

Thermal Degradation in Underground Cable Joints: Techniques, Causes, and Diagnostic Advances – A Review

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Underground cable (UC) joints are among the most failure-prone components in power distribution networks, particularly under thermal stress. This review explores a range of jointing methods and diagnostic approaches used to assess thermal degradation (TD) in UC joints. The discussion begins with the structural components of high-voltage cables, followed by a comparison of mechanical, electromagnetic, heat-shrink, cold-shrink, and exothermic welding techniques. Each method is evaluated based on materials, performance, application principles, and known limitations. The paper also analyses key contributors to TD, including electrical overloading, improper joint construction, and environmental exposure, with attention to material-level effects such as insulation embrittlement and conductor oxidation. Several diagnostic strategies are assessed, including infrared thermography (IRT), partial discharge (PD) testing, real-time thermal monitoring, and emerging tools like acoustic emission (AE) and AI-driven sensing. A comparative evaluation highlights the trade-offs between sensitivity, practicality, and field performance under various conditions. Accordingly, this review synthesises recent and foundational research to address three questions: (1) What are the dominant causes and pathways of TD in UC joints? (2) How do joint technologies and installation/maintenance practices influence thermal aging risk? (3) Which diagnostic techniques are most effective for detecting TD, and what are their limitations in field deployment? The findings emphasise the importance of integrated monitoring, standardised practices, and appropriate material selection to enhance long-term reliability. Future research should focus on the integration of advanced diagnostic technologies such as AI-driven predictive maintenance systems and real-time thermal monitoring to improve the detection of early-stage TD.

Keywords: underground cable joints; thermal degradation; jointing techniques; diagnostic methods; partial discharge monitoring

I. INTRODUCTION

Underground cables (UCs) were first used for electrical power transmission at large cities in late 19th century such as Berlin and New York to handle safety and aesthetic issues related with overhead lines (Orton, 2013; Valle *et al.*, 2012; Rafati *et al.*, 2024). The initial designs utilised paper-insulated lead-covered (PILC) cables, which were efficient at the time but were susceptible to insulation breakdown and moisture

infiltration (Zhou *et al.*, 2017). Synthetic polymers include ethylene propylene rubber (EPR) and cross-linked polyethylene (XLPE) transformed UC systems by providing exceptional dielectric strength and thermal stability (Barber and Alexander, 2013; Pleša *et al.*, 2019).

Long-distance deployment of UCs presents several technical and logistical difficulties, mostly related to cable length restrictions, thermal management, and voltage-related issues (Gordonnat and Hunt, 2020; Y. Li *et al.*, 2024).

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One important solution is the deliberate use of UC joints, which allow dependable, safe extension of cable runs over great distances. These joints preserve the electrical, mechanical, and thermal continuity of the cable system, ensuring safe and efficient power delivery across extended distances. Despite advancements in materials, design, and installation techniques, UC joints remain vulnerable to a range of failure mechanisms. These issues can compromise the overall integrity of the power system, leading to service interruptions, costly repairs, and, in some cases, safety hazards (Calcara *et al.*, 2019; M Pompili *et al.*, 2021; Bosisio *et al.*, 2025). Field studies have reported that 60–70% of UC system failures originate at joints or terminations, often due to improper installation or thermal aging (Calcara *et al.*, 2019; Massimo Pompili *et al.*, 2021).

One of the most common challenges in UC joints is electrical discontinuity (Udomluksananon *et al.*, 2023; Pompili and Calcara, 2024; D’Orazio *et al.*, 2023), often caused by improper crimping, corrosion, or misalignment of conductors (Mazzanti, 2021; Yong *et al.*, 2025). Electrical faults at the joint interface may result in elevated contact resistance, which not only increases power losses but also leads to localised heating. This electrical imbalance can escalate into more severe forms of degradation if not promptly addressed. Another prevalent issue is insulation failure, typically initiated by voids, contaminants, or improper layering of the joint insulation system. Such defects can cause partial discharges (PDs), which are localised dielectric breakdowns that progressively erode the insulation material and may eventually result in catastrophic electrical failure (Calcara *et al.*, 2019; Yong *et al.*, 2025).

Mechanical failures also contribute significantly to joint degradation (Alhusin *et al.*, 2022). These include tensile stresses during installation, ground movement over time, and vibration from fault currents or seismic activity. Improper joint anchoring or weak mechanical protection can cause micro-movements within the joint structure and may result into insulation fatigue or conductor loosening. Furthermore, environmental factors such as moisture ingress, chemical attack from surrounding soil, or thermal cycling due to seasonal variations can further exacerbate joint vulnerabilities (Bosisio *et al.*, 2025). Among all these

challenges, thermal degradation (TD) stands out as one of the most insidious and impactful failure modes in UC joints.

The increasing adoption of distributed energy resources (DERs), electric vehicles (EVs), and bidirectional power flows is introducing more frequent load variability and thermal cycling in UC systems, making joint hot-spots and insulation aging more difficult to manage in practice. In response, this review synthesises recent and foundational literature on: (i) UC structure relevant to heat generation and dissipation, (ii) practical jointing methods and how workmanship/geometry influence thermal behaviour, (iii) TD mechanisms at joint interfaces (including hot-spot formation and material aging), and (iv) diagnostic advances ranging from infrared thermography and PD testing to real-time thermal monitoring and data-driven approaches. Table 1 positions this review against existing surveys by highlighting that, while prior reviews focus on cable life-cycle management or PD diagnostics, fewer works integrate jointing practice, thermal failure mechanisms, and field-ready diagnostics into a single critical framework. The objective is to provide a structured reference for researchers and utility engineers and to clarify where current evidence is strong versus where lab-to-field gaps still limit confident decision-making.

Table 1. Comparison between this review and existing review literature on TD in UC joints and diagnostics

Ref.	Scope	Main strength	Main limitation
(Zhou <i>et al.</i> , 2017)	Life cycle analysis of power cables	Provides a clear overview of insulation aging and degradation across service time	Does not focus specifically on joint-related issues
(Govindarajan <i>et al.</i> , 2023)	Techniques to detect PD	Provides detailed explanation of PD techniques, signals and tools	Covers PD in detail without addressing other thermal or mechanical diagnostics
(Mingotti <i>et al.</i> , 2025)	Testing and reliability of MV cable joints	Overview on testing standards and recent trends in cable joint monitoring	Lacks comparative analysis of diagnostic tools and field performance
This review	Cable jointing methods, TD causes and diagnostics techniques	Combines cable jointing methods, failure mechanisms and diagnostics evaluation in one framework	Field-level validation and long-term performance data are still limited

II. STRUCTURES AND COMPONENTS OF UC

UCs serve a significant part in current power distribution networks, operating discreetly below ground to provide a continuous supply of electricity. In contrast to overhead lines that are vulnerable to open air conditions, these cables perform in tough underground settings surrounded by soil, moisture, heat, and pressure (Emmerling *et al.*, 2024; Rengaraj *et al.*, 2021). As a result, it is crucial that UCs are manufactured to provide both longevity and reliable electrical performance over an extended duration. In solving these issues, UCs are created with numerous layers (as shown in Figure 1), each performing a particular role. The layers serve numerous tasks beyond electrical conduction and play a significant role in heat management, moisture resistance, and protection against physical damage. However, like any system, every layer possesses restrictions, notably for prolonged exposure to heat. The fundamental components of UCs and their relevance are detailed as follows:

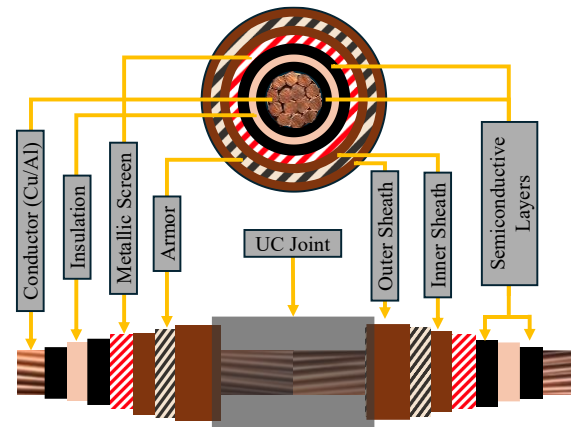


Figure 1. Fundamental structure of UC (adapted from Ozyesil *et al.*, 2024)

i. Conductor

The conductor is the fundamental component of the wire responsible for transmitting electricity (Lesur *et al.*, 2018). It is generally made of copper (Cu), owing to its superior electrical conductivity, or aluminium (Al), which is lighter and more cost-effective. The conductor generally consists of multiple fine strands intertwined rather than being a unique solid unit. This improves the elasticity of the cable, facilitating installation and accommodating slight underground movements.

ii. Insulation

The insulation covers the conductor to prevent electricity from dissipating into the surrounding material (Arikan *et al.*, 2023). Currently, XLPE is the predominant insulating material utilised in the UC systems. It exhibits excellent performance at elevated temperatures (up to approximately 90 °C) and possesses substantial

electrical resistance. Nevertheless, prolonged exposure to thermal and electrical stress can contribute towards degradation, resulting in a loss of its protective attributes.

iii. Semiconductive Layers

Semiconductive layers are thin layers situated between the conductor and insulation, as well as between the insulation and the outer sheath. These layers are responsible for enhancing the uniformity of the electric field within the wire (Nadolny, 2022; Ghosh and Das, 2022). In the absence of the semiconductive layers, some spots may endure increased stress, potentially compromising the insulation over time.

iv. Sheath

The sheath functions as a durable outer covering for the cable, securing the internal components from water, chemicals, and physical harm, including accidental digging. Materials such as polyvinyl chloride (PVC) or lead (Pb) are typically utilised for fabrication of the sheath. Despite its high strength, the sheath is susceptible to cracking when subjected to extreme heat or physical force (D’Orazio *et al.*, 2023; Jariyanurat *et al.*, 2024; Czapp and Dobrzynski, 2020; Chi *et al.*, 2020; G. Li *et al.*, 2024).

v. Cable Joints

Cables are typically installed in segments, which require connections at regular intervals through cable joints. Some of the most critical components of the system are represented by these joints. Although intended to replicate the structure of the cable, cable joints are subject to additional risks (Bao *et al.*, 2023; Lin *et al.*, 2024; Y. Sun *et al.*, 2024), including:

- Distorted electric fields: Small flaws in the shape or alignment of the joint can lead towards uneven electrical stress, which may damage the insulation.
- Material differences: The materials used in the joint may not expand and contract at the same rate as the cable when temperatures change. This can cause small gaps to form, making the joint weaker over time.
- Tiny defects at contact points: Air bubbles, dust, or other small imperfections at the connection can cause PDs.

Within UC system, joints are the most prone to failure (Massimo Pompili *et al.*, 2021). Research has demonstrated that joints fracture three to five times more frequently than the cable segments alone (Calcara *et al.*, 2019). A primary factor is thermal accumulation at these junctions. Inadequately built joints, characterised by weak or irregular crimping, could generate resistance, resulting in excessive heat from power losses (Bragatto *et al.*, 2023; Wu *et al.*, 2024; Moon, 2024). Moreover, joints are typically embedded deeper or enclosed in concrete for protection, which significantly hinders their cooling capacity. The materials employed at junctions, such as cold-shrink tubing for insulation, generally deteriorate more rapidly than the XLPE utilised in the primary cable, even under same thermal conditions.

III. METHODS OF CABLE JOINT

UC joints are used to connect or repair sections of underground power cables, preserving the mechanical strength, electrical continuity, and insulation integrity, with high moisture, chemical attack, and temperature variations resistances. Proper jointing is critical for system reliability and safety in power distribution and transmission.

There are several types of UC jointing methods (presented in Figure 2), each designed to suit specific cable types, voltage levels, environmental conditions, and operational requirements. Cable joints are designed to restore electrical insulation, mechanical integrity, and environmental sealing while ensuring low-resistance current transfer across the conductor connection. In practice, joint reliability depends on the specific joint type, as well as the stability of interfaces including conductor–connector, insulation–screen cutback, and sealing surfaces under thermal cycling, moisture exposure, and long-term aging. From a thermal-degradation perspective, the jointing methods reviewed in this section are compared using the following criteria:

- i. contact resistance and its stability under thermal cycling
- ii. electric-field control at the insulation and screen interfaces
- iii. sealing effectiveness against moisture ingress
- iv. heat dissipation capability of the joint body and surrounding media, and

- v. installation sensitivity and repeatability under field constraints. Recent studies increasingly highlight that small variations in installation quality and interface condition can produce measurable differences in hotspot formation and long-term thermal aging risk

A. Crimping

The crimping technique in UC joints is vital for reliable electrical connections in power distribution. It involves mechanically joining cables and connectors through deformation to create a strong, conductive connection (Jongwuttanaruk and Thavornwat, 2022). This method is favoured for its efficiency, cost-effectiveness, and preservation of UC conductive properties (Dacian *et al.*, 2024). Proper crimping minimises contact resistance, reducing energy losses and preventing overheating in high-current situations. It also offers superior mechanical strength over soldering, making it suitable for underground environments with soil stress and vibration.

However, the dominant thermal-degradation pathway in crimped joints is typically localised hotspot development driven by elevated or unstable contact resistance, which may arise from under-crimping, over-crimping, tool misalignment, contamination, strand damage, or geometric non-uniformity. Recent electro-thermal studies and defect-oriented investigations show that common crimping imperfections can produce distinct thermal signatures and accelerate insulation stress at the joint region (Lin *et al.*, 2024; Galliana *et al.*, 2023). The prominent crimping methods include mechanical crimping and magnetic pulse crimping (MPC).

1. Mechanical Crimping

Mechanical crimping techniques like hexagonal and deep indent are popular for simplicity and effectiveness (Che Rani *et al.*, 2025). Hexagonal crimping is easy but may compromise contact quality in 240 mm² stranded Al cables. Deep-indent crimping offers improved metal contact and reduced electrical resistance (Roccatto *et al.*, 2020). In UC joint system, maintaining resistance below 50 micro-ohms is essential to prevent overheating and joint failure. Crimp quality is influenced more by indentation shape and number

rather than the applied pressure (Jiao, 2024). The stepped deep indentation technique (PPE method) achieves better results by controlling cable and connector compression. This approach ensures complete connector barrel filling and enhances connections, even with variable compression pressures (Aher *et al.*, 2024; Han *et al.*, 2024).

2. Magnetic Pulse Crimping (MPC)

MPC is a technique for joining UC cable terminals without mechanical contact. It uses a high-power current pulse from a capacitor bank to create Lorentz forces that compress the cable lug onto the terminal (Saxena and Sharma, 2021). This method provides advantages over traditional crimping, such as better surface profiles and joint strength. Ali *et al.* (2024) demonstrated that EMPC results in lower contact resistance and minimal leak rates of 10^{-5} mbar·l/s using helium. Bogaert *et al.* (2012) studied groove patterns and confirmed the effectiveness of MPC for torsion-loaded joints. Saxena *et al.* (Saxena and Sharma, 2021) reaffirmed benefits of MPC, noting stronger and smoother joints. Zhou *et al.* (2024) in another study conducted simulations showing MPC enhances corrosion resistance and long-term connection reliability.

B. Heat-shrinking

The heat-shrink method is a widely utilised technique to securely connect underground power cables. It uses materials that shrink around a cable joint when heated, creating a strong and waterproof seal. This method protects cables from environmental damage and is adaptable to various sizes and conditions. Recent studies indicate that it provides excellent electrical insulation and mechanical strength. For instance, Johri *et al.* (2022) found that heat-shrink joints reduce electric field stress in medium voltage applications, preventing failures. Similarly, Li *et al.* (2020) demonstrated that heat-shrink joints are more moisture-resistant than cold-shrink alternatives, making them reliable in harsh conditions.

The heat-shrink joint is engineered for flexibility and strength. It consists of layers for insulation, shrink recovery, and mechanical protection. These joints operate effectively at voltage levels from 0.4 kV to 10 kV, ensuring stable electrical flow. Li *et al.* (2024), indicate that this structure preserves

electrical functionality under challenging conditions. Research by Qureshi *et al.* (2014), confirms that heat-shrink materials maintain insulation even after prolonged stress. Such characteristics make the method ideal for essential applications like underground mining and marine networks, where reliability is vital.

However, careful installation is crucial to ensure the maximum effectiveness of heat-shrink method. Issues such as trapped air or misalignment can compromise the joint insulation and causing failure. Additionally, correct heat application is essential in which the insufficient heat prevents proper shrinkage while excessive heat can damage the cable. Kiitam *et al.* (2016) highlighted that improper installation causes uneven heat distribution, negatively affecting performance. Nonetheless, these risks can be mitigated through proper training and meticulous attention.

C. Cold-shrinking

The cold-shrinking technique efficiently joins underground power cables using contracting silicone rubber components instead of heat. This method enhances safety, installation ease, and adaptability, particularly in environments with flammable materials or high voltages. It is particularly beneficial in harsh settings due to the materials' chemical resistance and thermal stability. A study by Li *et al.* (2020) highlighted that cold-shrink joints experience less PD in moist conditions, validating the application of the method in corrosive environments. Similarly, Alboyaci *et al.* (2022) confirmed that cold-shrink terminations have better electric field distribution and reduced failure rates compared to heat-shrink joints.

Cold-shrink joints comprise specialised components, including a pre-expanded sleeve and conductive tapes, made from durable silicone rubber. These components are designed for elasticity and thermal stability, with the joint sleeve contracting tightly over the cable interface upon installation. Through simulation processes, Yin *et al.* (2023) demonstrated that cold-shrinkable joints facilitate uniform electric field distribution, thereby reducing insulation stress and prolonging joint lifespan. Furthermore, Yu *et al.* (2024) further confirmed that cold-shrink silicone rubber retains its

electrical properties over time, ensuring reliability in long-term underground use.

Despite their advantages, cold-shrinking method requires careful management of technical aspects. Maintaining adequate interfacial pressure between the sleeve and cable is crucial to avoid dielectric breakdown. Modern designs incorporate pull cords and support tubes for easier installation and consistent compression. Studies have introduced methods for analysing pressure distribution across cold-shrink joints, which is critical to joint reliability in medium-voltage networks (Huang *et al.*, 2024). Additionally, the selection of compatible materials for joint components is vital to prevent issues like cracking, with ongoing research aiming to enhance silicone formulations and joint mechanical behaviour for advanced energy systems.

D. Exothermic Welding

Exothermic welding, or cadweld, is a common technique for creating durable electrical connections in UCs. This method is crucial for grounding and bonding where reliability and conductivity are essential. It involves a chemical reaction between metal oxide and reducing agent (commonly CuO and Al) that produces molten metal to bond conductors, resulting in a strong and low-resistance connection (Herron *et al.*, 2025; Fan *et al.*, 2021). This connection remains effective under harsh conditions and outperforms mechanical clamps in challenging environment (Durham *et al.*, 2020; Leeburn, 2021).

The exothermic welding process requires components like a mold, a crucible, and a pre-measured mixture. Igniting the mixture produces extreme temperatures (exceeding 1400 °C), melting the conductors and filling the mold cavity to create a uniform joint. Accurate mold design and compatibility are critical for ensuring effective welds, while misalignment can weaken connections (Wenbin Zhang *et al.*, 2022). Safe handling and stable alloys are emphasised to reduce risks during storage and transport (Yan *et al.*, 2022).

Nevertheless, technical issues must be addressed for optimal performance of the UC joint. Uneven electric field distribution can cause insulation stress and failures, particularly in high-voltage situations (Herron *et al.*, 2025; Uzelac, 2021). Proper installation techniques are essential to

mitigate these risks. Research indicates that poor workmanship is the primary cause of weld failures, not material limitations (Chikkam *et al.*, 2024). Innovations in inspection techniques can help ensure weld quality, making exothermic welding a reliable choice for underground power and grounding systems (Wenbin Zhang *et al.*, 2022; Yan *et al.*, 2022).

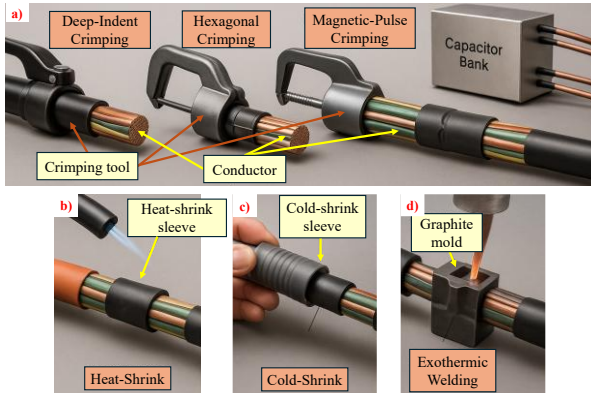


Figure 2. UC jointing method using (a) Crimping (based on Saxena *et al.* (2021) and Ali *et al.* (2024)); (b) Heat-shrinking (based on Qureshi *et al.*, 2014) ; (c) Cold-shrinking (based on Li *et al.* (2020)); (d) Exothermic welding (based on Zhang *et al.* (2022))

While jointing methods perform well under laboratory conditions, their reliability often declines in real-world environments due to factors like moisture, soil conditions, and installation quality. Crimped joints in tropical soils are prone to corrosion, increasing contact resistance and causing localised heating (Argaut, 2021). Exothermic welded joints, though strong, rely heavily on precise mold preparation, where minor misalignments or contamination during field work can weaken long-term performance (Christou, 2016). Heat-shrink joints often face issues in humid or windy environments that affect sealing quality, whereas cold-shrink joints are generally more reliable in such conditions due to the uniform, tool-free application (Li *et al.*, 2020; Mingotti *et al.*, 2025). These field conditions, combined with thermal gradients and faster insulation aging in humid climates, highlight the importance of validating joint designs under real operating conditions (Pugach *et al.*, 2019).

E. Comparison of the UC Jointing Methods

Table 2. Comparison of UC jointing methods (Qureshi *et al.*, 2014; Yang *et al.*, 2016; Taklaja *et al.*, 2016; Yang *et al.*, 2018; Durham *et al.*, 2020; Li *et al.*, 2020, 2021; Fan *et al.*, 2021; Hakim *et al.*, 2021; Alboyaci *et al.*, 2022; Wei Zhang *et al.*, 2022; Johri *et al.*, 2022; Yin, Wang and Miao, 2023; Moon, 2024; Sheng *et al.*, 2024; T. Li *et al.*, 2024; Yu *et al.*, 2024; Huang *et al.*, 2024; Lai *et al.*, 2024; Herron *et al.*, 2025)

Aspects	Crimping		Heat-shrinking	Cold-shrinking	Exothermic welding
	Mechanical	Electromagnetic			
Principle	Plastic deformation using crimping tool forming joint	Magnetic pulse causes joints to form	Polymer sleeve is heated to shrink and seal (making a joint)	Elastic sleeve contracts after removing support	Exothermic reaction melts and fuses conductors
Materials used	Cu/Al connectors	Capacitor banks and coils	Polyolefin and XLPE	Silicone rubber	CuO + Al graphite mold
Application range	LV/MV	High-precision industrial cables	LV/MV and marine utility	HV and oil and gas zones	Substation grounding
Durability	Moderate-high	Excellent	High	Very high	Excellent due to molecular bonding
Contact resistance	$\leq 50 \mu\Omega$ if optimal	Lower and uniform	Low if properly installed	Low	Very low ($\leq 50 \mu\Omega$)
Electric field distribution	Geometry-sensitive	Uniform with field shaping	Sensitive to voids	Uniform	Uneven if poorly molded
Advantages	Simple and accessible	Fast, precise and uniform process	Cost-effective	Safe process	Permanent and reliable
Limitations	Tool wear and spring-back	Expensive and complex setup	Requires heat and risk of uneven shrink	Storage affects elasticity	Field stress if misaligned

IV. THERMAL DEGRADATION AT UC JOINTS

TD in UC joints is referred to the decline of insulation and conductive materials as a result of prolonged or cyclic heating. This phenomenon is a primary contributor to joint failures in power systems, particularly when cables are subjected to high current loads or are installed in thermally resistive soils (Shaan et al., 2021; Stojanović et al., 2023). The heat produced from electrical losses or inadequate jointing can create localised hot spots that accelerate both chemical and mechanical deterioration in the insulation.

Materials such as XLPE experience degradation characterised by embrittlement and oxidation when exposed to high temperatures, which reduces the dielectric strength and elevates the risk of failure. Faulty installation practices, including the presence of voids or uneven compression, worsens this issue by concentrating thermal stress. Research indicates that even minor temperature elevations (ranging from 20 to 30 °C above ambient conditions) can drastically reduce the lifespan of insulation and provoke interfacial damage such as delamination or carbon tracking (Klimenta et al., 2022). According to IEEE 404, IEC 60502-4, and IEC 60840, cable joints must meet specific thermal, mechanical, and electrical performance requirements under accelerated aging tests. These standards guide qualification testing and diagnostic practices for medium- and high-voltage joints (Anon, 2012).

A critical aspect of TD analysis is the estimation of UC joint lifespan using Arrhenius-based aging models. These models describe the effect of temperature on the rate of chemical reactions and are commonly applied to estimate insulation degradation under elevated thermal conditions. The Arrhenius equation,

$$k = Ae^{\frac{-Ea}{RT}} \quad (1)$$

relates the degradation rate constant k to activation energy Ea , where R is the universal gas constant and T is absolute temperature. In polymeric materials like XLPE, typical activation energies range between 0.8 to 1.2 eV, depending on the degree of cross-linking and thermal stabilisation additives (Stojanović et al., 2023). By applying this model to accelerated thermal aging data, researchers can estimate how long the material would last under normal conditions. For

example, an increase of just 10 °C in operating temperature can reduce the insulation lifespan by half, as shown in simulation studies on cable joints (Klimenta et al., 2022). This approach helps in improving joint designs, setting temperature limits, and ensuring long-term performance in power systems.

A. Primary Causes of TD

TD in UC joints arises from a combination of electrical, mechanical, and environmental factors. Electrical overloading produces resistive (I^2R) heating at joint interfaces, especially in poorly compressed or undersized conductors, lead towards localised hotspots that accelerate insulation breakdown (Rafati et al., 2024). Improper jointing practices, such as misaligned connectors or insufficient crimp pressure, can disrupt heat dissipation and trigger thermal runaway. Environmental conditions, including backfill with low thermal conductivity, restrict heat dispersion and intensify thermal stress within the joint (Enescu et al., 2021). Recent studies increasingly demonstrate that when a joint develops a localised hotspot, secondary effects such as material softening, oxidation, loss of interfacial pressure, and PD activity can exacerbate heating, thereby creating a positive feedback loop that accelerates aging and increases the possibility of failure (Emdadi et al., 2025; Z. Zhang et al., 2025). Figure 3 summarises the primary causes of TD at UC joints.

1. Electrical drivers

An primary cause of overheating is increased or unstable contact resistance at the conductor–connector interface, often linked to improper compression, misalignment, corrosion, or incompatibility between the connection and conductor (Wu et al., 2024; Bao et al., 2023). As contact resistance builds, localised power loss (I^2R) intensifies significantly, generating hotspots that may exceed the thermal aging limit of the polymeric insulation surrounding the joint. Recent electro-thermal simulations and experimental investigations indicate that common joint faults generate unique temperature-rise patterns and can significantly change thermal stability under load, even when the bulk cable remains within acceptable limits (Chen et al.,

2024; Zhao *et al.*, 2023). In parallel, harmonic-rich and transient loading conditions, which arise from nonlinear loads, switching, and changing operating profiles, can increase effective losses and aggravate thermal gradients, contributing to accelerated insulation aging and PD initiation (Saleh *et al.*, 2025).

2. Installation and mechanical drivers

Joint workmanship influences TD through the evolution of interfaces with repeated thermal cycling as well as initial flaws (voids, inadequate stress control, and incomplete sealing). Cyclic expansion and contraction can cause micro-movements, progressive loss of interfacial pressure, and fatigue at critical interfaces including conductor-conductor interface and insulation-screen cutback, increasing the likelihood of both resistive heating and PD-related deterioration (Z. Li *et al.*, 2024; Mingotti *et al.*, 2025). Therefore, the cause of TD at UC joint is often not the joint type itself but the sensitivity of the joint design to workmanship variability and thermal-mechanical cycling.

3. Environmental and thermal-boundary drivers

A well-constructed joints may experience elevated temperatures when surrounding conditions restrict heat removal. High soil thermal resistivity (e.g., dry sand, compact clay), inadequate backfill, and vault or conduit environments can reduce effective heat dissipation and increase steady-state joint temperature (Ahmad *et al.*, 2025). Engineered backfill and thermal grouts have been shown to reduce operating temperature and mitigate hotspot severity, and are increasingly considered in thermal design and thermal-rating studies (Suleiman *et al.*, 2020). In addition, recent field-oriented reports link extreme ambient conditions, such as heatwaves and seasonal effects, with increased joint failure occurrence. This emphasises that climate-driven thermal stress can shift joints closer to thermal runaway conditions, especially in already-marginal installations (Alhusin *et al.*, 2022; Mazza *et al.*, 2024).

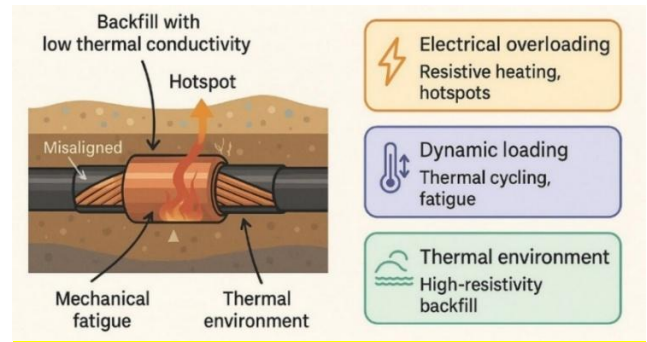


Figure 3. Primary causes of TD at UC joints (adapted from Rafati *et al.* (2024), Enescu *et al.* (2021), and Elsharkawy *et al.* (2022))

B. Material-Level Effects of TD

At the material level, prolonged thermal exposure significantly affects the integrity of joint components. Elevated temperatures in polymeric insulation like XLPE and EPR lead to degradation that diminishes dielectric strength and elasticity. This degradation results in embrittlement, cracking, and potential electrical failure over time (Klimenta *et al.*, 2022). Repeated thermal cycling worsens the issue, particularly at material interfaces with differing expansion rates.

Conductive materials such as Al and Cu in connectors experience oxidation and thermal creep at high temperatures. As a result, the contact resistance, deformation, and mechanical fatigue at contact points increase. In high-load scenarios, creep can loosen compression joints, raising the risk of arcing or PD (Wei Zhang *et al.*, 2022). The conductor-insulation interface is particularly susceptible to damage. Delamination and carbon tracking often begin at this interface, intensified by thermal stress and microvoids. These issues undermine the joint's capacity to endure electrical stress, facilitating moisture ingress and PD (Pompili *et al.*, 2020). Ultimately, TD compromises the joint electrically and structurally, highlighting the critical need for effective thermal management and material selection in joint design. Figure 4 presents the material-level effects of TD in UC joints.

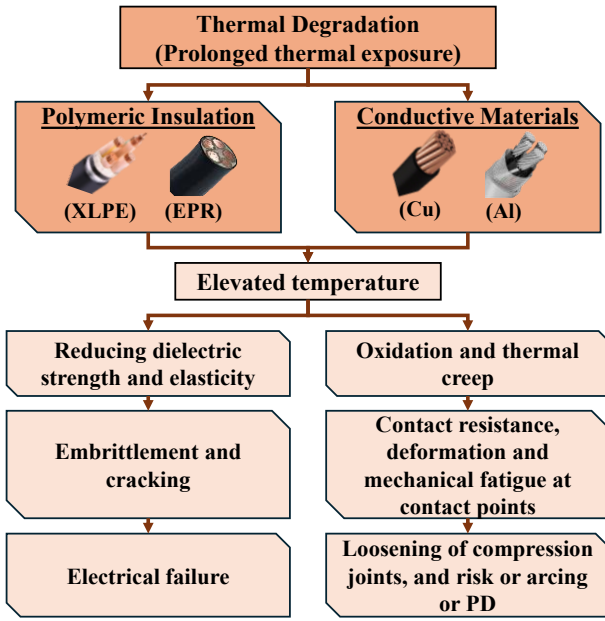


Figure 4. Material-level effects of TD in UC joints (adapted from Hakim *et al.* (2021), Klimenta *et al.* (2022), and Enescu *et al.* (2021))

V. TECHNIQUES FOR DETECTING TD

Detecting TD in UC joints is crucial for avoiding failures and enabling maintenance. Various diagnostic methods have been created to assess the integrity of the UC joints, which are often weak points in cable networks. These methods include non-contact infrared thermography (IRT), PD detection, and emerging sensor systems for real-time monitoring, each with distinct advantages based on conditions and degradation levels (Bandara *et al.*, 2024). In practice, TD-related defects might appear as surface-visible hotspots or internal-driven degradation. Therefore, diagnostic techniques are best interpreted according to: (i) defect stage (incipient or advanced), (ii) measurement access (buried or accessible joint bays), (iii) operational status of the method (online or offline), and (iv) sensitivity to environmental noise and operating conditions. Diagnosing incipient degradation, which is an early-stage thermal issues, poses a significant challenge. Combining multiple diagnostic methods with smart analytics, such as AI-enhanced image processing, is gaining recognition as a way to enhance accuracy and reliability in cable assessments (Govindarajan *et al.*, 2023; Song *et al.*, 2022). Recent literature increasingly emphasises data fusion, which combines thermal, electrical, and environmental measurements with analytics to reduce false

positives and detect early-stage TD more reliably than any single method alone (Xin *et al.*, 2025; L. X. Zhang *et al.*, 2025). This section reviews the most common approaches (Figure 5), emphasising their physical basis, practical constraints, and suitability for early-stage detection.

A. Infrared Thermography

IRT is one of the predominant diagnostic methods employed for detecting thermal irregularities in UC joints. This technique functions by capturing surface heat distributions through non-invasive thermal imaging devices, enabling the identification of hotspots that may suggest resistive heating or failure of insulation. This method is favourable due to the implementation and real-time imaging capabilities, which are particularly advantageous during routine evaluations or post-installation assessments (Li *et al.*, 2023; Hassan *et al.*, 2025).

Nonetheless, this approach also has its drawbacks. Given that IRT solely gauges surface temperature, it might overlook degradation concealed beneath thermally insulating outer layers or in buried joints that are difficult to access. Moreover, external environmental influences such as variations in ambient temperature, solar radiation, or soil coverage, can produce false positives or completely obscure thermal signatures (Heggås and Bakken, 2018). To address these challenges, advanced systems have been developed that utilise calibrated thermal thresholds, AI-driven defect classification, or the integration of PD data to enhance detection accuracy (Bandara *et al.*, 2024; Christou, 2016).

B. Partial Discharge Detection

PD detection stands as one of the most dependable diagnostic methodologies for evaluating insulation degradation attributed to thermal stress in UC connections. PD represents a localised dielectric failure that does not entirely bridge the insulation, and its occurrence frequently indicates the degradation of insulating materials due to the elevated temperatures or the formation of voids (Enescu *et al.*, 2021; Song *et al.*, 2022). As TD progresses, micro-voids and delamination within cable joints create conditions conducive to discharge activity.

Modern PD detection methods include both offline and online techniques. Offline techniques, such as Very Low Frequency (VLF) testing paired with PD analysis, provide accurate defect localisation. However, this method necessitates a shutdown of the system. Online methods, which involve High-Frequency Current Transformer (HFCT) sensors and Ultra-High Frequency (UHF) antennas, facilitate ongoing monitoring without disrupting power transmission (Govindarajan *et al.*, 2023). Recent advancements include the application of AI-algorithms to classify PD patterns. It is beneficial to assist in the distinction between PD induced by thermal factors and those resulting from mechanical stress or contamination (Kumar *et al.*, 2024). These advancements have transformed PD detection into not only a diagnostic instrument but also a facilitator in predictive maintenance.

C. Real-Time Thermal Monitoring

Real-time thermal surveillance involves the continuous monitoring of cable joint temperatures through integrated sensors, fibre-optic networks, or surface mounted thermocouples. This method is particularly advantageous for detecting unusual heating patterns that precede failure. Systems based on Real-Time Thermal Rating (RTTR) can simulate and forecast temperature fluctuations utilising live load and environmental information, providing operators with essential insights for thermal management (Barbieri *et al.*, 2021).

A popular technique employs Distributed Temperature Sensing (DTS) through optical fibres, providing high spatial resolution across extensive cable run. These systems identify small changes in thermal activity at joints that may elucidate

insulation degradation. Combined with remote data logging and cloud-based analytics, contemporary systems facilitate condition-based maintenance as opposed to conventional time-based servicing (Enescu *et al.*, 2021). Recent investigations also underscore the incorporation of humidity sensors and soil thermal resistivity probes to enhance the correlation between joint overheating and ambient factors (Millar, 2006).

D. Advanced and Emerging Techniques

Beyond conventional diagnostics, emerging techniques demonstrate potential for identifying early-stage TD. AI-enhanced infrared image analysis, for instance, facilitates automated recognition of minor thermal anomalies that may be disregarded in manual inspection. Acoustic emission (AE) monitoring is another innovative method that captures stress waves generated by cracking or delamination caused by thermal expansion and contraction cycles (Li *et al.*, 2023).

Furthermore, in cable systems employing resin or oil-based joint insulation, dissolved gas analysis (DGA) can detect chemical by-products generated by excessive heating, providing a chemical profile of thermal stress. Certain recent systems incorporate multi-parameter sensor platforms which are capable of capturing temperature, humidity, PD signals, and mechanical strain simultaneously for a comprehensive view of joint condition (Ghaforian *et al.*, 2025). These technologies, while still undergoing field validation, signify the next frontier in predictive diagnostics for underground power cables.

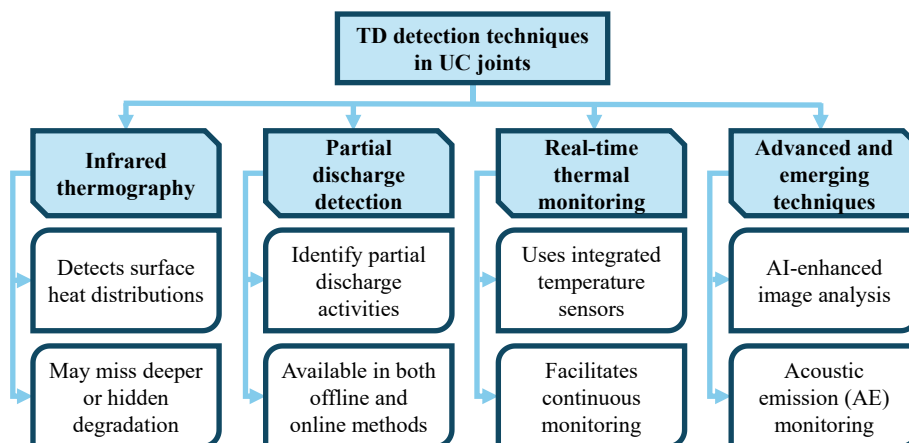


Figure 5. TD detection techniques in UC joints

E. Trade-Offs and Integration Issues in Diagnostic Applications

Many diagnostic techniques are known to be effective, but actual use in the field depends on several practical aspects. These include the full cost of the equipment, simplicity of the process, training level of the team, and suitability for different environments. IRT is fast and low-cost and does not require direct contact. However, this method only detects heat on the surface without detecting deeper problems (Swain *et al.*, 2022). PD testing can detect early internal faults and provide more detailed results (Kaziz *et al.*, 2023). Nevertheless, the process needs expert handling, proper filtering, and higher setup cost. Acoustic and ultrasonic tools are generally accurate and cheaper but affected by noise in urban and industrial areas (Wong and McCann, 2021). Due to these factors, selection of the right method often depends on balancing cost, accuracy, and simplicity. The best option depends on the actual need, such as planned inspection, quick testing, or continuous monitoring in a modern cable system. Consequently, the literature increasingly supports a tiered diagnostic strategy such as utilisation of low-cost screening (e.g., IRT) to prioritise assets, application of targeted high-sensitivity testing (e.g., PD) where risk indicators exist, and reserve continuous monitoring (e.g., thermal trending/DTS/RTTR where available) for critical circuits or locations with recurrent thermal constraints (Emdadi *et al.*, 2025; Tao *et al.*, 2025; Song *et al.*, 2022).

In addition to cost, usability, and diagnostic accuracy, significant consideration involves the integration of these methods into modern smart grid environments. As many utility networks transition toward digitalisation, the use of real-time monitoring becomes more widespread. This transition creates new technical challenges, especially when diagnostic tools need to communicate over wide-area networks. Data collected from field devices must remain accurate, timely, and consistent, which brings attention to potential issues such as signal latency, data loss during transmission, and compatibility across different communication protocols. Furthermore, the growing dependence on sensor-based monitoring systems and AI introduces additional risks related to data security. Monitoring devices installed in substations or UC pits are vulnerable to cyber threats, which may affect both data

integrity and system control. Achieving reliable and efficient integration with existing supervisory control and data acquisition (SCADA) (Beheshti Asl *et al.*, 2024), or IoT platforms (Fechet *et al.*, 2021), requires careful design, strict data validation, and attention to network architecture. Without addressing these challenges, the full value of intelligent diagnostics cannot be realised within UC systems.

F. Comparison of TD Detection Techniques

Table 3. Comparison of TD detection techniques

Techniques	Core principle	Advantages	Limitations	Best applications	References
Infrared thermography (IRT)	Captures surface heat radiation to detect hotspots	Non-invasive, fast, suitable for periodic inspections	Limited to surface-accessible joints; influenced by environment	Routine field inspection; early detection of hotspots	(Hassan <i>et al.</i> , 2025; Li <i>et al.</i> , 2023; Heggås and Bakken, 2018)
Partial discharge (PD) detection	Detects dielectric breakdown activity caused by thermal or insulation degradation	Sensitive to early-stage degradation; available for online/offline testing	Requires calibration; susceptible to noise and false positives	Joint insulation monitoring and fault prevention	(Song <i>et al.</i> , 2022; Govindarajan <i>et al.</i> , 2023; Kumar <i>et al.</i> , 2024)
Real-time thermal monitoring (RTTR)	Uses sensors/fibre optics to monitor joint temperature in real time	Continuous data, predictive modelling possible	Installation cost; may not detect mechanical defects directly	Long-term load management; hot-spot prediction	(Barbieri <i>et al.</i> , 2021; Enescu <i>et al.</i> , 2021; Millar, 2006)
AI-enhanced image processing	Applies AI to analyse thermal images for pattern recognition	Increases diagnostic accuracy; detects subtle anomalies	Still under development; requires high-quality training datasets	Automated IRT assessments and decision support	(Christou, 2016; Ghaforian <i>et al.</i> , 2025)
Acoustic emission (AE)	Detect sound waves generated by cracks or internal movement	Effective for detecting thermal cracking or delamination	Sensitive to ambient noise; limited spatial resolution	Monitoring of aged or composite joints	(Li <i>et al.</i> , 2023)
Dissolved gas analysis (DGA)	Analyses gas by-products in oil/resin from TD	Highly sensitive to chemical-level insulation failure	Applicable only in oil-filled or resin joints; invasive sampling needed	Specialised environments (resin, oil-filled joints)	(Christou, 2016)
Multi-parameter sensor systems	Combines temperature, PD, strain, humidity, etc., into a unified monitoring system	Holistic condition monitoring; long-term data analytics	Expensive and complex to deploy; requires integrated data management	Smart grid applications; critical infrastructure	(Song <i>et al.</i> , 2022; Ghaforian <i>et al.</i> , 2025)

Multiple diagnostic methods have been developed for monitoring of UC joints, but the effectiveness differ depending on specific situation. IRT offers rapid surface-level inspection but does not detect problems in deep insulation (Deng *et al.*, 2023). PD detection is more sensitive to internal voids but it is affected by signal noise and needs expert analysis (Govindarajan *et al.*, 2023). Acoustic methods are effective for finding mechanical cracks but suffer from ambient interference. Additionally, AI-based diagnostics offer the potential for automation but are constrained by the availability of labelled data and lack of generalisation across networks (Kumar *et al.*, 2024). While AI-based diagnostics show strong potential, their use in real-world UC monitoring is still limited. Models such as convolutional neural networks (CNNs) used for PD classification or thermal image recognition (C. Sun *et al.*, 2024), are trained on controlled laboratory data, which may not reflect the noise, environmental variability, or signal interference present in field conditions (Raymond *et al.*, 2021). A major issue is the lack of large, well-labelled datasets, which makes these models hard to generalise and increases false alarms.

Choosing the right diagnostic technique depends on several factors, including cost, environmental conditions, fault detection depth, and the operator's level of expertise. Setting up clear integration protocols, such as using IRT to identify thermal hotspots followed by PD testing to pinpoint the exact fault location, can help reduce false alarms and improve the detection accuracy. Until better validation and standard methods are developed, AI should be used as a supporting

tool, not a standalone solution. Despite this, the literature lacks a universally accepted best-practice model, underlining a clear direction for future research. These factors can result in false positives, lower accuracy, or delayed responses. For instance, cold-shrink joints may pass factory tests but fail in the field due to poor storage or humidity, particularly in tropical regions. Likewise, AI detection algorithms trained in labs may struggle with real-world noise and mislabelled data. Most research does not compare lab and field diagnostics, creating a significant research gap. This issue needs longitudinal field validation, standardised test protocols, and performance benchmarks that consider environmental factors. Table 4 outlines how the conditions in real-world field environments differ from controlled laboratory settings, emphasising the practical challenges that can affect the performance and reliability of diagnostic methods for UC joints.

G. Real-World Limitations and Lab-to-Field Contradictions

Diagnostic tools for UC joints are mainly tested in labs, which do not mimic real-world conditions. In labs, tools like PD sensors and IRT show high sensitivity due to controlled environments. Field conditions present unpredictable issues such as cable routing, signal interference (Harun *et al.*, 2021), soil moisture changes (Ocloń, 2021; Emmerling *et al.*, 2024), weather extremes (Li *et al.*, 2020; Alhammadi *et al.*, 2024), and varying joint quality.

Table 4. Summary of laboratory and field conditions in UC joint diagnostics

Aspect	Laboratory conditions	Field conditions
Installation quality	Performed by specialists under optimal setups	Depends on technician skills, site constraints, and environmental factors
Signal clarity	Clean and stable waveforms with minimal background interference	Prone to electrical noise, cross-talk, and signal distortion in active environments
Thermal monitoring	Controlled temperature, minimal external thermal fluctuation	Affected by ambient heat, airflow, and underground heat dissipation
Partial discharge	Short-distance testing, minimal attenuation or signal loss	Signal weakening over long cable lengths and due to aged insulation
Data interpretation	Clear signal boundaries and low variability	Overlapping fault patterns make analysis more complex
Moisture and soil impact	Typically, dry conditions or simulated moisture for controlled testing	Real exposure to rainwater, soil saturation, and variable trenching conditions

VI. CONCLUSION

TD remains one of the most critical issues affecting the reliability of UC joints. As power systems continue to carry heavier loads and operate under harsher conditions, the chances of overheating and insulation failure increase. This review has outlined the main causes of TD, such as jointing methods, insulation material breakdown, and environmental effects. Several diagnostic methods, such as IRT, PD analysis, and RTTR, were examined based on the ability to detect early indicators of joint failure. The selection of jointing techniques and use of high-quality materials during installation are equally important in minimising thermal stress. Crimping ensures low contact resistance and is suitable for high-current applications. Heat-shrink and cold-shrink joints are popular for their ease and reliability, while exothermic welding is preferred for grounding. Moving forward, combining multiple diagnostic approaches, especially those enhanced with sensors and AI, could improve early fault detection and condition monitoring. Beyond reviewing methods, this paper also highlights three key challenges: the gap between lab results and field reliability, the lack of standardised diagnostic protocols, and the limited reporting of failure cases from actual deployments. These gaps create uncertainty in decision-making and slow down the adoption of practical solutions. Addressing them through better integration of diagnostic tools and long-term field validation can significantly strengthen grid reliability. With proper tools, strategies, and validation, utility companies can protect their

underground systems more effectively and reduce the risk of unexpected outages.

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VIII. CONFLICT OF INTEREST

Authors declare that there is no conflict of interests regarding the publication of the paper.

IX. AUTHORS' CONTRIBUTION

The authors confirm contribution to the paper as follows:
study conception and design: A.L. Che Rani, T.M. Kuan;
data collection: A.L. Che Rani, T.M. Kuan; **analysis and interpretation of results:** A.L. Che Rani, T.M. Kuan;
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supervision: T.M. Kuan, M.N.M. Ansari, A.M. Ariffin, M. Osman; **validation:** T.M. Kuan, M.N.M. Ansari, A.M. Ariffin, M. Osman; **funding acquisition:** T.M. Kuan. All authors reviewed the results and approved the final version of the manuscript.

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