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A Review of Smart Nanosensors for Thermal and Mechanical Stress Monitoring in Power Cables

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ABSTRACT

Power cables are critical components of electrical power systems, whose reliability is strongly affected by thermal and mechanical stresses. Continuous condition monitoring is therefore essential for preventing insulation degradation, unexpected failures, and costly maintenance. In recent years, smart nanosensors have emerged as promising monitoring technologies owing to their high sensitivity, rapid response, and capability for real-time measurements. This paper presents a comprehensive review of smart nanosensors for thermal and mechanical monitoring of power cables. To provide a systematic perspective, the review is organized into six main categories: (i) fundamental concepts of cable degradation and nanosensing technologies, (ii) classifications of nanosensors, (iii) thermal monitoring applications, (iv) mechanical stress monitoring, (v) sensor integration and comparison with conventional monitoring methods, and (vi) current challenges, research gaps, and future trends. The review highlights the capabilities of graphene-, carbon nanotube-, and fiber optic-based sensors for accurate temperature and strain monitoring and discusses their potential for predictive maintenance in smart power systems. Finally, key challenges, including long-term durability, industrial integration, and standardization, are identified, and future research directions toward intelligent cable monitoring and smart grid applications are outlined.

1. INTRODUCTION

Power cables, as one of the most critical components of electrical energy transmission and distribution infrastructure, play a vital role in the reliability and stability of power grids [1, 2]. The increase in power transmission capacity, the development of smart grids, and the expansion of renewable energy sources have led to the operation of cables under more complex thermal and mechanical conditions [1, 3]. Under such conditions, temperature rise, mechanical stresses, vibrations, material fatigue, and insulation aging can lead to reduced cable service life and ultimately costly failures. Therefore, online condition monitoring of cables has become one of the primary priorities of the power industry [4]. Traditional methods of cable condition assessment are mainly based on periodic inspections, offline tests, and measurement of electrical parameters [1, 5]. Although these methods provide valuable information, they have limitations in early detection of hot spots, stress concentration, and localized damage. For this reason, the development of intelligent monitoring systems based on advanced sensors has received extensive attention from researchers in recent years [4]. The emergence of nanotechnology has created new opportunities in the field of sensors [6, 7]. Nanomaterials, due to their high surface-to-volume ratio, ultra-high sensitivity, capability to operate at small scales, and integrability with electronic and communication systems, have enabled the development of a new generation of smart sensors [8, 9]. Nanosensors are capable of measuring very small changes in temperature, strain, pressure, and other physical parameters with high accuracy and providing the necessary information online to asset management and predictive maintenance systems [10]. These capabilities have made nanosensors one of the key technologies in the development of smart power grids and future energy infrastructures [11]. Among various technologies, fiber optic sensors, particularly Fiber Bragg Grating (FBG) sensors, carbon nanotube-based sensors, graphene, and conductive nanocomposites have attracted special attention [12, 13]. These sensors, due to their immunity to electromagnetic interference, capability for simultaneous temperature and strain measurement, distributed monitoring along the cable, and compatibility with high-voltage environments, are considered suitable options for power cable health monitoring [14]. Given the rapid

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growth of research in the field of nanosensors and the increasing need of the power industry for intelligent monitoring systems, conducting a comprehensive review of existing technologies, advantages, challenges, and future trends seems essential [15]. Therefore, the present paper comprehensively reviews smart nanosensor technologies used in thermal and mechanical stress monitoring of power cables and, while analyzing research achievements, explains the future development paths of this technology. To illustrate the global research trend in nanosensor-based monitoring technologies, a bibliometric analysis was conducted using the PubMed database. The search results indicate a continuous increase in the number of publications over the past two decades, with a particularly noticeable growth after 2018 (Fig. 1). This upward trend reflects the increasing scientific interest in advanced sensing technologies for condition monitoring, structural health assessment, and predictive maintenance. The rapid development of nanomaterials, fiber optic sensing technologies, and intelligent monitoring systems has significantly contributed to the expansion of this research field. These observations further highlight the growing importance of smart nanosensors as promising tools for enhancing the reliability and operational safety of modern engineering infrastructures, including power cable systems.

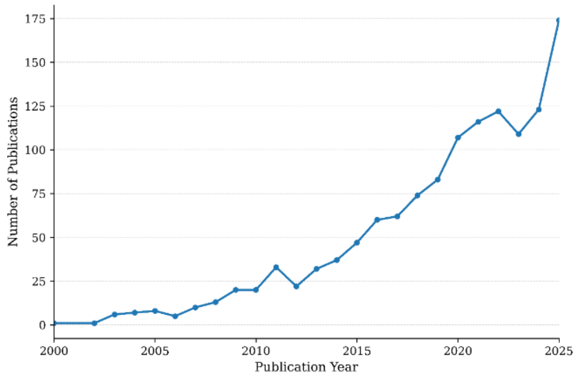

Fig. 1. Annual publication trend of research on nanosensor-based cable monitoring technologies retrieved from the PubMed database (search performed in July 2026).

2. Literature Review

Condition monitoring of power cables has been an important research topic in the field of power grid reliability over the past two decades [16, 17]. In one of the most comprehensive review studies, Song et al. examined online monitoring technologies for power cables and demonstrated that measuring parameters such as temperature, stress, vibration, partial discharge, and sheath current can play an effective role in early fault detection. This research also emphasized the importance of distributed sensors and intelligent cable condition assessment systems [4]. In the field of fiber optic sensors, numerous studies have focused on the application of FBG sensors for simultaneous temperature and strain measurement. Yassin et al., in a comprehensive review paper, showed that FBG sensors, due to their high sensitivity, small dimensions, corrosion resistance, and immunity to electromagnetic noise, are among the most successful technologies for structural health monitoring of structures and industrial equipment [18]. These sensors are capable of measuring very small changes in strain and temperature and enable multipoint measurements. Subsequently, researchers developed Distributed Fiber Optic Sensors (DFOS) based on Rayleigh and Brillouin scattering. This technology enables continuous temperature and strain measurement along several kilometers of cable and is recognized as one of the most promising solutions for health monitoring of longitudinal infrastructures [19]. In recent years, the use of nanomaterials in sensor design has grown significantly. Carbon nanotubes (CNTs), graphene, metal nanoparticles, and polymer nanocomposites, due to their high electrical conductivity, suitable flexibility, and high sensitivity to environmental changes, have been used to fabricate temperature and strain sensors. These sensors are capable of detecting very small changes in mechanical stress or localized temperature increases, thereby enabling the development of predictive maintenance systems [11]. In the field of high-voltage equipment, a review published on the application of FBG sensors in high-voltage equipment showed that these sensors have high capability for monitoring power cables, transmission lines, transformers, and insulators. The aforementioned research emphasized the capability for simultaneous stress and temperature measurement as well as deployment in environments with strong electromagnetic fields [14]. Despite significant advances, challenges such as decoupling the cross-sensitivity of temperature and strain, long-term stability of sensors, cost of interrogation systems, reliability in harsh industrial environments, and data integration with artificial intelligence systems remain. Recent studies show that the combination of advanced nanosensors with machine learning algorithms, Industrial Internet of Things (IIoT), and big data analytics can create a new generation of intelligent power cable monitoring systems [20].

3. Theoretical Foundations and Basic Concepts

3.1. Power Cables and Factors Affecting Their Performance

Power cables are among the most important equipment in electrical energy transmission and distribution networks and are responsible for the safe and stable transmission of electrical power (Fig. 2). In recent years, with the development of smart grids, increased load density, and expansion of renewable energy sources, the importance of cable reliability and condition monitoring has received more attention than ever before. According to the report by Song et al., power cables, as one of the most critical components of energy infrastructure, are affected by multiple factors including temperature, vibration, mechanical stress, partial discharge, sheath current, and environmental conditions, each of which can influence cable performance and service life [4]. One of the most important factors affecting cable performance is operating temperature. The flow of electric current through the conductor causes ohmic losses and heat generation [21, 22]. If heat dissipation is not properly performed, temperature increase accelerates insulation aging processes and reduces its electrical strength. In addition to thermal factors, cables are subjected to mechanical stresses caused by tension, pressure, bending, vibration, soil settlement, and temperature variations. These stresses can cause micro-cracks, damage to insulation layers, and ultimately reduce system reliability [4]. Given the increasing electrical, thermal, and mechanical stresses in modern networks, the use of online monitoring systems for cable condition assessment has become a necessity [16, 23]. Studies show that simultaneous monitoring of temperature and mechanical stress parameters can play an effective role in increasing reliability and preventing sudden cable failures [14]

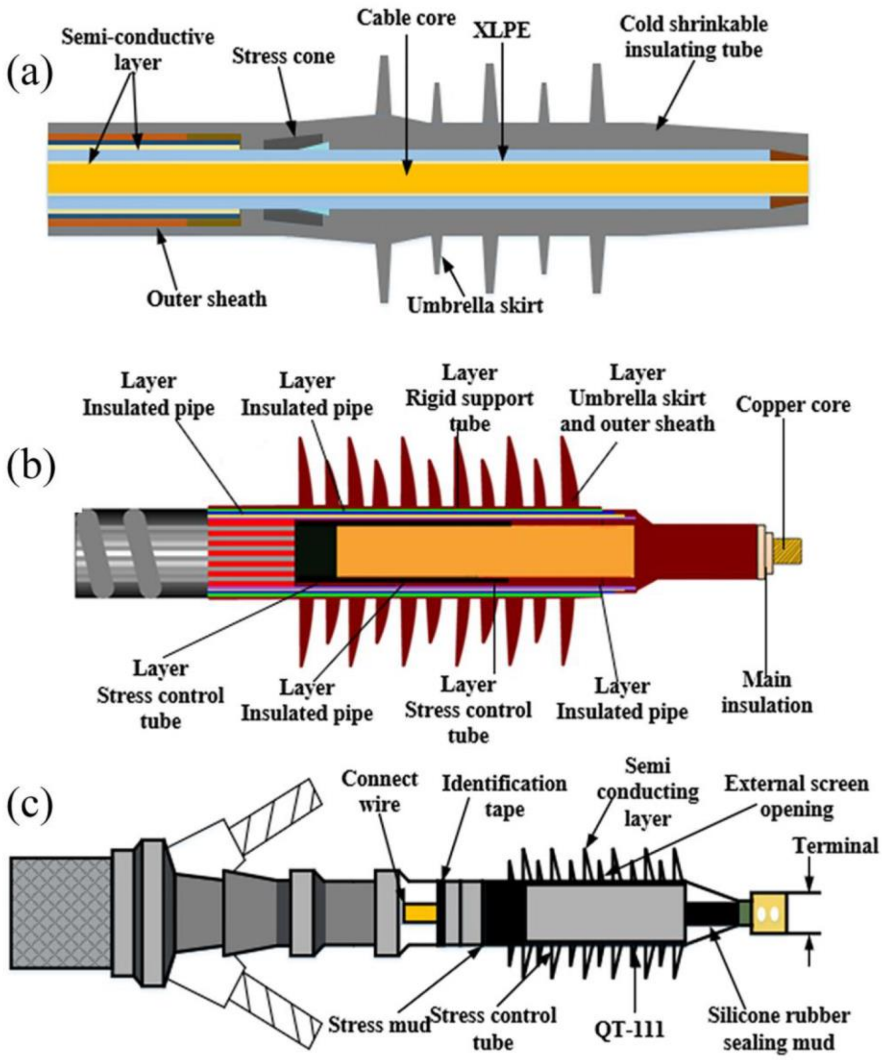

Fig. 2. Structure of cable terminal used in distribution power systems, electric multiple units, and wind farms [24].

3.2. Types of Thermal and Mechanical Failures in Power Cables

Power cable failures can be divided into two main categories: thermal failures and mechanical failures (Fig. 3).

a) Thermal Failures: Thermal failures are mainly caused by overload, faulty connections, inadequate ventilation, and increased ambient temperature. High temperature accelerates chemical reactions in the insulation structure and intensifies the aging process [25-27]. Densley demonstrated that the most important degradation mechanisms in power cables include thermal aging, electrical treeing, and water treeing, which ultimately lead to reduced dielectric strength and insulation failure. In XLPE-insulated cables, long-term temperature increases causes oxidation of the polymer structure, reduction of mechanical properties, and increased probability of partial discharge occurrence. Therefore, accurate temperature monitoring is recognized as one of the most important indicators of cable health [4, 28].

b) Mechanical Failures: Mechanical failures usually occur due to external forces or cumulative stresses over time. These failures include insulation cracking, mechanical fatigue, conductor deformation, damage from improper installation, and stresses from thermal expansion and contraction [29, 30]. Recent studies show that alternating load and temperature changes can cause cyclic strains in cables. These strains over time cause structural damage and reduce cable service life. Since many of these failures are not visible in the early stages, the use of online monitoring technologies for early detection has gained special importance [4, 31, 32] (Figs. 4 ,5)

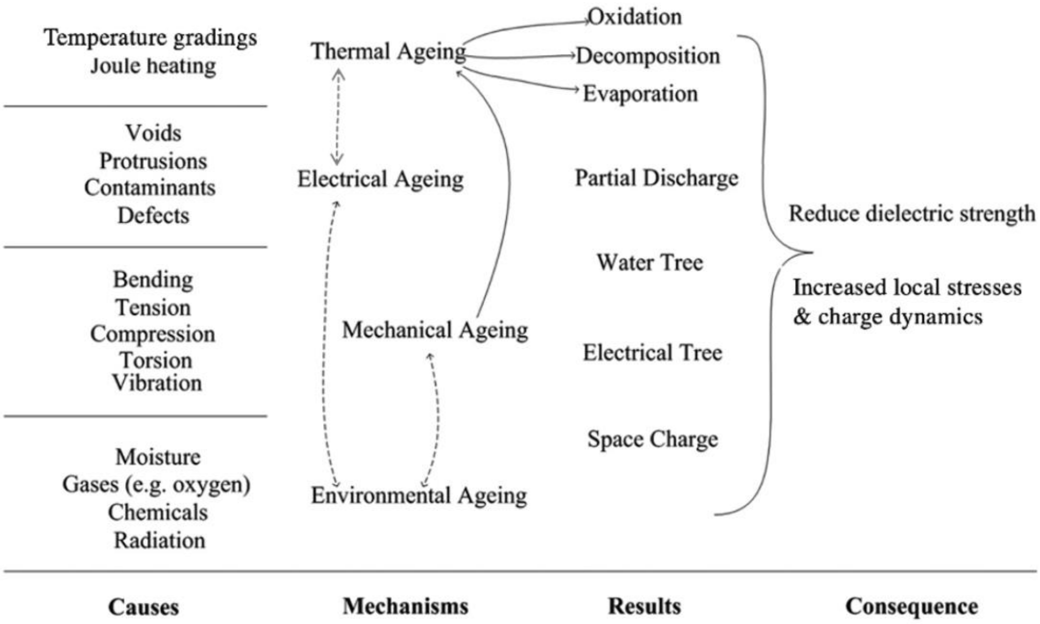

Fig. 3. Power cable polymeric insulation material aging correlations [23]

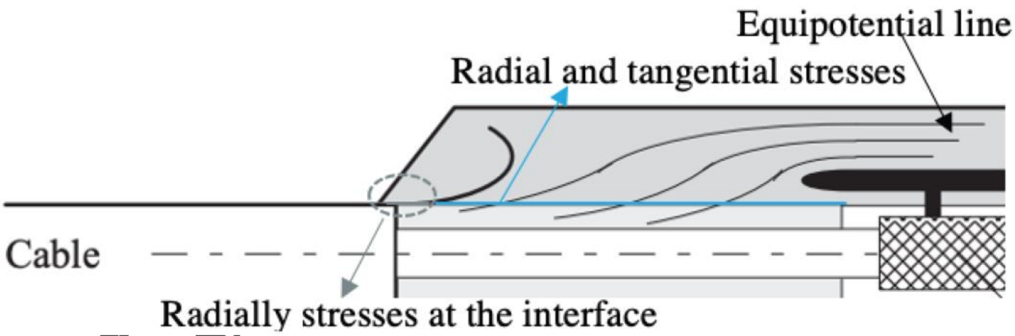

Fig. 4. Illustration of radial and tangential stresses at cable accessory interfaces [33]

Fig. 5. Examples of failure damages appeared at MV cable accessory interfaces due to multi-physical stresses combined with water ingress [33]

3.3. Introduction to Nanosensors, Classification, and Operating Principles

Nanosensors are a new generation of sensors that use nanomaterials or nanoscale components in their structure. The main characteristics of these sensors are high sensitivity, small dimensions, appropriate response speed, and the ability to detect very small changes in physical and chemical parameters [34-36]. The operating principle of nanosensors is based on converting physical changes such as temperature, strain, pressure, or vibration into a measurable signal. This signal can appear as a change in electrical resistance, change in capacitance, change in optical wavelength, or change in frequency [37, 38]. From a performance perspective, nanosensors used in power cable monitoring can be divided into four main categories:

- Electrical nanosensors
- Optical nanosensors conductivity, enable the detection of very small thermal and mechanical changes and are recognized as the next generation of intelligent power cable monitoring systems [39].

4. Types of Nanosensors Used in Power Cable Monitoring

Condition monitoring of power cables to increase network reliability, reduce unplanned outages, and optimize maintenance programs has received extensive attention in recent years [40]. In this regard, nanosensors, due to their small dimensions, high sensitivity, integrability with existing equipment, and capability for online monitoring of various parameters, have become one of the key technologies in cable health monitoring systems [41]. These sensors are capable of detecting very small changes in temperature, strain, and other performance parameters and providing valuable information for early fault detection [42].

4.1. Temperature Nanosensors

Temperature is one of the most important parameters affecting the performance and service life of power cables [43]. Increased operating temperature accelerates insulation aging processes, reduces electrical strength, and increases the probability of thermal failures (Fig. 6). Therefore, the development of high-accuracy temperature sensors with continuous monitoring capability has become one of the main axes of research in the field of cable health monitoring. In recent years, the use of carbon nanomaterials, particularly graphene and its derivatives, in the fabrication of temperature sensors has grown significantly. Graphene, due to its high thermal conductivity, high charge carrier mobility, and significant specific surface area, detects temperature changes with high sensitivity [44, 45]. A review by Nag et al. shows that graphene-based temperature sensors are capable of measuring very small temperature changes with fast response speed and suitable stability. Furthermore, the mechanical flexibility of these materials enables their use in intelligent monitoring systems and complex structures [46]. In addition to graphene-based resistive sensors, distributed fiber optic sensors have also found widespread application in power cable temperature monitoring. This technology enables measurement of temperature distribution along several kilometers of cable and allows operators to identify localized hot spots before failure occurs. The combination of fiber optic technology with temperature-sensitive nanomaterials has created a new generation of thermal sensors with high accuracy and reliability [47].

4.2. Strain and Stress Nanosensors

Mechanical stresses caused by installation processes, environmental vibrations, ground settlement, temperature variations, and cyclic loading can gradually degrade the structure of power cables [48] (Fig. 7). In many cases, these damages have no visible symptoms before final failure; therefore, continuous strain and stress measurement has become one of the key tools in cable health monitoring. Carbon nanotubes (CNTs) are among the most important materials used in the fabrication of strain sensors. High electrical conductivity, high length-to-diameter ratio, and suitable mechanical flexibility have made these materials sensitive to the smallest mechanical changes [49]. In CNT-based sensors, applied strain causes a change in the distance between nanotubes and consequently a change in electrical resistance. This change is used as an indicator of the applied stress. A review study published by Wang et al. shows that CNT, graphene, and nanodiamond-based sensors are capable of measuring very small strains with high sensitivity and have favorable performance in harsh industrial environments. This feature is particularly important for application in power cables, which typically operate under severe environmental conditions[49]. In addition to resistive sensors, FBG fiber optic sensors are also widely used for strain measurement in high-voltage equipment. These sensors, by measuring changes in reflected wavelength, enable precise monitoring of mechanical deformations and are completely immune to electromagnetic interference [50].

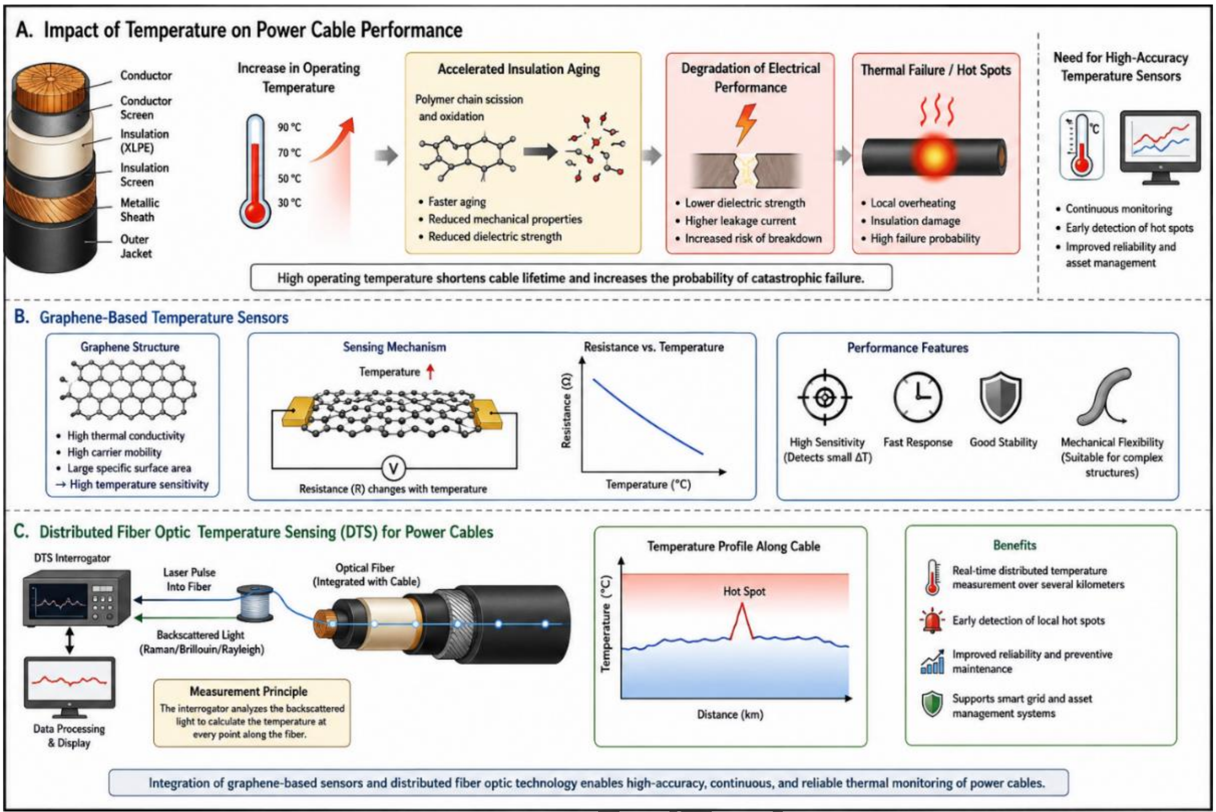

Fig. 6. Schematic illustration of temperature monitoring in power cables using graphene-based nanosensors and distributed optical fiber sensing systems.

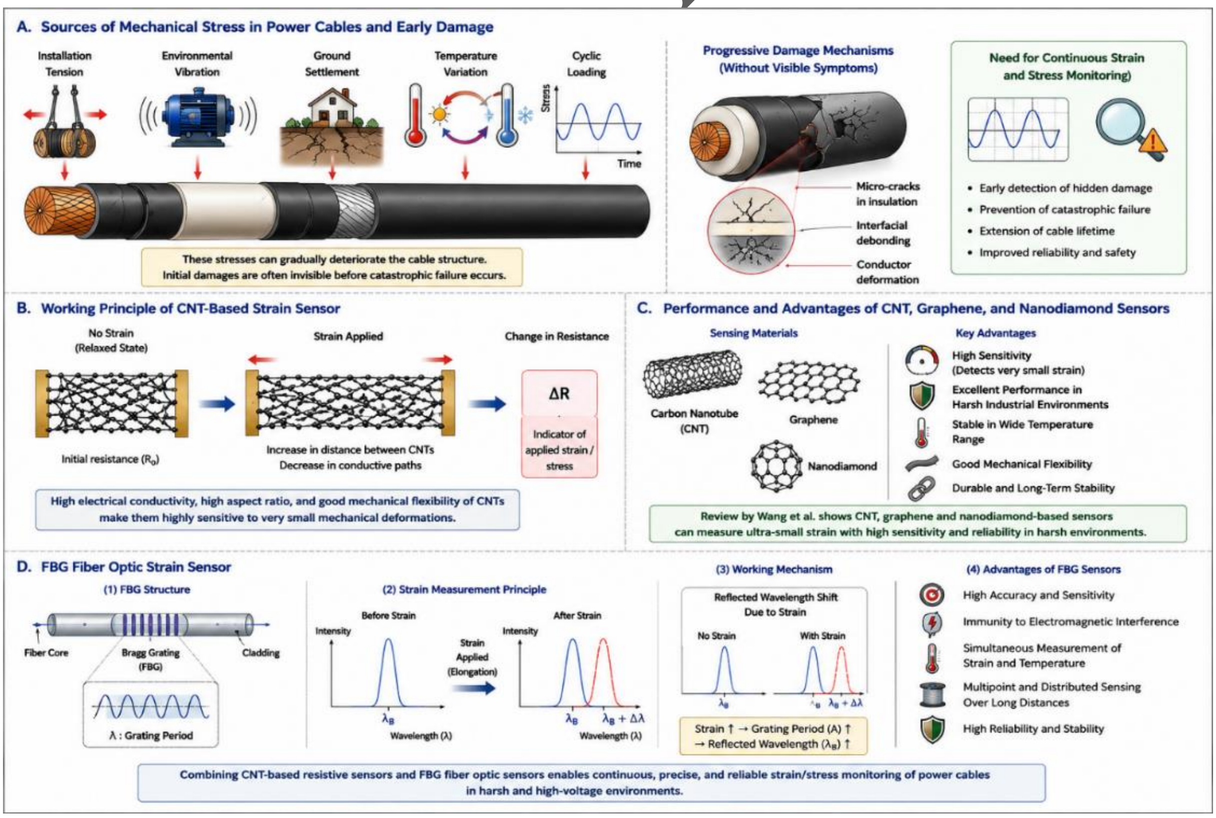

Fig. 7. Schematic representation of mechanical stress monitoring in power cables using carbon nanotube (CNT)-based strain sensors and fiber Bragg grating (FBG) sensors.

Advances in nanotechnology have led to the development of a new generation of sensors in which nanostructured materials are used as sensitive elements. The most important of these materials include graphene, carbon nanotubes, metal nanowires, metal nanoparticles, and conductive nanocomposites [51]. Graphene is one of the most prominent nanostructured materials in the field of sensors. This material, which consists of a single atomic layer of carbon with a hexagonal arrangement, has unique electrical, thermal, and mechanical properties. Geim and Novoselov, in their famous paper "The Rise of Graphene," demonstrated that this material has very high potential for the development of a new generation of ultra-sensitive sensors[52]. In addition to graphene, carbon nanotubes have also found widespread application in the fabrication of temperature and strain sensors due to their high mechanical strength and ability to form conductive networks. Metal nanowires such as silver and gold are also used in next-generation sensors due to their high conductivity and ability to fabricate flexible structures [52]. Recent studies have shown that sensors based on nanostructured materials have higher sensitivity, smaller dimensions, lower power consumption, and shorter response time compared to conventional sensors. These advantages have led to their rapid expansion in health monitoring systems for electrical equipment, particularly power cables.

4.3. Multifunctional Sensors

One of the important trends in the development of sensor technology is the design of multifunctional systems capable of simultaneously measuring multiple parameters. In applications related to power cables, simultaneous measurement of temperature and strain is particularly important because many failures result from the interaction of thermal and mechanical factors. In recent years, multi-core and multi-mode FBG sensors have been introduced as one of the most advanced multifunctional sensing technologies [53, 54]. These sensors are capable of simultaneously measuring changes in temperature, strain, torsion, and vibration. Published research shows that the use of multi-core structures increases measurement accuracy and reduces errors caused by cross-sensitivity of parameters [55, 56]. The main advantage of multifunctional sensors is the reduction in the number of sensors required, simplification of the installation process, and reduction of operational costs. Furthermore, the combination of these sensors with IoT systems and machine learning algorithms enables simultaneous analysis of multiple parameters and prediction of potential failures. For this reason, multifunctional sensors are expected to become one of the main pillars of intelligent power cable monitoring systems in the coming years [57, 58] (Fig. 8).

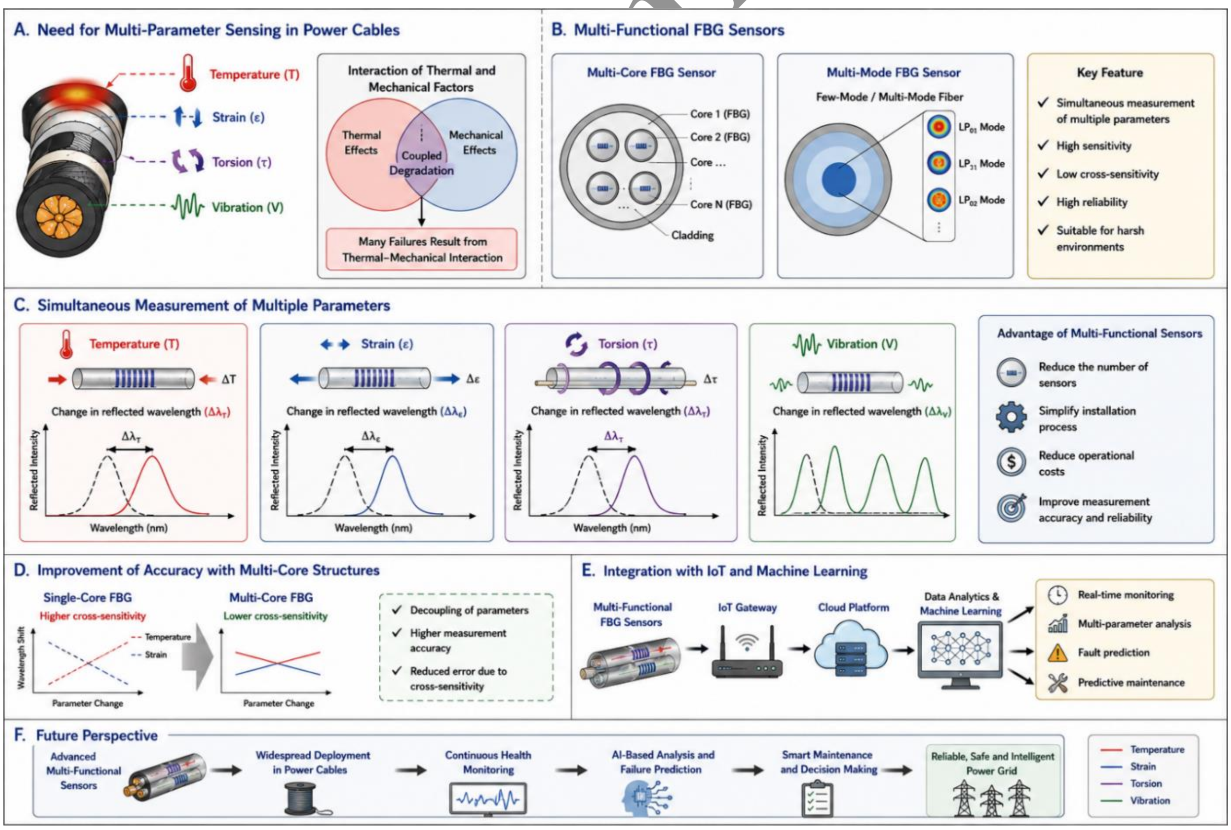

Fig. 8. Conceptual framework of multifunctional sensing in smart power cables based on advanced multi-core and multi-mode FBG sensors.

5. Application of Nanosensors in Thermal Monitoring of Power Cables

Increased operating temperature is one of the most important factors affecting the service life of power cables. Heat increase can accelerate insulation aging processes, reduce dielectric strength, and increase the probability of sudden failures. For this reason, continuous monitoring of the thermal condition of cables has become one of the most important asset management strategies in power networks. Advances in nanotechnology and the development of nanomaterial-based sensors have enabled accurate and online temperature measurement. According to the review study by Song et al., modern sensing technologies play a key role in power cable health monitoring and early detection of critical conditions [4].

5.1. Temperature Measurement and Recording

One of the most important applications of nanosensors in power cables is the continuous measurement and recording of temperature changes along the cable path. In traditional methods, temperature measurement is usually limited to a few points, while modern sensing systems enable distributed temperature monitoring along the entire cable length. Sensors based on fiber optics and advanced nanomaterials are capable of recording very small temperature changes with high accuracy. Studies show that fiber optic-based technologies, particularly Distributed Temperature Sensing (DTS) systems, enable temperature distribution measurement over long distances and are highly suitable for energy infrastructure monitoring [59]. Furthermore, the use of nanomaterials such as graphene has increased the sensitivity of temperature sensors. Accordingly, graphene-based temperature sensors have high sensitivity, appropriate response speed, and long-term stability and can be used for intelligent monitoring of industrial equipment [60].

5.2. Hot Spot Detection

Hot spots are among the most important initiating factors of failure in power cables. These spots usually occur at connection points, joints, areas with insulation defects, or sections with inadequate heat dissipation conditions. Localized temperature increase in these areas can cause gradual insulation degradation and ultimately electrical breakdown of the cable. The study by Song et al. shows that distributed temperature monitoring technologies are capable of detecting the smallest thermal increases along the cable and determining their exact location. This capability enables early detection of hot spots and prevents costly failures [4, 61]. Furthermore, Fiber Bragg Grating (FBG) fiber optic sensors, due to their high accuracy and immunity to electromagnetic interference, have been widely used for hot spot detection in high-voltage equipment. Ramnarine et al. have reported that these sensors can measure very small temperature changes under operating conditions of power networks [14].

5.3. Prediction of Temperature Rise and Damage Prevention

Today, the goal of advanced monitoring systems is not only temperature measurement but also prediction of future thermal behavior of the cable. Data obtained from nanosensors can be processed online in data analysis systems to determine the temperature rise trend before reaching critical conditions. According to results presented by Song et al., the combination of advanced sensing technologies with data analysis models and machine learning algorithms has enabled the development of Predictive Maintenance systems. In this approach, abnormal temperature increases are identified before failure occurs, and corrective actions are taken in a timely manner [4]. Additionally, DTS technology enables the calculation of Dynamic Cable Rating. In this method, the allowable current transmission capacity is determined based on actual cable temperature conditions, preventing thermal overload. Recent studies in the field of fiber optic sensors have shown that this technology can simultaneously increase network efficiency and significantly reduce the probability of thermal failures [59].

6. Application of Nanosensors in Mechanical Stress Monitoring of Power Cables

Mechanical stresses are one of the important and less visible factors in the gradual degradation of power cables. These stresses can arise from installation processes, tensile forces, environmental vibrations, ground settlement, and cyclic thermal changes. Unlike thermal damage, which is usually detectable by temperature increase, mechanical damage in many cases develops gradually and without visible signs. Therefore, the use of strain and stress nanosensors for online monitoring of these phenomena is of particular importance.

6.1. Detection of Bending, Tension, Vibration, and Mechanical Pressure

Strain nanosensors based on conductive nanomaterials such as carbon nanotubes (CNTs) and graphene are capable of converting very small changes in the mechanical structure of cables into electrical changes. In these sensors, applied strain changes the conductive network and alters electrical resistance. This feature enables the detection of bending, tension, and vibration with high sensitivity. A review study by Amjadi et al. (2016) shows that flexible nanomaterial-based sensors are capable of measuring very small strains with fast response and suitable stability and have significant performance in industrial and structural monitoring applications [62]. Other studies have also shown that carbon nanotube-based sensors have high sensitivity to mechanical deformation and are highly suitable for detecting small strains in engineering structures [63]. In power cable applications, these sensors can detect changes caused by environmental vibrations or stresses from thermal expansion and serve as an early indicator of mechanical damage.

6.2. Identification of Damage from Installation, Operation, and Environmental Conditions

A significant portion of power cable failures occur during installation or early operation stages. Excessive tension during cable pulling, unauthorized bending, and localized pressures can cause structural damage to insulation layers. Studies show that nanomaterial and fiber optic-based sensors enable monitoring of these initial stresses. In particular, FBG sensors are capable of recording very small strain changes in the cable structure and are highly useful for monitoring installation conditions [4]. On the other hand, environmental conditions such as soil settlement, moisture, and temperature variations can create secondary stresses in the cable. These stresses accumulate over time and cause gradual degradation of the cable structure. The use of nanosensors enables monitoring of these cumulative effects and plays an important role in preventing sudden failures.

6.3. Relationship between Mechanical Stress and Cable Service Life Reduction

Mechanical stresses play an important role in reducing the service life of power cables, as these stresses can cause micro-cracks in the insulation, increase stress concentration points, and accelerate aging processes. When mechanical stress is combined with thermal stress, its destructive effect multiplies. Experimental studies have shown that cyclic strains from alternating loading can cause mechanical fatigue in the insulation structure. This phenomenon gradually leads to reduced dielectric strength and increased probability of electrical breakdown. Accordingly, simultaneous monitoring of temperature and mechanical stress is essential for accurate assessment of remaining cable life. The combination of data from strain nanosensors with cable life models enables prediction of failure time and planning of preventive maintenance. This approach falls within the framework of Predictive Maintenance and plays an important role in increasing the reliability of power networks [14].

7. Methods for Integrating Nanosensors with Power Cables

One of the main challenges in using nanosensors in power cables is how to integrate them with the multilayer structure of the cable without disrupting electrical and mechanical performance. This integration must be carried out in such a way that both measurement accuracy is maintained and long-term durability under harsh operating conditions is guaranteed. Nanosensors are typically integrated into power cables in three ways:

1. Surface mounting on the outer layer of the cable
2. Embedding in the intermediate layers of the cable
3. Integration into the conductor or insulation structure during the manufacturing stage

Among these methods, the use of fiber optic sensors in the internal structure of the cable is more common due to high resistance to electromagnetic noise and the capability for distributed monitoring. Furthermore, nanomaterial-based sensors are usually applied as thin layers or polymer coatings on the cable. The most important technical challenges in this field include:

- Electromagnetic interference in high-voltage environments
- Flexibility limitations of some nanosensors
- Long-term stability under thermal and humidity conditions
- Difficulty in calibrating distributed sensors
- High implementation cost at industrial scale

Studies have shown that the development of stable nanostructured sensors resistant to environmental conditions is one of the most critical research paths in this field [4]. For successful implementation of nanosensors, there must be complete compatibility between the sensor and the multilayer cable structure, including the conductor, XLPE insulation, semiconductive layers, and metallic shield. Any disruption in this structure can affect the electrical performance of the cable. For this reason, sensors used must have small dimensions, high flexibility, and no interference with the electric field. Fiber optic sensors and some polymer nanocomposites are among the suitable options in this field. Long-term durability of nanosensors in industrial environments is one of the determining factors in their success. Power cables typically operate under harsh environmental conditions including high temperatures, humidity, mechanical pressure, and strong electromagnetic fields. Studies show that the use of protective polymer coatings and design of oxidation-resistant structures can increase the service life of nanosensors. Furthermore, the use of stable materials such as graphene and carbon nanotubes contributes to improving the long-term performance of these systems [62].

8. Advantages and Limitations of Nanosensors in Power Cable Monitoring

Nanosensors, as one of the most important modern technologies in the field of power cable condition monitoring, offer significant capabilities compared to traditional methods. These sensors, due to their utilization of nanomaterials (such as graphene, carbon nanotubes, and nanocomposites), have high sensitivity to changes in temperature, strain, and vibration and can detect very small changes that occur in the early stages of damage. One of the most important advantages of these sensors is the significant increase in measurement sensitivity and accuracy. The nanoscale structure increases the surface-to-volume ratio and consequently increases responsiveness to environmental changes. For example, graphene-based sensors are capable of detecting very small temperature or strain changes with short response time and low noise. Another important advantage is the capability for miniaturization and integration with the cable structure. This feature enables sensor installation in locations that are difficult or impossible to access with traditional methods. Furthermore, many nanosensors have Real-Time Monitoring capability, which is a requirement for modern power networks. However, this technology still faces serious limitations. One of the most important challenges is long-term stability under actual operating conditions. Power cables operate in environments with severe temperature variations, high humidity, mechanical stress, and strong electromagnetic fields, while many nanosensors have not yet been fully evaluated under such conditions. Another challenge is calibration issues and signal drift over time. Nanosensors, due to their high sensitivity, are subject to gradual performance changes that can lead to measurement errors in the long term. Additionally, electromagnetic noise in high-voltage environments is one of the limiting factors for the performance of some electrical nanosensors [4].

9. Comparison of Nanosensors with Traditional Condition Monitoring Methods

Traditional power cable monitoring methods include infrared thermography, point temperature measurement, indirect thermal models, and classical resistive sensors [64]. Despite their widespread application, these methods have fundamental limitations in terms of spatial coverage, accuracy, and continuous monitoring capability. In contrast, nanosensors and fiber optic-based technologies enable distributed and continuous monitoring along the cable [65, 66]. For example, Distributed Temperature Sensing (DTS) systems can record the temperature profile of the cable over several kilometers with high spatial resolution, while thermography only provides surface and point information. From a performance perspective, nanosensors have the following advantages over traditional methods:

- Higher sensitivity to early failure changes
- Real-time monitoring capability
- Integrability with intelligent systems and IoT
- Ability to detect pre-failure conditions

Nevertheless, traditional methods still hold their place in industry because they:

- Have lower initial cost
- Have simpler installation and operation
- Do not require complex infrastructure

Therefore, in practice, a hybrid approach (Hybrid Monitoring Systems) involving the simultaneous use of traditional methods and nanosensors is considered an optimal solution. Within the framework of Predictive Maintenance, nanosensors play a key role in the transition from periodic monitoring to intelligent and continuous monitoring, which directly leads to reduced sudden outages and increased network reliability.

10. Research Challenges and Existing Gaps

Despite significant advances in the field of nanosensors, this technology is still in the transition phase from laboratory research to industrial application. A review of recent studies reveals several fundamental gaps in this field that hinder their widespread commercialization in power cables [67].

1. Stability under Real Operating Conditions: One of the most important research gaps is the lack of field data under actual operating conditions. Most existing studies have been conducted under controlled laboratory conditions, while power cables operate in complex and unpredictable environments. The simultaneous effects of temperature, humidity, mechanical stress, and electromagnetic fields on nanosensor performance have not yet been fully investigated.

2. Industrial Integration and System Engineering: Another important challenge is Industrial Integration. Integrating nanosensors into the multilayer structure of the cable (conductor, semiconductive, XLPE insulation, and metallic shield) without disrupting electrical and mechanical performance is a complex engineering problem. In many cases, adding sensors can create stress concentration points or alter the electric field.

3. Lack of International Standards: Currently, standardization in the field of nanosensors for power cables has not yet been developed. The absence of common standards causes:

- Difficulty in comparing the performance of different sensors
- Non-reproducible study results
- Slowed industrial adoption

This issue is one of the main barriers to technology commercialization.

4. Calibration Challenges and Long-term Drift: Nanosensors, due to their high sensitivity, are subject to gradual performance changes (drift). This phenomenon can cause reduced accuracy over time. Furthermore, calibrating sensors in actual operating environments is very difficult because environmental conditions are constantly changing.

5. Lab-to-Field Gap: One of the most important research gaps is the distance between laboratory results and actual performance in power networks. Many sensors that perform excellently in papers have not yet been tested at industrial scale. This gap has kept the Technology Readiness Level (TRL) of many nanosensors low.

6. Need for Integration with Artificial Intelligence and Data Analytics: Currently, the volume of data generated by nanosensors is very large, but many systems lack advanced data analysis algorithms. Without the use of artificial intelligence, this data cannot be translated into actionable decisions. Therefore, the development of machine learning algorithms for sensing data analysis is a fundamental future requirement.

11. Future Perspective of Nanosensors in Power Cable Monitoring

Recent developments in the field of nanosensors indicate that this technology is moving from single-parameter systems toward intelligent multifunctional and integrated systems [66, 68]. In the near future, nanosensors will be used not only for temperature or strain measurement but also for simultaneous monitoring of multiple physical, chemical, and mechanical parameters in power cables.

1. Multifunctional Nanosensors: One of the most important future trends is the development of sensors capable of simultaneously measuring temperature, strain, pressure, and even insulation degradation. The use of conductive nanocomposites (such as graphene/CNT in polymer matrices) has enabled the design of sensors with multiple responses. These types of sensors can simultaneously record thermal and mechanical changes

and provide a more complete picture of cable condition [68, 69]. Studies have shown that the combination of nanostructured materials with flexible polymers can lead to the development of multifunctional sensors with high sensitivity and applicability under harsh environmental conditions [62].

2. Connectivity to the Internet of Things (IoT) and Smart Grids: One of the most important future paths is the integration of nanosensors with the Internet of Things (IoT) and smart power grids. In this structure, sensors continuously collect temperature and stress data and transmit it through communication networks to control centers [69]. This integration enables the creation of Smart Cable Systems capable of automatic monitoring, fault detection, and real-time alert transmission. According to the study by Song et al. [4], the combination of advanced sensors with digital infrastructure can play a key role in the development of smart power grids.

3. Data Analytics and Predictive Maintenance: In the future, the main value of nanosensors will not only be in measurement but also in the analysis of data generated by them. The large volume of data from real-time monitoring requires the use of machine learning and artificial intelligence algorithms. These algorithms will be capable of identifying abnormal patterns in the thermal and mechanical behavior of the cable and predicting the probability of failure. This approach, known as Predictive Maintenance, can significantly reduce maintenance costs and increase network reliability [57].

4. Future Applications in Smart Cables: In the future, power cables will not only act as an energy transmission path but will transform into intelligent Self-Monitoring Cable systems. These cables will be equipped with a network of nanosensors that monitor thermal and mechanical conditions along the entire cable path [58, 70]. This transformation will lead to the emergence of a new generation of energy infrastructure capable of:

- Automatic fault detection
- Prediction of critical conditions
- Optimization of transmission capacity
- Reduction of sudden outages

12. CONCLUSION

In this paper, the role of smart nanosensors in thermal and mechanical stress monitoring of power cables was reviewed. The review results show that nanosensors, due to their high sensitivity, small dimensions, real-time monitoring capability, and integrability with intelligent systems, are among the key technologies in upgrading cable condition monitoring systems. Nanosensors based on advanced materials such as graphene, carbon nanotubes, and nanocomposites are capable of detecting very small changes in temperature and mechanical stress and providing valuable information for cable condition analysis. This capability is particularly important in early detection of hot spots, mechanical damage, and prevention of sudden failures. Despite significant advantages, challenges such as long-term stability, implementation costs, calibration, and lack of comprehensive standards still hinder widespread industrial use of this technology. Therefore, future research development should focus on bridging the gap between laboratory and industrial application, increasing sensor durability, and integrating them with intelligent systems. Ultimately, it can be concluded that nanosensors will play an important role in moving the power industry toward smart grids and predictive maintenance, and in the near future, they will become one of the main components of modern energy transmission infrastructure.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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