years after installation [54]. This represents the element required to close the loop that this dissertation cannot close independently: connecting factory processing parameters and FAT measurements to in service cable performance.

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Appendix A

Appendix A — Full Data Tables

The tables in this appendix contain the complete numerical data underlying the figures and analysis in Chapter 4. They are provided for verification, secondary analysis, and completeness of the academic record. All tables in this appendix are numbered sequentially to provide a straightforward, chronological reference framework.

Phase 1 — Machine Distribution

Table A.1: Per-machine NCF rates — 2025 and Jan–May 2026 (Metric 1(i))

Machine	'25 (%)	'26 (%)	RR	T	Machine	'25 (%)	'26 (%)	RR	T
AR02	8.073	0.000	0.000	↓	EP15	1.696	0.000	0.000	↓
AR03	3.991	0.000	0.000	↓	EP23	11.108	15.241	1.372	↑
BL50	0.309	0.000	0.000	↓	EP27	12.479	19.883	1.593	↑
BL100	3.792	0.446	0.118	↓	EP28	8.403	8.525	1.015	↑
BL101	0.563	0.708	1.258	↑	EP51	0.545	0.000	0.000	↓
CB100	0.000	2.003	—	↑	EP100	12.651	8.706	0.688	↓
EP05	6.015	10.693	1.778	↑	EP101	12.004	19.625	1.635	↑
EP07	11.134	8.145	0.732	↓	EP102	29.107	19.107	0.656	↓
EP08	24.651	10.997	0.446	↓	GT16	0.050	0.000	0.000	↓
EP14	17.649	76.875 [†]	—	—	GT101	3.501	2.437	0.696	↓

[†]EP14 2026: one defect on near-zero output; excluded from comparative analysis.

Table A.4: Machine facility defect share — 2025 and Jan–May 2026 (Metric 1(ii)).

Machine	'25 Share	'26 Share	RR	T	Machine	'25 Share	'26 Share	RR	T
AR02	0.037	0.000	0.000	↓	EP23	1.126	1.854	1.647	↑
AR03	0.054	0.000	0.000	↓	EP27	0.039	0.045	1.154	↑
BL50	0.004	0.000	0.000	↓	EP28	0.008	0.007	0.875	↓
BL100	0.139	0.046	0.331	↓	EP51	0.004	0.000	0.000	↓
BL101	0.068	0.098	1.441	↑	EP100	0.726	0.368	0.507	↓
CB100	0.009	0.135	—	↑	EP101	1.099	2.175	1.979	↑
EP05	0.894	2.035	2.276	↑	EP102	1.760	1.702	0.967	↓
EP07	0.216	0.026	0.120	↓	GT16	0.002	0.000	0.000	↓
EP08	1.606	0.808	0.503	↓	GT101	0.095	0.134	1.411	↑
EP14	0.213	0.029	—	↓	MAN	0.437	0.424	0.970	↓
EP15	0.020	0.000	0.000	↓	Others	0.184	0.273	1.484	↑

Total: 2025: **8.741 %** | 2026: **10.158 %** | RR: **1.162 (↑)**

Table A.7: Machine defect-metre share — 2025 and Jan–May 2026 (Metric 1(iii)).

Machine	'25 Share	'26 Share	RR	T	Machine	'25 Share	'26 Share	RR	T
AR02	0.419	0.000	0.000	↓	EP23	12.879	18.256	1.418	↑
AR03	0.618	0.000	0.000	↓	EP27	0.452	0.444	0.982	↓
BL50	0.048	0.000	0.000	↓	EP28	0.095	0.064	0.674	↓
BL100	1.596	0.450	0.282	↓	EP51	0.049	0.000	0.000	↓
BL101	0.773	0.963	1.246	↑	EP100	8.309	3.621	0.436	↓
CB100	0.098	1.325	13.520	↑	EP101	12.577	21.410	1.702	↑
EP05	10.226	20.030	1.959	↑	EP102	20.141	16.755	0.832	↓
EP07	2.472	0.256	0.104	↓	GT16	0.024	0.000	0.000	↓
EP08	18.370	7.954	0.433	↓	GT101	1.086	1.323	1.218	↑
EP14	2.433	0.286	0.118	↓	MAN	5.000	4.176	0.835	↓
EP15	0.234	0.000	0.000	↓	Others	2.102	2.687	1.278	↑

Phase 2 — Defect Category Distribution

Table A.10: Defect category normalised to total production metres — 2025 vs. 2026 (Metric 1(iv)).

‡Consolidated Dielectric Strength RR = 0.678.

Category	'25	'26	RR	Category	'25	'26	RR
Sheath Appearance	1.045	2.281	2.183	Sheath Thickness	0.013	0.006	0.462
Conductor Insul. App.	0.383	0.381	0.995	Sheath Faults	0.218	0.139	0.638
Structural Aspects	0.910	1.287	1.414	Curing Rate	0.147	0.224	1.524
Partial Discharges	1.843	1.769	0.960	Footage / Meterage	0.032	0.063	1.969
Dielectric Strength‡	2.300	0.327	0.142	Marking	0.207	0.220	1.063
Di. Strength – Sheath	—	0.358	—	Unacceptable Length	0.063	0.060	0.952
Di. Strength – Insul.	—	0.874	—	Oxidation	0.008	0.025	3.125
Poorly Guided Cable	0.227	0.807	3.555	Customer Complaints	0.016	0.017	1.063
Packed in Incompl. Reel	0.033	0.089	2.697	Continuity	0.105	—	0.000
Cable Damaged/Handling	0.218	0.188	0.862	Inaccessible Ends	0.106	0.020	0.189
Deteriorated Reel	0.170	0.375	2.206	Core Diameter	0.004	—	0.000
APF Returns	0.123	0.371	3.016	Watertightness	0.011	—	0.000
Eccentricity	0.238	0.080	0.336	Internal Water Presence	0.054	—	0.000
Insulation Diameter	0.095	0.054	0.568	“CSI” Registries	0.003	—	0.000
Insulation Thickness	0.125	0.144	1.152	Tape Overlapping	0.005	—	0.000
				Color	0.040	—	0.000

Total: 2025: 8.741 % | 2026: 10.158 % | RR: 1.162 (↑)

Table A.11: Defect category defect-metre share — 2025 vs. 2026 (Metric 1(v)). ‡Consolidated

Dielectric Strength RR = 0.583.

Category	'25	'26	RR	Category	'25	'26	RR
APF Returns	1.404	3.653	2.602	Inaccessible Ends	1.217	0.195	0.160
Cable Damaged/Handling	2.490	1.849	0.743	Insulation Diameter	1.089	0.532	0.489
Color	0.453	0.000	0.000	Insulation Thickness	1.430	1.414	0.989
Conductor Insul. App.	4.385	3.752	0.856	Marking	2.366	2.162	0.914
Continuity	1.197	0.000	0.000	Oxidation	0.094	0.246	2.617
Core Diameter	0.047	0.000	0.000	Packed in Incompl. Reel	0.377	0.881	2.337
“CSI” Registries	0.038	0.000	0.000	Partial Discharges (PD)	21.089	17.416	0.826
Curing Rate	1.683	2.210	1.313	Poorly Guided Cable	2.592	7.944	3.065
Customer Complaints	0.182	0.166	0.912	Internal Water Presence	0.615	0.000	0.000
Dielectric Strength‡	26.318	3.220	0.122	Sheath Appearance	11.958	22.451	1.877
Di. Strength – Insul.	0.000	8.603	—	Sheath Faults	2.489	1.368	0.550
Di. Strength – Sheath	0.000	3.523	—	Sheath Thickness	0.143	0.062	0.434
Deteriorated Reel	1.946	3.693	1.898	Structural Aspects	10.406	12.670	1.218
Eccentricity	2.724	0.787	0.289	Tape Overlapping	0.054	0.000	0.000
Footage / Meterage	0.371	0.618	1.665	Unacceptable Length	0.717	0.586	0.818
				Watertightness	0.126	0.000	0.000

Phase 3 — Voltage Level Distribution

Table A.12: Internal defect rates and total metre throughput by voltage class — 2025 vs. Jan–May 2026 (EP100, EP23, EP08, EP102).

Voltage (kV)	2025			Jan–May 2026		
	Defect (m)	Total (m)	% Within Class	Defect (m)	Total (m)	% Within Class
5	26,580	320,027	8.306	0	0	0.000
6/10	930	81,490	1.141	0	11,085	0.000
6.35/11	183,075	978,738	18.705	62,786	659,620	9.519
8.7/15	545,902	3,512,629	15.541	137,813	1,036,329	13.298
12/20	336,508	1,067,064	31.536	112,329	488,325	23.003
15	0	31,020	0.000	—	—	—
15/25	—	—	—	0	55,970	0.000
18/30	103,693	521,536	19.882	20,275	104,731	19.359
19/33	38,325	71,220	53.812	3,504	5,763	60.802
26/45	6,518	46,007	14.167	1,885	3,450	54.638
30/60	19,201	130,876	14.671	12,063	132,329	9.116
35	8,702	58,308	14.924	5,903	10,600	55.689
52/90	0	350	0.000	—	—	—
64/110	0	2,817	0.000	0	0	0.000
76/132	5,652	101,404	5.574	7,240	92,503	7.827
150/170	0	11,672	0.000	0	0	0.000
127/220	3,206	24,849	12.902	850	4,407	19.287
Total	1,278,292	6,960,007	18.366	364,648	2,605,112	13.997

Table A.14: Share of global defect metres by Voltage Level — 2025 vs. 2026.

Voltage Level (kV)	2025 (%)	2026 (%)	RR
6/10	0.073	0.000	0.000
5	2.079	0.000	0.000
6.35/11	14.322	17.218	1.202
8.7/15	42.706	37.793	0.885
12/20	26.325	30.805	1.170
18/30	8.112	5.560	0.685
19/33	2.998	0.961	0.321
15/25	—	0.000	—
35	0.681	1.619	2.378
26/45	0.510	0.517	1.014
30/60	1.502	3.308	2.202
64/110	0.000	0.000	—
76/132	0.442	1.985	4.491
150/170	0.000	0.000	—
127/220	0.251	0.000	0.000

Table A.16: Share of global production metres by Voltage Level — 2025 vs. 2026.

Voltage Level (kV)	2025 (%)	2026 (%)	RR
6/10	0.013	0.000	0.000
5	0.382	0.000	0.000
6.35/11	2.630	2.410	0.916
8.7/15	7.843	5.290	0.674
12/20	4.835	4.312	0.892
18/30	1.490	0.778	0.522
19/33	0.551	0.135	0.245
15/25	—	0.000	—
35	0.125	0.227	1.816
26/45	0.094	0.072	0.766
30/60	0.276	0.463	1.678
64/110	0.000	0.000	—
76/132	0.081	0.278	3.432
150/170	0.000	0.000	—
127/220	0.046	0.000	0.000
Total	18.366	13.965	0.760

Phase 3 — Machine × Voltage Cross-Tables

Table A.18: Machine defect percentages by voltage level — 2025 (share of total plant defect metres).

Voltage Level (kV)	EP23	EP08	EP100	EP102	Other EPs	Other Mach.	MAN
6/10	0.000	0.000	0.043	0.000	0.013	0.000	0.000
5	0.000	1.241	0.000	0.000	2.841	0.000	1.122
6.35/11	0.746	6.310	0.000	1.493	4.539	0.718	0.662
8.7/15	10.919	6.868	4.257	3.450	9.407	2.187	3.045
12/20	0.428	3.951	1.879	9.458	5.074	0.290	0.768
18/30	0.000	0.000	0.377	4.062	1.956	0.000	0.503
19/33	0.287	0.000	0.231	1.271	0.634	0.090	0.269
35	0.000	0.000	0.000	0.406	0.186	0.000	0.000
26/45	0.000	0.000	0.304	0.000	0.159	0.043	0.000
30/60	0.094	0.000	0.803	0.000	1.826	0.189	0.614
64/110	0.000	0.000	0.000	0.000	0.027	0.098	0.000
76/132	0.000	0.000	0.264	0.000	0.956	0.074	0.199
150/170	0.000	0.000	0.000	0.000	0.132	0.044	0.040
127/220	0.000	0.000	0.150	0.000	0.415	0.000	0.022
Total	12.475	18.370	12.313	20.141	32.227	3.733	9.221

Table A.20: Machine defect percentages by voltage level — 2026 (share of total plant defect metres).

Voltage Level (kV)	EP23	EP08	EP100	EP102	Other EPs	Other Mach.	MAN
6/10	0.444	0.000	0.000	0.000	0.118	0.000	0.192
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6.35/11	0.606	5.585	0.000	1.556	8.635	0.280	0.920
8.7/15	13.774	1.508	1.153	0.569	11.064	2.898	2.853
12/20	0.126	0.861	0.316	12.558	10.503	0.062	0.579
18/30	2.235	0.000	0.000	0.267	1.551	0.125	0.248
19/33	0.432	0.000	0.000	0.000	0.613	0.000	0.000
25	0.000	0.000	0.000	1.592	0.176	0.000	0.000
35	0.515	0.000	0.000	0.213	0.000	0.000	0.000
26/45	0.233	0.000	0.000	0.000	0.193	0.000	0.000
30/60	0.334	0.000	1.154	0.000	2.838	0.158	0.871
64/110	0.000	0.000	0.000	0.000	0.000	0.000	0.000
76/132	0.000	0.000	0.893	0.000	5.203	0.000	1.107
150/170	0.000	0.000	0.000	0.000	0.338	0.000	0.000
127/220	0.000	0.000	0.105	0.000	0.751	0.092	0.000
Total	18.699	7.955	3.621	16.755	41.980	3.624	7.425

Table A.22: Defect Macro Categories Consolidated by Voltage Level for the Year 2025

Voltage Level	Electrical Defects	Structural Defects	Other Defects
6/10 kV	0.04343	0.01261	0.00000
5 kV	1.47900	1.93935	1.90842
6.35/11 kV	6.39372	4.96071	1.70471
8.7/15 kV	20.82183	12.19323	4.37272
12/20 kV	10.85260	8.25610	1.10320
18/30 kV	4.78195	2.10382	0.54262
19/33 kV	1.13869	1.25123	0.31730
35 kV	0.38025	0.12189	0.04301
26/45 kV	0.04950	0.35665	0.00000
30/60 kV	0.71837	2.04900	0.45965
64/110 kV	0.50060	0.15029	0.00000
76/132 kV	0.00000	0.79305	0.17378
150/170 kV	0.00000	0.17616	0.00000
127/220 kV	0.24766	0.30851	0.07052

Table A.24: Defect Macro Categories Consolidated by Voltage Level for the Year 2026

Voltage Level	Electrical Defects	Structural Defects	Other Defects
6/10 kV	0.00000	0.31095	0.44421
5 kV	0.00000	0.00000	0.00000
6.35/11 kV	6.88258	8.40369	2.61019
8.7/15 kV	13.31354	12.42152	7.91574
12/20 kV	7.57641	11.47041	3.96253
18/30 kV	0.70581	2.61137	1.10955
19/33 kV	0.43237	0.06256	0.55009
25 kV	0.00000	1.76759	0.00000
35 kV	0.06453	0.66385	0.00000
26/45 kV	0.07650	0.15609	0.00000
30/60 kV	1.34029	2.85623	1.15877
64/110 kV	0.00000	0.00000	0.00000
76/132 kV	1.49304	3.54353	2.21316
150/170 kV	0.11364	0.22396	0.00000
127/220 kV	0.67446	0.18151	0.09193

Phase 5 — Temporal Comparison

Table A.26: Defect type share shifts and rate ratios 2025 vs. Jan–May 2026.

Group	Defect Type	2025 (%)	2026 (%)	$\Delta\%$ Share	Trend	RR
Electrical & Insulation	Burned / Blown	19.581	13.073	−6.508	↓	0.668
	Partial Discharges	20.240	14.960	−5.280	↓	0.739
	Dielectric Strength	24.431	15.229	−9.202	↓	0.623
	Semiconductor SCI / SCE	3.353	2.561	−0.792	↓	0.764
Outer Sheath & Mechanical	Sheath Appearance	27.006	39.353	+12.347	↑	1.457
	Blisters / Bubbles	4.431	4.313	−0.118	↓	0.973
	Scratched / Damaged	2.934	7.278	+4.344	↑	2.480
	Water Marks	0.419	4.852	+4.433	↑	11.575
	Crease / Flattened	0.419	1.617	+1.198	↑	3.858
	Burned Material (Sheath)	1.557	4.043	+2.486	↑	2.597
Component & Tape	Al/PE Tape	0.958	2.426	+1.468	↑	2.532
	Water-swellaable Tape	1.018	0.539	−0.479	↓	0.530
	Copper Tape / Wires	0.060	0.000	−0.060	↓	0.000
	Shielding / Screening	0.719	0.674	−0.045	↓	0.938
Bobbin & Structure	Flange / Edge	2.395	6.334	+3.939	↑	2.645
	Tie Rod / Stay	0.000	2.426	+2.426	↑	∞
	Poorly Guided / Cabled	3.952	8.491	+4.539	↑	2.148
Process & Machinery	Machine Stop	0.000	0.135	+0.135	↑	∞
	Power Failure	0.060	0.000	−0.060	↓	0.000
	Caterpillar / Variator	0.299	0.539	+0.240	↑	1.801
	Pigmenter	0.180	0.270	+0.090	↑	1.500

Table A.28: Side-by-side comparison of machine share shifts, trends, and rate ratios (case-corrected and balanced).

Machine	25(%)	26(%)	$\Delta\%$	Sh	Trd	RR	Machine	25(%)	26(%)	$\Delta\%$	Sh	Trd	RR
AR02	0.120	0.000	-0.120	↓	0.000		EP102	17.306	14.286	-3.020	↓	0.834	
AR03	0.180	0.000	-0.180	↓	0.000		EP14	1.737	0.135	-1.602	↓	0.078	
BL100	1.976	0.539	-1.437	↓	0.273		EP15	0.060	0.000	-0.060	↓	0.000	
BL101	0.898	0.809	-0.089	↓	0.900		EP23	11.737	13.747	+2.010	↑	1.177	
BL50	0.060	0.000	-0.060	↓	0.000		EP27	0.539	0.135	-0.404	↓	0.250	
CB100	0.060	3.100	+3.040	↑	51.765		EP28	0.060	0.135	+0.075	↑	2.251	
EP05	12.754	19.811	+7.057	↑	1.553		EP51	0.060	0.000	-0.060	↓	0.000	
EP07	1.916	0.270	-1.646	↓	0.141		GT101	2.754	2.965	+0.211	↑	1.076	
EP08	14.192	6.739	-7.453	↓	0.475		GT16	0.060	0.000	-0.060	↓	0.000	
EP100	8.683	3.908	-4.775	↓	0.450		MAN	4.671	4.313	-0.358	↓	0.935	
EP101	17.545	25.876	+8.331	↑	1.490		Others	2.395	3.235	+0.840	↑	1.350	

Table A.31: Side-by-side comparison of voltage level share shifts, trends, and rate ratios.

Voltage	25(%)	26(%)	$\Delta\%$	Sh	Trd	RR	Voltage	25(%)	26(%)	$\Delta\%$	Sh	Trd	RR
5 kV	1.677	0.000	-1.677	↓	0.000		35 kV	0.958	0.809	-0.149	↓	0.844	
6/10 kV	0.240	0.674	+0.434	↑	2.813		26/45 kV	0.479	0.539	+0.060	↑	1.125	
6,35/11 kV	18.263	18.868	+0.605	↑	1.033		30/60 kV	5.928	7.143	+1.215	↑	1.205	
8,7/15 kV	36.886	31.536	-5.350	↓	0.855		52/90 kV	0.000	0.000	+0.000	↓	0.000	
12/20 kV	18.024	21.294	+3.270	↑	1.181		64/110 kV	0.180	0.000	-0.180	↓	0.000	
15/25 kV	0.000	1.078	+1.078	↑	∞		76/132 kV	2.994	11.590	+8.596	↑	3.871	
18/30 kV	8.144	3.100	-5.044	↓	0.381		150/170 kV	0.359	0.404	+0.045	↑	1.125	
19/33 kV	4.491	1.348	-3.143	↓	0.300		127/220 kV	1.138	1.617	+0.479	↑	1.421	

Table A.34: Cable position by defect type 2025 vs. Jan–May 2026.

Defect Type	Year	Exterior (%)	Interior (%)	Ext:Int
Burned / Blown	2025	48.6	3.4	159:11
	2026	33.0	4.1	32:4
Partial Discharges	2025	66.6	3.6	225:12
	2026	72.1	3.6	80:4
Dielectric Strength	2025	40.7	4.2	166:17
	2026	29.2	5.3	33:6
Semiconductor SCI	2025	5.4	5.4	3:3
	2026	5.3	21.1	1:4
Sheath Appearance	2025	6.4	21.5	29:97
	2026	3.8	12.0	11:35
Al/PE Tape	2025	6.3	43.8	1:7
	2026	0.0	77.8	0:14
All occurrences	2025	26.6	12.8	444:214
	2026	18.2	8.6	135:64

Table A.36: Partial Discharge (PD) intensity summary analysis by voltage level (2025 vs. 2026).

Voltage	2025				2026				Trend
	Mean (pC)	Med. (pC)	Max (pC)	% >200	Mean (pC)	Med. (pC)	Max (pC)	% >200	
6.35/11 kV	104	90	300	5.6	182	90	800	18.8	↑
8.7/15 kV	156	80	800	19.6	126	100	400	12.8	↓
12/20 kV	243	100	2000	27.5	130	80	900	9.7	↓
18/30 kV	187	150	800	7.7	40	40	40	0.0	↓
19/33 kV	144	90	500	11.1	161	103	400	25.0	↑
30/60 kV	75	75	80	0.0	230	115	500	33.3	↑

Table A.37: Partial Discharge (PD) intensity summary analysis by manufacturing unit (2025 vs. 2026)

Machine	2025				2026				Trend
	Mean (pC)	Med. (pC)	Max (pC)	% >200	Mean (pC)	Med. (pC)	Max (pC)	% >200	
EP23	233	120	2000	22.9	146	85	800	15.4	↓
EP102	138	100	700	10.2	114	80	550	12.1	↑
EP08	186	93	1000	26.9	184	93	900	16.7	↓
EP100	133	80	500	16.0	120	130	150	0.0	↓
EP05 [†]	430	430	800	50.0	—	—	—	—	—

[†]EP05 2025: Indicative only due to low sample density. No parseable pC records for EP05 in 2026.