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REVIEW

Review of condition monitoring and defect inspection methods for composited cable terminals

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Abstract

Composited cable terminals are critical for reliable power delivery of traditional and traction power supply systems. During its operation, the cable terminal continually undergoes complex circumstances where humidity, temperature, field strength, mechanical stress and other factors continuously change at different levels. In extreme cases, defects or even failures may occur in the cable terminals, leading to catastrophic accidents. This makes the condition monitoring and defect detection of composited cable terminals become an imperative need for the power industry. The "state-of-the-art" technology of cable terminal condition assessment is focussed and a systematic review of the current research progress of cable terminal condition assessment from the operation circumstances to failure mechanisms is provided. It covers both online/offline condition monitoring methods and defects detection approaches. In addition, challenges and future research directions for cable terminal condition assessment are also addressed. It is concluded that the non-destructive and non-intrusive methods like terahertz imaging and ultrasonic testing, and multi-source information fusion methods as well as the digital twin technology have been gaining popularity for cable terminal defect inspection. It is expected the presented work can provide a global field of vision for further advancement of both scholars and industrial engineers in this field.

1 | INTRODUCTION

As an essential component of cable systems, composited cable terminals have been widely deployed in traction power supply systems, distribution systems and renewable energy power plants. Compared with the main cable body, composited cable terminals have a high possibility to fail in hostile situations, which may result in significant financial losses of power industries [1]. Therefore, it is imperative to develop reliable composited cable terminal fault diagnosis and detection technology in order to discover incipient failure signatures and provide an early warning to power utilities to ensure the safe operation of the systems where the composited cable terminals are utilised.

High-speed electric multiple units (EMUs) provide fast and international transportation, which are operated under high speed, cross-regional and all-weather conditions. When the geographical region of train operation expands and the operating environment of EMUs becomes more complicated, the safe operation of high-speed EMUs becomes more challenging. As a crucial component of high-speed EMUs, composited cable terminals directly impact the safety and stability of the power supply system. With the rapid development of the national economy and the growing demand for national defence and military security, high speed, large capacity, low cost, long-distance and high reliability emerged as the main development direction of high-speed rail transportation. The rail transportation operators' primary concern has focussed on high-speed EMU's safety and stable service performance [2]. As one of the critical components of EMUs, the composited cable terminal is subjected to the combined effects of rapid hot and cold alternation, frequent transient overvoltage and continuous elastic vibration during its long-term operation, which may lead to the internal insulation layers separation, the micro air gaps formation and partial discharge [3]. With the growth of the air gap and the by-product of discharge, the degree of discharge and the size of the air gap may further increase, which finally lead to insulation failure [4–6]. Simultaneously, as the travel area of high-speed EMUs expands and the running speed and traction power of EMUs increase, the vehicle cable system is exposed to frequent hot and cold alternation. In addition, overvoltage becomes more common and vehicle body vibration becomes more durable, resulting in frequent failure of the composited cable terminals. It has been reported that faults in the vehicle cable system account for about 20% of all faults of the power supply system in EMUs, where composited cable terminals contribute 80% of vehicle cable system faults. The unique operating environment of extreme high and low temperatures has posed significant challenges to the safe operation of high-speed EMU's composited cable terminals as well as the insulation monitoring and protection of the power supply system of the new generation of high-speed EMUs.

In power systems, power cables are widely used in China for their compact footprint, easy installation and maintenance, and superior power transmission capability. Power cables are responsible for the transmission and distribution of electrical energy in the distribution system, and they play a critical role in guaranteeing the reliable operation of the power grid. Due to the numerous advantages (such as lightweight, easy installation, and big transmission capacity), cross-linked polyethylene (XLPE) cables are widely used in distribution systems. However, compared to the main cable body, the cable terminal has a complicated structure with relatively weak insulation, thus becoming the weakest point of the whole cable system. Besides the weak internal insulation, the harsh working environment and external damage are the major sources of cable accidents. Therefore, rapid detection of cable terminal faults is critical for improving their operating dependability.

Along with the foreseeable shortage of fossil energy resources, global power sectors are accelerating the integration of renewable energy into traditional power networks. Photovoltaic and wind energy cables are the most common cable systems in the existing renewable power plants. Solar cables are mostly used in photovoltaic power plants because of their high-temperature resistance, cold resistance, oil resistance, acid and alkali resistance, ultraviolet (UV) resistance, flame retardant and environmental protection, as well as their longevity. They are mostly employed in operating environments with more harsh climatic conditions. Solar cables can be used as photovoltaic power generating system connection cables as well as a link between the inverters of the solar farm and the transmission grid. Wind energy cables should have strong physical and mechanical qualities, outstanding low-temperature flexibility, and anti-ageing performance in addition to adequate electrical insulation. The cable system of the renewable plants, particularly the cable terminal, is prone to fail due to the rigorous working environment. As a result, strong wind conditions, long-term exposure to sunlight, as well as rain and snow, pose significant threats to the safe operation of composited cable terminals of renewable farms.

To the best knowledge of the authors, the articles, which systematically introduce the methods or techniques for condition monitoring and defect inspection of cable terminals utilised in traction power supply systems, distribution systems, and renewable energy power plants, are unavailable at present. Therefore, a comprehensive review is conducted in this paper. Compared to similar articles, this paper originates from the operating conditions and fault mechanisms of composited cable terminals in different application fields and focusses on various inspection methods and techniques. Both online monitoring and defect detection approaches of cable terminals are summarised. By summarising the pros and cons of the current methods or techniques in this field, potential issues are also pointed out and recommendations for future research and possible solutions are also provided.

2 | STRUCTURE OF CABLE TERMINALS

The medium- and low-voltage XLPE cable terminals are widely used in power systems and traction power supply systems. For power systems, the XLPE cable is normally operated at voltage levels of 10 kV and 35 kV. The schematic diagram of the cable terminal is shown in Figure 1a. The XLPE cable is

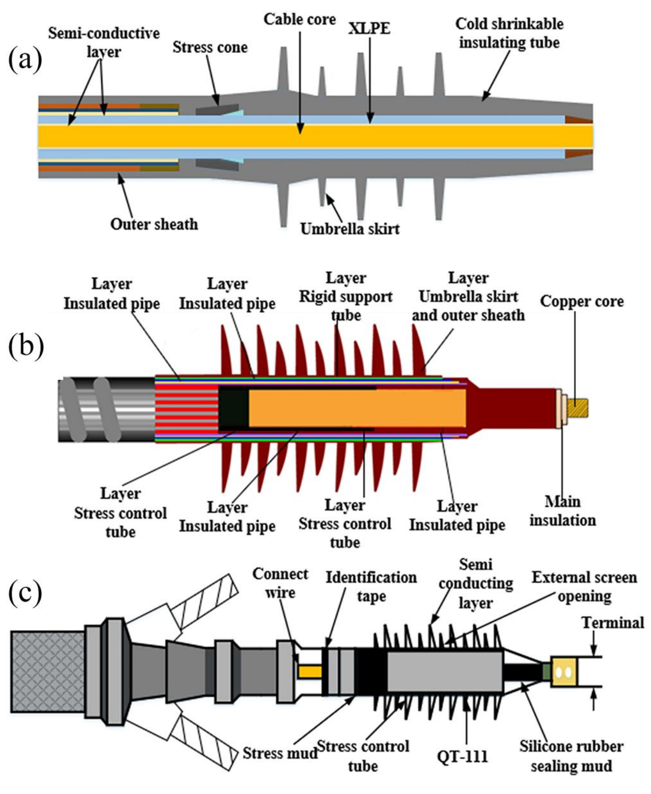

FIGURE 1 Structure of cable terminal used in (a) distribution power systems, (b) electric multiple units (EMUs), and (c) wind farms.

typically manufactured using the cold shrinkage method. For the traction power supply system, XLPE cables are mainly used in high-speed EMUs at a voltage level of 27.5 kV and its terminal structure is shown in Figure 1b. Figure 1c depicts the structure of a 35 kV medium voltage cable terminal in a wind farm.

The XLPE cable terminal for distribution systems normally consists of a silicone rubber umbrella skirt and jacket, an outer sheath, a semiconductor layer, a stress cone, shielding layers, a cold-shrinkable insulation tube, and XLPE main insulation [7, 8]. Ethylene propylene rubber (EPR) cable terminals are the most used cable terminals in the power supply system of high-speed EMUs. The EPR cable terminal mainly contains a silicone rubber umbrella skirt and jacket, four layers of insulation tubes and two layers of stress control tubes, where stress cones are not required. The structure of cable terminals for wind farms differs from that of EMUs and distribution systems in terms of the following three aspects. (1) The copper shield grounding wire is forced into the copper shield layer using a continuous tension spring, and then the insulating tape is wound around it. (2) After installing the steel armor grounding, the grounding wire is wrapped around the waterproof adhesive tape below the sheathing mouth. The steel armor is placed at the centre and the bottom half of the cable head is waterproof when the trident glove is cold shrunk. (3) The silicon rubber is used to seal the top of the cable termination from cement.

3 | OPERATING CONDITIONS AND FAULT MECHANISM OF CABLE TERMINALS

3.1 | Cable operating conditions

The safe operation of high-speed EMU has become more important along with the upgrade of the high-speed railway infrastructure and the increase in train speed. Due to the complex operation conditions, the composited cable connections of locomotive sets become more complicated, which may lead to incipient faults and accidents. Specifically,

(1) When the high-speed EMU travels over a large geographical scale with different temperature zones. The cable terminals are exposed to rapid variations in ambient temperature gradients and frequent hot and cold alternations. The fast and frequent hot and cold temperature changes further accelerate the ageing of cable terminal insulation materials, resulting in the degradation of the expansion capability of each cable layer.
(2) When the running speed of a high-speed EMU exceeds 300 km/h. The vehicle structure vibrates at a frequency of 20–50 Hz with the first-order elastic vibration frequency (45 Hz) in its centre. The constant elastic vibration of the EMU accelerates the delamination of the cable terminal insulation and produces air voids that cause partial discharge within the terminal.
(3) Frequent transient overvoltage may also occur during the EMU's starting, stopping and bow network offline processes, among which the bow network offline causes the largest overvoltage amplitude (up to 2.6 times the rated voltage) and create partial discharge or intensified discharge at the cable terminal. This, in the worst case, may result in insulation breakdown.

The distribution cable system is crucial to the safe and reliable operation of the power system. Distribution cable terminals are usually located in an open-air environment. They are more susceptible to the effects of the environment. The most devastating failure reasons for distribution cables include climate and environment as well as exterior damage. Natural variables, such as strong winds, windstorms, and lightning, are inevitable, and it is easy for the cable terminal to collide with neighbouring structures. The distribution cable terminals are also susceptible to corrosive damage either in a chemical or electrical form. Chemical corrosion refers to the presence of corrosive chemicals in the area where the cable is attached. These compounds will erode the cable over time, causing more extensive damages to the insulating layer and eventually resulting in cable failure. During the transmission of electricity, electrical corrosion develops, which results in a high electric field. The cable's outer skin is prone to break as a result of long-term exposure to the electromagnetic field, allowing moisture intrusion into the cable until it fails.

The distribution cable system may be subjected to more stress and is frequently overloaded, which undoubtedly exacerbates cable ageing, reducing the insulation performance and shortening the cable's life. At the same time, if the distribution cable is overloaded for a long period, massive heat will be created. Without adequate cooling systems, the cable may break.

The cable system of renewable energy farms can be primarily split into two streams, namely, cable system for wind farms and cable system for solar farms. Wind turbine cables are typically operated under harsh climatic conditions, such as cold seasons and substantial temperature variations between day and night. In solar farms, a large number of DC cables must be placed outdoors. Cables may be installed below dirt ground, on weedy rocks, on the sharp edges of roof structures, and they are exposed to the air during the installation and operation.

Cable failure due to moisture may occur as a result of cable installation error or its long-term operation in a humid environment. When operated in the hostile environment described above, the cable system is prone to fail and the cable terminals, as the weak link in the system, are even more prone to fail. Table 1 compares the operating conditions of high-voltage cable terminals of EMUs, power system distribution cable terminals, and renewable energy farms cable terminals.

TABLE 1 Operating conditions of electric multiple unit (EMU) cable terminals, cable terminals for distribution systems, and cable terminals for renewable energy farms.

Operating conditions	EMU cable terminal	Cable terminals for distribution systems	Cable terminals for renewable energy farms
Alternating hot and cold	Sudden change, maximum temperature difference 60 °C	Depends on the environment	Depends on the environment
Vibration	Continuous elastic vibration, approximately 20–50 Hz	Lesser	Frequent on the wind generator side
Transient overvoltage shocks	More frequent, up to about 3.5 times the rated voltage	Occasional	Occasional
Non-linear torsion	None	None	Frequently for the lead cable of wind turbine

3.2 | Cable terminal failure mechanism

3.2.1 | Fault-type statistics

Because of the imperfect installation practices, operating conditions and external damage, common flaws, such as electric tree branches, partial discharge, and umbrella skirt fouling flash, may happen to the cable terminal. The statistics of cable system faults in distribution systems, high-speed EMUs, and renewable energy farms are shown in Figure 2.

Cable terminals are the weakest point in cable insulation, and when the production quality of the cable terminal is imperfect, internal defects (e.g., air gaps, bubbles, and impurities) are unavoidable. These flaws will cause non-uniform distribution of electric fields in the cable. When a defect is regularly subjected to overvoltage transients and the field strength reaches the threshold, it will generate a discharge on its insulation, which is termed partial discharge. After a long period of cumulative partial discharge, the local discharge will cause the deterioration channel to gradually develop, resulting in the degradation of insulating performance and construction of a penetration channel. The common reasons for cable terminal defects are summarised as follows.

(1) The cable head production process is not well controlled during the manufacturing process, resulting in local discharge and breakdown due to bubbles, moisture, and contaminants in the cable terminal.
(2) During the cable's manufacture, the cablec's main body is damaged.
   - Excessive bending might damage the internal insulation or cause the formation of air voids in the cable.
   - With two or more grounding points, single-core cable grounding can result in the construction of a current loop in the grounding wire, a long-term thermal effect, and insulation destruction.
(3) Even in dry conditions, the cable system will trigger the interface along the surface discharge fault due to the change in load or ambient temperatures. This will result in temperature increase and drop, making the strength of the composited interface fail to meet the stipulated requirements.

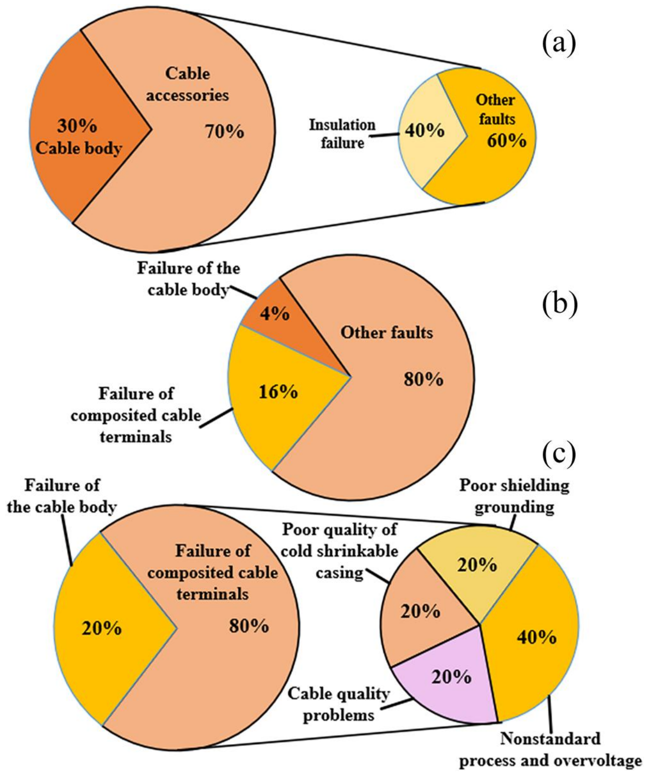

FIGURE 2 Cable fault statistics for (a) distribution systems (b) electric multiple units (EMUs), and (c) renewable energy farms.

3.2.2 | Failure mechanism analysis

The failure mechanism of cable terminals is explained based on the air gap flaws formation. According to ref. [9], the development of air gap discharge can be divided into three stages as shown in Figure 3.

Stage 1: The discharge is initiated when the air gap of the cable terminal contains a large number of burr protrusions, where the shallow air gap electric field is more easily concentrated near the semiconducting layer. The discharge channel is not fully established and the discharge on the insulation interfaces develops more rapidly. Since the shallow air gap acts as a semi-conducting layer (its electric potential is close to the ground) and the positive charge mass is much larger than the electron under sinusoidal voltage, the mobility of the positive charge and the electron has a significant difference, which means their discharge behaviour is inconsistent. The discharge towards the ground potential is unidirectional. At the same time, due to the narrow air gap in the pre-ageing period, less charge accumulated in the air gap will discharge. Furthermore, when the high voltage is applied, the protrusion around the burr generates an electric field in the internal air gap, resulting in internal discharge. The long-term action of this section of the burr is also gradually ablated smooth.

Stage 2: The internal discharge further develops in the second stage and the length of the air gap at some locations increases, which leads to the formation of long air gap channels. The discharge within the air gap near the core is more intense and the air gap further expands in the internal direction. Due to a large number of burrs within the air gap, the discharge development only leads to a partial penetration of the channel, which in turn promotes the formation of the internal air gap.

Stage 3: During this stage, the unipolar discharge to the ground increases with ageing time, and burr protrusions of the air gap are gradually ablated, which form a long open-air gap connected to the insulation surface. It also establishes the discharge channel from the inner area of the air gap to the semiconducting layer. Based on survey statistics, the majority of cable system faults are caused by incorrect installation practices, which introduce mechanical damage, particulate impurities, knife marks, and air gaps to the internal terminal defects, and these defects can be identified by partial discharge measurements [10]. T. Tanaka investigated the water trees in polyethylene-insulated cables and proposed corresponding solutions [11]. The effects of insulation shape, contaminants, and oxidation on the electrical properties of cable sections were investigated by J. Crine [12]. Through extensive experimental studies, J. Deng and C. Zhang et al. [13] concluded that the partial discharge at the pre-deterioration stage of the cable terminal is primarily affected by the knife mark cut burr, and the development of discharge at the later stage of deterioration is primarily related to the internal defects of the material as shown in Figure 4.

Through systematic studies, K. Zhou et al. [14, 15] discovered that the degree of discharge of different knife-mark defects is significantly different and certain characteristics can be extracted to provide a baseline for identifying the defects and realise the partial discharge characteristics of cable

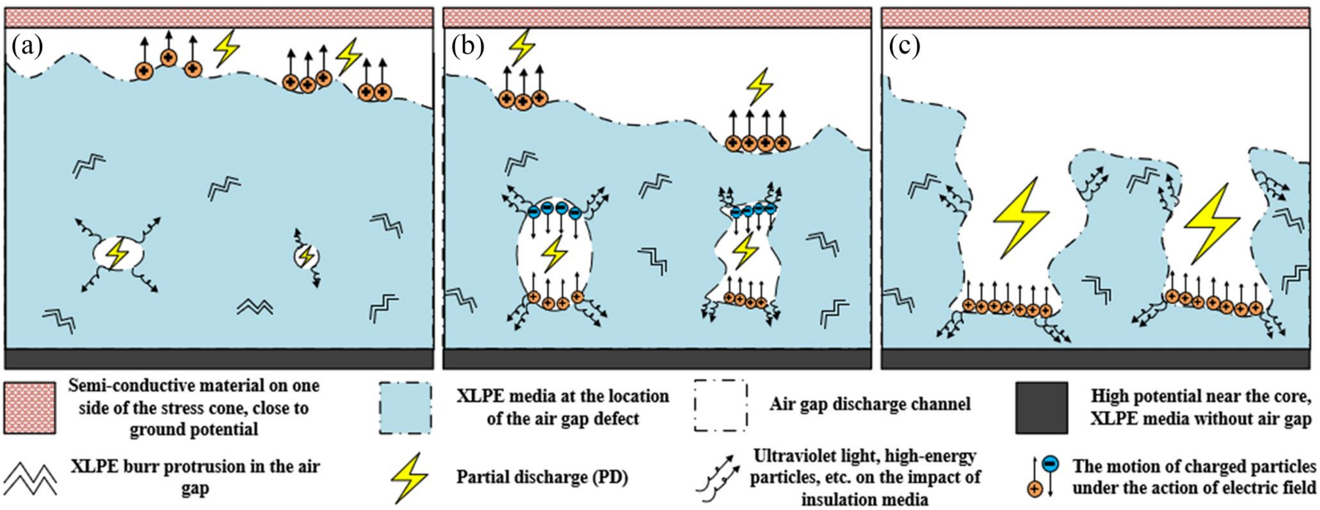

FIGURE 3 Illustrative diagram of discharge development caused by air gap defects: (a) the first stage, (b) the second stage, and (c) the third stage [9].

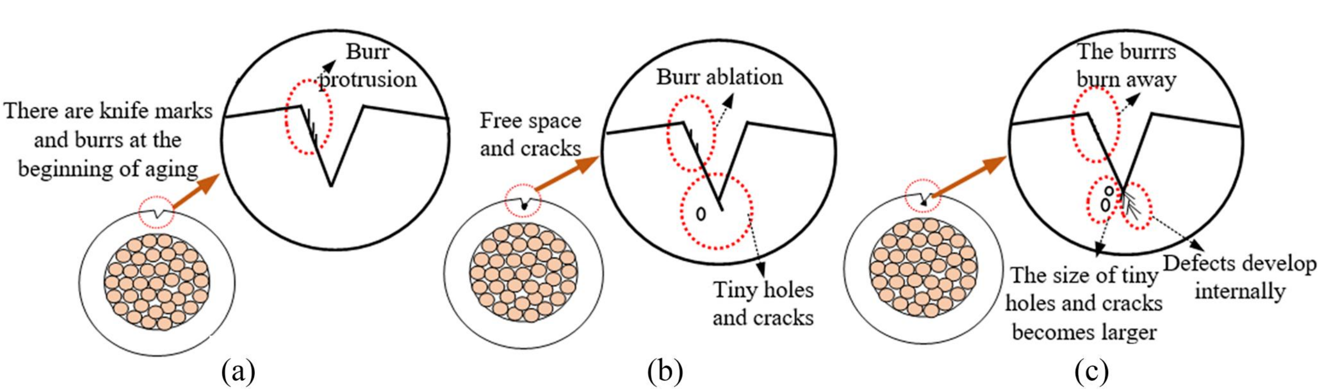

FIGURE 4 Illustrative diagram of knife incision defect. (a) No deterioration stage, (b) intermediate stage of deterioration, and (c) later stage of deterioration [11].

terminals under various loads. According to G. Liu et al [16], impurities inside cable joints can generate electric field distortion near fault locations, which can lead to main insulation failure when a particular breakdown field strength is exceeded. DC void partial discharge studies based on pulse sequence analysis (PSA) can be used to identify void defects in high-temperature superconducting cables [17].

Internal defects of composited terminals cause partial discharge, insulation breakdown, and explosion in the onboard cable system of high-speed EMUs. This has been posing a serious threat to the onboard electrical system's safety and reliability and raising a significant concern in the industry [18, 19]. The separation of the contact surfaces of the insulation layers will generate air gaps between the insulation layers. This is caused by the imbalance in the strength and stress distribution between the layers of materials inside the EMU's composited cables.

The air gap between insulation layers is a major factor in the formation and expansion of discharge channels at cable terminals, which eventually results in insulation blowouts. Air gap defects cause electric field distortion and air breakdown, resulting in discharge, which forms a discharge channel along with the insulation layer and stress control tube. As the micro air gap continues to expand, the discharge channel continues to extend until it ablates at the end of the stress control tube, resulting in cable insulation breakdown, cable termination breakdown, or even blowout [20, 21].

4 | ONLINE MONITORING AND DEFECT DETECTION METHODS

The inspection methods for cable systems can be split into two categories: online monitoring and defect identification. [22, 23] Partial discharge detection, reflection measurement, ultraviolet detection, and infrared (IR) detection belong to the online monitoring approaches. X-ray inspection, Acoustic emission (AE) detection, and terahertz non-destructive testing are typical defect detection technologies. Figure 5 depicts the main detection methods as well as their advantages and drawbacks.

4.1 | Online methods

4.1.1 | Partial discharge detection

Extensive studies have been performed to detect partial discharges for identification of cable terminal defects [24–26]. A partial discharge-based method for identifying defects in cable joints was proposed in ref. [27] where an overall classification accuracy of 96% was achieved. To further identify the type of discharge inside the cable terminals and determine the discharge location, L. Zhou et al. [23, 28] established a partial discharge testing system to study the discharge onset/extinction voltage, the discharge development process, and associated spectrum characteristics under different low-temperature conditions.

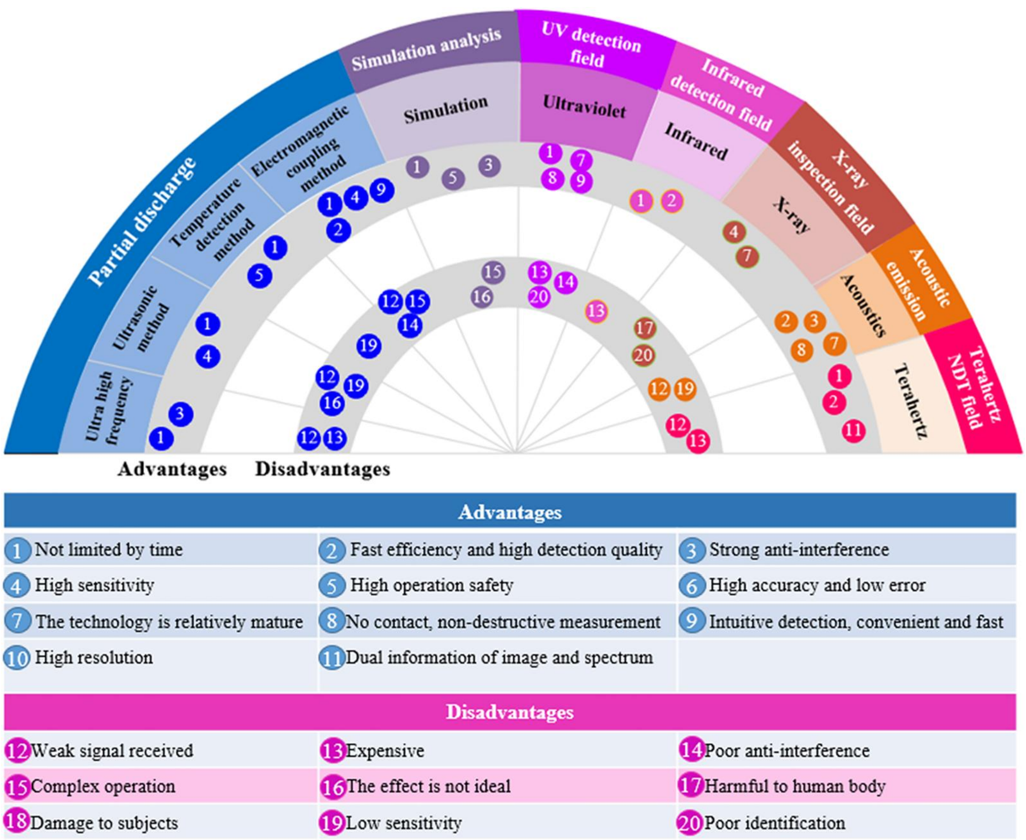

FIGURE 5 Comparison of different detection methods.

Moreover, characteristics of both positive and negative half-perimeter asymmetry of the discharge spectrum were revealed, which provided explanations for the frequent explosions of the vehicle cable terminals operating in alpine regions. Although a lot of work has been reported on partial discharge pattern classification, existing studies usually verify the developed approaches by using laboratory-made cable terminals without any environmental interferences to the measurement data. To further expand the applicability of the cable fault detection and classification methods to field practice, a feature extraction method was proposed based on high noise tolerance principal component analysis to classify cable joint defect types using partial discharge measurements in noisy situations [29]. In ref. [30], the Weibull distribution and Crow-AMSAA model were used to forecast different types of early faults of cable terminals based on a large number of cable terminal fault statistics. Meanwhile, the local discharge detection method can detect degradation states, such as electric dendrites and thermal oxygen ageing. L. Zhou et al. [31] investigated the local discharge characteristics and the growth of electrical dendrite when local air pressure acted on the electrical dendrite channel at different temperatures by considering the effect of local air pressure on the electrical dendrite initiation and growth characteristics of XLPE cables under different operating conditions. It was found that the electrical dendrite can easily penetrate the cable insulation under high temperatures and high abrasion conditions. Under high temperature and pressure, it was discovered that electric branches could easily pierce cable insulation. Partial discharge tests on ethylene-propylene rubber cable insulation at different stages of heat and oxygen ageing were carried out by L. Guo et al. [32]. The following section introduces different partial discharge detection methods, including ultra-high frequency (UHF), ultrasonic, temperature detection, and electromagnetic coupling methods.

(1) UHF method

The UHF approach primarily detects UHF signals between 300 and 3000 MHz for partial discharge detection, efficiently avoiding noise and interference in the low-frequency region. Cable terminals have a high failure rate and the presence of a shielding layer causes the UHF signal to attenuate quickly when the signal propagates through the cable body. Therefore, an external UHF sensor is usually installed near the cable terminal, and the local discharge source is located using the time difference method [33] to monitor the local discharge signal. Partial discharge monitoring has been developed by using UHF sensors to detect signals generated during partial discharges in high-voltage cable joints [34] shown in Figure 6. Considering that the partial discharge at cable terminals under different defects will generate other discharge pulses, T. Tang et al. [35] constructed four defects in 110 kV XLPE cable joints and used a broadband partial discharge detection system to obtain the time-frequency characteristics of discharge pulses. It has been reported that the discharge pulse waveforms at the starting stage under each defect are relatively stable, but the time–frequency characteristics are significantly different. This

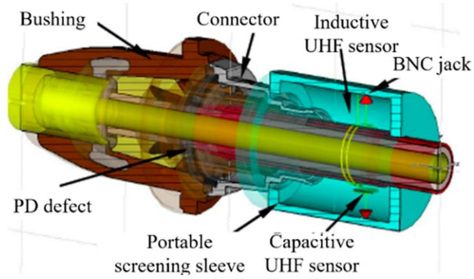

FIGURE 6 Partial discharge monitoring for high-voltage cable joints based on the ultra-high frequency (UHF) method [31].

provides an essential guideline for identifying the discharge type. However, due to the complex insulation structure of the cable accessories and their manual fabrication, their failure probability is much higher than that of the cable body. In addition, UHF signal transmission in the cable body attenuates quickly, so UHF detection technology is mostly used for fault detection of cable accessories or cable gas-insulated switchgear (GIS) terminals, transformer terminals etc. [36–39].

(2) Ultrasonic method

Besides the UHF method, ultrasonic methods were also developed for recognising the partial discharge type of cable joints. F. Gu et al. [40, 41] proposed an improved fractal transformation approach and a fractal feature-enhanced Hilbert-Huang transformation method. The researchers used intelligent algorithms to characterise the decaying of ultrasonic partial discharge signals along with the tangential and axial directions inside the cable terminals and successfully detect the defects inside the cables [42–44]. However, the complex mechanism of the cable terminal structure, material and operating temperature on ultrasonic wave propagation characteristics, and the attenuation of ultrasonic waves in the more absorbent composited material makes it difficult to penetrate the thicker material structure. Therefore, the accuracy of the ultrasonic partial discharge detection method is relatively low.

(3) Temperature detection method

Defects in the cable body and its accessories can cause an increase in the temperature of the cable surface. The temperature detection method aims to use fibre-optic sensors to capture the thermal distribution of the cable and subsequently identify the hot spots [45, 46]. First, laser pulses feed the cable surface temperature into the optical fibre, resulting in variable Larmann scattered light. Then, a voltage signal corresponding to the highest temperature point is generated based on the thermoelectric effect of the temperature sensor. Temperature detection has the advantage of being immured by electromagnetic interference and high reliability, given that the cable surface temperature is affected by the laying environment, load, and other factors. However, the method requires long-term historical measurement data to make a comparison to achieve a reasonable detection accuracy.

(4) Electromagnetic coupling method

The electromagnetic coupling method collects the cable shield partial discharge pulse by a broadband current sensor or high-frequency current transformer (HFCT). This method is the most widely employed method for detecting the partial discharge for cable accessories or terminals. Considering its excellent anti-electromagnetic interference performance, the electromagnetic coupling method was first applied to the partial discharge detection of power equipment such as GIS. Extensive studies have been conducted on the application of the electromagnetic coupling method in cable insulation detection [47, 48]. This method usually requires installing the sensors inside the cable body to form built-in electromagnetic coupling sensors. Sensors like HFCT can only be installed during the cable connection construction, limiting their applicability in-field testing. However, considering their small size, ease of field operation, and excellent detection sensitivity, external electromagnetically coupled sensors have been widely used [49, 50]. A schematic diagram of electromagnetic coupling detection is shown in Figure 7. For power cables, considering its condition is closely related to the level of partial discharge [51], the HFCT is usually installed at/near the cable body or the grounding wire of cable terminals as shown in Figure 7. When using HFTCs to detect thepartial discharge of cable terminals, the measurement results can be affected by low-frequency electromagnetic signals and are also vulnerable to the impact of pulse signals generated by other high-voltage equipment [52–54]. However, by combining other partial discharge inspection measures like UHF sensors and AE sensors, different defects inside the cable terminals can be detected and classified [55]. For commercial use, the HFCTs of different manufacturers, such as HVPD Ltd., EA Technology, Megger, Altanova Group, Powertest, Baoding Tianwei Xinyu Technology Development Co., Ltd., have been widely used in medium and high-voltage cables terminals.

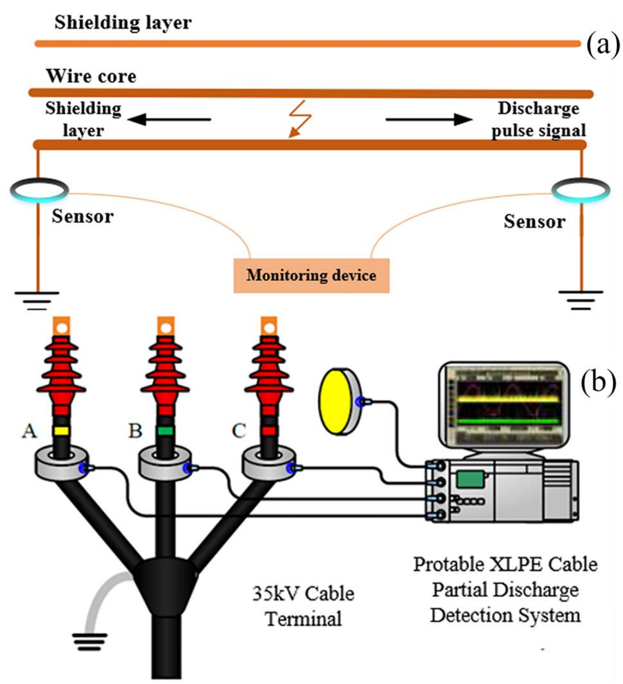

FIGURE 7 Electromagnetic coupling detection of partial discharge for cable and cable terminals. (a) Schematic diagram and (b) field test diagrammatic sketch.

(5) Simulation analysis

Regarding the partial discharge detection simulation analysis, a new capacitive strip sensor is developed for partial discharge measurements, which was validated on XLPE cable terminals using a simulation model based on the finite integration technique [56]. The results showed that the location of circumcision defects was closely related to their effects on the insulation performance of EP. L. Zhou et al. [57] performed finite element analysis of cable terminals with internal defects and analysed the phase-resolved partial discharge spectra according to PSA. Zhou also extracted the grayscale values of the PSA spectra using the K-means clustering method. In ref. [58], a three-dimensional finite-difference time-domain simulation model (FDTD) for cable terminals was established, which covered four common fault types: electric dendrite discharge, surface sliding discharge, air-gap discharge, and floating discharge. The effect of insulation defects and fault location on the propagation characteristics was also investigated.

4.1.2 | UV detection

Due to the local tips, burrs, dirt, and other local field strength distortion, high-voltage equipment always ionises the air and generates a corona, which emits a considerable amount of ultraviolet light [59]. UV imaging detection technology uses a specially designed optical sensing system to capture the ultraviolet light during air ionisation, which is then processed and projected on a monitor alongside the visible light image to display the local corona location and discharge intensity of high-voltage equipment [60, 61]. Figure 8 depicts the UV detecting scheme. Detecting insulators with UV video requires manual interpretation of discharge sites, which is time-consuming. An efficient UV

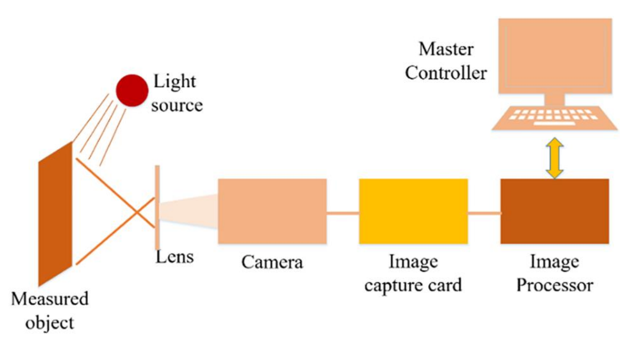

FIGURE 8 Diagram of cable fault detection using UV.

detection method was proposed, which employed an unmanned aerial vehicle to carry UV sensors for automatically collecting UV images and detecting the discharge location based on the spectral characteristics of corona discharge and the morphological characteristics of UV images [62]. Existing methods for assessing the condition of exterior insulation heavily rely on a single type of signal, which is susceptible to leakage and false detection. By collecting UV and IR signals and extracting underlying signatures during the partial discharge of cable joints, an edge computing-based detection unit was developed, which provides an approach for assessing the operational status of substation cable joints [63]. In the meantime, other researchers proposed hybrid methods by combining IR, Raman, and UV-visible spectra to detect faults of XLPE cables [64].

4.1.3 | Infrared detection

During operation, high-voltage electrical equipment may generate a massive amount of heat, which enables the use of IR rays for fault detection at the early stage. For example, oil leakage faults at cable terminals have been successfully detected by using IR thermography [65, 66]. Figure 9 shows the schematic diagram of IR fault detection. By applying voltage at various frequencies to cable terminals, the effect of high-frequency harmonics on hot spots of different types of cable terminals was revealed using IR thermography [67]. Given the high computational cost of processing a large number of IR images, machine learning techniques have been employed to automatically extract informative features from the original images and use the extracted features as the input of the neural network to achieve an intelligent diagnosis of equipment. For example, an automatic diagnosis method of cable defects was proposed, which used faster regions with convolutional neural network features and Mean-Shift to accurately locate the overheating region under various shooting angles and backgrounds, and subsequently, achieved automatic diagnosis of overheating defects [68]. In addition, deep learning algorithms were also applied to process a large volume of IR thermal images and identify the fault location of electrical equipment [69]. Last but not least, measurement data from ultrasonic, UV, and IR were combined to achieve a complete diagnosis of the external insulation condition of high-voltage equipment in substations using picture matching and information fusion algorithms [70].

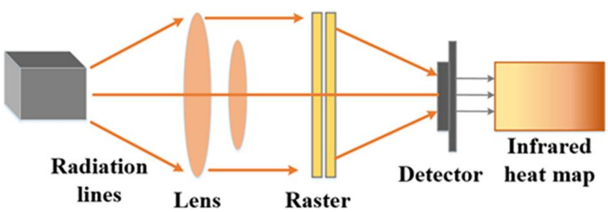

FIGURE 9 Schematic diagram of cable fault using infrared (IR) sensors.

4.1.4 | X-ray inspection

After X-ray irradiation, the signal is converted into a detection signal by a ray detector to generate effective digital imaging [71, 72]. Figure 10 illustrates an X-ray imaging scheme. The variation in material density will affect the X-ray display of cable accessories and terminals, which are made of different materials. The image colour of high-density materials will be much darker than that of low-density materials when X-ray is irradiated. If the material has a significant density difference, it will be difficult to observe the interior of the material with less density. This limits its capability to detect anomalies within the insulation. In response to this challenge, researchers used CT tomography and moved the X-ray along a designed path to continuously scan the measured cable sequentially at a full angle. In this way, each scan captures the X-ray image of the testing specimen in a thin layer [73]. After the scan, images of all layers are combined to provide a complete picture of the internal state of the cable terminals. H. Yi et al. [74] employed an X-ray scanning technique to detect internal faults of a 275 kV oil-filled cable. To diagnose 11 kV EPR cable defects, A. J. Reid et al. [75] used IR imaging, X-ray computed tomography, and scanning electron microscopy. Despite the above successful cases, X-ray becomes ineffective for detecting delamination and cracks and it may produce high-energy free radiation that is harmful to humans. This limits its usage for cable defect detection.

4.2 | Offline methods

4.2.1 | Acoustic emission measurement

The AE approach makes use of acoustic detection technology, which is less impacted by external electromagnetic noise and becomes an ideal non-invasive field detection method [76–78]. The absorption of acoustic waves by insulation materials rises when the frequency increases. As the high-frequency part of the acoustic signal created by local discharge decays rapidly, acoustic signals in the frequency range of 20–300 kHz are commonly used for fault detection. Given that the acoustic signal decays rapidly as it travels along the cable, this technique is primarily employed to detect local discharge near cable joints [79]. The majority of high-speed EMU vehicle cable terminals

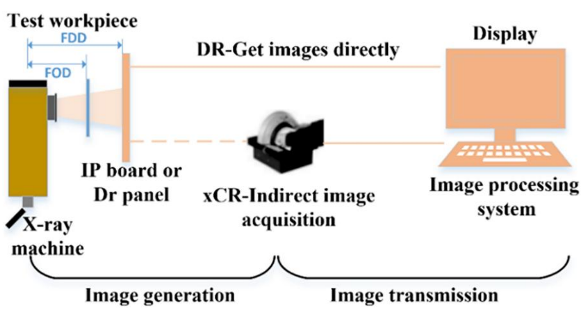

FIGURE 10 X-ray imaging principle.

are EPR cable terminals. T. Sakoda et al. used a number of AE signals to determine the EPR insulation breakdown. The flowchart of the AE approach [80] is shown in Figure 11. Y. Tian et al. [25] proposed a partial discharge localisfation method using acoustic signals of cable joints. By comparing the results of other online partial discharge detection methods, it was found that the AE signal inside the cable joints was significantly attenuated, which affected the sensitivity of the AE detection method.

4.2.2 | Terahertz nondestructive inspection

Compared to short-band electromagnetic waves, such as IR light, ultraviolet light, and X-rays, Terahertz (THz) waves have a wavelength range of 30 m to 3 mm. Due to the rich information provided by THz measurement, terahertz time domain spectroscopy (THz-TDS) and THz-TDS-based 2D scanning imaging technology have become more and more widely used in the field for non-destructive testing of composited material defects with a focus on interface characterisation and thickness measurement, internal defect detection (such as air gap, micro crack etc.), interface bonding defect detection, and so on.

A multimodal imaging method based on THz-TDS information was developed for interfacial characteristics and thickness measurements [81], which laid a foundation for THz non-destructive testing of non-polar molecular composites and ceramic-based composites [82]. Furthermore, based on reflection at the interface of successive layers, THz-TDS was utilised to detect the thickness of multilayer polyethylene composites by calculating the periodic variation of the refractive index during THz wave propagation in each layer of the material [83].

The intermolecular physical properties were used to detect the water content of transformer insulation paper using a transmission THz-TDS system, and the response signals of different terahertz time-domain and frequency-domain were obtained. Through curve fitting, the moisture content of the transformer paper was estimated. The non-uniform moisture distribution of the transformer paper was also examined by combining terahertz imaging [84]. To detect defects, such as air gaps and cracks inside composited materials, H. Mei et al. [85] developed a method to diagnose and classify the interfacial air gap and erosion defects in composited insulators based on the information provided by terahertz waves. By combining the deconvolution method, the proposed method was validated on three defect types of defects, including the single air gap defect, inclusion defect, and double-layer air gap defect. The relationship between the deconvolution waveform and sample defects is shown in Figure 12 [86]. F. Yang et al. [87] artificially created air-gap defects in real XLPE samples and used a transmissive THz-TDS system to perform spectral imaging measurements on the samples. The testing results demonstrated the feasibility of the terahertz technique for non-destructive detection of air-gap defects in XLPE from both theoretical and experimental perspectives. S. Takahashi et al. [88] applied terahertz reflection waves on insulating polymer shields to perform a non-destructive inspection of broken wires in copper cables with various size gaps. Water trees growing on the polymer surface or beneath the polymer were also successfully captured by using terahertz reflection waves [89], which are shown in Figure 13.

Previous studies also utilised the frequency-modulated continuous THz imaging method to test the bonding samples of aerospace thermal insulation composites. The bonding defects between thermal insulation composites and bonded substrates were investigated by combining image processing techniques [90]. Successful case studies have been reported to detect bonding defects in non-metal/metal bonded structures using the THz-TDS technique, which involve detecting information, such as signal amplitude, phase, refractive index,

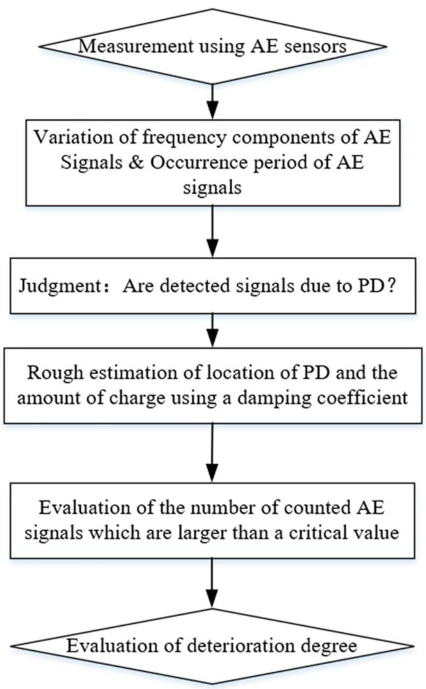

FIGURE 11 Cable terminal degradation diagnostic procedures using the Acoustic emission (AE) technique [80].

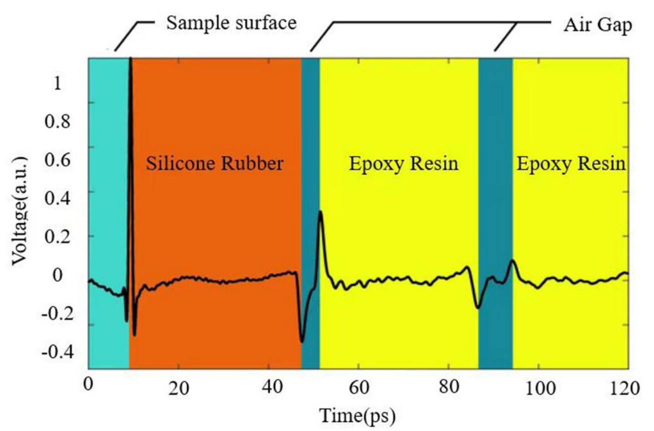

FIGURE 12 Relationship between the deconvoluted waveform and the defects using THz-TDS [83].

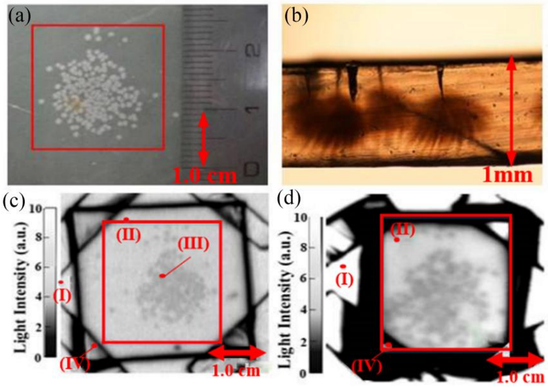

FIGURE 13 Views of the sample with water trees. (a) A surface view was taken by a digital camera. (b) A cross-sectional view by a polarisation microscope. (c) THz imaging of the sample with water trees. (d) THz imaging results were obtained by scanning the light intensity of reflected THz light pulses over the surface of a polyvinyl chloride sheath [86].

and delay time in the time-frequency domain, as well as two-dimensional THz images of the bonding surface [91, 92]. For interfacial bonding defects of composites, the non-linear behaviour of the non-metallic matrix intersection was measured by the THz-TDS technique to achieve preliminary detection of weak bonding defects [93, 94]. Based on this, reflection was used to calculate the time difference between the absorption peaks of the THz-TDS spectral lines to estimate the geometry of the defects inside the composited structure in a fixed imaging direction. Finally, the THz-TDS system was used to visualise the thickness distribution of the rubber sample. The delamination defects of the sample were successfully detected by combining THz imaging of the internal defects of different bonding structures with spectroscopic testing and visual imaging of a three-layer bonding structure [95, 96]. Previous studies also reported using terahertz technology to detect defects in simplified models of vehicle cable terminals. This method first used frequency-domain spectra to determine the presence of defects. Then, it used terahertz multi-mode imaging to determine the location and estimate the geometric size of defects. Finally, it employs time-domain spectra to determine the depth of defects [97, 98].

5 | CURRENT CONCERNS AND FUTURE RESEARCH DIRECTIONS

5.1 | Current concerns

(1) At the current stage, there are no applicable standards for cable terminal testing. There is still a gap in the validity of the cable defect detection methods using the artificially created defects in the laboratory and the faults that occur in real-life cable terminals.
(2) The operating condition of composited cable terminals is complex, especially for high-speed EMUs. Although certain work has been reported on the physical entity and simulated linkage of cable terminals, real-time monitoring of the cable terminals is still hard to achieve using existing techniques.
(3) Different cable diagnostic techniques individually focussed on assessing one aspect of a cable's condition and cannot provide the whole “picture” of the condition of the cable.
(4) Due to the long-term vibration of the vehicle body during the operation, the EMU's cable terminal has a high failure probability. Currently, comprehensive studies on cable terminal failures as a result of vehicle body vibration are still lacking.
(4) In the multilayer cylindrical composited construction, the underlying mechanisms of terahertz wave propagation and imaging are still unclear. In terms of structural shape and geometry, the EMU's composited cable terminal has a metal/non-metal multiphase composited multilayer cylindrical structure, which differs from the two-layer metal/nonmetal two-phase bonded structure or the three-layer non-metal flat composited structure. It is necessary to investigate the time-domain terahertz imaging mechanism of typical faults in multilayer composited cylinders or laminated columns.

5.2 | Future research directions

5.2.1 | Experimental aspects

(1) When applying terahertz techniques for defect inspection, the whole equipment requires a wired connection to the data acquisition terminal, which makes the examination quite inconvenient. To make the inspection faster and more convenient, it is possible to combine terahertz communication technology into the existing experiment setup. For example, Terahertz technology can identify multilayer cylindrical composited objects with curved surfaces. It is also worth investigating whether the detection angle affects the measurement results and how to minimise the associated detection errors.
(2) The cumulated vibration degrades the insulation performance for composited cable terminals. As a result, measurement data on the mechanical or electrical performance of the cable terminal over a longer time is preferred to perform joint diagnostics of cable conditions.
(3) Electro-thermal oxygen ageing is one of the significant reasons for electrical equipment degradation. However, electro-thermal oxygen ageing and its by-products are not characterised by existing terahertz technology. Therefore, connecting the electro-thermal oxygen ageing of cable terminals with the terahertz spectrum is vital to characterise better the electro-thermal oxygen ageing status of composited cable terminals.

5.2.2 | Theoretical and simulation aspects

(1) The current cable terminal defect detection is mainly performed using a single technique. It is critical to apply multi-source information fusion technology to evaluate the overall condition of cable terminals by integrating results

from different methods. In addition, it is also necessary to develop an intelligent condition assessment framework by establishing a threshold library to provide early warning of the cable terminal operation status based on multi-source information fusion technology.

(2) Terahertz technology is still at its early stage for cable defect detection. Therefore, it is necessary to further validate THz-based detection technology's performance in a field measurement environment.

(3) The existing terahertz imaging uses pixel points to capture the amplitude and other parameters carried by terahertz waves. Although the THz imaging helps determine the presence of the cable defects, it is difficult to identify the exact type of defects. Therefore, establishing a complete database of different kinds of defects is necessary to promote the applicability of THz techniques further.

(4) Cable terminals contain several digital twin characteristics, including time-varying operating circumstances, high-frequency vibration, frequent transient overvoltage shocks, and long-term operation without easy maintenance. The goal of the digital twin is to create a virtual twin of the cable terminal that can better reproduce any defects that may exist or have existed during the service.

6 | SUMMARY

This paper provides a comprehensive review of the detection of cable terminal faults. It also discussed future research directions in this area. The following conclusions can be derived.

(1) As non-destructive and non-intrusive methodologies, terahertz inspection technology and ultrasonic testing have been gaining popularity for cable terminal defect identification, and this trend is anticipated to continue in the near future if the power of terahertz emitter can be greatly improved and the anti-interference ability of the ultrasonic testing devices can be enhanced in the near future. Otherwise, it is believed that the most effective way for online monitoring and fault detection of cable terminals, at present, is still the traditional partial discharge online detection methods, especially the application of HFCT either for the ordinary distribution cable terminals or vehicle cable terminals.

(2) Employing multi-source information fusion to integrate the diagnostic results of different technology and develop an intelligent evaluation framework could be a future research direction to provide an early warning of abnormal operating conditions of cable terminals.

(3) Through the intercommunication between the actual measured data and the virtual simulation data, the physical entity and the digital twin infrastructure can ensure the same operation status of the cable terminal over the whole life cycle. It is also possible to build an information-physical system that can manage the health of the cable terminal throughout its life cycle by combining the digital twin and online operation monitoring data.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interests.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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