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Review

# Self-Healing Solid Insulating Materials for High-Voltage Applications: Mechanisms, Performance, and Future Directions

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**Abstract**

Self-healing materials feature a self-directed process to heal micro-damage, ensuring the recovery of mechanical strength and dielectric properties in the absence of external intervention. Self-healing insulation materials are an exciting development for enhancing the longevity of high-voltage (HV) electrical devices in stringent operating environments. This review provides a systematic approach to studying different self-healing strategies for HV insulation systems. This includes both extrinsic and intrinsic approaches. In this regard, the review critically examines the SMASH strategy, covalent adaptable network, magnetothermal healing, electroluminescent triggered repair, and artificial intelligence based diagnostics system in detail. The main damage modes of electrical devices (namely, electrical treeing, water treeing, partial discharge erosion, and space charge accumulation) and the characterization techniques needed to quantify healing performance. This review focuses on HVDC cable insulation, transformer dielectrics, wide bandgap semiconductor packaging, and offshore/sub-sea equipment in a systematic manner. The review also addresses the role of artificial intelligence in discovering new materials, predictive maintenance, and fault

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management in grids. Finally, the paper highlights eco-friendly molecular design, lifecycle sustainability, extreme-environment performance, industrial feasibility, and healing efficiency.

**Keywords**
Self-healing; solid insulating materials; high-voltage applications; dielectric breakdown; damage mitigation; microencapsulation; reversible chemistry; electrical tree; polymeric composites

## 1. Introduction

Electrical insulation at high-voltage (HV) levels is very important for safe operation of the power transmission system, energy infrastructure, electric vehicles, and power electronics. The insulating materials act as shields to withstand electric breakdown, partial discharge, and environmental degradation [1]. In general, epoxy resin, polyethylene (PE), cross-linked polyethylene (XLPE), silicone rubber, and polymer composites are utilized as insulating elements [2]. However, these insulating materials deteriorate under high electric fields, heat, operation, and environmental exposure [3]. In this case, electrical treeing, partial discharge-induced wear, water treeing, and thermo-oxidative aging take place. These processes gradually reduce the material's dielectric properties and ultimately cause insulation failure [4].

Traditional ways to improve insulating characteristics have been based on passive methods like nano filler addition, voltage stabilization, and network cross-linking modification [5]. These methods may prolong insulation life, but they cannot restore insulation properties after degradation. In this respect, the paradigm shift has been initiated for intelligent dielectric materials with self-healing capabilities. In insulation polymers, healing is expressed through the self-diagnosis and repair of dielectric damage. Self-healing in solid insulating materials occurs in two modes: extrinsic and intrinsic [6]. The extrinsic self-healing uses microcapsules and a vascular system, which release the healing agent at the moment of damage, while the intrinsic self-healing mode uses dynamic reversible bonding, such as hydrogen bonding, disulfide bonding, metal-ligand coordination and Diels-Alder reaction [7].

The self-healing of high-voltage insulation materials differs significantly from the self-healing of structural materials due to the following reasons. First, the process must restore the mechanical integrity of the material and provide the dielectric strength adequate for the operating electric field [8]. Second, the healing process has to be triggered automatically without any additional action within the time span of the partial discharge activity prior to the development of permanent damage. Third, the presence of mobile ions and dynamic bond networks must not impair the basic insulating characteristics of the material, such as volume resistivity, dielectric loss, and breakdown strength [9].

Progress in dynamic covalent chemistry, reversible cross-linking approaches, and nanocomposite design has enabled the creation of self-healing insulators for use in harsh conditions of high-voltage devices [10]. This paper gives an extensive discussion on the development, mechanisms, performance, and future perspectives of self-healing solid dielectric insulators for high-voltage applications. The focus of this review is on material design methods, self-healing performance of

materials under multi-component stresses, and future research trends in the field of smart insulators.

There are several reviews devoted to some aspects of this research field but not including HV-specific and cross-mechanistic synthesis, which this paper provides. For example, Pan et al. conducted a general review of polymeric materials for high-voltage applications, paying no attention to self-healing capabilities [3]. Yang et al. and Zhang et al. reviewed self-healing of electrically damaged materials and self-healing of electrically damaged materials under high electrical stress, respectively; however, in both cases, the scenarios involving electric stress considered included capacitors, batteries, actuators, and energy harvesters, but not HV insulation systems, and they do not compare the extrinsic, intrinsic, and physical field-assisted healing in terms of recovery of dielectric strength, volume resistivity, and manufacturing compatibility with current cables and apparatus production processes [4, 5]. Ng et al. examined self-healing mechanisms in conductive electronic products, an area where the objective of materials design is quite opposite to that of insulation materials since it deals with enhancing rather than inhibiting conductivity [9].

Three points distinguish this review from each of these: firstly, it discusses the self-healing mechanisms with respect to the damage modes and conditions of HV insulation (Sections 2-3); secondly, it provides a quantitative trade-off analysis among the healing mechanisms instead of simply describing the individual research works (Section 3.4); and thirdly, it considers the increasing convergence between AI-based diagnostics and predictive maintenance and the self-healing technologies (Section 5).

### *1.1 Literature-Search Methodology*

This article is structured as a critical review in the sense formalized by the SALSA (Search, Appraisal, Synthesis, Analysis) framework, which distinguishes critical reviews — which demand extensive, purposive searching combined with qualitative, conceptual synthesis — from systematic reviews, whose defining feature is a fully pre-registered, exhaustively documented, and independently reproducible search protocol. In line with this distinction, the search for this article was structured and documented to ensure transparency but was not pre-registered, and the author's team made full-text screening decisions. This section covers the Search and Appraisal stages. The resulting Synthesis is presented in Sections 3-6. Cross-study Section 4.2 presents the analysis of the reported healing measures.

#### 1.1.1 Search

Records were retrieved from Scopus, Web of Science (Core Collection), and IEEE Xplore, with supplementary searches in Google Scholar to capture recent preprints, theses, and conference proceedings not yet indexed in the primary databases — particularly from the IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP) and IEEE Electrical Insulation Conference (EIC). Search strings combined three concept clusters using Boolean AND/OR logic, summarized in Table 1 below.

**Table 1** Search string construction by concept cluster.

| Cluster | Terms (OR within cluster) |
|---|---|
| Healing mechanism | "self-healing" OR "autonomic healing" OR "dynamic covalent network" OR "covalent adaptable network" OR "vitrimer" OR "shape-memory-assisted self-healing" OR "SMASH" OR "supramolecular polymer" |
| HV/dielectric context | "High-voltage insulation" OR "dielectric breakdown" OR "electrical treeing" OR "water treeing" OR "partial discharge" OR "XLPE" OR "epoxy insulation" OR "space charge" |
| AI/diagnostics (secondary wave) | "Machine learning" OR "predictive maintenance" OR "closed-loop healing" OR "self-diagnosing" OR "fault detection" |

The final query combined clusters as (Cluster 1) AND (Cluster 2), with a second search wave of (Cluster 1) AND (Cluster 3) run to populate Section 5. Searches were limited to English-language journal articles, conference papers, and reviews published between January 2001 and June 2026. Reference lists of retrieved reviews already covering adjacent ground (e.g., [3-5, 9]) were manually backward-chained for primary studies missed by the keyword search, and forward citation tracking (via Scopus/Web of Science "cited by") was used to identify subsequent work citing these reviews.

#### 1.1.2 Appraisal

Records were screened at title/abstract level against the following inclusion criteria: (i) reports a self-healing mechanism with explicit or directly transferable relevance to solid dielectric/insulating polymer systems; (ii) reports quantitative or clearly described qualitative healing performance data; (iii) is published in a peer-reviewed journal, peer-reviewed conference proceedings, or is a standards document from IEC, ASTM, IEEE, or CIGRE. Records were excluded where: (i) self-healing was demonstrated exclusively in a conductive, semiconducting, or energy-storage context with no articulated pathway to insulation relevance; (ii) the source was a non-peer-reviewed aggregator, vendor datasheet, or blog (applied retrospectively to correct the use of such a source for the PD-erosion discussion in Section 2.3, following peer review); or (iii) the full text could not be retrieved. Full-text screening was applied to all records passing title/abstract screening. This process yielded several hundred candidate records from database searching.

This protocol was reported for transparency and reproducibility rather than the exhaustiveness of a systematic review. The contribution of the review, consistent with the critical-review format, is in the cross-mechanism, HV-specific synthesis and trade-off analysis provided in Sections 3.4 and 4.2, not in the completeness of the underlying search alone.

## 2. Fundamentals of Electrical Damage in Solid Insulators

A comprehensive understanding of self-healing mechanisms requires grounding in the types and mechanisms of electrical damage that such systems must address. Solid insulating materials in high-voltage equipment are damaged through multiple, often interconnected pathways that are not always well separated either spatially or temporally [11]. The primary failure modes include electrical treeing, water treeing, partial discharge (PD)-induced erosion, and space charge-induced aging [12]. Figure 1 maps a hierarchy diagram linking electrical stresses to damage modes, self-

healing material classes, activation stimuli, and target high-voltage applications, as organized across Sections 2-6 of this review.

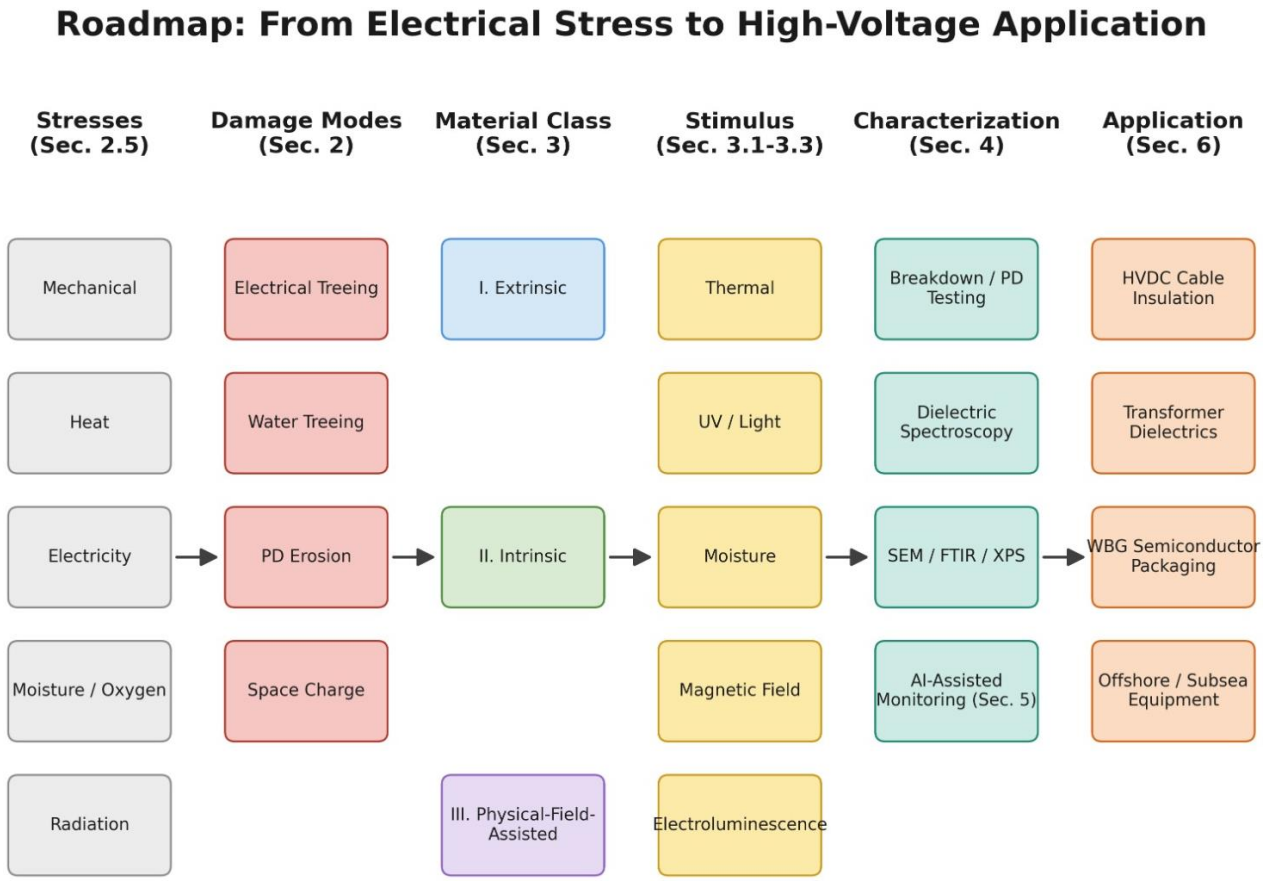



**Figure 1** Hierarchy diagram linking electrical stresses to damage modes, self-healing material classes, activation stimuli, and target high-voltage applications.

### *2.1 Electrical Treeing*

Electrical treeing is the pre-breakdown phenomenon in polymeric insulators under AC and impulse voltages [13]. It exhibits a tree-like network of micro-channels of a few microns in diameter) filled with gas at low pressure. The initiation phase is often triggered by field-enhancing defects, such as metallic protrusions, voids, or contaminant particles, in which the local electric field exceeds the material's intrinsic breakdown strength [14]. Once initiated, partial discharges within the tree channels generate high-energy electrons, ultraviolet radiation, and local thermal spikes. Eventually, the material undergoes chain scission, volatilization, and progressive channel propagation [14]. The tree growth rate depends on multiple factors, including voltage magnitude, frequency, and ambient temperature. These electrical trees ultimately lead to dielectric failure when the channel bridges the electrode gap [15]. Figure 2 shows the optical images of the electrical tree [16].

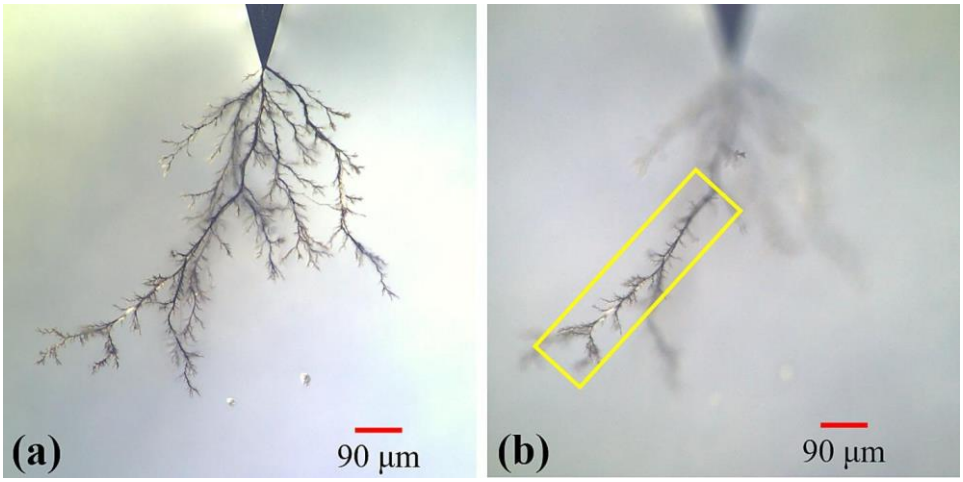



**Figure 2** Microscopic images of the electrical tree [16]. (a) Image captured by the 3D acquisition function of the digital microscope. (b) Image captured by 2D observation. Reproduced from Wang et al. [16] under the CC BY 4.0 license.

### *2.2 Water Treeing*

Unlike electrical trees, water trees grow in the presence of aqueous electrolytes underlow electric fields of a few kV/mm [17]. They consist of branched structures that include oxidized polymer chains filled with water or water vapor in micro-voids [18]. In power cables, water trees are especially hazardous. Such water trees lower the dielectric strength and act as a precursor for future electrical tree formation [19]. Morphology of water trees seen under an optical microscope is provided in Figure 3 [20].

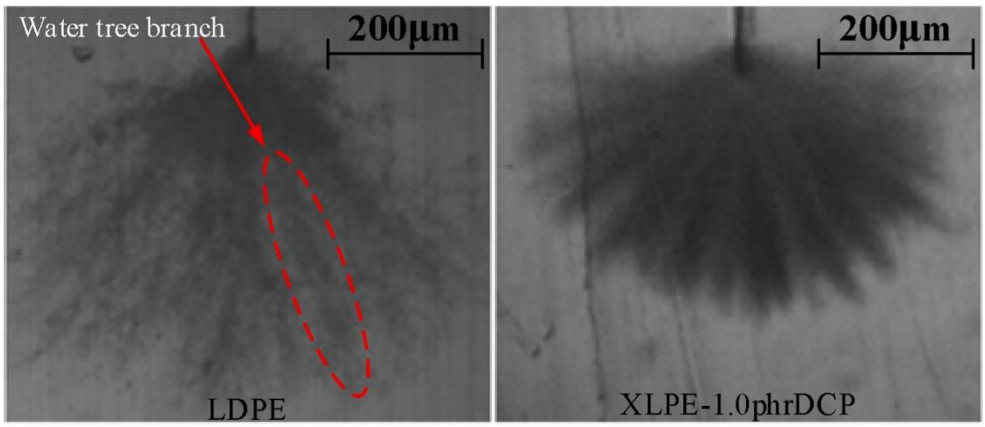



**Figure 3** Water tree morphologies in LDPE and XLPE specimens [20]. Reproduced from Chen et al. [20] under the CC BY 4.0 license.

### *2.3 Partial Discharge and Surface Erosion*

Many solid insulating materials have some degree of flaws during the manufacturing processes, such as micro-voids and microcavities. Since the permittivity ($\varepsilon_r$) of the gas inside the void is much smaller compared to the surrounding solid dielectric, the electric field stress becomes strongly focused inside the void. Thus, when the electric field becomes larger than the breakdown limit of the gas, a localized electrical discharge is triggered inside the void, which is called partial discharge

(PD) [21]. PD erodes the void wall through bombardment and heating, increasing the void dimension and surface roughness. This phenomenon is called PD-induced erosion and produces reactive species like ozone and nitrogen oxides, which degrade the polymer chain [22, 23]. In the end, PD causes breakdown of the insulation channel. Figure 4 is the schematic representation of the three main types of defects that cause partial discharge in the epoxy insulation system.

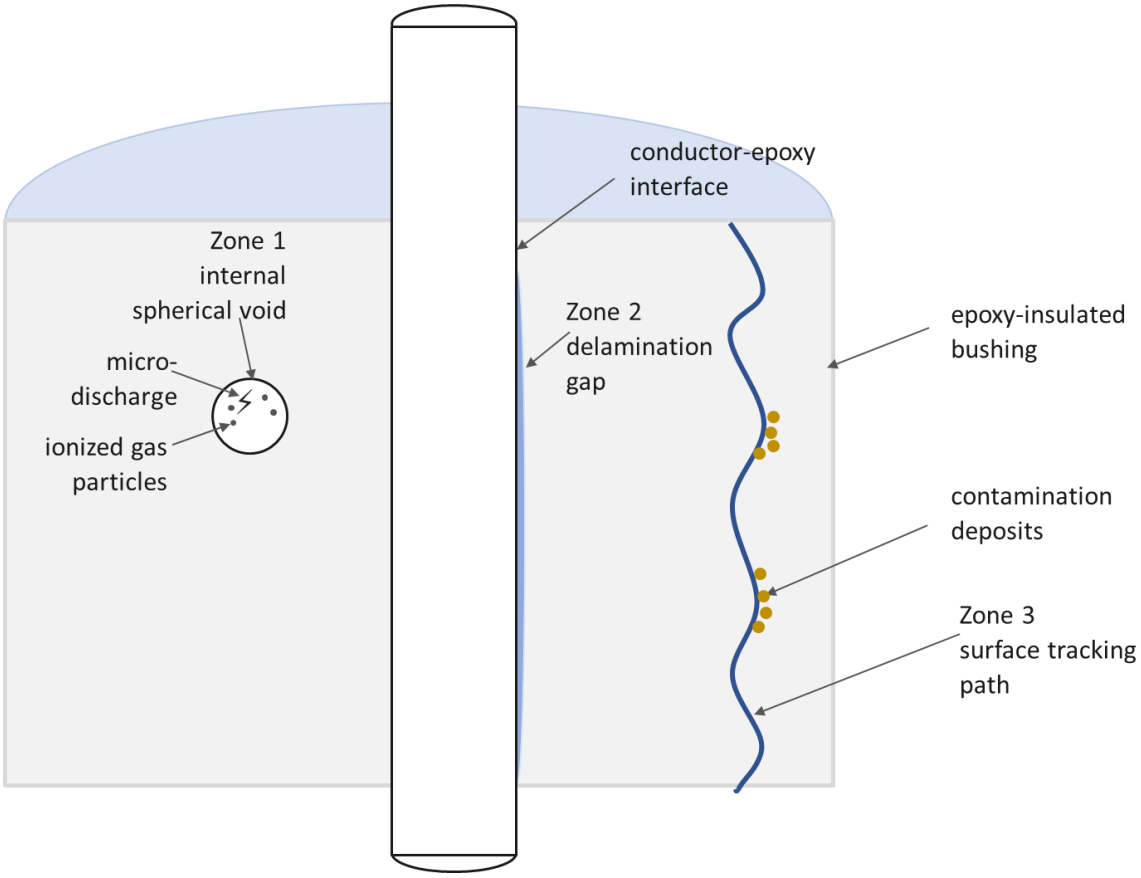



**Figure 4** Schematic of the cross-section of epoxy-insulated bushing identifying three primary partial discharge initiation zones: internal voids, conductor-epoxy delamination, and surface contamination paths.

### *2.4 Space Charge Accumulation and Electro-mechanical Failure*

Under high DC fields, charge carriers can become trapped at structural defects, forming space-charge layers [24]. Space charge distorts the internal electric field, elevating local field values beyond the material's capability. Severe accumulation also induces an electrostatic pressure that can mechanically deform or delaminate the insulation [25, 26].

### *2.5 Multi-Stress Aging Coupling*

In a high-voltage environment, degradation rarely occurs in isolation. For example, thermal aging accelerates thermo-oxidative chain scission, which enhances PD activity and trap density [27]. At the same time, mechanical vibration or thermal expansion-contraction cycles can create micro-cracks that provide channels for water ingress and tree initiation [3]. The coupling of these stresses results in a degradation that differs from the sum of their individual contributions. Figure 5 shows

an overview of aging under multiple stresses (i.e., mechanical, heat, oxygen, water, electricity, impact, and radiation) through simulation [28].

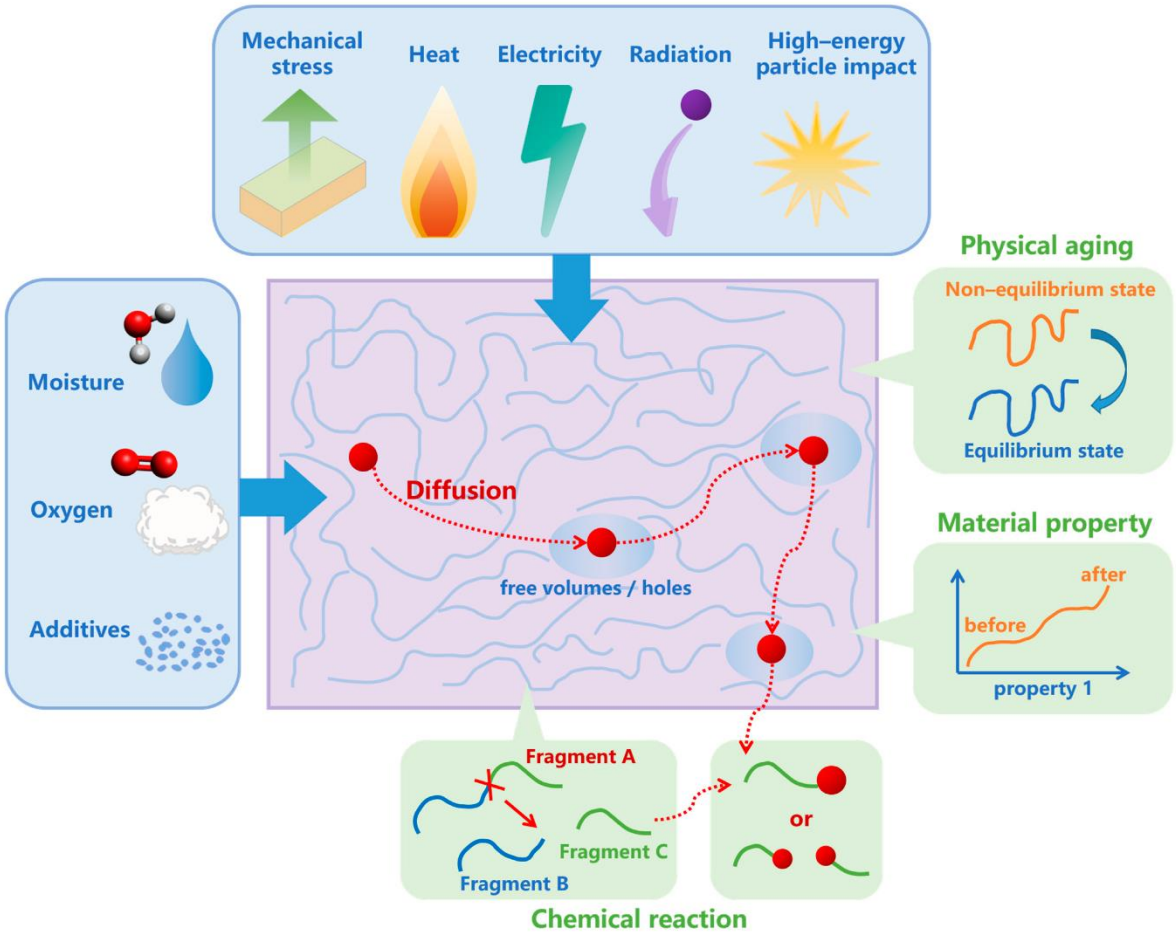



**Figure 5** An overview of aging mechanisms in the current aging simulation research [28]. Reproduced from Zhang et al. [28] under the CC BY 4.0 license.

## 3. Overview of Self-Healing Mechanisms and Concepts

Self-healing materials possess the intrinsic or extrinsic ability to restore their structural integrity and dielectric properties. In high-voltage applications, this ability to repair micro-damage in situ can prevent catastrophic insulation failure [29]. Self-healing in materials can be conceptually organized along several dimensions: (i) the source of healing agents (extrinsic vs. intrinsic), (ii) the trigger mechanism for healing activation, (iii) the chemical/physical basis of the healing process, and (iv) the extent of repeatability. The fundamental distinction between extrinsic and intrinsic self-healing lies in the origin of the healing functionality [30].

Healing functionality has been adopted as the primary organizing principle since it defines a material's fundamental compatibility with high-voltage service conditions: in the case of Extrinsic Systems (Section 3.1), the host matrix's inherent dielectric properties are retained but use up a limited supply of healing agent, while Intrinsic Systems (Section 3.2) in theory allow for an unlimited number of healing cycles but require the dynamic bond chemistry itself to satisfy the insulation's basic resistivity and loss requirements. In each category, the following subsections transition from the early demonstrations based on a single mechanism to more recent insulator designs which

improve the trigger mechanism, the delivery of the agent, or the bond chemistry in order to better meet the constraints specific to high voltage. Section 3.3 examines systems in which an external physical field or mechanical actuation assists or accelerates the underlying chemical repair, representing a step toward the sensor- and AI-triggered healing systems described in Section 5.

### *3.1 Extrinsic Self-Healing Systems for High-Voltage Insulation*

Extrinsic self-healing represents the earliest and most extensively investigated approach for engineering self-repairing polymers [31, 32]. The work by White et al. (2001) demonstrated that dicyclopentadiene (DCPD) monomer microcapsules dispersed within an epoxy matrix could achieve approximately 75% recovery of fracture toughness [31]. This concept was adapted for high-voltage insulation to arrest electrical tree propagation.

#### 3.1.1 Microcapsule-Based Systems

Researchers have designed microcapsule-based systems for dielectric applications using core-shell configurations. A typical microcapsule comprises a polymer shell encapsulating a liquid healing agent [33]. The electrical tree growth or crack formation ruptures nearby capsules due to local stress and heat at the tree tip. The released monomer flows into the tree channel or cracks along with the catalyst and polymerizes to form a solid that arrests further tree growth. The new polymer increases local breakdown strength and can reduce PD activity [34]. Experiments on epoxy-based self-healing composites show that such systems can significantly delay electrical tree propagation and improve breakdown performance, with reported use cases in HV apparatus and subsea cables where repair access is limited [34]. Figure 6 shows a typical self-healing polymer matrix with embedded microcapsules showing the self-healing mechanism.

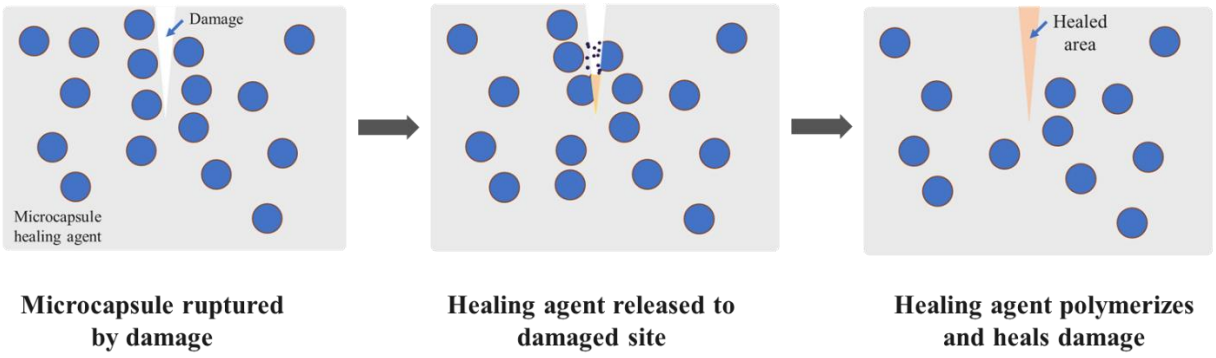



**Figure 6** Self-healing polymer matrix with embedded microcapsules showing the self-healing mechanism.

#### 3.1.2 Vascular Network Systems

Instead of discrete capsules, a vascular microchannel network delivers healing fluids [35]. The microchannel ruptures and releases healing agents into the defect region, forming a new polymer [36]. Compared to capsules, vascular networks can provide multiple healing cycles if reservoirs are replenishable. For HV insulation, vascular designs must balance channel size/volume to minimize permittivity perturbations and field distortion.

### 3.1.3 Advanced Triggering, Targeting, and Architecture Optimization

Although the microcapsule and vascular structures mentioned earlier had established the feasibility of external healing in HV insulation, three practical limitations have driven further research: the reliance on a single, frequently thermally activated trigger which may not coincide with the onset of electrical damage; the non-targeted distribution of the capsules that necessitates a high loading fraction and risks degrading baseline dielectric properties; and the low core-to-shell volume ratios which constrain the amount of healing agent available at the site of damage. The systems described below address one or more of these limitations, presented roughly in the order in which they mainly address them—trigger sophistication, spatial targeting, and finally architecture optimization.

Multi-Stimuli-Responsive Microcapsules. Recent innovations have transformed microcapsule systems into multi-responsive repair system [6]. Incorporating reversible Diels-Alder (DA) chemistry into both the microcapsule core and the surrounding matrix enables repeated healing at the same site. In their study, Zhu et al. (2025) developed a microcapsule/XLPE composite designed for electro-hydro hybrid tree aging failure mode [6]. The microcapsules are engineered with hyperbranched polysiloxane cores containing furan functional groups, urea-formaldehyde resin shells, and reversible DA adducts within the matrix. At a doping concentration of 1 wt.%, the composite material exhibits self-healing while maintaining XLPE's insulation performance [6]. Under thermal triggering, the reconstruction of reversible bonds assists in dual repair of both water tree and electrical tree damage. The system responded to multiple stimuli (thermal, light, and moisture) to provide self-healing across diverse failure scenarios [6]. Figure 7 shows the schematic illustration of microcapsule-based self-healing systems [37].

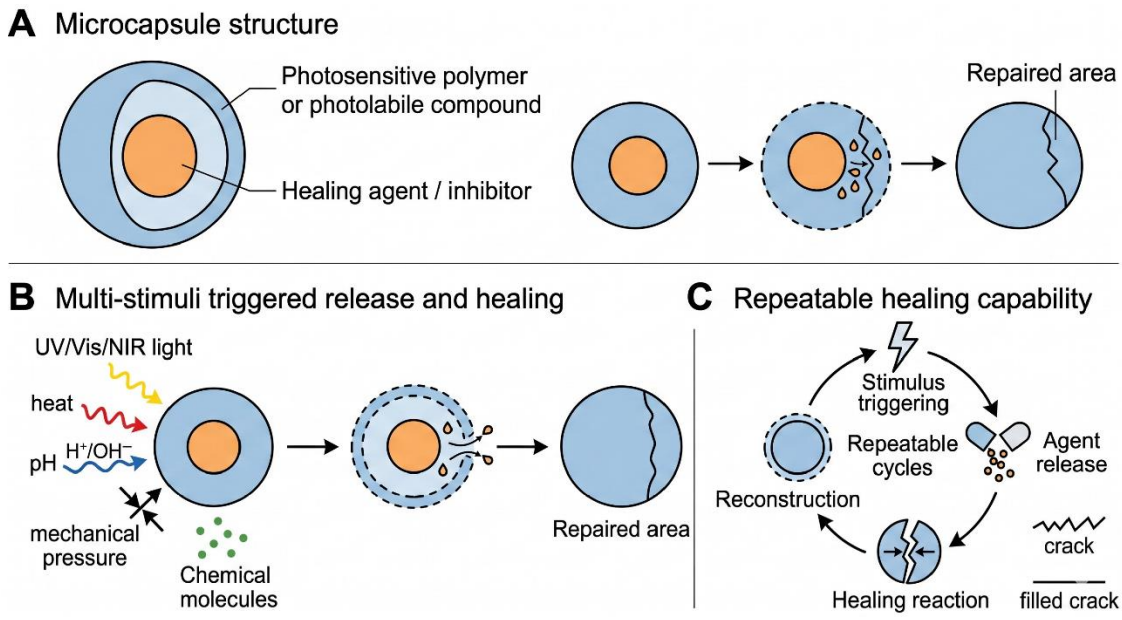



**Figure 7** (A) Microcapsule structure showing stimuli-responsive shell (e.g., photosensitive polymer or photolabile compound), encapsulated healing agent, and core/support material; (B) multi-stimuli triggered release and healing process under light (UV/Vis/NIR), heat, pH, mechanical pressure, chemical pressure, or specific molecules, leading to shell degradation, healing agent release, and repaired area

formation; (B) repeatable healing capability over multiple damage cycles, including stimulus triggering, agent release, healing reaction, and reconstruction [37]. Reproduced from Chen et al. [37] under the CC BY 4.0 license.

Electroluminescence-Triggered Healing. When electrical insulation starts to break down, it shows electroluminescence. A smart design uses this exact light to trigger a self-healing process [38]. In this design, when damage reaches a microcapsule, ultraviolet (UV) light emission triggers a reaction. This light automatically cures the healing liquid without any chemical curing agent. It creates a self-contained healing loop. Unlike thermally triggered systems that require bulk heating, EL-triggered healing is localized, preserving material properties in the nearby undamaged regions. Figure 8 illustrates the healing of damage using microcapsules incorporated into the polymer.

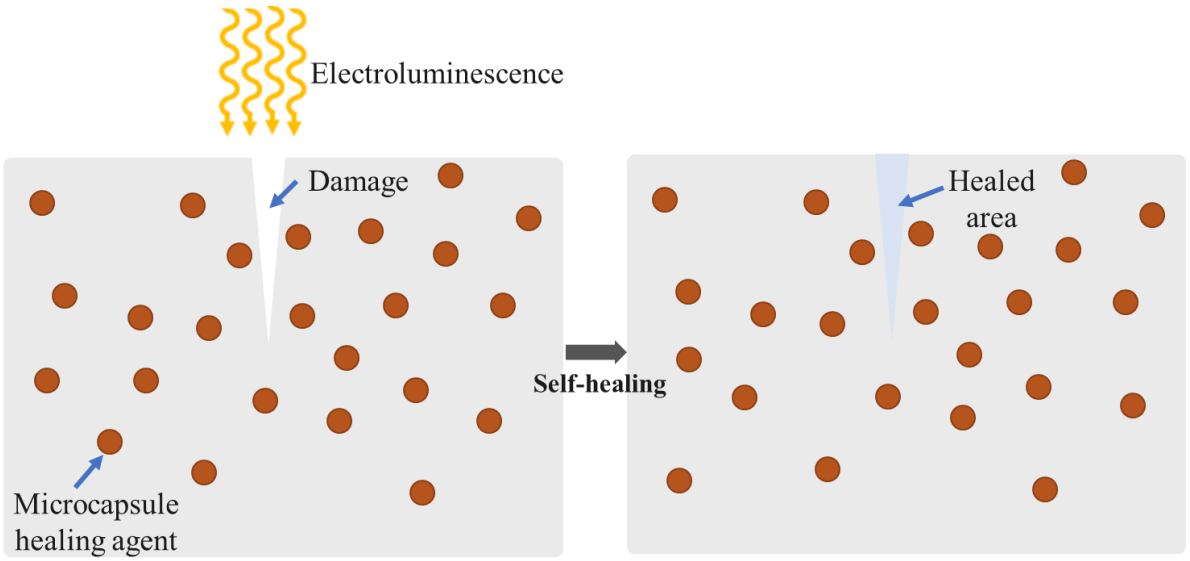



**Figure 8** Schematics showing the healing of damage with microcapsules.

Magnetic Targeted Delivery. Magnetic-targeted microcapsules represent an advanced extrinsic self-healing strategy that requires minimal healing-agent loading and retains matrix properties in high-voltage insulation [39]. By incorporating $Fe_3O_4$@$SiO_2$ nanoparticles into microcapsule shells, external magnetic fields guide these capsules to the damage zones [40]. This targeted distribution reduced the loading level (i.e., 1-5 wt.%) compared to conventional systems (i.e., 10-15 wt.%). The host material preserves the baseline dielectric strength, resistivity, and mechanical integrity. Researchers have developed three distinct architectures: phase-change microcapsules, UV-polymerization microcapsules, and dual-response raspberry-like microspheres [40]. Key innovations include self-reporting via fluorescence emission for damage visualization, phase-change designs, and multiple trigger options. The magnetic-targeted microcapsule systems offer a smart self-healing functionality without compromising essential dielectric performance.

High-Load Rigid Porous Architecture. Recently, researchers have developed rigid, porous microcapsules via subcritical water etching [41]. In this method, the glass microspheres were treated with subcritical water under controlled conditions of $OH^-$ concentration, temperature, and duration. By systematically optimizing treatment parameters, researchers generated nanoscale channels on the microsphere surfaces. The infiltration of flaxseed oil into the microcapsule was

achieved by subsequent gradient pressure [41]. The incorporation of 3 wt.% of hollow glass microspheres into epoxy resin composites preserved both the matrix properties and self-healing functionality. In multimodal damage scenarios, the system achieved a 96.2% recovery of insulation after electrical treeing [41]. The simultaneous improvement in mechanical strength and dielectric integrity makes this system attractive for high-voltage environments.

Multi-Layer Core-Shell Design for Water-Tree Repair. A tri-layer microcapsule design with nano-$SiO_2$ on the capsule surface, dispersed in the XLPE matrix, prevented microcapsule agglomeration [42]. An optimal doping concentration of 1.0 wt.% was found to be sufficient for effective healing while preserving the composite's electrical properties [42]. Here, room-temperature air RF plasma discharge was employed to hydroxylate the nano-$SiO_2$ surface layer. This modification, involving the grafting of silane coupling agents, resulted in uniform microcapsule distribution within the XLPE matrix [42]. When water tree branches reached the microcapsule locations, the ruptured capsules released internal repair materials and catalysts. These materials reacted with water to form an organic silicone resin that fills the water-tree cavities. The water-needle electrode method confirmed that the average water tree length in plasma-modified microcapsule/XLPE specimens was reduced by 24.86% compared to that of the non-modified specimens [42]. The internal structure of three-layer shell nucleus microcapsules is shown in Figure 9 [43].

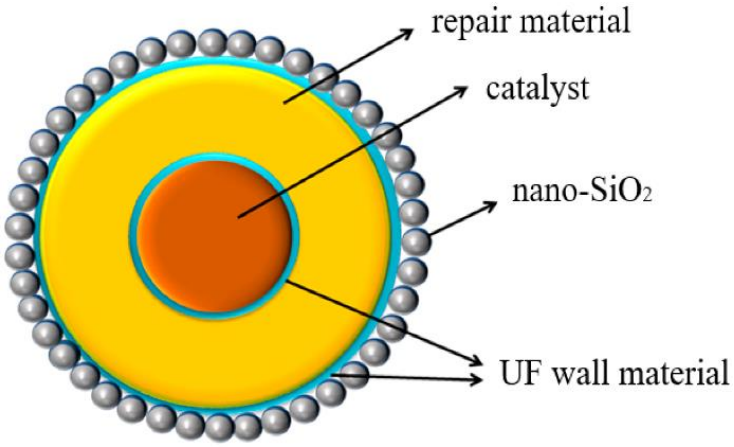



**Figure 9** Schematic structural model of three-layer shell nucleus microcapsules [43]. Reproduced from Zhu et al. [43] under the CC BY 4.0 license.

### *3.2 Intrinsic Self-Healing Through Dynamic Covalent Chemistry*

Intrinsic self-healing polymers repair damage through reversible chemical reactions embedded directly in their network, overcoming the limitations of finite reservoirs in external systems and, in principle, enabling an unlimited number of healing cycles at the same damage site [44]. The two types of chemistry responsible for this behavior are dynamic covalent bonds, which reconfigure through bond exchange or reversible cycloaddition (Section 3.2.1), and supramolecular interactions, which can reform without breaking any bonds (Section 3.2.3). Section 3.2.2 addresses covalent adaptable networks (CANs), a dual-network architecture that has recently achieved one of the most complete recoveries of both mechanical and dielectric properties reported for cable-grade XLPE. Hybrid systems, combining both chemistries, which are discussed in Section 3.2.4 are designed to strike a compromise between the rate of healing and the strength of the structure.

### 3.2.1 Dynamic Covalent Chemistry

Dynamic covalent bonds (DCB) allow the polymer network to rearrange and close damage at the molecular level [45]. Several dynamic covalent chemistries applicable to composite materials were developed [46], as shown in Figure 10.

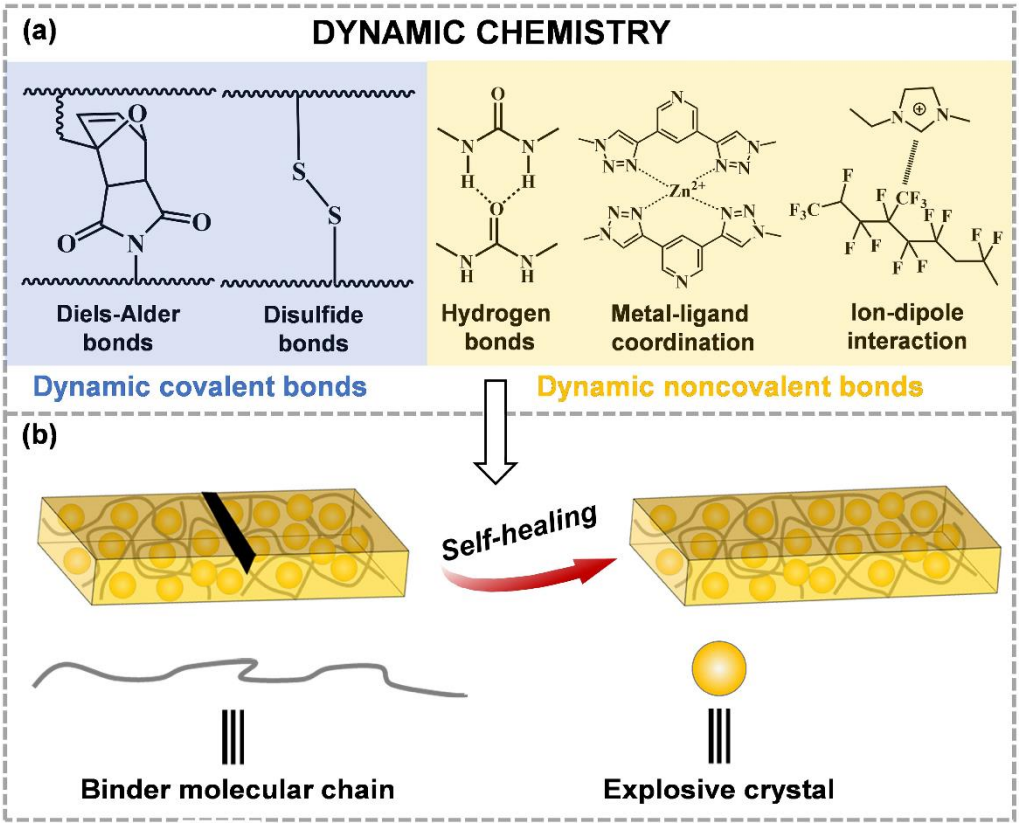



**Figure 10** Several typical self-healing methods for the crack-healing of composites [46]. Reproduced from Yang et al. [46] under the CC BY 4.0 license.

Disulfide bonds (S-S) are one of the most commonly used dynamic covalent bonds for self-healing polymers [47]. Under thermal activation or UV illumination, disulfide bonds experience an exchange reaction (metathesis), in which two disulfide bonds swap sulfur atoms for polymer network reorganization [47]. This makes it possible to repair damage without changing the overall cross-link concentration. Epoxy networks containing disulfides recover dielectric strength after electrical breakdown in high-voltage insulation [48]. Wu et al. synthesized a thermoplastic polyurethane network containing both disulfide and hydrogen bonds for room-temperature self-healing [49].

Another thermally reversible reaction suitable for self-healing is the Diels-Alder (D-A) reaction [50]. The D-A reaction between furan and maleimide groups forms a covalent bond at moderately lower temperatures (i.e., 80°C), and this reaction can be reversed at higher temperatures (above 110°C) [50]. This thermo-reversibility enables damage-induced network decoupling followed by re-crosslinking at the cracked interfaces upon cooling [51]. For insulating applications, D-A-based maleimide and epoxy systems can heal electrical tree channels through local thermal activation [52].

Imine bonds (C=N) offer reversible dynamic covalent chemistry under mild conditions without high temperatures [53]. The equilibrium-controlled imine formation is the condensation of an amine with an aldehyde and can be shifted toward bond reformation in the presence of moisture or mild

acid [53]. This chemistry is attractive for self-healing insulation because hydrolysis can autonomously recover the material under ambient conditions [54]. Dynamic fluorine-substituted carbamate bonds are also a form of dynamic covalent chemistry that has been studied regarding epoxy systems relevant to high voltage. Sun et al. developed an insulating epoxy network using this approach, deliberately orienting it around eco-friendly, green-dielectric design principles — a molecular-design approach discussed in more detail in Section 6.1 [7].

Beyond epoxy and polyurethane networks, disulfide exchange chemistry has also been incorporated into high-permittivity composite fillers and thin dielectric films for soft-electronic applications:

High-κ Composite Fillers. Researchers developed a composite by loading MXene nanosheets with cerium oxide ($CeO_2$). The $CeO_2$@MXene hybrid filler in a polysulfide polyurethane-urea (PSPU) elastomer matrix composite was synthesized via hydrogen-transfer reactions [55]. The resulting 5.25 vol% $CeO_2$@MXene/PSPU composite achieved a dielectric constant of 206 at 100 Hz. Impressively, the composite maintained a self-healing efficiency of 97.9%. Here, the dynamic disulfide bonds within the PSPU matrix facilitate network rearrangement and closure of damage. Second, $CeO_2$ loading reduces leakage current and minimizes local electric-field distortion [55].

While a dielectric constant of 206 is a significant asset for the composite's use as a capacitive energy storage material, it is a liability if the same chemical composition were used as a bulk high-voltage insulator. This permittivity is about two orders of magnitude higher than that of conventional insulation polymers—such as XLPE ($\varepsilon' \approx 2.3$) or epoxy ($\varepsilon' \approx 3$-4) [13]; at that level, it would concentrate electric field stress at material interfaces, increase the capacitive charging currents during AC operation, and lead to local heating due to dielectric losses. The leakage-current reduction and field-distortion mitigation reported in [55] were demonstrated within the composite's own dielectric-elastomer application context, not as bulk transmission-class insulation. Realizing the underlying disulfide-based self-healing chemistry for HV insulation would likely require decoupling it from the high-permittivity filler - for instance, by limiting the $CeO_2$@Mxene phase to a thin functional interlayer rather than having it as a bulk filler, or by using a core-shell structure that keeps the filler out of the primary field-carrying region.

Thin-Film Soft-Electronic Dielectrics. Researchers developed a self-healing polyurethane (PU)-based dielectric thin film with varying concentrations of dynamic disulfide bonds (0%, 10%, 30%, and 50%) [56]. Researchers fabricated these thin films by spin coating onto silicon substrates [56]. Notably, even the 10% disulfide formulation healed the damaged area by thermal treatment at 50°C for 5 hours. In some cases, spontaneous healing occurred at room temperature upon overnight contact. This method shows that disulfide exchange reactions can autonomously reconstruct the polymer network [56]. Voltage breakdown testing revealed that only 10 V was required to fail the initial films, which could now withstand up to ~30 V after thermal healing. It was suggested that the molecular reorganization during healing reinforced weak regions within the dielectric matrix [56].

### 3.2.2 Covalent Adaptable Networks (CANs) for XLPE Cable Insulation

Recently, the development of covalent adaptable networks (CANs) for cross-linked polyethylene (XLPE) has been a major breakthrough [57, 58]. Traditional XLPE with permanent cross-links possesses excellent dielectric and mechanical properties. CANs create a weak dynamic cross-linking

network, which is replaced by a strong, permanent cross-linking network after damage. The dual-network architecture coexists in the material through a hierarchical design. At service temperatures (≤70°C), the permanent network maintains structural integrity and insulation performance comparable to conventional XLPE. However, thermal activation triggers exchange reactions within the dynamic bond network when damage occurs. In the damaged region, chain mobility drives network rearrangement that closes the damage zone. Upon cooling, these dynamic bonds stabilize the healed structure [57]. In a recent research, Zhang et al. (2026) demonstrated that CAN-based polyethylene achieves nearly 100% recovery of both mechanical and electrical properties after damage [57]. Moreover, the recovered material exhibited higher toughness and superior electrical insulation than XLPE [57]. Figure 11 shows a schematic of CANs as an intermediate material class to bridge between thermosets and thermoplastics to combine key characteristics of both these materials.

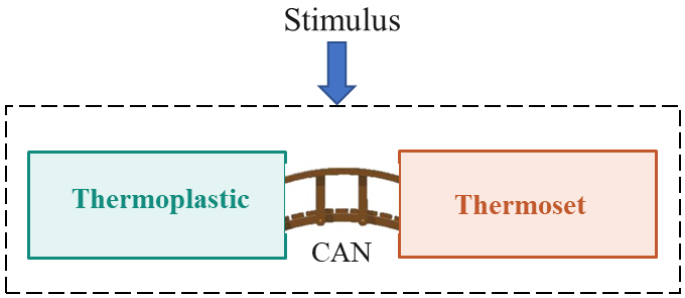



**Figure 11** CANs serve as a bridge, combining key characteristics of both thermosets and thermoplastics.

### 3.2.3 Supramolecular Interactions

Supramolecular polymer networks depend on non-covalent interactions to achieve reversible cross-linking [59]. These include hydrogen bonds, metal-ligand coordination, ionic associations, or π-π stacking [60]. Unlike dynamic covalent bonds, reversible supramolecular interactions can operate on faster timescales without external triggers [60].

Hydrogen bonding (H-bonding) is the most studied supramolecular interaction for self-healing polymers [61]. Multiple hydrogen bonds between complementary functional groups (e.g., amide, urethane, or urea moieties) can produce reversible cross-links [61]. The key advantage lies in engineering bond strength through molecular design. In this case, weaker H-bonds are involved in the process of healing and strong bonds require slower dynamics [61]. For high-voltage dielectrics, maintaining the H-bond network is important, as any contact with moisture will lead to a reduction of insulation resistance [62].

Another approach to supramolecular systems uses metal-ligand coordination, where transition metals are coordinated with electron-donor ligands in polymer chains [63]. They have controllable bond strength depending on the metal-ligand pattern. Recently, Ning et al. created a PEI copolymer with $Ti^{4+}$-catechol coordination bonds and obtained autonomous healing at room temperature with a breakdown field strength of 240 kV/mm [63]. In this case, the composite recovered 80% of its initial characteristics within 60 minutes. Thus, it is possible to create supramolecular systems with high performance characteristics [63].

3.2.4 Hybrid Covalent-Supramolecular Systems: Dynamic Dielectric Polymers (DDPs)

Recently, researchers have increasingly pursued hybrid self-healing materials based on multiple reversible interactions [51]. This scheme uses multiple mechanisms and allows improved mechanical strength through orthogonal bonding [64].

Dynamic dielectric polymers (DDPs) incorporate both supramolecular interactions and dynamic covalent bonds within a unified framework [2]. DDPs have the healing capability in their molecular structure, enabling repeatable self-healing at any damage site. The molecular engineering of self-healing dielectrics focuses on three design strategies [65]. It uses a reversible covalent network that offers distinctive healing kinetics with an activation temperature. It also includes supramolecular structures that enable rapid repair. Lastly, it contains a hybrid system that combines covalent and non-covalent dynamics to coordinate multi-stimulus responsiveness [65]. Wan et al. recently developed a self-healable and recyclable polyimide hybrid dielectric by modifying the molecular structure with novel oligomers [66]. This approach preserves the thermal stability and breakdown strength of conventional PI while maintaining its damage-repair capability. Similarly, ethylene-anisylpropylene copolymers show remarkable self-healing capabilities and dielectric properties suitable for practical applications, though the glass transition temperature (8-28°C) remains a limiting factor [67]. Figure 12 shows a schematic of the self-healing process of recyclable polyimide via heating.

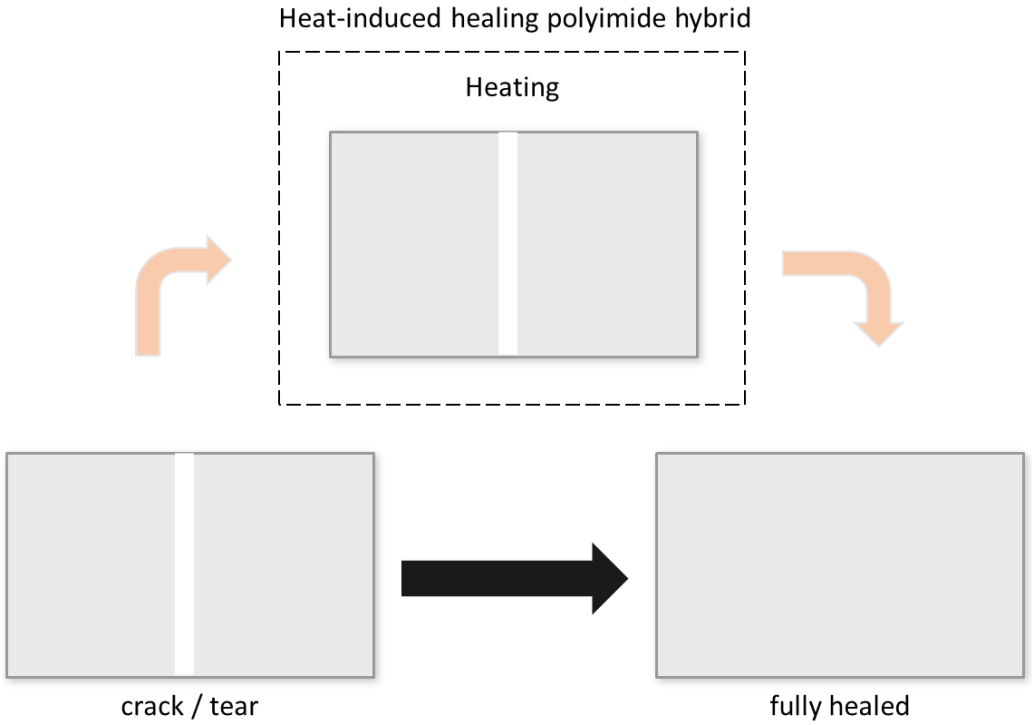



**Figure 12** Schematic of healing via heating of polyimide hybrid dielectric films.

### *3.3 Physical-Field-Assisted and Multi-Stimuli-Triggered Healing*

The systems above rely on triggers that operate on the molecular level - heat, moisture, or elapsed time. An alternative strategy couples an external physical field or macroscopic actuation to the chemical repair process, which enables healing to initiate remotely or to be synchronized with

a particular damage event. Two such approaches have been developed for HV insulation: shape-memory-assisted mechanical closure of damage channels (Section 3.3.1) and magnetically induced local heating (Section 3.3.2). This differs from the magnetic-targeting approach described in Section 3.1.3, where the field merely guides the position of the capsule; the field itself provides the thermal energy that causes the healing to take place.

### 3.3.1 Shape-Memory-Assisted Self-Healing (SMASH)

Shape-memory-assisted self-healing (SMASH) represents an innovative concept for high-voltage insulation [68]. In SMASH systems, the polymer network incorporates both shape-memory capability and reversible cross-links [69]. Because shape-memory actuation physically closes a damage channel before the chemical re-crosslinking step completes [68, 69], it is reasonable to expect that the two-stage mechanism will be more effective than chemical re-crosslinking alone in restoring the material's mechanical integrity at the site of damage - though this specific benefit has not been directly quantified for an electrical-tree-damaged HV insulation system.

In the PPG-MPUx-PA1-x system, the actuation temperature can be tuned between approximately 25°C and 60°C by adjusting the ratio of the weaker to the stronger hydrogen-bonding units in the network, and lower-actuation-temperature formulations retain about 80% of the shape-memory energy density of the original polymer; complete chemical re-crosslinking at the damage site then occurs at around 70°C [70].

Isolating the shape-memory contribution quantitatively from the underlying chemical re-crosslinking would require a controlled comparison, for example, testing SMASH-active PPG-MPUx-PA1-x against an otherwise identical composition where the shape recovery is mechanically suppressed or chemically decoupled and comparing the resulting breakdown-voltage recovery Δ between the two under identical electrical-tree damage protocols. To our knowledge, no controlled comparison has been reported for an HV-relevant SMASH system. We view this as a specific, testable open question rather than a proven result of the two-stage mechanical-chemical benefit.

The tunability is important for high-voltage applications because it separates the temperature required for physical shape recovery (i.e. channel closure) from the higher temperature needed for permanent chemical healing, enabling a formulation to be chosen such that the shape-memory actuation remains below the normal service-temperature limit of the component while the higher re-crosslinking temperature is only reached during a planned or fault-induced thermal excursion. Notably, this system demonstrated SMASH of centimeter-scale macroscopic punctures, in contrast to the sub-millimeter-scale scratches addressed by earlier SMASH work [70], representing a damage size more in line with the type of local channel damage associated with electrical treeing.

### 3.3.2 Magnetothermal Healing via Superparamagnetic Nanoparticles

The combination of superparamagnetic nanoparticles with an oscillating magnetic field makes a magnetothermal self-healing mechanism for high-voltage insulating materials [71]. As demonstrated by a research team at Tsinghua University, incorporating less than 0.1 volume % of γ-$Fe_2O_3$ superparamagnetic nanoparticles into a thermoplastic polymer matrix to enhance self-healing performance [71]. In another case, an isotactic polypropylene (iPP) matrix filled with $Fe_3O_4$ nanoparticles generated localized heat under an applied oscillating magnetic field through magnetic hysteresis loss and mechanical friction [72]. The superparamagnetic nature of these nanoparticles

confirmed the absence of residual magnetism after the external field is removed. This prevented any unwanted magnetic interference with the electrical field distribution in the insulation [72]. In another case, integrating 5-15 wt.% superparamagnetic iron oxide nanoparticles into a vinylogous urethane vitrimer matrix retained the magnetic properties while also ensuring reuse and recycling [73]. Figure 13 illustrates the magnetic healing of electric trees, from tree formation to the application of an oscillating magnetic field (OMF) and the migration of superparamagnetic iron oxide nanoparticles to produce healing [71].

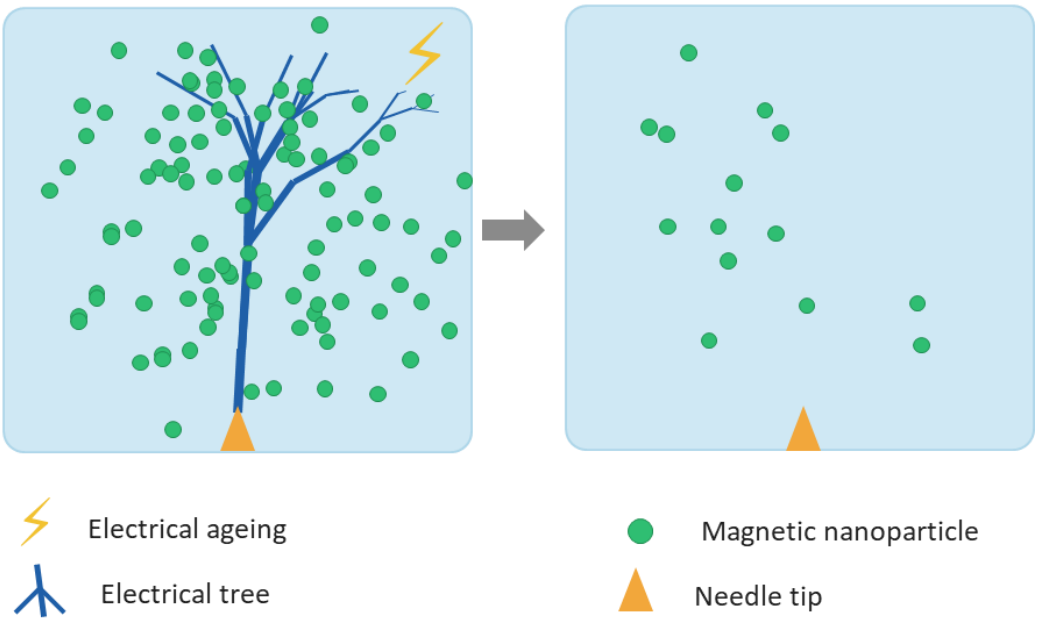



**Figure 13** Schematics of the magnetic healing of electric trees, starting from tree formation, application of an oscillating magnetic field (OMF) to produce healing.

### *3.4 Comparative Trade-Offs and Strategy Selection for HV Applications*

The preceding sections describe each self-healing strategy largely in isolation, consistent with how each was originally reported. Selecting an appropriate strategy for a given HV application, however, requires weighing these approaches against one another on shared criteria: how often a particular site can be healed, how healing chemistry or filler affects baseline dielectric properties, what initiates healing and how fast, and what healing metric was actually measured. Table 2 summarizes these trade-offs across the extrinsic, intrinsic, and physical-field-assisted strategies reviewed above.

**Table 2** Comparative trade-off analysis of self-healing strategies for high-voltage insulation applications.

| Mechanism | Trigger | Effect on Dielectric Properties | Reported Metric* | Best-Fit HV Application | Key Trade-off/Limitation |
|---|---|---|---|---|---|
| **I. Extrinsic Self-Healing Systems (Section 3.1)** | | | | | |
| Microcapsule-based systems [31, 33, 34] | Rupture by tree-tip stress/heat; no external trigger needed | New polymer raises local breakdown strength, lowers PD activity [34] | Delayed tree growth, improved breakdown (qualitative) | Sealed HV apparatus, subsea cables with limited repair access [34] | No repeat healing at same site; unused capsules elsewhere are a wasted reservoir |
| Vascular networks [35, 36] | Channel rupture on damage; replenishment needs external infrastructure | Channel volume must be minimized to avoid permittivity/field distortion | Not quantified for HV case in source | Larger, accessible equipment (e.g., transformers) | Network itself is a built-in field-distortion risk unless replenishment is engineered in |
| Multi-stimuli DA microcapsules [6] | 1 wt.%; thermal, light, or moisture | Maintains XLPE baseline insulation performance at this loading [6] | Dual water-/electrical-tree repair (qualitative); cf. Table 1's ">80% after 3 cycles" | XLPE cable insulation under combined electro-hydro aging | Added formulation complexity; cycle ceiling beyond reported data unknown |
| EL-triggered microcapsules [38] | Autonomous — triggered by breakdown's own electroluminescence; catalyst-free | Localized cure preserves properties in surrounding undamaged region | Qualitative (self-contained loop demonstrated) | Components sensitive to bulk thermal loading during healing | Trigger is autonomous, but repeatability is unchanged from standard capsules |
| Magnetic-targeted microcapsules [39, 40] | 1-5 wt.% vs. 10-15 wt.% conventional; external magnetic field for targeting | Preserves baseline strength, resistivity, mechanical integrity at reduced loading | Self-reporting via fluorescence (not a healing-efficiency number) | Applications where minimizing total filler loading is critical | Requires external field-generation hardware; added system complexity |

| | | | | | |
|---|---|---|---|---|---|
| High-load rigid porous microcapsules [41] | 3 wt.% matrix loading; 88.2% core loading per capsule (Table 1) | Preserves matrix and baseline properties | 96.2% insulation recovery after electrical treeing | Severe, one-time damage where dose size matters more than repeatability | Rigid architecture maximizes agent volume but remains inherently single use |
| Multi-layer core-shell, water tree [42, 43] | 1.0 wt.% optimal | Preserves composite's electrical properties at this loading | 24.86% reduction in average water-tree length | Underground/water-exposed XLPE cable insulation | Tree-length metric not directly comparable to breakdown-based efficiencies elsewhere (Section 4.2) |
| **II. Intrinsic Self-Healing Systems (Section 3.2)** | | | | | |
| Disulfide dynamic covalent networks [47-49] | Thermal or UV; near-room-temperature healing reported by Wu et al. [49] | Demonstrated dielectric-strength recovery after breakdown [48] | Qualitative recovery (no numeric η reported for base system) | Bulk epoxy/thermoset insulation, inaccessible components needing repeat healing | Each healing event needs local heat or UV access to the damage site |
| Diels-Alder networks [50-52] | ~80°C to bond, >110°C to reverse | Not separately quantified in source | Qualitative (thermal/mechanical characterization only) | Equipment tolerant of localized heating to 80-110°C | Reversal temperature may be hard to reach without bulk heating in energized equipment — not discussed in source |
| Imine bonds [53, 54] | Moisture or mild acid; autonomous | Not quantified for HV context in source | Not reported numerically for HV insulation | Humidity-controlled environments favoring non-thermal healing | Moisture-triggered healing raises the same humidity-management concern as H-bonded networks |

| | | | | | |
|---|---|---|---|---|---|
| High-κ/thin-film disulfide composites [55, 56] | 5.25 vol% $CeO_2$@MXene; 0-50% disulfide content (PU films) | ε’ = 206 at 100 Hz ($CeO_2$@MXene/PSPU) — roughly 90× XLPE’s ε’ ≈ 2.3, with a reported dielectric loss (tan δ) of 0.19; PU films tested only at ~10-30 V (thin-film scale) | 97.9% SH efficiency (mechanical strength); breakdown 10 V → 30 V (PU film) | Energy-storage/soft-electronics dielectrics, not transmission-class HV insulation as reported | High ε’ aids capacitive storage but would cause field distortion and local heating if used directly as HV insulation — not addressed in source |
| Covalent Adaptable Networks, XLPE [57, 58] | Thermal, above service temperature (stable ≤70°C) | Comparable to XLPE at service temp; superior after healing [57] | ~100% recovery of mechanical and electrical properties | Cable-grade XLPE insulation — closest current match to existing manufacturing | Strongest reported result, but extrusion-line scalability not yet addressed (Section 6.6) |
| H-bonded supramolecular networks [61, 62] | None required beyond intrinsic bond dynamics | Sensitive to ambient humidity; moisture can compromise insulation resistance [62] | Not quantified for HV dielectric context in source | Dry/humidity-controlled HV environments (e.g., indoor switchgear) | Weaker H-bond arrays heal faster but sacrifice structural robustness (explicit trade-off in source) |
| Metal-ligand coordination [63] | Autonomous, room temperature | High breakdown field strength, 240 kV/mm | 80% property recovery after 60 min | Fast, autonomous room-temperature healing with high breakdown strength | Single-study result; long-term cycling and humidity sensitivity not yet reported |
| Hybrid DDPs [66, 67] | Multi-stimulus (design-dependent) | Preserves thermal stability and breakdown strength of conventional PI [66] | Qualitative (PI); ethylene-anisylpropylene reports usable SH but $T_g$ 8-28°C | Applications needing both fast local response and long-term robustness | Near-ambient $T_g$ (8-28°C) risks glass-to-rubber transition within normal HV service swings |

| | | | | | |
|---|---|---|---|---|---|
| **III. Physical-Field-Assisted Healing (Section 3.3)** | | | | | |
| SMASH [68-70] | Thermal actuation for shape recovery + subsequent chemical re-crosslinking; specific temperature windows not given for the HV case | "Substantially improved" dielectric-strength recovery — qualitative only | Not quantified in source | Macroscopic punctures/channel-type damage where physical closure meaningfully reduces the gap before chemical healing completes | Link between shape-memory recovery ratio and dielectric recovery is asserted, not quantitatively demonstrated |
| Magnetothermal, SPIONs + OMF [71-73] | <0.1 vol% γ-$Fe_2O_3$ (Tsinghua); 5-15 wt.% in SPION-vitrimer variant; remote oscillating field | Super-paramagnetism avoids residual magnetism/field interference [72] | Not separately quantified for HV breakdown recovery in source | Embedded/inaccessible HV components (subsea, encapsulated power electronics) | Requires external field-generation infrastructure; low nanoparticle loading needs careful dispersion control |

*"Reported Metric" reflects the specific basis (breakdown strength, tree-length reduction, mechanical toughness, etc.) used by each cited source. These bases are not directly interchangeable; see the discussion in Section 4.2.

Three general observations emerge from this comparison. First, extrinsic microcapsule and vascular systems remain best suited to situations in which physical repair access to the site of damage is genuinely unavailable after installation (e.g., subsea cables, embedded apparatus) and where a single high-confidence healing significantly outweighs the requirement for multiple, repeated healing events at a single site — their primary cost is the finite capacity of a reservoir of healing agent and, for most architectures, a low enough loading fraction to minimize impact and eventual degradation of baseline dielectric properties.

Second, intrinsic dynamic covalent and supramolecular systems are most desirable wherever the repeated healing events at a single site dominates the service life of an apparatus — most notably, cable-grade XLPE (polyethylene) insulation, where CAN (covalent adaptable networks) systems (Section 3.2.2) currently offer the most complete, directly comparable recovery of mechanical and dielectric properties; their trade-off shifts from one of reservoir capacity to one of chemistry-dependent access to the site of damage: disulfide and Diels-Alder networks require thermal or UV access to the damage site, hydrogen-bonded networks trade the time of healing against structural integrity and require moisture control, and chemistries optimized for a high dielectric constant in energy-storage applications (as illustrated by the case of $CeO_2$@MXene/PSPU in Section 3.2.1) are not without additional engineering, necessarily appropriate to HV insulation, where the same high permittivity would concentrate electric fields and thus increase capacitive loading rather than reduce it.

And third, the physical-field-assisted systems described in Section 3.3 are characterized less by the property they recover than by the remoteness of their actuation: magnetothermal healing, in particular, is of special interest to power electronics encapsulation and other inaccessible geometries, for which a non-contact actuation mechanism is the critical requirement rather than the chemistry per se.

The second pattern is a methodological one: the healing metrics quoted through Section 3.1-3.3 are not measured on a common basis. Some are defined relative to breakdown or dielectric-strength recovery, others relative to tree-length reduction, and others relative to mechanical toughness. Reported dielectric properties are similarly uneven across mechanisms: of the seventeen systems compared in Table 1, only the $CeO_2$@MXene/PSPU composite (Section 3.2.1) reports a specific loss-tangent value alongside its permittivity and healing efficiency; the remaining sixteen do not report loss tangent at all. Section 4.2 discusses this inconsistency and its implications for cross-study comparison.

To make this reporting gap concrete rather than descriptive, Table 3 isolates the subset of systems from Table 1 for which both a filler/dopant loading and at least one dielectric-adjacent recovery metric are jointly reported. This narrower comparison does not replace Table 1's broader trade-off analysis; it responds directly to the question of whether loading level, healed dielectric performance, and loss tangent can be compared side by side across mechanisms — and shows that, of the eight qualifying systems, only one permits that comparison to be completed in full.

**Table 3** Filler/dopant loading versus reported dielectric-adjacent recovery metrics and loss-tangent (tan δ) reporting status, for the subset of Table 1 systems with sufficient quantitative data.

| System (Section) | Loading | Healed/Recovered Metric | tan δ Reported? |
|---|---|---|---|
| $CeO_2$@MXene/PSPU (3.2.1) | 5.25 vol% | 97.9% SH efficiency (mechanical) | Yes — 0.19 (at ε′ = 206) |
| Disulfide PU thin film (3.2.1) | 10-50% disulfide | 10 V → 30 V breakdown (thin-film scale) | No |
| Magnetic-targeted microcapsules (3.1.3) | 1-5 wt.% | Preserves baseline strength (qualitative) | No |
| High-load rigid porous microcapsules (3.1.3) | 3 wt.% (88.2% core) | 96.2% recovery after electrical treeing | No |
| Multi-layer core-shell, water tree (3.1.3) | 1.0 wt.% | 24.9% reduction in water-tree length | No |
| Multi-stimuli DA microcapsules (3.1.3) | 1 wt.% | Maintains XLPE baseline (qualitative) | No |
| CANs, XLPE (3.2.2) | N/A (bulk network) | ~100% mechanical + electrical recovery | No |
| Metal-ligand coordination, PEI (3.2.3) | N/A (bulk network) | 240 kV/mm; 80% recovery @ 60 min | No |

Table 4 brings to light a gap that was only suggested in the earlier sections: although space-charge accumulation driven by a DC field is one of the four main damage mechanisms identified in Section 2.4, not a single one of the seventeen mechanisms examined in Section 3 has been shown to counter this effect. The only system mentioned in this review that achieves space-charge suppression — Zhang et al.'s reversible-thioester PE-SHx network, which reduced the space charge by 94% (Section 6.7) — is at present considered only as a potential future application for HVDC systems and is not here compared with the other mechanisms. This imbalance indicates that space-charge-oriented healing chemistry, rather than electrical-tree healing (which is already well represented among the extrinsic, intrinsic, and physical-field-assisted types), should be regarded as the more urgent open issue in HVDC insulation design.

**Table 4** Damage-mode coverage of self-healing mechanisms reviewed in Section 3.

| Mechanism (Section) | Electrical Treeing | Water Treeing | PD Erosion | Space Charge |
|---|---|---|---|---|
| I. Extrinsic Self-Healing Systems | | | | |
| Microcapsule-based (3.1.1) [34] | √ | - | √* | - |
| Vascular networks (3.1.2) [35, 36] | ~ | ~ | - | - |
| Multi-stimuli DA microcapsules (3.1.3) [6] | √ | √ | - | - |
| EL-triggered microcapsules (3.1.3) [38] | √ | - | - | - |
| Magnetic-targeted microcapsules (3.1.3) [39, 40] | ~ | ~ | - | - |
| High-load rigid porous (3.1.3) [41] | √ | - | - | - |
| Multi-layer core-shell, water tree (3.1.3) [42, 43] | - | √ | - | - |
| II. Intrinsic Self-Healing Systems | | | | |
| Disulfide DCB networks (3.2.1) [47-49] | √ | - | - | - |
| Diels-Alder networks (3.2.1) [50-52] | √ | - | - | - |
| Imine bonds (3.2.1) [53, 54] | ~ | - | - | - |
| High-κ/thin-film disulfide (3.2.1) [55, 56] | - | - | - | - |
| CANs, XLPE (3.2.2) [57, 58] | ~ | ~ | - | - |
| H-bonded supramolecular (3.2.3) [61, 62] | ~ | - | - | - |
| Metal-ligand coordination (3.2.3) [63] | ~ | - | - | - |
| Hybrid DDPs (3.2.4) [66, 67] | ~ | - | - | - |
| III. Physical-Field-Assisted Healing | | | | |
| SMASH (3.3.1) [68-70] | √ | - | - | - |
| Magnetothermal, SPIONs + OMF (3.3.2) [71-73] | √ | - | - | - |

Legend: √ = explicitly demonstrated against this damage mode in the cited source; ~ = plausible or implied but not directly tested against this mode; - = not addressed. *Secondary effect reported alongside primary tree-arrest function [34].

## 4. Healing Performance Evaluation and Characterization

Systematic characterization of self-healing insulating materials requires electrical, mechanical, morphological, and chemical evaluations [74]. Two established standards are relevant to characterizing insulation conditions, though for different purposes. IEC 60270 defines charge-based partial discharge (PD) measurement techniques, which can detect residual voids or incomplete healing [75]. ASTM D1830 is a thermal-endurance test for flexible sheet insulating materials using a curved-electrode method [76], relevant to long-term thermal aging rather than PD activity. However, self-healing materials require specialized metrics and in-situ monitoring techniques beyond these baseline methods [77].

### *4.1 Electrical Performance Evaluation*

Dielectric integrity is the most important criterion for self-healing insulation. Breakdown voltage recovery is assessed by the dielectric strength with either standardized sphere-plate or needle-plate electrode configurations under AC or DC stress [77]. Researchers commonly use Weibull distribution analysis in multiple-breakdown experiments [74]. This reflects a weakest-link failure model, in which

breakdown initiates at the single most severe defect rather than a bulk-averaged property; a healed sample's Weibull shape parameter, not only its scale parameter, therefore indicates whether healing removed the most severe defects or merely improved the average condition.

Partial discharge (PD) monitoring is used to assess damage and evaluate healing efficacy. According to IEC 60270, charge-based PD measurements can detect residual voids or incomplete healing [75]. Recently, PD monitoring has demonstrated that radio frequency (RF) techniques can detect discharge activity associated with degradation [78]. Electrical treeing experiments can evaluate the effectiveness of self-healing during insulation failure. A needle-plate electrode under controlled AC voltage was employed to initiate and propagate electrical trees. The healing efficiency is quantified by the reduction in tree length or tree density after healing.

Dielectric spectroscopy can also reveal the efficacy of a self-healing system [77]. Dynamic bonds, nanoparticles, or residual healing agents may influence the dielectric constant and loss factor. One commercially available self-healing material, HELIOS, exhibited high dielectric losses at low frequencies, as detected by broadband dielectric spectroscopy [79].

This influence is not always a bulk-chemistry effect. Capsule shells, residual healing agents and nanofillers establish internal interfaces at which charge accumulates under an applied field, producing Maxwell-Wagner-Sillars (MWS) interfacial polarization. This low-frequency rise in permittivity and loss is distinct from the host polymer's intrinsic dipolar response and can be mistaken for a genuine change in dielectric performance if not separated out. In healed areas, the leakage current is also determined by the depth and density of charge traps formed by healing agents or ionic species. Shallow traps enhance leakage by detrapping/hopping conduction, while deeper traps and lower free volume reduce leakage.

### *4.2 Mechanical Performance Evaluation*

As per ASTM D638, tensile testing provides information on healing performance, including Young's modulus, ultimate tensile strength, and elongation at break. Fracture toughness characterization is also important for assessing healing after mechanical damage. It was suggested that healing efficiency be evaluated using both strength- and toughness-based measurements. Healing efficiency indicators (η) are conventionally defined as the ratio of a healed property to its pristine value [80]. For electrical properties, these indicators are dielectric strength, partial discharge voltage, and breakdown voltage.

However, the η values stated throughout this review are not measured on a common basis and thus are not directly comparable between studies for at least three reasons. First, the property being stated as η varies by study: some report η relative to breakdown or dielectric-strength recovery (e.g., the ~100% recovery of both mechanical and electrical properties reported for CAN-based XLPE [57]); others to a percent reduction in tree length rather than a recovery ratio at all (e.g., the 24.86% reduction in water-tree length reported for three-layer core-shell microcapsules [42]); and others to mechanical toughness or tensile-property recovery rather than any electrical property, following the convention standard in the broader elastomer self-healing literature (e.g., the ~75% recovery of fracture toughness in the original DCPD/epoxy system [31]). This convention is directly relevant to Section 3.2.1: the 97.9% self-healing efficiency reported for $CeO_2$@MXene/PSPU [55] is stated alongside that composite's dielectric constant of 206, plausibly reflecting tensile-property recovery after a cut-and-rejoin healing cycle rather than dielectric performance.

Second, even studies reporting η on an electrical basis do not always use the same electrical property: dielectric strength, partial discharge inception voltage, and absolute breakdown voltage are related but distinct quantities, and a material's recovery on one does not necessarily follow its recovery on another. Third, some studies report η as a normalized ratio, while others report only an absolute before/after value, which cannot be converted to a ratio without knowing the pristine baseline — for example, breakdown voltage rising from ~10 V to ~30 V after healing in disulfide-based PU thin films [56] represents a threefold increase, but not necessarily full recovery to an undamaged baseline, which the source does not report.

This heterogeneity means that superficially similar efficiency figures cannot be assumed to reflect comparable material performance. A mechanical self-healing efficiency of 97.9% and an insulation recovery after electrical treeing of 96.2% [41], for instance, describe different properties, ascribed to different protocols, on materials submitted to different damage severities; neither figure on its own connotes whether the healed material would withstand the same operating voltage for the same length of time as the pristine material. Similarly, a percent reduction in tree length is not commensurate with a percent recovery of breakdown strength, because a partially arrested tree still constitutes a preferential breakdown path after its growth has measurably ceased [14, 15]. Correlating these dissimilar bases — determining what a given tree-length reduction typically corresponds to in breakdown-voltage recovery for a given class of materials, for instance — has rarely been attempted in the reviewed literature and represents an open gap rather than a simple reporting inconsistency.

A minimum reporting standard that would allow healing efficiencies to be compared across studies would minimally require specification of: (i) which single property η was calculated from (dielectric or breakdown strength, PD inception voltage, tree length, or mechanical toughness), (ii) the damage protocol that produced the initial defect (e.g., needle-plate electrode geometry with applied voltage and duration, or mechanical scratch/cut depth), and (iii) whether recovery is expressed relative to pristine, undamaged baseline or damaged, pre-healing state. Section 6.6 discusses the need for standardized protocols and community-consensus metrics in this field in general, and this identified property-basis inconsistency is one specific component that would need to be addressed.

### *4.3 Morphological and Chemical Characterization*

Direct visualization of damage and healing validates proposed mechanisms. Optical microscopy is primarily used to observe electrical tree morphology [81]. Scanning electron microscopy (SEM) provides higher-resolution imaging of healed interfaces, tree channels, and microcapsule rupture. Transmission electron microscopy (TEM) reveals nanoparticle distribution and healing-agent penetration at the nanometer scale. Fourier transform infrared spectroscopy (FTIR) detects reversible Diels-Alder adducts or disulfide bond reformation [80]. X-ray photoelectron spectroscopy (XPS) provides surface-sensitive chemical state information.

Recent innovations have revolutionized electrical tree imaging. Researchers have discovered that electrical tree channels in silicone gel can induce a self-excited fluorescence effect under applied electric fields for three-dimensional in situ fluorescence imaging [81]. This method allows optical sectioning along the Z-axis without physical slicing. Complementing this approach, a research group at Tianjin University developed a phosphorescence-based electrical tree imaging (PI-LF) strategy

using oxygen-responsive, room-temperature phosphorescent organic materials [81]. The technique visualizes electrical trees from dense micro-branch regions to coarse conductive pathways [81].

### *4.4 In-Situ and Real-Time Monitoring Techniques*

Real-time monitoring techniques can observe healing activation and provide feedback on healing success. Aggregation-induced emission (AIE) fluorophores, when used with confocal microscopy, enable self-reporting via fluorescence upon polymerization of the healing agent. The electrical tree channels naturally emit fluorescence under field stress. These systems offer built-in damage-sensing capability without requiring external probes or dyes [80].

## 5. AI-Driven and Predictive Approaches

Integrating artificial intelligence (AI) and machine learning (ML) into self-healing insulation research represents a paradigm shift from passive material development to adaptive systems [82]. This section reviews emerging AI-driven approaches across different domains.

The four subsections that follow (5.1-5.4) each address a different segment of a conceptual closed loop involving sensing, decision, and repair—localizing sites of damage, anticipating repair timing, and eliciting physical healing. This mapping matters because the systems described below are control and prediction architectures built atop — rather than replacements for — the underlying chemical and physical healing mechanisms reviewed in Section 3. For instance, Section 5.1 targets spatial damage localization and closed-loop thermal triggering; Section 5.2 targets AI-guided discovery of the underlying dynamic-bond chemistry itself; Section 5.3 targets timing of intervention; and Section 5.4 targets fault detection at a grid-scale rather than a component level. When relevant, we also note the extent to which a given system ties back to a Section 3 mechanism.

### *5.1 Autonomous AI Systems*

Prof. Cheng-Hui Li's team at Nanjing University developed the first fully autonomous self-diagnosing and self-healing system [82]. Their innovation completed a closed-loop healing cycle without human intervention. The team incorporated an ionic liquid ([BMIM]TFSI) into a thermoplastic polycaprolactone (PCL) matrix at 33.3 wt.% loading. The liquid-state ionic liquid exhibited excellent ionic conductivity, enabling damage sensing. It also formed a dynamic cross-linked network through ion-dipole interactions, providing material flexibility. To enable efficient thermal repair, the material exhibited a melting point around 60°C [82]. Here, a high-sensitivity eight-port impedance measurement system collected 28-dimensional complex impedance vectors across the material surface, capturing weak electrical signals indicative of damage in real time. These data were fed into a backpropagation neural network (BPNN) for deep learning training [82].

The AI model decoded the damaged spatial coordinates from a complex electrical signal, achieving prediction accuracies of $R^2 = 0.987$ for x-coordinates and $R^2 = 0.977$ for y-coordinates, and provided reliable navigation for subsequent targeted repair [82]. Using response surface modeling (RSM), the system correlated damage characteristics with repair conditions and efficiency. The AI then calculated optimal repair parameters for different damage severities and achieved >99% healing efficiency [82]. A selective heating resistor array activated the micro-heating units at AI-localized damage positions. Joule heating rapidly raised the local temperature above the melting

point. The polymer chain reflowed and repaired the damage within seconds to minutes. Throughout the process, the system continuously monitored impedance to evaluate efficacy. Once the AI determined that complete healing had occurred, the heating automatically terminated [82].

This system demonstrated a complete intelligent closed loop for material self-repair. Its full autonomy makes it suitable for extreme environments where human intervention is impossible. For high-voltage applications, this model could be adapted to detect partial discharge or electrical tree initiation and autonomously trigger localized healing [83] .

The AI system's core contribution here — namely, the localization of damage in sub-components from impedance data, followed by closed-loop, spatially-selective Joule heating — is fundamentally a control architecture rather than a healing chemistry specific to the PCL/ionic-liquid matrix in which it was demonstrated [82]. In principle, the same architecture could serve as the physical trigger layer for several of the thermally-activated intrinsic mechanisms described in Section 3.2, each of which currently specifies a required activation temperature but not how that temperature would be localized and delivered within an energized HV component: CAN-based XLPE (Section 3.2.2, dynamic-network activation above its ~70°C service ceiling [57]), Diels-Alder re-crosslinking (Section 3.2.1, forms at ~80°C [50]), and the SMASH actuation/re-crosslinking sequence (Section 3.3.1, 25-60°C actuation, ~70°C re-crosslinking [70]) are all, in this sense, waiting on the same kind of localized-heating trigger this AI system already provides. Nevertheless, the reviewed literature does not address the question of damage sensing itself: the Nanjing system's spatial localization depends on the ionic liquid's inherent electrical conductivity for its impedance signal [84], whereas XLPE and cured epoxy are, by design, materials of very low ionic conductivity. Whether an equivalent impedance-based sensing approach would work for these HV-relevant matrices, or whether a different sensing modality — the partial-discharge-based prognostics discussed in Section 5.3, or the fluorescence-based self-reporting discussed in Section 3.1.3 — would be needed to supply the localization signal instead, remains an open integration question rather than a demonstrated result.

### *5.2 Machine Learning for Self-Healing Polymer Discovery*

AI-guided approaches are also being applied to accelerate the material's discovery, replacing the conventional trial-and-error paradigm. Researchers have trained models on thousands of vitrimer examples generated by molecular dynamics (MD) simulations to predict the glass transition temperature ($T_g$) across a large compositional space [84]. These vitrimers are cross-linked polymers with self-healing capabilities via covalently adaptable networks (CANs). They trained seven different AI models on 8,400 examples from MD simulations across six molecular representations [84]. These models learned to predict the $T_g$ of self-healing plastics. Rather than choosing a single model, they used an ensemble approach that combined all seven models. Afterward, they screened 1 million theoretical materials and identified 2 novel candidates with unique properties. These two novel vitrimers were synthesized experimentally and validated to have glass-transition temperatures higher than those of any existing bifunctional vitrimers [84]. For high-voltage applications, they can now create custom materials tailored to their needs, with the combination of electrical strength, heat resistance, and self-healing ability.

This ML-guided discovery process is relevant to the covalent adaptable network (CAN) chemistry described in Section 3.2.2 since vitrimers are the general category of polymers that CAN-based systems fall into — the SPION-vitrimer nanocomposite mentioned in Section 3.3.2 [71] also uses the

same basic terminology. The two new vitrimers found using this method were tailored specifically for their glass transition temperature [84], which, as explained in Section 6.6, is a relevant design constraint for HV service-temperature compatibility. Whether the same ensemble-ML approach could be extended to jointly optimize $T_g$ alongside HV-relevant dielectric properties — permittivity, loss factor, and breakdown strength — rather than $T_g$ in isolation represents a natural extension connecting this materials-discovery method to the property requirements outlined throughout Section 3.2.

To apply this workflow to HV insulation, it needs to be reformulated as a multi-objective rather than a single property optimization. In the work of Zheng et al., the $T_g$ was predicted alone from a molecular representation using ensemble models [84]; an HV-relevant pipeline, by contrast, would need to simultaneously predict $T_g$ (service-temperature compatibility), relative permittivity and loss tangent at power frequency (baseline dielectric performance), and a bond-exchange activation energy (trigger-temperature control, per the compatibility concern in Section 3.4) from the same or an extended descriptor set. Because these targets trade off against one another - higher cross-link density raises breakdown strength but also raises $T_g$ and slows exchange kinetics - such a model would need to output a Pareto front of candidates rather than a single optimum, letting an engineer select a composition that, for example, trades marginal breakdown strength for an activation temperature safely below a target component's service ceiling. This, together with an active-learning loop (in which each round of synthesized and characterized candidates retrains the model), would also address the data-scarcity issue raised in Section 5.5, as each experimental cycle would aim for maximum information gain across the joint property space, not just $T_g$ alone. To the best of our knowledge, the published literature has not trained a jointly constrained model for self-healing HV dielectrics. We believe adapting the ensemble/high-throughput screening architecture of [84] to this multi-property goal is the most direct the near-term path.

### *5.3 Predictive Prognostics for Electrical Treeing*

AI-driven prognostic frameworks can also predict insulation failure in real time before breakdown occurs, triggering self-healing activity. A study on electrical treeing in epoxy developed a prognostic framework for estimating time-to-failure (TTF) under electrical treeing stress [85]. The degradation parameter was the voltage difference between consecutive partial discharge (PD) pulses. Using PD data from 18 training samples, an average model determined the RMS voltage difference at breakdown. By tracking this pattern, they could accurately predict the timing of the breakdown [85]. The system continuously monitors the insulation and automatically triggers healing when electrical trees are detected. This early intervention could extend the operational life of high-value equipment, though this review has not quantified the magnitude of the benefit.

This prognostic approach addresses a different aspect of the closed loop than the spatial localization described in Section 5.1: instead of determining where the damage has occurred, it assesses when action is required, based on trends in the PD pulse-sequence data as breakdown is approached [85]. If combined with a mechanism that reports the location of the damage—for instance, the fluorescence-based self-reporting that has already been shown for magnetic-targeted microcapsules (Section 3.1.3) or the aggregation-induced-emission fluorophores mentioned in Section 4.4—a TTF-type prognostic model could in principle provide the timing signal which tells

when a healing trigger should be activated. In contrast, a separate self-reporting mechanism gives the location.

### *5.4 Grid-Level Self-Healing Control Models*

AI methods are also being applied to fault detection and response in electrical grids [86]. A recent study constructed a system using ensemble learning with random forests and gradient-boosted decision trees [86]. This system detected faults with 96.3% accuracy and responded 15% faster than traditional methods [86]. In power systems serving millions of people, even small improvements in speed and accuracy can prevent blackouts and save money. For high-voltage insulation, this kind of grid-level AI could be integrated with a self-healing material. Here, the network fault detection will trigger localized insulation repair before system-level failures propagate. Realizing this integration would require coupling grid-level fault detection with component-level healing triggers, which has not yet been demonstrated.

Fault-detection accuracy and response speed at the grid level primarily identify which piece of equipment requires action, rather than localizing damage within a single component (Section 5.1) or predicting timing (Section 5.3). Of the mechanisms reviewed in Section 3, magnetothermal healing (Section 3.3.2) is the most natural pairing for a grid-level trigger of this kind: because the oscillating magnetic field is applied remotely and non-invasively, a grid-level fault-detection system could, in principle, activate it for a specific piece of embedded or otherwise inaccessible HV equipment once that equipment has been flagged, without requiring physical site access.

### *5.5 Challenges in AI Integration*

Despite the progress, translating these concepts into engineering practice still faces several major obstacles. The first hurdle is the data scarcity. Because high-voltage experimental data for self-healing polymers is limited, training machine learning models is challenging. While molecular dynamics simulations can fill these gaps, we need real-world experimentation under electrical stress [85]. Once we have the data, the next challenge is real-time processing. If a system must identify damage and trigger a healing response in real time, processing speed becomes critical. Current deep learning models often struggle to process this information quickly enough on available embedded hardware. For high-voltage applications, AI systems must interface with existing PD monitoring, temperature sensing, and other diagnostic infrastructure [85]. However, the ultimate engineering test is achieving autonomy under high-voltage conditions. Achieving self-healing in a material while the insulation is energized requires a balancing act. The process must be controlled to prevent a catastrophic failure. Finally, black-box-type AI predictions may be unacceptable for safety-critical applications. Before these systems are widely adopted, we need to implement explainable AI methods so humans can understand, validate, and trust model decisions.

Each of the integration gaps identified in Sections 5.1-5.4 — sensing-modality transfer, prognostic-to-trigger coupling, and remote-trigger-to-fault-detection pairing — is, in effect, a specific instance of this broader interfacing challenge: none of the AI systems reviewed here were demonstrated on the HV-specific chemistries discussed in Section 3, and closing that gap experimentally is a prerequisite for any of the autonomous closed-loop concepts in this section to be realized for HV insulation specifically, rather than for the bespoke matrices in which they were originally demonstrated.

## 6. Future Research Directions

This section outlines critical future research directions that will shape the next generation of self-healing solid insulating materials for high-voltage applications. Several transformative opportunities for self-healing remain underexplored. These future directions cover molecular design innovation, industrial scalability, multi-functional integration, and characterization methodologies.

### *6.1 Molecular Structure Engineering for Eco-Friendly Dynamic Dielectrics*

This conceptual change towards smart dielectrics requires basic developments in terms of molecular structure design. As stated in a review article, eco-friendly dielectric polymers that adapt to environmental changes and can self-heal and self-recycle may bring a major leap in smart grid systems and power electronics [2]. However, designing molecular structures having good dielectric properties is still a challenge. It is essential for future research to focus on the design of dynamic dielectric polymers (DDPs) using reversible chemical bonds, which allow macroscopic healing and recycling [2]. One possible route would be extending the list of chemistries of dynamic covalent bonds appropriate for high-voltage systems. The newly emerging chemistry, including the imine bond, boronic ester bond, and transesterification network, requires examination under electric field conditions. Combining these dynamic bonds with conventional polymer matrices marks an important research issue. Collaboration between high-voltage insulation technology and polymer chemistry is inevitable to accomplish this task [2].

### *6.2 Integration of Artificial Intelligence in Material Design and Diagnostics*

Pan et al. noted that integrating AI-driven materials design, digital characterization, and application-related modeling could lead to the development of high-voltage polymeric systems [3]. Future work should establish open-access databases of self-healing material properties to train machine learning models for predicting the required material properties. High-throughput screening with automated synthesis and characterization would reduce the total time frame for targeted material design.

### *6.3 High-Temperature and Extreme Environment Performance*

The next-generation power electronics and energy storage systems require high-temperature dielectrics. Recent research on polymer dielectrics for high-temperature energy storage capacitors has revealed challenges of thermal stability, conduction loss, and energy storage performance [87]. Furthermore, aromatic dielectric materials lose their self-healing ability after electrical breakdown. Future research must address the mechanisms underlying the conduction loss that leads to high-temperature performance degradation. Exploring of the cessation of self-healing behavior in polymer dielectrics is an important direction [87]. Semi-alicyclic polyimides were found to control charge transfer effects and reduce carbonaceous residue [88]. They have demonstrated self-healing at 150°C, with maximum discharge energy densities of 3.29-6.48 J/cm$^3$ [88]. Applying these design principles to other polymer systems under combined thermal and electrical stress is essential for many applications.

Beyond elevated operating temperature, HV Insulation used outdoors must contend with a particular set of extreme environmental conditions: continuous exposure to ultraviolet radiation,

humidity cycles, and surface contamination, all of which can reduce hydrophobicity and lead to electrical tracking. This section has examined self-healing silicone rubber formulations for outdoor HV applications, focusing on their healing mechanisms, application considerations, and measurement methods that differ from those used for the high-temperature capacitor systems mentioned above [1]. Another area for the research agenda outlined in this section is to extend self-healing design to address both thermal and outdoor weathering extremes jointly, rather than treating these as separate issues.

A related but separate question is whether the dynamic bond chemistry that enables healing remains stable over many use cycles in a multi-decade service life. Most intrinsic systems in Section 3.2 report healing efficiency after a single damage-repair cycle; few report performance after tens or hundreds of cycles or under combined thermal cycling, moisture ingress, and continuous electrical stress rather than one controlled healing event. Repeated bond exchange may in principle cause gradual network degradation through side reactions, oxidation of exchangeable groups, or loss of stoichiometric balance between complementary functional groups — all of which would be reflected in decreasing healing efficiency, premature debonding, or reduced dielectric performance over time. Cycling-fatigue protocols for dynamic-bond insulation, analogous to multi-cycle testing already standard in structural self-healing materials, are needed before these systems can confidently be served as service-life claims.

### *6.4 Multi-Functional Smart Insulation Systems*

The development of self-reporting mechanisms that provide real-time visualization of damage without external probes should be integrated with self-healing functionality. In addition, multi-responsive healing systems would activate under electrical, thermal, optical, or magnetic stimuli, depending on the service condition. Lastly, the hierarchical healing approaches would provide rapid initial electrical insulation restoration followed by slower mechanical strength recovery. The goal for smart dielectrics is the versatility of self-reporting and self-healing capabilities [89].

### *6.5 Application in Wide-Bandgap Semiconductor Packaging*

The emergence of wide-bandgap semiconductors presents an opportunity for self-healing insulation. These devices can operate at higher voltages, frequencies, and temperatures than conventional Si-based systems. In a recent study, researchers used semi-alicyclic polyimides as insulating layers in high-voltage SiC power module devices [88]. These layers reduced the electric field strength to 43% and improved the discharge voltage by 101% compared to uncoated substrates [88]. Future research should explore integrating self-healing capabilities into packaging materials for wide-bandgap devices. The self-healing polyimide coatings on SiC power modules would represent a significant step toward practical applications.

### *6.6 Industrial Scalability and Standardization*

Adapting lab-scale self-healing materials for use in commercial high-voltage equipment involves scalable manufacturing, and the difficulties vary according to the mechanism involved. Regarding extrinsic systems, multi-layer core-shell microcapsules and magnetically responsive shells (Section 3.1.3) demand specialized monomer chemistries and multi-step encapsulation procedures, unlike

the well-established, one-step compounding process employed in the case of conventional nano-filler-reinforced XLPE. For intrinsic systems, compatibility with the current manufacturing infrastructure presents an additional problem: continuous XLPE extrusion lines run at fixed line speeds and at fixed peroxide-crosslinking temperatures, and it has not yet been determined whether dynamic-bond monomers (for example, those functionalized with disulfide or Diels-Alder groups) can be incorporated without affecting the cross-linking kinetics or the extrusion rate; similarly, epoxy-based intrinsic systems have to be compatible with the existing B-stage curing schedules used in the production of transformers and bushings. Physical-field-assisted methods introduce a third type of scalability issue, namely one relating to deployment rather than to synthesis: magnetically targeted healing (Section 3.1.3) and magnetothermal healing (Section 3.3.2) require external field-generating equipment for which the cost, the size of the coils or actuators, and the field penetration depth for buried or subsea cable installations have not been assessed at asset scale, and the maintenance requirements of such auxiliary systems over a multi-decade service life are not addressed in the sources examined here. Finally, and regardless of the manufacturing method, the long-term stability of dynamic bond networks when subjected to the combined effects of continuous electrical stress, thermal cycling, and moisture ingress typical of HV service — rather than the single- or a few-cycle laboratory healing demonstrations described in Section 3.2 — is still an open question; without accelerated-aging data obtained after repeated healing cycles, it is not possible to tell whether the dynamic bonds that allow healing also represent a separate long-term degradation pathway. At the same time, the field needs standardized testing procedures to achieve regulatory acceptance, as mentioned in Section 4.2. The community must agree on specific criteria for healing efficiency.

### *6.7 Self-Healing Solid Insulation for HVDC Systems*

HVDC technology is extremely important for the transmission of renewable energy sources. In HVDC conditions, the conductivity of polymer insulation material becomes very sensitive to temperature and increases exponentially with it [90]. During operation, Joule heating raises the temperature near the conductor, increasing conductivity in that region. It creates electric field distortion that leads to an accelerated process of degradation and breakdown. Zhang et al. (2026) have created reversible thioester bonds in polyethylene (PE-SHx), thus introducing a heat-stable polar trap in the network structure [91]. PE-SH100 showed the best results, with 93% and 94% reductions in high-temperature conductivity and space charge, respectively, and field distortion below 5% at 90°C [91].

### *6.8 Nano-Engineered Self-Healing Dielectrics*

The fusion of nanotechnology and self-healing polymers promises amazing potential. The design of nanomodified self-healing dielectric material utilizes the special characteristics of nanofillers for the enhancement of electrical, mechanical, and self-healing performance. In the study reported by Vertuccio et al. (2026), the incorporation of carbon nanotubes was in the hydrogen-bonded epoxy [92]. As a result, the composite demonstrated a ~99% healing performance and an elevated $T_g$ above 200°C. In the current study, the $Fe_3O_4$@$SiO_2$ microcapsules were employed along with nano-$Al_2O_3$ in the epoxy matrix. The optimization of the 2% microcapsules/1% $Al_2O_3$/epoxy composition ensured a relative dielectric constant equivalent to that of epoxy alone but elevated dielectric

strength by 2.32%. The magnetic targeting mechanism helps the accumulation of microcapsules in damage sites.

## 7. Conclusions

Self-healing solid insulating materials have emerged as a compelling solution to one of the most persistent challenges in high-voltage engineering. This review systematically surveys the field from foundational damage mechanisms to cutting-edge material strategies and emerging AI-driven techniques. Extrinsic systems based on microcapsule and vascular network technologies have shown clear efficacy in arresting electrical tree propagation and restoring breakdown strength in epoxy and XLPE matrices. Examples of such advancements include magnetic-targeted capsule delivery, eggshell-like high-load architectures, and multi-responsive Diels-Alder microcapsule/XLPE composites that have increased repeatability of healing with dielectric characteristics. At the same time, inherent self-healing mechanisms (disulfide bond metathesis, Diels-Alder reaction, imine formation, hydrogen bonding, and metal-ligand interactions) have allowed for the spontaneous restoration of mechanical and dielectric properties in the absence of external reagents. Covalent adaptable network-based polyethylene with simultaneous restoration of electrical and mechanical properties is a step forward toward creating sustainable cable insulation. New generations of SMASH systems, magnetothermal self-healing through superparamagnetic nanoparticles, electroluminescence-induced restoration, and multi-mechanism dynamic dielectrics are some examples that deal with multi-stress failure scenarios. Artificial intelligence and machine learning technologies have paved the way to a new area. They are used to create autonomous closed-loop self-healing systems that can localize damage and optimize the triggering of repair processes.

However, some important questions persist. The scaling of healing approaches from the lab level to the industrial scale requires effective process engineering. Healing effectiveness must be proven under the combined influence of electrical, thermal, and mechanical loads. There is an urgent need for standard test procedures for evaluating the healing efficiency. In addition, there is a need for an efficient characterization of the stability of dynamically changing bond networks under various stresses. From the perspective of the future, the combination of advances in molecular engineering, nanotechnology, the sustainability challenge, and AI-aided design would lead to the development of a smart dielectric material that would not only heal itself but would also self-diagnose and adapt to service conditions.

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## Author Contributions

Mohammad Mazedul Islam: Methodology, formal analysis, writing (original draft). Neel Hasan: formal analysis, writing (original draft). Ahmed Sharif: conceptualization, methodology, formal analysis, resources, supervision, writing (original draft).

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**Data Availability Statement**

Data supporting this study is included within the article.

**AI-Assisted Technologies Statement**

We used Grammarly to check the grammar, spelling, and punctuation of this document. The tool was used exclusively for proofreading and copyediting assistance. The authors have thoroughly reviewed and edited the AI-assisted text to ensure its accuracy and accept full responsibility for the content of the manuscript.

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