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REVIEW OPEN ACCESS

Advances in Polymeric Insulating Materials: Global Progress in These 10 Years

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ABSTRACT

This journal, *High Voltage*, celebrates its 10th anniversary in 2026. To commemorate this significant milestone, this comprehensive special review article showcases the latest global research progress and cutting-edge advancements in polymeric insulating materials, a critical component that underpins high-voltage systems and is vital to modern infrastructure. The analysis of the literature on polymer insulating materials produced over the period from around the world was conducted by 11 researchers and presented on a regional basis. Distinctive research can be highlighted in different places, such as materials for power generation and transmission in the Nordic region, charge transport and space charge in France, molecular design in China, and revitalised current integration methods in Japan. The survey reveals that research on winding insulation in rotating machines has been highly active over the past decade due to advancements in power electronics. Particularly notable is the attention given to partial discharges under low pressure related to the development of electric aircraft. Additionally, solid insulation in cables and other components of high-voltage direct current (HVDC) transmission systems and other emerging themes, such as green, lower-carbon insulation, have attracted interest. Materials such as polypropylene-based blends for HVDC applications, multilayers in aeronautic cables and polyimide-based nanocomposites for windings and power module packaging have been particularly investigated. The importance of research using computer-aided methods, such as numerical analysis, computational science, materials informatics, neural networks, and machine learning, has been steadily growing.

1 | Introduction

Epoxy resin was first patented in Germany in 1934 [1]. Polyethylene (PE) became more affordable after Ziegler–Natta catalysts were introduced into the production in 1953 [2]. This shows that the study of the electrical insulating properties of organic polymer materials has a long history. However, many unknown phenomena still exist in the electrical insulating properties of polymers, and much research is still being done. Furthermore, much research has recently been conducted to address various challenges. Typical topics are research on the

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emergence of new equipment, such as smart grids and electric vehicles/aircrafts supported by advances in power electronics, and new research methods related to digital technology, machine learning, and artificial intelligence (AI). In addition, needs to cope with environmental issues such as global warming, zero-carbon-emission, environmental friendliness, recyclability, and harsh environments such as space, radiation environments, and cryogenic temperatures are also increasing.

With this background, it is quite valuable to summarise the progress of global research on polymer insulating materials over the past decade to commemorate the 10th anniversary of *High Voltage*. Therefore, at the initiative of Y. Ohki, this review paper presents an overview of research around the world surveyed by 11 researchers, each representing different regions and countries.

Figure 1 shows an overview of the research carried out during this decade and summarised in this work. The research has been driven mainly by needs in applications to insulation in power systems. Advances in polymeric materials production are considered, along with the way materials can be modelled and characterised and their failure anticipated using improved techniques. The review also addresses how materials are incorporated into systems and how the insulation of such systems can be designed, tested and validated to impart a long service life. Although the primary focus is on conventional polymeric insulating materials, selected functional polymer dielectrics are also considered when their fabrication, charging, dielectric characterisation, or application is directly connected to high-voltage (HV) engineering and insulation diagnostics.

The survey is presented by grouping large geographical regions, and ordered from east to west. The way the different regions have contributed to these different research topics is briefly discussed.

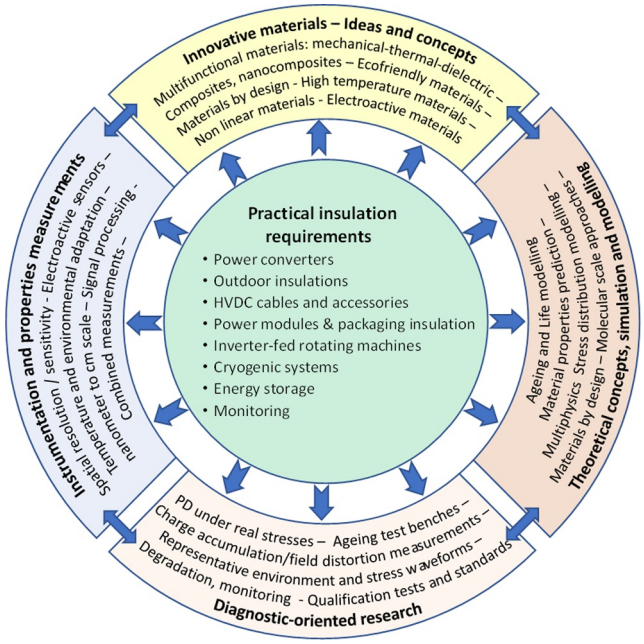


FIGURE 1 | Outlook of research activities carried out in this decade in the field of insulations for power equipment. The research is driven by different application fields.

2 | Research Progress in the Last Decade

2.1 | Japan

This section reviews the latest research activities carried out by various institutions in Japan.

Waseda University: Waseda University has been one of the leading institutions in research into polymer insulating materials since the late 1960s, when research began in Japan. Since Prof. Kichinosuke Yahagi passed away in 1985, Prof. Yoshimichi Ohki has led the research, but he also retired in March 2025. Unlike many other researchers, he has also done extensive research on the properties of inorganic dielectric materials and device development [3]. Over the past decade, his research on polymer insulating materials has focused first on nanocomposites (NCs). As shown in Figure 2, the glass transition temperature and electrical conductivity of the resin vary significantly depending on the type of nanofiller added. This clarifies that the effect of the minute amount of filler added extends to the resin itself and provides an explanation for the insulating property improvement effect of NCs [4].

He has received large-scale research funding from the Nuclear Regulation Authority in Japan and is involved in research examining the insulation integrity of cables used in nuclear power plants (NPPs). In this research study, he demonstrated that the current integration method, although rooted in a simple principle [5], is highly effective for evaluating insulator integrity. For example, the research study indicates that the volume resistivity (ρ) of silicone rubber (SiR) or SiR-insulated cable increases with thermal ageing and further increases when the sheet or cable is exposed to the amounts of radiation exposure and steam exposure anticipated during the design-basis event. ^{29}Si nuclear magnetic resonance (NMR) analyses revealed that the increase in ρ is due to the cross-linking of SiR. Therefore, we do not need to worry about the insulation degradation of SiR in NPPs [6]. Since April 2025, Professor Yasuhiro Tanaka's group

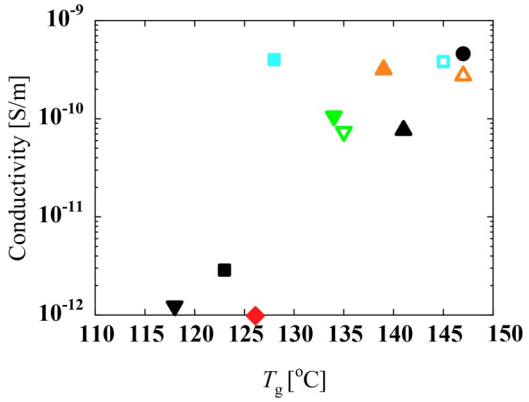


FIGURE 2 | DC conductivity (σ) at 160°C measured for various epoxy resin NCs with MgO nanofillers as a function of the glass transition temperature (T_g) [4]. MgO, magnesium oxide; NCs, nanocomposites.

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at Tokyo City University has been conducting this research on the insulation integrity in NPPs after the retirement of Y. Ohki.

At Waseda University, there was also Professor Toshikatsu Tanaka, who came from the Central Research Institute of the Electric Power Industry. Although it has been more than 15 years since he retired from the university, he has continued to be very active in research. Regarding NCs, in addition to reviewing research [7], he has proposed a novel theory that nanofillers act as quantum dots [8], and is actively involved in machine learning and other fields, leading the younger generation of researchers.

The University of Tokyo: At the University of Tokyo, there is a research group headed by Professor Akiko Kumada, who currently serves as President of the IEEE Dielectrics and Electrical Insulation Society (DEIS). This group is exploring a broad spectrum of research, from gases to solid insulators, by blending advanced measurement techniques with molecular design and insulation diagnosis. They are leveraging modern digital technologies, including AI and machine learning, to push the boundaries of innovation.

Young members of the group, Shimakawa et al. have combined materials informatics, molecular simulation, quantum-chemical descriptors, filler properties, and experimental metadata to develop a machine learning framework for predicting thermal and electrical conductivity [9], clarified the important role of ion-polymer interactions in ion hopping transport [10] and further demonstrated that adjusting the charge distribution of side chains can improve thermal transport without reducing mobility [11]. These findings show that blending computational methods, data science and experiments leads to the efficient development of advanced polymer insulating materials, as shown in Figure 3.

To enhance motor efficiency, pulse-width-modulation (PWM) based inverter drives are essential, but their steep voltage waveforms intensify insulation challenges. Their research addresses these issues in both stator coils and gel-based encapsulation materials. They developed a Pockels-effect-based potential measurement technique using a bismuth germanate ($Bi_4Ge_3O_{12}$, BGO) crystal [12] and performed transient simulations [13], leading to a method for suppressing localised heating in stress-grading systems under the application of PWM. This work forms a compact framework for diagnosis, modelling, and mitigation of insulation stress in inverter-driven rotating machines [14]. In parallel, they studied degradation mechanisms in silicone gel. After clarifying potential distribution and creeping discharge behaviour at the gel/solid interface [15], they showed that repetitive impulses induce electrical treeing [16]. Recent work by Umemoto et al. further demonstrated how moisture and waveform shape affect partial discharge (PD) characteristics [17], contributing to a unified understanding of gel insulation degradation.

In addition, they measured the temperature dependence of the surface charge of a DC gas-insulated switchgear (GIS) with a simulated epoxy resin model spacer and found that the electric field significantly increases due to polarity reversal and homocharge accumulation, especially at high temperatures [18]. Furthermore, they simulated this result using a bipolar charge transport model, which considers charge trapping, de-trapping, and recombination. They concluded that the experimental results are understandable by assuming high-density deep traps [19].

Regarding epoxy NCs, Nakamura et al. in Professor Kumada's group have directly visualised the initiation and propagation of electrical trees using advanced X-ray phase-contrast imaging [20], elucidating the effects of nanofillers on tree propagation and PD activity, and demonstrating the tree propagation suppression effect of nanofiller dispersion [21], highlighting the promising potential of epoxy NCs as insulation systems for next-generation HV equipment.

Nagoya University: At Nagoya University, which has long been a polymeric insulating materials research centre in Japan, Professors N. Hayakawa and H. Kojima are leading the research. First, they are receiving large-scale research funding from the government and conducting joint research with electrical equipment manufacturers to reduce the size of gas-insulated power equipment, including GIS. Specifically, they are attempting to apply functionally graded materials (FGMs), which change the physical properties of the spacer locally, to mitigate the electric field enhancement that occurs in the triple junction consisting of conductors, spacers, and gas, such as GIS.

Specifically, as shown in Figure 4, they have developed a method for producing insulating spacers with distributions of

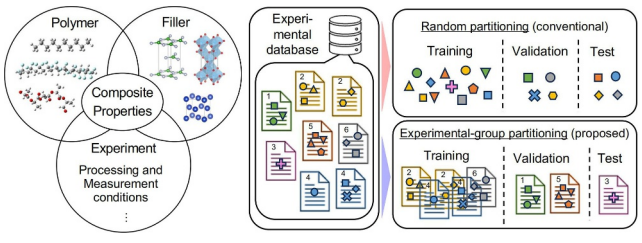


FIGURE 3 | Metadata-integrated machine learning framework for polymer NCs. Processing and experimental conditions are utilised to predict material properties while preventing data leakage and improving transferability [9]. NCs, nanocomposites.

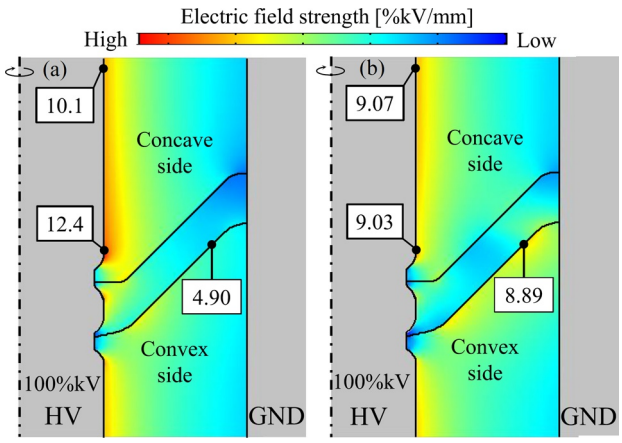


FIGURE 4 | Electric field distribution of the developed cone-type ε-FGM spacer for GIS: (a) Uniform spacer, (b) ε-FGM spacer [22]. FGM, field-grading material; GIS, gas-insulated switchgear.

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permittivity and electrical conductivity by ejecting multiple composite materials with different values of these properties from their respective storage tanks, mixing them while continuously and arbitrarily changing the blending ratio, and then heat-moulding the final mixture in a casting mould [22]. For example, filling an epoxy resin with 26.9 vol% strontium titanate, having a relative permittivity of 332, and 13.4 vol% SiO_2, which has a low permittivity, produces a composite with a relative permittivity of 12.7. The maximum electric field of a GIS spacer is reduced by 27% by casting this composite and an epoxy composite filled with 41.7 vol% SiO_2, while changing their mixing ratio spatially. The breakdown voltage (BDV) of this spacer in 0.6 MPa-abs sulphur hexafluoride (SF_6) was demonstrated to be 28% higher than that of a conventional spacer, enabling a 30% reduction in GIS pipe diameter and a 50% reduction in cross-sectional area and volume [23]. They are developing an insulating spacer with inclined permittivity and conductivity, making it suitable for DC GIS applications [24].

Furthermore, intending to apply traditional aircraft lubricating oils as a cooling and insulation fluid of electric aircraft motors, they are investigating the dielectric breakdown characteristics as a function of flow rate and temperature and found that in the assumed operating environment of aircraft motors, the dielectric strength of the lubricating oils is equal to or greater than that of mineral oil. The application of lubricating oil insulation is expected to lead to higher voltages and higher power densities in electric aircraft motors [25].

Their research also focuses on the applicability of cellulose nanofiber, a biomass-derived, low-environmental-burden material, as an insulating material for rotating machinery. The PD inception field and breakdown field of moulded plates are negatively correlated with thickness and environmental humidity. In the future, they will further refine the porosity to maintain dielectric strength and reduce permittivity [26].

Tokyo City University: In the mid-2010s, Professors Yasuhiro Tanaka and Hiroaki Miyake of Tokyo City University, along with Professor Emeritus Tatsuo Takada, introduced band calculations using molecular orbital methods to study traps and charge behaviour in polymer insulating materials [27]. This is a pioneering study, along with that of Huzayyin et al. [28] and others, and is important in that this method has been widely used around the world, especially in China, mainly by their ex-students who returned to China, as a way to explain space charge distribution measurements [29].

In addition, as the laboratory that developed the pulsed electroacoustic (PEA) method, they have made it possible to simultaneously measure PEA and leakage current or thermally stimulated current, or to measure PEA under electron or proton beam irradiation [30]. They also developed a PEA device capable of measuring up to 150°C, and measured the space charge distribution accumulated in epoxy resin and analysed the effect of curing agents using the molecular orbital theory [31].

Furthermore, they have developed a PEA method that applies voltage pulses synchronized with the applied voltage, and are investigating the charge distribution that accumulates when a DC, AC or square-wave voltage is applied to polyimide (PI) and epoxy resins used for insulation in power modules at high temperatures, such as 150°C and 500 Hz [32]. In addition, by measuring the space charge distribution in a sample to which a voltage is applied through a gap, they are attempting to prove that the space charge accumulated inside voids in the sample reduces the PD inception voltage [33].

Moreover, as already mentioned, they re-vitalised the current integration method and demonstrated its usefulness, sometimes by combining it with the PEA method to evaluate the insulation behaviour of cable and its joint. Figure 5 depicts how space charge accumulates at the interface between low-density polyethylene (LDPE) and ethylene propylene rubber (EPR) [34].

Toyohashi University of Technology: At Toyohashi University of Technology, research has been conducted by Professor Emeritus Naohiro Hozumi, who retired in March 2023, and his successors, Professor Yoshinobu Murakami and Associate Professor Tomohiro Kawashima. As for the PEA method, they improved acoustic matching between the polymer insulator and the acoustic detector by introducing a polymer acoustic coupler, which boosted sensitivity to four times that of conventional aluminium couplers. This made it easy to perform long-term continuous space charge measurements even with heat cycles in thick ultra-high voltage (UHV) cable insulations [35]. In addition, they have enabled two-dimensional PEA measurements by electrically or mechanically scanning the sensor [36].

Second, they enabled measurement of the voltage-dependent space-charge distribution within a sample using the PEA method by implementing the following three improvements [37]. (1) The bias voltage and the acoustic response signal are correlated to obtain the reference waveform at any time, allowing charge density calibration. (2) The reference waveform can be obtained by extracting only the frequency components where the space charge cannot follow the bias voltage. (3) Stable signal processing using numerical Laplace deconvolution has been made possible.

Third, in the charge microscopy developed as an application of the PEA, a polymer acoustic coupler was used to minimise aberrations, allowing three-dimensional space charge measurements and charge spreading observation across the interface between different insulators [38].

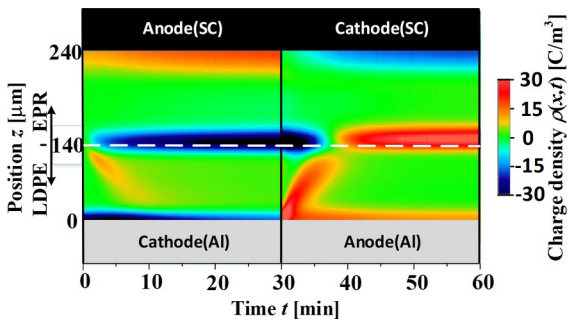


FIGURE 5 | Space charge accumulation at the LDPE/EPR interface [34]. EPR, ethylene propylene rubber; LDPE, low-density polyethylene.

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In PD measurement, unlike the traditional method of linking the discharge pulse peak value to the AC voltage phase angle at that moment, they can now connect features such as the rise and fall of the waveform on the ns scale to the defect shape. This is done by observing all discharge pulse waveforms using digital measurement technology [39]. Their research has also made it possible to identify the waveform using deep learning [40].

Furthermore, they have opened up the possibility of fabricating heat-dissipating composites with electrical and thermal properties applicable to automotive power modules by fabricating composites of thermoplastic PI and oriented hexagonal boron nitride (hBN) using an electrostatic adsorption method that allows for easy control of the composite structure as depicted in Figure 6 [41].

University of Hyogo: Professor Yusuke Kikuchi of the University of Hyogo is currently the chairman of the Investigation Committee, dealing with inverter surge insulation in motors, at the Institute of Electrical Engineers of Japan. For this reason, his group is primarily working on this issue. They are using a power supply developed by venture company Nexfi Technology, which can simulate surge voltage pulses occurring in SiC inverter-driven motors, with a high repetition rate and high dV/dt (V: voltage and t: time) [42]. They found that the repetitive partial discharge inception voltage under inverter surges in twisted pairs decreases and approaches the single partial discharge inception voltage (PDIV) when the pulse repetition frequency reaches several tens of thousands of pulses per second, as shown in Figure 7 [43].

Ehime University: The group of Professors Kazunori Kadowaki and Ryotaro Ozaki at Ehime University has also been active. First, they have confirmed through both experiments and simulations that space charge packets formed in LDPE stagnate because the mobility of charge carriers decreases as the electric field increases [44]. In addition, for measuring space charge distribution using the PEA method, they have developed a stepped electroacoustic (SEA) method that does not require deconvolution, based on the principle that if a step-function pressure wave is generated from the space charge and measured using a detection system with a time-differential function, a steep and nonbounced impulse response can be obtained. They have actually succeeded in measuring the space charge distribution in a distribution cable [45]. Furthermore, by adopting the SEA method with a piezoelectric sensor thicker than the sample, they have succeeded in a direct observation of the electric field distribution within a polymer insulating material [46]. They have also succeeded in reproducing the attenuation in a polymer insulator of the propagating pressure wave, generated from space charge, by simulation using a viscoelastic model [47].

In addition, they demonstrated that a software-assisted current integration method [5], which integrates the output of an ammeter, can perform equivalent analysis to the current integration method in a study of the charge behaviour of a 6.6 kV CV cable [48]. In Japan, crosslinked polyethylene (XLPE)-insulated cables are called CV cables.

National Institute of Technology, Matsue College: Professor Masumi Fukuma at the National Institute of Technology, Matsue College, developed an advanced two-dimensional current integration metre. It features an upper electrode with 60 needles and a lower plane electrode, capable of simultaneously monitoring electric current distribution at 60 different points in an epoxy resin sample [49]. Furthermore, he investigated the time lag in formation and the voltage dependence of space charge in polypropylene (PP) by applying low-frequency trapezoidal voltages with varying peak values [50].

Osaka Research Institute of Industrial Science and Technology (ORIST): Kitani's team at ORIST has been diligently developing equivalent circuits to replicate results obtained through the current integration method for various polymer insulating materials, such as PI [51, 52]. Their work has shed light on how initial state disturbances, such as residual space charges, can affect the measurement results.

Kyushu Institute of Technology: Professor Masahiro Kozako's laboratory at Kyushu Institute of Technology is equipped with full-scale HV power generators. It has also advanced PD and high-frequency measurement facilities for evaluating the insulation reliability of various types of electric power apparatus, inverter-fed rotating machines and power modules. Its distinctive feature is the capability to generate inverter surge voltages with extremely fast voltage rise rates, often referred to as high dV/dt, which have become increasingly important with the widespread use of SiC and GaN power devices. Using these facilities, the laboratory investigates the comprehensive

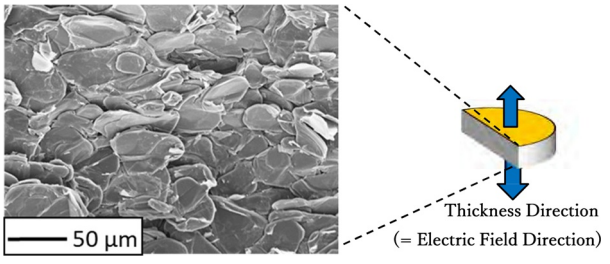


FIGURE 6 | SEM image of a fractured surface of the composite with the hBN plane oriented parallel to the electric field direction [41]. hBN, hexagonal boron nitride.

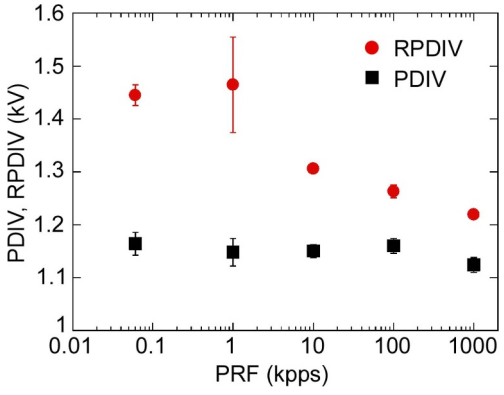


FIGURE 7 | Dependences of PDIV and RPDIV on the PRF [43]. PDIV, partial discharge inception voltage; PRF, pulse repetition frequency; RPDIV, repetitive partial discharge inception voltage.

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characteristics of PD, insulation degradation, and lifetime, as well as the propagation of high-frequency signals under practical operating conditions. The laboratory is also actively developing advanced insulating materials, including polymer NCs and inorganic dielectrics, investigating their dielectric properties, PD and electrical breakdown phenomena, and degradation mechanisms under high-temperature and high-electric-field conditions. Leveraging its experimental facilities, it conducts large-scale collaborative research with various industrial partners, including electric power utilities, thereby contributing to the practical development of next-generation HV insulation technologies [53, 54].

Summary: Japan is the country that invented the PEA method and revolutionised the current integration method, and this is reflected in recent research trends. First, Tokyo City University, which has played a pivotal role in the development of both methods, has made it possible to apply both methods under harsh conditions such as at high temperatures (currently up to 150°C), under electron beam and proton irradiation, and with thin samples of around 25 μm, thereby meeting diverse needs such as those in power electronics applications. Second, Toyohashi University of Technology has achieved accurate high-speed calibration of PEA results by developing innovative signal processing methods and equipment applicable to actual-scale UHV cables and connectors. Ehime University has developed a modified PEA method using a long pulse width, making it possible to easily determine space charge distribution and electric field distribution without complex signal processing. Waseda University has contributed to the current integration method through its active use in large-scale national projects, raising awareness of its high practicality, and has promoted the software-assisted current integration method, together with Ehime University. National Institute of Technology, Matsue College has contributed to the method by creating a measurement device capable of fine two-dimensional measurement, and the ORIST has established a programme to interpret measurement results using circuit model analysis.

In other research areas, while institutions such as Nagoya University, Toyohashi University of Technology, University of Hyogo, and Kyushu Institute of Technology are working to resolve current challenges regarding various power equipment and devices, universities such as the University of Tokyo and Waseda University are pursuing theoretical research by leveraging methods such as quantum mechanical calculations and machine learning. Consequently, Japan is producing results in both practical achievements directly applicable to industry and theoretical sides.

2.2 | China

This section reviews the latest research activities carried out by various institutions in China.

Xi'an Jiaotong University: As a pioneering institution in electrical insulation research, Xi'an Jiaotong University has been deeply engaged in the field of electrical insulation since the 1960s, nurturing a large number of professionals for China and delivering a series of academic outcomes. For polymer insulation materials, Professor Shengtao Li has led and conducted in-depth research, which achieves various breakthroughs.

In the past decade, he has concentrated on the research of high-voltage direct current (HVDC) cable insulation. His achievements reveal that the XLPE of different chain structures optimises DC conductivity characteristics across different dimensions, which matches different application environments. Crosslinked polyethylene with short chains contributes to a notable reduction in DC conductivity at elevated temperatures, whereas crosslinked polyethylene with long chains demonstrates an enhanced cross-linked network and increases the voltage coefficient [55].

The early applications of PP-based insulation were mainly developed in Japan through PP laminated paper insulated cables, whereas Europe, especially Italy, pioneered the commercialisation of extruded modified PP insulated power cables. Recent researches in South Korea have made significant progress in developing high-temperature PP-based insulation materials for advanced power cable applications. Korean researchers have demonstrated that blending with highly packed elastomeric domains can improve the dielectric insulation characteristics at elevated temperatures [56]. They also introduced trace amounts of polyvinylidene fluoride (PVDF) into PP to construct deep trap and inhibit charge transport, which effectively improves the high-temperature DC breakdown strength of PP-based dielectrics [57].

To align with the development of green and low-carbon power equipment, Sui's group has also conducted a mechanistic study on the insulating properties of PP. It is confirmed that compared with XLPE, PP is more prone to insulation deterioration under small stress [58], which is manifested as a lower elastic limit strain ε_e. As shown in Figure 8, when the strain is below ε_e, the amorphous layer thickness of PP increases and its breakdown strength only exhibits a slight decrease. Although the strain exceeds ε_e, a large number of microvoids can be observed in PP, leading to a sharp rise in carrier mobility and an abrupt deterioration in breakdown strength [59].

Based on this insulation deterioration mechanism, the incorporation of elastomers into PP can significantly enhance ε_e [60]. Therefore, XLPE remains robust for conventional applications, whereas PP is the candidate for future HVDC systems.

Tsinghua University: The group of Professor Qi Li at Tsinghua University conducts fundamental and applied investigations focused on dielectric polymers, with particular emphasis on energy-storage and energy-conversion technologies [61–63]. In their most recent contribution, published in *Nature Materials*, they delineated the charge-transport mechanisms operative in dielectric macromolecules under simultaneous high-temperature and high-electric-field extremes [64]. Leveraging supramolecular design principles, the authors engineered a class of polyrotaxane-structured dielectric polymers that functioned as intrinsic 'molecular dampers'. As shown in Figure 9, the mechanical bond formed between crown-ether macrocycles and PI backbones enables the conversion of vibrational energy into elastic potential energy, thereby suppressing localised segmental motions and phonon-assisted interchain charge transfer at elevated temperatures [64]. The deployment of such materials is

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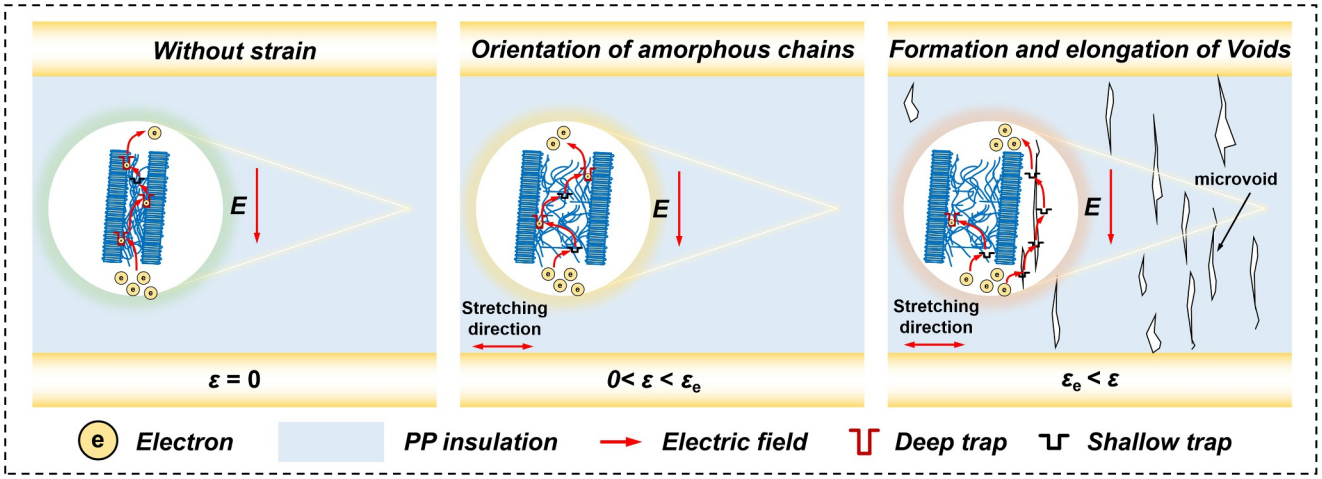


FIGURE 8 | Schematic illustration of the structural evolutions and carrier transport with increasing strain [59].

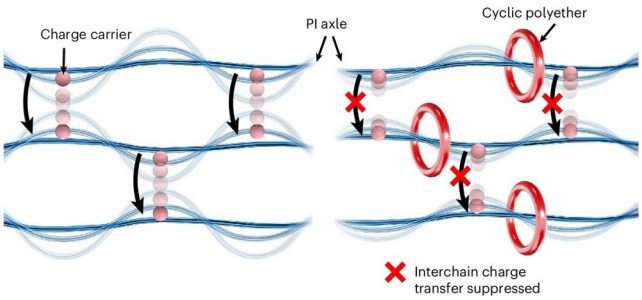


FIGURE 9 | A schematic diagram showing suppressed charge conduction by restricting molecular chain vibration [64].

expected to transcend the conventional thermal and power ceilings of electrical apparatus and electronic devices, concomitantly effecting a substantial reduction in thermal-management expenditure.

Huazhong University of Science and Technology: In recent years, Professor Xiaolin Xie from Huazhong University of Science and Technology has made significant progress in the field of electronic packaging insulation. His research demonstrates that the introduction of fillers such as spherical α-Al_2O_3 and nanosilica/silver nanowires into the traditional epoxy matrix can effectively ensure filler dispersibility. Although improving the thermal and mechanical properties, this modification can further reduce the dielectric loss of the packaging materials [65, 66], making it have a wider range of applications.

North China Electric Power University: At North China Electric Power University, there is a research group headed by Professor Yang. They have targeted the abrupt escalation of leakage loss in dielectric films under simultaneous high-temperature and high-field stress [67]. By implementing a surface-structure reinforcement strategy for polymeric dielectrics, as shown in Figure 10, the team successfully suppresses electrode charge injection under these extreme conditions. The discharge energy densities of the H-Al_2O_3/polyetherimide film with an efficiency of ~90% at 150°C (6.57 J/cm^3) and 200°C (4.22 J/cm^3) achieved in this work outperform those of most of the previously reported results for PEI-based composites [68–71]. The concept of using anions to regulate the electrode/dielectric interfacial charge

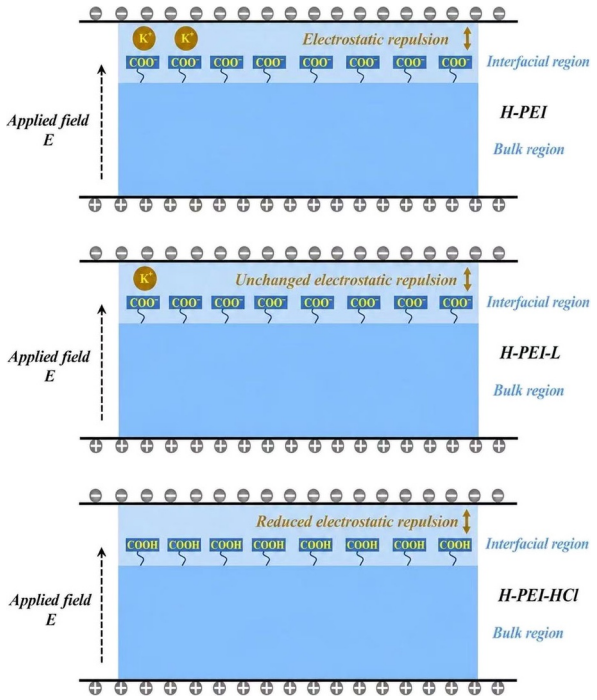


FIGURE 10 | Schematic illustration of electrode/H-PEI films' interfacial charge transport behaviour [67]. PEI, polyetherimide.

transport could be easily extended to other polymer dielectrics for high-temperature capacitive performance.

Harbin Institute of Technology: Harbin Institute of Technology mainly focuses on the insulation issues in wireless communication and flexible electronics. The group of Professor Jiaqi Zhu incorporates poly-(diallyl dimethyl ammonium chloride)-functionalised nanodiamond (ND@PDDA) into the aramid nanofiber (ANF) with high thermal conductivity, which effectively addresses the inherent agglomeration issue of conventional fillers. When 50 wt.% of ND@PDDA is introduced, the composite film achieves an obvious reduction in dielectric constant, while still maintaining excellent properties in terms of volume resistivity and dielectric loss [72]. His research findings have well catered to the application requirements in the relevant fields.

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China Electric Power Research Institute: China Electric Power Research Institute has conducted a series of research on HVDC cables and has also participated in the formulation of several standards for the Chinese power industry [73, 74]. For the ethylene-propylene rubber (EPDM) used in reinforced insulator of HVDC cables, the group of Professor Benhong Ouyang adds Ag nanoparticles grown on ZnO nanosheets (ZnO@Ag) into EPDM. This modification enables the ZnO@Ag/EPDM composite to exhibit nonlinear resistivity without a sharp decline in its breakdown strength. Consequently, the electric field distortion of stress cone is alleviated, thereby optimising the whole insulation performance of HVDC cables [74].

China Southern Power Grid Electric Power Research Institute: China Southern Power Grid Electric Power Research Institute is primarily devoted to power-system-equipment simulation testing and HVDC transmission technologies. Under the leadership of Wenbo Zhu, a high-temperature magnetron-sputtering protocol was implemented to functionalise polytetrafluoroethylene (PTFE), as shown in Figure 11 [75]. Modified PTFE specimens with systematically varied sputtering durations were fabricated, and their DC surface discharge, surface flashover and electrical ageing characteristics were comprehensively characterised over the temperature range 20°C–200°C. The synergistic influence of magnetron-sputtering modification and elevated temperature on the underlying insulation mechanisms was elucidated. Experimental evidence reveals that surface discharge intensity increases monotonically with temperature, whereas magnetron-sputtering surface engineering significantly suppresses PD activity. Flashover voltage exhibits a non-monotonic dependence on sputtering time, initially increasing and subsequently decreasing. Magnetron-sputtering modification accelerates surface potential decay, augments shallow-trap density, effectively inhibits charge accumulation, suppresses localised discharges [76, 77], and thereby enhances both surface electrical insulation performance and resistance to ageing.

Tianjin University: The research group led by Professor Boxue Du and Professor Meng Xiao at Tianjin University has focused on improving the dielectric performance of PP films under high-temperature and high-electric-field conditions for advanced film capacitor applications. By introducing long-chain branched structures into PP, the group regulated molecular chain entanglement and crystallization behaviour, thereby improving the breakdown strength and energy storage performance of metallised PP capacitor films [78]. Furthermore, the group developed ultraviolet irradiation modification strategies to construct stable polymer networks, suppress charge transport and enhance the dielectric stability of PP films [79]. In addition, functional molecular modification and blending approaches, including furan-functionalised PP and cyclic olefin copolymer/PP composites, were employed to regulate trap distribution, inhibit charge migration, and optimise polarization behaviour, resulting in improved dielectric performance under elevated temperatures [80, 81].

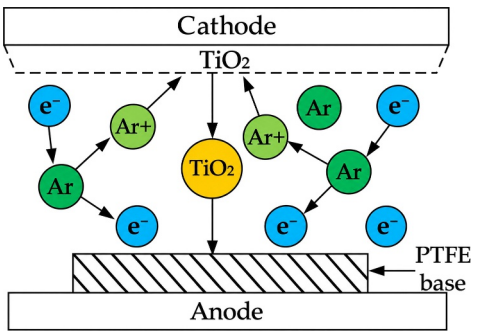


FIGURE 11 | Working principle of magnetron sputtering [75].

Chongqing University: At Chongqing University, Professor Jian Li and his research team have focused on the development of environmentally friendly vegetable insulating oils for HV transformer applications [82]. The group improved the operational stability of vegetable insulating oils, the team proposed ester exchange modification and antioxidant regulation strategies to optimise molecular structures, suppress oxidation reactions, and enhance dielectric reliability under long-term electrical stress [83]. Furthermore, the team incorporated exfoliated h-boron nitride nanosheets (BNNSs) into vegetable insulating oil, which increased electrical resistivity, reduced dielectric loss, and promoted the formation of efficient thermally conductive pathways through electric-field-induced nanosheet alignment. As a result, the composite insulating oil achieved simultaneous enhancement in electrical insulation and heat-transfer performance [84].

Shanghai Jiao Tong University: At Shanghai Jiao Tong University, Professor Xingyi Huang and his group have focused on the development of advanced thermally conductive yet electrically insulating polymer materials for high-power electrical and electronic applications. The advanced polymer NC films constructed by electrospinning polymer/BNNSs NC fibres, vertically folding the electrospun NC fibres, and subsequent pressing exhibit high thermal conductivity enhancement and outstanding flexibility. The NC films exhibit thickness dependent in-plane thermal conductivity, which can reach 16.3 W/(m·K) in the 18 μm thick NC film with 33 wt.% BNNSs. In addition, the NC films have superior electrically insulating properties compared with the pristine polymer, such as reduced dielectric loss, increased electrical resistivity and enhanced breakdown strength [85]. Furthermore, the group developed a multilayer poly(vinyl alcohol) (PVA)/BNNS nanonetwork structure by electrostatic spraying of BNNSs onto electrospun PVA nanofibers. The PVA/BNNS NCs achieved an ultrahigh in-plane thermal conductivity of 21.4 W/(m·K) at 22.2 vol% BNNS addition. The overlapping BNNSs established continuous phonon transport channels and reduced interfacial thermal resistance, thereby enabling efficient heat dissipation while maintaining excellent electrical insulation and mechanical flexibility [86].

Wuhan University: At Wuhan University, Professor Ju Tang and his research team have focused on surface modification of solid insulators for improving the dielectric reliability of HVDC insulation systems [87]. By introducing nano-SiC/epoxy functional coatings onto epoxy insulating substrates, the group regulated surface conductivity and trap characteristics, promoting charge dissipation and suppressing surface charge accumulation under high electric-field stresses [88]. The influence of SiC filler content on surface charge accumulation behaviour was systematically investigated, revealing that optimised SiC incorporation can modify surface charge distribution through enhanced trap regulation [89]. Furthermore, the team studied the charge dissipation characteristics of SiC/epoxy coatings and demonstrated that increasing SiC content can

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increase homo-charges and weaken the electric field near the HV electrode. Consequently, because of the improved effect of homo-charges on flashover voltage, the addition of SiC leads to the boost of flashover voltage [90].

Zhejiang University: At Zhejiang University, Professor Xiangrong Chen and his research team have investigated the electrical insulation performance enhancement and charge-transport mechanisms of polymeric insulation materials for HV power cables. The group introduced aromatic voltage stabilizers with tailored electron-withdrawing and electron-donating groups into XLPE. It was found that the addition of the voltage stabilizers enhances DC breakdown strength and inhibits the accumulation of space charges in the XLPE. The results show that the XLPE blend with the addition of 4-n-propylbenzoic acid has a 23.3% increment in the DC breakdown strength compared to that of the reference XLPE among the used voltage stabilizers [91]. The group also compared PP and XLPE under repeated voltage polarity reversal and found that PP contained deeper traps and accumulated substantially less space charge than XLPE, thereby clarifying the potential advantage of PP as a recyclable insulation material for line-commutated-converter HVDC cables [92].

Tongji University: At Tongji University, Professor Zhenlian An and his research team have focused on surface modification of polymeric dielectrics for HV electrical insulation applications. To suppress charge transport under high electric fields, the group employed direct fluorination to form charge-blocking surface layers on polyethylene, which increased interfacial barriers and reduced charge injection and bulk space-charge accumulation [93]. Furthermore, direct fluorination of epoxy insulation was shown to regulate surface conductivity and trap characteristics, significantly suppressing surface charge accumulation and reducing local electric-field distortion along the insulating surface [94].

Beyond the aforementioned institutions, numerous other Chinese universities have also made influential contributions to the field of polymer dielectrics, including but not limited to Hunan University, South China University of Technology, collectively forming the profound and diverse academic foundation of China's research in this area.

Driven by the rapid development of new power systems featuring high penetration of renewable energy and power electronics, advanced polymer dielectric with high-temperature stability, high breakdown strength and electrical insulation performance have become increasingly important. The past decade has witnessed remarkable advancements in polymer dielectric through molecular design in China. In several emerging dielectric material systems, domestic research in China has not only demonstrated strong competitiveness but also begun to show early promise of technological leadership in specific applications.

2.3 | The Nordic Region

2.3.1 | *Outlook*

In the Nordic region, comprising Denmark, Finland, Norway and Sweden, research activities within the area of HV engineering have traditionally been intense and led to number of pioneering developments in energy transmission and generation systems. Fundamental and applied research are carried out in several industrial and academic organisations of the region including few large international companies whose achievements and findings, however, are not widely disseminated for obvious reasons.

The electric power supply system is today trans-national in its nature and will most likely become in the future even more complex. Issues related to the common electricity market, high-voltage alternating-current (HVAC) and HVDC interconnections, security and efficiency of energy supply and rapidly evolving integration of renewable energy trigger the carried-on research and innovations leading to a flora of cooperation projects. Among them are the projects related to the development of new insulation materials, focussed on the required increase in the network capacity that must come from a development of new insulation systems, with a demand to further raise their operating electric and thermal stress levels.

2.3.2 | *Sweden*

Chalmers University of Technology, Royal Institute of Technology and Borealis: In the joint projects of these institutions the focus has initially been on XLPE and the desired progress achieved by producing the material with fewer impurities, reducing this way the negative effects imposed by the presence of contaminants and crosslinking byproducts. In the longer run, this approach became ineffective, mainly due to high costs involved in making the material purer. Instead, the possibilities provided by using small additions of voltage stabilizers and nanofillers were checked by testing electric withstand capability and resistance to degradation by electrical treeing (illustrated in Figure 12) as well as evaluating their impact on electrical conductivity. Several promising stabilizers of benzil-, thioxanthone-, fullerene- and melamine-types have been identified and characterised. Majority of them exhibit positive impact on the resistance to electrical treeing in XLPE, ranging from 20% up to

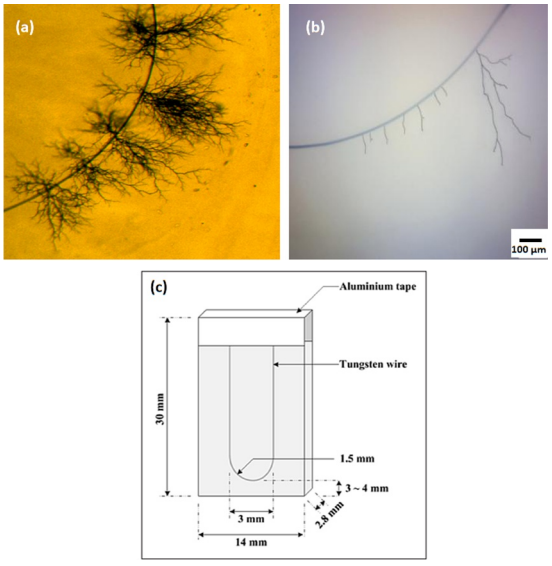


FIGURE 12 | Appearance of electrical trees grown under (a) AC and (b) DC voltages in (c) samples of tested material compositions with embedded tungsten wire electrodes.

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well above 100% of the increased tree initiation field and correlating these results with electronic properties of the stabilising molecules indicate that electron scavenging plays here the dominant role [95–99].

The addition of nanofillers to XLPE also yields a similar, though not equally strong effect [100–104]. More recently, research has focused on thermoplastic ternary blends (PE/PP/styrenic) that combine excellent recyclability with a very low electrical conductivity, making them promising candidates for HVDC cable insulation [105–108]. In parallel, significant effort has been directed towards developing byproduct-free curing routes for polyethylene copolymer blends to eliminate peroxide residues and outgassing while maintaining high insulation performance [109, 110].

Chalmers University of Technology also collaborates with other companies on the development and implementation of innovative material solutions based on polyetheretherketone for slot liner insulation of electric motors for electromobility [111]. Moreover, Kapton-based films and laminates for magnet wires/busbar insulation and slot liners are being advanced [112]. These provide advantages over traditionally used materials, in particular, high dielectric strength, low losses and reduced thickness and allow designing more compact and efficient electrical propulsion systems.

ABB, Hitachi Energy, NKT, Royal Institute of Technology and Chalmers University of Technology: Another direction of the Swedish research has concentrated on FGMs for HVAC and HVDC cable accessories. Earlier, the research focused on the use of SiC particles, where detailed studies revealed that the nonlinear current–voltage characteristics originated from Schottky-type potential barriers formed between the particle contacts [113]. Particle size, doping level and moisture were shown to influence the effective height of the barrier and the onset of nonlinearity, providing a physical basis for interpreting the behaviour of percolated SiC–polymer composites used in HVDC accessories [114, 115].

A major conceptual shift occurred with the introduction of nanostructured fillers such as graphene oxide (GO), reduced graphene oxide (rGO) and graphene nanoplatelets. The latter, in extruded LDPE NC, offers additionally various unique properties [116, 117]. In silicone matrices, percolated networks were obtained at loadings below 3 vol%, giving rise to sharp nonlinear transitions and well-defined conductivity saturation at high fields [118, 119]. Further advances were made through polymer-grafted rGO or polymer-grafted ZnO nanoparticles [120, 121]. Controlled graft lengths allowed precise tuning of inter-flake distances and hopping barriers, producing sharply defined nonlinear resistivity drops followed by stable saturation. These systems required far lower filler loadings than conventional SiC-based field-grading compounds. The most recent developments involve use of geometrically engineered ZnO tetrapods. Their anisotropic shape ensures strong local field enhancement at the tetrapod tips, guaranteeing that at least one arm remains favourably oriented relative to the applied electric field [122]. Currently, also composites based on EPDM rubber dopped with an organic filler, of volume fractions above the percolation threshold, are in focus, which demonstrate significant variations of dielectric properties with the applied electric field strength and temperature [123] and allow to tailor them for specific conditions of the cable operation.

2.3.3 | *Finland*

VTT Technical Research Centre of Finland and Tampere University (TAU): These institutions have placed particular emphasis on advancing PP-based insulation materials for HV applications. In the EU Horizon 2020 project GRIDABLE, nanostructured PP–silica insulation materials were developed for HVDC cable and capacitor applications (Figure 13). Special focus areas were improvements in space charge accumulation and breakdown strength by optimization of trap depth distribution and charge mobility. Chemical surface functionalisation of the silica nanoparticles was in central role, providing pathways to effective dispersion of nanoparticles in the host polymer matrix in up-scaled insulation compounds. The final manufactured medium voltage (MV)-sized demonstrator cable showed excellent dielectric performance in type tests compared to the XLPE reference cable and good dispersion of nanofiller [124]. For the HV film capacitor demonstrator, successful production of 5.5 μm thick silica-filled biaxially oriented (BOPP-SiO_2) capacitor film was demonstrated on an industrial scale, followed by element winding and assembly into prototype capacitor units. Modified trap density of states (DOS), decreased dielectric losses, reduced charging current and conductivity were demonstrated for the NC films, all of which indicated improved performance through nano structuration. Nevertheless, nanoparticle agglomeration and the associated risk of void-formation upon biaxial stretching of thin films still constitute a challenge for the nanocompounds, as any agglomerates, impurities or voids can mask the overall improvements in dielectric behaviour for large film areas [125, 126]. Building on this, the Horizon Europe project NEWGEN continues thermoplastic HVDC cable insulation development, focussing on space charge mitigation via molecularly defined polymeric additives in PP-based insulation blends. Recent findings show that low concentrations of PP grafted with maleic anhydride and different polar amines can be used as space charge mitigating additives in extruded PP-based HVDC cable insulation [127]. Finally, beyond polymeric insulation, other insulation concepts such as thermally

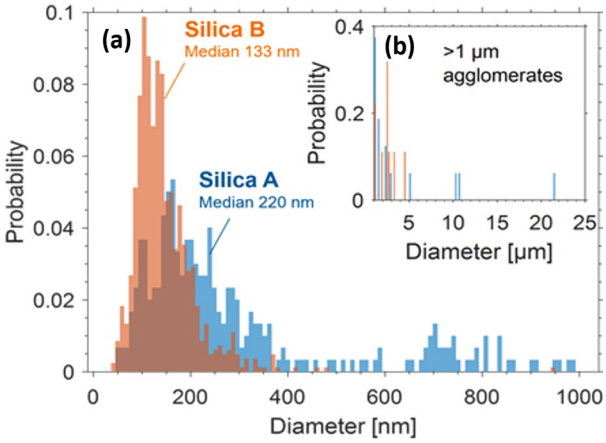


FIGURE 13 | Cross-sectional SEM analysis of PP-based nanocompounds with 2 wt.% of functionalised silica nanoparticles: (a) Silica agglomerate size characteristics derived from several SEM micrographs; (b) focus on large agglomerates [124]. PP, polypropylene.

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sprayed ceramic coatings (which are not extensively studied in the dielectric community) have also been explored by these institutions. Thermally sprayed ceramic coatings do not in general exhibit very high dielectric strength but are easily sprayable on various challenging surface geometries and have high resistance to temperature, chemicals and wear; therefore, they can be used in certain specific applications as dielectric coatings [128].

2.3.4 | *Norway*

Nexans and Chalmers University of Technology: In addition to the above-listed actions, research efforts cooperatively performed by Nexans and Chalmers have concentrated on aspects related to the performance of cable insulation materials, including studies of ageing, degradation and breakdown phenomena under HVAC and HVDC stresses. An important part of the work had also been dedicated to resolving in detail the impact of surface topography (roughness) on cable joint performance. Findings of this work revealed that the extruded insulation surface exhibits localised enhancements of electric field, charge injection and accumulation that shapes unique DC degradation and breakdown patterns (Figure 14). It is also shown that higher levels of polymer surfaces roughness strongly reduce their DC performance [129, 130]. Later work has quantified limited yet still measurable levels of electro-thermal DC ageing on peelings extracted from cable samples before and after HVDC cable qualification test programs, especially pronounced in space charge accumulation measured by means of PEA method [131].

SINTEF Energy Research and Norwegian University of Science and Technology (NTNU): Research of this group has been related to liquid insulation systems, with special focus on the occurrence of a very fast breakdown streamer. This work—together with other international studies—was summed up in an extensive CIGRE study [132]. One pivotal issue concerned the question how pre-breakdown streamers can abruptly accelerate 10 to 100-fold at voltages above breakdown level and how the large differences in this acceleration can arise amongst various commercial insulation liquids. It became clear that working only with mineral oils, consisting of thousands of different molecules, hampered development of the basic understanding of what governs the streamer behaviour. A collaboration with physical chemists allowed to bring in quantum chemistry tools, offering insight into liquid's molecular properties that govern streamer development [133], demonstrating how background fields reduce ionisation potentials of the molecules (Figure 15). A recent study on high field conductivity [134], reveals how threshold for space charge limited currents may occur at sharp voltage flanks and influence local fields. Building on studies of liquids, the group has also focused on insulation behaviour under stresses from fast-switching voltages from power electronic sources, where space charge phenomena play an important role [135].

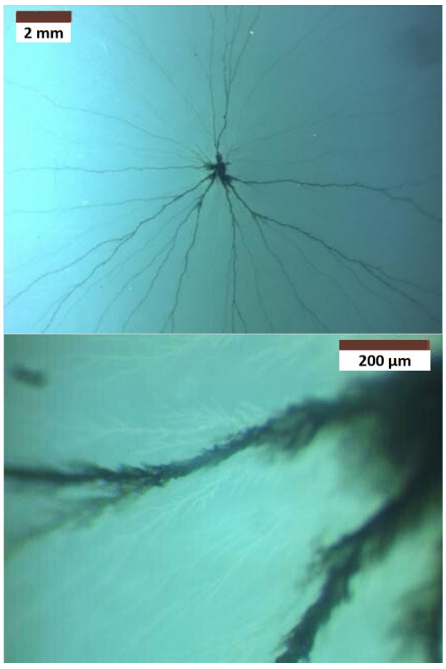


FIGURE 14 | Characteristic pattern of DC breakdown channels in XLPE cable insulation exposed to high electric field with a main radial channel and treeing channels spreading from it outwards. XLPE, crosslinked polyethylene.

2.4 | Central Europe

During the last decade, almost all the relevant departments of the German-speaking Technical Universities plus a few additional groups have been active in researching and developing novel or improved polymeric electrical-insulation materials, and/or new methods and concepts for their investigation, optimisation and application. Most of the recent work is briefly reviewed below in three subsections (Austria, Germany and Switzerland) and in alphabetical order of location within the subsections. In several laboratories, there has been a significant focus on silicone rubbers for HVDC applications and on their space-charge behaviour. In addition, several other materials such as polyamides, XLPE and LDPE, as well as various polymer-based composites and foam-like polymer systems have been considered. In terms of advanced materials processing, 3D printing of polymers for electrical insulation as an example of additive manufacturing, as well as surface treatment for improving interface properties and charge trapping have been studied—often in collaboration with materials scientists. In

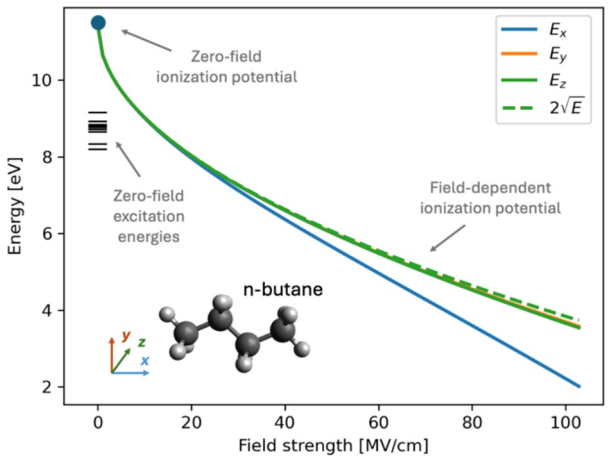


FIGURE 15 | Field-dependent ionisation potential of n-butane molecule for an externally applied electric field along the *x*-, *y*- and *z*-axes. The $2\sqrt{E}$ term is the classical result, included for completeness [133].

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addition to the widely used PEA methods, significantly enhanced laser-induced pressure-pulse (LIPP) experiments with reasonable repeatability have been implemented for detailed investigations of space-charge transport and storage. Last, but not least, polymer-based electrically insulating liquids (oils) and their ageing behaviour, and polymers with self-healing capabilities received considerable attention in Central-European laboratories. The following summary has been kept concise, as all the cited conference papers and journal publications are quite readily available; please consult the original texts for further details.

2.4.1 | *Austria*

Technische Universität Graz (Austria): Among other topics, materials-related research at Graz University of Technology is partially focused on investigating whether medium-voltage alternating-current cables are also suitable for medium-voltage direct-current (MVDC) applications. Such a re-use of existing cables may facilitate higher current-carrying capacity in distribution networks without the need to replace or re-install cables in cities where rising electricity demand (e.g., for e-mobility, heat pumps, etc.) might otherwise be very challenging for the already heavily used underground-cable infrastructure [136, 137].

2.4.2 | *Germany*

Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen: At RWTH Aachen University, dielectric properties and the breakdown strengths of syntactic foams were investigated within the temperature range of liquid nitrogen, that is, for applications with cryogenics—in the present case, for potential use in high-temperature superconducting (HTS) cables [138–140].

Technische Universität Berlin: The Department of High-Voltage Engineering at the Technical University of Berlin focuses an essential part of its materials research on direct, simultaneous measurements of space-charge profiles and polarization/depolarisation currents in SiR. To minimise deformation of the elastomer samples during measurements, the LIPP method has been chosen as the main experimental technique. In comparison to earlier LIPP implementations, the experimental repeatability was significantly improved by use of a spray-coated metal-plate target for the laser pulses. The spray-coated target film which partially evaporates during operation can be replaced automatically between consecutive runs, and the process can be (automatically) repeated many times over a period of several hours. Parameters influencing measurement accuracy and reproducibility were carefully investigated, enabling further improvements to the LIPP method [141–143]. Recently, the influence of pre-conditioning was investigated. It was found that, in the case of SiR, memory effects prevent exact repetition of space-charge experiments on the same sample, as the whole sample history strongly influences the sample behaviour [141–146].

Technische Universität Braunschweig: In addition to other research, investigations on 3D-printed polymeric electrical-insulation disks were performed at the Technical University Braunschweig. The influence of infill, component orientation, printing temperature and printing speed on permittivities and dissipation factors was assessed. 3D-printed (softer) conducting electrodes were compared with metallic electrodes in breakdown experiments [147, 148]. The materials-related work is paving the way for a more extensive use of state-of-the-art additive manufacturing in electrical insulation.

Technische Universität Darmstadt: At the Technical University of Darmstadt, the impact of nano-fillers on the space-charge behaviour of SiR was carefully investigated. DC dielectric properties of SiR were optimised by adjusting the content of carbon-black nanofillers [149, 150]. The impact of new types of fillers was simulated for the purpose of nonlinear refractive field control [151]. HVDC insulating materials were studied by comparative DC-conductivity measurements under high-frequency and mixed-frequency HV stresses [152, 153].

Technische Universität Dortmund: DC conductivity measurements carried out at the Technical University of Dortmund to characterise SiR showed a strong dependence on the DC-field stress and on the electrode material used. For improving reproducibility, titanium was identified as a suitable electrode material [154]. Similar investigations were also carried out on alternative electrically insulating oils [155] and on the lubricant-XLPE interfaces that are relevant in power-cable accessories [156]. The research in Dortmund formed the basis for the concept of 'apparent DC conductivity' in SiR as introduced in ref. [157].

Technische Universität Dresden: DC operation is the only option for power transmission over long distances, for example, offshore wind farms located far from the coast. Due to the limited space available offshore, compact solutions are required for all components. In terms of space requirements, DC GIS offer enormous advantages over air-insulated systems. Research into the gas-solid insulation system of DC GIS was carried out at Dresden University of Technology [158], showing that mixed AC/DC voltages—typical for AC–DC converter systems—lower the electrical stress at gas-solid interfaces compared to pure DC. Recent research activities have been focused on shear stresses causing thermal-mechanical ageing of the insulation system of rotating machines [159].

Leibniz Universität Hannover: At the Schering Institute of the Leibniz University Hannover, space-charge-induced ageing of polymeric materials under high DC stress was reviewed [160]. With respect to e-mobility applications (slot insulation in stators of electric motors), the impact of electrical ageing and temperature changes on polyamide-6 and polyamide-6.6 samples was investigated [161].

Karlsruher Institut für Technologie: The high-frequency dielectric behaviour of the inner and outer semiconducting layers in XLPE cable systems was studied at the Karlsruhe Institute of Technology with respect to temperature effects and compared with flat samples made from the same semiconducting material (carbon-black-filled XLPE) [162].

Technische Universität München: The interaction between polymer matrix and filler particles was studied at the Technical University of Munich [163]. The influence of silica nano-fillers on the arc behaviour of SiR for composite insulators in outdoor applications was also studied in detail [164–166]. On insulators of HVDC GIS, the space-charge properties of epoxy

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resin with and without nano-fillers were experimentally assessed [167, 168].

Universität Potsdam: At the University of Potsdam's Faculty of Science (partially in collaboration with Chalmers University of Technology in Gothenburg, Sweden), polymer-based nano-composites have been demonstrated to be useful for reduced space-charge transport (lower conductivity) as well as for enhanced space-charge storage (better charge retention). Thus, the same nano-composites may be employed in both more effective electrical-insulation systems (electro-passive dielectrics) and more efficient electret-transducer devices (electro-active dielectrics) [169]. Good examples are bulk (3D) nano-composites of LDPE with magnesium oxide [170] and inorganic surface (2D) islands on PP films that self-organised during surface treatment with an orthophosphoric-acid (H_3PO_4) solution [171]. In both (and several other) cases, inorganic nano-islands hold space charge very well and prevent its movement, thus leading to reduced transport of charge carriers, higher breakdown strength and enhanced electret stability.

Hochschule Schweinfurt-Würzburg: A main research topic at the Schweinfurt-Würzburg University of Applied Sciences is the transient dielectric behaviour of oil-press-board barrier systems. The characteristics of such insulation systems under mixed AC/DC stress are of particular interest for HVDC bushings and converter transformers [172–174].

Universität Stuttgart: At the University of Stuttgart, the focus is on power transformers. For HVDC converter transformers, the electrical conductivity of oil itself and of oil-impregnated pressboard, which depends on ageing by-products, has been investigated [175]. Another polymer-related research topic was the compatibility between SiR and mineral oil [176].

Hochschule Zittau/Görlitz: In a recent project at the Zittau/Görlitz University of Applied Sciences, carried out in collaboration with the Leibniz Institute of Polymer Research in Dresden, controlled roughening/wrinkling/structuring processes for silicone-elastomer surfaces were developed [177]: roughened or wrinkled or triangularly structured silicone surfaces were employed at electrode-insulator interfaces and shown to lead to different levels of interfacial cavity areas and various changes or improvements in electrical breakdown and PD. Possible applications are found in silicone-rubber accessories for connecting HV cables [177].

2.4.3 | Switzerland

Eidgenössische Technische Hochschule Zürich: A broad spectrum of research activities in HV engineering is being pursued at ETH Zurich. In particular, the effects of humidity and temperature on the dielectric properties of polyethylene terephthalate (PET) films [178] have been investigated. Here, the PET films were used as an example for studying changes of the dielectric properties in polymeric solids. Due to the extremely high global warming risk of SF_6, its replacement by environmentally more friendly insulation gases ('eco gases') is a must. At ETH Zürich, comprehensive research on alternative gases has been initiated recently—see, for example, ref. [179]. Recent promising research was also focused on vitrimers, a class of polymers with self-healing capabilities [180].

2.5 | Western Europe

2.5.1 | Italy

From 2015 onward, the Italian literature on dielectrics and electrical insulation progressively moved away from treating insulation as a passive material checked by fixed thresholds and towards treating it as a multi-physics system whose condition depends on coupled electrical, thermal, environmental, and measurement variables. This shift is especially visible in HVDC cable research, where electric-field distribution depends not only on geometry but also on conductivity gradients, temperature gradients, ageing, and transient operating conditions. It is also visible in the partial-discharge field, where recent Italian work has increasingly emphasised sensor behaviour, signal interpretation, and defect classification rather than discharge amplitude alone.

Within this landscape, the University of Bologna has played a leading role in linking insulating material development, ageing, diagnostics and predictive life modelling; the University of Genova and the University of Trieste have advanced partial-discharge monitoring and decision criteria and the University of Palermo has deepened the understanding of HVDC space-charge and discharge phenomena; and Sapienza University of Rome has linked dielectric diagnostics to both insulating liquids and service failures in medium-voltage assets. Prysmian, as the major Italian industrial player in the field, reflects the practical translation of many of these themes into 525 kV extruded HVDC cable systems.

University of Bologna: from dielectric spectroscopy to electro-thermal design. The University of Bologna has developed one of the clearest Italian research trajectories in the nondestructive assessment of polymeric insulation. In the 2021 paper [181] on low-voltage cable insulation used in NPPs, broadband dielectric spectroscopy was shown to provide measurable markers of ageing that correlate with more conventional mechanical indicators of degradation. The importance of this result lies in its practical implications: it suggests that electrical response can be used as a proxy for material condition before destructive testing becomes necessary, which is one of the main outcomes of the TEAMCABLES EU project. The 2022 follow-up on on-site dielectric spectroscopy moved the method closer to field deployment by proposing a portable high-frequency measurement setup and assessing its sensitivity to operating conditions [182]. Moreover, a novel multiscale model linking changes in dielectric properties with the chemical species formed during ageing was developed and described in paper [183] in 2022. A further step came in 2023, when antioxidant-modified XLPE systems were analysed, showing that additives affect trap structure, conductivity, and permittivity under both AC and DC conditions [184]. Overall, these studies make Bologna a major Italian reference point for translating polymer chemistry and ageing into operational diagnostics.

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The development of nanostructured materials for HVDC cable and capacitor applications has also been a key research topic over the last decade. In particular, bulk nanofillers have been studied to reduce space charge accumulation within cable insulation [185, 186], within the framework of two major EU projects, GRIDABLE (2017–2021) and NEWGEN (2022–2026). Graphene nanocoatings applied at the electrode/insulation interface have also been developed, demonstrating their effectiveness in reducing space charge injection from the electrode, particularly under high electric field and temperature, see Figure 16. This, in turn, reduces charge accumulation in the insulation bulk and mitigates local electric field enhancement [187].

Another research area investigated by the University of Bologna concerns insulation for inverter-fed electrical machines. Recent work shows that machine insulation cannot be adequately evaluated using partial-discharge inception tests alone if thermal stress and realistic inverter waveforms are neglected. A 2023 contribution demonstrated that finite-element prediction of PD inception can be extended from idealised insulation models to complete windings, representing an important step towards design-stage prediction rather than purely empirical qualification [188], see Table 1. By 2026, a coherent electrothermal qualification method for electrical-machine insulation had been proposed, reflecting a broader Italian shift towards service-representative combined stressing instead of isolated acceptance tests [189].

The final topic highlights Bologna's internationally recognized contribution to HVDC cable reliability. Here, the main focus is not only dielectric strength but also lifetime under time-varying electrothermal stress. Early work in 2015 already pointed to the significance of load cycles and voltage polarity reversal for HVDC cable ageing [190]. Subsequent studies formalised how electrical and thermal transients reshape feasible geometric design and expected lifetime, whereas a 2023 review consolidated the life and reliability modelling literature into a systematic framework [191]. The 2025 review on HVDC cable-system testing further connected these models to practical qualification procedures, including development tests, type tests, prequalification and post-installation verification [192, 193].

Bologna's overall achievement over the past decade has therefore been the integration of material behaviour, numerical design, ageing investigation, diagnostics and system-level testing into a coherent insulation-engineering workflow.

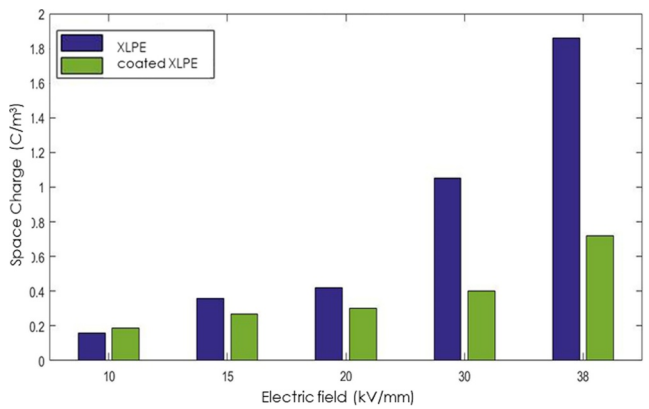


FIGURE 16 | Space charge measured on XLPE (blue) and XLPE-graphene coated insulation (green) versus electric field at room temperature. XLPE, crosslinked polyethylene.

University of Genova and University of Trieste: PD sensing, patterns, and decision rules. At the University of Genova, researchers have focused on the front end of partial-discharge diagnostics: how signals are generated, sensed and interpreted. Their 2024 study on enamelled wires under thermal stress [194] showed that partial-discharge inception voltage evolves in a systematic way as thermal ageing progresses, making PDIV a potentially useful condition indicator instead of a single qualification number. In a second line of work, they used transient earth voltage measurements as a nonintrusive tool for switchgear PD analysis, highlighting the value of field-compatible sensing where intrusive connections are impractical [195]. A very recent paper on high-frequency current transformers complements this by showing that online PD monitoring requires careful metrological characterisation of the sensor itself, including frequency response and impulse behaviour, before advanced classification can be trusted [196].

The University of Trieste provides a complementary methodological contribution. Rather than basing acceptance decisions on discharge magnitude alone, his 2024 IEEE Access paper proposed partial-discharge acceptance criteria for AC rotating-machine insulation systems based on the shape of PRPD patterns [197]. This is important because discharge amplitude depends strongly on instrumentation, coupling, and defect history, whereas pattern shape can carry more robust information about defect typology. Read together, the Genova and Trieste lines point towards the same broader conclusion: the Italian partial-discharge community has increasingly shifted from threshold-centric testing towards sensor-aware and morphology-aware diagnostics, laying groundwork for more reliable automated interpretation.

University of Palermo and Sapienza University of Rome: HVDC applications, liquid dielectrics and network reliability. Researchers at the University of Palermo have contributed decisively to the Italian understanding of HVDC cable insulation as a coupled electrical, thermal, and measurement-physics problem. A central issue in extruded HVDC cables is that electric-field distribution is affected by space charge and conductivity gradients, which themselves depend on temperature and material state. The 2019 papers on the pulsed electro-acoustic method clarified both the value and the industrial limitations of space-charge measurements for HVDC cables [198, 199]. Subsequent work [200] showed that air-void defects and acoustic reflections can complicate interpretation, meaning that measurement reliability becomes part of the physics problem rather than an external detail. This is a major insight, because it warns against reading space-charge data as if they were direct, artefact-free state measurements.

Palermo's work also clarified the role of thermal gradients and transients. The 2020 study on axial heat transfer [201] showed that temperature gradients alter space-charge accumulation and therefore modify electric-field distributions inside HVDC cable insulation. In 2021, they extended this logic to PD during load transients, showing that PD behaviour changes with the time-varying temperature gradient [202]. The 2022 work on DC-periodic voltage then addressed a further challenge: under

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TABLE 1 | Predicted PDIV, peak (pk) value, versus measured PDIV (pk).

Types	Insulation layer	D_t (μm)	Predicted $PDIV_{pk}$ (kV)	Measured $PDIV_{pk}$ (kV)	Error (%)
Phase-to-phase random wound machines (room temperature)	Nomex paper (80 μm)	140	1.26	1.275	−1.18
	NMN paper (190 μm)	250	1.72	1.70	1.18
	NMN paper (240 μm)	300	1.94	1.925	0.78
Phase-to-ground random wound machines (room temperature)	Nomex paper (80 μm)	110	0.98	0.975	0.51
	NMN paper (190 μm)	220	1.37	1.35	1.48
	NMN paper (240 μm)	270	1.44	1.45	−0.69
Turn-to-turn hairpin machines (room temperature)	Polyimide-FEP (125 μm)	250	1.50	1.51	−0.66
	Polyimide-FEP (175 μm)	350	1.85	1.83	1.09
Phase-to-ground random wound machines (180°C)	Nomex paper (80 μm)	110	0.74	0.80	−7.50
	NMN paper (190 μm)	220	0.92	0.925	−0.54
	NMN paper (240 μm)	270	1.03	1.125	−8.44
Turn-to-turn hairpin machines (180°C)	Polyimide-FEP (125 μm)	250	1.19	1.30	−8.46
	Polyimide-FEP (175 μm)	350	1.45	1.62	−10.49

Note: D_t is the insulation thickness.
Abbreviations: FEP, fluorinated ethylene propylene; NMN, Nomex Mylar Nomex; PDIV, partial discharge inception voltage.

DC stress, the absence of a classical AC phase reference makes conventional PRPD approaches incomplete, so the temporal evolution of discharge activity must be analysed differently [203]. These contributions have been especially valuable because they bring together physical interpretation, modelling and experimental constraints in a field where hidden state variables strongly influence insulation performance.

Sapienza University of Rome has contributed in a different but equally relevant way. The 2017 paper on partial-discharge detection in dielectric liquids argued that available standards reflected earlier circuitry and narrower diagnostic assumptions than those required by newer liquids and modern measuring techniques [204]. The 2020 review on pre-breakdown phenomena in ester fluids broadened that perspective by synthesising streamer and breakdown behaviour in alternative dielectric liquids, an increasingly relevant issue as ester-based systems gain importance [205]. On the asset side, the 2021 study of defective medium-voltage underground cable joints connected diagnostics to actual network failures, showing how summer temperature conditions, joint design and operating stress can combine to produce field-relevant reliability problems [206]. Sapienza's role in the Italian landscape has therefore been to connect dielectric phenomena to both standards evolution and utility operation.

Prysmian and the industrial translation of Italian research. Prysmian is the clearest industrial counterpart to the academic lines reviewed above. In 2019, the company announced qualified 525 kV extruded land cable systems using both P-Laser and XLPE insulation, demonstrating that very HV extruded systems were moving beyond development into qualified technology [207]. In 2022, Prysmian reported successful development and testing of the first 525 kV extruded submarine full cable system, a milestone of direct relevance for offshore transmission and long interconnectors [208]. In 2023, that progress translated into project execution through the first UK contract for a 525 kV XLPE submarine system [209]. Most recently, Prysmian announced on 2 March 2026 that its 525 kV submarine HVDC systems had been qualified up to 90°C operation, increasing transfer capability from around 2 GW to about 2.5 GW per link [210]. These milestones reflect the same Italian priorities visible in university research: better polymeric systems, stronger understanding of electrothermal transients, tighter testing logic and more confidence in real cable-system operation.

2.5.2 | *UK*

High voltage research work in the UK can be traced back to 1938 with the 2-MV HVDC supply installation [211]. Since then,

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the HV laboratory and research have undergone significant changes in the UK and the current main laboratories and their typical research in the UK universities are briefly addressed in the following sections. Due to limited space, the section on high voltage research is focused on universities in Manchester, Glasgow, Cardiff and Southampton.

Manchester University: High voltage research in Manchester University has been an integral part of the work since the 1950s when the first High Voltage laboratory was opened at the University of Manchester. When the headquarter of National Grid moved to Coventry, it also sponsored Manchester University High Voltage Laboratory and donated HV suppliers from Leatherhead laboratories and formed the National Grid High Voltage Research Centre. It is now home to the largest HV laboratory of any UK university and is capable of testing equipment designed for use on the 400 kV power system. Apart from the general HV voltage testing, the research work by the Manchester University group focuses on two areas: (i) transformers are critical for electricity transmission and distribution systems and are found at all voltage levels. The Manchester University researchers have studied various aspects of power transformers and developed new ways to analyse how they are ageing and estimating their lifetime to ensure strategic maintenance deployment. (ii) Condition monitoring of assets in the systems is another area research. Future energy networks will comprise of millions of assets and devices. Monitoring their condition in real time means it is possible to push these devices further if needed during emergencies. Figure 17 shows the breakdown and withstand voltages of the mineral oil at the increasing gap distances under lighting impulse [212]. It shows that both the 50% BDVs and withstand voltages (= 1% breakdown probability) are increased with the liquid gap distance as expected. Meanwhile, it is also noted that there is no polarity effect on the BDV and withstand voltage, as the breakdown results are comparable between impulse polarities at each gap distance. The maximum difference in 50% BDV is observed at the gap distance of 15 mm, where the positive impulse has only 2.1% higher BDV than the negative impulse. The maximum difference in withstand voltage is shown at 5-mm gap distance, where the negative withstand voltage is higher than that under positive lightning impulse by only 5.6%. Such small differences are not significant, considering the variance of the breakdown data observed during the experiments.

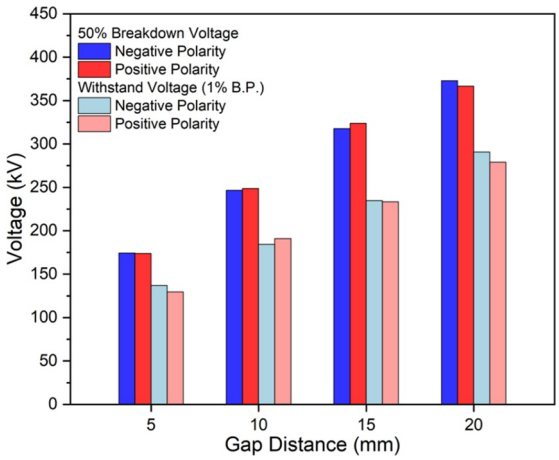


FIGURE 17 | 50% BDVs and withstand voltages of mineral oil at various gap distances under lightning impulse, bare electrode [212]. BDVs, breakdown voltages.

University of Strathclyde: The HV research in the University of Strathclyde involves both gas and solids. The group is engaged in both fundamental and applied research covering electrical plant, HV materials and components, pulsed power technologies, discharges in gases and fluids, nonthermal plasma for environmental and bio-medical applications.

The group has a strong track record of pioneering research into many practical applications of HV technology. The research conducted covers a range of topics, including: (i) ultra-fast high energy switches for particle beam fusion experiments; (ii) measurement and location of PDs in electrical insulation; (iii) diagnosis of defects in HV equipment such as GIS, transformers and cables and (iv) inactivation of bacteria using electrical impulses, nonthermal plasma for environmental and bio-medical applications. Their recent study [213] by comparing mineral oil and easter liquids under nano pulses shows ester liquids exhibit competitive dielectric performance under nanosecond impulse stress when compared with mineral oil. Both natural and synthetic esters showed BDVs within the same operational range as mineral oil across a variety of field utilization factors, with polarity dependence consistent with established streamer theories. Partial discharge tests show that esters underwent less deterioration than mineral oil under both positive and negative polarity stressing, confirming its superior long-term stability.

Cardiff University: The Advanced High Voltage Engineering Research Centre is based in the Cardiff University. The modern HV and high-current test laboratories are used for research into HV systems and phenomena in electrical power and transport applications. In particular, the research into high-current lightning direct-effects finds application in the aerospace, power and communication sectors. The work is concerned principally with the lightning performance of materials, structures and systems.

The National Grid Centre is a Research Centre of Excellence established in 2005 between Cardiff University and National Grid. The Centre has particular expertise in HV insulation systems, protection against overvoltage, earthing systems and the safety of electrical systems.

Their recent research [214] on the performance of grounding systems with and without a conductive aggregate compound covering in order to examine the low-resistivity materials use as a minimisation technique of grounding impedance was carried out. Experimental investigations were conducted by employing several vertical ground electrodes subjected to currents of variable frequency upto 10 MHz. The following findings were obtained: (i) Increasing electrode length is an effective tool to reduce the grounding impedance at low frequencies, whereas at higher frequencies, an inductive behaviour is observed with increasing electrode length. (ii) The use of a conductive aggregate compound is an effective technique to reduce the grounding impedance and provide an economic system. A reduction rate of more than 20% was obtained over frequency for the electrode partially covered with a conductive aggregate compound. (iii) The normalised impedance (Z/R ratio) is

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around the unit for electrode covered (partially or totally) with a conductive aggregate compound, leading to conclude that the material helps obtain a reduced grounding impedance and avoid the significant impedance rise at higher frequencies.

Southampton University: The University is well known for its research work on HV technologies. The laboratory is named in commemoration of Tony Davies, Professor of Electrical Power Engineering. The laboratory moved to its current site in 1991 and was extended in 2002 with a second hall and an additional materials/measurements laboratory. In recognition of his enormous personal contribution to the establishment of a world-class HV facility, the laboratory was renamed to Tony Davies High Voltage Laboratory in 2004.

The laboratory carries out research in all areas of HV engineering, from advanced materials to electric grid operation, including condition monitoring, HV engineering, plasma and space science. In addition, the laboratory provides an unique opportunity for industries to test their products. As the laboratory is certified to ISO9001:2015 (Quality), ISO14001:2015 (Environmental) and ISO 45001:2018 (Health and Safety) under the scope 'Development, product type testing and consultancy services related to HV plant and accessories'.

Various research activities have been carried out in this laboratory, especially in new cable developments using new materials. The work presented in Figure 18 [215] shows the effect of semiconducting materials on the space charge behaviour of three types of PP-based thermoplastic insulating polymers. Mechanically flexible and strong semiconducting materials prepared with 30 wt.% of carbon black showed uniform carbon black nanoparticle dispersion with low electrical resistivity ($< 5\ \Omega{\cdot}cm$) over a broad temperature range (25°C–90°C). Based on the results, it was found that the space charge behaviour of the PP-based insulation polymer is closely associated with the semiconducting screen attached to it and is affected by the bonding method, applied electric field, and temperature. Thermally bonded SC/PP/SC samples demonstrated stronger charge injection than films bonded using natural force. Both homocharge injection from the electrodes and heterocharges accumulation in the sample was significantly enhanced at 60°C compared to 25°C. These injected charges are highly mobile at a high DC field of 40 kV/mm, which potentially migrated from the injection electrode to the opposite electrode and intensified the heterocharge accumulation at the opposite electrode. The higher charge mobility was verified by higher DC conductivity at 60°C. Apart from the charge amount, charge mobility and distribution in the insulation layer also strongly affected the local electric field distribution. Although thermally bonded PP-B sandwich film exhibited lower amount of accumulated charges at 20 kV/mm and 60°C, the local field which was enhanced was higher than at 40 kV/mm and 60°C due to the higher amount of positive heterocharges near the cathode caused by the lower charge mobility and less charge recombination. Overall, SC-A/C prepared in this work outperforms SC-B and could possibly meet the technical requirement for HVDC cable application.

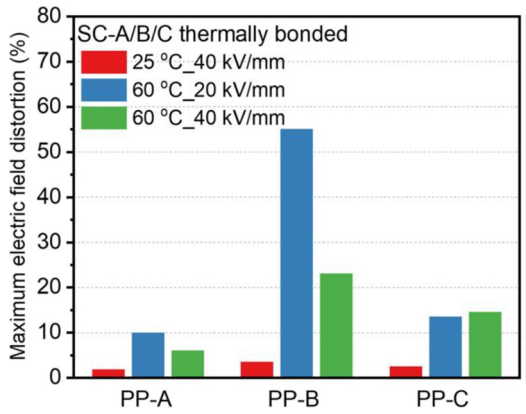


FIGURE 18 | Comparison of maximum field distortion observed during the voltage-on process of thermally bonded SC/PP/SC films at 25°C/60°C [215]. PP, polypropylene.

This work highlights the critical role played by semiconducting screens in HVDC cables and provides useful information and guidance on semiconducting screen design for PP-based polymers.

Liverpool University: In addition to the above, the work done by Liverpool University in HV area over last 30 years is also well known. Their work on switchgear has attracted attention from industries and the National Grid. HV work has been done now in Energy and Power Research group. The particular research areas focus on (i) modelling of physical processes occurring inside high current and HV circuit breakers; (ii) experimental validation of the modelling and (iii) exploring new forms of environmentally friendly switchgear.

Glasgow University: There is also a group in Glasgow Caledonian University and they have contributed to PD measurement and examined the maximum EV penetration that can be allowed without network upgrading and avoid overloading of medium voltage cables and distribution transformers in residential distribution power systems. A methodology is proposed to model the EV penetration and their effects on operational temperature of medium voltage cables and transformers, with charging scenarios and harmonic currents taken into consideration.

The current distribution of high-voltage or current laboratories in the UK is reasonable. They have done high quality research in the UK and served industry well. All the laboratories not only carry out the first-class research but also do some consultant work for industries. By doing this, the quality of HV research in the UK and its applications in industries can be maintained.

2.5.3 | France

This section addresses action in the field of insulating materials design, characterisation and modelling by labs in France having activities in the field of power engineering.

University of Toulouse: The Laboratory of Plasma and Energy Conversion holds two large groups working in the field of insulation materials representing over 20 permanent researchers. The Lab was at the origin of the first International Conference on Solid Dielectrics in 1983 and hosted the International Conference on Dielectrics in 2024.

Within the Solid Dielectrics and Reliability group, head presently by Prof. L. Boudou, recent research activities deal with the

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modelling of ionic charge transport in XLPE, particularly in relation to HVDC cable insulation, extending and refining bipolar charge transport models with the incorporation of ionic contributions [216, 217]. Simulations in the field distribution in cable accessories aim at identifying optimal design and properties of elastomers used as joint materials [218]. Space charge measurements by PEA method are currently investigated, with recent inputs related to the signal conditioning [219] and to the radiation effects in insulating materials [220, 221]. The group develops original methods to probe insulations: in recent years, the photo-stimulated discharge spectroscopy coupled to space charge measurement by laser intensity modulation method (LIMM) has been implemented as a potential tool for trap spectroscopy, applied to PP and polyethylene naphthalate films [222]. Luminescence methods are enriched with the recent development of mechano-luminescence measurements, as a way to monitor bond breaking under tensile stress in epoxy resins, see Figure 19 [223]. Finally, electrostatic methods based on atomic force microscopy technique are exploited to approach charging phenomena at nanoscale, notably as regards the behaviour at interfaces in polymer NCs [224]. The mitigation of space charge accumulation in XLPE was demonstrated by interposing a NC layer with silver nanoparticle acting as artificial charge traps near the interfaces [225].

The group on Dielectric Materials in Energy Conversion was headed by Dr. M-L Locatelli up to end-2025. The activities of the group concern dielectric materials and insulation systems within electrical energy conversion devices, as well as technologies for the 3D integration of power converters. One important route of research concerns PI and its NCs for integrated electronics applications with the revelation of substantial improvement of the high temperature behaviour of the NCs with boron nitride nanofillers [226, 227] and achievement of very high breakdown strength reaching 1000 kV/mm, see Figure 20 [228]. The group also has developed nonlinear materials with as objective to form stress-grading layers in the passivation of power modules [229], exploiting dielectrophoresis to optimise high permittivity particles laying [230]. To mitigate triple points in substrates for wide bandgap semiconductor power modules, original ceramic substrate architecture and functionalisation have been proposed [231]. Materials for PCB-embedded power electronics packages are currently explored enabling self-healing and favouring recycling of modules. The group has been pioneering in proposing epoxy-based vitrimers to this end [232]. Other activities concern PD prevention, particularly in the field of electrical machines and low pressure [233]. Solutions to improve the performances and environmental footprint using self-bonding wires have been investigated [234].

University of Montpellier: The solutions developed by the Electrical Engineering, Materials and Systems team in the IES Laboratory at the University of Montpellier concern notably original characterisation methods that can be directly adapted to components and implemented on site. These are in particular the so-called 'thermal stimulus' techniques for space charge measurements, which the team is developing and for which it enjoys international recognition. Recent research has dealt with the development of the thermal step method for HVDC cable, notably the design of a DC–DC converter and its use in a high-current application to produce thermal stimulus [235]. In addition, significant research is done in collaboration with other groups on space charge measurement in liquids, see Figure 21. Thermoelectric ageing under long term (up to 3 years) in XLPE-insulated HVDC cables has been investigated pointing to progressive heterocharge build-up in the course of time [236]. Another axis of research concerns NCs processing for electrical insulation with the processing and investigation of multilayer PI and PI-based NCs [237].

University of Grenoble: The Dielectrics group at G2ELab, University of Grenoble is another recognized group in dielectrics in the French organisation. The group has traditional activity and

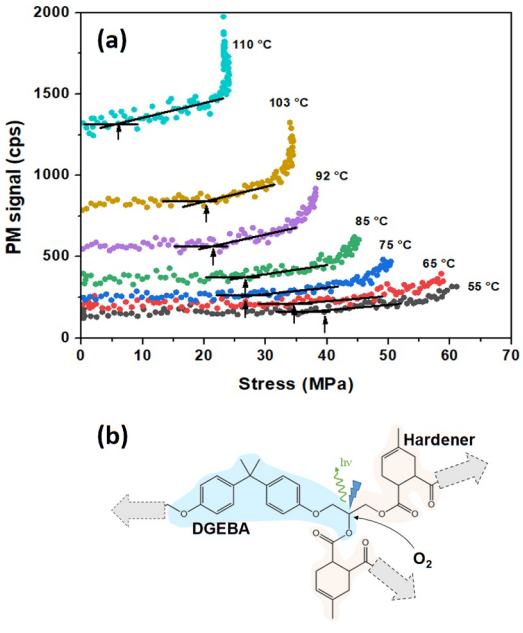


FIGURE 19 | (a) Luminescence versus stress curves at different temperatures obtained from DGEBA-based epoxy under tensile stress. (b) Sketch of the emission mechanism. The presence of oxygen is a necessary condition for mechanoluminescence in epoxy, pointing to mechanical stress-induced oxidation [223].

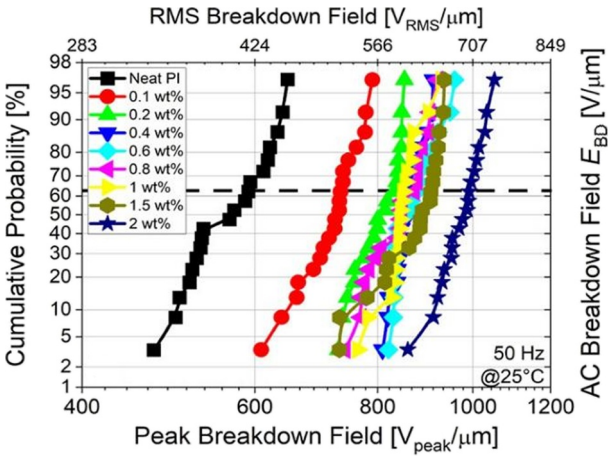


FIGURE 20 | Weibull cumulative probability of failure versus both the AC peak and RMS breakdown fields for PI with different contents of SiO_2 nanoparticles functionalised with 3-aminopropyltriethoxysilane [228]. PI, polyimide; RMS, root mean square.

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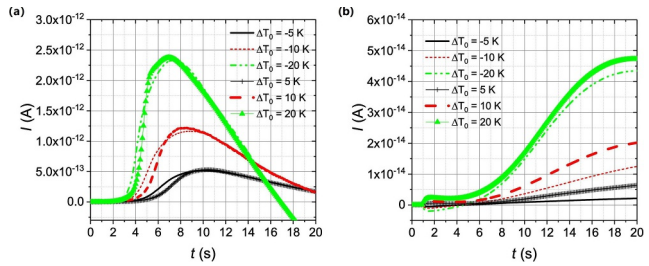


FIGURE 21 | Estimating the effect of liquid convection with thermal steps measurements on liquids: The thermal perturbation leads not only to a perturbation of the electric charge, also a movement of the liquid depending on its viscosity. Thermal step currents in (a) low and (b) high viscosity liquids when stimuli of different amplitudes ΔT_0 are applied [248].

recognition in the field of liquid dielectrics and polymer gels. Over the last 10 years, efforts have been put on the investigation of the initiation and propagation of streamers in liquids (e.g., liquid nitrogen [238], water [239] and cyclohexane [240]) and more generally on the interaction between gas insulation and dielectric surfaces. In addtion, the group has recognized expertise and continuous activity in the characterisation for silicone polymers for electrical insulation [241] and impact of water on polymer insulation behaviour.

University of Lyon: Ampere lab in Lyon has facilities for AC, DC HV and lightning pulses tests. The team of Prof. Beroual has developed extensive research in the field of insulating oils, notably with nanofluids [242], and considering synthetic ester, natural ester, and mineral oils. Another long-term activity of the group is with the investigation of surface flashover and creeping discharge phenomena [243]. Later activities concern mitigating PD Activity in PCB-embedded power electronic modules [244].

University of Paris-PSL: The group of Stéphane Holé at ESPCI, Paris, develops instruments for space charge measurements under various principles, including the LIPP method, and for different application means. Original approaches are developed for probing the dielectric double layer at solid-liquid interface [245] in collaboration with laps as P'Lab in Poitiers. In the field of HV, recent achievements concern the probing of laminated insulations at cryogenic temperatures intended for superconducting cables [246].

Actions at the National level: A National Network (SEEDS) gathers academic research in France related to Power Engineering. Within this network the Dielectrics Group has been very active over the last 10 years, with notably the organisation of three summer schools with international opening (Porquerolles summer schools), focused on insulations, mostly of polymeric nature or composites with polymeric matrix and with specific topic at each edition, the last one in 2024 being on multifunctional materials [247]. The network supports collaborative research; notably, in last years, space charge measurements have been implemented in liquids between Universities of Montpellier, Poitiers, Paris and Toulouse [248]. Aside from University labs, recent institutes have been founded in France in the last decade aiming at fostering research and development and improve competitiveness in key sectors. In the field of HVDC technologies, the Supergrid Institute in Lyon leads research on materials and stresses endowed in HVDC and MVDC applications and related diagnosis [249, 250]. In Toulouse, IRT Saint Exupery is focused on the aerospace field, whose research is carried out mainly on materials endurance and PD diagnosis and modelling [251, 252].

2.5.4 | *Wrap-Up for Europe*

In this review, Northerm, Central and Western Europe regions have been split in different sections for convenience. However, these regions have got largely common research policies and common objectives in the recent years through the European Union and strong interactions with nonmember countries such as UK and Switzerland. The development of offshore wind farms, the needs for reinforcing the energy grid and improving solidarity have pushed research on HVDC energy transmission, materialised with multiple subsea links and onshore links between France and Italy and France and Spain and with HVDC corridors in Germany under construction with 525 kV buried cables [253, 254]. Such policies have pushed the research on polymeric insulations for HVDC cables, with not only XLPE, but also XLPE-based NC insulation and PP-insulated cables. At present research on PP cables is still very active with large European actions as Gridable and Newgen projects involving VTT Technical Research Centre and Tampere University in Finland, Twente University in Netherlands, University of Bologna among others [186, 255]. Research in Europe on PP-based materials for cables has also been conducted by the University of Southampton, the UK [256, 257] and University of Chalmers in Sweden [86].

Besides, silicone materials with incorporating different nanofillers have been investigated in the universites of Zitau and Darmastdt (Germany). The research on HVDC technologies has also boosted the development of instruments for space charge characterisation in cables, using thermal step method at University of Montpellier, France, by PEA at University of Palermo, Italy, University of Toulouse, France, by pressure wave propagation method at Sorbone University, France [258] and University of Berlin, Germany [143]. Another axis of research associated with HVDC technologies is the development of bipolar model for charge transport, in order to account for space charge build-up and nonlinear effects, also with accounting for ionic contributions to charge transport. Contributors are from the University of Toulouse [217], University of Southampton [259], the UK, Chalmers University, Sweden [260, 261] and recently University of Bologna, Italy. Finally, first principle calculations for determining the electronic properties of polymers have been implemented, historically at Imperial College, the UK [262, 263], and later at University of Sevilla, Spain [264], and KTH Royal Institute of Technology, Sweden [265].

The increasing electrification of transportation is another major driver for the development of advanced insulation materials. The widespread adoption of wide-bandgap power semiconductors (SiC and GaN) requires insulating materials capable of operating at higher temperatures while withstanding repetitive high-dV/dt voltage stresses. This has stimulated extensive research on polymer NCs and other advanced dielectric materials for power

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electronic modules, with the aim of improving thermal conductivity, dielectric endurance and resistance to PD. Significant contributions in this field have been made by the Universities of Toulouse, Bologna, Southampton, and Grenoble, in close collaboration with major industrial partners, including STMicroelectronics, ELANTAS, and Infineon [226]. At the same time, the progressive electrification of aircraft, supported by European initiatives such as Clean Sky [266] and, more recently, Clean Aviation [267], has renewed interest in PD-free insulation technologies capable of operating under higher service voltages and reduced-pressure conditions. These developments have also fostered research on PD diagnostics under nonconventional electrical stresses—including repetitive impulse, PWM, high-frequency and DC voltages—for which conventional measurement techniques are often inadequate. European research groups, including the Universities of Manchester, Bologna, Toulouse and Southampton, have made significant contributions to the development of advanced insulation materials as well as PD diagnostic methodologies for next-generation transportation and power-electronic systems [189, 233, 268].

2.6 | South America

2.6.1 | *Brazil*

Research activities in Brazil have included functional polymer dielectrics and electret-based technologies relevant to HV engineering, together with work on composite insulators and power cables.

University of São Paulo and Federal University of Paraíba: Researchers at these universities were among the first to demonstrate that fused deposition modelling (FDM) 3D printing could fabricate ferroelectrets with geometrically controlled cavities. Assagra et al. [269] initially used acrylonitrile butadiene styrene, achieving stable piezoelectric performance under elevated temperature conditions [269]. The group subsequently developed a single-step process using PP, the standard ferroelectret polymer [270]. The three-layer design achieved performance comparable to conventional PP-foam ferroelectrets, demonstrating that standard FDM printing enables rapid prototyping of functional ferroelectret geometries [270]. Figure 22 shows micrographs of real 3D-printed PP structures with the triangular pattern (Figure 22a,b), and a typical cross-section with two cavities (Figure 22c) [270].

Among the subsequent device-oriented applications, the work most directly related to HV engineering combined a fluorinated ethylene propylene ferroelectret hydrophone with machine learning to classify the condition of mineral insulating oil in power transformers [271]. The method provides a rapid, on-site complement to conventional dissolved gas analysis and physicochemical testing, illustrating how functional polymer dielectrics can support insulation diagnostics.

In the field of corona charging and characterisation of piezoelectric polymer films, Giacometti and co-workers from University of São Paulo have contributed through the constant-current corona triode technique, originally conceived with Professor Bernhard Gross in the 1970s–1980s. In 2018, Giacometti [272] presented an enhanced version optimised for thin

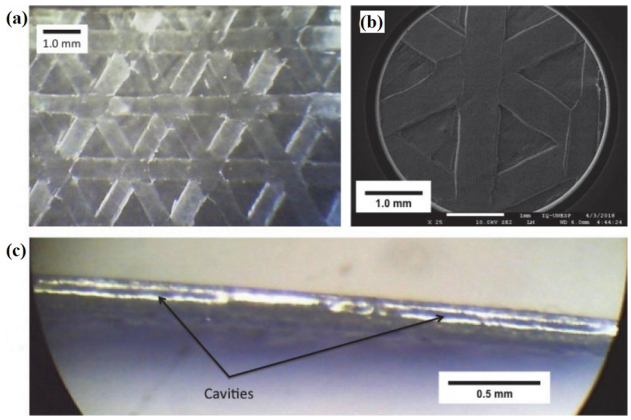


FIGURE 22 | Micrographs of a 3D-printed PP ferroelectret fabricated in a single-step FDM process: (a) Top view of the bottom and central layers showing the triangular fill pattern; (b) SEM image of the triangular pattern; (c) cross-section revealing two air cavities [270]. These controlled cavity geometries yield piezoelectric coefficients up to 200 pC/N, comparable to conventional PP-foam ferroelectrets. FDM, fused deposition modelling; PP, polypropylene.

dielectric films (300–500 nm), enabling in situ measurement of charge storage and transport at significantly lower cost than electron-beam methods, with modern digital electronics further improving accuracy and ease of operation [272]. In a 2022 retrospective [273], Giacometti et al. reviewed how this technique enabled key findings on PVDF and P(VDF-TrFE), including metastable ferroelectric polarization and ferro-to-paraelectric phase transitions [273].

Other contributions: Ferreira et al. [274], in a multi-institutional collaboration, demonstrated a polymeric composite insulator instrumented with optical fibre sensors for real-time monitoring of HV transmission lines, deployed on a 230 kV line in the Brazilian Interconnected System [274]. In the area of cryogenic dielectric characterisation, researchers at Universidade Federal de Minas Gerais developed a system for determining dielectric strength, dissipation factor, and permittivity of polymeric materials at 77 K, validated on Nomex/Kapton/Nomex laminates within the first Brazilian HTS power cable project (SUPERCABO) [275].

2.6.2 | *Argentina*

Pontificia Universidad Católica Argentina: Salvatierra et al. [276] investigated electrical treeing in silicone dielectric gels used as encapsulants in power electronics. By varying the mixing ratio of a two-component commercial silicone, they produced microstructures from liquids to elastomers and showed that treeing transitions from self-healing streamers in liquids to permanent branched trees in elastomers, with gels exhibiting a hybrid regime [276]. The self-healing rate scaled with the liquid fraction in the crosslinked matrix, linking the two-phase microstructure to the material's ability to partially recover from electrical degradation [276].

2.6.3 | *Chile*

Federico Santa María Technical University: Research at Universidad Técnica Federico Santa María (UTFSM) has focused on degradation mechanisms in polymeric insulation studied

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through PD analysis, extending beyond the conventional 50/60 Hz regime.

Electrical treeing in epoxy resin under very low frequency (VLF, 0.1 Hz) excitation was investigated by Donoso et al. [277]. Trees at 0.1 Hz exhibited branch-type morphologies with time-to-breakdown roughly 50 times longer than at 50 Hz, a ratio that does not scale linearly with the frequency reduction, indicating degradation mechanisms beyond simple cycle counting [277]. Partial discharge pulses were analysed using nonlinear time series analysis (NLTSA), which generated richer cluster structures than conventional pulse sequence analysis (PSA) [277], with further analysis confirming deterministic chaotic PD dynamics at both frequencies [278]. However, neither approach provided a clear indicator of tree growth stage, motivating the waveform-based methods described next.

The electrical tree progression in epoxy resin under variable frequency excitation was investigated by the same group [279]. Electrical tree growth across frequencies from 0.1 to 350 Hz was probed using PD waveform techniques, identifying waveform-based parameters that enable consistent monitoring of tree growth across a wide frequency range [279]. A subsequent DWT-PCA methodology [280], applied to samples tested at 50–550 Hz, classified PD pulses into two groups associated with different branch morphologies: Group (a) with filamentary branches, and Group (b) with darker, presumably more conductive branches (Figure 23) [280]. Moreover, from a diagnostic standpoint, the repetition rate of Group (b) discharges increased by approximately one order of magnitude at the postcrossing stage, enabling identification of tree crossing, the precursor of insulation failure [280]. A comprehensive benchmarking confirmed that waveform-based parameters outperformed PRPD, PSA and NLTSA in detecting tree crossing, with lower variability across voltage amplitudes and frequencies [281].

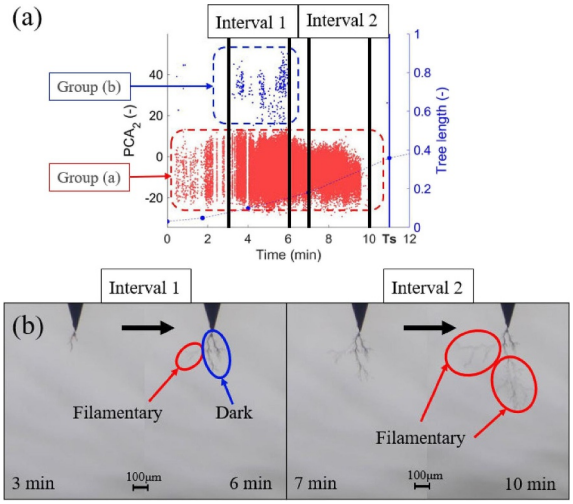


FIGURE 23 | Correlation between PD pulse groups and electrical ree branch morphology in a sample of epoxy resin at 10 kV–50 Hz: (a) Time evolution of PD activity during the first 12 min, showing Interval 1 with both Group (a) and Group (b) discharges, and Interval 2 with only Group (a) discharges; (b) Optical images of the tree at the beginning and end of each interval [280]. PD, partial discharge.

More recently, research at UTFSM has addressed the degradation of internal solid-solid interfaces in composite insulators under DC excitation, motivated by upcoming HVDC transmission in Chile. Schurch et al. [282] developed a model epoxy-silicone rubber interface with embedded electrodes. Under negative DC excitation, longer voltage steps improved breakdown performance, whereas shorter steps increased PD activity and more severe carbonisation along the tracking path, as shown in Figure 24. Notably, conventional PD parameters showed no clear evolution during degradation, highlighting the challenge of diagnosing interfacial tracking under DC [282].

Finally, at UTFSM, Ardila-Rey et al. developed PD source separation techniques for polymeric insulation diagnosis. In ref. [283], a method enabled separation of multiple PD sources and noise on a 3-D map, validated on epoxy resin and XLPE cable samples [283]. In ref. [284], the approach was extended to ultra-high frequency measurements using a dual-antenna energy-ratio method, achieving effective separation on NOMEX and methacrylate specimens even with three simultaneous sources [284].

2.7 | The United States

The University of Texas at Dallas and Virgina Tech: A distinctive feature of recent research activities in the United States is the increasing emphasis on application-driven insulation design, in which dielectric materials and insulation systems are not studied in isolation but are instead developed, optimised, and validated within their real operating environments. A representative example of this approach is the work of the research group led by Professor Mona Ghassemi at The University of Texas at Dallas—and previously at Virginia Tech—which has focused on the insulation and thermal design of MVDC power cables for future all-electric wide-body aircraft (AEA). In contrast to conventional sample-based testing in dielectric research, where simplified samples are tested under various conditions, these studies treat electrical insulation as an integral component of a fully coupled multiphysics system. This allows translation of physics-based modelling to practical design. In the context of wide-body AEA, the central objective is not merely to demonstrate dielectric strength or PD resistance but to design, fabricate and validate MVDC cable systems that simultaneously satisfy electrical, thermal, weight and volume constraints imposed by aircraft operation. A challenge investigated by this research is the operation of MVDC cables at cruising altitudes, where ambient pressure drops to approximately 20 kPa [285]. Under such low-pressure conditions,

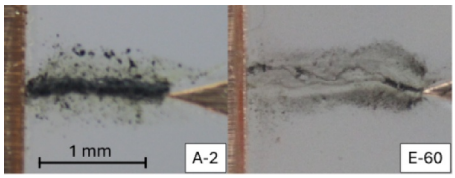


FIGURE 24 | Interfacial tracking paths at the epoxy resin/SiR interface under negative DC excitation for different voltage step durations: Shorter steps (A-2) produce darkly carbonised traces, while longer steps (E-60) result in more diffuse and lighter paths, indicating less aggressive degradation [282]. SiR, silicone rubber.

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convective heat transfer is severely diminished, resulting in a strong coupling between thermal limits, current-carrying capability (ampacity), and insulation performance. To address this, the group established a comprehensive multiphysics modelling framework in which electrostatic, thermal, and computational fluid dynamics (CFD) physics are fully coupled [285–287]. This framework enables realistic prediction of temperature rise, electric-field distribution, and heat-dissipation pathways under both atmospheric and high-altitude operating conditions. This application-driven multiphysics approach is rooted in earlier work by Professor Mona Ghassemi on polymeric insulation systems based on fibreglass-reinforced plastic, where coupled electro-thermal and CFD modelling was used to evaluate insulation performance under realistic environmental conditions, including wind, icing and partial-discharge-induced heating [288, 289]. For DC operation, the modelling framework further accounts for the strong dependence of electric-field distribution on the temperature- and field-dependent electrical conductivity of polymeric insulation materials, thereby capturing the coupled electro-thermal behaviour that dominates DC cable performance. Within this modelling environment, insulation is treated as a design variable, not a fixed material choice. These multilayer multifunctional electrical insulation (MMEI) structures incorporate high-performance polymeric insulating materials, including PI films such as Kapton MT+, fluoropolymers and silicone-based layers. The materials and layer thicknesses are selected and dimensioned based on coupled electro-thermal-CFD simulations to meet the stringent electrical, thermal, and mass constraints of aircraft MVDC operation. Core conductor diameter, insulation build-up, and overall cable geometry are optimised concurrently to achieve maximum power density with minimum mass and volume, while maintaining adequate dielectric margins under DC stress [285–287]. The approach was extended to bipolar MVDC cable architectures, including noncircular configurations such as rectangular, square and coaxial bipolar geometries [290–292], where conductor spacing and geometry were explicitly optimised by balancing electric-field stress, thermal interaction, and geometric constraints. Beyond the cable itself, cable ducts and installation environments were also incorporated into the modelling framework [293], allowing assessment of confinement effects, airflow restriction, and thermal bottlenecks that are typically neglected in insulation studies. The same application-driven multiphysics design methodology was further extended to extraterrestrial power systems, including the design and optimization of MVDC bipolar power cables for long-duration lunar surface power transmission, where insulation performance must be evaluated under extreme vacuum and severe thermal cycling conditions [294, 295]. In these studies, the modelling results were not treated as abstract predictions but were used to guide physical design and experimental validation. Optimised cable geometries and MMEI configurations were fabricated and tested under both DC voltage stress and reduced-pressure conditions, directly representative of aircraft environments [296–300]. Extensive measurements of partial-discharge characteristics and DC dielectric strength demonstrated clear performance advantages of optimised MMEI-based MVDC cables over conventional insulation systems, particularly under low-pressure operation where PD inception and breakdown behaviour are strongly altered [299, 300]. This body of work represents an application-driven approach to insulation research within the United States: electrical insulation is no longer evaluated 'in vacuum', but is instead co-designed with thermal management, geometry, installation constraints and system-level objectives.

Recent research in the United States has increasingly addressed polymeric insulation challenges in HV high-power-density power module packaging, driven by the rapid adoption of (ultra) wide-bandgap (U/WBG) semiconductor devices. In these compact modules, insulation failure is often governed by localised electric-field enhancement at ceramic–metal–polymer interfaces and triple points, rather than by bulk material properties, rendering traditional sample-based insulation testing insufficient. A representative example of this application-driven approach is the work of Professor Mona Ghassemi at The University of Texas at Dallas, where insulation behaviour is evaluated directly within realistic power-module geometries using physics-based modelling. Early studies established design-oriented electric-field analysis frameworks and mitigation strategies, including geometric field shaping and polymeric field-grading concepts [301, 302]. However, the most recent and distinctive contributions have focused on insulation performance under high-frequency and high-slew-rate voltage stress, conditions that are increasingly representative of modern WBG power electronics yet remain largely unexplored in insulation research. In particular, the work advanced the study of polymeric encapsulation materials, especially silicone gel, under high-frequency square voltage waveforms with very fast rise times, moving beyond conventional DC and power-frequency testing. These investigations demonstrated that insulation behaviour including PD inception and dielectric strength is strongly dependent on dV/dt, repetition frequency and waveform shape, rather than voltage magnitude alone [303]. Such stress conditions produce electric-field dynamics and charge processes that cannot be inferred from low-frequency or DC measurements, highlighting a critical gap in existing insulation qualification practices. Furthermore, combined material-based and geometric mitigation strategies, including nonlinear field-dependent conductivity polymeric layers and substrate protrusion techniques, were evaluated under these extreme switching conditions. Although these approaches were shown to reduce electric-field concentration under moderate conditions, the results revealed that at very high frequencies and slew rates, insulation performance can still be fundamentally limited, even when multiple mitigation strategies are applied [304]. This finding underscores the emerging insulation bottleneck associated with next-generation WBG power modules. To support insulation evaluation under such electrically noisy environments, advanced PD diagnostics, including optical detection methods, were incorporated to overcome electromagnetic interference (EMI) associated with fast switching [305].

A further distinctive contribution from the research group led by Professor Mona Ghassemi addresses the lifetime of polymeric insulation systems under high-frequency, high-slew-rate voltage stress and reduced atmospheric pressure, extending insulation research into operating regimes that have not been previously explored. In ref. [306], Type I motor winding insulation systems based on polyester-imide basecoat and polyamide-imide topcoat polymeric materials were investigated under bipolar square-wave voltages with rise times as short as 50 ns and frequencies up to 30 kHz, explicitly accounting for subatmospheric

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pressures down to 20 kPa representative of high-altitude operation of envisaged wide-body all-electric aircraft. Complementary to this, the companion paper [307] extended the investigation to much higher switching frequencies, reaching up to 200 kHz, under atmospheric pressure, enabling systematic evaluation of insulation behaviour in a frequency regime not previously examined. Together, these two studies provide a coordinated experimental assessment of polymeric insulation lifetime spanning reduced-pressure aerospace environments and extreme high-frequency excitation, well beyond the limits of conventional inverter-fed insulation testing. The results demonstrate that reduced pressure significantly accelerates partial-discharge activity and insulation degradation, whereas at very high frequencies the insulation lifetime exhibits non-monotonic behaviour, reflecting the competing roles of discharge delay, charge transport and space-charge dynamics. These findings establish new insight into polymeric insulation behaviour directly relevant to U/WBG-based motor drives and aerospace power systems, where electrical and environmental stresses exceed the scope of existing qualification practices.

NASA Glenn Research Center (GRC), NASA Ames Research Center, and University Space Research Association (USRA): Beyond aircraft electrical systems, similar insulation challenges arise in space environments where pressure, radiation, and thermal extremes simultaneously affect dielectric behaviour. NASA research centres and USRA have conducted extensive experimental research on electrical insulation systems intended for operation in extreme aerospace and space environments, with particular emphasis on HV operation, reduced mass and enhanced reliability under conditions relevant to lunar surface missions. A central outcome of this effort is the development and validation of the Micro-MMEI system, Figure 25a, originally motivated by the need to reduce insulation mass while maintaining or improving dielectric performance for future electrified aircraft and space power systems. The MMEI concept is based on stacking multiple thin polymeric dielectric layers—primarily PI (Kapton), fluoropolymers (PFA, PTFE), and selected functional layers—using controlled fuse-bonding processes. Systematic dielectric breakdown testing demonstrated that optimised MMEI configurations achieve at least 70% improvement in dielectric BDV compared to monolithic Kapton films across a wide thickness range, with the best-performing structures exhibiting up to ~91% higher breakdown strength [308], Figure 25b. This enhancement translates directly into nearly 98% reduction in required insulation thickness for equivalent dielectric strength, representing a significant improvement for mass- and volume-constrained aerospace applications. Beyond dielectric strength, NASA GRC demonstrated that the multilayer architecture inherently supports multifunctionality, including improved corona resistance, PD mitigation, moisture barriers, EMI shielding, and enhanced thermal durability. Full-scale validation was performed using 1-m-long, three-phase HV bus bar prototypes, where MMEI-insulated systems passed HiPot and PD tests up to 15 kV AC. Compared to state-of-the-art mica-based insulation systems, MMEI prototypes were shown to be ~15% lighter or ~12% thinner while meeting the same electrical qualification limits [309]. These developments are particularly relevant for lunar applications, where power transmission components must operate under vacuum, extreme thermal cycling (below −240°C to above 120°C), radiation exposure and electrostatically charged

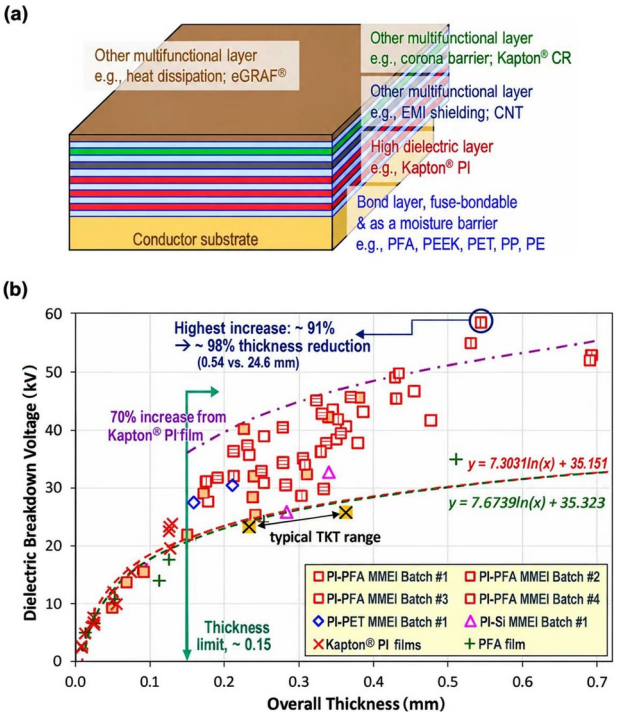


FIGURE 25 | (a) Typical design concept of MMEI structures, (b) overall dielectric performance of MMEI structures compared to SOA insulation materials [309]. MMEI, multilayer multifunctional electrical insulation. SOA, State-of-Art.

regolith [310]. NASA GRC studies highlight that conventional terrestrial insulation materials suffer accelerated ageing and discharge phenomena under such conditions, motivating lightweight multilayer insulation systems with improved resistance to electrical stress and environmental degradation. In parallel with multilayer insulation architectures, NASA GRC has also advanced thermally conductive polymer composite insulation systems aimed at improving heat dissipation in high-power-density electric machines. A representative example is the development of polyphenylsulfone (PPSU)–hBN composite films processed via twin-screw extrusion [311]. Polyphenylsulfone was selected due to its high glass transition temperature, chemical resistance, mechanical toughness and low moisture absorption, making it a promising matrix for electrified aircraft insulation systems. Systematic incorporation of micro- and nano-sized hBN platelets (up to ~24 wt.%) demonstrated simultaneous improvements in thermal conductivity and dielectric strength. Thermal conductivity increased by as much as ~370% at the highest filler loading relative to neat PPSU, whereas dielectric breakdown strength increased by approximately 16% [311]. The improvements were attributed to the formation of thermally conductive pathways facilitated by platelet alignment during extrusion and effective embedding of hBN within the polymer matrix. Importantly, even at elevated filler loadings, the composites maintained mechanical flexibility, which is critical for winding and cable fabrication. Thermal ageing experiments at 200°C (30°C below PPSU T_g) for 40 days showed that dielectric strength of higher hBN-loaded composites did not degrade and in some cases slightly improved, possibly reflecting the higher thermal stability of the hBN filler and its influence on composite behaviour during ageing [311]. These results highlight the feasibility of engineering

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thermally conductive yet dielectrically robust insulation films for megawatt-class electric propulsion systems. To further optimise manufacturability and performance tradeoffs, NASA GRC investigated heterogeneous thermoplastic networks based on blends of PPSU and thermoplastic PI with hBN fillers [312]. Co-continuous polymer morphologies were achieved through controlled composition and twin-screw extrusion, demonstrating modest improvements in thermal conductivity at comparable filler loading levels, with an observed tradeoff in dielectric strength. Blended PI/PPSU systems exhibited intermediate dielectric strength relative to neat polymers and demonstrated that filler dispersion, polymer–polymer interfaces, and processing-induced anisotropy strongly influence through-plane thermal conductivity. However, a trade-off between dielectric breakdown strength and thermal conductivity was observed at high filler contents, emphasising the need for balanced design strategies [312]. Beyond laboratory performance, NASA GRC has evaluated PPSU and PPSU–hBN composites under realistic space environmental exposure. As part of the MISSE-13 mission, pristine PPSU and PPSU–10 wt.% hBN films were exposed for approximately 0.44 years in the low Earth orbit (LEO) wake environment [313]. Post-flight inspection revealed discolouration and increased surface roughness, attributed to UV radiation and atomic oxygen exposure. Thermogravimetric analysis showed minimal mass loss ($\leq$ 0.001%), whereas Raman and ATR-FTIR spectroscopy indicated changes in C–S and ether linkages associated with radiation-induced ageing [313]. Importantly, incorporation of hBN reduced surface roughness evolution and modified degradation pathways, indicating that the presence of hBN influences surface degradation behaviour under LEO wake exposure conditions [313]. At the molecular level, a recent computational study has further examined the thermal properties of PPSU using large-scale atomistic molecular dynamics simulations [314]. These simulations predicted glass transition temperatures, thermal expansion coefficients, and thermal conductivity values consistent with experimental data, providing microscopic insight into chain conformation, density evolution and phonon-mediated heat transport mechanisms. The modelling framework establishes a predictive foundation for designing PPSU-based NCs with enhanced thermal transport while maintaining dielectric integrity. Collectively, these efforts demonstrate NASA's integrated approach to insulation development, spanning polymer chemistry, composite processing, dielectric evaluation, environmental durability testing, and molecular-scale modelling. The work extends beyond traditional dielectric strength testing to address coupled thermal–electrical performance, manufacturability and space-environment survivability, all critical for next-generation electrified aircraft and space power systems.

Georgia Institute of Technology and University of Connecticut: Although the previous sections focus on system-level behaviour and environmental stressors, other efforts address the discovery of dielectric materials themselves using data-driven approaches. A distinct research direction in the United States has emerged from the work of Professor Rampi Ramprasad and collaborators, first at the University of Connecticut and later at the Georgia Institute of Technology, focussing on data-driven discovery and inverse design of polymeric dielectric materials. Unlike conventional dielectric research, where materials are synthesised and then characterised, this approach treats polymer materials design space for dielectric applications in which structure–property relationships are learnt from data and subsequently used to propose new materials. The foundational contribution of this work is the development of physically meaningful numerical representations ('fingerprints') of molecules and polymers that capture chemical structure and connectivity (later extended to morphological descriptors). Early studies introduced hierarchical motif-based fingerprints capable of mapping chemical structures to electronic and dielectric properties using machine-learning models [315]. These descriptors enabled prediction of multiple properties and even reconstruction of candidate molecules possessing targeted characteristics, demonstrating the feasibility of inverse materials design. The methodology was extended to polymers, where fingerprints based on repeating chemical building blocks, block pairs, and triplets provided increasingly detailed representations of polymer structure [316]. To enable large-scale learning, the group generated curated first-principles databases of polymer materials containing structural, electronic, and dielectric properties. One dataset included more than one thousand polymers with computed bandgap and dielectric constant, forming a consistent foundation for rational design [317]. These databases were then used to train predictive machine-learning models that could estimate material properties rapidly, eliminating the need for exhaustive quantum-mechanical calculations. Building on this framework, the researchers introduced inverse-design strategies in which genetic algorithms search the chemical space for polymers meeting specified property targets, enabling direct discovery of candidate dielectric materials [316]. The effort culminated in the Polymer Genome platform, an informatics infrastructure linking polymer fingerprints to experimentally relevant properties such as dielectric constant, bandgap, glass-transition temperature, and density [318]. By combining high-throughput computation, curated datasets, and surrogate learning models, this platform allows on-demand property prediction and screening of new polymer chemistries.

Building on these foundational informatics tools, Ramprasad's group increasingly integrated polymer informatics with dielectric performance metrics relevant to high-field polymer dielectrics, in close collaboration with Professors Yang Cao and Gregory Sotzing at the University of Connecticut. A representative example is a study on polymer dielectrics tolerant to electric-field and temperature extremes, which established a workflow that begins with 'gold-standard' experimental measurements of temperature-dependent breakdown strength (E_{BD}) for commercial dielectric films and then derives screening guidelines using correlated, physically meaningful proxy properties [319]. In that work, the authors identify key proxies—including band gap, electron injection barrier at the aluminium electrode, and cohesive energy density—along with glass transition temperature (thermal stability proxy) and dielectric constant (polarization proxy), and use machine learning models to screen a library of over 13,000 previously synthesised polymers, followed by experimental validation of selected candidates. The study explicitly links high-field breakdown strength and elevated-temperature operation to quantifiable and screenable descriptors, rather than relying solely on dielectric constant or bandgap as isolated targets. This integrated 'informatics + physics + experiment' direction was further strengthened by high-impact demonstrations of molecularly engineered, flexible polymer dielectrics for high-temperature electrification applications. In ref. [320], they report an all-organic polyolefin-based dielectric design strategy that breaks

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the traditional inverse relationship between thermal stability (T_g) and electronic bandgap by employing a modular architecture (rigid bicyclic aliphatic motifs in the backbone to preserve high bandgap, and aromatic groups placed as side groups to raise T_g). One optimised polymer exhibits $T_g \approx 244$°C while maintaining a large bandgap of ~5 eV and significantly suppressed high-field conduction, enabling a record energy density of 6.5 J/cm^3 at 200°C—reported as an approximately two-fold improvement over the best previously reported flexible dielectric polymers or polymer composites at that temperature. Notably, this work explicitly highlights relevance to electrification applications and high-field high-temperature dielectric performance. Most recently, ref. [321] extends the same UConn–Georgia Tech ecosystem to an AI-driven discovery paradigm ('polyVERSE') that couples rule-based polymer structure generation (focused initially on ROMP-accessible chemistries) with multitask graph-neural-network property prediction and screening using application-driven thresholds on T_g, bandgap, and dielectric constant. The study reports a newly identified polynorbornene dielectric (PONB-2Me5Cl) discovered in silico and then synthesised and characterised, achieving an energy density of 8.3 J/cm^3 at 200°C—reported to exceed the performance of commercially available polymer dielectrics at this temperature. The study demonstrates a complete closed loop—AI generation → property prediction → screening → synthesis → dielectric testing—and explicitly frames the performance gap in the 85°C–200°C range where commercial solutions are limited.

Texas Instruments Incorporated and industrial HV packaging insulation: Complementing material discovery, industrial developments address insulation reliability within compact power-electronic packages where electric-field concentration becomes the dominant constraint. A complementary research direction in the United States has emerged from industrial development of HV semiconductor packaging, where insulation is not treated as a bulk material property but as a localised design constraint governed by electric-field concentration within compact device geometries. Representative contributions are found in the work of Enis Tuncer and collaborators at Texas Instruments Incorporated, where the reliability of polymeric insulation is addressed directly inside integrated circuit and power module packages rather than through standalone dielectric samples. Early studies examined the electrical behaviour of encapsulation and moulding compounds used in semiconductor packages. These materials are typically highly filled epoxy-based composites whose electrical conductivity and polarization behaviour depend strongly on filler content, moisture and processing conditions. Experimental investigations showed that moisture content, filler loading, curing conditions and sample thickness strongly influence polarization and dielectric response in HV moulding compounds [322, 323]. Measurements of DC conductivity and dielectric relaxation demonstrated that conduction is strongly influenced by the heterogeneous composite microstructure [324, 325]. These results show that insulation behaviour depends on local material composition, interfaces, and processing conditions. Subsequent work implemented package structures to manage electric-field stress. HV semiconductor packages were developed in which electric-field concentration is mitigated using geometric shaping of conductors, controlled spacing between conductive elements and incorporation of dielectric layers with engineered permittivity [326, 327]. Capacitive isolation structures implemented within organic substrates demonstrated that isolation performance was achieved through redistribution of electric-field lines within the substrate [328]. Later package concepts introduced embedded spacers, dielectric protrusions and isolated die configurations to reduce local electric-field concentration within the package geometry [329]. A further strategy involved permittivity engineering within the package. High-relative-permittivity dielectric layers and conductive field-plate concepts were used to smooth electric-field gradients at critical interfaces [330]. By tailoring the dielectric constant locally, the electric-field distribution within the package is modified to reduce peak field levels.

To conclude, research in the United States is characterised by an application-driven approach, with polymeric insulation being developed and evaluated for advanced power electronics, transportation electrification, and electric power infrastructure. The work is distinguished by the integration of multiphysics modelling, AI-assisted materials design, and reliability assessment under realistic operating conditions.

3 | Outlook

The present panel of research having been developed over the world in the last 10 years is obviously incomplete given the broadness of needs in the field of electrical insulation in power equipment and the prominent role taken by polymers in this domain. Therefore, the present work pretends by no way to be exhaustive. Below is a wrap-up of the activity summarised in this review.

3.1 | Application Field Standpoint

Regarding the application field, the increasing global electrification of our society pushes researches in our field to HV and extra HV cables notably using HVDC energy transmission. In this domain, managing the stress is particularly critical in accessories. Research in this field involving nonlinear materials and accessories design is certainly more active than reflected here due to strategic aspects and the reluctance to diffuse in the public domain. The 'standard' for polymer-insulated cables has moved from 320 to 400 kV and even 525 kV in recent years. Polymer-insulated cables have been qualified for 640 kV and standards are discussed to qualify 800 kV [192]. This goes with increasing transmission length that can be several thousand km long for submarine cables. This higher field range would probably not be covered by XLPE insulation, but rather with thermoplastic materials offering potentially greater service temperature.

Besides, much research focused on the need for insulation in power electronic applications, notably for packaging purposes with demanding requirements in terms of high-field and high-temperature resistant materials and thermal management. Aircraft electrification is at its beginning, with very large power requirements to manage for developing electrical propulsion systems and managing aeronautic environment constraints such as low pressure. Power electronics involves fast-varying stresses from PWM, and managing the insulation is a challenge as the exact impact of these stresses at the material level is still not completely understood and the distribution of stresses is not

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fully controlled. Space applications have further very demanding specifications due to the severe environmental conditions, the utmost importance of reliability, and the need for light-weight solutions, resulting in increased stresses. Aside from this mainstream, there are niche applications as cryogenic dielectrics for HTS power management. Cryogenic electrical systems could be a solution for increasing the efficiency and capacity of propulsion systems in aviation. This would lead to very complex challenges for the insulation of such systems that would need to accommodate thermal, electrical and mechanical stresses in association with materials of different nature.

3.2 | Insulating Materials Standpoint

The above needs have been addressed by investigating new materials and new solutions and approaches to designing materials. In the field of power cables, research has considered modifying XLPE to improve its performance, notably by using nanofillers. Alternatives to XLPE are currently largely explored. Thermoplastic PP-based blends indeed offer the advantage of skipping the crosslinking step and of being in principle recyclable. The service temperature can be greater than that of XLPE, allowing more power to be transmitted for a similar conductor section. There are still challenges in controlling the microstructure of the blends and the impact of microstructure, not forgetting the fact that the thermal conductivity of PP is lower than that of XLPE, which alters the gain in ampacity. Research on NCs with thermoplastic PP blends has been going on with achievements on the compatibilisation of silica nanoparticles [331]. However it is not clear at present if such materials have a real future in cable applications.

Regarding capacitors, a notable collaborative effort was within the EU project Gridable (2017–2021), aiming at developing recyclable thermoplastic NC insulation materials. Within the project, the compatibilisation of silica nanoparticles for (PP)-based high-performance capacitor insulation was deeply investigated using various routes and probing methods [332].

The problem of managing DC field distribution is tackled by working on composite materials having nonlinear properties. Ethylene-propylene rubber and silicone-based composites notably have been heavily studied associated with GO or zinc oxide fillers. Considering highly demanding applications in terms of endurance and breakdown strength, multilayer dielectrics are investigated. The question of the thermal management is also addressed in many studies by developing multilayers and (nano-)composite materials with fillers as hBN.

New routes for designing materials have been opened, with the data-driven approaches enabling materials properties anticipation based on their structures. It is believed that AI-based approaches will strongly develop in the future. It must be combined with traditional physics-based approaches that deepen our understanding and description through the modelling of charge trapping phenomena, transport mechanisms, interfacial effects and the role that polymer structure and nanofillers play in determining the electronic properties of insulation. The environmental impact of materials is addressed with the replacement of SF_6 for gas insulation. In addition, PP recyclability is put forward for the insulation of power cables and self-healing materials as vitrimers have appeared for electrical insulation [180, 232]. These aspects of greener materials and processes ought to be more investigated in the future, including consideration of recycled materials and blends [333, 334].

3.3 | Characterisation and Diagnotics Standpoint

Finally, the characterisation and testing of materials and systems have progressed and adapted to the new needs. Space charges can be measured on HV cables and start to be measured on cable accessories. Different methods, such as PEA, LIPP, LIMM, and thermal step, are available now and adapted to various shapes of materials from μm to the cm scale in thickness. PD measurements face challenges with the low and hazardous occurrence under DC stress up to the detection with applying ever faster varying stresses, such as under PWM stresses and harsh environments. Ageing and endurance of polymers, composites and blends should be better understood, at a time when new materials are coming and their long-term behaviour not really known. The research on treeing phenomena has been reactivated over several years with the involvement of new visualisation methods and the need for understanding materials at high field/frequency. The behaviour and improvement of materials in the high frequency/high field/high temperature situations is investigated and different centres have reported the availability of facilities.

3.4 | AI-Assisted Methodologies

Artificial intelligence and particularly machine learning approaches are being introduced and deeply impact our research field as many others. It is particularly applied for fast material screening [335], establishing formulation-properties relationships and for identifying signatures and advance in degradation from a diagnosis perspective.

At the material design step, machine learning was combined with first-principles calculations, notably for optimising material structure from the perspective of energy storage. The modelling methods have progressed greatly in complexity, tackling issues such as high-temperature application, stability, and electron transport, for example, refs. [321, 336]. Nevertheless, the validation by experience is still necessary, especially for the aspects of endurance of materials in situations representative of service stresses. New methodologies can be implemented at this second level: by combining experimental characterisation, electrical and dielectric measurements, multiphysics simulation and operating data, AI-assisted approaches can help establish quantitative relationships between processing parameters, measured electrical responses and application-oriented performance.

Insulation condition monitoring and diagnosis is the second largest field in which data-driven machine learning has been applied. The methods may identify drift in system behaviour and potentially the failure mechanisms. They also handle representative signatures in harsh signals. In PD detection, machine learning models such as convolutional neural networks process HV sensor data to identify and classify tiny electrical discharges before they cause system failure [337].

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With the capability to treat mass data, real-time health monitoring is envisioned combining communicating sensors with AI, for tracking insulation integrity on power grids and machinery in real time, reducing unexpected equipment breakdowns and guiding preventive maintenance [338]. Now, PD at the system scale remains a complex problem. At present, AI should be considered a supportive analytical tool that complements the knowledge and experience of HV diagnostic experts. Continued research, improved datasets and advancements in machine learning algorithms are required before fully automated PD interpretation becomes a practical reality.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. Wikipedia, "Epoxy," https://en.wikipedia.org/wiki/Epoxy.

2. Wikipedia, "Polyethylene," https://en.wikipedia.org/wiki/Polyethylene.

3. Y. Ohki, "Attracted to Dielectric Materials Research," *IEEE Electrical Insulation Magazine* 40, no. 5 (2024): 6–22.

4. K. Mori, N. Hirai, Y. Ohki, Y. Otake, T. Umemoto, and H. Muto, "Effects of Interaction Between Filler and Resin on the Glass Transition and Dielectric Properties of Epoxy Resin Nanocomposites," *IET Nanodielectrics* 2, no. 3 (2019): 92–96.

5. Y. Ohki, N. Hozumi, and Y. Tanaka, "Current Integration Method as a Highly Reliable Tool for Measuring Dielectric Properties," *IEEE Electrical Insulation Magazine* 42, no. 2 (2026): 20–32.

6. Y. Ohki, N. Hirai, and Y. Tanaka, "Effects of Exposure to Radiation and Steam on Silicone Rubber Cables Removed From a Nuclear Power Plant," *High Voltage* 11, no. 2 (2026): 482–493.

7. T. Tanaka, "Progress in Nanodielectrics: Future From the Past Decade," *IEEE Transactions on Dielectrics and Electrical Insulation* 32, no. 1 (2025): 102–116.

8. T. Tanaka, "Multifunctional Quantum Dot Nanofillers in Polymer Nanocomposites," *IEEE Transactions on Dielectrics and Electrical Insulation* 32, no. 5 (2025): 2631–2638.

9. H. Shimakawa, A. Kumada, and M. Sato, "Prevention of Leakage in Machine Learning Prediction for Polymer Composite Properties," *Journal of Chemical Information and Modeling* 64, no. 9 (2024): 3621–3629.

10. H. Suzuki, H. Shimakawa, A. Kumada, and M. Sato, "Molecular Dynamics Study of Ionic Conduction in Epoxy Resin," *IEEE Transactions on Dielectrics and Electrical Insulation* 29, no. 1 (2022): 170–177.

11. H. Yokoyama, H. Shimakawa, A. Kumada, and M. Sato, "Modulating Thermal and Electrical Conductivities in Polymers: An Approach Toward Extracting Molecular Design Rules Through Atomistic Simulations," *Applied Physics Letters* 124, no. 18 (2024): 182905.

12. A. Kumada, T. Nakamura, K. Hidaka, Y. Tsuboi, and T. Yoshimitsu, "Potential Distribution on the Stress Grading System of High-Voltage Rotating Machines–I. Measuring System," *IEEE Transactions on Dielectrics and Electrical Insulation* 22, no. 6 (2015): 3163–3169.

13. T. Nakamura, A Kumada, H Ikeda, et al., "Potential Distribution on the Stress-Grading System of High-Voltage Rotating Machines–II. Transient," *IEEE Transactions on Dielectrics and Electrical Insulation* 26, no. 5 (2019): 1495–1502.

14. T. Umemoto and T. Nakamura, "Power Density and Temperature Rise Estimation at End-Turn Stress Grading System of Large Rotating Machines Under PWM Waveform," *IEEE Transactions on Dielectrics and Electrical Insulation* 28, no. 1 (2021): 90–97.

15. M. Sato, A. Kumada, K. Hidaka, K. Yamashiro, Y. Hayase, and T. Takano, "Surface Discharges in Silicone Gel on AlN Substrate," *IEEE Transactions on Dielectrics and Electrical Insulation* 23, no. 1 (2016): 494–500.

16. S. Nakamura, A. Kumada, K. Hidaka, et al., "Electrical Treeing in Silicone Gel Under Repetitive Voltage Impulses," *IEEE Transactions on Dielectrics and Electrical Insulation* 26, no. 6 (2019): 1919–1925.

17. T. Umemoto, M. Sato, U. Tsuboi, and A. Kumada, "Influence of Applied Waveforms and Pressure on Partial Discharge Characteristics in a Converter-Fed Motor Winding Model for Electric Propulsion Aircraft," in *2025 IEEE Electrical Insulation Conference (EIC)* (IEEE, 2025), 1–4.

18. H. Shimakawa, M. Sato, A. Kumada, et al., "Temperature Dependence of Surface Charge Accumulation on DC-GIS Insulating Spacer," *IEEE Transactions on Power Delivery* 37, no. 6 (2022): 4539–4547.

19. H. Shimakawa, A. Kumada, K. Hidaka, et al., "One-Dimensional Modeling of Charge Transport in Epoxy for DC-GIS Insulating Spacer," *IEEE Transactions on Dielectrics and Electrical Insulation* 28, no. 4 (2021): 1457–1464.

20. T. Nakamura, M. Tokuhiro, A. Kumada, K. Hidaka, T. Kato, and T. Yamagiwa, "X-Ray Phase Imaging of Electrical Treeing in Filled Epoxy," in *2017 IEEE Conference on Electrical Insulation and Dielectric Phenomenon (CEIDP)* (IEEE, 2017), 777–780.

21. T. Nakamura, T. Yoshimitsu, T. Yokoi, et al., "Tree Propagation and Partial Discharge Phenomena of Nanocomposite Epoxy," in *2018 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)* (IEEE, 2018), 486–489.

22. Y. Miyazaki, H. Kojima, H. Masui, et al., "Breakdown Characteristics of Cone-Type ε-FGM Spacer for Gas Insulated Switchgears," *IEEJ Transactions on Fundamentals and Materials* 141, no. 10 (2021): 546–551.

23. K. Okamoto, N. Hayakawa, M. Hikita, et al., "Distinctive Downsizing of Cone-Type Insulating Spacer for 245 kV Class GIS by Functional Insulating Materials," in *CIGRE Science & Engineering* (2022).

24. H. K. Rachmawati, K. Kato, N. Zebouchi, and N. Hayakawa, "Electric Field Grading and Discharge Inception Voltage Improvement on HVDC GIS/GIL Spacer With Permittivity and Conductivity Graded Materials (ε/σ-FGM)," *IEEE Transactions on Dielectrics and Electrical Insulation* 29, no. 5 (2022): 1811–1817.

25. N. Hayakawa, N. Nakazawa, S. Noguchi, et al., "Breakdown Characteristics of Streaming Lubricating Oil Toward Higher Power Density Motors for Electric Powered Aircraft," in *2025 IEEE International Conference on Dielectric Liquids (ICDL)* (IEEE, 2025), 1–4.

26. K. Kimura, H. Kojima, N. Hayakawa, et al., "Electrical Insulating Properties of Cellulose Nano-Fiber (CNF) Board for Electrical Insulation Systems of Rotating Machines," in *24th International Symposium on High Voltage Engineering* (2025).

23977264, 2026, 5, Downloaded from https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/hve2.70257 by Chalmers University Of Technology, Wiley Online Library on [16/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

27. T. Takada, H. Kikuchi, H. Miyake, Y. Tanaka, M. Yoshida, and Y. Hayase, "Determination of Charge-Trapping Sites in Saturated and Aromatic Polymers by Quantum Chemical Calculation," *IEEE Transactions on Dielectrics and Electrical Insulation* 22, no. 2 (2015): 1240–1249.

28. A. Huzayyin, S. Boggs, and R. Ramprasad, "Density Functional Analysis of Chemical Impurities in Dielectric Polyethylene," *IEEE Transactions on Dielectrics and Electrical Insulation* 17, no. 3 (2010): 926–930.

29. W. Wang, Y. Tanaka, T. Takada, S. Iwata, H. Uehara, and S. Li, "Influence of Oxidation on the Dynamics in Amorphous Ethylene-Propylene-Diene-Monomer Copolymer: A Molecular Dynamics Simulation," *Polymer Degradation and Stability* 147 (2018): 187–196.

30. K. Enoki, K. Endo, H. Miyake, and Y. Tanaka, "Surface and Internal Charge Measurement in Fluorinated Polymer Irradiated by Electron Using Non-Contact Type PEA Method," *IEEJ Transactions on Fundamentals and Materials* 141, no. 12 (2021): 665–671.

31. J. Li, X. Kong, B. Du, et al., "Effects of High Temperature and High Electric Field on the Space Charge Behavior in Epoxy Resin for Power Modules," *IEEE Transactions on Dielectrics and Electrical Insulation* 27, no. 3 (2020): 832–839.

32. C. Dai, Y. Tanaka, H. Miyake, K. Sato, X. Chen, and A. Paramane, "Space-Charge Characteristics in Epoxy Composites Under Square Pulse Wave of Different Polarities With Various Frequencies at Various Temperatures," *IEEE Transactions on Dielectrics and Electrical Insulation* 29, no. 1 (2022): 137–144.

33. K. Endo, K. Enoki, H. Miyake, and Y. Tanaka, "A New Method of Measuring Electron-Hole Pairs With the PEA Method Immediately After Electron Beam Irradiation," *IEEJ Transactions on Fundamentals and Materials* 142, no. 1 (2022): 23–28.

34. T. Tohmine, K. Iguchi, K. Sonoda, et al., "The Influence of Polarity Reversal on Two-Layered EPR and LDPE Simulating DC Cable Joints," *IEEJ Transactions on Fundamentals and Materials* 139, no. 2 (2019): 78–84.

35. S. Zahra, S. Morita, M. Utagawa, et al., "Space Charge Measurement Equipment for Full-Scale HVDC Cables Using Electrically Insulating Polymeric Acoustic Coupler," *IEEE Transactions on Dielectrics and Electrical Insulation* 29, no. 3 (2022): 1053–1061.

36. G. Mazzanti, B. Diban, A. Tzimas, et al., "Space Charge Measurements on Flexible Factory Joints for HVDC Extruded Cables," *IEEE Transactions on Dielectrics and Electrical Insulation* 33, no. 1 (2026): 528–539.

37. X. Li, T. Kawashima, Y. Murakami, N. Hozumi, and P. Morshuis, "Calibration for Pulsed Electroacoustic Space Charge Measurement Using Frequency-Resolved Analysis," *IEEE Transactions on Dielectrics and Electrical Insulation* 32, no. 2 (2025): 797–804.

38. K. Yasuda, X. Li, M. Utagawa, T. Kawashima, Y. Murakami, and N. Hozumi, "Three-Dimensional Space Charge Microscopy Using a Focused Ultrasound Transducer," in *2022 9th International Conference on Condition Monitoring and Diagnosis (CMD)* (IEEE, 2022), 807–810.

39. T. Kawashima, Y. Murakami, N. Hozumi, et al., "Nanosize Filler Effect on Propagation of Electron Avalanche in Terms of Waveform Characteristics of Partial Discharge," *IEEE Transactions on Dielectrics and Electrical Insulation* 30, no. 6 (2023): 2642–2649.

40. T. Kawashima, H. Quang, Y. Murakami, and N. Hozumi, "Discrimination of Insulation Condition Based on Partial Discharge Waveform Using Deep Learning," in *2023 International Symposium on Electrical Insulating Materials (ISEIM)* (IEEE, 2023), 1–4.

41. Y. Murakami, Y. Ichiba, T. Kawashima, and N. Hozumi, "Filler Particle Size Effect on Electrically and Thermally Properties of Thermal Conductive Thermoplastic Polyimide/Hexagonal Boron Nitride Composite Materials Fabricated by the Electrostatic Adsorption Method," *IEEJ Transactions on Electrical and Electronic Engineering* 19, no. 10 (2024): 1590–1595.

42. T. Okuda, Y. Nishimura, K. Nishioka, S. Kishimoto, Y. Kikuchi, and T. Nakamura, "A 5-kV Pulse Generator With a 100-kV/μs Slew Rate Based on Series-Connected 1700-V SiC MOSFETs for Electrical Insulation Tests," *Review of Scientific Instruments* 92, no. 11 (2021), 114705.

43. Y. Kikuchi, J. Matsusue, F. Yamada, T. Okuda, and T. Nakamura, "Repetitive Partial Discharge Phenomena on Electrical Motor Coil Windings Under High-Repetition Nanosecond Pulsed Voltages Driven by SiC MOSFET Inverter," *IEEE Access* 11 (2023): 68826–68835.

44. R. Ozaki, K. Takeda, T. Yano, S. Yudate, and K. Kadowaki, "Simulation of Space Charge Dynamics in Low-Density Polyethylene Using the Gaussian Disorder Model," *IEEE Transactions on Dielectrics and Electrical Insulation* 29, no. 3 (2022): 891–897.

45. K. Kadowaki, M. Maehata, S. Yudate, and R. Ozaki, "Application of SEA Method to Power Cables for Space Charge Measurement Without Deconvolution," *IEEE Transactions on Dielectrics and Electrical Insulation* 31, no. 4 (2024): 2252–2254.

46. K. Kadowaki, S. Yudate, R. Ozaki, and M. Fukuma, "Direct Observation of Electric Field in Solid Dielectrics Using SEA Method With Piezoelectric Sensor Thicker than Test Specimen," *IEEE Transactions on Dielectrics and Electrical Insulation* 32, no. 5 (2025): 3114–3116.

47. R. Ozaki and K. Kadowaki, "Analysis of Attenuation and Dispersion of Acoustic Waves in Low-Density Polyethylene," *IEEE Transactions on Dielectrics and Electrical Insulation* 27, no. 6 (2020): 2007–2013.

48. K. Kadowaki, M. Maehata, S. Yudate, and R. Ozaki, "Direct Observation of Space Charge and Leakage Current in 6.6 kV CV Cable Using Very Long Pulse Voltage Without Deconvolution," in *2024 10th International Conference on Condition Monitoring and Diagnosis (CMD)* (IEEE, 2024), 69–72.

49. Y. Sekiguchi and M. Fukuma, "Electrical Charges and Currents Distribution Analysis in Plaque Samples by the DCIC-Q(t) Method," in *2017 International Symposium on Electrical Insulating Materials (ISEIM)* (IEEE, 2017), 609–612.

50. M. Fukuma and Y. Sekiguchi, "Parallel Measurements of Q(t) and Space Charge Distribution in PP Film," in *2023 International Symposium on Electrical Insulating Materials (ISEIM)* (IEEE, 2023), 1–4.

51. R. Kitani, S. Iwata, and T. Tsuya, "Evaluation of Behavior of Q(t) Measurement and Noise Effects," in *2024 IEEE 5th International Conference on Dielectrics (ICD)* (IEEE, 2024), 1–4.

52. R. Kitani, S. Iwata, T. Tsuya, H. Uehara, T. Okamoto, and T. Takada, "Circuit Models of Q(t) Data and Analyses of Saturation Time Dependency on Delay Parameters," *IEEE Access* 12 (2024): 39152–39165.

53. L. Safura Lumba, M. Kozako, M. Hikita, H. Sato, and M. Soeda, "Power Line Communication Application for Enhanced Partial Discharge Monitoring: From Theory to Application," *IEEE Transactions on Dielectrics and Electrical Insulation* 31, no. 6 (2024): 2915–2921.

54. Y. Yao, M. Miyagawa, M. Hikita, et al., "Partial Discharge and Degradation Characteristics of Cast Resin Transformers Due to Bipolar Impulse Application," *IEEE Transactions on Dielectrics and Electrical Insulation* 31, no. 6 (2024): 3489–3496.

55. J. Qu, S. Wang, S. Xu, N. Wang, Q. Zhang, and S. Li, "Microstructural Tailoring of XLPO for Enhanced DC Conductivity Characteristics in HVDC Cable Insulation," *Chemical Engineering Journal* 525 (2025): 170478.

56. D.-K. Kim, S. H. Lee, T. H. Kwon, et al., "Study on High-Temperature and High-Voltage Insulation Characteristics of Polypropylene Blend With Highly Packed Elastomeric Domains for Power Cable Applications," *Polymer Testing* 120 (2023): 107942.

23977264, 2026, 5, Downloaded from https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/hve2.70257 by Chalmers University Of Technology, Wiley Online Library on [16/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

57. O. Lee, D. K. Kim, H. Kim, et al., "Improving the High-Voltage Insulation Properties of Polypropylene by Introducing Trace Addition of Polyvinylidene Fluoride: An Experimental and Simulation Study," *Composites Science and Technology* 259 (2025): 110939.

58. H. Sui, K. Wu, G. Zhao, K. Yang, J.-Y. Dong, and J. Li, "Greatly Enhanced Temperature Stability of Eco-Friendly Polypropylene for Cable Insulation by Multifold Long-Chain Branched Structures," *Chemical Engineering Journal* 485 (2024): 149811.

59. K. Wu, H. Sui, Q. Qi, et al., "Small Strain-Induced Abrupt Drop in the Electrical Breakdown Strength of Polypropylene Insulation," *Nano Letters* 25, no. 45 (2025): 16270–16277.

60. X. Chi, L. Cheng, W. Liu, X. Zhang, and S. Li, "Characterization of Polypropylene Modified by Blending Elastomer and Nano-Silica," *Materials* 11, no. 8 (2018): 1321.

61. T. Zeng, L. Meng, Q. Li, et al., "Enhancing Energetic Disorder in All-Organic Composite Dielectrics for High-Temperature Capacitive Energy Storage," *Nature Communications* 16, no. 1 (2025): 5620.

62. K. Zou, P. Bai, K. Li, et al., "Electronic Cooling and Energy Harvesting Using Ferroelectric Polymer Composites," *Nature Communications* 15, no. 1 (2024): 6670.

63. Q. Li, L. Chen, M. R. Gadinski, et al., "Flexible High-Temperature Dielectric Materials From Polymer Nanocomposites," *Nature* 523, no. 7562 (2015): 576–579.

64. R. Wang, Y. Zhu, S. Huang, et al., "Dielectric Polymers With Mechanical Bonds for High-Temperature Capacitive Energy Storage," *Nature Materials* 24, no. 7 (2025): 1074–1081.

65. C. Chen, Y. Xue, X. Li, et al., "High-Performance Epoxy/Binary Spherical Alumina Composite as Underfill Material for Electronic Packaging," *Composites Part A: Applied Science and Manufacturing* 118 (2019): 67–74.

66. C. Chen, H. Wang, Y. Xue, et al., "Structure, Rheological, Thermal Conductive and Electrical Insulating Properties of High-Performance Hybrid Epoxy/Nanosilica/AgNWs Nanocomposites," *Composites Science and Technology* 128 (2016): 207–214.

67. M. Yang, Y. Zhao, Z. Wang, et al., "Surface Ion-Activated Polymer Composite Dielectrics for Superior High-Temperature Capacitive Energy Storage," *Energy & Environmental Science* 17, no. 4 (2024): 1592–1602.

68. C. Yuan, Y. Zhou, Y. Zhu, et al., "Polymer/Molecular Semiconductor All-Organic Composites for High-Temperature Dielectric Energy Storage," *Nature Communications* 11, no. 1 (2020): 3919.

69. Y. Zhou, Q. Li, B. Dang, et al., "A Scalable, High-Throughput, and Environmentally Benign Approach to Polymer Dielectrics Exhibiting Significantly Improved Capacitive Performance at High Temperatures," *Advanced Materials* 30, no. 49 (2018): 1805672.

70. A. Azizi, M. R. Gadinski, Q. Li, et al., "High-Performance Polymers Sandwiched With Chemical Vapor Deposited Hexagonal Boron Nitrides as Scalable High-Temperature Dielectric Materials," *Advanced Materials* 29, no. 35 (2017): 1701864.

71. L. Ren, H. Li, Z. Xie, et al., "High-Temperature High-Energy-Density Dielectric Polymer Nanocomposites Utilizing Inorganic Core–Shell Nanostructured Nanofillers," *Advanced Energy Materials* 11, no. 28 (2021): 2101297.

72. X. Wang, W. Cao, Z. Su, et al., "Fabrication of High Thermal Conductivity Nanodiamond/Aramid Nanofiber Composite Films With Superior Multifunctional Properties," *ACS Applied Materials and Interfaces* 15, no. 22 (2023): 27130–27143.

73. B. Ouyang, X. Cheng, K. Huang, Y. Zhang, and Z. Qin, "Effects of Conductive Carbon Black Type and Content on the Performance of Polypropylene Cable Shielding Materials," *Journal of Applied Polymer Science* 142, no. 45 (2025): e57753.

74. B. OuYang, Z. Liu, X. Wang, T. Zhang, C. Zhang, and Q. Chi, "Investigation of Electrical Properties of ZnO@Ag/EPDM Composites," *AIP Advances* 10, no. 9 (2020): 095108.

75. L. Yuan, X. Zheng, W. Zhu, B. Wang, Y. Chen, and Y. Xing, "Study on the Electrical Insulation Properties of Modified PTFE at High Temperatures," *Polymers* 16, no. 3 (2024): 316.

76. B. Du, J. Jiang, J. Li, and W. Zhu, "Effects of ZnO Magnetron Sputtering on Surface Charge and Flashover Voltage of Oil-Impregnated Paper," *High Voltage* 4, no. 4 (2019): 308–315.

77. G. C. Montanari, D. Fabiani, F. Palmieri, D. Kaempfer, R. Thomann, and R. Mulhaupt, "Modification of Electrical Properties and Performance of EVA and PP Insulation Through Nanostructure by Organophilic Silicates," *IEEE Transactions on Dielectrics and Electrical Insulation* 11, no. 5 (2004): 754–762.

78. M. Xiao, M. Zhang, and B. Du, "Crystallisation Regulation of Long-Chain Branched Polypropylene on Dielectric Performance and Energy Density for Metallised Film Capacitors," *High Voltage* 8, no. 5 (2023): 921–930.

79. M. Xiao, K. Wang, Y. Song, and B. Du, "Dielectric Performance of Polypropylene Films Modified by UV Irradiation for HVDC Capacitors," *IEEE Transactions on Dielectrics and Electrical Insulation* 31, no. 1 (2024): 176–183.

80. M. Xiao, Y. Zhao, and B. Du, "Dielectric Performance of Furan-Functionalized Polypropylene Film for HVDC Capacitors," *IEEE Transactions on Dielectrics and Electrical Insulation* 31, no. 1 (2024): 160–167.

81. M. Xiao, M. Zhang, B. Du, and K. Fan, "Improving the Dielectric Properties of Polypropylene for Metallised Film Capacitors Based on Cyclic Olefin Copolymer Blending," *IET Nanodielectrics* 7, no. 3 (2024): 140–149.

82. J. Li, S. Yao, B. Du, and W. Yao, "Analysis to Principle Problems and Future Prospect of Research on Vegetable Insulating Oils and Their Applications," *High Voltage Engineering* 41, no. 2 (2015): 353–363 (in Chinese).

83. C. Wei, Z. Huang, H. Chen, Z. Zheng, Y. Luo, and J. Li, "Antioxidant and Dielectric Properties of Vegetable Insulating Oil Through Ester Exchange," *High Voltage Engineering* 51, no. 9 (2025): 4730–4739 (in Chinese).

84. W. Yao, Z. Huang, J. Li, L. Wu, and C. Xiang, "Enhanced Electrical Insulation and Heat Transfer Performance of Vegetable Oil Based Nanofluids," *Journal of Nanomaterials* 2018 (2018): 1–12.

85. J. Chen, X. Huang, B. Sun, and P. Jiang, "Highly Thermally Conductive yet Electrically Insulating Polymer/Boron Nitride Nanosheets Nanocomposite Films for Improved Thermal Management Capability," *ACS Nano* 13, no. 1 (2018): 337–345.

86. J. Chen, H. Wei, H. Bao, P. Jiang, and X. Huang, "Millefeuille-Inspired Thermally Conductive Polymer Nanocomposites With Overlapping BN Nanosheets for Thermal Management Applications," *ACS Applied Materials and Interfaces* 11, no. 34 (2019): 31402–31410.

87. Z. Pan, C. Pan, J. Tang, B. Hu, Y. Luo, and Y. V. Serdyuk, "Influence of SiC/Epoxy Coating on Surface Charging Phenomenon at DC voltage—Part I: Charge Accumulation," *IEEE Transactions on Dielectrics and Electrical Insulation* 29, no. 4 (2022): 1333–1342.

88. Z. Pan, J. Tang, C. Pan, Y. Luo, Q. Liu, and H. He, "Contribution of Nano-SiC/Epoxy Coating With Nonlinear Conduction Characteristics to Surface Charge Accumulation Under DC Voltage," *Journal of Physics D Applied Physics* 53, no. 36 (2020): 365303.

23977264, 2026, 5, Downloaded from https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/hve2.70257 by Chalmers University Of Technology, Wiley Online Library on [16/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

89. Z. Pan, C. Pan, J. Tang, B. Hu, Y. Luo, and Y. V. Serdyuk, "Influence of SiC/Epoxy Coating on Surface Charging Phenomenon at DC voltage—Part II: Charge Dissipation," *IEEE Transactions on Dielectrics and Electrical Insulation* 29, no. 4 (2022): 1343–1352.

90. P. Han, Z. Pan, S. Mao, Y. Ye, J. Tang, and C. Pan, "Understanding the Effect of SiC/Epoxy Coating on Surface Flashover Under DC Voltage: From Surface Charge Accumulation," *Journal of Physics D Applied Physics* 56, no. 40 (2023): 405106.

91. Y. Shi, X. Chen, F.-B. Meng, Z. Hong, M. Awais, and A. Paramane, "Enhancement of Insulation Properties of Cross-Linked Polyethylene Utilizing Aromatic Voltage Stabilizers With Electron-Withdrawing and Electron-Donating Groups," *ACS Applied Polymer Materials* 4, no. 2 (2022): 1422–1430.

92. A. Paramane, X. Chen, C. Dai, and Y. Tanaka, "Correlation of Traps Inside XLPE and Polypropylene With Space Charge Dynamics Under Polarity Reversal Condition," *IET Science, Measurement and Technology* 15, no. 4 (2021): 329–342.

93. Z. An, X. Chen, C. Liu, F. Zheng, and Y. Zhang, "Significantly Reduced Fluorination Time Needed for Suppression of Space Charge in Polyethylene by Increasing the Fluorination Temperature," *Journal of Physics D Applied Physics* 45, no. 38 (2012): 385303.

94. Y. Liu, Z. An, J. Cang, Y. Zhang, and F. Zheng, "Significant Suppression of Surface Charge Accumulation on Epoxy Resin by Direct Fluorination," *IEEE Transactions on Dielectrics and Electrical Insulation* 19, no. 4 (2012): 1143–1150.

95. M. Jarvid, A. Johansson, J. M. Bjuggren, et al., "Tailored Side-Chain Architecture of Benzil Voltage Stabilizers for Enhanced Dielectric Strength of Cross-Linked Polyethylene," *Journal of Polymer Science Part B: Polymer Physics* 52, no. 16 (2014): 1047–1054.

96. M. Jarvid, A. Johansson, M. Andersson, et al., "Polyolefin Composition for Medium/High/Extra High Voltage Cables Comprising Benzil-Type Voltage Stabiliser," US Patent no. 10941276 (2021).

97. M. Jarvid, A. Johansson, R. Kroon, et al., "A New Application Area for Fullerenes: Voltage Stabilizers for Power Cable Insulation," *Advanced Materials* 27, no. 5 (2014): 897–902.

98. H. Wutzel, M. Jarvid, J. M. Bjuggren, et al., "Thioxanthone Derivatives as Stabilizers Against Electrical Breakdown in Cross-Linked Polyethylene for High Voltage Cable Applications," *Polymer Degradation and Stability* 112 (2015): 63–69.

99. M. Jarvid, A. Johansson, V. Englund, et al., "High Electron Affinity: A Guiding Criterion for Voltage Stabilizer Design," *Journal of Materials Chemistry A* 3, no. 14 (2015): 7273–7286.

100. D. Liu, A. M. Pourrahimi, R. T. Olsson, M. S. Hedenqvist, and U. W. Gedde, "Influence of Nanoparticle Surface Treatment on Particle Dispersion and Interfacial Adhesion in Low-Density Polyethylene/Aluminium Oxide Nanocomposites," *European Polymer Journal* 66 (2015): 67–77.

101. D. Liu, A. T. Hoang, A. M. Pourrahimi, et al., "Influence of Nanoparticle Surface Coating on Electrical Conductivity of LDPE/Al2O3 Nanocomposites for HVDC Cable Insulations," *IEEE Transactions on Dielectrics and Electrical Insulation* 24, no. 3 (2017): 1396–1404.

102. A. M. Pourrahimi, L. K. H. Pallon, D. Liu, et al., "Polyethylene Nanocomposites for the Next Generation of Ultralow-Transmission-Loss HVDC Cables: Insulation Containing Moisture-Resistant MgO Nanoparticles," *ACS Applied Materials and Interfaces* 8, no. 23 (2016): 14824–14835.

103. L. Pallon, A. M. Pourrahimi, D. Liu, et al., "Polymer Composition and Electrical Devices," US Patent no. 11034824 (2021).

104. X. Chen, D. Murdany, D. Liu, et al., "AC and DC Pre-Stressed Electrical Trees in LDPE and Its Aluminum Oxide Nanocomposites," *IEEE Transactions on Dielectrics and Electrical Insulation* 23, no. 3 (2016): 1506–1514.

105. A. Soroudi, Y. Ouyang, F. Nilsson, et al., "Highly Insulating Thermoplastic Nanocomposites Based on a Polyolefin Ternary Blend for High-Voltage Direct Current Power Cables," *Nanoscale* 14, no. 21 (2022): 7927–7933.

106. Y. Ouyang, A. M. Pourrahimi, A. Lund, et al., "High-Temperature Creep Resistant Ternary Blends Based on Polyethylene and Polypropylene for Thermoplastic Power Cable Insulation," *Journal of Polymer Science* 59, no. 11 (2021): 1084–1094.

107. Y. Ouyang, A. M. Pourrahimi, I. Östergren, et al., "Highly Insulating Thermoplastic Blends Comprising a Styrenic Copolymer for Direct-Current Power Cable Insulation," *High Voltage* 7, no. 2 (2022): 251–259.

108. A. Bjurström, H. Edin, H. Hillborg, et al., "A Review of Polyolefin-Insulation Materials in High Voltage Transmission; From Electronic Structures to Final Products," *Advanced Materials* 36, no. 52 (2024): 2401464.

109. M. Mauri, A. Hofmann, D. Gomez-Heincke, et al., "Click-Chemistry-Type Crosslinking of a Low-Conductivity Polyethylene Copolymer Ternary Blend for Power Cable Insulation," *Polymer International* 69, no. 4 (2020): 404–412.

110. M. Mauri, A. Peterson, A. Senol, et al., "Byproduct-Free Curing of a Highly Insulating Polyethylene Copolymer Blend: An Alternative to Peroxide Crosslinking," *Journal of Materials Chemistry C* 6, no. 42 (2018): 11292–11302.

111. Md. J. Islam, P. Altmann, T. Hammarström, et al., "Development of Sustainable Slot Liners for 800 V+ Oil-Cooled Electrical Machines for Passenger Cars," in *2025 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD)* (IEEE, 2025), 1–6.

112. M. Bailoni, O. Shtyka, T. Hammarström, and S. Nategh, "A cost-Effective and Sustainable Conductor Insulation for Electrical Machine Used on BEV Applications," *IEEE IES Resource Center* (2025).

113. C. Önneby, E. Mårtensson, U. Gäfvert, A. Gustafsson, and L. Palmqvist, "Electrical Properties of Field Grading Materials Influenced by the Silicon Carbide Grain Size," *Proceedings of the IEEE 7th International Conference on Solid Dielectrics* (2001), 43–45.

114. E. Mårtensson, U. Gäfvert, and U. Lindefelt, "Direct Current Conduction in SiC Powders," *Journal of Applied Physics* 90, no. 6 (2001): 2862–2869.

115. E. Mårtensson, U. Gäfvert, and C. Önneby, "Alternate Current Characteristics of SiC Powders," *Journal of Applied Physics* 90, no. 6 (2001): 2870–2878.

116. K. Gaska, X. Xu, S. Gubanski, and R. Kádár, "Electrical, Mechanical, and Thermal Properties of LDPE Graphene Nanoplatelets Composites Produced by Means of Melt Extrusion Process," *Polymers* 9, no. 1 (2017): 11.

117. K. Gaska, R. Kádár, A. Rybak, A. Siwek, and S. Gubanski, "Gas Barrier, Thermal, Mechanical and Rheological Properties of Highly Aligned Graphene-LDPE Nanocomposites," *Polymers* 9, no. 7 (2017): 294.

118. Z. Wang, J. K. Nelson, H. Hillborg, S. Zhao, and L. S. Schadler, "Graphene Oxide Filled Nanocomposite With Novel Electrical and Dielectric Properties," *Advanced Materials* 24, no. 23 (2012): 3134–3137.

119. W. Li, U. W. Gedde, and H. Hillborg, "Structure and Electrical Properties of Silicone Rubber Filled With Thermally Reduced Graphene Oxide," *IEEE Transactions on Dielectrics and Electrical Insulation* 23, no. 2 (2016): 1156–1163.

120. M. Wåhlander, F. Nilsson, R. L. Andersson, A. Carlmark, H. Hillborg, and E. Malmström, "Reduced and Surface—Modified

23977264, 2026, 5, Downloaded from https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/hve2.70257 by Chalmers University Of Technology, Wiley Online Library on [16/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Graphene Oxide With Nonlinear Resistivity," *Macromolecular Rapid Communications* 38, no. 16 (2017): 1700291.

121. M. Wåhlander, F. Nilsson, R. L. Andersson, et al., "Tailoring Dielectric Properties Using Designed Polymer-Grafted ZnO Nanoparticles in Silicone Rubber," *Journal of Materials Chemistry A* 5, no. 27 (2017): 14241–14258.

122. H. Greijer, N. Mirotta, E. Treossi, et al., "Tuneable Conductivity at Extreme Electric Fields in ZnO Tetrapod-Silicone Composites for High-Voltage Power Cable Insulation," *Scientific Reports* 12, no. 1 (2022): 6035.

123. R. Hussain and S. Jafari, "Measurement of Electrical Properties on EPDM Rubber-Based Composite Material Using Different Sample Configurations," in *2025 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)* (IEEE, 2025), 172–176.

124. G. Perego, C. Mazel, C. Koelblin, et al., "Development and Perspectives of Nanocomposite Thermoplastic Cable Insulation for HVDC Applications," in *Jicable-HVDC'25—International Symposium on HVDC Cable Systems*, Vol. A1–3 (2025), 6p.

125. I. Rytöluoto, M. Niittymäki, P. Seri, et al., "Biaxially Oriented Silica–Polypropylene Nanocomposites for HVDC Film Capacitors: Morphology-Dielectric Property Relationships, and Critical Evaluation of the Current Progress and Limitations," *Journal of Materials Chemistry A* 10, no. 6 (2022): 3025–3043.

126. K. Lahti, I. Rytoluoto, M. Niittymaki, E. Saarimaki, and M. Paajanen, "From Laboratory to Industrial Scale: Comparison of Short- and Long-Term Dielectric Performance of Silica-Polypropylene Capacitor Films," in *2020 IEEE 3rd International Conference on Dielectrics (ICD)* (IEEE, 2020), 661–664.

127. M. Niittymäki, I. Rytöluoto, K. Lahti, B. Diban, G. Mazzanti, and T. Rheinberger, "Novel Grafted Additives for Space Charge Mitigation in Extruded HVDC Cable Insulation," in *2025 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)* (IEEE, 2025), 572–575.

128. M. Niittymäki, "Electrical Performance of Insulating Ceramic Coatings in Different Environmental Conditions," (PhD Thesis, Tampere University, 2022).

129. E. Doedens, E. M. Jarvid, C. Frohne, and S. M. Gubanski, "Enhanced Charge Injection in Rough HVDC Extruded Cable Interfaces," *IEEE Transactions on Dielectrics and Electrical Insulation* 26, no. 6 (2019): 1911–1918.

130. E. Doedens, "Topographical Impact on Space Charge Injection, Accumulation and Breakdown in Polymeric HVDC Cable Interfaces," (PhD Thesis, Chalmers University of Technology, 2020).

131. B. Singh, E. Doedens, M. E. Jarvid, and R. Guffond, "Insight Into 525 kV HVDC Cable System Performance Through Peeling Characterizations," in *2024 IEEE 5th International Conference on Dielectrics (ICD)* (IEEE, 2024), 1–4.

132. L. E. Lundgaard, Q. Liu, O. Lesaint, and I. Madshaven, "Dielectric Performance of Transformer Liquids–Summary of a CIGRE Study," *IEEE Electrical Insulation Magazine* 39, no. 5 (2023): 7–16.

133. N. Davari, P.-O. Åstrand, M. Unge, L. E. Lundgaard, and D. Linhjell, "Field-Dependent Molecular Ionization and Excitation Energies: Implications for Electrically Insulating Liquids," *AIP Advances* 4, no. 3 (2014): 037117.

134. Ø. L. Hestad, T. G. Aakre, and L. E. Lundgaard, "Conduction and Electric Fields in Dielectric Liquids in Needle-to-Plane Gaps," *IEEE Transactions on Dielectrics and Electrical Insulation* 31, no. 5 (2024): 2433–2442.

135. I. Semenov, T. Grav Aakre, I. Gunheim Folkestad, I. Smisethjell, K. Niayesh, and L. E. Lundgaard, "Partial Discharge Inception in Ceramic Substrates Embedded in Silicone Liquid, Silicone Gel, and Mineral Oil at Fast Voltage Rise and Sinusoidal Voltage," *IEEE Transactions on Dielectrics and Electrical Insulation* 31, no. 4 (2024): 1721–1728.

136. P. Ratheiser and U. Schichler, "DC Leakage Current Measurements: Contribution for the Qualification of Extruded MVAC Cables for DC Operation," in *2021 IEEE International Conference on the Properties and Applications of Dielectric Materials (ICPADM)* (IEEE, 2021), 450–453.

137. P. Ratheiser and U. Schichler, "Impact of Semi-Conductive Layers on the DC Conductivity of XLPE MVAC Cables," in *2024 IEEE 5th International Conference on Dielectrics (ICD)* (IEEE, 2024), 1–4.

138. D. Winkel, R. Puffer, and A. Schnettler, "Investigation on the Dielectric Material Parameters and the Electric Conductivity of Syntactic Foam at the Liquid Nitrogen Temperature Range," *IEEE Transactions on Applied Superconductivity* 25, no. 3 (2015): 1–5.

139. D. Winkel, R. Puffer, and A. Schnettler, "Investigation of the Breakdown Process of Syntactic Foam Under Lightning Impulse Stress at Liquid Nitrogen Temperature," *IEEE Transactions on Dielectrics and Electrical Insulation* 22, no. 2 (2015): 1134–1141.

140. S. Seibel, R. Puffer, and A. Schnettler, "Influence of Coupling Agents on Partial Discharge and Electrical Breakdown of Syntactic Foams at LNT," *IEEE Transactions on Applied Superconductivity* 28, no. 4 (2018): 1–4.

141. S. Spelzhausen, M.-R. Ionian, and R. Plath, "Influence of Coupling Materials on Space Charge Measurements of Silicone Elastomers," in *2018 IEEE International Conference on High Voltage Engineering and Application (ICHVE)* (IEEE, 2018), 1–4.

142. S. Spelzhausen, M.-R. Ionian, and R. Plath, "Temperature Dependent Space Charge and Charge Decay Characteristics at Silicone Rubber/Silicone Grease Interfaces," in *2018 IEEE 2nd International Conference on Dielectrics (ICD)* (IEEE, 2018), 1–4.

143. S. Spelzhausen, M.-R. Ionian, R. Gerhard, and R. Plath, "Time-Resolved Measurement of Space-Charge Evolution in Dielectric Films or Slabs by Means of Repeatable Laser-Induced Pressure Pulses," *Review of Scientific Instruments* 91, no. 5 (2020): 055105.

144. F. Rösch, R. Gerhard, R. Plath, P. Rössler, and J.-P. Scholz, "Influence of Repeated Electric-Stress Application on Space-Charge Profiles and Time-Dependent Currents in Silicone Rubber," in *2024 IEEE International Conference on High Voltage Engineering and Applications (ICHVE)* (IEEE, 2024), 1–4.

145. P. Rössler, F. Rösch, J. P. Scholz, et al., "Influence of Pretreatment on the Results of Space Charge Measurements on Silicone Rubbers," in *2024 IEEE International Conference on High Voltage Engineering and Applications (ICHVE)* (IEEE, 2024), 1–4.

146. J.-P. Scholz, F. Rösch, P. Rössler, and R. Plath, "Characterisation of Space Charge Accumulation in Silicone Rubber Using Thermally Stimulated Discharge Currents (TSDC)," in *2024 IEEE International Conference on High Voltage Engineering and Applications (ICHVE)* (IEEE, 2024), 1–4.

147. M. Kahn and M. Kurrat, "Optimizing Printing Parameters on Dielectric Properties in Additive Manufacturing," in *2024 IEEE 5th International Conference on Dielectrics (ICD)* (IEEE, 2024), 1–4.

148. M. Kahn, L. Tiedemann, and M. Kurrat, "High Voltage Design of Additive Manufactured Dielectric Test Samples," *IET Conference Proceedings* 2023, no. 46 (2023): 612–616.

149. R. Hussain and V. Hinrichsen, "Thermally Stimulated Depolarization Currents on Silicone Rubber With Nanofillers," in *2018 IEEE Electrical Insulation Conference (EIC)* (IEEE, 2018), 200–203.

150. R. Hussain, J. Moxter, and V. Hinrichsen, "Influence of Temperature and Electric Field Strength on the Space Charge Behavior of Liquid Silicone Rubber With Carbon Black Nanofillers," *IEEE Transactions on Dielectrics and Electrical Insulation* 27, no. 2 (2020): 427–432.

23977264, 2026, 5, Downloaded from https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/hve2.70257 by Chalmers University Of Technology, Wiley Online Library on [16/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

151. J. Moxter and V. Hinrichsen, "Mathematical Model for Numerical Simulations of Relaxor Ferroelectric and Antiferroelectric Fillers for Nonlinear Refractive Field Control Materials in High-Voltage Insulation Systems," in *2023 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)* (IEEE, 2023), 1–8.

152. M. Kempf and M. Koch, "Experimental Setup for Measuring the Dielectric Properties of Solid Insulating Materials Under High Frequency and Mixed Frequency High Voltage Stress," in *2024 IEEE International Conference on High Voltage Engineering and Applications (ICHVE)* (IEEE, 2024), 1–4.

153. T. Lübeck, T. Müller, and M. Koch, "Comparative Conductivity Measurement on Insulating Materials for HVDC Equipment," in *2025 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)* (IEEE, 2025), 15–19.

154. C. F. Niedik, C. Freye, F. Jenau, D. Haring, G. Schroder, and J. Bittmann, "Investigation on the Electrical Characterization of Silicone Rubber Using DC Conductivity Measurement," in *2016 IEEE International Conference on Dielectrics (ICD)* (IEEE, 2016), 1114–1118.

155. P. Rumpelt and F. Jenau, "Investigation on Conductivity Measurement of Alternative Insulating Oils in Conjunction With Different Electrode Materials Under DC Stress," in *2017 IEEE 19th International Conference on Dielectric Liquids (ICDL)* (IEEE, 2017), 1–5.

156. C. F. Niedik and F. Jenau, "Investigation on Interaction Between Lubricants and Polymeric Cable Insulations," in *2018 IEEE International Conference on High Voltage Engineering and Application (ICHVE)* (IEEE, 2018), 1–4.

157. D. Haring and F. Jenau, "Apparent DC Conductivity of Silicone Rubber Compounds," in *2020 IEEE 3rd International Conference on Dielectrics (ICD)* (IEEE, 2020), 1–5.

158. M. Kosse, C. Klein, K. Frey, C. Kuettinger, T. Haupt, and M. Foehr, "Investigation of the Gas-Solid Insulating System in DC GIS Exposed to AC–DC Mixed Voltage for Offshore Bipole Applications at ± 525 kV DC," in *VDE-Fachtagung Hochspannungstechnik* (2020), 512–517: ISBN: 978-3-8007-5353-6.

159. L. Elspass, S. Schlegel, H. Bärnklau, A. Gündel, J. Proske, and M. Kosse, "Test Procedure to Assess the Resilience of Rotating Machine Insulation Systems Against Shear Stress," *IEEE Electrical Insulation Magazine* 42, no. 2 (2026): 33–41.

160. H. Hirte, S. Kornhuber, S. Braun, and P. Werle, "Review on Space Charge Induced Aging and Voltage Endurance Tests of Polymeric Insulating Materials Under High DC Voltage," in *2022 International Conference on Diagnostics in Electrical Engineering (Diagnostika)* (IEEE, 2022), 1–5.

161. L. Stahl and P. Werle, "Investigations on Different Polymers Used for Insulation in e-Mobility Applications," in *2023 IEEE Electrical Insulation Conference (EIC)* (IEEE, 2023), 1–4.

162. T. Maier and T. Leibfried, "Frequency Measurement of the Dielectric Properties of Semiconductive Layers in XLPE-Cables," in *2017 IEEE Conference on Electrical Insulation and Dielectric Phenomenon (CEIDP)* (IEEE, 2017), 692–695.

163. J. Deschler, J. Seiler, and J. Kindersberger, "Detection of Charges at the Interphase of Polymeric Nanocomposites," *IEEE Transactions on Dielectrics and Electrical Insulation* 24, no. 2 (2017): 1027–1037.

164. J. Seiler and J. Kindersberger, "Polymer-Filler Interactions and Polymer Chain Dynamics in the Interphase in Silicon Nanocomposites," in *2016 IEEE International Conference on Dielectrics (ICD)* (IEEE, 2016), 15–18.

165. A.-S. Rempe, J. Seiler, M.-S. Appavou, S. Huber, G. J. Schneider, and J. Kindersberger, "Characterization of Polymer-Filler Interactions for a Model Nanocomposite Based on Silicone Rubber," in *2016 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)* (IEEE, 2016), 639–642.

166. A.-S. Rempe, J. Kindersberger, M. Spellauge, and H. P. Huber, "Characterization of Nanocomposites Based on Silicone Rubber by Ultrashort Pulse Laser Ablation," *IEEE Transactions on Dielectrics and Electrical Insulation* 28, no. 5 (2021): 1604–1611.

167. T. Wendel, J. Kindersberger, and M. Hering, "Influence of Field Strength and Temperature on the Space Charge Distribution in Epoxy Under DC Stress," in *2018 IEEE International Conference on High Voltage Engineering and Application (ICHVE)* (IEEE, 2018), 1–4.

168. M. Stuefer and J. Kindersberger, "Electric Properties and Dielectric Spectra of Epoxy-Based Nanocomposites," in *2018 IEEE International Conference on High Voltage Engineering and Application (ICHVE)* (IEEE, 2018), 1–4.

169. R. Gerhard, "Dielectric Materials for Electro-Active (Electret) and/or Electro-Passive (Insulation) Applications," in *2019 2nd International Conference on Electrical Materials and Power Equipment (ICEMPE)* (IEEE, 2019), 91–96.

170. Q. D. Nguyen and R. Gerhard, "LDPE/MgO Nanocomposite Dielectrics for Electrical-Insulation and Ferroelectret-Transducer Applications," in *2018 IEEE 2nd International Conference on Dielectrics (ICD)* (IEEE, 2018), 1–4.

171. Q. D. Nguyen, J. Wang, D. Rychkov, and R. Gerhard, "Depth Profile and Transport of Positive and Negative Charge in Surface (2-D) and Bulk (3-D) Nanocomposite Films," in *2019 2nd International Conference on Electrical Materials and Power Equipment (ICEMPE)* (IEEE, 2019), 298–300.

172. F. Schober, S. Harrer, A. Kuchler, F. Berger, W. Exner, and C. Krause, "Transient and Steady-State DC Behavior of Oil-Impregnated Pressboard," *IEEE Electrical Insulation Magazine* 32, no. 4 (2016): 8–14.

173. L. Roth, H. P. Öftering, M. H. Zink, et al., "Investigation of Charge Carrier Transport Processes in Transformer Oil-Pressboard Barrier Systems by Simultaneous Kerr-Effect and Polarization Current Measurements," in *2022 IEEE 21st International Conference on Dielectric Liquids (ICDL)* (IEEE, 2022), 1–5.

174. L. Roth, M. H. Zink, A. Küchler, et al., "Comparison of Transient and Steady State Dielectric Behaviour of Different Oil and Oil-Pressboard Barrier Systems," *IET Conference Proceedings* 2023, no. 46 (2025): 1–7.

175. F. Vahidi, S. Tenbohlen, K. Rapp, and A. Sbravati, "Electrical Conductivity of Oil and Oil-Impregnated Pressboard Dependent on Aging Byproducts," in *2017 International Symposium on Electrical Insulating Materials (ISEIM)* (IEEE, 2017), 712–715.

176. S. Karambar and S. Tenbohlen, "Compatibility Study of Silicone Rubber and Mineral Oil," *Energies* 14, no. 18 (2021): 5899.

177. A. J. Amalanathan, F. Kopsch, A. Knapp, et al., "Interfacial Behavior of Structured Planar Silicone Interfaces for Power Cable Accessories," *IEEE Transactions on Dielectrics and Electrical Insulation* 33, no. 2 (2026): 1262–1271.

178. F. Küchler, R. Färber, and C. M. Franck, "Humidity and Temperature Effects on the Dielectric Properties of PET Film," in *2020 IEEE Electrical Insulation Conference (EIC)* (IEEE, 2020), 179–183.

179. C. M. Franck, "Green Developments in Gaseous Insulation Systems," in *2024 IEEE 5th International Conference on Dielectrics (ICD)* (IEEE, 2024), 1–13.

180. F. Bill, O. Pischler, and C. M. Franck, "Vitrimers—A Step Towards a More Sustainable Transmission Grid?," in *2025 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)* (IEEE, 2025), 650–654.

181. D. Fabiani and S. V. Suraci, "Broadband Dielectric Spectroscopy: A Viable Technique for Aging Assessment of Low-Voltage Cable Insulation Used in Nuclear Power Plants," *Polymers* 13, no. 4 (2021): 494.

23977264, 2026, 5, Downloaded from https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/hve2.70257 by Chalmers University Of Technology, Wiley Online Library on [16/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

182. S. V. Suraci, C. Li, and D. Fabiani, "Dielectric Spectroscopy as a Condition Monitoring Technique for Low-Voltage Cables: Onsite Aging Assessment and Sensitivity Analyses," *Energies* 15, no. 4 (2022): 1509.

183. S. V. Suraci, X. Colin, and D. Fabiani, "Multiscale Modeling of Permittivity of Polymers With Aging: Analysis of Molecular Scale Properties and Their Impact on Electrical Permittivity," *IEEE Transactions on Dielectrics and Electrical Insulation* 29, no. 5 (2022): 1795–1802.

184. S. V. Suraci, D. Mariani, and D. Fabiani, "Impact of Antioxidants on DC and AC Electrical Properties of XLPE-Based Insulation Systems," *IEEE Access* 11 (2023): 76132–76141.

185. G. C. Montanari, P. Seri, M. Karttunen, M. Paajanen, K. Lahti, and I. Rytöluoto, "Investigation of Nanocomposite Polypropylene for DC Capacitors: A Feasibility Study," *IEEJ Transactions on Fundamentals and Materials* 139, no. 2 (2019): 105–112.

186. G. Mazzanti, F. Wurm, C. Vergine, et al., "The Horizon Europe NEWGEN Research Project: For a New Generation of High-Voltage DC Insulation Materials, Cables, and Systems After 24 Months Since the Start of the Project," *IEEE Industry Applications Magazine* 31, no. 4 (2025): 72–82.

187. Z. Lei, D. Fabiani, C. Li, et al., "Effect of Graphene Coating on Space Charge Characteristic of XLPE and Semiconductive Layer at Different Temperatures," *IEEE Access* 7 (2019): 124540–124547.

188. J. Gao, A. Rumi, Y. He, and A. Cavallini, "Towards a Holistic Approach to Inverter-Fed Machine Design: FEM-Based PDIV Prediction of Complete Windings," *IEEE Transactions on Dielectrics and Electrical Insulation* 30, no. 6 (2023): 2870–2877.

189. A. Rumi, L. Zanotti, A. Cavallini, and P. Seri, "Coherent Electro-Thermal Qualification of the Insulation System for Electrical Machines," *IEEE Access* 14 (2026): 8188–8196.

190. G. Mazzanti, M. Marzinotto, and A. Battaglia, "A First Step Towards Predicting the Life of HVDC Cables Subjected to Load Cycles and Voltage Polarity Reversal," in *2015 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)* (IEEE, 2015), 783–786.

191. G. Mazzanti, "Updated Review of the Life and Reliability Models for HVDC Cables," *IEEE Transactions on Dielectrics and Electrical Insulation* 30, no. 4 (2023): 1371–1390.

192. G. Mazzanti, "HVDC Cable System Testing," *High Voltage* 10, no. 6 (2025): 1349–1370.

193. B. Diban, G. Mazzanti, and P. Seri, "Life-Based Geometric Design of HVDC Cables—Part 2: Effect of Electrical and Thermal Transients," *IEEE Transactions on Dielectrics and Electrical Insulation* 30, no. 1 (2023): 97–105.

194. I. Khan, F. Guastavino, L. Della Giovanna, and E. Torello, "Partial Discharge Inception Voltage Monitoring of Enameled Wires Under Thermal Stress Over Time," *Energies* 17, no. 18 (2024): 4578.

195. F. Guastavino, L. D. Giovanna, F. Gallesi, and E. Torello, "Transient Earth Voltage Sensor Measurements as a Nonintrusive Tool for Partial Discharge Analysis in Switchgears," *IEEE Transactions on Dielectrics and Electrical Insulation* 31, no. 6 (2024): 2930–2937.

196. L. Della Giovanna, F. Guastavino, and E. Torello, "Experimental Study of High-Frequency Current Transformer for Partial Discharge Detection Using Frequency and Impulse Metrics," *Metrology* 6, no. 2 (2026): 24.

197. A. Contin and A. Piccolo, "Partial Discharges Acceptance Criteria for AC Rotating Machines Insulation Systems," *IEEE Access* 12 (2024): 160219–160233.

198. A. Imburgia, P. Romano, G. Chen, et al., "The Industrial Applicability of PEA Space Charge Measurements, for Performance Optimization of HVDC Power Cables," *Energies* 12, no. 21 (2019): 4186.

199. A. Imburgia, P. Romano, G. Rizzo, F. Viola, G. Ala, and G. Chen, "Reliability of PEA Measurement in Presence of an Air Void Defect," *Energies* 13, no. 21 (2020): 5652.

200. G. Rizzo, P. Romano, A. Imburgia, and G. Ala, "Review of the PEA Method for Space Charge Measurements on HVDC Cables and Mini-Cables," *Energies* 12, no. 18 (2019): 3512.

201. G. Rizzo, P. Romano, A. Imburgia, F. Viola, and G. Ala, "The Effect of the Axial Heat Transfer on Space Charge Accumulation Phenomena in HVDC Cables," *Energies* 13, no. 18 (2020): 4827.

202. G. Rizzo, P. Romano, A. Imburgia, and G. Ala, "Partial Discharges in HVDC Cables—The Effect of the Temperature Gradient During Load Transients," *IEEE Transactions on Dielectrics and Electrical Insulation* 28, no. 5 (2021): 1767–1774.

203. A. Imburgia, G. Rizzo, P. Romano, G. Ala, and R. Candela, "Time Evolution of Partial Discharges in a Dielectric Subjected to the DC Periodic Voltage," *Energies* 15, no. 6 (2022): 2052.

204. L. Calcara, M. Pompili, and F. Muzi, "Standard Evolution of Partial Discharge Detection in Dielectric Liquids," *IEEE Transactions on Dielectrics and Electrical Insulation* 24, no. 1 (2017): 2–6.

205. U. M. Rao, I. Fofana, A. Beroual, et al., "A Review on Pre-Breakdown Phenomena in Ester Fluids: Prepared by the International Study Group of IEEE DEIS Liquid Dielectrics Technical Committee," *IEEE Transactions on Dielectrics and Electrical Insulation* 27, no. 5 (2020): 1546–1560.

206. M. Pompili, L. Calcara, L. D'Orazio, D. Ricci, A. Derviškadić, and H. He, "Joints Defectiveness of MV Underground Cable and the Effects on the Distribution System," *Electric Power Systems Research* 192 (2021): 107004.

207. A. Bareggi, P. Boffi, S. Chinosi, et al., "Current and Future Applications of HPTE Insulated Cables Systems," Paper B1-307 in *CIGRE Science & Engineering* (2019), 34–44.

208. D. Pietribiasi, G. Berardi, and A. Franchini, "Special Qualification and Characterization Tests on 525 kV HVDC Submarine Cable System," Paper C2-3, JICABLE 2023.

209. Prysmian Group, "Prysmian to Deliver the First 525 kV HVDC XLPE Submarine Cable System in the UK," (2023), https://www.prysmian.com/en/media/press-release/prysmian-first-525-kv-submarine-cable-system-in-the-uk. Accessed April 2026.

210. Prysmian, "Prysmian Takes the Next Step for Increased Power in Affordable Submarine Cables," (2026), https://www.prysmian.com/en/media/press-releases/prysmian-takes-the-next-step-for-increased-power-in-affordable-submarine-cables. Accessed April 2026.

211. W. E. Burcham, "The Cavendish High—Voltage Laboratory 1935–39," *Notes and records of the Royal Society of London* 53, no. 1 (1999): 121–134.

212. H. Yu, Q. Liu, Z. Wang, C. Krause, and M. Wilkinson, "Breakdown Characteristics of Transformer Liquids With Winding Conductor Segments Under Lightning Impulse," *IEEE Transactions on Dielectrics and Electrical Insulation* 32, no. 4 (2025): 2099–2107.

213. C. Williamson, M. J. Given, and S. J. MacGregor, "Evaluation of Ester Dielectric Liquids for Sustainable Nanosecond Pulsed Power Systems," *IEEE Transactions on Plasma Science* 54, no. 4 (2025): 1–11.

214. O. Kherif, S. Robson, H. Griffiths, N. Harid, D. Thorpe, and A. Haddad, "On the High Frequency Performance of Vertical Ground Electrodes and LRM Application," *IEEE Transactions on Electromagnetic Compatibility* 66, no. 5 (2024): 1655–1664.

215. M. Zhou, H. Wang, X. Ren, G. Chen, Y. Luo, and F. Yu, "Investigation on Effect of Semiconducting Screen on Space Charge Behaviour of Polypropylene-Based Polymers for HVDC Cables," *High Voltage* 7, no. 5 (2022): 968–981.

23977264, 2026, 5, Downloaded from https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/hve2.70257 by Chalmers University Of Technology, Wiley Online Library on [16/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

216. S. Le Roy and M. Q. Hoang, "A Bipolar Charge Transport Model to Simulate the Impact of Nanometric Scale Processes on the Space Charge Behaviour in Polyethylene," *Journal of Physics D Applied Physics* 55, no. 46 (2022): 465303.

217. S. Le Roy, A. Ndour, R. Guffond, J. Fernandez, and G. Teyssèdre, "Modelling the Ion Behaviour in Polyethylene Containing by-Products and Submitted to High DC Field Stress," *Journal of Physics D Applied Physics* 58, no. 25 (2025): 255304.

218. G. Teyssedre, T. T. N. Vu, and S. Le Roy, "Insulating Materials for HVDC Cable Accessories: Effects on the Electric Field in Nonstationary Situations," *IEEE Electrical Insulation Magazine* 38, no. 5 (2022): 6–17.

219. A. Pujol, L. Berquez, F. Baudoin, and D. Payan, "PSpice Modeling of the Pulsed Electroacoustic Method for Dispersive Polymer Sample Application," *Review of Scientific Instruments* 91, no. 10 (2020): 105112.

220. Z. J. Gibson, J. R. Dennison, and V. Griseri, "Effects of Radiation Type on Charge Transport in Aged Polymers," *IEEE Transactions on Plasma Science* 54, no. 3 (2025): 1–8.

221. N. Belkahla, G. Teyssedre, N. Saidi-Amroun, S. Mouaci, and M. Saidi, "Evaluating PET and PEN Under Gamma Irradiation: Insights into Material Stability," *Radiation Physics and Chemistry* 236 (2025): 112912.

222. D. Mendoza Lopez, G. Teyssedre, L. Boudou, et al., "Electronic Properties of Polyethylene Naphthalate as Derived From Photo-Stimulated Discharge, Luminescence Experiments and Quantum Chemical Calculation," *Journal of Physics D Applied Physics* 57, no. 31 (2024): 315502.

223. B. Robbiani, J.-L. Augé, and G. Teyssèdre, "Mechanoluminescence Driven by Oxidation Reactions in Epoxy Resins," *Polymer Degradation and Stability* 232 (2025): 111101.

224. M. Houssat, C. Villeneuve-Faure, N. Lahoud Dignat, and J.-P. Cambronne, "Nanoscale Mechanical and Electrical Characterization of the Interphase in Polyimide/Silicon Nitride Nanocomposites," *Nanotechnology* 32, no. 42 (2021): 425703.

225. L. Milliere, K. Makasheva, C. Laurent, B. Despax, L. Boudou, and G. Teyssedre, "Silver Nanoparticles as a Key Feature of a Plasma Polymer Composite Layer in Mitigation of Charge Injection Into Polyethylene Under DC Stress," *Journal of Physics D Applied Physics* 49, no. 1 (2015): 015304.

226. S. Diaham, F. Saysouk, M.-L. Locatelli, and T. Lebey, "Huge Improvements of Electrical Conduction and Dielectric Breakdown in Polyimide/BN Nanocomposites," *IEEE Transactions on Dielectrics and Electrical Insulation* 23, no. 5 (2016): 2795–2803.

227. S. Diaham, P. Lambkin, L. O'Sullivan, and B. Chen, "Intrinsic AC Dielectric Breakdown Strength of Polyimide Films at the Extreme: New Breakthrough Insights on Thickness Dependence," *Advanced Materials Interfaces* 11, no. 5 (2023): 2300822.

228. S. Diaham, I. Benfridja, and T. Kennedy, "Polyimide-Based Nanocomposites With Ultra-High Dielectric Breakdown Strength: A Review and New Record," *ACS Applied Electronic Materials* 7, no. 21 (2025): 9729–9742.

229. S. Diaham, Z. Valdez-Nava, T. T. Le, L. Leveque, L. Laudebat, and T. Lebey, "Field Grading Composites Tailored by Electrophoresis—Part 3: Application to Power Electronics Modules Encapsulation," *IEEE Transactions on Dielectrics and Electrical Insulation* 28, no. 2 (2021): 348–354.

230. G. Belijar, Z. Valdez-Nava, S. Diaham, L. Laudebat, T. B. Jones, and T. Lebey, "Dynamics of Particle Chain Formation in a Liquid Polymer Under AC Electric Field: Modeling and Experiments," *Journal of Physics D Applied Physics* 50, no. 2 (2016): 025303.

231. D. Kenfaui, Z. Valdez-Nava, L. Laudebat, et al., "Innovative Ceramic-Matrix Composite Substrates With Tunable Electrical Conductivity for High-Power Applications," *Science and Technology of Advanced Materials* 23, no. 1 (2022): 735–751.

232. B. Arati, V. Bley, P.-Y. Pichon, and G. Teyssedre, "New Self-Healing Dielectric for High-Reliability, High-Performance PCB-Embedding Materials for Power Electronics Applications," *IEEE Access* 11 (2023): 133967–133978.

233. P. Pietrzak, D. Malec, A. Picot, et al., "Improved Modelling of PDIV Evolution Over Time Under Multiple Ageing Factors for Insulation of inverter-fed Electrical Machines," *IEEE Transactions on Industry Applications* 59, no. 5 (2023): 5329–5340.

234. M. Q. Nguyen, S. Dario, D. Malec, et al., "Environmental Assessment and Dielectric Performances of the Secondary Electrical Insulation in Low Voltage Motors Impregnated by Different Techniques," *Engineering* 9, no. 10 (2017): 860–873.

235. M. Jebli, T. Martire, J.-C. Laurentie, G. Pellecuer, L. Boyer, and J. Castellon, "Development of Multicellular Converter With Magnetic Coupler for Space Charge Measurement on DC Cable," *European Journal of Engineering Education* 24, no. 5–6 (2022): 227–237.

236. H. Yahyaoui, J. Castellon, S. Agnel, et al., "Behavior of XLPE for HVDC Cables Under Thermo-Electrical Stress: Experimental Study and Ageing Kinetics Proposal," *Energies* 14, no. 21 (2021): 7344.

237. S. Akram, J. Castellon, S. Agnel, K. Zhou, J. Habas, and M. T. Nazir, "Multilayer Polyimide Nanocomposite Films Synthesis Process Optimization Impact on Nanoparticles Dispersion and Their Dielectric Performance," *Journal of Applied Polymer Science* 138, no. 4 (2020): 49715.

238. R. Chassagnoux, O. Lesaint, N. Bonifaci, O. Gallot-Lavallée, C. Creusot, and A. Girodet, "Pre-Breakdown and Breakdown Phenomena in Liquid Nitrogen With a Tape–Plane Electrode Geometry," *IEEE Transactions on Dielectrics and Electrical Insulation* 30, no. 4 (2023): 1681–1689.

239. P. Adda, O. Lesaint, N. Boussetta, and E. Vorobiev, "Vapor Bubble and Streamer Initiation in Water Under Long Duration Impulses," *IEEE Transactions on Dielectrics and Electrical Insulation* 25, no. 5 (2018): 1967–1973.

240. O. Lesaint and L. Costeanu, "Positive Streamer Inception in Cyclohexane: Experimental Characterization and Cavitation Mechanisms," *IEEE Transactions on Dielectrics and Electrical Insulation* 25, no. 5 (2018): 1949–1957.

241. I. Silva, P. Rain, L. Lacquement, and F. Gentils, "Charge Transport in a Filler-Free Silicone Rubber: Exploring Non-Linear Mechanisms and the 'Liquid-Like' Anomaly," in *2024 IEEE 5th International Conference on Dielectrics (ICD)* (IEEE, 2024), 1–4.

242. H. Khelifa, E. Vagnon, and A. Beroual, "AC Breakdown Voltage and Partial Discharge Activity in Synthetic Ester-Based Fullerene and Graphene Nanofluids," *IEEE Access* 10 (2022): 5620–5634.

243. A. Reffas, H. Moulai, and A. Beroual, "Creeping Discharges Propagating on Natural Ester Oils/Pressboard Interface Under AC and Lightning Impulse Voltages," *IEEE Transactions on Dielectrics and Electrical Insulation* 25, no. 5 (2018): 1814–1821.

244. P. Bruyere, E. Vagnon, and Y. Avenas, "Field Plate Integration for Mitigating Partial Discharge Activity in PCB-Embedded Power Electronic Modules," *Energies* 17, no. 9 (2024): 2035.

245. V. Berry, L. Zheng, P. Leblanc, S. Holé, and T. Paillat, "Numerical Investigation of Electric Charge Measurement by PWP Method at Solid and Liquid Interfaces," *Journal of Electrostatics* 132 (2024): 103991.

246. L. Zu, S. Holé, N. Lallouet, G. Gamper, and C.-É. Bruzek, "Breakdown Field Strength of Lapped Kraft Paper, PPLP, or Kapton in Liquid Nitrogen," *IEEE Transactions on Dielectrics and Electrical Insulation* 32, no. 6 (2025): 3727–3735.

23977264, 2026, 5, Downloaded from https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/hve2.70257 by Chalmers University Of Technology, Wiley Online Library on [16/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

247. S. Diaham, G. Teyssèdre, and P. Notingher, "Report on the 3rd Thematic School on Dielectrics 2024," *IEEE Electrical Insulation Magazine* 41, no. 3 (2025): 27–33.

248. X. Sidambarompoulé, P. Notingher, J.-C. Laurentie, T. Paillat, and P. Leblanc, "Thermal Stimulus Method Applied to Insulating Liquids: Numerical Analysis and Discussion of the Thermal Convection Effects," *Journal of Electrostatics* 112 (2021): 103593.

249. T. Vu-Cong, C. Toigo, F. Jacquier, et al., "Long-Term Partial Discharge Behavior of Protrusion Defect in HVDC GIS," *IEEE Transactions on Dielectrics and Electrical Insulation* 29, no. 6 (2022): 2294–2302.

250. C. Toigo, A. Perez, T. Vu-Cong, et al., "Insulating Materials Characterization for the Development of MV/HV DC Equipment," in *2022 IEEE 4th International Conference on Dielectrics (ICD)* (IEEE, 2022), 138–141.

251. R. Acheen, C. Abadie, T. Lebey, and S. Duchesne, "Electrical Stress Mapping in a Type II Machine Supplied by Inverters Using Si and SiC-Based Components," *IET Electric Power Applications* 14, no. 6 (2020): 981–990.

252. Y. Kemari, C. Van de Steen, G. Belijar, et al., "A Townsend's Secondary Ionization Coefficient Estimation Method for Partial Discharge Inception Voltage Prediction for Insulating Polymers," in *2022 IEEE 4th International Conference on Dielectrics (ICD)* (IEEE, 2022), 226–229.

253. G. Mazzanti, "High Voltage Direct Current Transmission Cables to Help Decarbonisation in Europe: Recent Achievements and Issues," *High Voltage* 7, no. 4 (2022): 633–644.

254. TenneT, "TenneT Accelerates Grid Expansion and Energy Transition," (2023), Updated 2025.

255. G. Mazzanti, B. Diban, R. E. Diaz, et al., "The Influence of Space Charges on the Life Exponent From Accelerated Life Tests on PP-Based HVDC Cable Insulation. Part 2: Binary Blends and Final Comparison With Ternary Blends," *IEEE Transactions on Dielectrics and Electrical Insulation* (2026): 1–10.

256. H. Wang, Y. Luo, M. Zhou, X. Ren, and G. Chen, "Accelerated Thermal Ageing on Performance of Polypropylene-Based Semiconducting Screen for High Voltage Direct Current Cable applications—Effect of Antioxidants," *High Voltage* 9, no. 2 (2024): 410–418.

257. P. Ketsamee, A. Vaughan, and T. Andritsch, "Surface Functionalization and Humidity on Charge Transport in PP/TiO_2 and PP/MgO Nanocomposites," *IEEE Transactions on Dielectrics and Electrical Insulation* 31, no. 4 (2024): 1738–1747.

258. A. Marian, S. Hole, N. Lallouet, E. Marzahn, and C. E. Bruzek, "Demonstration Tests of a 320-kV-Class DC Superconducting Cable for Transmission of High Powers," *IEEE Electrical Insulation Magazine* 36, no. 1 (2020): 30–40.

259. N. Liu, M. He, H. Alghamdi, et al., "An Improved Model to Estimate Trapping Parameters in Polymeric Materials and Its Application on Normal and Aged Low-Density Polyethylenes," *Journal of Applied Physics* 118, no. 6 (2015): 064102.

260. A. Hoang, Y. Serdyuk, and S. Gubanski, "Charge Transport in LDPE Nanocomposites Part II—Computational Approach," *Polymers* 8, no. 4 (2016): 103.

261. E. Doedens, E. M. Jarvid, R. Guffond, and Y. V. Serdyuk, "Space Charge Accumulation at Material Interfaces in HVDC Cable Insulation Part II—Simulations of Charge Transport," *Energies* 13, no. 7 (2020): 1750.

262. F. Saiz and N. Quirke, "The Excess Electron in Polymer Nanocomposites," *Physical Chemistry Chemical Physics* 20, no. 43 (2018): 27528–27538.

263. Y. Ren, K. Wu, D. F. Coker, and N. Quirke, "Thermal Transport in Model Copper-Polyethylene Interfaces," *Journal of Chemical Physics* 151, no. 17 (2019): 174708.

264. F. Saiz, D. Cubero, and N. Quirke, "The Excess Electron at Polyethylene Interfaces," *Physical Chemistry Chemical Physics* 20, no. 39 (2018): 25186–25194.

265. U. W. Gedde, M. Unge, F. Nilsson, and M. S. Hedenqvist, "Mass and Charge Transport in Polyethylene—Structure, Morphology and Properties," *Polymer* 266 (2023): 125617.

266. Clean Aviation, "Clean Sky 2 Achievement Report 2014–2024," (2025).

267. Clean Aviation, "Clean Aviation Joint Undertaking," (2026).

268. C. Emersic and I. Cotton, "Experimental Comparison of Partial Discharge Between Fast-Switching Pulse Waves and Square Waves," *Journal of Physics D Applied Physics* 55, no. 38 (2022): 385502.

269. Y. A. O. Assagra, R. A. P. Altafim, R. A. C. Altafim, and J. P. Carmo, "Piezoelectrets With Well-Defined Cavities Produced From 3D-Printed Acrylonitrile Butadiene Styrene Structures," *Electronics Letters* 51, no. 24 (2015): 2028–2030.

270. Y. A. O. Assagra, R. A. P. Altafim, J. P. do Carmo, et al., "A New Route to Piezo-Polymer Transducers: 3D Printing of Polypropylene Ferroelectrets," *IEEE Transactions on Dielectrics and Electrical Insulation* 27, no. 5 (2020): 1668–1674.

271. D. R. de Luna, T. Palitó, Y. Assagra, et al., "Ferroelectret-Based Hydrophone Employed in Oil Identification-A Machine Learning Approach," *Sensors* 20, no. 10 (2020): 2979.

272. J. A. Giacometti, "Constant-Current Corona Triode Adapted and Optimized for the Characterization of Thin Dielectric Films," *Review of Scientific Instruments* 89, no. 5 (2018): 055109.

273. J. A. Giacometti, O. N. Oliveira, and R. M. Faria, "Investigation of Ferroelectricity and Piezoelectricity in Polar and Non-Polar Polymers," *Brazilian Journal of Physics* 52, no. 3 (2022): 73.

274. T. V. Ferreira, G. S. Bolacell, M. A. da Rosa, et al., "Technological Development of a Composite Insulator for High Voltage Transmission Line Monitoring," *IEEE Electrical Insulation Magazine* 39, no. 2 (2023): 7–16.

275. V. S. Andrade, W. C. Boaventura, M. A. Neves, and X. Granados, "Dielectric Characterization of NKN in LN2 Using a Proposed Arrangement," *IEEE Transactions on Applied Superconductivity* 34, no. 3 (2024): 1–5.

276. L. M. Salvatierra, L. I. Kovalevski, P. L. Dammig Quina, et al., "Self-Healing During Electrical Treeing: A Feature of the Two-Phase Liquid-Solid Nature of Silicone Gels," *IEEE Transactions on Dielectrics and Electrical Insulation* 23, no. 2 (2016): 757–767.

277. P. Donoso, R. Schurch, J. Ardila, and L. Orellana, "Analysis of Partial Discharges in Electrical Tree Growth Under Very Low Frequency (VLF) Excitation Through Pulse Sequence and Nonlinear Time Series Analysis," *IEEE Access* 8 (2020): 163673–163684.

278. P. Donoso, R. Schurch, and J. Ardila-Rey, "Partial Discharges in Electrical Trees Grown at 0.1 (VLF) and 50 Hz Analyzed Using PRPD and NLTSA," in *2021 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)* (IEEE, 2021), 200–203.

279. C. Madariaga, R. Schurch, J. Ardila-Rey, O. Muñoz, and S. Fingerhuth, "Partial Discharge Electrical Tree Growth Identification by Means of Waveform Source Separation Techniques," *IEEE Access* 9 (2021): 64665–64675.

280. O. Muñoz, R. Schurch, and J. A. Ardila-Rey, "Electrical Tree Growth Identification by Means of Discrete Wavelet Transform (DWT) and Principal Component Analysis (PCA)," *IEEE Transactions on Instrumentation and Measurement* 72 (2023): 1–9.

23977264, 2026, 5, Downloaded from https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/hve2.70257 by Chalmers University Of Technology, Wiley Online Library on [16/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

281. R. Schurch, O. Munoz, J. Ardila-Rey, P. Donoso, and V. Peesapati, "Identification of Electrical Tree Aging State in Epoxy Resin Using Partial Discharge Waveforms Compared to Traditional Analysis," *Polymers* 15, no. 11 (2023): 2461.

282. R. Schurch, D. Herrera, D. Figueroa, and J. Ardila-Rey, "Characterization of Degradation and Breakdown of Silicone-Epoxy Resin Interface Under DC," in *2025 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)* (IEEE, 2025), 93–96.

283. J. A. Ardila-Rey, R. Schurch, N. M. Poblete, S. Govindarajan, O. Muñoz, and B. A. de Castro, "Separation of Partial Discharges Sources and Noise Based on the Temporal and Spectral Response of the Signals," *IEEE Transactions on Instrumentation and Measurement* 70 (2021): 1–13.

284. J. A. Ardila-Rey, M. Cerda-Luna, R. Rozas-Valderrama, B. Albuquerque de Castro, A. L. Andreoli, and B. Cevallos, "A New Technique for Separation of Partial Discharge Sources and Electromagnetic Noise in Radiofrequency Measurements Using Energy Ratios of Different Antennas," *High Voltage* 6, no. 3 (2021): 525–530.

285. A. Azizi, M. Ghassemi, and J. Lehr, "Heat Transfer Challenges for MVDC Power Cables Used in Wide Body all Electric Aircraft Under Low Pressures," *IEEE Access* 10 (2022): 111811–111819.

286. A. Azizi and M. Ghassemi, "Design of High Power Density MVDC Cables for Wide-Body all Electric Aircraft," *IEEE Transactions on Dielectrics and Electrical Insulation* 30, no. 5 (2023): 2315–2324.

287. A. Azizi and M. Ghassemi, "An Analysis of Parameters Affecting Ampacity in Aircraft Bipolar MVDC Power Cables via Coupled Electrical, Thermal, and Computational Fluid Dynamic Modelling," *High Voltage* 9, no. 6 (2024): 1208–1220.

288. M. Ghassemi and M. Farzaneh, "Coupled Computational Fluid Dynamics and Heat Transfer Modeling of the Effects of Wind Speed and Direction on Temperature Increase of an Ice-Covered FRP Live-Line Tool," *IEEE Transactions on Power Delivery* 30, no. 5 (2015): 2268–2275.

289. M. Ghassemi, M. Farzaneh, and W. A. Chisholm, "A Coupled Computational Fluid Dynamics and Heat Transfer Model for Accurate Estimation of Temperature Increase of an Ice-Covered FRP Live-Line Tool," *IEEE Transactions on Dielectrics and Electrical Insulation* 21, no. 6 (2014): 2628–2633.

290. A. Saha, A. Azizi, and M. Ghassemi, "Optimal Bipolar MVDC Power Cable Designs for Future Wide-Body all Electric Aircraft," *IEEE Transactions on Dielectrics and Electrical Insulation* 31, no. 4 (2024): 2074–2083.

291. A. Saha and M. Ghassemi, "Optimized Design of ± 5 kV, 1 kA Rectangular Power Cable for a Low Pressure of 18.8 kPa for Envisioned all-Electric Wide-Body Aircraft," *IEEE Access* 12 (2024): 28654–28665.

292. A. Saha and M. Ghassemi, "Design and Environmental Performance of Rectangular Bipolar Cables for all-Electric Wide-Body Aircraft," *IEEE Transactions on Industry Applications* 62, no. 3 (2025): 5386–5395.

293. A. Saha and M. Ghassemi, "Design and Analysis of Medium Voltage DC Cable Ducts for Electric Aircraft Considering Thermal and Electrical Insulation Requirements," *IEEE Transactions on Plasma Science* 53, no. 8 (2025): 2058–2067.

294. A. Saha and M. Ghassemi, "Designing High-Power Density MVDC Bipolar Power Cables for Power Transmission on the Moon," *IEEE Transactions on Aerospace and Electronic Systems* 61, no. 2 (2025): 5079–5087.

295. A. Saha and M. Ghassemi, "Optimal Design of High-Power Density MVDC Bipolar Power Cables for Lunar Power Transmission," *Aerospace* 11, no. 8 (2024): 685.

296. M. A. Rahman, A. Saha, and M. Ghassemi, "Optimized Fabrication Process and PD Characteristics of MVDC Multilayer Insulation Cable Systems for Next Generation Wide-Body All-Electric Aircraft," *Energies* 17, no. 12 (2024): 3040.

297. S. Chowdhury, A. Saha, M. A. Rahman, S. P. Kalakonda, and M. Ghassemi, "Study of Partial Discharge Characteristics of Optimally Fabricated MMEI Flat Samples Under DC and Their DC Dielectric Strength for Applications in Envisaged all-Electric Wide-Body Aircraft," *IEEE Access* 12 (2024): 88547–88557.

298. A. Saha, S. Chowdhury, M. Asifur Rahman, and M. Ghassemi, "Analysis of Partial Discharge Characteristics and Dielectric Strength in Multilayer Insulation Systems for MVDC Cables in Future all-Electric Wide-Body Aircraft," *IEEE Transactions on Dielectrics and Electrical Insulation* 32, no. 4 (2025): 2284–2293.

299. S. Chowdhury, M. A. Rahman, and M. Ghassemi, "Comparative Analysis of Partial Discharge and Dielectric Strength of Multilayer Multifunctional Electrical Insulation (MMEI) Samples Under AC and DC Conditions at Atmospheric and Low Pressure," *IEEE Transactions on Plasma Science* 53, no. 9 (2025): 2401–2409.

300. M. A. Rahman, S. Chowdhury, and M. Ghassemi, "Comparative Study of Partial Discharge Characteristics and Dielectric Strength in Multilayer Multifunctional Electrical Insulation (MMEI)-Based and Conventional MVDC Power Cables for all Electric Aircraft," *IEEE Transactions on Plasma Science* 54, no. 3 (2026): 1180–1191.

301. M. M. Tousi and M. Ghassemi, "Combined Geometrical Techniques and Applying Nonlinear Field Dependent Conductivity Layers to Address the High Electric Field Stress Issue in High Voltage High-Density Wide Bandgap Power Modules," *IEEE Transactions on Dielectrics and Electrical Insulation* 27, no. 1 (2020): 305–313.

302. M. M. Tousi and M. Ghassemi, "Characterization of Nonlinear Field-Dependent Conductivity Layer Coupled With Protruding Substrate to Address High Electric Field Issue Within High-Voltage High-Density Wide Bandgap Power Modules," *IEEE Journal on Emerging and Selected Topics in Power Electronics* 8, no. 1 (2020): 343–350.

303. P. Adhikari, Y. Sun, M. Ghassemi, J. Hu, and J. He, "Dielectric Breakdown Characteristics of Silicone Gel for (U)WBG Power Modules Under AC, DC, and High-Frequency Square Wave Stress," *IEEE Transactions on Dielectrics and Electrical Insulation* (2026): 1.

304. P. Adhikari and M. Ghassemi, "Electric Field Mitigation in (U)WBG Power Module Using Nonlinear Field-Dependent Conductivity Layer and Protruding Substrate Under High-Frequency, High-Slew-Rate Square Wave Voltages," *IEEE Transactions on Dielectrics and Electrical Insulation* 32, no. 5 (2025): 3078–3088.

305. P. Adhikari, B. Adhikari, E. Arafat, and M. Ghassemi, "Comparative Analysis of Partial Discharge Phenomena in Silicone Gel Under DC Voltage Utilizing Optical and Electrical Techniques for (U)WBG Power Module Applications," *IEEE Transactions on Dielectrics and Electrical Insulation* 33, no. 1 (2026): 651–660.

306. S. P. Kalakonda, M. Abedin Khan, and M. Ghassemi, "Evaluation of Insulation Lifetime Under Short Rise Time and High-Frequency Square Wave Voltages at Subatmospheric Pressures," *IEEE Transactions on Dielectrics and Electrical Insulation* 33, no. 1 (2026): 462–470.

307. E. Arafat, M. A. Rahman, F. Islam, and M. Ghassemi, "Time to Breakdown for Type I Motor Winding Insulation Under High Frequency, High Slew Rate Square Wave Voltages," *High Voltage* (2026): hve2.70174.

308. E. E. Shin, "Development of High Voltage Micro-Multilayer Multifunctional Electrical Insulation (MMEI) System," in *AIAA Propulsion and Energy 2019 Forum* (American Institute of Aeronautics and Astronautics, 2019), 1–14.

309. E.-S. E. Shin, "Feasibility of Micro-Multilayer Multifunctional Electrical Insulation (MMEI) System for High Voltage Applications," in *2023 IEEE Electrical Insulation Conference (EIC)* (IEEE, 2023), 1–6.

23977264, 2026, 5, Downloaded from https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/hve2.70257 by Chalmers University Of Technology, Wiley Online Library on [16/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

310. M. Lizcano, T. S. Williams, E.-S. E. Shin, D. Santiago, and B. Nguyen, "Aerospace Environmental Challenges for Electrical Insulation and Recent Developments for Electrified Aircraft," *Materials* 15, no. 22 (2022): 8121.

311. T. Williams, B. Nguyen, and W. Fuchs, "Polyphenylsulfone-hBN Composite Insulation," in *2020 IEEE 3rd International Conference on Dielectrics (ICD)* (IEEE, 2020), 541–545.

312. W. K. Fuchs, R. L. Weaver, B. N. Nguyen, and T. S. Williams, "Balancing Manufacturability With Performance: Achieving Extrudable, High Thermal Conductivity, and Dielectrically Robust Thermoplastic Composites," *IEEE Transactions on Dielectrics and Electrical Insulation* 32, no. 4 (2025): 1890–1895.

313. T. S. Williams, W. K. Fuchs, B. N. Nguyen, K. K. de Groh, and D. Santiago, "Exposure of Polyphenylsulfone and Polyphenylsulfone-Hexagonal Boron Nitride Composite Films in the LEO Wake Environment," *MRS Advances* 9, no. 10 (2024): 725–729.

314. E. N. Skountzos, A. Ravichandran, M. Lizcano, and J. W. Lawson, "Molecular Dynamics Simulations for the Prediction of the Conformational, Dynamic, and Thermal Properties of Poly(Phenylsulfone) (PPSU) and Their Dependence on Molecular Weight," *Industrial and Engineering Chemistry Research* 64, no. 14 (2025): 7360–7369.

315. T. D. Huan, A. Mannodi-Kanakkithodi, and R. Ramprasad, "Accelerated Materials Property Predictions and Design Using Motif-based Fingerprints," *Physical Review B: Condensed Matter* 92, no. 1 (2015): 014106.

316. A. Mannodi-Kanakkithodi, G. Pilania, T. D. Huan, T. Lookman, and R. Ramprasad, "Machine Learning Strategy for Accelerated Design of Polymer Dielectrics," *Scientific Reports* 6, no. 1 (2016): 20952.

317. T. D. Huan, A. Mannodi-Kanakkithodi, C. Kim, V. Sharma, G. Pilania, and R. Ramprasad, "A Polymer Dataset for Accelerated Property Prediction and Design," *Scientific Data* 3, no. 1 (2016): 160012.

318. C. Kim, A. Chandrasekaran, T. D. Huan, D. Das, and R. Ramprasad, "Polymer Genome: A Data-Powered Polymer Informatics Platform for Property Predictions," *Journal of Physical Chemistry C* 122, no. 31 (2018): 17575–17585.

319. C. Wu, L. Chen, A. Deshmukh, et al., "Dielectric Polymers Tolerant to Electric Field and Temperature Extremes: Integration of Phenomenology, Informatics, and Experimental Validation," *ACS Applied Materials and Interfaces* 13, no. 45 (2021): 53416–53424.

320. A. A. Deshmukh, C. Wu, O. Yassin, et al., "Flexible Polyolefin Dielectric by Strategic Design of Organic Modules for Harsh Condition Electrification," *Energy & Environmental Science* 15, no. 3 (2022): 1307–1314.

321. R. Gurnani, S. Shukla, D. Kamal, et al., "AI-assisted Discovery of High-Temperature Dielectrics for Energy Storage," *Nature Communications* 15, no. 1 (2024): 6107.

322. A. Garcia, N. Warner, N. A. D'Souza, et al., "Reliability of High-Voltage Molding Compounds: Particle Size, Curing Time, Sample Thickness, and Voltage Impact on Polarization," *IEEE Transactions on Industrial Electronics* 63, no. 11 (2016): 7104–7111.

323. D. D. Cornigli, S. Reggiani, A. Gnudi, et al., "Electrical Characterization of Epoxy-Based Molding Compounds for Next Generation HV ICs in Presence of Moisture," *Microelectronics Reliability* 88, no. 90 (2018): 752–755.

324. E. Tuncer, "Direct Current Conductivity of Semiconductor Packaging Mold Compounds," in *2018 IEEE Electrical Insulation Conference (EIC)* (IEEE, 2018), 381–384.

325. M. P. McGarry, E. Tuncer, and M. Lee, "Millimeter-Wave Complex Permittivity of Silica/Alumina-Filled Epoxy-Molding Compounds," *Journal of Infrared, Millimeter and Terahertz Waves* 41, no. 10 (2020): 1189–1198.

326. E. Tuncer, "High Voltage Semiconductor Device Lead Frame and Method of Fabrication," US Patent #11,881,445 B2 (2024).

327. E. Tuncer, "Electric Field Control for Bond Pads in Semiconductor Device Package," US Patent #11,881,461 B2 (2024).

328. E. Tuncer, M. Gupta, D. Heussner, S. O'Connor, and T. Tran, "Organic Substrate High-Voltage Performance: Plausible Capacitive Isolation Technology in Integrated Circuit Package Bill of Materials," *Electrical Engineering* 101, no. 3 (2019): 1053–1058.

329. E. Tuncer, "Semiconductor Device Package With Isolated Semiconductor Die and Electric-Field Curtailment," US Patent #12,266,595 B2 (2025).

330. E. Tuncer, "Integrated High Voltage Electronic Device With High Relative Permittivity Layers," US Patent # US 2025/0111987 A1 (2025).

331. X. He, I. Rytoluoto, R. Anyszka, et al., "Silica Surface-Modification for Tailoring the Charge Trapping Properties of PP/POE Based Dielectric Nanocomposites for HVDC Cable Application," *IEEE Access* 8 (2020): 87719–87734.

332. A. Mahtabani, D. La Zara, M. Niittymäki, et al., "Molecular Layer Deposition of Polyurea on Silica Nanoparticles and Its Application in Dielectric Nanocomposites," *Journal of Physical Chemistry C* 127, no. 24 (2023): 11736–11747.

333. A. K. Diallo, E. Helal, G. Gutiérrez, et al., "Graphene: A Multifunctional Additive for Sustainability," *Sustainable Materials and Technologies* 33 (2022): e00487.

334. I. Shirzaei Sani, N. R. Demarquette, and E. David, "Enhancing the Dielectric Properties of Recycled Polyolefin Streams Through Blending," *Sustainability* 17, no. 9 (2025): 4123.

335. S. Takamoto, C. Shinagawa, D. Motoki, et al., "Towards Universal Neural Network Potential for Material Discovery Applicable to Arbitrary Combination of 45 Elements," *Nature Communications* 13, no. 1 (2022): 2991.

336. S. Hu, L. Meng, M. Wang, et al., "Rational Design of Polymeric Dielectrics Guided by Insightful Understanding of Electron Transfer/Transport in Aperiodic Systems," *npj Computational Materials* 12, no. 1 (2026): 181.

337. R. A. M. Dalila and A. K. Turkben, "Artificial Intelligence Based Partial Discharge Detection Using CNN and KNN to Increase the Quality of Electrical Insulation," *Discover Computing* 28, no. 1 (2025): 101.

338. M. Florkowski and P. Mikrut, "Real-Time Generation of Synthetic Partial Discharge Images for AI-Assisted Diagnostics," *Expert Systems With Applications* 331 (2026): 133263.

23977264, 2026, 5, Downloaded from https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/hve2.70257 by Chalmers University Of Technology, Wiley Online Library on [16/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License